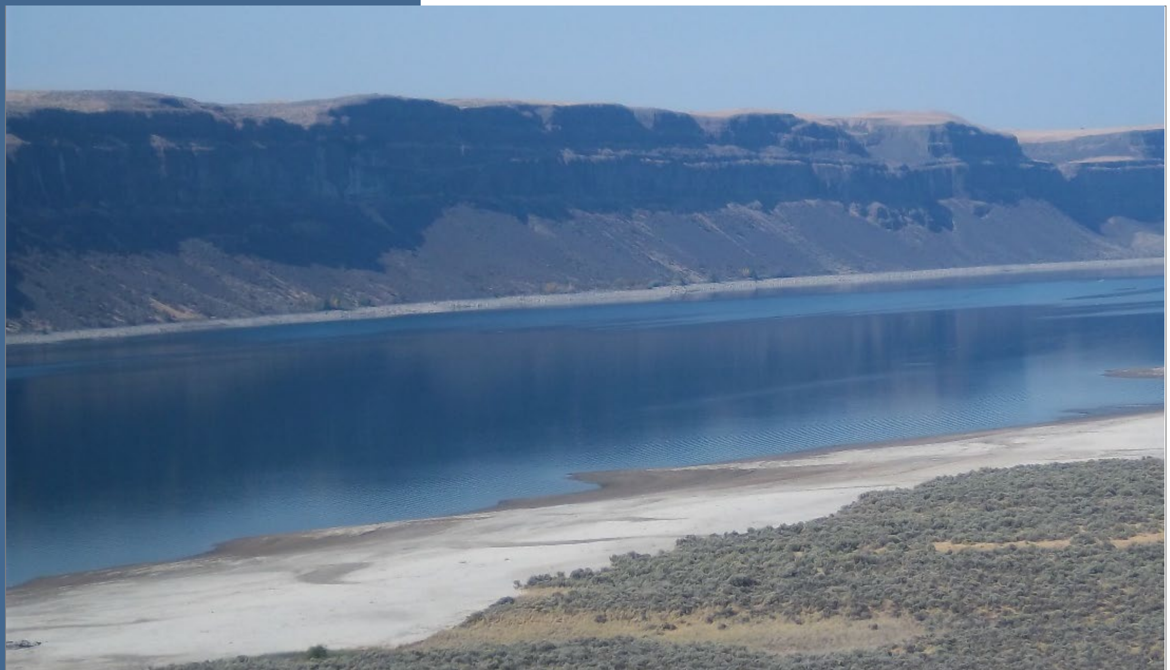

Columbia River Basin 2021 Long-term Supply and Demand Forecast

Technical Supplement Report

Office of Columbia River

Washington State Department of Ecology

Central Regional Office

Union Gap, Washington

August 2022, Publication 22-12-001

DEPARTMENT OF ECOLOGY State of Washington

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Other Relevant Documents and Websites

Publication 21-12-006: 2021 Columbia River Basin Long-Term Water Supply and Demand Forecast Legislative Report[1]
Publication 21-12-012: About the 2021 Columbia River Basin Long-Term Water Supply and Demand Forecast[2]
2021 Columbia River Basin Long-Term Water Supply and Demand Forecast Data Access Website[3]

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[1] https://apps.ecology.wa.gov/publications/SummaryPages/2112006.html
[2] https://apps.ecology.wa.gov/publications/SummaryPages/2112012.html
[3] https://storymaps.arcgis.com/stories/08bc55d5ef5a4b6f9f961d7084866960

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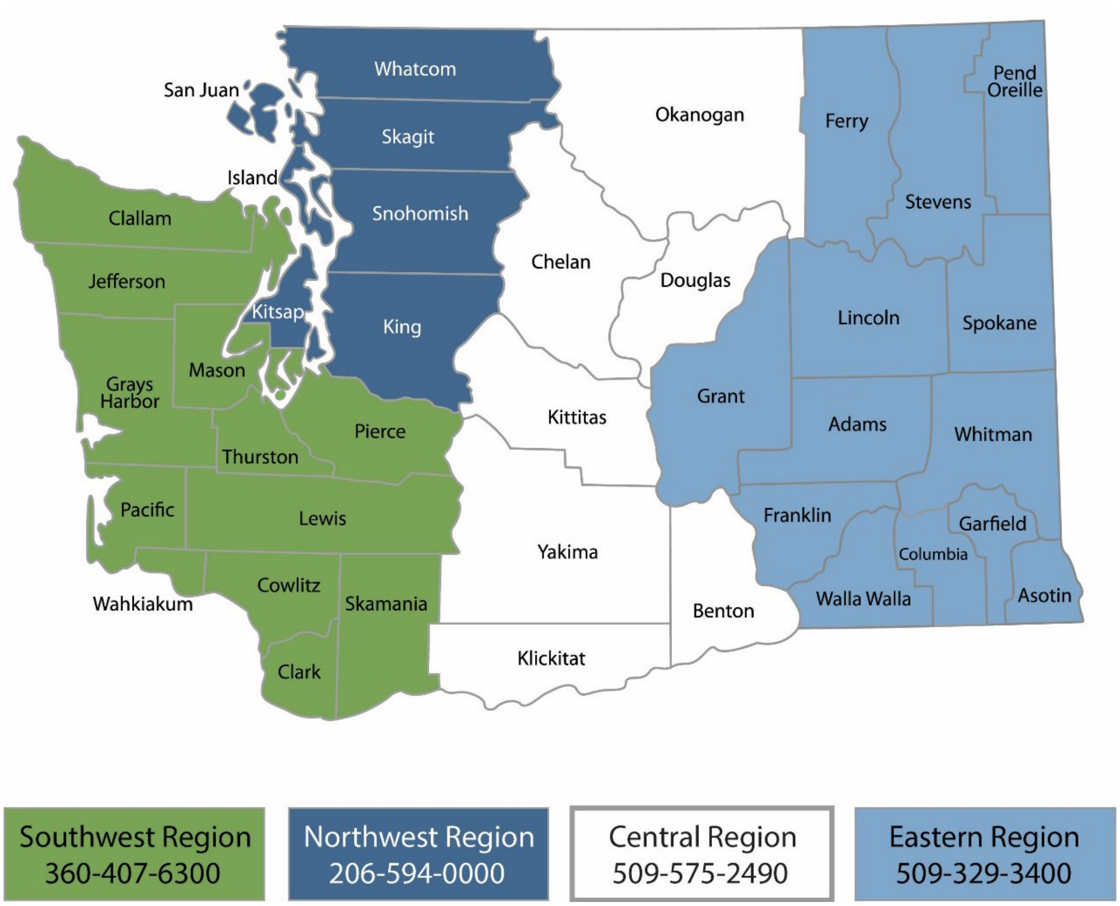

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Central	Benton, Chelan, Douglas, Kittitas, Klickitat, Okanogan, Yakima	1250 W Alder St Union Gap, WA 98903	509-575-2490
Eastern	Adams, Asotin, Columbia, Ferry, Franklin, Garfield, Grant, Lincoln, Pend Oreille, Spokane, Stevens, Walla Walla, Whitman	4601 N Monroe Spokane, WA 99205	509-329-3400
Headquarters	Across Washington	PO Box 46700 Olympia, WA 98504	360-407-6000

Columbia River Basin
Long-Term Water Supply & Demand Forecast

2021 Technical Supplement

Office of Columbia River
Washington State Department of Ecology
Central Regional Office
Union Gap, WA

August 2022 | Publication 22-12-001

DEPARTMENT OF
ECOLOGY
State of Washington

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Acknowledgements

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INTRODUCTION – Purpose of the Technical Supplement

The Office of the Columbia River (OCR) released the *2021 Washington State Legislative Report: Columbia River Basin Long-Term Water Supply and Demand Forecast* (Ecology Publication No. 21-12-006). The Legislative Report summarized the results of studies that explored the impacts that future changes in climate, economic factors, and water management may have on the water supply and demand in the Columbia River Basin, with a particular focus on Washington State. This information will help legislators, water managers, industry, and agency professionals plan for future conditions that will likely be quite different from those we have experienced in the past, which were the conditions under which the water supply systems within the Columbia River Basin were built to reliably deliver water.

This Technical Supplement complements the 2021 Legislative Report, expanding on a number of aspects, namely:

- Providing methodological details underlying the approach, modeling, and results published in the 2021 Legislative Report (*SECTION 1-Methodology Underlying the 2021 Long-Term Water Supply and Demand Forecast*).

- Providing additional methodological detail, analysis, and results for the modules that targeted emerging policy issues (*SECTION 2–Modules*). The five modules included in the 2021 Legislative Report were:
    - Module 1: Residential Demand Forecasting
    - Module 2: Double Cropping
    - Module 3: Seniority-Based Water Rights Interruption
    - Module 4: Estimating Low Flows
    - Module 5: Hydropower Demand Forecasting
    - Module 6: Evaluating Trends in Groundwater Levels

- Describing in further detail the outreach efforts that were carried out before and during the development of the 2021 Forecast, including the Forecast team's responses to public comments received during the public review period (*SECTION 3–Outreach Efforts that informed the 2021 Long-Term Water Supply and Demand Forecast*).

SECTION 1 – Methodology Underlying the 2021 Long-Term Water Supply and Demand Forecast

Overview of approach

Approach synopsis

Forecasting water availability in the Columbia River Basin is multi-faceted, as is any effort made to assess changes in water supplies and demands that takes into consideration both biophysical and human dimensions. Our team has expertise in the different and interconnected water supplies and demands, and the data and methods available to quantify the conditions in this complex water system. In this section, we provide an overview of the methods we used to estimate expected changes in each type of supply and demand, as well as a further look into data- and model-based scenarios we might face in the future. This *2021 Technical Supplement to the Long-Term Water Supply and Demand Forecast* provides further technical details beyond this brief introduction that is also included in the Legislative Report.

This Forecast considers surface water and groundwater supply (Table 1.1) and estimates four types of demands, including water needs to meet the out-of-stream demands of agricultural and residential sectors, and to meet the instream needs of fish species and hydropower production (Table 1.1). In collaboration with the Office of Columbia River, Washington State University (WSU) and its partners (University of Utah and Aspect Consulting) applied a range of methods to quantify expected changes in these supplies and demands by 2040 (Table 1.1). The results are based on different sources of data, and can inform decisions that apply across different geographies. Therefore, the results are provided for four different geographic scopes (Figure 1.1, Table 1.1), fulfilling the following specific objectives:

- **Columbia River Basin:** Estimate climate-driven changes in surface water supplies and demands upstream of Bonneville Dam in seven U.S. States and British Columbia, with a particular focus on eastern Washington.
- **Washington's Watersheds:** Conduct an in-depth analysis of surface water supply and demands for each of eastern Washington's 34 Water Resource Inventory Areas (WRIAs).
- **Washington's Aquifers:** Evaluate groundwater trends in four different aquifer layers within the Columbia Plateau Regional Aquifer System plus a fifth area outside this Aquifer System, for each of 16 groundwater subareas in eastern Washington.
- **Washington's Columbia River Mainstem:** Estimate changes in supplies in the context of the Mainstem's legal, regulatory, and management schemes.

TABLE 1. 1 SUMMARY OF THE COMPONENTS OF THE 2021 FORECAST, THE METHODS USED TO ESTIMATE CHANGES BY 2040 AND BEYOND, AND THE GEOGRAPHIC SCOPES FOR WHICH RESULTS ARE PRESENTED AND DISCUSSED

			Methods	Geographic Scopes
SUPPLIES	Surface water		Integrated modeling of historical (1986-2015) and multiple future scenarios (2026-2055). Climate change impacts also modeled through 2070 (2056-2085).	Columbia River Basin (including focus on eastern Washington) Washington's Watersheds Columbia River Mainstem
SUPPLIES	Groundwater		Trends analysis using existing well depth data	Washington's Aquifers
DEMANDS	**Out of stream**	Agricultural	Integrated modeling of historical (1986-2015) and multiple future scenarios (2026-2055). Climate change impacts also modeled through 2070 (2056-2085).	Columbia River Basin (including focus on eastern Washington) Washington's Watersheds
DEMANDS	**Out of stream**	Residential	Data-based estimates of per capita use and population growth projections Only municipal and self-supplied domestic uses	Eastern Washington Washington's Watersheds
DEMANDS	**Instream**	Flows for fish	Independent simulation modeling study (Mauger et al. 2021)	Washington's Watersheds
DEMANDS	**Instream**	Flows for fish	Compared integrated modeling results to flow regulations	Columbia River Mainstem
DEMANDS	**Instream**	Hydropower	Review existing data and information from power entities	Columbia River Basin

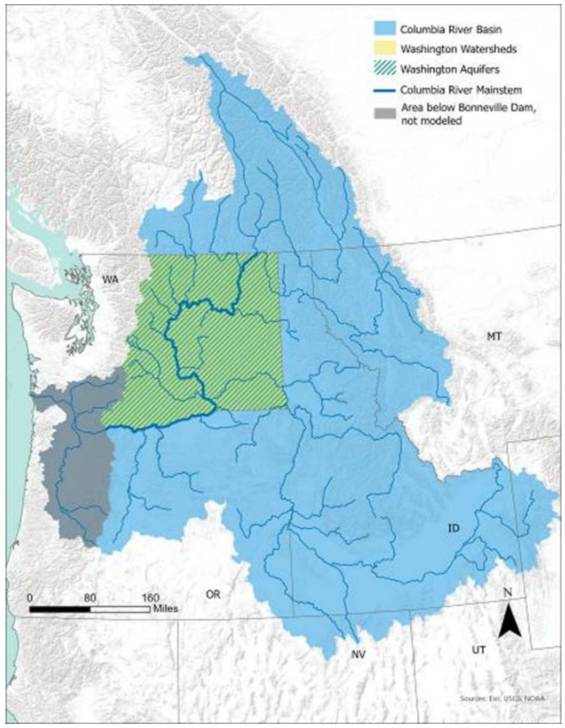

FIGURE 1. 1 LONG-TERM WATER SUPPLIES AND DEMANDS WERE FORECAST THROUGH 2040 AND BEYOND, AND RESULTS ARE PROVIDED FOR FOUR DIFFERENT GEOGRAPHIC SCOPES: COLUMBIA RIVER BASIN, WASHINGTON'S WATERSHEDS, WASHINGTON'S AQUIFERS, AND THE COLUMBIA RIVER MAINSTEM.

Similar to the 2016 Forecast, the 2021 Forecast:

- Integrated hydrological, crop production, and river operations (dams and reservoirs) models to evaluate expected changes in water supply and agricultural water demand (Figure 1.2, diagram);
- Estimated changes expected in residential water demand (formerly called municipal water demand) based on expected changes in population, focused on the Washington State portion of the Columbia River Basin;
- Explored potential changes in hydropower production based on that industry's projections of electricity needs;
- Explored a range of climate change scenarios (34 possible climate futures), crop production scenarios (changing planting dates and crop mixes), and the effect of water projects under development on water capacity; and
- Assumed groundwater is generally not limiting, as we currently do not have the models necessary to integrate groundwater with surface water modeling (though we evaluate this assumption via the groundwater trends analysis; see the *Water Supply Forecast for Washington's Aquifers* section).

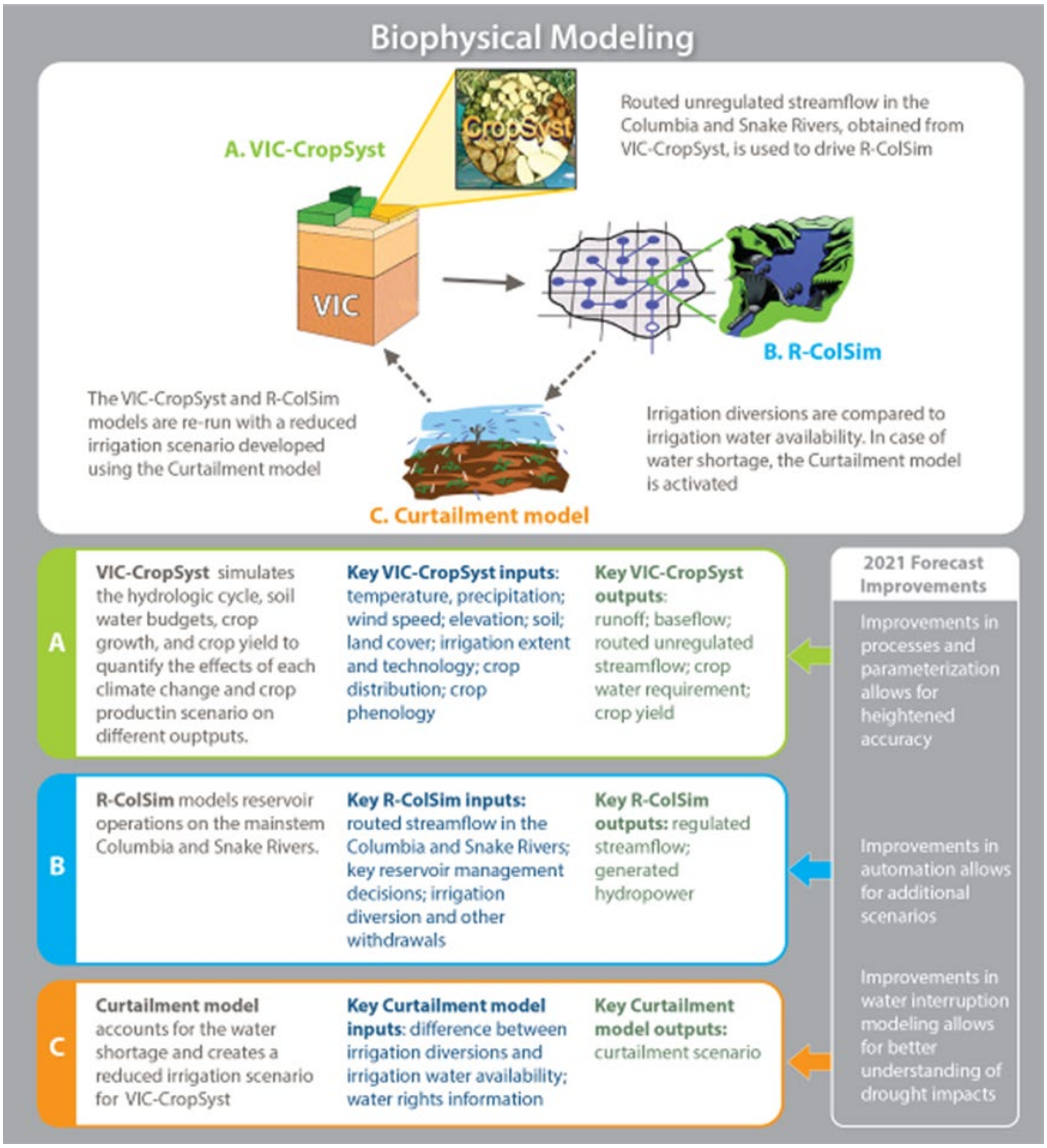

Figure 1. 2 Biophysical modeling framework for forecasting surface water supply and agricultural water demand across the Columbia River Basin. The diagram represents the basic modeling framework used since the 2011 Forecast.

