Title

Work Plan for Howard A. Hanson Dam Forecast Informed Reservoir Operations

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FORECAST INFORMED RESERVOIR OPERATIONS (FIRO)

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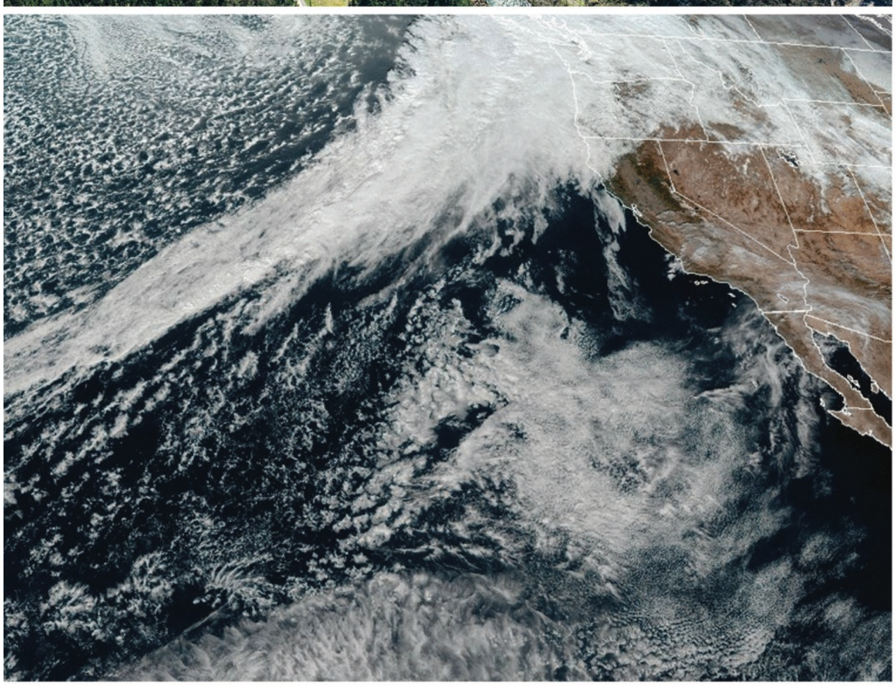

Howard A. Hanson FIRO Steering Committee

- **Marty Ralph:** Director, CW3E, Scripps Institution of Oceanography, UC San Diego
- **Cary Talbot:** National Lead, FIRO Program, Engineer Research and Development Center, USACE
- **Jessica Knickerbocker:** Tacoma Water (Tacoma Public Utilities)
- **Sara Marxen:** USACE Seattle District
- **Joe Intermill:** National Oceanic and Atmospheric Administration (NOAA) National Weather Service, Northwest River Forecast Center
- **Kevin Werner:** NOAA Northwest Fisheries Science Center
- **Mary Strazer:** King County Flood Management
- **Eric Warner:** Muckleshoot Indian Tribe
- **Nancy Rapin:** Muckleshoot Indian Tribe
- **Joe Forbis:** USACE Engineer Research and Development Center

KING COUNTY FLOOD CONTROL DISTRICT

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Center for Western Weather and Water Extremes SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

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TACOMA PUBLIC UTILITIES

MUCKLESHOOT INDIAN TRIBE

NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION U.S. DEPARTMENT OF COMMERCE

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Abbreviations

For brevity, this document uses the following abbreviations:

Abbreviation	Definition
ac-ft	acre-feet
AR	atmospheric river
AWSP	Additional Water Storage Project
cfs	cubic feet per second
CHPS	Community Hydrologic Prediction System
CW3E	Center for Western Weather and Water Extremes
CWMS	Corps Water Management System
DST	decision support tool
FDWR	first diversion water right
FIRO	Forecast Informed Reservoir Operations
FVA	Final Viability Assessment
HAHD	Howard A. Hanson Dam
HEC	Hydrologic Engineering Center
HEC-HMS	HEC Hydrologic Modeling System
HEFS	Hydrologic Ensemble Forecast System
HEMP	hydrologic engineering management plan
kcfs	1,000 cubic feet per second
kg m-2 s-1	kilogram meters squared per second
m	meter
m^3/s	cubic meters per second
mb	millibar
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NWFRC	Northwest River Forecast Center
NWS	National Weather Service
PVA	Preliminary Viability Assessment
RCP	representative concentration pathway
SDWR	second diversion water right
SSP	Second Supply Project
USACE	United States Army Corps of Engineers
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WCM	Water Control Manual
WCP	Water Control Plan
WDFW	Washington State Department of Fish & Wildlife
WY	water year

Section 1. Introduction

Howard A. Hanson Dam (HAHD), owned and operated by the U.S. Army Corps of Engineers (USACE) Seattle District and depicted in Figure 1-1 below, was built in 1961 on the Green River, in the central Cascade Mountains in King County, Washington. Eagle Gorge Reservoir is the name of the water body impounded by HAHD. The dam protects communities in the Green River Valley—including Auburn, Kent, Tukwila, and Renton—and an estimated $21.5 billion in property.

Figure 1-1*. HAHD and Eagle Gorge Reservoir.*

In addition to reducing flood risk, the dam provides flow augmentation for fish in the summer and fall, including endangered Chinook salmon and steelhead, and municipal water supply for about 700,000 people served by Tacoma Water and partners. Tacoma Water relies on water storage at the dam to meet summer peak demand and minimum instream flow requirements. Tacoma Water's primary water source is a diversion from the Tacoma Headworks Diversion Dam on the Green River, a few miles downstream of HAHD (Figure 1-2).

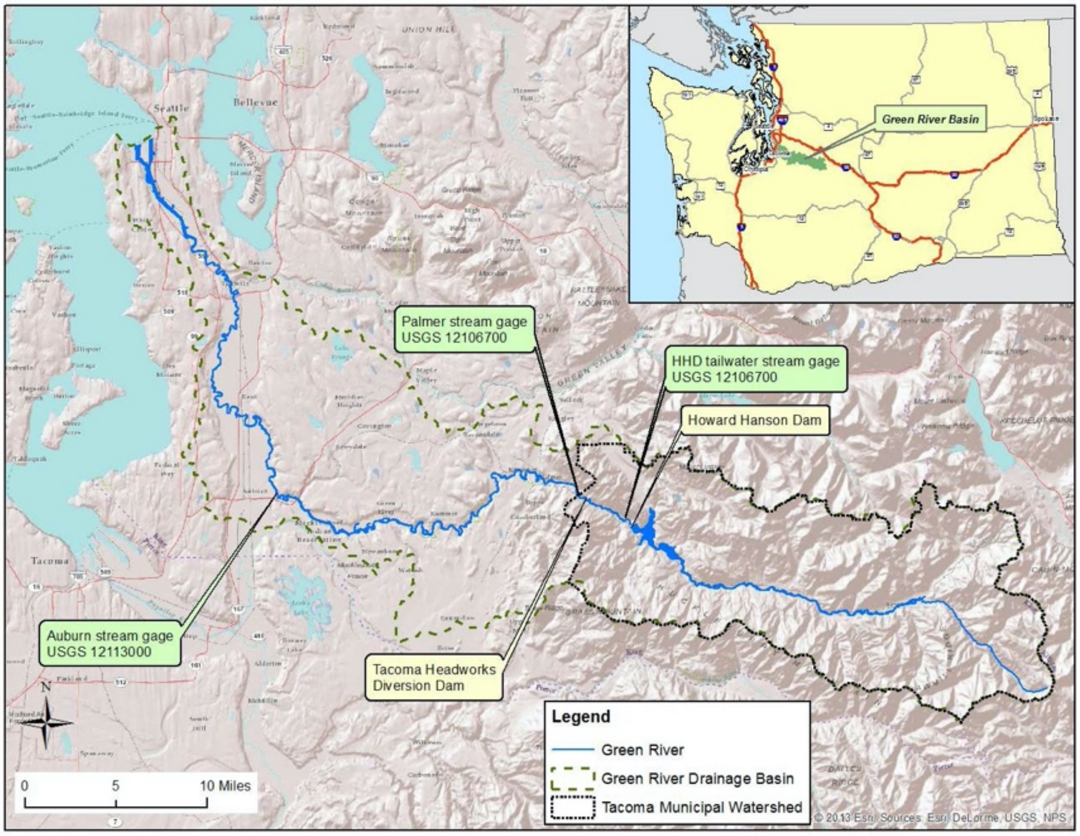

Figure 1-2. *Map of the Green River basin.*

The reservoir, filled each spring from precipitation and runoff from the Cascade Mountains' snowpack, is operated to be at roughly 50% capacity at the start of the summer and is emptied before the winter, when its main function is flood risk management. Atmospheric Rivers (ARs) are the dominant type of storm responsible for over 93 percent of all flood costs in the state of Washington, according to National Flood Insurance Program payouts for flood damages from 1978 to 2017 (Corringham et al. 2019). AR precipitation is expected to contribute 15–20 percent more of total precipitation in the latter half of the 21st century, and the most extreme ARs are projected to become more frequent as the climate warms (Gershunov et al. 2019). Decreased snowpack and earlier peak flows are also projected to occur with climate change (Mauger et al. 2015). Thus, improved AR forecasts are critical for future reservoir management.

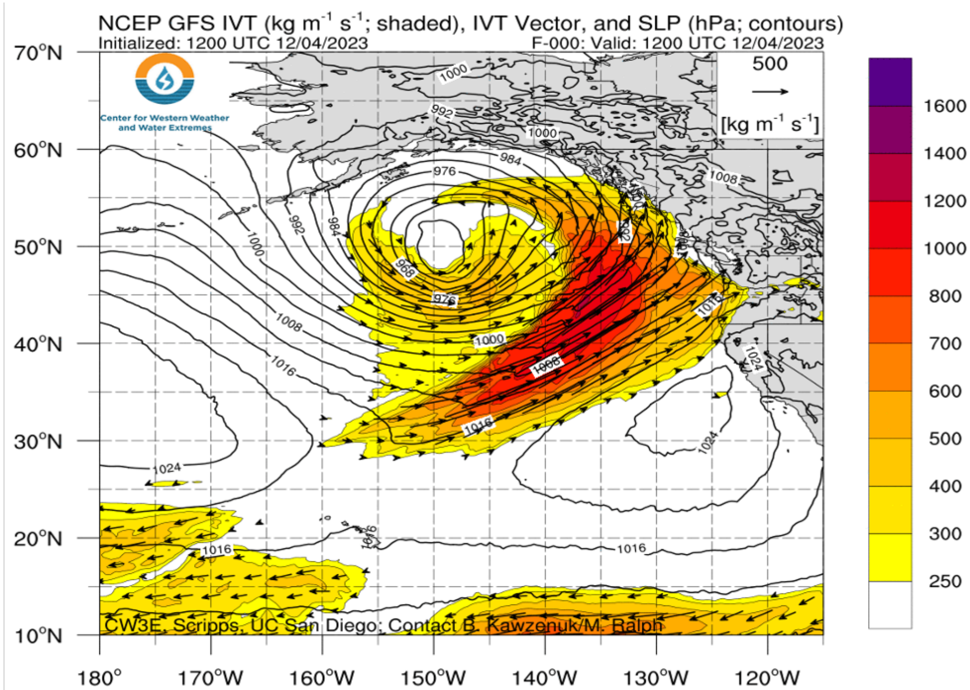

Figure 1-3. *A strong AR making landfall in Washington on December 4, 2023, as represented by integrated water vapor (color) and sea level pressure (contour).*

Recognizing the significance of AR storms (Figure 1-3), the potential impacts of climate change in the Green River basin, and significant capital investments in existing and planned infrastructure, Forecast Informed Reservoir Operations (FIRO) is being explored at HAHD. FIRO is a reservoir management strategy that integrates modern precipitation and streamflow forecasts into day-to-day decisions about when to store or release water in anticipation of future conditions to ensure adequate storage for summer months and sufficient flood storage space during the winter AR season. Since ARs are the main driver of floods in this region and the absence of ARs can result in droughts, successfully implementing FIRO at HAHD depends on getting AR forecasts right.

FIRO is a reservoir operations strategy that better informs decisions to retain or release water by integrating additional flexibility in operation policies and rules with enhanced monitoring and improved weather forecasts (American Meteorological Society 2020).

This project builds on advancements in AR forecast skill that have resulted from over 10 years of research and a robust AR Reconnaissance program led by the Center for Western Weather and Water Extremes (CW3E) at U.C. San Diego's Scripps Institution of Oceanography. FIRO successes to date include Lake Mendocino in Northern California and Prado Dam in Southern California. FIRO operations at Lake Mendocino resulted in 19 percent more water storage (Figure 1-4). The FIRO viability assessment at Prado Dam showed comparable results, with about 10 percent more water storage possible with FIRO. Due to these and other successes, hundreds of USACE reservoirs nationwide are being screened for FIRO potential.

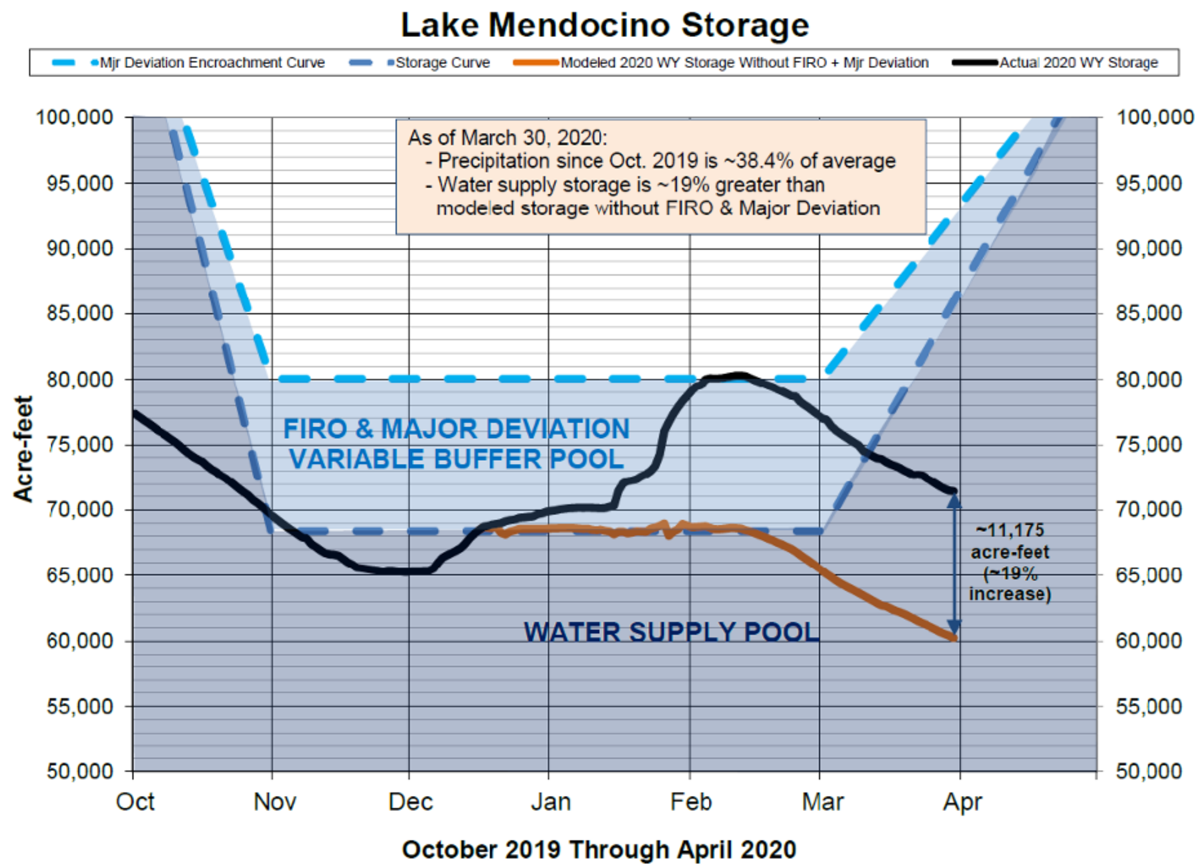

Figure 1-4. *Lake Mendocino storage increased by 19 percent during major deviation operations in water year 2020.*

Tacoma Water and the USACE Seattle District are collaborating with CW3E, USACE Engineer Research and Development Center, the National Oceanographic and Atmospheric Administration (NOAA) National Weather Service, the National Marine Fisheries Service, King County River and Floodplain Management, and the Muckleshoot Indian Tribe to assess the benefits of reservoir management scenarios using forecasts. Construction of the downstream Fish Passage Facility and the Additional Water Storage Project present unique opportunities to explore how FIRO at HAHD might increase the benefits of those investments through operational flexibility. Overall, this project has the potential to produce four major benefits:

- Flood risk management
- Water supply reliability
- Environmental instream flows for fish
- Resilience to climate change

A Steering Committee was formed to oversee this FIRO project and to:

- Foster collaboration, cooperation, and meaningful input by key partners.