New or improved aspects unique to this 2021 Forecast (Figure 1.2) include:

- *More detailed simulations of crop water requirements and irrigation needs*. Through fully coupling the hydrological (VIC) and crop production (CropSyst) models we were able to use the full functionality of the stand-alone CropSyst model, rather than the simplified version used previously.

- *More accurate and credible estimates of surface water supply and agricultural water demand,* thanks to updated and improved land cover, irrigation extent and leaf area index values based on remotely sensed data and derived data products coupled with an extensive calibration of key parameters in the integrated VIC-CropSyst model. We used agriculture inventory and field trials data to calibrate the crop parameters of all major crops in eastern Washington, particularly those for fruit trees and forage. Additionally, we calibrated key soil parameters that influence the movement of water through the soil and drainage into streams using observations from 213 streamflow gauges.
- *Better inclusion of plausible changes in temperature and precipitation extremes* that could be particularly impactful on water supply and demand. We modeled water supply and demand under an expanded set of 34 climate change scenarios. This larger set of climate change scenarios were developed using 17 different global climate models, each run under two alternative greenhouse gas scenarios. Through this set of climate change scenarios, our team was able to better capture the range of possible climate futures.
- *Deeper exploration of climate change impacts on water supply and demand.* Along with the statutory mandated results for the 20-year forecast (through 2040), we used results from a longer term, 50-year outlook (through 2070) to help elucidate the continued trends in water supply and demand changes in response to changing climatic factors.
- *Data-driven evaluation of the potential impacts of double cropping on agricultural water demand,* now and in 2040. We leveraged a related project to provide remotely-sensed estimates of current double cropping extent, and modeled the impacts of this practice on irrigation water demand. Analysis of existing data from other states across the western United States, which demonstrate similar climatic characteristics to those Washington State may experience in the future, provided support for evaluating future changes to double cropping in Washington by 2040. (See Module 2.)
- *Finer scale estimates of interruptions to water users and their impacts on curtailment, crop yields, and instream flow deficits.* Curtailment modeling in this Forecast is based on a more detailed set of water rights that considers instream flow provisions that are included in water rights documents for individual rivers in eastern Washington. In addition, the assignment of interruptions is targeted to the place of use, producing tighter estimates of curtailment. Further, we then modeled crop yields and changes to instream flow deficits should the expected curtailments be implemented in watersheds with adopted instream flow rules. We also perform an exploratory analysis of capturing seniority-based water rights interruption (see Module 3).
- *More detailed analysis of seasonal residential water demand.* We gathered information and data from large "Group A" water providers' water system plans to obtain monthly estimates of residential water demand, allowing us to explore the summer overlap of potential increased demands with reduced supplies. (See Module 1.)

- *More detailed exploration of factors that could significantly affect the demands for electricity from hydropower.* We reviewed available information on the transition to electric vehicles, expansion of data centers, and the adoption of additional renewable energy targets. (See Module 5.)
- *A new evaluation of projected changes in low flows that could lead to vulnerabilities for fish species.* We incorporated into our findings existing projections of low flows by 2040, developed by the University of Washington's Climate Impacts Group (Mauger et al. 2021), to help understand changes in flows that could pose further challenges for fish. (See Module 4.)
- *Deeper analysis of trends in groundwater that highlight future vulnerabilities in groundwater supply.* This analysis focusing on Washington State groundwater trends provides a foundation for integration of surface and groundwater supply modeling in future Forecasts, and complements the surface water supply results. (See Module 6.)

These enhancements help the results hone in on the vulnerabilities arising from expected future changes in water supply and demand, as well as improving our confidence in the results of the 2021 Forecast.

Surface water supplies for our region reflect the current management of the existing reservoir system. The integrated VIC-CropSyst model was linked to reservoir and water use curtailment models that enabled evaluation of how a changing water supply might impact: future reservoir storage and releases, irrigation application amounts, crop yields, and how frequently some groups of water users might see their water use interrupted. The 2016 Forecast did not model all dams in the Columbia River Basin, as there are more than 400 dams (both storage and run-of-the-river) operated to meet a variety of purposes. Reservoir modeling captured operations of the major storage dams on the Columbia and Snake Rivers, and the five major reservoirs in the Yakima Basin (Keechelus, Kachess, Cle Elum, Tieton and Bumping Lake). Dam management captured within ColSim included operations for power generation, flood control, instream flow targets, water storage, and stream flow regulation.

The modeling effort assumed that dam management would not change in the future to better understand how changes in infrastructure and management could change the water supplies entering Washington State in the future, and to help interpret the modeling results. Washington State University (WSU) in collaboration with OCR carried out a preliminary survey of basin water managers, to gain insights into water supply planning, project development, and water management (see the *Water Masters Survey* section, below).

Model Outputs

The integrated hydrological, crop and water management models provided estimates of water supply and agricultural demand (Figure 1.3). Instream demands were not determined from model outputs but were represented through the adopted state and federal instream flows, which were assumed to be the same in the historical (1986-2015) and future (2040) time periods. Historical and forecast municipal demands were included in the modeling framework by withdrawing the consumptive use portions from surface water availability. Demand of water to produce hydropower were also estimated separately.

The models were able to forecast a variety of potential impacts, including predicted surface water supply, total irrigation demand, unmet irrigation demand due to curtailment, decreases in crop yield due to curtailment, and provide spatially specific results for each watershed.

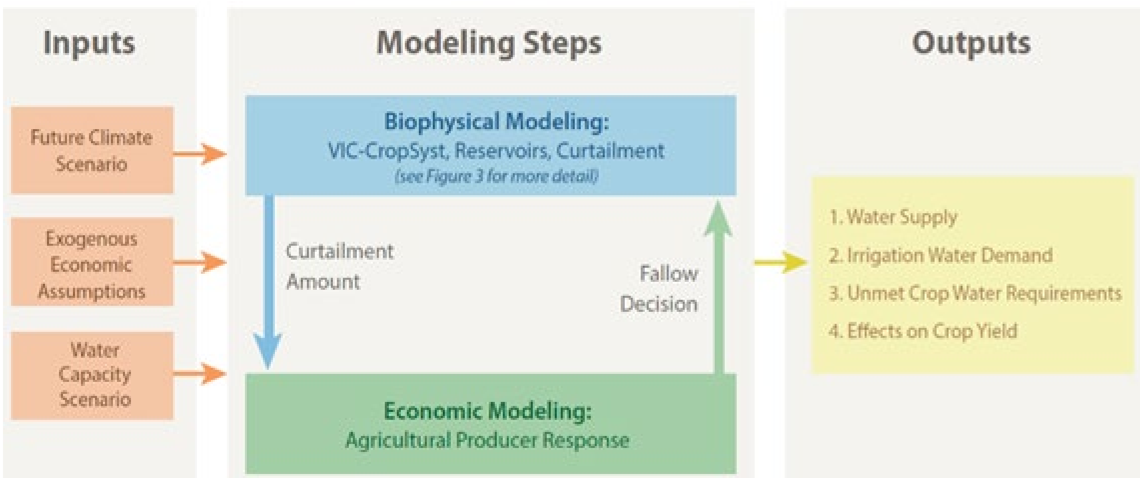

FIGURE 1. 3 INTEGRATION OF BIOPHYSICAL MODELING (SURFACE WATER SUPPLY, CROP DYNAMICS AND CLIMATE) WITH ECONOMIC AND POLICY (HUMAN DECISION-MAKING) MODELING.

Methodological Details

This section outlines in more detail the methodology used in this 2021 Forecast, and includes information on the extent of the study area, the data sources, a description of the various components of the model, and a description of the integrated modeling framework.

Study Area

The Columbia River Basin is the fourth largest watershed in North America in terms of average annual flow, encompassing all or parts of Idaho, Montana, Nevada, Oregon, Utah, Washington, Wyoming, and British Columbia (BC) (Figure 1.1). The basin drains approximately 258,000 square miles including nearly 40,000 square miles in BC. For thousands of years, the 1250-mile long river has shaped the economy and lives of the indigenous people who lived near it. Over the past two hundred years, the basin has been developed extensively for hydropower generation, irrigation, navigation, and flood control. In fact, steamboats began operating on the river as early as 1836 and the first hydroelectric dam in the Pacific Northwest (PNW) was built on the Spokane River in 1885. The river is currently also managed for the protection of salmonid species listed under the Endangered Species Act for: municipal and industrial supplies, the maintenance of water supplies in accordance with tribal treaties, and recreation. Creating a myriad of competing demands for water.

Forecasting future water supply and demand in the Columbia River Basin is further complicated by the size and complexity of the river system, as well as the multiple jurisdictions through which it flows. Because reliable access to water is essential for existing and future regional economic growth plus environmental and cultural enhancement, resource managers are tasked with conducting such forecasts. The urgency and importance of forecasting water supply and demand continues to grow as seasonal variations in water supply and demand have resulted in localized shortages with increasing regularity. Due to population growth, climate variability and change, and increased implementation of regulatory flow requirements. Competing demands on the region's freshwater resources will likely increase in the future, specifically in summer months when demand is high. Water supply is also anticipated to decrease during these summer months of peak demand due to long-term shifts in temperature, precipitation, and exacerbating summer unmet water demand.

Data Sources for Integrated Modeling

Climate Data

Historical

For historical climate inputs, we used two data sets: Livneh (Livneh et al., 2013) and GridMet (Abatzoglou, 2013). The Livneh dataset provided daily maximum temperature, daily minimum temperature, daily total precipitation, and daily average wind speed. Besides the variables the Livneh dataset provides, GridMet also includes daily shortwave solar radiation, daily maximum, and daily minimum relative humidity. For this project, we used the Livneh dataset for the Canadian portion of the CRB and used GridMet for U.S. portion (over the boundary area, wherever GridMet is available, it will be used). The GridMet dataset was used over the U.S. due to a known cold bias in the Livneh dataset where a constant temperature lapse rate is used (Walton and Hall, 2018). Both datasets are spatially interpolated from weather station observations. Because the datasets are based on most of the same observations, and there are no subareas crossing the U.S.-Canada border, data continuity concerns were minimized at the U.S.-Canada border. The Livneh dataset covers the entire continental U.S. and the Canadian portion of the CRB from the year 1915 to the year 2015 with a spatial resolution of 1/16°. GridMet covers the entire continental U.S. from the year 1979 to current, with a spatial resolution of 1/24°. The GridMet dataset has been aggregated to 1/16° resolution at daily time step. When using Livneh, we used the Variable Infiltration Capacity (VIC) model internal weather generator (the MT-CLIM based algorithm) to estimate solar radiation and humidity to calculate reference and actual evapotranspiration (ET). In contrast, when using GridMet, the solar radiation and humidity (daily maximum and minimum) are directly ingested into the model.

Future (Including Downscaling)

The projected climate data are downloaded from Northwest Knowledge Network (University of Idaho), which were statistically downscaled from 17 GCM models' results by using Multivariate Adaptive Constructed Analogs (MACA) method (http://www.climatologylab.org/maca.html) (Abatzoglou and Brown, 2012). There are two different downscaled datasets covering CONUS-plus (i.e. portion of Canada in the CRB domain). The MACAv2-LIVNEH dataset (with 1/16-deg (~6km) resolution) uses the 6-km (1/16th degree) daily product of Livneh et al. (2013) from 1950-2011 that also incorporates the Canadian portion of the CRB. The other (i.e.MACAv2-METDATA) uses the GridMet daily dataset at a ~4-km grid (1/24th degree) from 1979-2012. The climate variables from both data sets include maximum temperature, minimum temperature, maximum and minimum relative humidity, precipitation accumulation, downward surface shortwave radiation, wind-velocity, and specific humidity. Same with historical climate data, MACAv2-METDATA was aggregated into 1/16th degree resolution and we use MACAv2-LIVNEH for the Canada portion. These 17 GCM models includes: bcc-csm1-1, BNU-ESM, CanESM2, CNRM-CM5, CSIRO-Mk3-6-0, GFDL-ESM2G, GFDL-ESM2M, HadGEM2-CC365, HadGEM2-ES365, inmcm4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MIROC-ESM-CHEM, MIROC-ESM, and MRI-CGCM3. Each downscaled GCM data included historical period (1950-2005) and future period from 2006 to 2099 with RCP scenarios of 4.5 and 8.5 (van Vuuren et al., 2014), respectively.

Bias Adjustment Process

Each of the 17 global circulation models (GCMs) from which we derived future climate inputs has its own model bias when compared to observed climate data. To remove this bias we performed bias-correction on all results using the ratio method for streamflow (Eq. 1) or the difference method (Eq. 2) for other variables evaluated in the report (e.g. irrigation demand, curtailment). Each GCM has its own historical and future climate time series that was used to drive the models (e.g. VIC-CropSyst, RColSim). We first simulated water supply, water demand, etc. using historical GCM, RCP 4.5 future, and RCP 8.5 future scenarios for each of the 17 GCMs plus the observed historical scenario (17 x 3 + 1 = 52 scenarios). We next calculated the 20th, 50th, and 80th percentiles for each variable. Then we performed bias adjustment using either the ratio or difference methods. The ratio method removes bias by multiplying the historical baseline data time series by the ratio of future to historical data. The difference approach removes bias by adding the difference between future and historical to the historical baseline.

$$Future_{Ratio} = GCM_{Future}/GCM_{Historical} * Baseline \quad (1)$$

$$Future_{Diff} = GCM_{Future} - GCM_{Historical} + Baseline \quad (2)$$

Land Cover, Soils, and Management

For hydrological model calibration, we are using the same natural vegetation and crop (all crop types are coded as "11", i.e. corn for VIC runs) as the previous 2016 Forecast (see previous technical report for more detailed information). In the VIC calibration runs, the model is run as if it is standalone from CropSyst (i.e., CropSyst is not triggered). For simulating water supply, the model simulation was conducted using the same mode as the VIC calibration run (i.e., using a predefined monthly leaf area index) and with no irrigation. The following section describes the crop types for water demand simulation.

Crop Distribution

Three data sources for crop distributions are used for this project. The first one is the Cropland Data Layer (CDL) from USDA for 2018 (https://www.nass.usda.gov/Research_and_Science/Cropland/SARS1a.php). This data set is produced annually mainly by using high spatial resolution satellite imagery (e.g., 30-meter Landsat TM/ETM+, 56-meter AWiFS, 10-meter SENTINEL-2) and extensive checking against agricultural ground truth data (Boryan et al., 2011). The second source is the Washington State Department of Agriculture (WSDA) Agricultural Land Use Geodatabase which is updated via ground surveys or by using outside sources such as the United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) CDL. (https://agr.wa.gov/departments/land-and-water/natural-resources/agricultural-land-use). The current map we used for this report contains crop data collected and stored for Washington as of 12/31/2018. The third data source (particularly for Canadian portion of the CRB) is Annual Crop Inventory (ACI) developed by the Earth Observation Team of the Science and Technology Branch at Agriculture and Agri-Food Canada (AAFC) (https://open.canada.ca/data/en/dataset/ba2645d5-4458-414d-b196-6303ac06c1c9). This product has a 30 meter resolution since 2011 and we used the 2018 data for this report.

Irrigation

The extension of irrigation is based on three data sources: 30-meter resolution of annual irrigation map at the year 2018 of IrrMapper over the western US (Ketchum et al., 2020); the field scale irrigation information (irrigation type over each field) from WSDA Agriculture Land Use layer over the Washington state; and the 250-m resolution irrigation fraction map from MODIS over the Canada by using same method as MIrAD-US (Moderate Resolution Imaging

Spectroradiometer (MODIS) Irrigated Agriculture Dataset for the United States) (Pervez et al., 2010) (by Pruett, Matthew Joel). Since we have no irrigation type information outside Washington state, we used the dominant irrigation type of each major crop type within the Washington state to assign the irrigation technology for the irrigated crops outside Washington state. If no information is available, we set “sprinkler” as the default (for irrigated fields). The fraction of irrigated area over each VIC GridCell (i.e. ~6km X 6km) are aggregated from these 30m or 150m resolution irrigated extensions, or field boundaries from WSDA.

Soils Data

In the conventional VIC setup a vertical distribution of three soil layers is usually used. In this version of VIC-CropSyst, a 17-layer system was introduced, by expanding the middle layer into 15 layers (Malek et al., 2017). This increased layering helps the dynamic simulation of root growth by distributing the soil moisture across the rooting zone more accurately.

The STATSGO2 soil database is the primary source of data on soil classification, distribution and hydrological properties. Surveyed soil layers from STATSGO2 are redistributed into 1/16th degree resolution and 17 layers, providing data in the format required for VIC-CropSyst runs. Soil data for the Canadian portion of the CRB was obtained from the 1/16th degree soil dataset developed by Elsner et al. (2010). This dataset is based on Maurer et al. (2002) which in turn is based on gridded datasets developed as part of the Land Data Assimilation System (LDAS; Mitchell et al. 1999) project. Empirical functions developed by Saxton et al. (1986) were implemented in VIC-CropSyst to estimate some soil parameters such as soil hydraulic conductivity, field capacity, wilting point, and bulk density, based on their relationships with soil texture (percent sand and clay).

Crop Phenology and Management Data

Crop management such as planting date, fertilization, irrigation, and harvest criteria adopted in a region, provides important information to enhance the crop model output estimations. However, management decisions are particularly difficult since their observations depend on individual farmer decisions rather than on physical properties, and these may vary significantly over short distances.

As most crops in the U.S. receive adequate fertilization and irrigation levels, all simulations were performed under potential conditions, i.e., without any water and nutrient stress; being the solar radiation, air temperature, CO_2 atmospheric concentration, and crop characteristics the main major growth defining factors. For this reason, the full irrigation strategy on a single soil type that represented average regional soil physical characteristics was used in our simulations.

The CO_2 atmospheric concentration crop response was considered transient (Figure 1.4). The transient climate response to cumulative CO_2 emissions is a metric of climate change that directly relates the primary cause of climate change (cumulative CO_2 emissions) to global mean temperature change (MacDougall and Knutti, 2016).

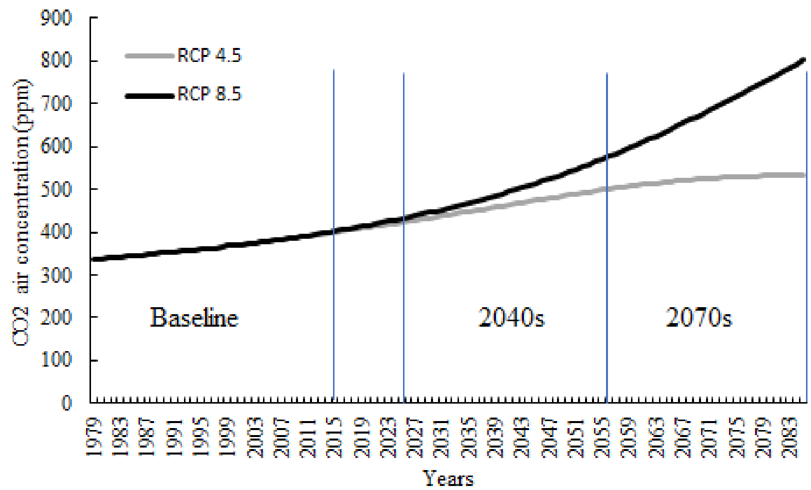

FIGURE 1. 4 YEARLY ATMOSPHERIC CO_2 CONCENTRATION FOR THE BASELINE (1979-2015) AND FUTURE PERIOD (2040S AND 2070S) UNDER RCP4.5 AND RCP8.5 SCENARIOS.

Regarding irrigation over a large-scale region, each field has different irrigation dates and amounts. In this context, it may be reasonable to assume that this variety results from a limited number of irrigation strategies applied to a diversity of situations. Therefore, it is more plausible to try to characterize irrigation strategies than to characterize the diversity of irrigation dates and amounts over the study region. In this project, the management adopted were the same throughout the simulation period.

Irrigation for all crop types was based on two criteria, i) one day after emergence (for annual crops) or bud break event (for perennial fruit crops) to ensure no water stress at the beginning of crop development and ii) applied whenever the soil moisture maximum allowable depletion (MAD) is observed at a fraction (0.5) of the current root depth, which is function of irrigation type (Table 1.2).

A single planting date that represents the average date of the most usual plating period in the States of Washington, Oregon, Idaho and Montana (USDA)[5] was used to run the model`s parameterization, sensibility analysis and calibration. The simulations were performed for a period of 36 years from 1980 to 2015 using daily meteorological variables (minimum and maximum air temperature, solar radiation, wind speed, precipitation, and maximum and minimum air humidity) in 11 sites spread across CRB (Figure 1.5).

[5] United States Department of Agriculture. National Agricultural Statistics Service, Field Crops Usual Planting and Harvesting Dates. Available online: https://www.nass.usda.gov/Publications/Todays_Reports/reports/fcdate10.pdf

TABLE 1. 2 IRRIGATION TYPE AND THEIR MAIN PARAMETERS USED IN THIS PROJECT.

Irrigation type	MAD* (-)	Efficiency (%)	Maximum capacity (mm/day)
Big gun	0.5	55	30
Center pivot	0.2	85	20
Drip	0.1	97	20
Flood	0.5	50	30
Furrow	0.5	50	30
Rill	0.5	50	30
Sprinkler	0.5	80	30
Subsurface drip	0.2	100	8
Wheel line	0.5	70	30

*MAD = Maximum available depletion of soil moisture

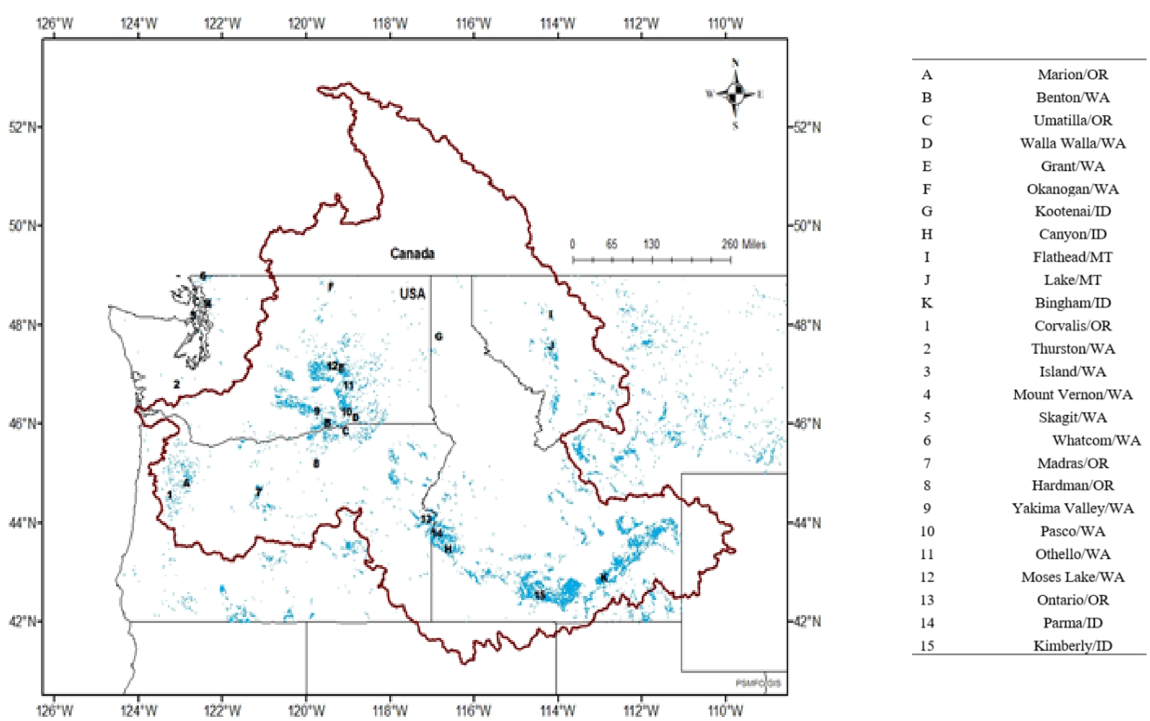

FIGURE 1. 5 IRRIGATION EXTENSION AREA OVER U.S. COLUMBIA RIVER BASIN AND SITE LOCATIONS USED FOR MODEL CALIBRATION (LETTERS) AND FIELD TRIALS OBSERVATIONS (NUMBERS).

For most annual and fruit crops, harvest events were triggered when plants reached the physiological maturity; the exceptions were for sweet corn and green peas that were harvested during the grain filling stage. For perennial herbaceous plants such as hops and mint, the harvest was done right after the flowering event (Nakawuka et al., 2017). For perennial hay crops, the last harvest event was set for early October; however, clipping events were triggered every time plants canopy or biomass amounts reach predetermined levels for the occurrence of this event (Figures 1.6-1.9).

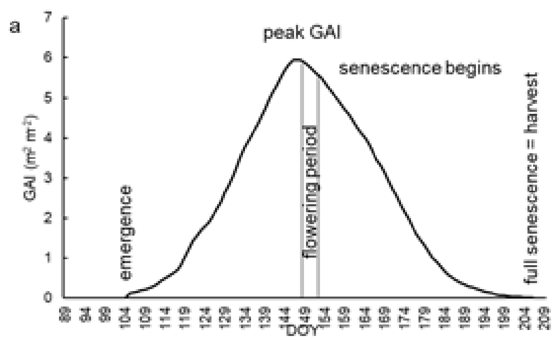

FIGURE 1. 6 ILLUSTRATION OF DIFFERENT CRITERIA USED FOR HARVEST EVENT BASED ON DEVELOPMENT AND PHENOLOGICAL STAGE EVENTS FOR A) OATS IN MARION COUNTY, OREGON – 1981

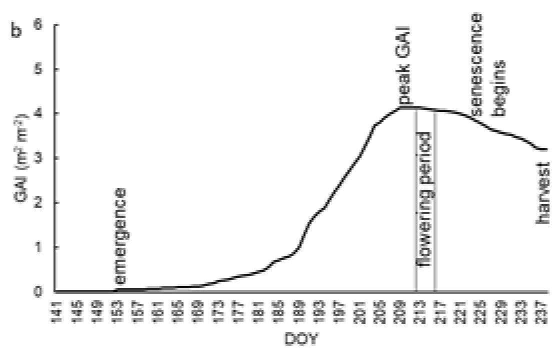

FIGURE 1. 7 ILLUSTRATION OF DIFFERENT CRITERIA USED FOR HARVEST EVENT BASED ON DEVELOPMENT AND PHENOLOGICAL STAGE EVENTS FOR B) SWEET CORN IN MARION COUNTY, OREGON - 1980

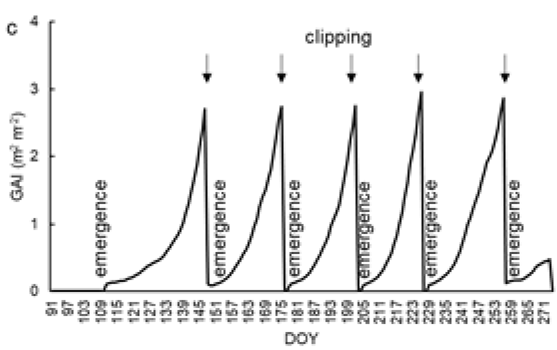

FIGURE 1. 8 ILLUSTRATION OF DIFFERENT CRITERIA USED FOR HARVEST EVENT BASED ON DEVELOPMENT AND PHENOLOGICAL STAGE EVENTS FOR C) PASTURE GRASS IN GRANT COUNTY, WASHINGTON -1983

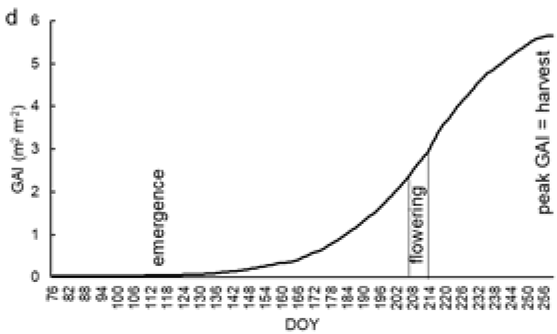

FIGURE 1. 9 ILLUSTRATION OF DIFFERENT CRITERIA USED FOR HARVEST EVENT BASED ON DEVELOPMENT AND PHENOLOGICAL STAGE EVENTS FOR D) HOPS IN MARION COUNTY, OREGON - 1993. GAI IS THE GREEN AREA INDEX (M^2 M^{-2})

Streamflow and Water Management Data

Water Rights

The Washington Department of Ecology's Water Rights Tracking System (WRTS) was consulted for water rights information in Washington State. The database has information related to the water rights' priority date, purpose of use, annual water quantity, maximum instantaneous rate of withdrawal, point of diversion, and place of use. This information was used primarily to model the curtailment process. Curtailment or interruption of certain water rights happens when there is insufficient water to meet all demands, including instream flow demands. Interruptible water rights were queried in WRTS by instream flow provision for Methow River, Wenatchee River, Colville River, Okanogan River, Columbia River, and Little Spokane River. Interruptible water rights include both surface and groundwater rights. Both were included in our curtailment analysis. After identifying interruptible rights, their places of use were overlaid with the 2018 WSDA cropland data layer to calculate interruptible cop acreage and to identify grid cells where curtailment occurs. As a result of this analysis, the Little Spokane interruptibles were omitted because the vast majority of these are small water rights for lawn irrigation.

In the Yakima River Basin, where reservoir operations were modeled using Yakima RiverWare, we used the water right information that the U.S. Bureau of Reclamation (USBR) originally incorporated into the Yakima RiverWare model. For each irrigation district, this information consisted of a time-series of paper water rights and observed diversions for non-proratable (senior) and proratable (junior) water right holders.

Water Masters Survey

Understanding when water rights get curtailed based on priority and local hydrologic conditions is important to accurately forecast water demand. It affects what crops people may grow, the marketability of water rights to other parties, the processing fee people pay for water rights, and other factors.

As described above, interruptible water rights were identified by their instream flow provision in the WRTS database. Because curtailment impacts actual river flows, WSU was able to integrate the effects of these curtailments into the model. However, in some tributaries, water rights are also curtailed in response to calls from senior water right holders (e.g. Yakima, Walla Walla, Okanogan). Right-by-right curtailment information for water calls does not exist in Ecology's database, so our ability to model their impact on streamflow was limited.

In the 2021 Forecast, WSU prepared a survey for Ecology water masters in an effort to better understand this missing data set. Without this information, the model assumes 100% reliability for water rights even where we know that priority water calls are common, resulting in overestimation of water use by junior water rights. We received primarily qualitative information from our meetings with water masters. The only quantitative data came from the Wenas stream patrolman and the Walla Walla watermaster. This was an improvement over the 2016 survey response which yielded only qualitative information that could not be readily assimilated into the model. The 2021 survey results enabled us to create a water priority call module for the Touchet River in Walla Walla (see Module 3).

WSU proposes that Ecology begin to collect data from water masters and stream patrolmen that details when a water call is made, which classes were affected, and duration of the interruption. We further recommend that these data be kept in a centralized database, either as part of WRTS or in a different system, that can be searched electronically. This would greatly facilitate future efforts by WSU to integrate curtailment data directly into the model. Over time, this will bring into better focus the reliability of junior water rights in basins with priority water calls. The first step toward collecting this data was taken In August 2021, when we created an electronic survey for watermasters to record curtailment events.

Given that the WRTS database has just gone through a lengthy update, this recommendation may not occur in time to provide rigorous data for the 2026 Forecast. In the interim, therefore, WSU proposes that Ecology build a spreadsheet to track water right curtailment. This would provide quantitative data to inform curtailment modeling for the next Forecast.

Instream Flow Rules

Instream flow rules at different locations in Washington State were used to determine whether there is a need to curtail interruptible water right holders. Interruptible water rights are those that can be curtailed in low flow years if there is insufficient flow to fulfill instream flow requirements. The instream flow targets, on which curtailment decisions are made, are based on Washington Administrative Codes (WAC Title 173).

In the WRIAs belonging to the Yakima River Basin (WRIAs 37, 38, and 39), interruption of water rights is based on a different mechanism. Instead of the binary "water on/water off" process operable in other areas, water use in the Yakima Basin is prorationed among interruptible water rights. Proration rates are based on the calculation of the Total Water Supply Available (TWSA) every year. This includes streamflow, usable return flows, and reservoir storage. The proration rate is determined by matching the TWSA against demand, as detailed in Hubble (2012).

Reservoir Operations

The reservoir operation rules for the Columbia River mainstem are those used by Hamlet and Lettenmaier (1999). The reservoir operations of ColSim (Hamlet and Lettenmaier, 1999) were implemented in the R programming language so the model could be run on a cluster computer. This R version of ColSim is called RColSim (Malek *et al.*, in review). In the Yakima River Basin, reservoirs are operated according to the rules described in USBR's interim comprehensive basin operation plan (USBR, 2002).