- Take advantage of new and emerging forecast science and technology and adjust to the impacts of climate change to maximize multiple benefits of reservoir operation.
- Provide USACE with sufficient analysis to consider using forecasts to allow conservation and municipal water to be stored in the flood pool, and to consider moving the spring refill curve to an earlier date, to help meet water storage targets for ecosystem and municipal purposes while not adversely affecting flood risk.

The HAHD FIRO project will investigate this ***key question:*** *How can improved forecasts of landfalling ARs and associated precipitation and runoff be used to improve the reliability of spring refill to meet instream flows for fish and water supply storage objectives, improve the effectiveness of summer water management in advance of the fall flood transition period, maintain or improve operations for downstream flood risk management, and ensure forecasts and operations are flexible enough to respond to a changing climate without impacting flood risk, water storage reliability, and flows for fish?*

The Steering Committee comprises leaders from key partners and interested groups that are knowledgeable, collaborative, and authorized to represent their organization. Their role is to guide the process and make policy decisions via consensus. Steering Committee co-chairs are responsible for establishing committee membership, setting meeting agendas, and setting the tone and direction for the overall effort. The Steering Committee meets quarterly and receives progress updates from the technical work teams. Work teams, consisting of staff assigned by Steering Committee members, are convened based on the project's needs. Their work is guided by the tasks outlined in the Preliminary Viability Assessment scope and include the topic areas listed in the text box to the right. Work team members provide data and key reference documents, perform technical analyses, and develop draft documents for the Steering Committee throughout the viability assessment.

Work Teams

- Observations
- Meteorology
- Hydrology
- Weather and Water Forecast Verification
- Water Resources Engineering
- Decision Support
- Communications
- Environment

The Steering Committee follows the process outlined in Figure 1-5 below. Each step of the process integrates research and operations to explore the potential for FIRO at HAHD. Section 4 of this workplan serves as an initial scope of work for the Preliminary Viability Assessment. Any operational modifications at HAHD that are recommended at the end of this process must be assessed and approved by USACE via deviations and/or updates to the HAHD Water Control Manual, the USACE document that establishes operational requirements and guidelines for the dam. This FIRO viability assessment process is designed to inform and feed directly into the eventual update analysis of the Water Control Manual, which governs dam operations.

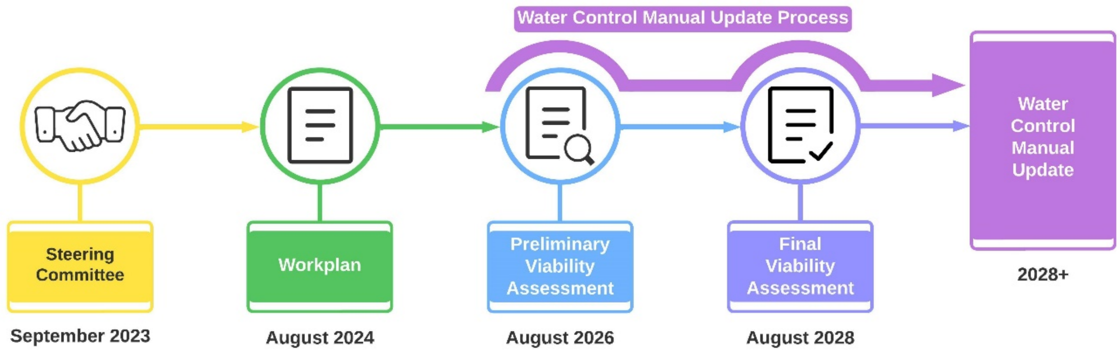

Figure 1-5. *FIRO viability is assessed according to a systematic process. If FIRO is viable, the body of work produced by this process will inform an update to the USACE Water Control Manual.*

Howard A. Hanson Dam FIRO Steering Committee

Co-Chairs:

- **F. Martin Ralph:** Director, CW3E, Scripps Institution of Oceanography, UC San Diego
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- **Nancy Rapin:** Muckleshoot Indian Tribe
- **Joe Forbis:** USACE Engineer Research and Development Center

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Mauger, G. S., Casola, J. H., Morgan, H. A., Strauch, R. L. Jones, B., Curry, B., Busch Isaksen, T. M., Whitely Binder, L., Krosby, M. B., & Snover, A. K. (2015). State of knowledge: Climate change in Puget Sound. Report prepared for the Puget Sound Partnership and the National Oceanic and Atmospheric Administration. Climate Impacts Group, University of Washington, Seattle. doi:10.7915/CIG93777D

Section 2. Background and Context

2.1 Watershed Description

Located in the central Cascade Mountain Range, the Green River watershed (483 square miles) is about 25 miles north of Mount Rainier. The upper watershed features a long U-shaped valley that runs between two east–west parallel ridges and empties into the Puget Sound Lowland. Figure 2-1 below shows the extent of the watershed. The Green-Duwamish River is about 100 miles long and flows through steep mountain valleys with forested slopes. The major peaks in or near the watershed are between 5,135 and 5,715 feet high (Snowshoe Butte, Meadow Peak, Blowout Mountain, and Pyramid Peak). The river begins flowing westward 50 miles from Stampede Pass to the city of Auburn and then northwestward 20 miles to the ancestral Black River, where it becomes known as Duwamish River. The Duwamish River then flows northwesterly 11 miles to Elliott Bay in Seattle. The Howard A. Hanson Dam (HAHD), operated by the U.S. Army Corps of Engineers (USACE), is at about river mile 65.

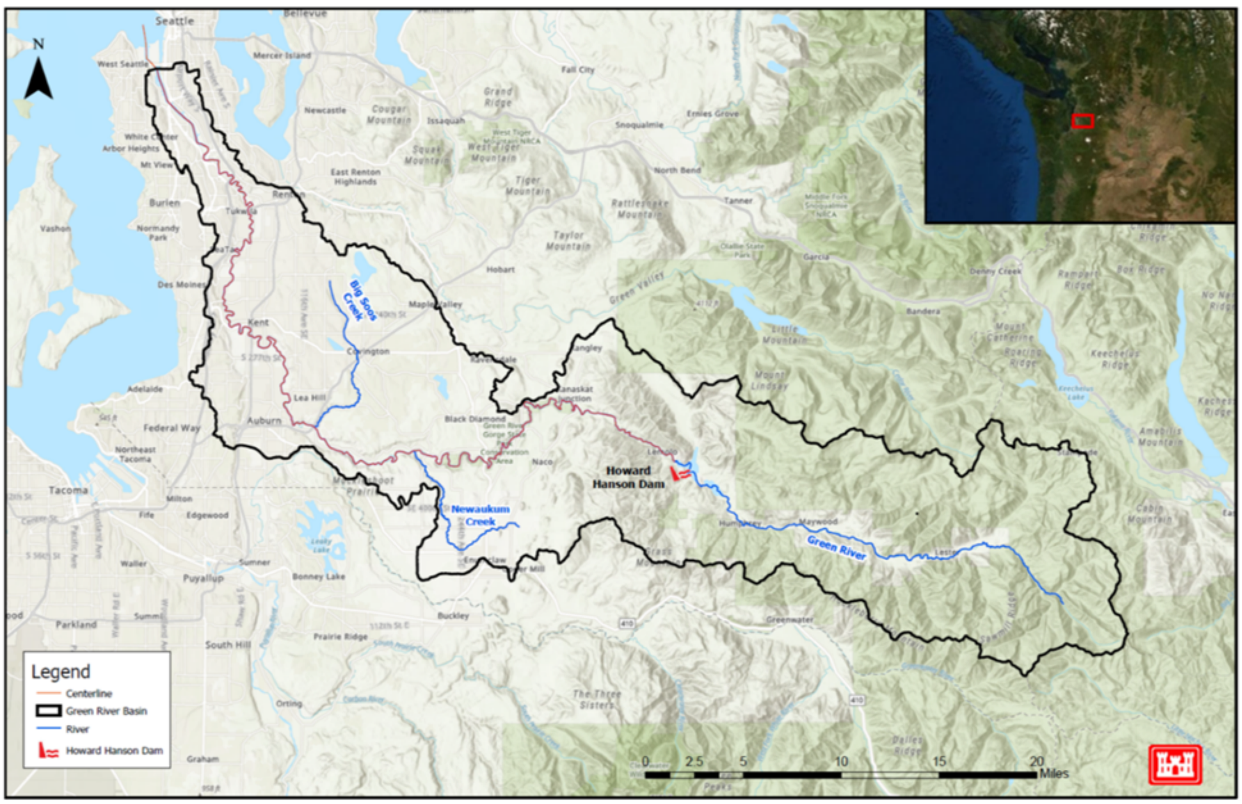

Figure 2-1. *Green River Basin and location of Howard A. Hanson Dam (USACE).*

Principal tributaries to the Green River include Soos Creek, Newaukum Creek, Smay Creek, Sunday Creek, and the North Fork Green River. The Tacoma Headworks Diversion Dam and intake for the Tacoma water supply is located 3.5 miles downstream from HAHD. The Upper Green River sub-watershed begins from the Green River headwaters, on the western crest of the Cascade Mountains at Blowout Mountain, and extends 30 miles west to HAHD, which forms the downstream boundary of this sub-watershed at river mile 64.5 (Figure 2-2 below).

Figure 2-2. *Upper Green River sub-watershed (King County Department of Natural Resources and Parks).*

2.1.1 Climate

With temperatures running from temperate to cold, the climate of the Green River watershed consists of moist air from the Pacific Ocean that moves over the Cascades, becoming rain or snow and bringing cool summers and mild winters. Major storms, mostly in the form of atmospheric rivers (ARs), occur during the fall and winter producing heavy rains (USACE 2011).

Climate change in this region is causing warmer temperatures, more intense extreme precipitation, and less snowpack. Snowpack has been a reliable indicator of how efficiently the reservoir can be refilled during the spring months, but variability of the snowpack during winter months causes uncertainty in the timing of reservoir refill each year. The highest runoff typically occurs in the winter in frequent sharp, short peaks, while the spring runoff tends to occur in smaller, longer peaks. Climate studies indicate a shift toward earlier runoff, with a higher initial runoff peak, but a diminished "second runoff" peak in the spring and lower flows for a longer period in the summer (Mauger et al. 2018), The 30-year (1987–2016) "normal" inflow volume during April to July is 237,000 acre-feet (ac-ft), but the past 70 years shows a trend toward lower flows that are occurring upstream of HAHD due to reductions in snowpack and shifts in the hydrological cycle. below shows monthly averaged historical and future streamflow projections in the Green River basin, where both scenarios reflect a loss in spring peak and project the watershed to be rain-dominant by 2079 (Harrell 2018).

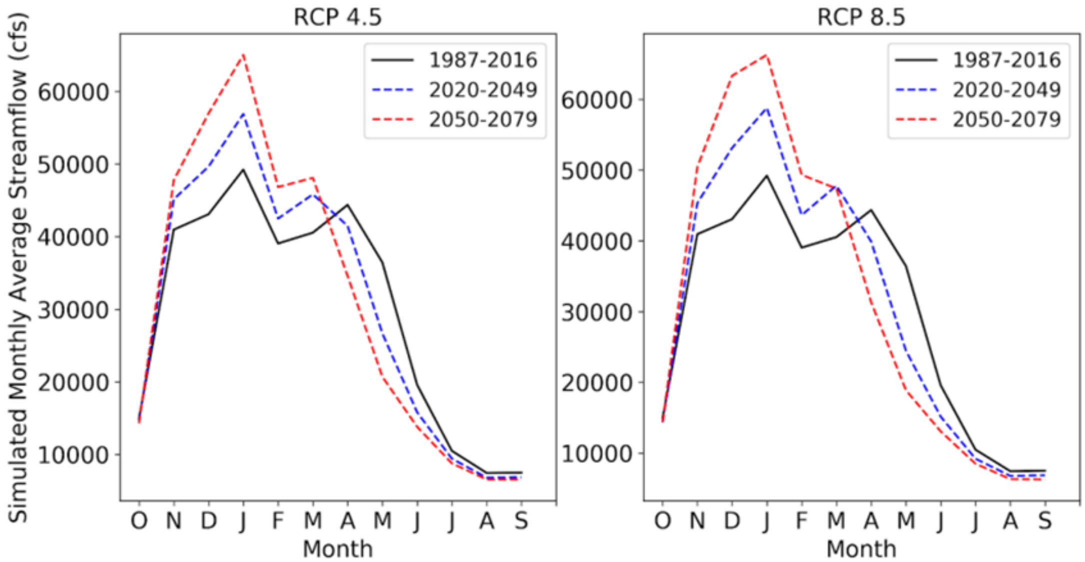

Figure 2-3. *Historical and future streamflow projections in the Green River basin for representative concentration pathway (RCP) 4.5 scenario (left) and RCP 8.5 scenario (right; Harrell 2018).*

Recent climatological studies along the U.S. West Coast have shown that landfalling AR storms produce twice as much precipitation as non-AR storms. In western Washington, 96 percent of all peak daily flows were associated with AR storms (Neiman et al. 2011). Further research will provide valuable information on forecast skill to implement FIRO at HAHD.

2.1.2 Weather

Precipitation in the watershed varies based on location and elevation across the Green River basin. Above HAHD, the basin is low in elevation for the Cascade Mountain range, so the weather is in a transitional zone between rain-dominated and snow-dominated winter precipitation (USACE 2020). Normal annual precipitation ranges from less than 36 inches near the river's mouth to over 124 inches along the basin's highest elevations, while the normal annual precipitation at HAHD is 86 inches (USACE 2011). About 75 percent of the annual precipitation falls from October through March. Snowfall in the basin also varies based on elevation and distance from Puget Sound. Mean annual snowfall varies from about 5 inches (Kent) to 439 inches (Stampede Pass). During the winter seasons, winds can range from 20 to 30 miles per hour during storms (USACE 2011).

"Of 48 annual peak daily flows on 4 watersheds in Western Washington, 46 were associated with landfalling atmospheric rivers [1980 and 2009]."

Flooding in Western Washington: The Connection to Atmospheric Rivers. (2011). Paul J. Neiman, Lawrence J. Schick, F. Martin Ralph, Mimi Hughes, and Gary A. Wick J. Journal of Hydrometeorology.

2.1.3 Hydrology

Stream levels can rise rapidly during high-intensity rainfall, which can cause erosion and turbidity. Although the Green River drainage area increases from 230 square miles near Palmer to 399 square miles near Auburn, the average annual runoff volume only increases by 20 percent due to less precipitation in the lower basin (USACE 2011). Most of the Green River floodplain lies in the valley from Auburn downstream to Tukwila; infrastructure in the floodplain is protected by levees with a bank-full capacity of about 12,000 cubic feet per second (cfs; USACE 2011). Outside these levees, there is about 73 square miles of drainage area that contributes to runoff into the Green River through openings in the levees. During high flows, these openings may be slowed, shut off, or reversed depending on water surface levels on both sides of the levee (USACE 2011). Below Tukwila, the flow of the Green River varies with Puget Sound tides.

2.1.4 Population and Land Use

The Green River basin lies within King County, which has a population of 2.252 million (2021), and the area adjoining Duwamish Waterway makes up the Seattle metropolitan area, which has a population of 733,919 (2021).

With the presence of HAHD and decreased risk of flooding in the valley, the basin has changed from primarily agricultural land with small farms producing dairy products, berries, and vegetables to commercial, industrial, warehousing, and shopping centers (USACE 2011). The Duwamish Waterway (Seattle's industrial district) in the lower section of the valley consists of steel and metal product plants, shipbuilding and repair, transportation manufacturing, and Boeing's aircraft manufacturing factory (USACE 2011).

Land ownership of the Green River watershed upstream of the Tacoma Headworks Diversion Dam is about two-thirds publicly owned and one-third privately owned, with Tacoma Water owning the majority of the land immediately adjacent to the river (Table 2-1; Tacoma Water 2018).