Naturalized Flows

The integrated model requires data for "naturalized" or "reconstructed" stream flows to calibrate and correct the bias in estimates of simulated streamflow. The effects of human intervention have been removed from observed flows in these naturalized flows. This information was primarily collected from the Bonneville Power Administration's no regulation, no irrigation streamflow dataset (BPA, 2014). For stations where naturalized streamflow data were unavailable from this source, we used naturalized flow provided by the University of Washington's Climate Impacts Group (UW CIG) (Elsner et al., 2010). For locations where data were not available from either source, it was not possible to perform bias correction on simulated streamflow outputs.

Economic Forecasting

Changes in crop mix over time can significantly affect the quantity and timing of water demand. Crop mix is determined by numerous factors external to Washington State. It is not feasible to directly model all of these factors – which includes supply and demand for agricultural goods in the U.S. and the rest of the world – so our approach is to statistically analyze historical trends in crop mix to produce a forecast of future crop mix. This approach assumes past trends will continue into the future, which is reasonable when modeling macro factors like global supply and demand for food goods.

We used the same general approach in this report as was used in the past three iterations, which can be summarized briefly as follows. Previous versions of the Technical Report provide a more detailed overview. A statistical/econometric approach called a Vector Autoregression (VAR) is used to forecast changes in the overall share of irrigated acres between major crop groups. The major crop groups are fruits, vegetables, grains, and hay crops. The key feature of a VAR model in this context is that there is a limited amount of irrigated acres in the region, so an increase in the amount of one crop group requires a decrease in another.

Univariate time-series statistical models are used to forecast economically important crops that constitute a relatively small number of acres such as wine grapes and blueberries. In theory, the potential increase in area planted in these crops is practically unlimited by physical conditions. Rather, economic factors are limiting. A statistical approach called Autoregressive Integrated Moving Average (ARIMA) is used to forecast these series ahead based on past trends.

Downscaling Projected Irrigated Crop Area at State Level to each WRIA

The economic model projected the changing rate of major irrigated crops at state level from current (in the year 2018 as the baseline) to 2040 (Table 1.3). The downscaling process distributes the rate into each WIRA, while keeping the entire irrigated area balanced (i.e. no change). For example (for each WIRA), if the projected total irrigated area is higher than the baseline, the unchanged irrigated crops (under projection) will reduce at a certain common rate to fill the gaps (until their total area becomes zero); vice versa, the unchanged irrigated crops will expand in a certain rate to occupy the reduced irrigated area according to the change rate.

TABLE 1. 3 THE PROJECTED CHANGE IN IRRIGATED CROPS OVER WASHINGTON STATE

Irrigated crop	Change rate (2018-2040)
Apple	0.0982
Blueberry	1.6983
Cereal Grain	0.0695
Cherry	0.1704
Grape, Wine	0.1546
Hay/Silage	0.0028
Hops	-0.2687
Other Fruit	-0.2316
Vegetable	0.003

Biophysical Modeling

Calibration and Evaluation

Hydrologic Model Calibration

As mentioned earlier, the calibration on hydrological parameters were conducted with traditional VIC standalone and the crops are simulated the same as natural vegetation (parameterized as field corn).

VIC parameters also include watershed-scale hydrologic properties that either cannot be measured directly or have significant spatial variations that need to be calibrated by iteratively comparing simulated results against observations. The following five parameters in VIC-CropSyst are automatically calibrated: BI, Ds_{MAX}, Ds, Ws, and D2:

- BI is the parameter controlling the shape of variable infiltration capacity curve;
- Ds_{MAX} is the maximum baseflow from the lowest soil layer;
- Ds is the fraction of Ds_{MAX} where non-linear baseflow begins;
- Ws is the fraction of the maximum soil moisture (of the lowest soil layer) where non-linear baseflow occurs; and,
- D2 is the soil depth of the lowest soil layer. These are the standard VIC parameters used for calibration.

Calibration Methods

The automatic calibration is based on the multi-objective complex evolution (MOCOM-UA) global optimization method (Yapo et al., 1998). Six metrics/objectives are selected to evaluate model performance:

1) Nash-Sutcliff model efficiency coefficient (NSE):

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{T}\left(Q_m^t - Q_o^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q_o}\right)^2} \tag{3}$$

where $\overline{Qo}$ is the mean of observed discharges, and Q_m^t and Q_o^t are modeled and observed discharge at time t (here we use monthly time step), respectively.

2) Nash-Sutcliffe efficiency with logarithmic values (ln NSE)

To account for the effect of low flows in our evaluation of model performance, we use the logarithmic value of the NSE as in equation 3.

3) Relative bias in annual flow

$$\text{RelBias} = \left|\frac{\overline{Q_m}}{\overline{Q_o}} - 1\right| \quad (4)$$

$\overline{Q_m}$ and $\overline{Q_o}$ is the average annual modeled flow and observed flow, respectively.

4) Coefficient of determination (r^2)

$$r^2 = \left(\frac{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})(Q_m^t - \overline{Q_m})}{\sqrt{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2}\sqrt{\sum_{t=1}^{T}(Q_m^t - \overline{Q_m})^2}}\right)^2 \quad (5)$$

5) Absolute average peak flow difference (AvgPeakDiff)

$$\text{AvgPeakDiff} = \left|\overline{Q_o^{peak}} - \overline{Q_m^{peak}}\right| \quad (6)$$

The average peak flow is calculated from average monthly flow (i.e., the maximum value).

6) Root mean square error (RMSE)

$$\text{RMSE} = \sqrt{\frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{T}} \quad (7)$$

The multiple objectives of the calibration is to get the Pareto set, where solutions cannot be improved without degrading at least one of the other objectives. To standardize the above matrices, the NSE, Ln NSE, and r^2 metrics are multiplied by -1 (as greater numbers are preferable for these metrics) and the standardized variable is minimized.

Calibration Data Sets and Screening

Because the calibration model runs were performed under no irrigation conditions (i.e., no water withdrawal from streams for irrigation) and reservoir influences, naturalized streamflow data sets were used for model calibration. We used four major data sources for this report (with the total number of stations for this calibration shown):

1) Streamflow from USGS GAGES-II Reference stations and the drainage area larger than 200 km^2;

2) No Regulation No Irrigation (NRNI) data products from USACE (197);

3) Naturalized streamflow from Columbia Basin Climate Change Scenarios Project (CBCCSP) of University of Washington (166); (33); and,

4) Naturalized streamflow for the Umatilla basin (1) (Figure 1.10).

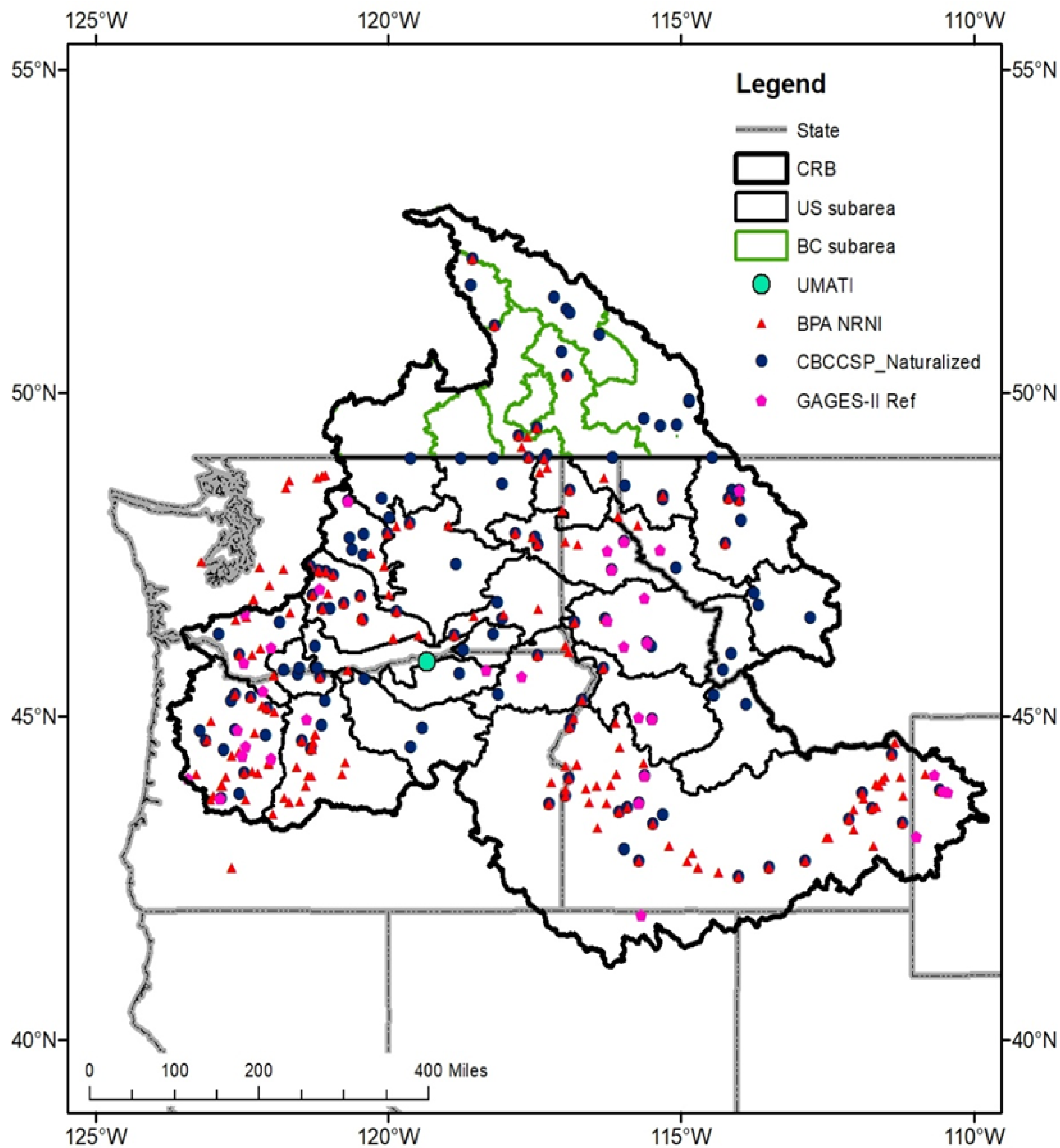

FIGURE 1. 10 HYDROLOGICAL GAUGES/STATIONS WITH NATURALIZED STREAMFLOW DATA FOR MODEL CALIBRATION. (NOTE: THIS FIGURE SHOWS ALL STATIONS. WE SCREENED THESE TO A SMALLER SET OF STATIONS FOR OUR OWN USE. CRB: COLUMBIA RIVER BASIN; US: UNITED STATES; BC: BRITISH COLUMBIA.

The corresponding grid cells for each station were identified by using VIC grid cell flow direction and the estimated accumulated area (comparing with each station's contribution area). Among these 397 stations, 317 of them were successfully identified with a corresponding VIC grid cell (by visual interpretation with VIC generated watershed boundary with 1:250,000 scale of USGS Hydrologic unit codes (HUC) boundary map) (https://water.usgs.gov/GIS/metadata/usgswrd/XML/huc250k.xml). To eliminate biases due to inconsistencies in drainage area and because of the limitations of VIC in simulating small watersheds, we used the following approach. The stations with drainage areas larger than 500 km^2 and that are within 25% error in calculated drainage area were selected. (Note that the flow direction file created using GIS and a digital elevation model gives the VIC-simulated drainage area; this is compared to the drainage area reported with the streamflow observations.) After this screening process, 274 stations were left for the calibration process. If several datasets provided the same stations, the order of priority of use was as follows: USGS reference gauges > NRNI > CBCCSP naturalized flow.

Calibration Procedure

Calibration was conducted using a nested approach, in which the most up-stream stations were calibrated first, followed by the remaining grid cells at the next station downstream, etc., until the whole watershed was calibrated. For example, the most up-stream (headwater) stations were set to a level 0 and with increasing levels moving downstream. Through this iteration, 39 levels are identified over the CRB basin. Figure 1.11 (contains 5 levels from level 0 to 4 for an example watershed) depicts an example of the hierarchy of watershed levels.

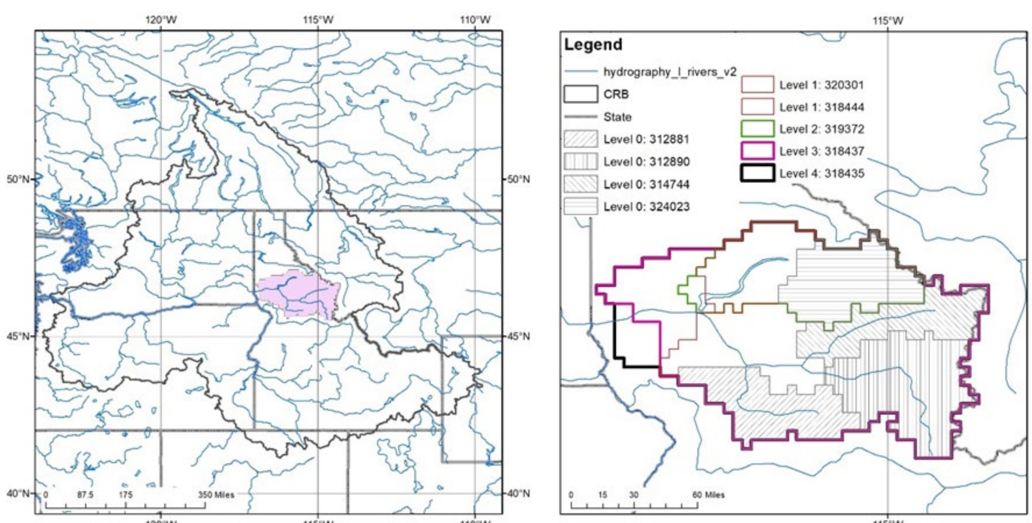

FIGURE 1. 11 EXAMPLE WATERSHED LEVELS FOR MODEL CALIBRATION. (THE LEFT PANEL SHOWS THE LOCATION OF THIS SAMPLING WATERSHED; THE RIGHT PANEL SHOWS THE WATERSHED BOUNDARIES FOR DIFFERENT LEVELS.)

For model calibration, we compared routed model output from 1980-current for comparison against naturalized streamflow. The routing was conducted with the VIC routing post-process developed by Lohmann et al. (1996, 1998). If the observations (after the year 1981) were less than two years, the station was removed from analysis and the calibration moved to the next level. If the maximum of the average NSE and Ln NSE was equal or higher than 0.5, then we accepted the calibrated soil parameters for this watershed (and set the station as valid). Otherwise, this station was removed from calibration and steps into the upper level watershed for calibration.

Hydrologic Calibration Results

Figure 1.12 shows the distribution of NSE along the drainage area. Figure 1.13 shows the final calibrated stations/watersheds and the values for evaluation metrics. Overall, with increasing drainage area, the model gives better results in terms of NSE.

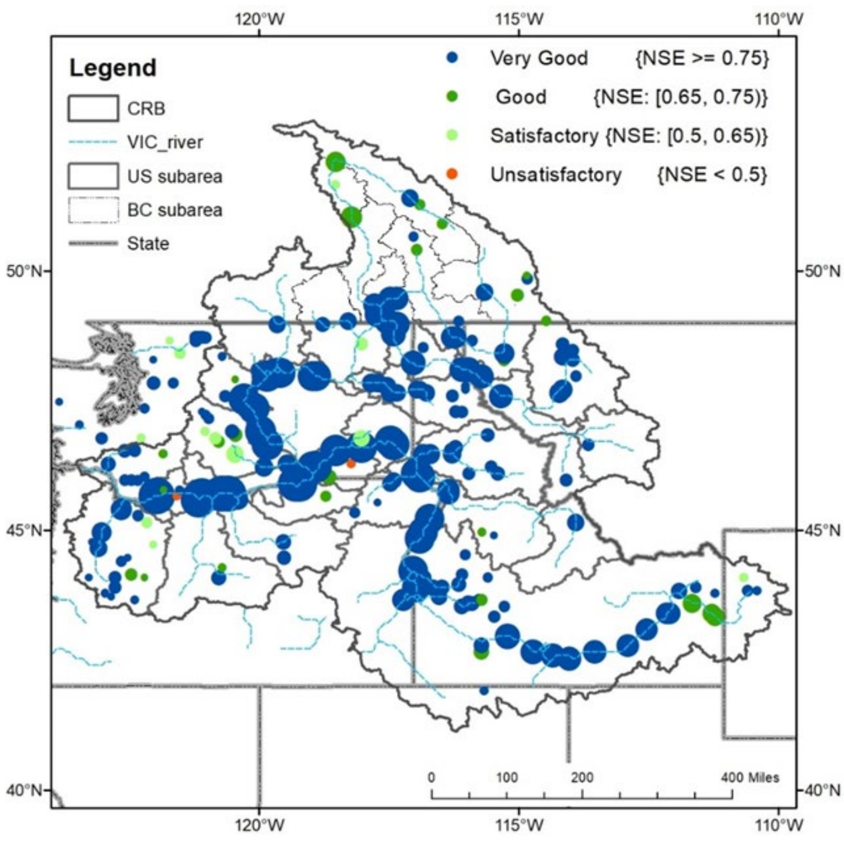

FIGURE 1. 12 NSE VALUES AND ITS DISTRIBUTIONS OF STATIONS THAT WERE USED FOR MODEL CALIBRATION AND THEIR RELATIONSHIPS WITH THE SIZE OF DRAINAGE AREA. NSE CATEGORIES FOR EACH CALIBRATION STATION AND THE SYMBOL FOR THEM ARE SCALED WITH DRAINAGE AREA.

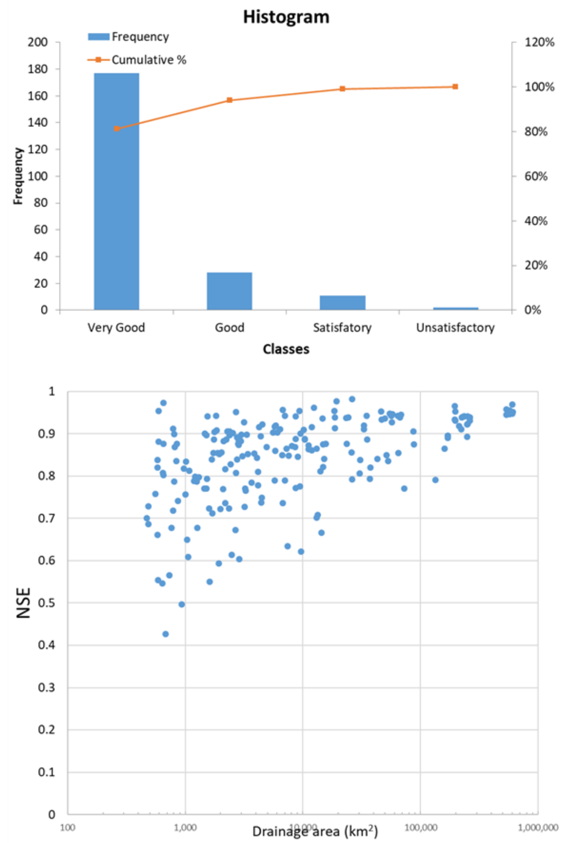

FIGURE 1. 13 NSE VALUES AND ITS DISTRIBUTIONS OF STATIONS THAT WERE USED FOR MODEL CALIBRATION (SHOWN IN FIGURE 1.12). TOP PANEL: LEFT Y-AXIS AND COLUMN BARS: THE NUMBER OF STATIONS/BASINS FALLS IN EACH NSE RANKING/CATEGORIES AND THE RIGHT Y-AXIS AND LINE SHOWS THE ACCUMULATIVE PERCENTAGE; BOTTOM PANEL: NSE VALUE DISTRIBUTIONS FOR EACH STATION WITH VARIOUS DRAINAGE AREA.

Modeling Application

Modeling Water Supply

Routing and Streamflow Bias-correction

VIC streamflow was routed to 66 outlets across the Columbia River Basin (Table 1.4). The routing program is a Fortran code that calculates daily streamflow at user-defined outlet grid cells. The routing scheme uses equations from Lohmann et al. (1996). Output from hydrologic models sometimes inherits systematic bias arising from errors in the meteorological inputs, uncertainties from the calibrated parameters, and other sources. These types of error can lead to misleading information when used in water resources planning studies. Bias correction is a statistical approach which can reduce these types of errors while keeping the model-derived, physically based signals mostly intact (Hamlet et al. 2013). The bias-correction methodology described in

Snover et al. (2003) was applied to VIC-CropSyst routed flows. The methodology is a percentile-based bias-correction technique, which uses simulated historical flows and naturalized observed historical data to create statistics which help translate any simulated data point to its corresponding observed data point. This is accomplished by using the percentile of the simulated data in the simulated sample space and finding the point which falls on the same percentile in the observed sample space.

Routed VIC flows were bias corrected to BPA's no regulation, no irrigation (NRNI) dataset (BPA, 2014) at locations where these data were available. Two gauge locations in Okanogan (Okanogan River at Tonasket and at Mallot) were bias corrected to data from the University of Washington's Climate Impacts Group (Elsner *et al.*, 2010). For locations without any naturalized flow data, we did not perform any bias correction. Streamflow inputs to RColSim were all bias corrected, whereas several locations used to quantify inflows to Washington from across the border and contributions from tributaries to the Columbia mainstem required use of uncorrected flows. Table 1.4 summarizes the gauge locations where routing and bias correction were performed, along with the model or analysis that made use of routed flow at those locations.

TABLE 1. 4 GAUGE LOCATIONS OF ROUTED AND BIAS-CORRECTED FLOWS.

StationID	Drainage	Bias Corrected	Analysis
ALBEN	PEND OREILLE RIVER AT ALBENI FALLS DAM	Yes	RColSim
ANATO	SNAKE RIVER NEAR ANATONE	Yes	WA inflows
ARROW	COLUMBIA RIVER AT KEENLEYSIDE DAM	Yes	RColSim
BIRCH	COLUMBIA RIVER AT BIRCHBANK	Yes	WA inflows
BONFE	KOOTENAI RIVER AT BONNERS FERRY	Yes	RColSim
BONNE	COLUMBIA RIVER AT BONNEVILLE DAM	Yes	RColSim
BOUND	PEND OREILLE RIVER AT BOUNDARY DAM	Yes	RColSim
BROWN	SNAKE RIVER AT BROWNLEE DAM	Yes	RColSim
CABIN	CLARK FORK RIVER AT CABINET GORGE DAM	Yes	RColSim
CHELA	CHELAN RIVER AT CHELAN DAM	Yes	Columbia tribs

CHIEF	COLUMBIA RIVER AT CHIEF JOSEPH DAM	Yes	RColSim
COLFA	FLATHEAD RIVER AT COLUMBIA FALLS	Yes	RColSim
COLKE	COLVILLE RIVER AT KETTLE FALLS	Yes	RColSim, Columbia tribs, Curtailment
CORRA	KOOTENAY RIVER AT CORRA LINN DAM	Yes	RColSim
CRABC	CRAB CREEK NEAR BEVERLY	No	Columbia tribs
DALLE	COLUMBIA RIVER AT THE DALLES	Yes	RColSim
DUNCA	DUNCAN RIVER AT DUNCAN DAM	Yes	RColSim
DWORS	N. FORK CLEARWATER AT DWORSHAK DAM	Yes	RColSim
FLAPO	FLATHEAD RIVER AT KERR DAM	Yes	RColSim
FLASF	FLATHEAD RIVER AT HUNGRY HORSE DAM	Yes	RColSim
GCOUL	COLUMBIA RIVER AT GRAND COULEE DAM	Yes	RColSim
HCANY	SNAKE RIVER AT HELLS CANYON DAM	Yes	RColSim
ICEHA	SNAKE RIVER AT ICE HARBOR DAM	Yes	RColSim
JDAYY	COLUMBIA RIVER AT JOHN DAY DAM	Yes	RColSim
JOHND	JOHN DAY RIVER AT MCDONALD FERRY	No	WA inflows, Columbia tribs
KETTL	KETTLE RIVER NEAR LAURIER	No	WA inflows
KLIPI	KLICKITAT RIVER NEAR PITT	No	Columbia tribs
LGOOS	SNAKE RIVER AT LITTLE GOOSE DAM	Yes	RColSim, Columbia tribs
LGRAN	SNAKE RIVER AT LOWER GRANITE DAM	Yes	RColSim
LIBBY	KOOTENAI RIVER AT LIBBY DAM	Yes	RColSim
LISPO	LITTLE SPOKANE RIVER NEAR DARTFORD	Yes	RColSim

LLAKE	SPOKANE RIVER AT LONG LAKE DAM	Yes	Columbia tribs
LMONU	SNAKE RIVER AT LOWER MONUMENTAL DAM	Yes	RColSim
MCNAR	COLUMBIA RIVER AT MCNARY DAM	Yes	RColSim
METPA	METHOW RIVER NEAR PATEROS	Yes	RColSim, Columbia tribs, Curtailment
MICAA	COLUMBIA RIVER AT MICA DAM	Yes	RColSim
MILNE	SNAKE RIVER AT MILNER	Yes	RColSim
NACCL	NACHES RIVER AT COTTONWOOD CAMPGRND NEAR CLIFFDELL	Yes	Yakima-RW
NACTI	NACHES RIVER BELOW TIETON RIVER NEAR NACHES	Yes	Yakima-RW
NOXON	CLARK FORK AT NOXON RAPIDS DAM	Yes	RColSim
OKANA	OKANOGAN RIVER AT MALOTT	Yes	RColSim, Columbia tribs, Curtailment
OKANO	OKANOGAN RIVER NEAR TONASKET	Yes	RColSim, Curtailment
OXBOW	SNAKE RIVER AT OXBOW DAM	Yes	RColSim
PALHO	PALOUSE RIVER AT HOOPER	no	Columbia tribs
PALIS	SNAKE RIVER NEAR IRWIN	Yes	RColSim
PRIRA	COLUMBIA RIVER AT PRIEST RAPIDS DAM	Yes	RColSim
REREG	DESCHUTES RIVER AT MOODY NEAR BIGGS	No	WA inflows, Columbia tribs
REVEL	COLUMBIA RIVER AT REVELSTOKE DAM	Yes	RColSim
RISLA	COLUMBIA RIVER AT ROCK ISLAND DAM	Yes	RColSim

ROCKY	COLUMBIA RIVER AT ROCKY REACH DAM	Yes	RColSim
SIMNI	SIMILKAMEEN RIVER NEAR NIGHTHAWK	Yes	RColSim, WA inflows, Columbia tribs, Curtailment
SPALD	CLEARWATER RIVER AT SPALDING	Yes	RColSim, WA inflows
SPOKA	SPOKANE RIVER AT SPOKANE	Yes	WA inflows
UMATI	UMATILLA RIVER NEAR UMATILLA	No	Columbia tribs
WALST	WALLA WALLA RIVER AT STATE LINE	Yes	RColSim, Columbia tribs
WANAP	COLUMBIA RIVER AT WANAPUM DAM	Yes	RColSim
WANET	PEND DOREILLE RIVER AT WANETA DAM	Yes	RColSim, Columbia tribs
WELLS	COLUMBIA RIVER AT WELLS DAM	Yes	RColSim
WENMO	WENATCHEE RIVER AT MONITOR	Yes	RColSim, Columbia tribs, Curtailment
WENPE	WENATCHEE RIVER AT PESHASTIN	Yes	RColSim, Curtailment
YACLE	YAKIMA RIVER AT CLE ELUM	Yes	Yakima-RW
YAEUC	YAKIMA RIVER AT EUCLID	Yes	Yakima-RW
YAKEA	YAKIMA RIVER AT EASTON	Yes	Yakima-RW
YAKKI	YAKIMA RIVER AT KIONA	Yes	Columbia tribs, Yakima-RW
YAKUM	YAKIMA RIVER AT UMTANUM	Yes	Yakima-RW
YAPAR	YAKIMA RIVER NEAR PARKER	Yes	RColSim, Yakima-RW

WRIA-Level Water Supply

We calculated the water supply generated within each of the 34 WRIAs as follows: for the subbasins crossing state borders (e.g. Walla Walla and Okanogan), we replaced bias-corrected streamflow with the sum of runoff and baseflow (unrouted flow) for grids located inside Washington. For the WRIA boundaries that do not correspond with watershed boundaries, we summed runoff and baseflow within the respective WRIA boundary. For the remaining locations where WRIA boundaries matched watershed boundaries (COLKE, LISPO, CHELA, WENMO, and METPA), we used bias-corrected flow.

Columbia River Water Supply and Regulated Flow

Water supply for the entire CRB was estimated as the bias-corrected streamflow at Bonneville Dam. The RColSim model was run without water demand to calculate regulated water supply at Priest Rapids, McNary, and Bonneville Dams. Regulated flows were compared with state-adopted instream flow rules at Priest Rapids and McNary Dams (WAC 173-563-040) and Federal Biological Opinion flows at all three dams. The Federal Biop flow targets for Priest Rapids and McNary have not been updated since the original 2000 Biological Opinion for the Federal Columbia River Power System (U.S.A.C.E., 2000). A revision was made for Bonneville in the 2014 BiOp (U.S.A.C.E, 2014), which introduced target flows for the months of June through August. We used these 2000 BiOp flows and 2014 BiOp revisions to create our regulated flow plots.

Water Supply Shift

We quantified timing of streamflow in terms of the timing of center of mass (Stewart *et al.,* 2005). The timing of center of mass (COT) measures the day of year, starting from October 1st, for which cumulative flow to the left of COT balances cumulative flow to the right of COT, much like how the weight to the left of the center of mass of an object balances the weight to the right of the center of mass. We calculated COT for historical and future flows for the CRB as a whole and in all 34 WRIAs (WRIAs 37, 38, and 39 were grouped together and WRIAs 44 and 50 were grouped together). The shift in streamflow timing was calculated as the difference between future and historical COT. Larger negative shifts in COT reflect earlier streamflow timing in the future. In addition to calculating COT at the WRIA level, we calculated supply COT from bias-corrected streamflow at the Bonneville Dam to estimate water supply shift for the CRB as a whole.

Modeling Snowmelt Influence

We quantified the fractional contribution of snowmelt to runoff using a snowmelt tracker (Li et al., 2017). The snowmelt tracker uses a water balance approach to calculate the snowmelt fraction, accounting for snow processes such as accumulation, sublimation, and infiltration to extract snowmelt derived runoff from total runoff. The fraction is then the ratio of runoff from snowmelt to total runoff and ranges between 0 and 1. A snowmelt fraction of 1 indicates that all runoff is originating as snowmelt. We calculated the snowmelt fraction for historical and future time periods for each of the WRIAs in Washington.

Modeling Agricultural Water Demand and Yield

CropSyst Parameterization

CropSyst crop parameters describe the crop's phenology, canopy growth, transpiration, biomass production, and yield (Scarpare et al., 2022). These parameters are crop and region-specific and there is no single standard source of information. Initially, the crop parameter values were taken from existing model applications in the region (Malek et al., 2017, 2018; Rajagopalan et al., 2018).

For the purposes of this study, the critical parameters that needed fine-tuning through communications with local experts were planting and harvest dates, timing of various phenological (growth) stages and canopy cover at different growth stages under irrigation management. To account for site-specific and local variation in crop growth/development, management information collected from field trials (under ten years old), including average sowing, flowering and heading (when available), harvest dates, total irrigation water applied and yield were used as the main source of calibration information. These field trials, conducted mostly by the University Extension group, include a range of management practices and crop varieties that represent the diversity of farmers' practices in the Pacific Northwest. Moreover, information from local growers, available statistics of usual planting and harvest dates (USDA National Agricultural Statistics Service, 2010), and other sources of literature were used to ensure they reflect reality in terms of actual practices in a region.

Twenty-five crops among cereal grains, vegetables, fruits, root crops, leguminous, forages and oil seeds crops were addressed in this study (Table 1.5).

TABLE 1. 5 CROP CALIBRATION – CROP NAMES (COMMON AND SCIENTIFIC) AND TYPES CALIBRATED IN THIS PROJECT.

Crop name	Scientific name	Crop type*
Alfalfa hay	*Medicago sativa*	Perennial_forage_C3
Apple	*Malus domestica*	Perennial_fruit_C3
Barley spring	*Hordeum vulgare*	Annual_cereal_C3
Beans dry	*Phaseolus vulgaris*	Annual_legume_C3

Blueberry	*Cyanococcus*	Perennial_fruit_C3
Canola	*Brassica napus*	Annual_oilseed_C3
Cherry	*Prunus avium*	Perennial_fruit_C3
Clover hay	*Trifolium*	Perennial_forage_C3
Corn grain	*Zea mays*	Annual_cereal_C4
Corn sweet	*Zea mays* subsp. Mays	Annual_cereal_C4
Grape wine	*Vitis vinifera* or *labrusca*	Perennial_fruit_C3
Grass hay	----------	Perennial_forage_C3
Hops	*Humulus lupulus*	Perennial _herbaceous_C3
Lentil	*Lens culinaris*	Annual_cereal_C3
Mint	*Mentha*	Perennial_forage_C3
Oats	*Avena sativa*	Annual_cereal_C3
Onion bulbs	*Allium cepa*	Annual_bulb_C3
Pears	*Pyrus*	Perennial_fruit_C3
Peas dry/green	*Pisum sativum*	Annual_legume_C3
Potatoes	*Solanum tuberosum*	Annual_tuber_C3
Radish	*Raphanus raphanistrum* subsp. *sativus*	Annual_vegetable_C3
Sod seed grass	----------	Annual_grass_C3
Triticale spring	×*Triticosecale*	Annual_cereal_C3
Wheat (spring and winter)	*Triticum*	Annual_cereal_C3

* C3 and C4 are distinct carbon fixation pathways through photosynthesis.

Although there is usually initial information about some parameter values (most of the time based on specific measurements reported in the literature), they values do vary from site to site (Wallach et al., 2001). Therefore, regardless of the study area characteristics and the used model, calibration is a necessary procedure. Mechanistic models in general contain a large number of parameters that usually takes the same fixed value for all sites and years. Other sources of uncertainty come from upscaling, which is necessary when the process-based crop models are used for regional applications, usually applied for a more appropriate framework to inform decision making.

There is no possibility to address all parameters during calibration but, instead, it is possible to identify those parameters that most strongly affect the model output using the sensitivity analysis approach (de Jong van Lier et al., 2015). In the sensitivity analysis, model parameters are varied in turn by a small amount within the region of a best estimate or standard case (Drechsler, 1998). For each parameter, the resulting relative change in the state variable is divided by the relative variation in the parameter to obtain sensitivity coefficients (Confalonieri, 2010; Saltelli et al., 2002). This identifies which parameter should be identified and measured most carefully to assess the state of the environmental system, and which environmental factors should be managed preferentially.