Table 2-1. *Land Ownership within the Green River Watershed Upstream of Tacoma Water's Diversion Dam (adapted from Tacoma Water 2018).*

Landowner	Acres	Percentage of Green River Watershed
TOTAL PUBLIC	**98,139**	**66.6%**
Washington State Department of Natural Resources	42,331	28.7%
U.S Forest Service	37,319	25.3%
Tacoma Water	16,363	11.3%
City of Seattle	1,662	1.1%
USACE	431	0.3%
Other Public	33	0.02%
TOTAL PRIVATE	**49,308**	**33.4%**
Weyerhaeuser	23,894	16.2%

Landowner	Acres	Percentage of Green River Watershed
BTG Pactual	15,227	10.3%
Muckleshoot Federal Corporation	8,531	5.8%
Burlington Northern Santa Fe Railroad	1,386	0.9%
Other Private	270	0.2%
OVERALL TOTAL	**147,447**	**100.0%**

2.1.4.1 Forestry

Depending on the landowners, commercial forest management occurs in the upper Green River watershed. Tacoma Water's Forest Land Management Program focuses on protecting water quality and natural systems and manages its timber lands based on their Habitat Conservation Plan (Tacoma Water 2001, 2018). Tacoma Water conducted timber harvest between 2006 and 2014 to provide fish habitat logs in the Green River and tributaries, rotational thinning, and hardwood conversion (Tacoma Water 2018). Other landowners manage logging on their forested lands in the watershed according to their forest management plans and Washington State Forest Practices Application permit approvals. Between 2006 and 2016, the state issued 146 Forest Practices Applications, and 5,428 acres of timber were harvested (Tacoma Water 2018).

2.1.4.2 Hydropower

As noted by USACE (2012), before HAHD was authorized, hydroelectric power was considered for HAHD but ultimately found to be not economically viable. However, given increased interest, the Federal Energy Regulatory Commission issued a preliminary permit (P-14594) to Tacoma to construct and run a hydroelectric project at HAHD and a draft reconnaissance report in 1982 recommended raising the conservation pool to 1,185 feet for a hydropower facility. HAHD does not currently provide any hydroelectric power (USACE 2011).

2.1.4.3 Recreation

Recreational activities are only allowed in the eastern part of the Green River watershed via an entry gate at Friday Creek (Tacoma Water 2019). The U.S. Forest Service allows dispersed recreation and other multiple-use activities on their land in this eastern area—such as snowmobiling, sightseeing, hiking, backpacking, fishing, and hunting—if the activity follows the memorandum of understanding between Tacoma Water and the U.S. Fish and Wildlife Service (USFWS; Tacoma Water 2019). The Green River watershed provides hunting opportunities annually with special permit hunts which are co-managed by the Muckleshoot Indian Tribe, the Washington State Department of Fish & Wildlife (WDFW), and Tacoma Water. An agreement between Tacoma Water and Friends of the Green River allows river recreationalists (e.g., rafters, kayakers) to access the Green River downstream of the Tacoma Water diversion (Tacoma Water 2018).

2.1.5 Fish Resources

The Green River watershed supports runs of coho, pink, and chum salmon; rainbow and cutthroat trout; the threatened Chinook salmon; and steelhead. Endangered bull trout can also be found rearing in the Green River, but there is no spawning population. Spawning and rearing occur in the river downstream of Tacoma Water diversion and accessible tributaries. WDFW manages the Soos Creek Salmon Hatchery near Auburn with rearing ponds at Palmer and Icy Creek. The Muckleshoot Indian Tribe manages the Keta Creek Hatchery just east of Auburn (USACE 2011).

When enough fish are present, Tribal gillnet fisheries for Chinook, Coho, chum, and pink salmon, as well as steelhead trout, occur in Elliott Bay and the Green-Duwamish River. Sport fishing is a popular activity in these areas. Fisheries do not occur in these areas every year for every species. These fish face many challenges, especially Chinook and steelhead. Terminal fisheries are based on preseason estimates of returns that are updated, where possible, with in-season test fisheries or other updates.

Fishing is not allowed in the closed portions of the upper watershed but is allowed in lakes and streams east of the Friday Creek gate (Tacoma Water 2018). Hatchery fish were planted upstream of HAHD for many years, but this practice was found to be inefficient with the current dam configuration. Plantings are not currently made upstream of the Tacoma Water diversion but may continue after the completion of the juvenile fish bypass facility.

The Muckleshoot Indian Tribe has treaty fishery rights on the Green River and, along with WDFW, co-manages fish and wildlife resources in the basin (USACE 2011). Executive Order 13175 (Consultation and Coordination with Indian Tribes), issued by President Clinton, directs the U.S. Environmental Protection Agency to consult with tribes before promulgating rules (and associated policies and guidance) with tribal implications (65 Federal Regulation 67249; November 9, 2000). Policy directives issued by the U.S. Department of Defense, including USACE, require preservation and protection of fishery resources in the Green River basin and consultation with the Muckleshoot Indian Tribe about possible impacts to treaty rights (USACE 2011).

In 2019 and 2022, the National Marine Fisheries Service (NMFS) and USFWS, respectively, completed biological opinions that address the effects of HAHD operations on bull trout, Chinook salmon, and steelhead under Section 7 of the Endangered Species Act. A requirement of the NMFS biological opinion was to build a downstream fish passage facility at HAHD by 2030 to reconnect 45 percent of the Green River basin's salmon and steelhead habitat that is currently isolated above the dam (NMFS 2019).

2.1.6 Partnerships in the Watershed

Many partners in the Green Basin watershed help collect data and provide information that contributes to the operation of HAHD, including the Muckleshoot Indian Tribe, USACE, the U.S. Geological Survey (USGS), National Weather Service, the Natural Resources Conservation Service, USFWS, WDFW, NMFS, the Washington State Department of Ecology, the King County Flood Control Zone District, Tacoma Water, and the city of Kent. The Green River Flow Management Committee, formed in 1987, is coordinated by USACE and consists of resource agencies, the Muckleshoot Indian Tribe, Tacoma Water, boaters and recreational interested parties and state and county government agencies. The committee coordinates flow management issues on the Green River on a collaborative basis when water is stored in the reservoir for conservation purposes (USACE 2011).

2.1.6.1 Importance of the Tribes

The upper Green River watershed was originally inhabited by Native American tribes, including the Skopamish, Sk'tehlmish, Smulkamish, and St'kamish bands. Most of these bands have been united into the federally recognized Muckleshoot Indian Tribe (USACE 1999), which continues to use the watershed. Executive Order 13175 and policy directives issued by USACE and the U.S. Department of Defense require coordination and consultation with the Muckleshoot Indian Tribe to assess any possible impacts to treaty rights (USACE 2011). Together with WDFW, the Muckleshoot Indian Tribe co-manages Green River fishery resources and is directly involved in HAHD operations.

2.2 Howard A. Hanson Dam

2.2.1 Overview

HAHD, owned and operated by USACE, is on the upper reach of the Green-Duwamish River in King County, 65 river miles above the mouth. USACE operates HAHD, described further in Table 2-2, upstream of the Tacoma Water intake. The dam serves multiple purposes by providing flood risk reduction, municipal water supply, and flow augmentation for fish. Flood risk reduction in the Green-Duwamish River basin is done by capturing excess water runoff from the river's upper drainage area and releasing it under controlled conditions. At the end of the winter flood season, water is gradually stored in the reservoir beginning as early as mid-February for municipal water supply and for conservation (low flow augmentation) purposes.

Table 2-2. *HAHD features.*

Feature	Description
Construction material	Earth and rockfill structure with inclined core drain and filters
Height above bedrock	235 feet (71.6 m)
Total length, including spillway and abutments	675 feet (205.7 m)
Thickness	Base 960 feet (292.6 m), crest 23 feet (7 m)
Concrete spillway	Capacity 107,000 cfs, invert at 1,176 feet
2 spillway Tainter gates (each)	45 x 30 feet (13.7 x 9.1 m)
2 tunnel Tainter gates	10 x 12 feet (3.05 x 3.7 m)
Outlet tunnel, concrete lined, horseshoe shape	19 feet wide x 900 feet long (invert at 1,035 feet, normal maximum capacity 10,000 cfs)
Bypass 48-inch diameter pipe	Invert at 1,069 feet, approximately 650 cfs in capacity (used during summer operations instead of gated tunnel)
Reservoir length	7 miles (11.3 km)
Eagle Gorge Reservoir capacity	104,000 ac-ft (128,282,000 cubic m)

2.2.2 Existing Operations

The USACE Seattle District operates HAHD to provide: flood-risk management of the Green River, low-flow augmentation for fish conservation during the summer and fall, ecosystem restoration, and water supply for municipal and industrial purposes. USACE operates HAHD on a seasonal basis for flood protection. In the fall, the reservoir is drawn down to the minimum pool of about 600 ac-ft around November 1, depending on conditions, when flood control season begins. When the reservoir is at its minimum, the flood storage volume is 104,000 ac-ft. Flood control season extends into February, when refill typically begins. During flood control season, the pool is kept empty. Any stored flood flows are managed by release through the 19-foot diameter outlet tunnel until minimum pool is reached. High inflows to the reservoir can occur during refill. The reservoir may be evacuated before these flows and returned to the refill elevation afterward. Full refill of the conservation and water supply storage is typically reached sometime in May or June. The National Weather Service defines minor, moderate, and major flooding at the Auburn gage (river mile 32) as 9,000, 12,000, and 14,000 cfs, respectively. Local side flows below HAHD are considered when making releases to manage these flow thresholds.

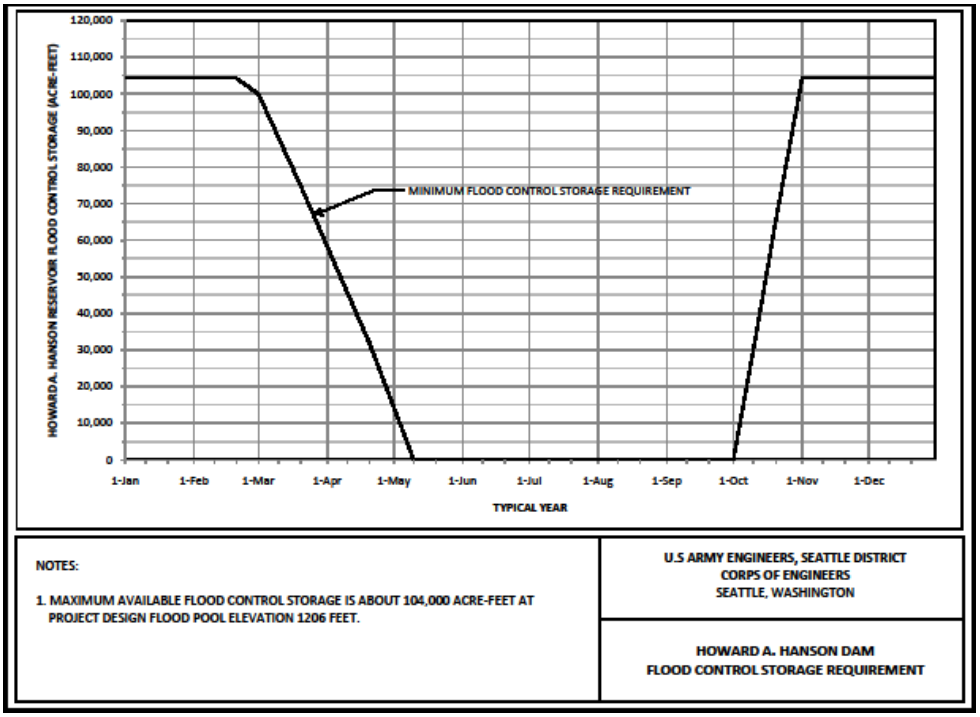

Figure 2-4. *Minimum reservoir storage allocated for flood risk management (USACE 2014).*

During minimum flood pool requirement, reservoir elevation is held to a turbidity pool elevation of 1,076 feet (approximately 600 ac-ft of storage with sediment), with the USACE practice of a slightly higher elevation to maintain water quality. The 1,076-foot turbidity pool elevation is targeted when not operating the dam during a flood event. During a flood event, floodwaters are stored in the reservoir and the maximum outlet tunnel discharge is generally limited to 10,000 cfs. During extreme inflow events, the spillway would be used to discharge water from the project to maintain adequate reservoir storage to prevent dam overtopping or to prevent water from overtopping the spill gates. Under this scenario, it is possible that flows downstream from the dam would exceed 12,000 cfs at Auburn. The frequency of floods that would exceed this 12,000-cfs threshold is predicted to occur less than once every 100 years (USACE 2011). To date, the spillway has not been used. On rare occasions, it is possible that no flow would be discharged from the dam to maintain flows below 12,000 cfs at the Auburn stream gage. No flow would occur if the local inflow below the dam was forecasted to exceed 12,000 cfs. This situation has occurred once (in 2009) since operations were started in 1962.

2.2.3 Flow and Ramping Rate Requirements

In addition to the flood control storage requirements below (Table 2-3), USACE tries to meet an instream flow requirement in the Water Control Manual (WCM) of 110 cfs at the Palmer Gage (at 98 percent reliability). Other instream flow requirements are associated with Tacoma's water rights, but these are separate from, and not requirements imposed on, USACE. These flow requirements adopted by Tacoma Water are shown in Table 2-3.

Table 2-3. *Green River minimum flows. Adopted by Tacoma Water at USGS Station Nos. 12113000 and 12107000, per 1995 Settlement Agreement with Muckleshoot Indian Tribe (NMFS 2019).*

Time period	**Auburn MIF in cfs**	**Palmer MIF in cfs**
For Tacoma's First Diversion Water Right Claim		
Wet Years	350	
Wet to Average Years	300	
Average to Dry Years	250	
Drought Years	250-225	
For Tacoma's Second Diversion Water Right		
July 15 – Sept 15	400	200
Sept 16 – Oct 31	NA	300
Nov 1 – July 13	NA	300

Source: Tacoma 1995 (in Tacoma 2001)

Ramping rates are designed to protect the recreational public from dangerous increases in river flow and to ensure that down-ramping avoids stranding fish. Ramping rates depend on the purpose, flow conditions, and time of year (Table 2-4). For instance:

- Up-ramping rate is set at 1 foot per hour, except during flood operations.
- Down-ramping rates, to avoid fish stranding on banks and gravel bars, apply to discharges of less than 1,500 cfs at USGS gage 12105900 on the Green River below HAHD less.

Table 2-4. *HAHD down-ramping guidelines (NMFS 2019).*

Time Period	Daylight Hours	Night Time Hours
February 16 - May 31	0 in/hr	2 in/hr
June 1 – October 31	1 in/hr	1 in/hr
November 1 – February 15	2 in/hr	2 in/hr

For a more detailed review of HAHD flow requirements related to fish, see Appendix A.

USACE manages spring refill to meet minimum instream flow requirements, mimic natural flow, and store water. Figure 2-5 below depicts the allocations of storage according to the various agreements.

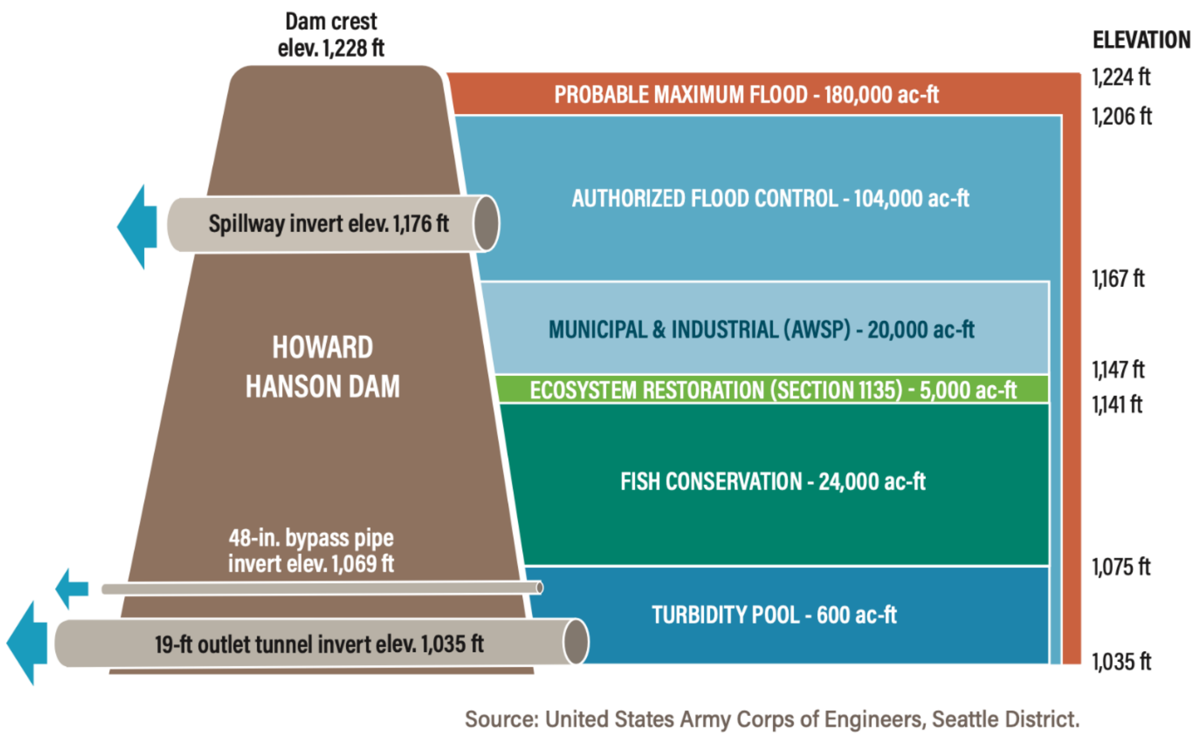

Figure 2-5. *HAHD spring water storage and allocation*

2.2.4 Tacoma Water Rights

Since 1913, Tacoma Water has diverted water from the Green River and now serves nearly 700,000 people directly or through partners in Tacoma and University Place, plus portions of Puyallup, and Pierce and South King counties. Most of their supply comes from the Green River diversion. Tacoma Water operates the Tacoma Headworks Diversion Dam at river mile 61, which is located just below the Upper Green River sub-watershed. Tacoma Water restricts public access to the watershed to protect its water supply.

Tacoma Water has water rights on the Green River, which include the first diversion water right (FDWR) claim for 113 cfs, plus a water permit for the second diversion water right (SDWR) of up to 100 cfs. The FDWR can only be used if river flows at the Auburn gage are above 250 cfs, which is almost always the case. The FDWR is available most of the time (>99 percent) but is not able to be stored.

The SDWR is conditional based on Green River flow measured at the Palmer and Auburn gages. Minimum flows must be present at both gages for this water right to be usable. Therefore, SDWR is only available approximately 60 percent of the time on an annual basis. The SDWR may be accounted for in the reservoir behind HAHD in the spring at a rate not to exceed the SDWR maximum of 100 cfs. However, USACE is not bound to a maximum storage rate when storing water behind HAHD. Tacoma Water can withdraw SDWR water from the reservoir later at any rate (no maximum rate applies when Tacoma Water wishes to use previously stored water). The SDWR can store up to 20,000 ac-ft in the Eagle Gorge Reservoir. Then, when needed in the peak summer season, the stored water may be used at a rate that is limited only by pipe and plant capacity.

The SDWR is shared as part of a partnership. The Second Supply Project (SSP) Agreement defines the rights and obligations of the partnership in relation to Tacoma Water's Regional Water Supply System. Tacoma Water has a 15/36 participant share, and each of the city of Kent, Covington Water District, and Lakehaven Water & Sewer District have 7/36 Participant Shares. Generally, these shares represent a participant's proportional right to receive water delivered by the SSP. It should be noted that only the SDWR is included in the SSP Project and Tacoma Water's FDWR is solely used for its own needs (i.e., not for use by the partners, with only force-majeure exceptions).

When deciding to use water from the Green River source, water is used by Tacoma Water on a prioritized availability basis, which means:

- It is first determined if SDWR water is available, and how much may be diverted or stored. This water right is interruptible based on minimum instream flows in the river at both the Palmer and Auburn gages. Minimum flows vary by gage and time of year. The SDWR is usually fully available in the winter, unavailable in the summer, and partially available in the spring and fall. A portion of this water right is usually available approximately 60 percent of the days each year.
- It is then determined if water is available from the FDWR, and how much of this right may be used. Tacoma Water must ensure a minimum flow at the Auburn gage is present in order to use the FDWR. Use of the SDWR and FDWR occurs in the priority order mentioned below, until either the instantaneous maximum allowed flow rate of the water right is fully used, or no more water is needed. If additional water is needed, the use of the next right is initiated.
- During the reservoir fill period (from approximately February 15 until May or June), Tacoma Water uses water in the following priority (if available): FDWR (as SDWR is placed into storage), SDWR-Run-Of-River, then SDWR-Stored. The other SSP partners use water in the following priority (if available): SDWR-Run-Of-River, their remaining share of SDWR-Run-Of-River placed into storage, then SDWR-Stored.
- The Reservoir drawdown period begins after spring refill has been completed (Typically in May or June) and lasts through the summer and into fall until all the stored water has been used, USACE declares a need to begin flood control, or on December 1 (whichever comes first). The reservoir is typically empty around November 1. During this time Tacoma Water uses water in the following priority (if available): SDWR-Run-Of-River (not usually available at this time of year), then FDWR, then SDWR-Stored. The other SSP partners use water in the following priority (if available): SDWR-Run-Of-River (not usually available at this time of year), then SDWR-Stored.
- During the winter period, storage has been depleted, the reservoir is available for flood control, and water is usually plentiful on the Green River. Tacoma Water uses water in the following priority: SDWR-Run-Of-River, then FDWR. The other partners use SDWR-Run-Of-River.

North Fork Wells is a field of seven wells with a capacity of 84 million gallons per day on the North Fork of the Green River above HAHD. When there is turbidity in the reservoir, the wells produce non-turbid water, which is piped into the water system instead of using river water. This water right is used when the water at the pipeline diversion dam is too turbid for use or to relieve some of the water demand on flows in the Green River. It is not an additive water right, meaning it can only be used in lieu of the FDWR or SDWR direct diversion.

2.2.5 Section 1135 Storage (NMFS Biological Opinion 2-15-19)

USACE has been implementing the Section 1135 ecosystem WCR-2014-997-5 restoration project, which added 5,000 ac-ft of water stored in Eagle Gorge Reservoir, used to incrementally augment streamflow to protect steelhead redds from dewatering, and/or to improve spawning conditions for Chinook salmon. Ecosystem restoration projects downstream from the dam have been conducted by USACE since 2003.

2.3 Environmental Conservation and Restoration

Coordination is critical for protecting the natural resources of the Green River system. Research, education, management, and monitoring are all key components of environmental conservation and restoration.

Listed Species in the Vicinity of HAHD

- Northern spotted owl
- Marbled murrelet
- Grizzly bear
- Canada lynx
- Bull trout
- Puget Sound Chinook salmon
- Puget Sound steelhead

2.3.1 Environmental Objectives

A wide array of fish and wildlife species inhabit the Green River basin, both upstream and downstream of HAHD. Seven threatened or endangered species are known to occur or potentially could occur near HAHD (see text box; USACE 2022a).

In addition to these seven species, endangered Southern Resident killer whales feed on the salmon and other fish species from the Green River. To help protect the sensitive and federally listed fish and wildlife species in the Green River watershed, Tacoma Water's Habitat Conservation Plan (2001) was developed per the Endangered Species Act and highlights 20 major habitat conservation measures covering 32 species.

Notable wildlife in the basin's forested areas include black-tailed deer, elk, black bears, cougars, and mountain goats (USACE 2011). Other native species found along the lowland basin, valley, and foothill areas include beavers, muskrats, minks, river otters, red foxes, opossums, weasels, bobcats, coyotes, martens, and wood ducks (USACE 2011).

2.3.1.1 Fisheries

Fisheries management is a high priority in the Green River watershed. In addition to the varieties of salmon, trout, and steelhead in the Green River system, other fish species include whitefish, sculpins, suckers, northern pike minnow, and Pacific and river lamprey (USACE 2011, Tacoma Water 2001).

Since 1911, the Tacoma Headworks Diversion Dam has blocked federally threatened salmon, steelhead, and bull trout from migrating upstream. The diversion dam is now outfitted to pass some adult fish above both dams when juveniles can migrate safely downstream through HAHD. Tacoma Water's Habitat Conservation Plan (2001) named these key fisheries issues:

- Upstream and downstream fish passage around HAHD.
- Reintroduction of spawning gravels below HAHD.

- Restoration of fish habitat above HAHD.
- Streamflow and water storage for streamflow augmentation releases.

Figure 2-6 below provides an overview of the different sub-watersheds in the Green River basin. The sub-watersheds are defined by the life stages of salmon in each area, geography and topography, and land use (King County 2021):

- **Upper Green River sub-watershed.** Since 1911, salmon access has been blocked by the Tacoma Headworks Diversion Dam. Resident rainbow trout, coastal cutthroat trout, whitefish, and mountain whitefish are salmonids are found here.
- **Middle Green River sub-watershed.** Most spawning by Chinook, pink, sockeye, and chum salmon, as well as steelhead trout, occur in the middle reach.
- **Lower Green River sub-watershed.** This area is currently used for the upstream and downstream migration and rearing for all native salmon species and provides limited spawning habitat.
- **Duwamish Estuary sub-watershed.** Young fish migrate from freshwater streams and rivers to the estuary. Adults migrate from saltwater through the estuary to freshwater. Estuary habitat is important for all species, but especially for Chinook, chum, and char.
- **Nearshore sub-watershed.** All juvenile anadromous salmon use the nearshore to acclimate to saltwater, feed, and move toward the ocean.

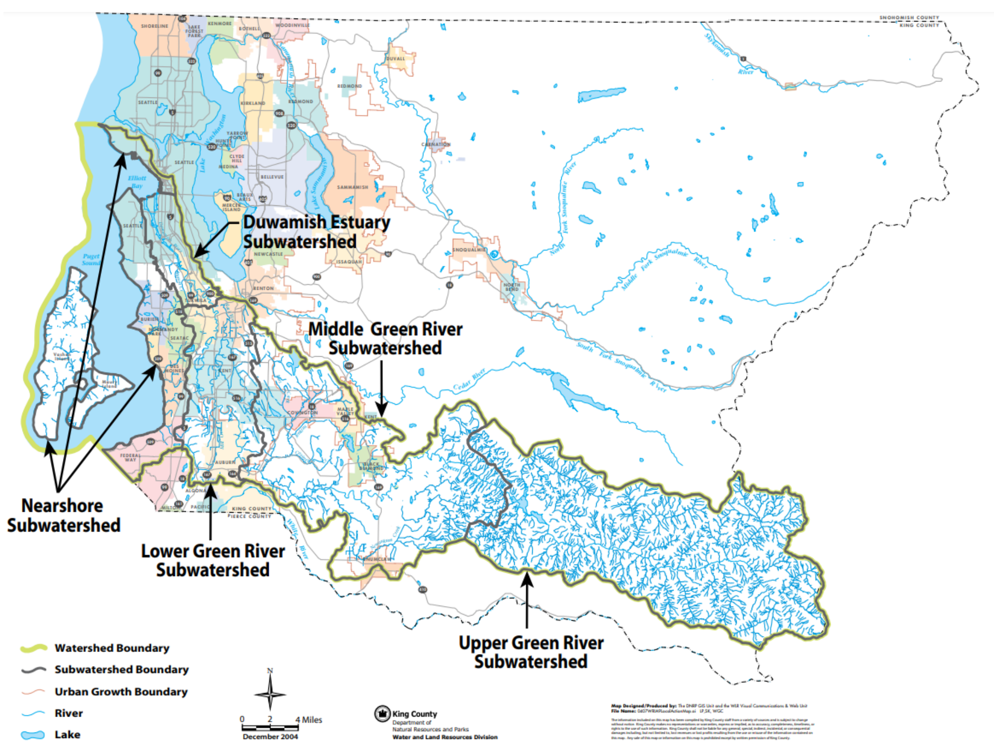

Figure 2-6. *Green River basin sub-watersheds (King County 2021).*

Integrated and coordinated management, restoration, and funding can help protect and restore fishery habitat in the basin. See Section 2.3.3 for information on a downstream fish passage facility underway as part of the Additional Water Storage Project (AWSP).

2.3.2 Additional Water Storage Project

Authorized by Congress in Section 101(b)(15) of the Water Resources Development Act of 1999, the AWSP was a collaborative process involving USACE, NMFS, USFWS, the Muckleshoot Indian Tribe, the Washington State Department of Ecology, WDFW, and Tacoma Water. The purpose of the AWSP was to improve storage features of HAHD to meet water supply needs of the Puget Sound area and to provide ecosystem restoration for fish and wildlife in the basin (USACE 2011). The AWSP was originally planned to have two main phases to provide municipal and industrial storage from Tacoma Water's SDWR (Tacoma Water 2018, USACE 2011):

- **Phase I.** Provide storage of 20,000 ac-ft (to elevation 1,167 feet). Phase I has been implemented and raised the conservation pool elevation from 1,147 feet to 1,167 feet. However, the fish passage facility included in the Phase I recommendation has not been constructed.
- **Phase II.** Increase storage of 12,000 ac-ft (to elevation 1,177 feet). Implementation of Phase II is dependent upon the evaluation of the success of Phase I and future engineering evaluations to determine whether the embankment can safely contain an increased reservoir load. Consensus of state and federal resources agencies, the Muckleshoot Indian Tribe, Tacoma Water, and USACE is also required. There is no agreement on Phase II as of the date of this workplan.

Over the past 10-plus years, USACE, Tacoma Water, and other partners have conducted several fish habitat projects and monitored water quality, fish, and wildlife habitats in support of the AWSP (USACE 2011). The municipal part of the storage is filled by the SDWR.

Tacoma Water and USACE currently have a Project Cooperation Agreement outlining the relationship between Tacoma Water and USACE during construction of the AWSP Phase 1. All elements of the AWSP have been completed except for development of a juvenile downstream fish passage facility. The downstream fish passage facility is expected to be complete by 2030 and operational in 2031.

Tacoma Water engages in various activities in cooperation with USACE. These activities include developing and maintaining environmental mitigation sites as well as improving and using Tacoma Water's lands to enable more water storage capacity. Tacoma Water has committed to the goal of reintroducing anadromous salmon and steelhead upstream of HAHD. Tacoma's Adult Trap and Haul Facility became operational in 2007; however, only limited experimental releases have been made due to delays in constructing the downstream fish passage facility at HAHD.

2.3.3 AWSP Fish Passage

As part of the AWSP and as a requirement from an NMFS biological opinion, USACE must design and complete a downstream fish passage facility at HAHD by the end of 2030 and begin operating the facility by early 2031 for the juvenile salmon outmigration period (NMFS 2019). The goal of the facility is to reconnect the Green River basin's salmon and steelhead habitat currently isolated above HAHD and allow for peak passage of juvenile salmon through the reservoir and facility during the middle of the spring refill period. See Figure 2-7 below for the location and excavation of the fish passage facility (USACE 2022a).

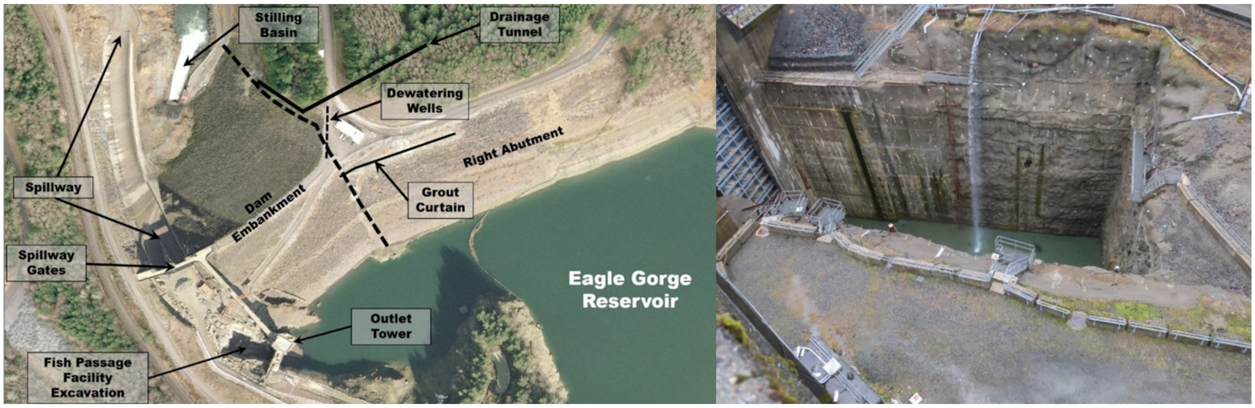

Figure 2-7. *Fish passage facility location and excavation at HAHD (USACE 2022a).*

2.3.3.1 Improved Access to Upper Green River

Tacoma Water releases adult anadromous fish above HAHD based on the direction of state and tribal fisheries managers and requests written direction from the fisheries managers on which fish to transport and when to begin transport (Tacoma Water 2018). Once the fish passage facility at HAHD is complete, there will be improved access for fish to spawn and rear in the upper Green River.