In this project, the model's sensitivity analysis consisted of changing a single parameter at once, by 5% within a predefined interval being the remaining parameters fixed on default values, which were considered to be the mean values of the total variation range (Saltelli, 2002). Six crop input parameters (Transpiration use efficiency (TUE, g mm^{-1}), Radiation used efficiency (RUE, g MJ^{-1}), Evapotranspiration crop factor (kc, -), Maximum water uptake (MWU, mm d^{-1}), Maximum root depth (MaxRD, m) and maximum canopy cover (CCmax, -)) were selected (Table 1.6).

TABLE 1. 6 SENSITIVITY ANALYSIS - CROP PARAMETER RANGE USED IN THE SENSITIVITY ANALYSIS.

	Spring Wheat (C3)			Corn grain (C4)		
	Minimum	Default	Maximum	Minimum	Default	Maximum
TUE (g mm^{-1})	4.000	5.105	6.205	6.000	7.658	9.308
RUE (g MJ^{-1})	1.400	1.621	1.876	1.800	2.084	2.297
MWU (mm d^{-1})	8.000	10.721	14.367	9.000	11.487	14.660
kc (-)	0.800	1.021	1.241	0.800	1.021	1.241
k (-)	0.400	0.511	0.652	0.400	0.511	0.652
CCmax (-)	0.750	0.868	0.957	0.750	0.868	0.957
MaxRD (m)	1.000	1.216	1.551	1.000	1.477	2.079

TUE - Transpiration Use Efficiency (g mm^{-1}), RUE - Radiation Use Efficiency (g MJ^{-1}), MWU – Maximum Water Uptake (mm d^{-1}), kc – Evapotranspiration crop factor (-), k - Light extinction coefficient (-), CCmax – Maximum Canopy Cover (-), MaxRD - Maximum Root Depth (m).

The scenario assumed for this analysis consisted of average output variation (from 1980 to 2015) of the above ground biomass (Mg ha^{-1}) and actual evapotranspiration (ETa, mm) of spring wheat, and corn for grain, a C3 and C4 crop type[6], respectively. Aiming to cover the range of the climate types in the study area, four locations across CRB: Marion County-OR, Grant County-WA, Bingham County-ID and Lake County-MT were selected (Figure 1.14).

First, the absolute sensitivity $\sigma(y/k)$ is calculated as:

$$\sigma(y/k) = \delta y/\delta k \quad (8)$$

where δy is the variation of the output variable of the model and δk is the variation of the input parameter. Next, the relative sensitive index σ_r (y/k) is calculated as:

$$\sigma_r(y/k) = \sigma(y/k)\ \frac{k}{y} \quad (9)$$

where k is the default parameter value and y is the output value. The higher the relative sensibility value, the more sensitive the model output is to the considered parameter.

CropSyst calibration was performed in three main steps. Primary emphasis was focused on the crop length and the occurrence of a few important phenological events such as: crop emergence, beginning and end of flowering, beginning of yield formation, end of vegetative growth, and maturity if reached. Using the most common planting date, growing degree-day parameters were adjusted to approximate flowering and maturity dates typical of the CRB within a particular site was located.

Next, canopy cover (CCmax, beginning and full senescence – if reached) and above ground dry matter were calibrated concomitantly since canopy development drives crop water use, which is intrinsically related to yield. In this step, adjustments in the initial, maximum, and green canopy cover at the time of maturity (biomass accumulation has ended) were made. Next, based on sensitivity analysis results, manual adjustments to the transpiration-use efficiency (TUE) and harvest index (HI) parameters related to biomass assimilation and partitioning were made to fine-tune the simulated yields, when necessary. Calibration was considered finalized when simulated yields presented the same order of magnitudes as the local experiments (on dry basis).

Regarding the sensitivity analysis, the relative sensitivity distribution for spring wheat and corn in the four regions studied are presented (Figure 1.14).

[6] C3 and C4 are distinct carbon fixation pathways through photosynthesis.

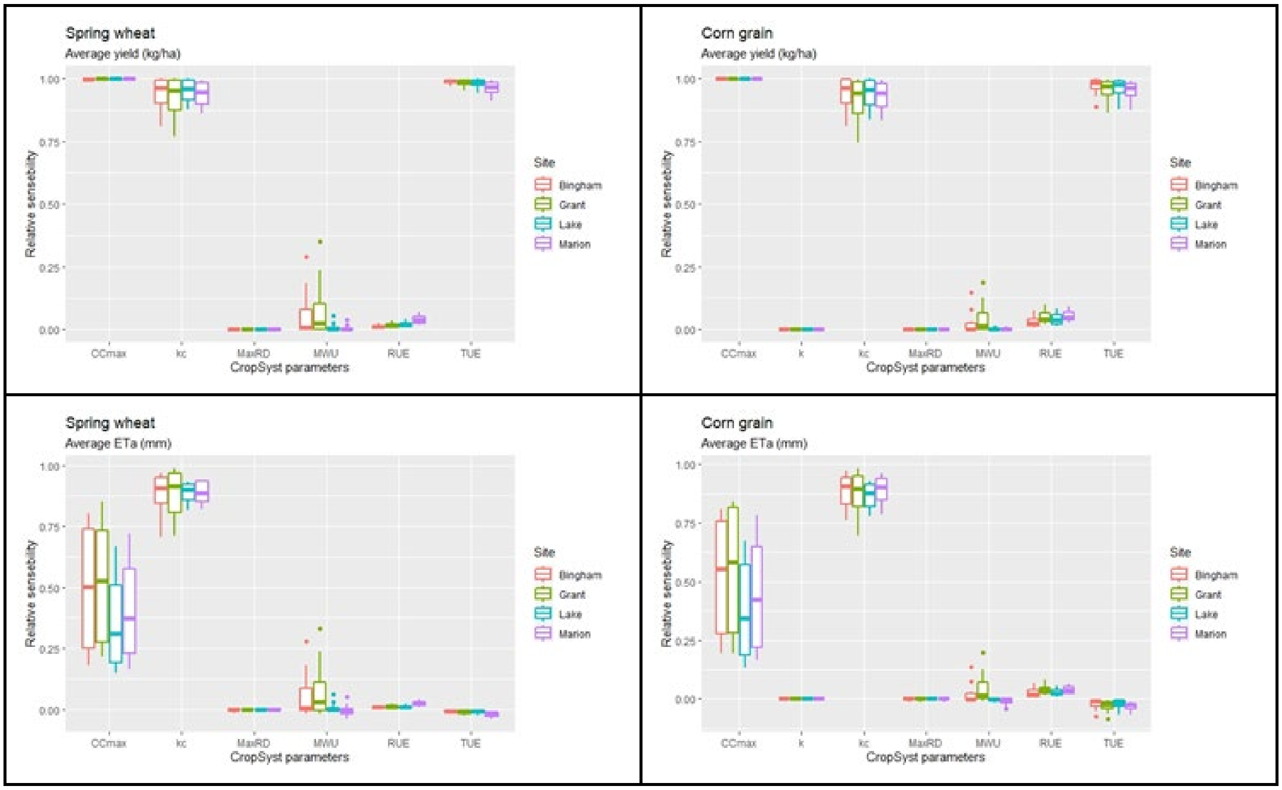

Figure 1. 14 Relative sensibility distribution for six CropSyst parameters (TUE, RUE, kc, CCmax, MWU, MaxRD and k) for spring wheat and corn grain above ground biomass (AGB, Mg ha^{-1}) and actual evapotranspiration (ETa, mm) in four sites along CRB (Marion-Or, Bingham -Id, Lake -mt and Benton-WA).

Regardless of the location and production level, the sensitivity analysis results indicated that TUE, kc, and CCmax have great influence on CropSyst results since they are directly related to biomass accumulation; being kc, and CCmax also directly related to the water demand, i.e., ETa. On the other hand, RUE and maximum water uptake input parameters did not play a significant role in the prediction of biomass and the ETa within their ranges of uncertainty. These initial findings agree with other studies (Confalonieri et al., 2006, Confalonieri et al., 2010) who reported the energy-related CO_2 assimilation parameters as TUE of great importance in CropSyst.

Relative sensitivity σ_r (Eq. 8) can be interpreted as the fraction of relative change in an input parameter that will propagate in some output, in our case, yield and evapotranspiration predictions. Small relative sensitivity values (close to zero) suggest the parameter value only slightly affects modeling results and might as well be considered as a model constant. On the other hand, a high absolute value of sensitivity of the model to a parameter made predictions very vulnerable to measurement and calibration errors (de Jong van Lier et al. 2015).

In general, it was observed that the sensitivity analysis variations were consistent among all four sites. The consistency of these relationships across the locations was an indication that they reflected the model structure rather than a specific location.

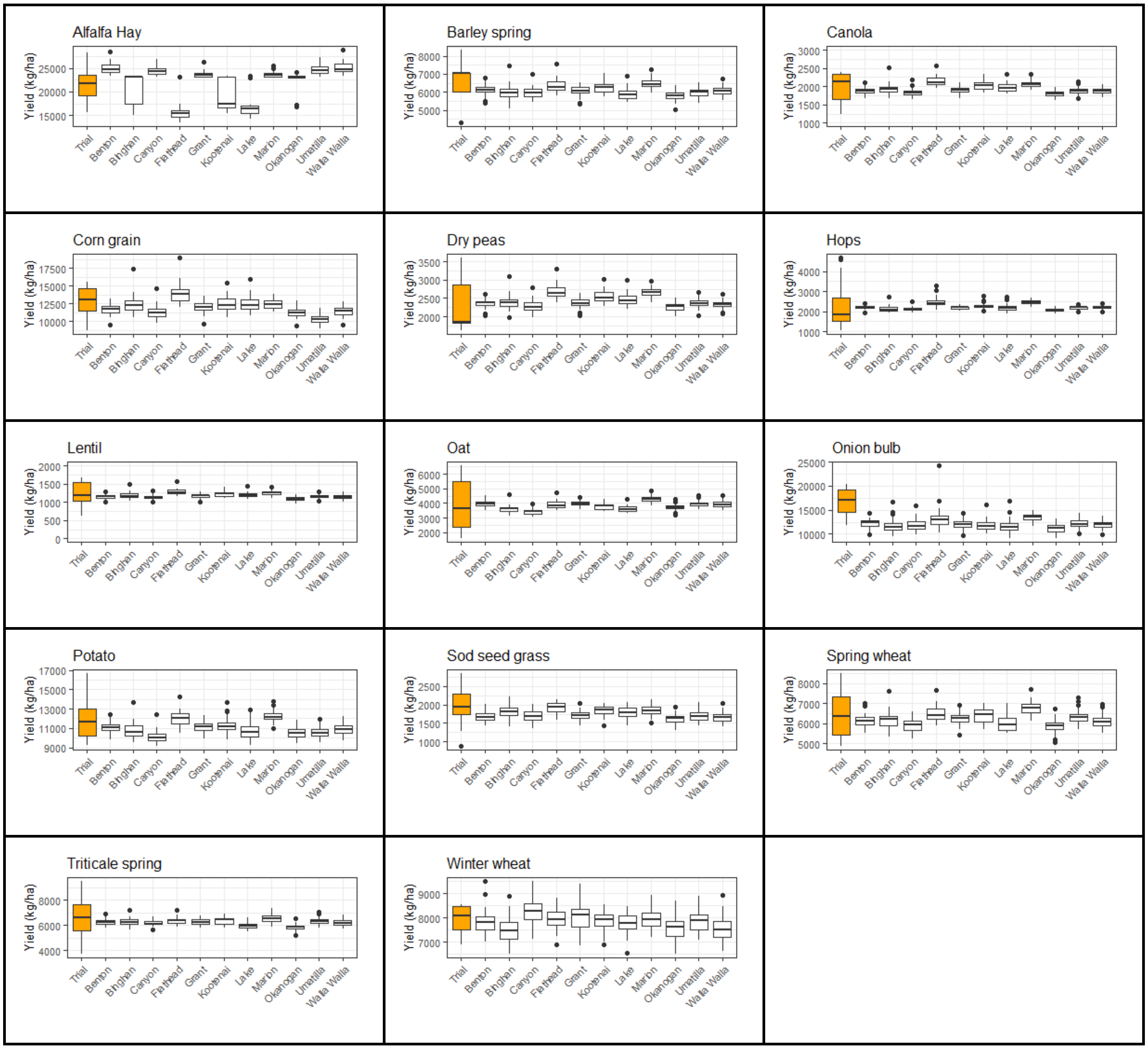

FIGURE 1. 15 DRY MATTER YIELD CALIBRATION IN KG HA^{-1} FOR ALL ELEVEN CALIBRATED SITES AGAINST FIELD TRIAL RECORDS.

Throughout the crop development, water requirement is determined from a crop coefficient at full canopy and ground coverage determined by canopy green area index. Crop growth is then simulated for the whole canopy by calculating unstressed biomass growth based on potential transpiration and on crop intercepted photosynthetically active radiation. Finally, crop yield is determined according to the harvest index (ratio between harvestable yield and aboveground biomass) and translocation factor. Evapotranspiration crop factors (kc) were obtained for FAO[7] while CCmax and TUE were adjusted to reflect the yield levels during calibration (Figure 1.15).

Conveyance Loss and Ground/Surface Water Splits

VIC-CropSyst generates "top-of-crop" irrigation demand in units of mm/day for each crop type in each grid cell. The top-of-crop demand is the irrigation amount delivered to the field. Some of this water is used by the crop and some is lost through evaporation, runoff, and deep percolation. The top-of-crop demand does not include conveyance losses like seepage from canals. The same rates of conveyance loss as in the previous (2011, 2016) Forecasts were adopted. These rates are given in terms of percentage of surface water diversion:

- 15% for irrigation demand originating from the Columbia Basin Project region,
- 10% for irrigation demand originating within a one-mile corridor of the Columbia River mainstem (this is assuming that the place of use of withdrawn water is closer to the point of withdrawal and there is less scope of losses associated with travel through a canal system),
- 25% for irrigation demand in the Yakima River Basin region,
- 25% loss for all other watersheds in Washington with a canal system, except for Methow (WRIA 45),
- 40% for irrigation demands in Methow, based on information from the Methow's watershed plan, and
- 20% otherwise.

The top-of-crop demand from CropSyst includes water derived both from surface water and groundwater sources. In order to separate groundwater from surface water demand, we multiplied total demand (groundwater + surface water) by groundwater fraction. The groundwater fractions were determined using a variety of data sources. For WRIAs 32, 37, 38, 39, 45, 47, and 48, the fractions were calculated from the WRTS water rights database as the fraction of water entitlements derived from groundwater. The process of estimating groundwater fractions from the WRTS database was manually intensive, so for the remaining WRIAs we assumed a groundwater fraction of 0.2 based on average estimates reported in WRIA watershed planning documents. The groundwater fraction for grids upstream of Brownlee was estimated from the distribution of groundwater and surface-water irrigated acreage in the Eastern Snake River Plain. Approximately 2/3 of acres are irrigated with surface water and 1/3 with groundwater (Lindholm, 1986). The Odessa subarea was divided between grids in the groundwater sector, making up about 85% of Odessa, and the surface water sector, which is part

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[7] http://www.fao.org/3/x0490e/x0490e0b.htm

of the Columbia Basin Project. For the future scenarios, we assumed that 100% of the Odessa would be converted to surface water. All remaining grids were assumed to have a groundwater fraction 0.2.

TABLE 1. 7 FRACTION OF IRRIGATION DEMAND COMING FROM GROUNDWATER BY SUBAREA.

Subarea	GW Fraction
WRIA 32	0.35
WRIA 38&39	0.05
WRIA 45	0.1
WRIA 48&49	0.25
Upstream of Brownlee	0.35
Odessa Historical GW subarea	1
Odessa SW subarea	0
Odessa Future	0
Otherwise	0.2

Conversion of Irrigation Depth (mm) to Irrigation Volume (acre-feet)

Irrigation depth was converted to a volumetric irrigation water requirement in two steps. In the first step, area-weighted irrigation depth for each WRIA and each crop was calculated from VIC-CropSyst output using the areas given in the VIC-CropSyst land-use input file. We applied a grid fraction cutoff of 0.01, meaning that crops occupying < 0.01 of a grid cell were not simulated. This was done to reduce computation time. Equation (10) shows how area-weighted irrigation depths were calculated, where d_{avg} is the crop and WRIA-specific, area-weighted irrigation depth (mm/day), $A_i$is the crop area in grid cell i, and d_i is the crop irrigation depth in grid cell i.

$$d_{avg} = \sum_i (A_i * d_i)/\sum_i A_i \qquad (10)$$

In the second step, we multiplied area-weighted irrigation depth by crop area from the 2018 WSDA cropland data layer and aggregated the daily values to a monthly time step. We then split the total irrigation demands between groundwater and surface water using the fractions given in Table 1.7. Conveyance loss was calculated from the estimate of surface water demand and conveyance loss fraction (CL) according to Equation (11).

$$ConveyanceLoss = Demand_{SW} * [\, CL \,/\, (1 - CL)] \quad (11)$$

The values of *CL* by basin are provided in the preceding sub-section: *Conveyance loss and ground/surface water splits*.

Columbia River Basin Demand

Agricultural demand for the entire CRB was estimated by summing total demand within Washington and total demand outside Washington. While demand within Washington was calculated as average irrigation depth multiplied by crop area from the WSDA cropland data layer, demand outside Washington was calculated using crop areas from the VIC-CropSyst land-use input file. Since areas < 0.01 of a grid cell were not recorded in the simplified land-use file, this procedure underestimated demands outside of Washington on the order of 5%.

Reservoir Modeling

Columbia River

Reservoir Model: RColSim

We used a version of the Columbia Simulation Reservoir Model (ColSim) (Hamlet et al. 1999) that runs as a script in the R programming language. The RColSim model (Malek *et al.,* in review) has the same functionalities as ColSim. RColSim represents the key physical characteristics of the Columbia River water resources system and models the main storage reservoirs and run-of-river dams along the mainstem Columbia River. It also includes the Snake, the Kootenai, the Clark Fork, and the Pend Oreille tributaries (Figure 1.16). Other smaller tributaries, such as the Yakima River, are not included in ColSim. Due to the regional importance of the Yakima River Basin, however, a separate reservoir model called Yakima RiverWare was used in the 2021 Forecast for the Yakima River (see the *Yakima-RiverWare* sub-section below).

RColSim uses VIC-simulated streamflow, reservoir rule curves, and net withdrawals as input. Grid-by-grid runoff and baseflow were routed and aggregated to monthly flow prior to bias-correction against naturalized streamflow data products according to the procedure outlined in the *Streamflow Routing and Bias Correction* sub-section of the *Modeling Water Supply* section. The monthly bias-corrected flows were then downscaled to a weekly timestep to match the timestep of the model. This process involved approximating daily bias-corrected flow as the daily routed flow multiplied by the ratio of bias-corrected to routed flow, followed by aggregating the daily bias-corrected flow to a weekly timestep. Daily agricultural demand was calculated according to the procedure outlined in the *Modeling Agricultural Demand* section and aggregated to the drainage areas for each gauge in RColSim (see Table 1.4) and then aggregated to a weekly timestep. Weekly curtailment for the tributaries was calculated according to the *Curtailment Subject to Instream Flows* sub-section of the *Water Rights Curtailment (Interruption) Modelling* section. The curtailment amount was subtracted from total demand (surface water irrigation and residential demand) to give the adjusted demand input, which accounts for conveyance losses, return flows, consumptive water use, and curtailment. Simplifying assumptions were made that return flow resulting from conveyance loss reaches the basin outlet within the weekly timestep and that return flows are equal to conveyance losses. While not strictly true, the error resulting from these assumptions is very small compared to the flow of the Columbia River. An exception to these assumptions was made for the Columbia basin project, for which the point of withdrawal is located far upstream of where the return flow is known to enter the Columbia River. We used data from Hills *et. al.* (2020) to calculate the proportion of withdrawals near Grand Coulee Dam that flow back into the Columbia near Priest Rapids, Wanapum, and McNary dams.

Remaining inputs to the RColSim model relate to operation of the dam according to rule curves. Reservoir levels in RColSim are regulated based on flows forecasted for January through September. The operation rules of the water resources system for hydropower production, flood evacuation, and major flow targets that existed in 1999 and that were originally used in Hamlet and Lettenmaier (1999) have been minimally modified to capture important changes to the operating rules (Alan Hamlet, personal communication).

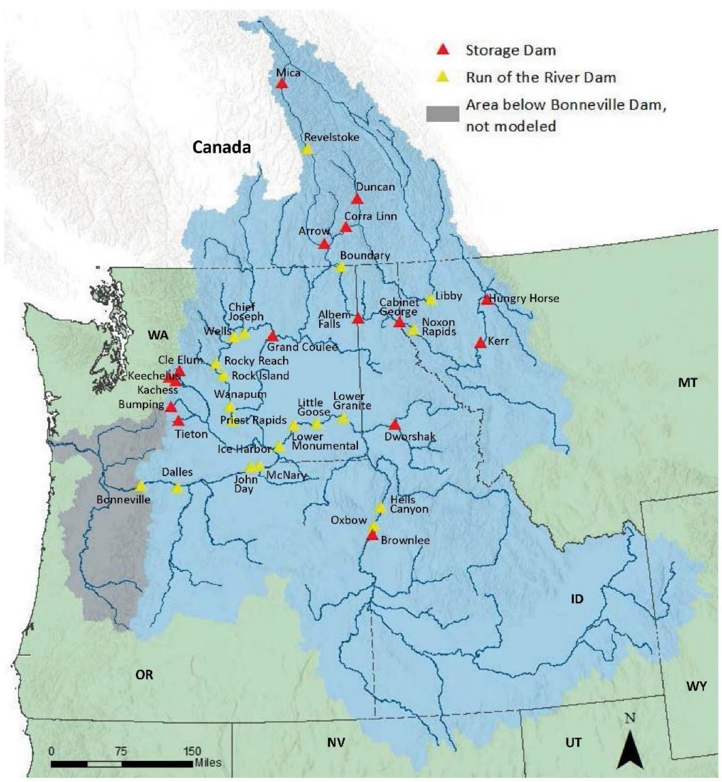


FIGURE 1. 16 DAMS IN THE COLUMBIA RIVER BASIN THAT ARE INCLUDED IN THE COLSIM MODEL (FIGURE FROM RUSHI ET AL. IN PREPARATION).

Yakima River

Yakima-RiverWare

We used a reservoir operations and water management model which is specifically developed for the Yakima River Basin (YRB) by USBR and HDR Engineering using the RiverWare software. A general overview of the RiverWare software and modeling can be found in Zagona et al., (2001). The Yakima-RiverWare model is embedded with detailed information about YRB's water infrastructure, management, and water rights, to simulate dam operations and water flow in the river network of YRB. We used the 8.1 version of Yakima-RiverWare for this study. Provided with a water management rules and policy information, the model is run using the daily bias-corrected VIC simulated streamflow (unregulated) at 13 locations (streamflow gauges) to simulate prorationing level at Parker (Proration control point of the basin) and streamflow at different point of the basin, especially at the most downstream point of the YRB which is at Kiona. These 13 inflow locations consist of five major reservoirs (Bumping, Cle Elum, Kachess, Keechelus, Rimrock) and rest are the stream gage locations at the major confluences and tributaries of the Yakima River. A list of inflow locations which were used as input to Yakima-RiverWare, their relative geographical location in the YRB and detailed procedure of routing and bias-correction of VIC simulated streamflow can be found in Malek et al., (2018).

We run the Yakima-RiverWare model using daily bias-corrected VIC simulated inflows for four climate scenarios (historical baseline (1979-2015), GCM historical (1950 – 2005), RCP 4.5 (2006 - 2094) & RCP 8.5 (2006 -2094)) to generate the daily output of streamflow values at Kiona (the most downstream point in YRB, abbreviated as YAKKI) and at Parker (proration control point, abbreviated as YAPAR) along with the daily prorationing level at YAPAR. Then, the streamflow output was monthly aggregated by summing up the daily streamflow in a month and the prorationing level for a month is calculated by averaging the daily prorationing values in a month. Note that the simulations of RiverWare models are computationally slow for longer time frames because it stores every variable internally, so we ran the model on segmented data with enough spin-up period to improve the model performance. It means we ran the model for multiple times to cover the whole time-period. For an instance, in case of GCM-historical, instead of running the Yakima-RiverWare model for all 56 years together, we segmented the data into two time frames i.e., 1950-1980 and 1975 – 2005 and then, ran the model on these two time frames separately. More details on the development of the Yakima-RiverWare model, its modification and application in climate change studies can be found in Vano et al., (2010).

Water Rights Curtailment (Interruption) Modeling

Modeling of Curtailment Subject to Instream Flows

In the 2021 Forecast we modeled the frequency and magnitude of curtailments in Eastern Washington, on a weekly basis, for the historical time period (1986-2015), and forecasted curtailment for the 2026-2055 time period. Modeled water supply (historical or forecast) in the appropriate geography was compared to state instream flow requirements, and the legislated trigger points for curtailment were used to estimate how often interruptible and proratable water users would see their water use curtailed during those two time periods. For locations in Washington State for which instream flow targets exist, if the routed and bias-corrected VIC-CropSyst streamflow minus surface water demand was less than the target instream flow in any week, the demand from interruptible grid cells (excluding conveyance losses) associated with that location were curtailed for that week.

Curtailment of interruptible water right holders at the watershed scale was modeled for the Wenatchee (45), Methow (48), Okanogan (49), and Colville (59) watersheds. The curtailment model used for this analysis identifies when the water supply remaining after accounting for agricultural and municipal surface water demands is insufficient to meet instream flow requirements. In the event of a water shortage, the amount of water curtailed is estimated as the VIC-CropSyst irrigation demand within interruptible grid cells multiplied by the interruptible acreage for each crop type.

Curtailment in the mainstem Columbia River occurs only when the April through September total unregulated flow volume at The Dalles Dam is projected to be less than 60 million acre-feet according to Ecology's Columbia River interruption program. After analyzing the results, we determined that the model was unable to reliably capture the 60 million acre-ft trigger point, so we instead calculated the frequency with which Columbia River flows failed to meet state instream flow rules at nine control points where Columbia River interruptibles are provisioned.

Modeling Actual Streamflow

Actual streamflow is the natural water supply minus the water demands adjusted for curtailment. It is a close analog to gauge flow. Actual streamflow for basins with curtailment in favor of instream flows was determined according to Equation (12):

$$Actual\ Flow = Q_{nat} - I_D + C \tag{12}$$

Naturalized flow (Q_{nat}) was determined according to methods reported in the *Routing and Streamflow Bias Correction* sub-section. Irrigation demand (I_D) and curtailment magnitude *C* were calculated using the methodology from the *Modeling of Curtailment Subject to Instream Flows* sub-section of the *Water Rights Curtailment (Interruption) Modelling* section. Actual streamflow for Yakima was considered equal to the regulated flow output from Yakima-RiverWare (see *Yakima-RiverWare* sub-section of the *Reservoir Modelling* section) at the Parker gauge (for WRIA 39) and the Kiona gauge (WRIA 37). That is, actual streamflow in Yakima was calculated as the natural water supply minus net agricultural withdrawals (prorationed withdrawals minus return flows). See the next sub-section called *Modeling Impact of Curtailment and Crop Yield* for a discussion of how proration rates were determined.

Modeling Impacts of Curtailment on Crop Yield

We modeled the impact of reduced irrigation on crop yields due to water right curtailment in favor of instream flow and water prorationing in Yakima. The deficit-irrigation demand modeling required three steps. In the first step, VIC-CropSyst was run under full irrigation to generate an irrigation schedule. In the second step, the proration rates for each day with scheduled irrigation were calculated. For instream interruption, the rate is binary--full irrigation when the flow is above the flow rule and no irrigation when the flow is below the flow rule. The curtailment model generates a time series of curtailment events used to assign a proration rate of 1 in the absence of an event (full irrigation) and 0 in the presence of an event (no irrigation). For Yakima, proration rate is a percentage of full irrigation that depends on the forecasted total surface water available. In a given year, irrigation districts in Yakima agree to share the same proration rate among proratable and non-proratable water users. The result is a modified proration rate (MPR) that is greater than the nominal proration rate. The MPR was calculated with the following equation:

$$MPR \; = (\frac{PR*proratable\ entitlements + nonproratable\ entitlements)}{total\ entitlements}) \tag{13}$$

For the watersheds with an instream flow rule (Wenatchee, Methow, Okanogan, and Colville), we used output from the curtailment model to determine days and crops with curtailment. For WRIAs in Yakima (Lower Yakima, Upper Yakima, and Naches), we modified Yakima RiverWare proration rates according to Eq (13) to reflect sharing within irrigation districts. Next, the deficit irrigation schedule consisting of binary (instream flow curtailment) or fractional (Yakima) proration rates was run in VIC-CropSyst. Deficit-irrigation and full-irrigation yields were aggregated by four crop groups: (1) high value perennials, (2) high value annuals, (3) other field crops, and (4) forage. The crop types in each of these groups are given in Table (1.8). Yield impact was calculated as the percentage difference between deficit and full-irrigation yield for each of the historical and future scenarios. We only reported results for crop groups with > 100 acres of interruptible crop area.

TABLE 1. 8 CROP TYPES FOR EACH GROUP USED TO DETERMINE DEFICIT IRRIGATION AMOUNTS DURING A CURTAILMENT.

High value perennials	High value annuals	Other field crops	Forage
Blueberry Apples Cherry Peach Pear Grape Grape Grape Hops	Carrots Oats Dill Carrots Grass Seed Buckwheat Yellow Mustard Pepper Sugarbeet Canola Soybeans Sunflower Onion Potato Sod Seed Triticale Mint Sweet Corn	Green Pea Barley Corn Dry Bean Spring Wheat Winter Wheat Pea	Alfalfa Hay Grass Hay

SECTION 2 – Modules

Module 1 - Residential Demand Forecasting

Introduction

Municipal water demands make up a small percentage of total water demands in the Columbia River Basin (less than 10% of total demands in eastern WA), but are an important component of water use (Barik et al. 2017). Recent legislation, (e.g., the 2018 Whatcom County vs. Hirst, Futurewise, et al. decision) has placed increased importance on understanding water availability for residential water users (both municipal and domestic) in the State of Washington. This sharpened focus on residential water use has highlighted the need for a more rigorous evaluation of the direct and indirect impact of water management decisions for all water users in the Basin.

In the 2016 Water Supply and Demand Forecast, consumptive water use estimates were calculated using aggregated annual water use data from USGS Water Use reports (performed every 5 years). From these datasets, it was estimated that 11% of out of stream water use was devoted to residential uses (municipal and self-supplied) in 2005. To project future demands, estimates of anticipated population growth were multiplied by annual per capita water use. Census block info from the OFM were projected forward using logistic growth to provide estimates of population in 2035. Per capita demands were multiplied by the population of each county present in each WRIA, and then summed. Lacking a more sophisticated methodology, consumptive use was estimated by subtracting the mean wastewater returns by county for the years 1985, 1990 and 1995.

While this previous method has adequately served past Forecasts, the need for an improved municipal demand forecast has been a focal point of discussion with the Policy Advisory Group and the State Caucus. Both groups endorsed the shift from annual to monthly or weekly water use data to improve forecasting and expressed interest in improving our understanding of how municipal sector conservation plays a role in changes to water use over time. These new 2021 Forecast results reflect three updates including 1) an improved estimate of population growth, 2) locally derived estimates of monthly municipal and domestic water demand, and 3) refined estimates of indoor and outdoor consumptive water use.

Methods

Population Forecasting

Previous iterations of the CRB Water Supply and Demand Forecast used a logistic growth model to estimate domestic water user population change using 2010 census block data from the WA Office of Financial Management (OFM) for the year 2035. In this 2021 report, population projections are developed using an empirical-based modeling approach that takes advantage of both community- and state-level population forecasting efforts to provide an updated estimate of urban and rural population growth across Eastern Washington. In total, 59 communities with water systems supporting more than 1000 connections were assessed, and projected population estimates for WA CRB counties were taken directly from the OFM.

Data Collection and Methodology

Estimating changes to population size in small areas (e.g., administrative levels below the state level) can be challenging for a number of reasons. Small area boundaries are more likely to change over time and these areas tend to have less data available in less detail, which can decrease the reliability of any population estimates made, particularly when sample sizes are small and variability is large. For these reasons, it can be difficult to apply the same methodologies and tools as used at the larger (e.g. state or national) scales for projecting population change. However, there have been many methodologies developed to deal with the limitations of small area population projections ranging from extrapolation or regression-based methods to component, ratio, or sample-based strategies (Swanson and Tayman, 2012). The strengths and weaknesses of small area population projection methodologies depend in part on the quantity and quality of data available. Based on the available data and the limitations of various small-area methodologies, this report uses a combination of three extrapolation-based methods to derive a mean estimate of population change in small communities in 2040.

While extrapolation methods are relatively simplistic, research suggests that extrapolation provides not only reasonable estimates of population projections for small areas in both the short and long-term, but that estimates tend to be no less accurate than those from more complex population projection models (Armstrong, 1984; Chi, 2009; Smith, 1997). Here, community-level population projections for the years 2030 and 2040 were estimated using: 1) Simple Extrapolation- Linear Estimation, 2) Complex Extrapolation- Logistic Curve Fitting, 3) Ratio Extrapolation- Share of Growth. Extrapolation models vary in their complexity, and while they have a number of weaknesses - including an inability to account for demographic differences- they have relatively small data requirements which means they can be used in cases were limited data preclude the use of more complex projection models (George et al., 2004). The three methods chosen here represent different degrees of complexity, ranging from very simple (linear estimation), to moderately (logistic fitting) and relatively complex (share of growth). In selecting three methods, we are able to compare future projections and derive a mean estimate of 2040 population change.

S*imple Extrapolation- Linear Regression.* While logistic regression is commonly used to estimate population growth at larger scales, to be accurate they also require longer time-series of data (30 yrs or more) than were available for many of the communities sampled here (Punmia et al., 1995). Given the variability in data availability and quality at the community-level, one of the methods chosen for estimating future population change was a simple extrapolation. This method requires minimal data inputs, and can provide reasonable estimates of growth or decline, especially over shorter time periods. Simple Linear Regression (SLR) (Eq 14) was used to create a linear model that minimizes the sum of squares of residuals/error (SSE) for a best fit regression line:

$$E(y) = \beta_o + \beta_1 x \tag{14}$$

where E(y) = is the mean or expected value of y, for a given value of x, β_o = y-intercept population parameter, β_1 = slope population parameter.