2.4 References

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Section 3. Preliminary Technical Studies Plan

3.1 Extreme Precipitation Events and Their Impact on Runoff

Preliminary technical studies related to extreme precipitation events in the Green River watershed will seek to evaluate the storm characteristics responsible for variability in forecast error that can drive subsequent variability and impacts on streamflow and runoff in the basin. Storm characteristics are divided into two categories that include a plan to better understand the processes associated with extreme precipitation related to landfalling atmospheric rivers (ARs) and their predictability.

3.1.1 Extreme Precipitation and ARs

To better understand extreme precipitation and its relationship to landfalling ARs in the Green River watershed, the meteorology team aims to create a catalog of these features to evaluate the meteorological characteristics responsible for precipitation extremes. An example of the catalog of landfalling ARs, derived from the Ralph et al. (2019) AR scaling technique, illustrates the annual frequency and intensity/duration characteristics of ARs at the coast and over the watershed (Figure 3-1).

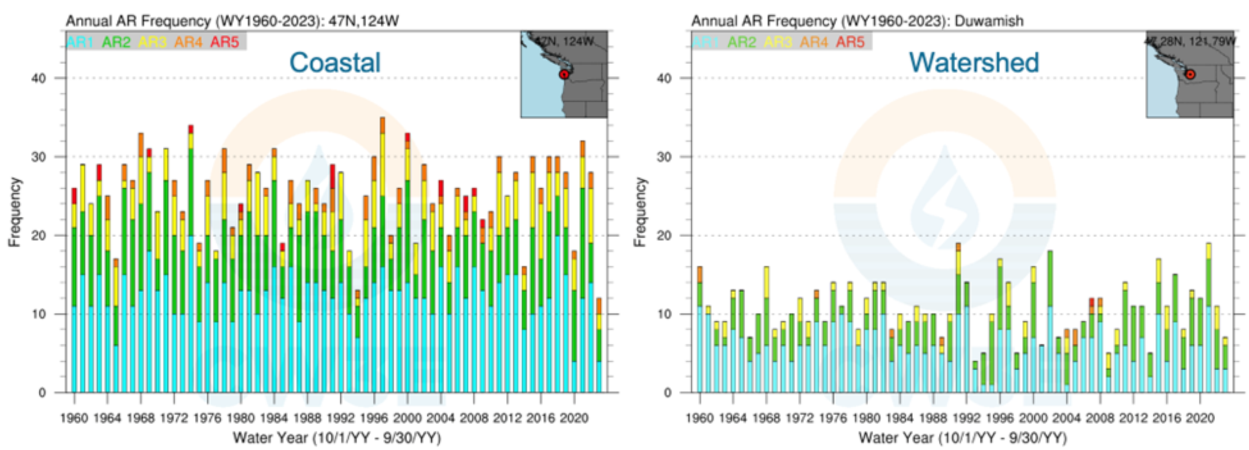

Figure 3-1. *Annual frequencies of ARs for water years 1960–2023 at a coastal location (left) and the watershed location (right). Colors represent AR scale values based on Ralph et al. (2019). The data source is a long-term analysis product called the ERA5.*

From this AR catalog, the meteorology team can identify not only the frequency of weak, moderate, or strong landfalling ARs, but also their common characteristics such as their preference for west-southwest orientations (not shown). By merging the AR catalog with a precipitation chronology, preliminary technical studies have also identified preferred AR characteristics associated with heavy precipitation. For example, although landfalling ARs with southwest orientations produce on average the largest storm-total precipitation, landfalling ARs with more westerly orientations are more efficient, producing relatively larger storm-total precipitation values at lower AR intensities.

The remaining tasks associated with the preliminary technical studies related to Section 3.1.1 will involve completing and summarizing both the AR and precipitation catalogs and exploring aspects of precipitation forecast skill in the Green River basin in coordination with the verification team.

3.1.2 Processes Influencing Forecast Skill

The technical studies will also produce a diagnostic analysis of the meteorological processes influencing precipitation forecast skill via case studies in coordination with the verification team. With a secondary objective to support the observation team in analyzing landfalling ARs and their structure, the meteorology team will investigate model forecasts of a landfalling AR in early December 2023 where the Center for Western Weather and Water Extremes (CW3E) released 27 radiosondes over the course of 81 hours. From this analysis, we expect the following outcomes:

- Demonstrated value of in-situ atmospheric observations at high temporal resolution during a landfalling AR.
- Improved understanding of the structure of landfalling ARs over the Green River watershed.
- Identification of model forecast errors, when compared to in-situ observations, in the structure of the landfalling AR and related parameters (e.g., freezing level, precipitation).

3.1.3 Supporting Observations Team

A key component of Section 3.1.2 is supporting the observation team in analyzing landfalling ARs and their structure. This support also includes (1) helping the team identify where and when to launch balloons to best sample atmospheric conditions during landfalling ARs that can help to understand the key physical processes responsible for precipitation in the basin, and (2) preparing analyses of collected observations that illustrate these physical processes. These analyses are showcased elsewhere in this workplan (see Section 3.3) and will be used in case studies as part of Section 3.1.2.

3.1.4 Key Findings

- Catalogs of landfalling ARs and precipitation over the Green River watershed demonstrate preferred characteristics responsible for larger and/or more efficient storm-total precipitation.
- Case studies will help identify the meteorological processes influencing precipitation forecast skill and will leverage in-situ observations, including from early December 2023, where 27 radiosondes were launched over the course of 81 hours.

3.2 Observe and Monitor Watershed Hydrometeorology

In this preliminary technical study, the observations team have begun to observe and monitor the hydrometeorology of the Green River basin during cool-season precipitation events, including those associated with ARs, to determine precipitation type and the resulting runoff characteristics. Sensors installed in the Green River basin measure hydrometeorological properties associated with ARs that bring large atmospheric moisture fluxes to the watershed and result in heavy precipitation, saturated soils, and high streamflow rates. In addition, the team has the capacity with these stations to observe the snow level "bend" toward higher terrain, including spatiotemporal variability, to quantify the impact that terrain has on snow levels. These stations conduct measurements continuously year-round.

3.2.1 Station Installations

Over the past year, the observations team has sited and installed three continuously observing stations (Figure 3-2 below). These stations were sited after an analysis to determine where existing stations with available data were located and assessing the topography and precipitation climatology within the basin, in order to maximize their utility for FIRO goals. All stations observe the following hydrometeorological state variables: temperature, relative humidity, air pressure, liquid precipitation, incoming solar radiation, snow depth, and wind speed and direction. One station (Maywood) also observes soil moisture at six depths below the ground down to 1 meter. The goal of this site is primarily to observe precipitation infiltration into the soil and how soil moisture modulates the transition of incoming precipitation to streamflow, support hydrologic modeling efforts, and to monitor snowpack drainage as appropriate.

The other two stations (Headworks and BNSF Y-Line) also observe precipitation type and snow level, via laser disdrometers and vertically pointing radars. The major goals of these two sites are to understand rain/snow partitioning in the watershed and its variability in significant storm events. One station was sited at a lower elevation in the watershed, below Howard A. Hanson Dam (HAHD) at 270 meters, and one inside the watershed at a higher elevation of 480 meters.

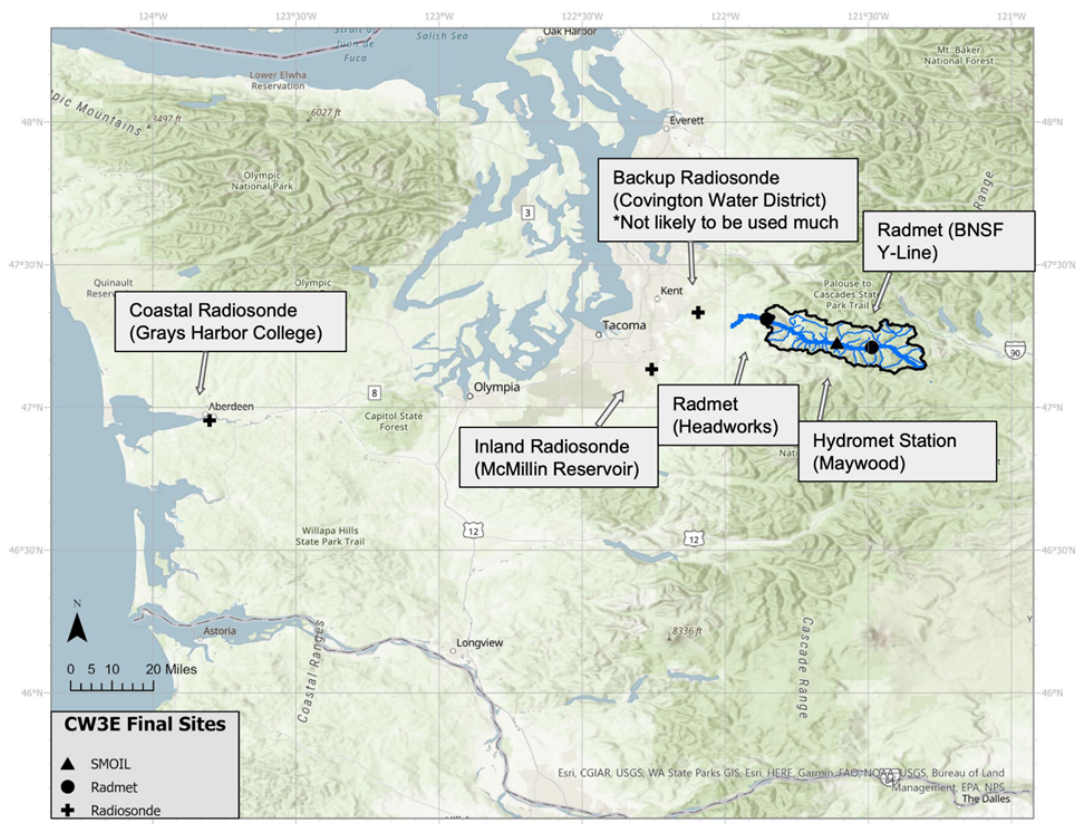

Figure 3-2. *Stations sited as part of this project. The Green River watershed is outlined in black.*

In water year (WY) 2024, all three stations in the watershed were installed and began making continuous measurements reported in near real-time. Radiosonde sites are described in Section 3.3.

3.2.2 Data Collection

During WY 2024, three stations collected continuous observations beginning in October 2023. Observations are being used in a variety of ongoing applications that will be described in detail in the technical report for this work, which will be released in August 2024. These applications include:

- Automatic ingestion of the observations into National Weather Service (NWS) systems via the creation of NWS Location Identifiers through the Hydrometeorological Data Acquisition System.
- Forecast verification.
- Case study of an impactful event in early December 2023, in collaboration with the meteorology team. This case study will also use observations described in Section 3.3.
- Assessment of snow level bending observations, including intra- and inter-storm variability.

3.2.3 Partnership with the Meteorology, Hydrology, and Forecast Verification Teams

The observations collected as part of these deployments will support analyses aimed at providing better and more certain forecasts of precipitation associated with ARs. A case study, in close collaboration with the CW3E FIRO meteorology and forecast verification teams, is ongoing for the event observed in early December (Figure 3-4), and the findings will be described in detail in the final technical report. In addition, the observations team will work with the hydrology team to leverage the soil moisture observations taken at the central Maywood site (Figure 3-2).

3.2.4 Key Findings and Summary

Key findings:

- Stations were sited to maximize utility for the project. Siting included assessing climatological precipitation patterns using PRISM (PRISM Climate Group 2023), along with creating an inventory of stations with data available in near real-time in and near the watershed.
- Case studies conducted in collaboration with the meteorology, hydrology, and forecast verification teams, using data described here and in Section 3.3, will advance our knowledge and lead to positive forecast outcomes and better decision support.

The final report for this technical study will include more details on the case study from December 2023 (Figure 3-4) and will also provide statistical information about the observed atmospheric characteristics over the first year, including observations of snow level variability and bending, precipitation phase, and other relevant quantities.

3.3 Investigate AR Signatures in the Atmospheric Vertical Structure

In this preliminary technical study, we investigate AR signatures in the atmospheric vertical structure over the Green River basin using radiosonde measurements conducted during six distinct events in WY 2024. Accurately representing the vertical structure of ARs during landfall and as they move through the watershed is critical to understanding meteorological variables associated with landfalling ARs in the region, including how much precipitation will be associated with a given event and whether it will arrive as rain or snow. High temporal and vertical resolution radiosonde observations allow us to understand these processes at fine scales and assess how well our models can resolve them.

3.3.1 Launch Location and Siting Deployments

Over the past year, the observations team has sited three possible radiosonde launch locations: one at the coast and two just upstream of the Green River basin (Figure 3-2). During WY 2024, we focused our efforts on the more inland site at the McMillin Reservoir. Deployments were tasked with our AR Reconnaissance program, leveraging regular forecasting discussions conducted during the winter season and the potential for upstream sampling by field campaign aircraft. The observations team also responded to requests and input from our partners at NWS Seattle and the FIRO meteorology team.

3.3.2 Data Collection

During WY 2024, the observations team collected observations via 110 total vertical profiles in six distinct AR events. Their trajectories (Figure 3-3 below) illustrate the differences in storm orientation throughout the season and within individual events. Observations are being used in a variety of ongoing applications that will be described in detail in the technical report for this work, to be released in August 2024. These applications include:

- Automatic ingestion of the observations into the Global Teleconnection System for assimilation by global numerical weather prediction models.
- Forecast verification.
- Case study of an impactful event that occurred in early December 2023.
- Assessment of AR characteristics as measured by the radiosondes and combined with observations described in Section 3.2.

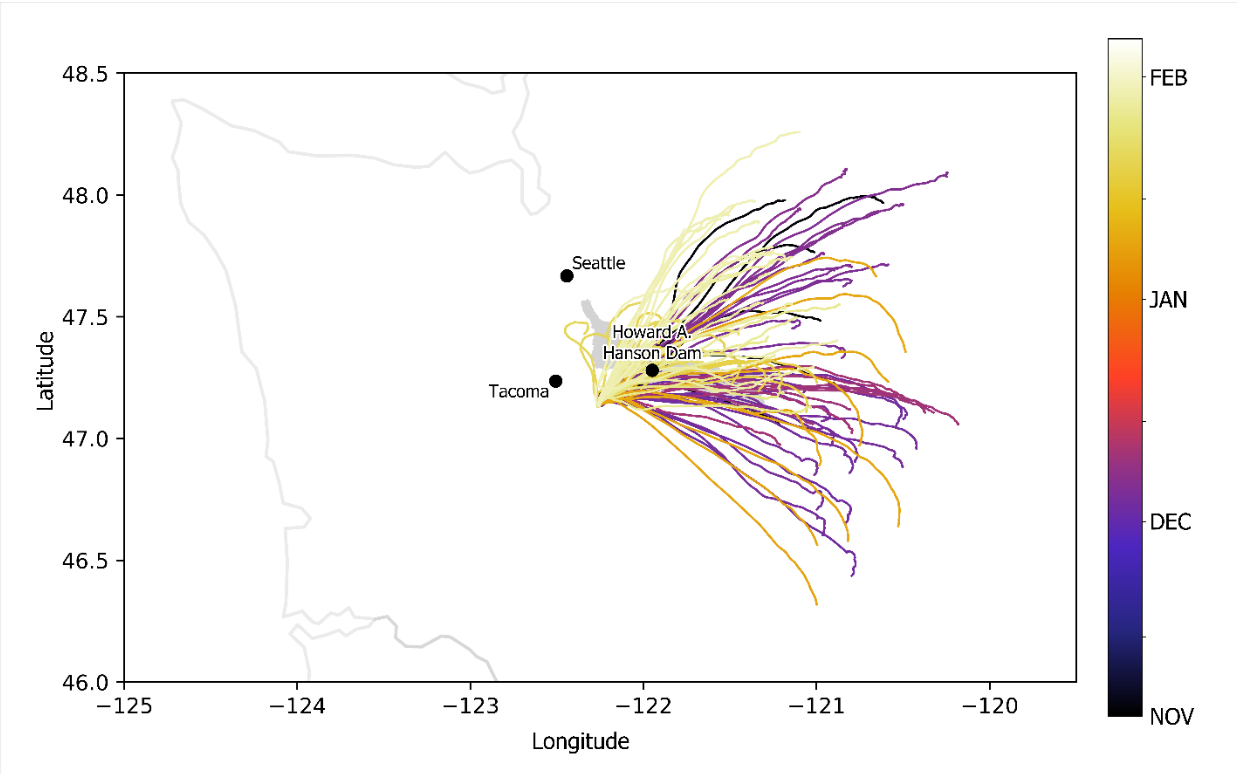

Figure 3-3. *Trajectories of all radiosondes released as part of this project from the McMillin Reservoir site, color coded by time within the season.*

3.3.3 Partnership with the Meteorology and Forecast Verification Teams

The observations collected as part of these deployments provide the initial conditions for modeling studies and can provide better and more certain forecasts of precipitation within ARs. Throughout the season, the observations team conducted near real-time analysis of the collected observations. A case study, conducted in close collaboration with the CW3E FIRO meteorology and forecast verification teams, is ongoing for the event observed in early December (Figure 3-4), and the findings will be described in detail in the final technical report.

For Figure 3-4, data in panel (a) are interpolated to 25-millibar (mb) isobaric surfaces between 1,000 mb and 250 mb. Panel (a) also includes the trajectories of all 27 radiosonde paths from warm to cool colors. Periods with AR conditions following the Ralph et al. (2019) AR scale are shaded gray in panel (b). Inflow and outflow data in panel (c) are obtained from the U.S. Army Corps of Engineers (USACE). All other data are provided by CW3E. Observations and analysis are supported at CW3E by the USACE-sponsored FIRO program and by Tacoma Water.

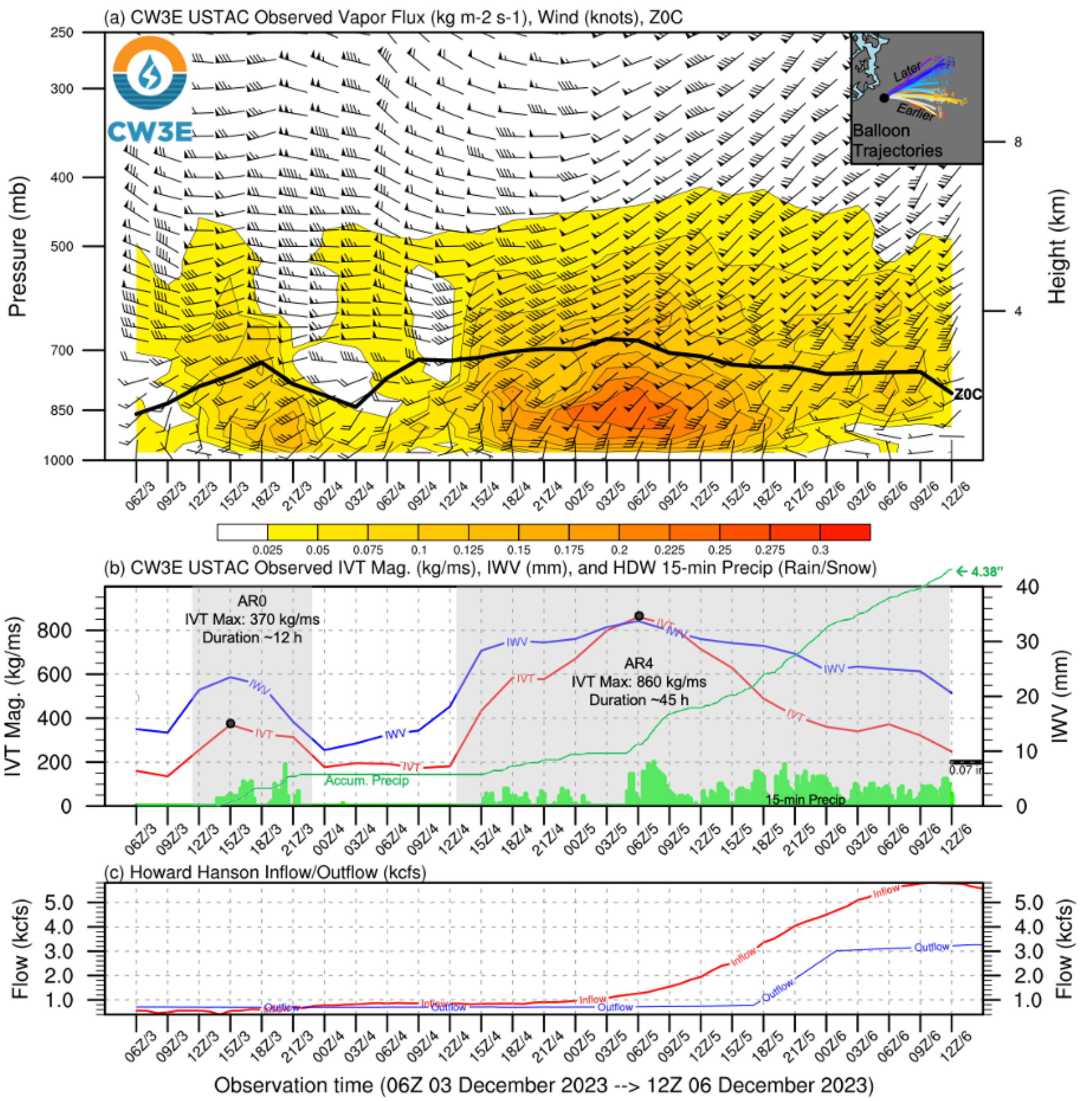

Figure 3-4. *(a) Time-height analysis of three-hourly radiosonde-derived water vapor flux in kilogram meters squared per second (kg m-2 s-1; shaded), wind (knot convention; barbed), and height of the 0 °C isotherm for 0600 UTC 3 December 2023 through 1200 UTC 6 December 2023 at the designated Tacoma (USTAC) launch site; (b) time series of three-hourly radiosonde-derived integrated vapor transport (kg m-1 s-1; red line), integrated water vapor (mm; blue line), 15-min precipitation (inches; bars scaled to the maximum value of 0.07 inches) and period-accumulated precipitation (inches; dark green line) at the Headworks (HDW) site at HAHD; and (c) hourly inflow in 1,000 cubic feet per second (kcfs; red line) and outflow (kcfs; blue line) at the Howard A. Hanson Reservoir.*

3.3.4 Key Findings and Summary

Key findings:

- The 110 profiles collected at the McMillin Reservoir launch location are useful for diagnosing precipitation processes and assessing how well numerical weather prediction models can reproduce these processes.
- Case studies conducted in collaboration with the FIRO meteorology and forecast verification teams will advance our knowledge and lead to positive forecast outcomes and better decision support.

The final report for this technical study will include more details on the case study from December 2023 (Figure 3-4) and will also provide statistical information about the observed storm characteristics, including integrated vapor transport, integrated water vapor, and other relevant quantities.

3.4 References

PRISM Climate Group. (2023). *PRISM climate data.* Oregon State University, https://prism.oregonstate.edu

Ralph, F. M., Rutz, J. J., Cordeira, J. M., Dettinger, M., Anderson, M., Reynolds, D., Schick, L. J., & Smallcomb, C. (2019). A scale to characterize the strength and impacts of atmospheric rivers. *Bulletin of the American Meteorological Society, 100*(2), 269–289.

Section 4. Preliminary Viability Assessment Scoping

4.1 Overview and Purpose

The objective of the Preliminary Viability Assessment (PVA) is to conduct technical studies that describe meteorological, hydrological, water resource engineering, and environmental work, as well as develop enhanced monitoring, decision support tools, and communication materials for the U.S. Army Corps of Engineers (USACE) and local partners to consider using for Forecast Informed Reservoir Operations (FIRO) testing and operationalization. This section develops key questions and recommended tasks for the PVA, with the expected outcome of producing sufficient analyses and supporting documentation to assist with a deviation request to the local sponsors and USACE to implement FIRO at Howard A. Hanson Dam (HAHD).

The PVA technical work will be conducted by teams that represent cross-cutting science and engineering disciplines. These include eight focus areas: observations, meteorology (including climate change), hydrology, weather and water forecast verification, water resources engineering (WRE), decision support, communications, and environmental considerations. Each focus area will form a team composed of subject material experts on FIRO with team members that bring in expertise specific to the watershed. The teams will create a project charter that develops a plan for the PVA and a responsibility matrix for members of that team. Team leads will report on progress at each Steering Committee meeting and obtain feedback from Steering Committee members and interested parties.

4.2 Observations

4.2.1 Context

The observations task is focused on collecting and disseminating data in near real-time to support current reservoir operations, improved forecasts, better physical process understanding, and data and informational requirements of multiple other tasks. The work conducted here will build upon the work conducted during the preliminary technical studies and described in Section 3. The observations team will also continue to review and assess the current observational network and make recommendations for improvement where appropriate, with a particular eye toward forecast verification applications.

4.2.2 Tasks

4.2.2.1 Team Charter and Collaboration with Other Work Teams

The observations team will develop a team charter with specific tasks as described below, which build on the work conducted in the preliminary technical studies. The team will continue to engage with operational forecasters at the National Weather Service (NWS) Seattle Weather Forecast Office, and other agencies collecting observations in and near the watershed, such as the U.S. Department of Agriculture's National Resource Conservation Service. In addition to engaging external entities, significant collaboration will take place between the meteorology, hydrology, verification, and decision support teams to ensure work products and information effectively meet requirements for the PVA. Additional tasks may be added at the discretion of the Steering Committee while developing the PVA.

4.2.2.2 Network Analysis with a Focus on Verification Applications

In this task, the observations team will conduct a rigorous network evaluation to ensure the monitoring networks meet the needs of the HAHD FIRO PVA and Final Viability Assessment (FVA), encompassing observation types deemed critical to the effort by the meteorology, hydrology, and forecast verification teams. We expect observation types to include precipitation, snow, soil moisture, and streamflow, amongst other potential quantities. In particular, this network evaluation will focus on the network's ability to meet forecast verification requirements for HAHD FIRO.

After observations of interest are defined, the observations team will create an inventory of stations and observation types available in real time. We will conduct the following analyses: a cluster analysis of landscape characteristics, assessment of elevation coverage relative to the hypsometry of the Green River basin, representation of precipitation climatology variability throughout the basin, and an assessment of data reliability for all existing stations—operated by the Center for Western Weather and Water Extremes (CW3E) or not—reporting in real time in the basin during storm events. Additional analyses may be considered in collaboration with the forecast verification team. We will assess where to best site two additional surface meteorology stations with soil moisture profiles down to 1 meter, supplementing the station installed during the preliminary technical studies, and install those stations during the second year of this period of performance. We will also document any additional gaps that may be addressed during future funding phases.

4.2.2.3 Continued Data Collection from Existing Stations and Storm-Based Sampling

This task will ensure robust data streams from the three stations installed during the preliminary technical studies, including regular (at least once per year) maintenance visits to the sites, as well as visits to promptly deal with any issues with hardware. Visits will continue to be scheduled in close coordination with Tacoma Water staff. The observations team will continue collaborating with NWS and other data users to ensure the data are available in near real-time in their systems and through their preferred mechanisms. We will continue to track any real-time communication outages and make contingency plans to minimize outages in future (e.g., having redundant communications platforms, such as the platform that will exist at the Headworks Radar Meteorology site). We will also work to maximize the utility of observations by Tacoma Water and other operational partners. For example, providing threshold-based alerts, daily updates, or customized visualizations as requested by partners and with iteration expected.

Following the successful completion of radiosonde field campaigns in the preliminary technical studies, in this task, the observations team will sample at least three impactful storms each water year (WY), beginning when the period of performance starts in WY 2025. Storm sampling will either be at our inland location or a coastal location, as appropriate, with decisions on storms and locations to be made in collaboration with NWS, the CW3E-led Atmospheric River (AR) Reconnaissance team, and the CW3E meteorology team. Close coordination with the AR Reconnaissance team will enable us to leverage offshore sampling of impactful ARs to increase the potential impact of the radiosonde forecasts, the physical process information to be gained from both offshore and onshore vertical profiles of the same storm, and the utility for forecast verification and model diagnostics. As in the preliminary technical studies, in addition to being used for process studies and forecast verification in other tasks, the observations team will provide data from the radiosondes in near real-time to global operational weather prediction models for data assimilation via the World Meteorological Organization's Global Telecommunication System. We will also continue working with the National Centers for Environmental Prediction to provide these data streams via a pathway that enables NWS to view them within their Advanced Weather Interactive Processing System.

4.2.3 Expected Outcomes

Through the process of performing the tasks identified above—in collaboration with the meteorology, hydrology, and forecast verification teams—the observations team expects to develop substantial insight on the key physical processes at work in extreme events in the HAHD area of interest, which will be critical to improve forecasts. The observations team's work developing the PVA aims to fill identified gaps in the observation network to better represent watershed characteristics and hydrometeorological conditions with reliable, near real-time monitoring stations. Data from these stations will be leveraged for multiple sections of the FVA and will immediately be implemented into operational practices as appropriate and in collaboration with NWS and other partner agencies. These data will also be provided as needed for situational awareness regarding antecedent conditions in the watershed and storm-scale variability during events, in collaboration with the decision support team. Over the long term, the period of record of these stations will support better representation of the changing climatology of the watershed and provide valuable information for decision support.

The preliminary technical studies and PVA will inform where additional observations or areas of interest for HAHD might be, even if initially out of scope. These needs can be addressed in the FVA or as activities to continue expanding and improving upon the observation network in the FIRO implementation phase.

4.3 Meteorology

4.3.1 Key Findings and Summary

Datasets compiled as part of the preliminary technical studies indicate that the mean areal precipitation over the larger Duwamish River basin contains a WY annual average of approximately 66 inches, wherein 28 percent falls in "extremes" in the top 5 percent of wet days over the course of approximately 15 calendar days. Coincidentally, around 30 percent of the annual precipitation also falls in association with landfalling ARs, which average around 25 per year along the Pacific Northwest Coast. These ARs account for an average of approximately 62 percent of the extremes; however, in any given year, ARs can account for around 20–90 percent of extreme precipitation events.

The primary goal of the meteorology effort is to identify the physical processes associated with precipitation extremes across the Green River basin, evaluate their predictability in coordination with the verification team, and use this information to help understand the potential viability of FIRO at Howard Hanson. This goal is related to Section 4.5 on forecast verification. The secondary goal of the meteorology effort also involves climate and climate change, specifically addressing how storm and precipitation characteristics may change in future climates and how these changes could influence the potential viability of FIRO at Howard Hanson.

4.3.2 Precipitation Extremes and ARs

4.3.2.1 Background

Landfalling ARs are important to both annual and extreme precipitation in the Green River basin. The purpose of these tasks is to further summarize the relationships among landfalling ARs and extreme precipitation specifically over the Green River basin, and to evaluate the forecast skill of precipitation events over the basin in coordination with the forecast verification team.

In addition to climatological analyses of the influence of ARs on extreme precipitation events and their forecast skill over a long period of record, additional tasks will investigate case studies of high-impact events that contained either large precipitation and inflow and/or forecast errors relating to large precipitation and inflow. These analyses will leverage other local data as well as in situ observations collected by the CW3E field team.

4.3.2.2 Key Questions and Tasks

The following key questions related to precipitation extremes and ARs will be addressed by the meteorology team, in coordination with the forecast verification team, as part of the PVA:

- What fraction of extreme precipitation events over the Green River basin is associated with landfalling ARs?
- What meteorological processes influence spatial and temporal variability in precipitation during landfalling ARs?
- How does the precipitation forecast skill differ between AR-related and non-AR-related events over the Green River basin?
- What meteorological processes produce challenges to precipitation forecast skill during extreme events?
- How do in situ observations help scientific understanding and model validation of extreme precipitation events?

The following tasks will be conducted during the PVA:

1. Leverage AR and precipitation catalogs developed during the Workplan Preliminary Technical Studies to further evaluate and summarize relationships between precipitation extremes and landfalling ARs.
2. Quantify and summarize precipitation forecast skill as a function of lead time for AR-related and non-AR-related precipitation events over the Green River basin using a reforecast dataset.
3. Conduct case studies of high-impact events to the Green River basin, including events that contained low precipitation forecast skill, and leverage in situ observations.

4.3.2.3 Expected Outcomes

The tasks investigating the physical processes responsible for extreme precipitation and their influence on precipitation forecast skill over the Green River basin, specifically related to landfalling ARs, will provide context for evaluating the predictability of large inflow/streamflow events into the reservoir at HAHD.

4.3.3 Climate and Climate Change

4.3.3.1 Background

HAHD and the Green River basin provide several benefits to the Tacoma region such as water supply, flood risk management, and resources for fish. Unlike many California reservoirs where FIRO has been applied, HAHD and its reservoir are completely emptied each fall for flood risk management and refilled every spring for water supply and environmental uses. While there are likely several ways traditional FIRO techniques and ideas can benefit the Green River basin and its resources, future concerns regarding the ability to refill, insufficient flows for fish, timing of runoff for refill, the potential for decreased winter snowpack, the possibility of adding storage space to the reservoir, and future changes in extreme precipitation make climate change an essential piece of the FIRO equation. A rigorous scientific analysis of how climate change will impact the basin can help guide future potential HAHD and reservoir operations changes that will need to be considered.

The Green River basin, above HAHD, is particularly vulnerable to climate change. Studies show a declining snowpack and earlier snowmelt due to warming, which impact water storage and management, increasing reliance on unpredictable spring rains (Harrell 2018). Climate models also predict more extreme precipitation events, complicating reservoir operations. Research indicates that ARs, which heavily influence the basin, are expected to become more intense and frequent, further challenging water management in the area.

4.3.3.2 Key Questions and Tasks

The following key questions related to climate change will be addressed by the meteorology team as part of the PVA:

- How will peak snowpack dynamics change as a function of climate change?
- How will seasonal precipitation patterns change as a function of climate change?
- How will the frequency of extreme events related to ARs change as a function of climate change?
- What impact will climate change have on precipitation type over the Green River basin?

Subsequent tasks to be conducted during the PVA will explore the potential for FIRO Water Control Plan (WCP) strategies to mitigate the impacts of anticipated climate change in the Green River basin.

4.4 Hydrology

4.4.1 Context

The Hydrology task is primarily focused on meeting the data and informational requirements of the WRE task. The hydrology team will address the provision of streamflow observations, forecasts, and hindcasts based on the following services:

- NWS's Northwest River Forecast Center (NWRFC) Community Hydrologic Prediction System (CHPS) and Hydrologic Ensemble Forecast System (HEFS).
- USACE's Corps Water Management System (CWMS) Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS).

To date, USACE FIRO pilot projects have not considered using HEC-HMS, which means additional work will be required to ensure WRE task requirements can be met.

The hydrology task is primarily focused on meeting the data and informational requirements of the WRE analysis of alternative WCPs that leverage streamflow forecasts.

4.4.2 Tasks

4.4.2.1 Team Charter and Collaboration with Other Work Teams

The hydrology team will develop a team charter with specific tasks as described below. Significant collaboration will take place with the WRE team to ensure that the work products effectively meet the WRE team's requirements for the PVA.

4.4.2.2 Curate Historical Observations of Inflow

Diversions and water use upstream of HAHD impact inflows and can compromise the quality of a calibrated streamflow model if the hydrology team does not properly account for them. The team will make a concerted effort to ensure the historical inflow records used in PVA analyses are well understood and best represent "unimpeded" or "full natural flow" conditions.

4.4.2.3 Review of Seattle District's HAHD Inflow Model

The hydrology team will review the ability of the HEC-HMS inflow model to simulate historical observations and provide forecasts with the lead times required for envisioned FIRO WCP strategies. The team will address and correct identified gaps and deficiencies if feasible within the project timeline.

4.4.2.4 Review of NWRFC's HAHD Inflow Model

The hydrology team will review the ability of the NWRFC's CHPS inflow model to simulate historical observations and provide forecasts with the lead time required for the envisioned FIRO WCP strategies. The team will address and correct identified gaps and deficiencies if feasible within the project timeline.

4.4.2.5 Critical Duration Analysis

The hydrology team will evaluate historical precipitation and streamflow records to estimate the most appropriate critical duration for inflow to HAHD. The critical duration will be used for the frequency analysis and is needed to scale individual large events within the hindcast period of record.

4.4.2.6 Frequency Analysis

A frequency analysis for the critical duration will be conducted to ensure that the range of scaling factors used in the hindcast preparation adequately covers the extremes needed for robustness testing within the hindcast period of record (e.g., 500-year, three-day inflow event).

4.4.2.7 HEC-HMS Hindcasts

The hydrology team will work with the USACE Seattle District to explore the potential to generate HEC-HMS hindcasts required by the WRE team.

4.4.2.8 HEFS Hindcasts

The hydrology team will work with the NWRFC to develop the HEFS hindcasts needed for the WRE team's evaluation of WCP alternatives. To the greatest extent possible, hindcasts will be consistent with the NWRFC's real-time operations so the WRE evaluation results represent expected operations. HEFS hindcasts will be generated for:

- The period of record (beginning in WY 1990).
- Scaled events (two to three selected events incrementally scaled to cover 100- to 500-year recurrence intervals).
- Synthetic events outside of the HEFS period of record (if available).

4.4.2.9 HEFS Real-Time Forecasts

The NWRFC publishes the HEFS forecasts in real time on their website. The hydrology team will work with the NWRFC to access operational HEFS forecasts in order to develop familiarity with the HEFS forecasts, assess their reliability, and integrate them into candidate decision models.

4.4.2.10 Climate Change Investigations

The hydrology team will support climate change investigations by providing guidance and potentially simulated and forecast datasets that reflect selected climate change scenarios on streamflow and streamflow forecasts.

4.4.2.11 Collaboration with Other Teams

As stated above, the hydrology team will work closely with the WRE team to ensure delivered products and information meet the WRE team's needs. The hydrology team will also collaborate with the forecast verification team (Section 4.5) to assess and document the quality and uncertainty of the USACE Seattle District's HEC-HMS and NWRFC's HAHD inflow models.

4.4.3 Expected Outcomes

Through the process of performing the tasks identified above, the hydrology team expects to develop substantial insight on the predictability of HAHD inflows and refine the process for delivering analysis and hindcasts in support of the WRE team's efforts.

4.5 Weather and Water Forecast Verification

4.5.1 Introduction

Weather and water forecast verification is paramount to the concept of FIRO, wherein forecast information could be leveraged for water management decisions. Water managers need confidence in the forecast information and context for predicted weather and hydrologic conditions to utilize forecasts to the maximum extent.

The goal of the forecast verification effort is to provide forecast skill analyses for multiple components of the hydrometeorological system impacting reservoir operations at HAHD. This evaluation will focus particularly on the scales that dictate the development of meteorological mechanisms responsible for precipitation generation, localized orographic patterns, rain-snow partitioning, and resulting streamflow or inflow into the reservoir. It will also serve as a pathway to identify opportunities for advancing AR prediction, such as physical process identification, model analysis and improvement, and observation quality and spatial distribution.

4.5.2 Baseline Assessment Using Historical Forecast Information for Precipitation and Inflow

4.5.2.1 Context

Long-term forecast skill assessments ultimately provide users with knowledge on how well and at with what lead times models can predict different magnitudes and characteristics of extreme precipitation events using long periods of data records (typically between 10 and 30 years). This effort provides a baseline for forecast skill of precipitation and inflow predictions on relevant time scales and with spatial bounds associated with reservoir operations at HAHD. It ultimately serves as the starting point for further partitioning of the meteorological and hydrologic characteristics that could affect predictability of precipitation and runoff generation.

4.5.2.2 List of Key Questions and Tasks

- The following key questions for long-term forecast skill evaluations will be addressed by the verification team as part of the PVA:
- What is the skill of precipitation and inflow forecasts within the Howard Hanson operational basin?
- What are the relationships between precipitation and inflow forecast skills?
- The following tasks will be conducted during the PVA:
- Identify relevant Green River basin information (e.g. regulations, diversions, important tributary locations) to better approximate the operational basin extent.
- Obtain observations of precipitation and inflow for HAHD and relevant location information relative to the dam and important tributaries.
- Compute mean areal precipitation forecast skill from archived or reforecasted global and high-resolution models and determine lead times with evidence of forecast skill. Precipitation totals can be examined on sub-daily, daily, and multiday timescales.

- Compute skill of multi-volume totals of inflows into Howard Hanson using reforecasted and archived inflow forecasts generated from (or simulated from a matching configuration of) the CNRFC's HMS.
- Identify pathways to intercompare links between atmospheric and hydrologic forecast skill.

4.5.2.3 Expected Outcomes

The expected outcome of this effort will be a series of statistical skill measures of precipitation and inflow for HAHD using several metrics, models, and aggregation times relevant for operations.

4.5.3 Post-Event Precipitation Verification to Contextualize Forecast Evolution for Impactful Events

4.5.3.1 Context

Each winter season, ARs can bring considerable rainfall and runoff to the Green River basin that vary alongside the duration, intensity, position, and life cycle evolution of ARs. Understanding the variability in forecast evolution allows the verification team to study and rectify how different scales of variability and uncertainty impact the decision-making process and actionable timelines for reservoir operations. Understanding forecast variability is especially important when AR forecasts are highly uncertain (e.g., forecasts of an AR look significantly different from that of the previous day's forecast). When forecasts are particularly challenging, it is important to analyze what components of the forecast were correct and/or highly variable. To increase forecast utility, we will provide post-event and post-season verification statistics of precipitation to guide future science investigations and case study analysis that will ultimately improve understanding of AR predictability and variability.

4.5.3.2 List of Key Questions and Tasks

- The following key questions for long-term forecast skill evaluations will be addressed by the verification team as part of the PVA:
- What were the precipitation forecast errors of several high-impact events in the Green River basin?
- What were the overall seasonal errors of precipitation forecasts in the Green River basin for the last several years?
- How do individual AR storms and their forecast errors contribute to the overall seasonal precipitation error?
- Are there any additional observations that can help the verification team understand the error characteristics of extreme precipitation and vapor flux?
- The following tasks will be conducted during the PVA:
- Analyze several WYs of seasonal and event-total precipitation errors in the Green River basin and compute the percentage of seasonal error for each AR occurring during the season.

- Provide list of poorly forecasted (i.e., bust) case studies and their precipitation error tendencies.
- Evaluate case studies of high-resolution forecasts against unique and/or opportune observations made during extreme precipitation events.

4.5.3.3 Expected Outcome

- The expected outcome of this effort will be a report on a series of WY evaluations of precipitation on daily, event, and seasonal time scales. It will include a quantitative evaluation of the fraction of ARs to the seasonal total error of precipitation as well as findings on any relevant trends in forecast tendencies.

4.5.4 Identifying and Aligning Forecast Errors with Meteorological Characteristics, Observations, and Modeling Development

4.5.4.1 Context

Forecast evaluation provides valuable context for other FIRO-related development areas, including understanding the role of meteorological characteristics and hydrologic processes on precipitation and inflow predictability, or how errors in forecasts can depend on quality observations to make solid conclusions about the state of model predictions. This section outlines the integration and coordination of forecast skill information with the meteorological, hydrologic, and observation teams.

- Precipitation errors can be influenced by meteorological and hydrological mechanisms that span scales from localized to synoptic in nature. After identifying precipitation error, as described in Section 4.5.3, the verification team will look at key factors potentially affecting the predictability of precipitation and inflow and their associated skill. These factors include large-scale factors such as landfall, intensity, and duration of an AR, as well as localized influences like freezing level, which is the elevation where precipitation is partitioned by phase into rain or snow. The verification team will provide forecast skill assessments of key factors to the meteorological team for further process review and study.
- Identification of systematic model forecast errors will be coordinated with the modeling team to identify unresolved physical processes and/or dynamical features that are targeted for forecast improvement. The verification team will build pathways between model development and verification to iterate on findings associated with AR and precipitation prediction and model integration.
- Finally, the verification group will coordinate with the observations team to collocate spatial model errors with the availability of observations to identify gaps in the spatial extent of available observations, identify opportunities for unique or additional sampling, utilize CW3E-specific observations for site-specific or regional forecast verification in near real-time, and coordinate approaches to improve or resolve issues with observations to support better model verification.

4.5.4.2 List of Key Questions and Tasks

The following key questions for team coordination and integration will be addressed by the verification team as part of the PVA:

- What is the landfall, intensity, and position forecast skill for ARs making landfall near the Green River basin?
- What is the forecast skill of the volume of precipitation falling as rain or snow during key events?
- What are other scales of factors influencing precipitation and runoff predictability?
- What are some key differences between regional and global forecast errors associated with ARs impacting the Green River basin?
- What are some pathways for exploring improvements to precipitation and AR forecasting using regional models?
- How do spatial forecast skill errors align with observations of precipitation, wind, temperature, humidity, and additional measurements of precipitation type/phase?
- Which station observations are available as part of operational gridded observation datasets?
- Are there opportunities to improve observation density, targeted observation deployment, and/or improved quality based on results of verification?
- The following tasks will be conducted during the PVA:
- Provide assessments of landfall, intensity, and position skill of forecasts for ARs making landfall near the Green River basin.
- Calculate the forecast skill of volumetric precipitation in areas where there are sub-freezing temperatures.
- Iterate with the meteorology team to subset the above characteristics to identify related patterns of forecast errors.

4.5.4.3 Expected Outcomes

The expected outcomes of this task include:

- A summary report of the forecast errors from global and regional forecast models over the Green River watershed with an overlay of available observations.
- A list of priorities for model development based on verification outcomes.
- A report that summarizes the characteristics of ARs (and other features) that influence forecast skill over relevant time periods.

4.6 Water Resources Engineering

4.6.1 Context

The WRE task seeks to gain insight toward the rigorous assessment of FIRO for HAHD. The PVA serves as a testing ground where the WRE team will learn the complexities of the HAHD system and how to effectively and accurately simulate candidate reservoir operations that integrate forecasts into their decision logic. Experience with previous FIRO projects has shown that the lessons learned through the PVA contribute to a significantly better and more robust FVA.

The WRE tasks associated with the PVA are also intentionally "exploratory." While practical considerations are primary (and necessary), there is more room to try less conventional and even novel approaches that may not be immediately targeted for a WCM. This research approach serves to push the limits of conventional reservoir management and provides opportunities to advance the state of the science and practice.

4.6.2 Tasks

4.6.2.1 Organizational Approach: Hydrologic Engineering Management Plan

The general approach taken by the WRE team to demonstrate FIRO viability at HAHD will follow the process developed by previous FIRO projects. A hydrologic engineering management plan (HEMP) will be developed that describes the WRE team, process, and components of the assessment.

> The goal of the HEMP is to create an evaluation framework whereby alternative WCPs that use streamflow forecasts can be compared with existing (i.e., baseline) operations as well as each other.

The HEMP will be collaboratively developed by the WRE team and vetted with the HAHD Steering Committee. The HEMP contains the following sections.

- Objective of technical analysis and overview of process.
- WCP alternative requirements, constraints, and considerations.
- WCP alternatives to be evaluated (baseline and FIRO).
- Metrics for evaluating the viability and efficiency of alternatives.
- Tasks and subtasks.
- Project delivery team members and their roles.
- The schedule for completing technical analyses.
- Risks to success.

4.6.2.2 Modeling and Simulations

The WRE team will establish a modeling framework to account for the movement of water as it affects HAHD operations.

4.6.2.3 Water Accounting

As shown in Figure 2-5, the movement and storage of water associated with HAHD is quite complex. This includes activities within and below the HAHD watershed. The simulation framework will strive to account for the structure of water movement and storage to the greatest extent feasible. Where detailed data are not available, reasonable estimations will be made based on well-informed guidance.

4.6.2.4 Reservoir Operations

Reservoir operations for each of the selected FIRO alternatives and the non-FIRO baseline will be modeled through a combination of CWMS and research applications (e.g., the Ensemble Forecast Operations model). Reservoir operations models will be configured to simulate storage and releases while providing information needed to quantitatively assess the performance metrics identified in the HEMP. The time step of reservoir operations simulations will be determined during the study. It may be possible to simulate the system at a daily time step, or an hourly time step may be required during flood operations.

4.6.2.5 Simulation Plan

The WCP alternatives identified in the HEMP will be simulated using water accounting and reservoir operations over a lengthy period of record (around 30 years) as well as for a collection of extreme events representing return intervals up to 500 years (0.002 percent annual probability of exceedance). Information from the simulations will be collected and processed to compute the performance metrics identified in the HEMP.

4.6.2.6 WCM Update On-Ramp

The WRE team will align the PVA work as closely as possible with the requirements and information needs associated with a potential HAHD WCM update.

4.6.2.7 Address Barriers Associated with Full Use of Streamflow Ensembles

In concert with other FIRO projects, the WRE team will work toward integrating reservoir operations models into CWMS that fully leverage the uncertainty in streamflow forecast ensembles. This work will include code migration, documentation, testing, and training.

4.6.2.8 Collaboration with Other Teams

The WRE team will rely upon the hydrology team (see Section 4.4) for the following information:

- Curated inflow observations that consider water management activities by upstream entities.
- Daily time step for the period of record.
- Hourly time step for significant or scaled events.
- Consensus on the critical duration for reservoir operations.
- Frequency analysis of reservoir inflows.
- Potential recalibration of the HAHD inflow model used/provided by the NWRFC.
- Generation of period-of-record hindcasts using HEFS and perhaps HEC-HMS.
- Generation of scaled hindcasts for alternative testing outside the period of record.
- Potential generation of synthetic hindcasts.

The WRE team will rely upon the verification team (see Section 4.5) for the following information:

- Assessment of the USACE Seattle District's and NWRFC's reservoir inflow simulation modeling. This modeling will be used to assess the need to recalibrate the inflow model.

The WRE team will collaborate with the decision support team (see Section 4.7) to ensure that candidate alternatives are appropriately supported with established tools and near real-time data.

4.6.3 Expected Outcomes

Through the process of performing the tasks identified above, the WRE team expects to develop substantial insight on the potential for HAHD to benefit from FIRO. In addition, the experience gained through the PVA process is expected to sharpen and improve the WRE assessment associated with the FVA, as well as the eventual WCM update.

4.7 Decision Support

4.7.1 Context

Where appropriate, reservoir operators have been (informally) using forecasts for some time. FIRO creates a paradigm shift for explicitly using forecasts in WCPs. This shift places new demands on information systems and reservoir modeling frameworks to support the formal decision-making process. These demands include the developing and integrating FIRO capabilities into established USACE tools such as CWMS.

The decision support task focuses on activities that identify, collect, refine, and develop data and technology transfer applications beneficial to reservoir operations decision making. This task will leverage experience from other FIRO projects but will be tailored to the specific needs and decision makers associated with HAHD and its beneficiaries.

> Decision support is a key pillar of FIRO, and the process of identifying and improving informational systems cuts across all disciplines and partner agencies.

4.7.2 Tasks

4.7.2.1 Team Charter

The decision support team will develop a team charter— a one-page document that outlines the team's roles, responsibilities, and a list of general tasks. Additional tasks may be added while developing the PVA.

4.7.2.2 Identify and document key decision makers.

4.7.2.3 Catalog existing decision support tools (DSTs) used by HAHD operations and partner agencies.

4.7.2.4 Conduct DST workshop(s).

4.7.2.5 Identify additional DSTs that may support FIRO operations.

4.7.2.6 Develop FIRO-specific needs assessment.

4.7.2.7 Work with developers to prototype new information sources identified in Subtask 4.7.1.6.

4.7.2.8 Collaboration with Other Teams

The DST team will work closely with nearly every PVA work team. The closest collaboration will take place with the Observations, Meteorology, WRE, and Environmental teams.

4.7.3 Expected Outcomes

Through performing the tasks identified above, the decision support team expects to develop substantial insight on informational needs of reservoir operations. The team will work toward prototyping new informational environments where cross-cutting data and forecasts are provided in an intuitive fashion. Experience and progress gained during the PVA will be carried forward and refined during the FVA effort.

4.8 Communications

4.8.1 Context

The communications team supports the project's communications and outreach needs as identified by the Steering Committee. Tasks focus on translating technical information into accessible terminology and messaging that capture the key milestones, accomplishments, and challenges of this project in a way that audiences will quickly and easily understand. This translation is essential to ensure that elected officials, agency representatives, advocacy groups, taxpayers, and other interested parties are aware of and can support all steps of the FIRO process, leading to improved reservoir operations with multiple benefits.

4.8.2 Tasks

4.8.2.1 Form a Communications Team and Develop a Team Charter

Members of the Steering Committee, as well as their support staff (particularly public affairs staff), will be polled for availability to participate on the HAHD communications team. Members will then develop a team charter including the following tasks:

- Prepare fact sheets as the HAHD FIRO Steering Committee reaches key milestones such as publication of the workplan, PVA, and FVA.

- Identify opportunities to communicate progress, benefits, and other unique aspects of the HAHD FIRO project, including public events, major milestones, inquiries, and conferences or workshops.
- Create communication products as needed (e.g., videos, infographics, other visuals) and distribute them via social media, websites, press releases, and other outlets as directed by the Steering Committee co-chairs.
- Contribute to drafting the PVA and FVA introduction and executive summary.

4.8.2.2 Collaborate with Other Teams

The communications team will work closely with other work teams, particularly the WRE and environmental teams, to ensure the information they produce is accurately and concisely translated.

4.9 Environmental Considerations

4.9.1 Context

Fish resources are a main driver of water management in the Green River. Significant investments have already been made to restore fish resources in the river, and further investments will need to be made, including designing and constructing a downstream fish passage facility at HAHD.

The HAHD FIRO PVA will explore a range of operational alternatives to determine if, and to what extent, FIRO operations may enhance environmental instream flows for fish. The environmental work team will ensure that this analysis will be sufficient to inform decisions on future operations based on team members' knowledge as well as lessons learned in other FIRO projects, notably Russian River FIRO, where FIRO operations were found to benefit the habitat of three endangered salmonids.

4.9.2 Tasks

4.9.2.1 Form an Environmental Team and Develop a Team Charter

An environmental work team will be formed based on the interest, availability, and expertise of Steering Committee members or their staff. Participants outside the organizations represented on the Steering Committee may be included. Work team lead(s) will also be identified, and they will convene the team kick-off meeting. The first meeting will focus on developing a team charter. At this meeting, the team will review the tasks listed below and modify or expand them as needed. While fish resources are the main focus, the team will consider other environmental factors relevant to FIRO operations such as water quality, vegetation, and sediment management.

4.9.2.2 Develop Environmental Metrics for Assessing FIRO Alternatives

In close coordination with the WRE team, the environmental work team will develop environmental metrics, against which the FIRO alternative approaches can be compared with respect to potential benefits.

4.9.2.3 Provide Data and Information and Support Drafting the Environmental Section of the PVA

This workplan only presents cursory information on fish resources. To ensure the PVA analyses are robust regarding fisheries, the environmental work team will provide additional data and information to the WRE work team, other teams, and the Steering Committee as needed. The environmental work team may also choose to convene a technical workshop by itself or jointly with other teams to share information, discuss key issues, and reach agreement on a path forward.

4.9.2.4 Network with Other FIRO Pilot Projects

As needed, the environmental work team may wish to coordinate with environmental work team members from other FIRO pilot projects to benefit from their experiences and lessons learned. For example, the Willamette River basin will soon kick off a FIRO project, and this watershed has similar fish resource considerations.

4.10 References

Harrell, J. 2018. Predicting Streamflow and Snowpack Sensitivities to Climate Change in the Pacific Northwest's Green River Basin. Significant Opportunities in Atmospheric Research and Science Program. https://opensky.ucar.edu/islandora/object/manuscripts%3A980/datastream/PDF/download/citation.pdf

Section 5. FIRO Implementation Strategy

5.1 From FIRO Viability Assessment to Water Control Manual Update

This workplan serves to provide context and act as the scoping document for the rest of the Forecast Informed Reservoir Operations (FIRO) viability assessment process for Howard A. Hanson Dam (HAHD), as shown in Figure 5-1. After finalizing the workplan, the FIRO Steering Committee will pivot to the Preliminary Viability Assessment (PVA). The FIRO team will develop a detailed PVA outline, including a list of tasks and assignments, at a technical workshop, after which all work teams will transition into the next step of the process. The PVA will outline meteorological, hydrologic, engineering, and environmental parameters related to FIRO operationalization for local sponsors and the U.S. Army Corps of Engineers (USACE) to consider including in the Water Control Manual (WCM). The PVA will assess FIRO viability at HAHD and specify additional analyses needed to develop the Final Viability Assessment (FVA) and a potential WCM update.

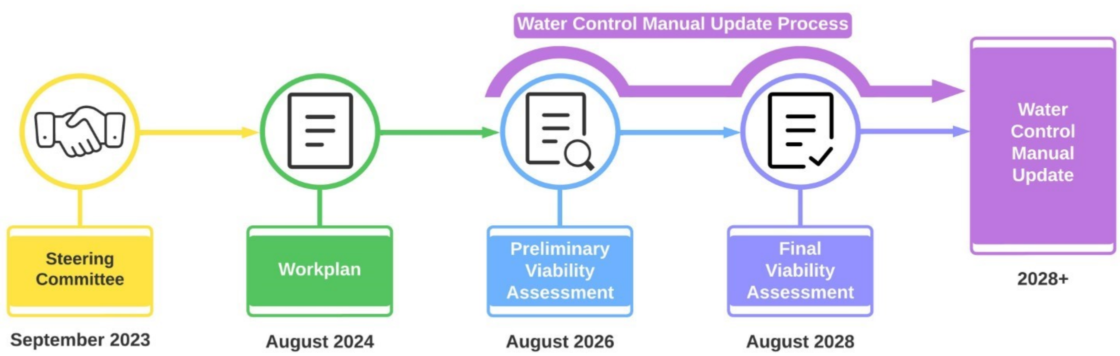

Figure 5-1. *FIRO and WCM update timeline at HAHD.*

5.1.1 Potential Planned Deviation

The FIRO process typically tests FIRO operations via approved planned deviations to the Water Control Plan (WCP). As the PVA is developed, information will become available to determine if a deviation to the WCP is feasible to test FIRO strategies. If the information indicates a deviation is feasible from a technical standpoint, the Steering Committee will consider making a recommendation to the local sponsors and USACE regarding a short-term planned deviation. This process would involve scoping out the technical analyses involved in assessing the deviation, preparing environmental documentation, and conducting related work.

5.1.2 Potential Enhancements to the Corps Water Management System

FIRO WCP strategies that cannot be reasonably configured within USACE's Corps Water Management System (CWMS) have little chance of being integrated into USACE operations and WCM updates. Efforts will be made to integrate effective FIRO WCP strategies developed or used in the PVA and FVA into CWMS through established USACE processes. Integration includes software migration, testing, documentation, and training. The FIRO WCP strategy migration pathway into CWMS is not unique to the HAHD FIRO project but is a shared requirement for several FIRO projects. Nonetheless, the HAHD FIRO project will share in efforts and responsibility to complete this step in the research-to-operations process.

5.2 Implementation Timeline

Ideally, the WCM update process will either overlap with, or begin toward the end of, the FIRO viability assessment process, as shown in Figure 5-1 above, to ensure efficient FIRO implementation. FIRO implementation includes efforts introduced during the PVA and later developed in the FVA to support FIRO outcomes into the future. Specific findings and recommendations within the research areas of forecast skill assessment and enhancement, water resources engineering, observations, weather forecasting, hydrologic modeling, and an understanding of environmental objectives are all fundamental components of the viability assessment process. Following this foundational work, FIRO implementation is pursued through deviation requests to the USACE Northwest Division before being permanently implemented by updating the HAHD WCM. One of the central needs for FIRO implementation is a WCP that utilizes forecasts to inform reservoir release decisions. This process will require the support of local sponsors and USACE.

Section 6. Appendices

6.1 Flow Management for Fisheries

Flow management at Howard A. Hanson Dam (HAHD) is adjusted seasonally to account for fisheries and aquatic habitat per the National Marine Fisheries Services (NMFS) biological opinion issued in 2019 (NMFS 2019).

The conservation season ends and flood season typically begins in November when significant landfalling atmospheric rivers bring precipitation to the area. To prepare for the flood season, the pool behind HAHD is lowered until there is no active storage except for flood events, per the Water Control Manual (WCM):

> Flood control operations will make maximum beneficial use of available storage during each flood event and will be based upon a channel capacity that will safely carry a discharge of 339.84 m^3/s (12,000 cfs) near Auburn. To provide a margin of safety against errors in forecasted local inflow, the project outflow will be regulated to target flows near Auburn to an objective flow of 283.20 m^3/s (10,000 cfs) on a rising hydrograph. The objective flow will be increased during recession to evacuate storage as rapidly as practicable, the amount of increase to be based upon observed and forecasted precipitation and the shape of the recession hydrograph. The maximum objective flow is equal to the control flow of 339.84 m^3/s (12,000 cfs).

There are guidelines for both up-ramping (i.e., increasing discharge) and down-ramping (i.e., decreasing discharge). Up-ramping rates, which are designed for public safety as well as fisheries, are limited to 6 inches per hour as feasible. During floods up-ramping rates rise to 1 foot per hour, higher rates are allowed if necessary. Down-ramping rates only apply if outflows are below 1,500 cubic feet per second (cfs). Ramping rate criteria limit fish getting trapped in shallow areas cut off from the main channel, where they are subject to bird predation and dewatering.

During flood season, there are restrictions on outflow meant to avoid scouring, which harms redds. Through February 28, the U.S. Army Corps of Engineers (USACE) restricts maximum outflows to 5,000 cfs for forecasted inflows less than 12,000 cfs unless flood and/or dam safety issues require larger releases. Down-ramping rates from November 1 through February 15 are limited to 2 inches per hour.

February is the transition month between flood season and spring refill season. The start of refill varies, but usually occurs mid to late month. Down-ramping rate guidelines change on February 16 through May 31 to 0 inches per hour for daylight hours and stay at 2 inches per hour for night hours. Daylight hours are defined as one hour before sunrise to one hour after sunset.

From mid/late February through May, the refill plan often utilizes proportional capture—which is to store a percentage of the inflow hydrograph so the shape of the reservoir discharge hydrograph will be like the natural inflow hydrograph. This plan is determined by using various tools and looking at historical runoff hydrographs, ESP traces, short-term weather and hydrologic forecasts, and water supply forecasts. Day-to-day adjustments of this plan are based on rain and flow measurements and near-term forecasts.

Full refill of the conservation and water supply storage generally occurs in late May to early June depending on the year, with later refill occurring in higher runoff years and earlier refill targeted in lower runoff years. From June 1 through October 31, the down-ramping rate is reduced to 1 inch per hour, night and day.

Conservation season typically begins in July but can start earlier in low runoff years. The WCM states:

> The summer conservation period spans the period of approximately July through October. The reservoir will be held at maximum summer conservation elevation of 355.7 m (1167 feet) until storage releases are required to either augment flows or discharge water for municipal use. Normally, drawdown of the reservoir to meet low flow augmentation demands usually begins in July and continues through October. In the event of an exceptionally dry fall, if storage is available, augmentation will continue until winter precipitation increases river base flow to a level adequate to sustain discharge below the Tacoma Water diversion above the 3.12 m^3/s (110 cfs) minimum instream flow requirement at Palmer. As soon as conditions indicate conservation storage is no longer needed, the reservoir will be drafted to be near elevation 327.7 m (1,075 feet) for flood control.

The reservoir drawdown guide curve (see Table 6-1) ensures that the 110-cfs minimum flow target at Palmer is met with 98 percent reliability (Chart 7-1 in the HAHD WCM) to allow passage of adult salmon in the lower river during low flow years.

Table 6-1. *Allocation of conservation guide curve water.*

Month	Monthly Allocation (acre-feet)	Average release rate (cfs)
July	2,600	42
August	5,200	85
September	6,500	109
October	6,500	106
November	2,700	46

An additional 5,000 acre-feet of water is stored per Section 1135 of the Water Resources Development Act of 1986 (commonly known as "1135 Water") to support fisheries. Additionally, Tacoma Water and their second supply partners currently donate half of their municipal pot storage (up to 10,000 acre-feet) to be used as 1135 Water as part of the Additional Water Storage Project implementation. The 1135 Water is determined through biweekly consultation meetings with the Green River Flow Management Committee consisting of members from the Muckleshoot Indian Tribe and state, federal, and county resource agencies. USACE considers input to adjust the refill and release regime.

6.2 References

NMFS. (2019). Biological Opinion on Howard Hanson Dam Operations and Maintenance, Green River (HUC 17110013) King County, Washington. NMFS No.: WCR-2014-997. https://www.nws.usace.army.mil/Portals/27/docs/environmental/resources/2018EnvironmentalDocuments/2019_02-15_HowardHansonDam_WCR-2014-997.pdf