Complex Extrapolation- Logistic Curve Fitting. Population projections, particularly for large populations (e.g., national scale) are commonly made using an assumption of logistic growth. To produce accurate results, this method requires more data than a simple linear regression, needing base-period data for more than two dates and requiring assumptions about the growth and carrying capacity of the population center of interest. Greater data input requirements mean that this model is able to cope better with non-linear population change; however, it is fairly mechanistic in its assumptions and thus does not necessarily guarantee that results will be more accurate.

$$P_t = K/(1+(K-P_0)/P_0)e^{-kt}) \tag{15}$$

Where P_t = projected population estimate, P_0 i= initial population value, K = carrying capacity, k = growth rate, and t = time.

Ratio Extrapolation- Share of Growth. Ratio extrapolation methods are commonly used where nested population data exists. The most complex model used here, this method relies on a smaller population area (e.g., city) being part of a larger "parent" area (e.g., county) for which existing future projections are available. The Share of Growth method estimates the population change rather than population size, where it assumes that the share of the change in population size in the smaller area, relative to the parent area, will be the same in the projected time frame as it was during the base period (Eq 16).

$$P_{it} = P_{il} + [((P_{il} - P_{ib})/(P_{jl} - P_{jb}))(P_{jt} - P_{jl})] \quad (16)$$

Here, P_{it} = projection for the small area, P_{il} = small area launch year, $P_{ib\ i}$= small area base year, P_{jl} = parent launch year, $P_{jb\ i}$= parent base year, and P_{jt} = parent projected year.

For this project, community-level population projections were made by collecting existing historical and future forecasted population information from online data sources and reports. These data were then used to project community populations out to the year 2040. Community-level data collection efforts were focused around major municipal water provider systems (Group A providers with >1000 connections) and/or communities that had population estimation reports available through growth management plans or other available population-related resources (n = 59). County population forecasts, which are assumed here to project population change for the rest of the WA CRB, were obtained directly from the OFM. All other communities without major water provider systems or growth management plans are assumed to be accounted for in county-level estimates.

Community Level Estimates

Community-level population data were collected from a variety of sources including: 1) the Washington OFM Small Area Estimates Program, 2) United States Census Bureau city and town intercensal datasets, 3) Annual Water Provider System Plans, and 4) Comprehensive Water System Plans, which are updated approximately every seven years. Data sources for most of the communities evaluated were obtained from the Office of Financial Management's Small Area Estimates Program 2010 Census estimates (https://ofm.wa.gov/washington-data-research/population-demographics/population-estimates/small-area-estimates-program) or their Water System Plans. As the basis for this assessment is to better understand future changes to municipal water demand, data collection effort focused primarily on population projection reports from municipal water providers, with supplemental information coming from city growth management plans, or state or federal census data. In cases where historical and future population estimates were provided, both were collected. For communities where future population projections were unavailable, historical data were used to forecast growth out to the year 2040 as the mean population projections were made using each of the three extrapolation methods detailed above.

County Level Estimates

County-level estimates of population growth for the 18 counties that fall within the CRB were collected directly from the OFM, which provide future forecasts for growth out to the year 2040 and offer low, medium, and high growth scenarios. OFM estimates are made using state population data, in combination with the most recent estimates of fertility, mortality, and net migration (OFM, 2018). Low and high projections are used to provide a range of projection uncertainty, which is generally higher for rapidly growing and small counties. To produce these projections, the OFM used a combination of linear estimation, shift-share, growth-share, and constant-share ratio extrapolation methods, and an average trending decade migration method to estimate county-level population change (OFM, 2018). Data for this report relied on medium-growth estimates for each county made between the years 2010-2040.

Water Demand Forecasting

In this Forecast, we focus on the portion of the CRB that overlaps much of Eastern Washington, including 21 counties and 33 Water Resource Inventory Areas (WRIAs). Home to more than 3.2 million people, this area contains thousands of drinking water provider systems and hundreds of thousands of individually managed groundwater wells used for household drinking water supplies. This analysis focuses on residential water demands within the Washington portion of the CRB, which accounts for approximately 10% of the total water demand within the basin. For the purposes of this study, residential water demands refer to water that is used in or around the home (excluding water used for industrial or commercial purposes), and was divided into two categories. Municipal demands refer to water provided by community water systems that supply groups of customers through a piped network. Here, we limited "municipal" to a subset of the systems defined by the Washington Department of Health as "Group A" systems (serving > 15 connections). Those households supplied by "Group B" municipal systems (serving < 15 connections) and those obtaining water via means other than a water provider system (e.g. privately-owned drinking water well) were lumped as "domestic" water demands due to a lack of spatially-explicit data.

Data Sources

Water demands for the municipal and domestic sectors were estimated from publicly available data. By limiting estimates of municipal water demands to those from large (>1000 connections) Group A water provider systems, information about historical and projected future water use and water rights information could be captured from each system's Comprehensive Water System Plan. The WA Department of Health requires large Group A systems to publish and update their plans every seven years. Many of these plans were available online, however; when they were not on a water provider's website, they were requested from the DOH archive. This assessment relied on the most recently available version of the document for data collection purposes and ranged in publication years from 2000-2020. Out of the 77 large Group A water providers identified, sufficient data was available in these reports (either online or from DOH repositories) for 45 of these cities, which were compiled to represent municipal demands in this Forecast.

Water demand data for all remaining household water users were considered as domestic water use and were estimated from the United States Geological Survey (USGS) Water Use Reports. These reports are issued every five years and provide mean water use information (e.g., surface vs. groundwater use, water use by sector, etc.) at the county level for the entire nation at five-year intervals (Dieter et al., 2018). Data for this assessment came from the 2015 Water Use Report and included reports for per capita (gallons/person/day) water use for domestic self-supplied categories.

Monthly Use Estimates

While some municipal water providers included in this study directly reported monthly water use data, other municipal providers and the USGS reports of domestic water use estimates, occurred at an annual timestep. For those reporting annual water use data, estimates of mean monthly water use were made using the following two assumptions: 1) Municipal and domestic water use within the same county have approximately similar monthly water use patterns. For instances where one or more municipal systems reported monthly use in a given county, the mean percent of water used each month was used to estimate monthly use for any remaining municipal or domestic water uses that only reported annual values. 2) If no monthly water use data are available in a county, municipal and domestic monthly water use was assumed to be equal to the percent of mean monthly water used across all municipal systems reporting monthly data.

Future Estimates of Water Use

Monthly municipal and domestic water use were projected into the future through the year 2040. Estimates of future water use were based on projected population data developed at the city and county level over the given time period of interest (see Population Forecasting). City population projections were calculated using historical information from city comprehensive plans and related comprehensive water system plans. Population projections at the county level were used or quantifying domestic use and were extracted directly from the WA Office of Financial Management census reports (OFM, 2017). Changes in per capita water demands were not factored into this assessment. Rather, future monthly water use was estimated for municipal and domestic water uses by multiplying the relevant city- or county-level populations by the mean historical per capita monthly water use for each population for a given year.

Consumptive Water Use

When considering the impacts of changing water supply and demand in the CRB, it is important to quantify demands in terms of the water that is consumptively used. Consumptive water use is that water which is removed from the environment through processes such as evaporation, transpiration, or consumption by humans, livestock, or plants. In Washington, this term is further clarified through a specific definition that states consumptive use "means a use of water whereby there is a diminishment of the overall amount or quality of water in the water source" (WAC 173-545-030).

The previous CRB Forecast report measured consumptive use by calculating the difference between 2016 water withdrawals and reported return flows from the 1970s-1990s (Shaffer, 2008). In this Forecast, monthly estimates of water use allow for a more detailed assessment of consumptive use in the residential sector through differentiation between indoor and outdoor water use. To approximate indoor vs. outdoor water use, we relied on the minimum month model for estimating outdoor water use (Mini et al., 2014) that assumes water use during winter months is representative of year-round indoor household water use. Here, we used the mean water use data for the months of December, January, and February for quantifying indoor water use. Outdoor water use was assumed to be the remainder of the total water used after subtracting indoor water use. Any negative values produced using this methodology for outdoor water use estimation were changed to a value of 0.

For estimates of domestic consumptive use, this assessment followed guidance from the WA Department of Ecology that assumes household consumptive water use for self-supplied water users (e.g. permit-exempt well users, households with septic systems) is 10% (indoors) or 80% (outdoors) of total water use in a given time period (Culhane and Nazy, 2015). Estimates of municipal consumptive use cannot be made using the same assumptions for domestic consumptive use, where water is assumed to be withdrawn and returned near the place of use. In municipal systems, water is supplied via piped infrastructure and returned to wastewater treatment facilities sometimes far from the actual place of use. To estimate whether municipal water is being consumptively used, information on source water withdrawals and wastewater discharge locations were identified. Source water information (i.e., withdrawal location and type of water source) on a water provider's primary, active water source was obtained from Comprehensive Water System plans or the WA DOH Sentry database (https://fortress.wa.gov/doh/eh/portal/odw/si/Intro.aspx). In locations where groundwater is used for water supply, the WA DOH Sentry database was also used to identify the well depth and likely aquifer system being used. Where a location used multiple water sources and the ratio of water used from each source was not available, the primary source was assumed to be the largest water right volume identified in the WRTS database. Wastewater discharge information was collected from the WA PARIS database (https://ecology.wa.gov/Regulations-Permits/Guidance-technical-assistance/Water-quality-permits-database). Water providers with National Pollution Discharge Elimination System (NPDES) permits indicate discharge to a surface water source, while providers with a Municipal to Ground Surface Water Discharge Permit (SWDP) permit discharge to a groundwater source. Based on the types of wastewater discharge methods used in the study region, it was assumed that groundwater discharges return to the uppermost unconfined aquifers only.

From this information, a set of case assumptions were created to provide a coarse estimate of indoor and outdoor consumptive use in municipal water systems. In this estimate, indoor consumptive use was assumed to be 0 if water was withdrawn and returned to the same source (Li et al, 2017). In the case where water was withdrawn and returned to a different source, consumptive use was assumed to be 100%. The exception is when groundwater withdrawals from an unconfined aquifer were discharged to groundwater, where we assumed groundwater returns similar to those proposed in Culhane and Nazy (2015) of 80%.

TABLE 2. 1 ASSUMPTIONS BASED ON WATER WITHDRAWAL AND WASTEWATER DISCHARGE INFORMATION FOR MUNICIPAL WATER SYSTEMS USING SURFACE WATER (SW) AND/OR GROUNDWATER (GW) IN THE CRB.

Case	Withdrawal (WD)	Discharge (D)	WD and D source	Indoor CU	Outdoor CU
I	SW	SW	same	0%	100%
II	SW	SW	different	100%	100%
III	GW - confined	SW	different	100%	100%
IV	GW - unconfined	SW	different	100%	80%

V	SW	GW	different	100%	100%
VI	GW - confined	GW	same	100%	100%
VII	GW - unconfined	GW	same	0%	80%

Scaling Demand to the WRIA-Level

For the purposes of the Forecast, household water demand data (municipal and domestic) were scaled to the WRIA level to facilitate integrated, basin-wide assessment. In cases where a county or city area spanned one or more WRIA, the partial demand assigned to each WRIA was assumed to be proportional to the percent of the city's or county's land area in each WRIA.

Module 2 – Double Cropping

Introduction

The agricultural practice of double and triple cropping – common in tropical and sub-tropical climates – has the potential to become more widespread in temperate climates due to climate change (Seifert and Lobell, 2015). A current gap in the literature is assessing whether double cropping will increase in regions like the Columbia River Basin (CRB) that grow a diverse array of high-value fruit and vegetable crops. This region constitutes most of the USDA designated Fruitful Rim production region, which accounts for an outsized share of economic returns to agriculture relative to cropland area and healthy food directly consumed by people. Double cropping is already common in parts of California and Arizona. The question is whether the practice will migrate north. There would be several significant implications of this occurring, or not. Greater food production is of course important, especially if it partially offset other negative impacts from climate change (Schlenker and Roberts, 2009). In contrast to rainfed systems, farmers switching from single to double cropping in irrigated systems impose a very direct externality on other farmers by increasing their consumptive use of water from irrigating two crops. When using groundwater this depletes an aquifer faster. In a surface water system, the result is lower streamflow and water availability for downstream irrigators.

There are a few reasons to believe that increased double cropping could increase in the CRB. Irrigation allows farmers to control soil moisture so that temperature is the only exogenous variable limiting earlier planting and later harvesting. Another reason is the diversity of crops gives farmers a lot more flexibility in finding combinations that could be double cropped as is already done in warmer parts of California and Arizona. Lastly, climate change appears to have a much stronger effect on growing season length in the western U.S. than in the East (Kunkel et al., 2004; Kukal and Irmak, 2018).

There were four separate analyses done in regards to double cropping:

1. The objective of one was to empirically examine the relationship between climate and rate of double cropping in irrigated production in the coastal western U.S. where there is a wide range in climatic conditions. While having an adequately warm climate is a necessary condition for double cropping, there is substantial variation across and within regions. For example, Germany and Belgium have similar CI values to Bangladesh and Vietnam (Ray and Foley, 2013). The empirical strategy is to exploit the substantial geographic variation in growing season length and temperature that exists in this region due to its north-south orientation, as well as variation in coastal proximity.

2. Another double cropping analysis used satellite imagery to get a better estimate of current double cropping rates in Washington. The USDA does not specifically create a dataset to measure double cropping so there is a potential for error in using their survey data. Satellites that take images of fields every 1-2 weeks provides a second measure of current double cropping rates.

3. We completed a survey of growers to characterize historical, current and potential future double cropping activities.

4. We estimated the water footprint of a single versus double cropped system using CropSyst.

Relationship between Climate and Double Cropping in the Western U.S.

A warming climate may increase the intensity of heat, or growing degree days at various times of the year, while also lengthening the growing season (Scarpare et al., 2022). The degree to which it does either depends on the region. In the last 50 years, the number of frost free days has increased much more in the western U.S. compared to the eastern half of the country. A potential major implication of this on agriculture is the potential to double or triple crop where only one cropping per year was possible in the past.

Our region of study is five western U.S. states that have significant areas of highly diverse irrigated agriculture and that rely on surface water derived from snowmelt. Parts of this region –

concentrated in California and Arizona – are known to have extensive double cropping. Also, it's north-south axis facilitates exploiting cross-sectional variation in climate for prediction of future cropping trends for the cooler parts of the region, which is important since this report is focused on future conditions for Washington State.

Data

Cropping Intensity

Data for measuring cropping intensity by county for parts of Arizona, California, Oregon, Washington, and Idaho are drawn from the last four waves (2002, 2007, 2012, and 2017) of the Census of Agriculture (USDA NASS). We collected the data using the Census Download Query Tool (www.nass.usda.gov/Quick_Stats/CDQT/). The Tables referenced in the next two paragraphs refer to the Census of Agriculture Tables accessed through this tool, which are updated every 5 years.

The CI denominator – irrigated extent – is the number of acres that could be irrigated. Table 10 (accessed through the Census Download Query Tool) reports the number of irrigated cropland harvested for crops in the relevant Census year, as well as acres irrigated one or more times in the past five years (since the last Census). We use the former because of the use of fallowing within many irrigated crop production rotations. However, this may not matter because we are interested in relative CI across counties. Using the 5-year number would typically lead to a lower CI for all counties. While this value includes the term "harvested", the question pertains to how many acres were used to harvest crops in the relevant Census year. In other words, it reports a value of 1 for a double cropped field.

The CI numerator – total acres of irrigated crops harvested inclusive of double cropping – is not specifically reported in the Census. It must be constructed by summing acres harvested by crop group reported in Tables 25-35 in the Census, accessed through the Census Download Query Tool. Census questions reported in these tables specifically instructs farmers to include the same field twice if it is double cropped. Crop groups are field crops, grasses and legumes, orchards, vegetables, floriculture, Christmas trees, and "other". Wine grapes are included within the orchard crop category. The "other" category includes important specialty crops such as hops, mint, and sweet corn that are mostly irrigated in the area of study. Irrigated acres harvested, the variable of interest for this study, is reported for field crops, grasses and legumes, and "other" crops. No separate irrigated value is reported for vegetables, tree fruit and nuts, berries, and horticulture crops. Since these crops are almost exclusively irrigated in the region of study, we assume the harvested acres reported for each county is all irrigated.

A small, but significant, number of harvested acre values are not reported for disclosure reasons. For field crops, grasses and legumes, and other an assumption has to be made about the percent of the reported acres harvested that is irrigated. In most cases, there is both an irrigated and a total harvested acres value for at least one wave of the Census for a crop group/county. When that is the case, the average of the irrigated percent for all available waves is multiplied by the total harvested acres for the group/county to impute an irrigated harvested value. If the irrigated harvested acres value is missing for all waves of the Census then the state-level irrigated percent is used. The same approach is used for cases of non-reporting due to disclosure. Most are not reported due to disclosure reasons that result from having a small number of farms account for a significant share of crop group area in a county. While many of these values may be small – and thus could be deemed to be effectively zero – there are instances where the unreported number likely constitutes a significant share of total irrigated cropland area in the county. This can be discerned by looking at reported acres in other Census years. This arises when there are only a few farms that produce most of the crop in the county. This is somewhat uncommon for irrigated specialty crops.

There is an unavoidable level of error in using the Census data to estimate CI because it is only observed indirectly. This is less of a concern in major irrigated agricultural counties where the value is relatively unaffected by missing a thousand or so acres, just as an example, in the denominator or numerator. However, there are several counties in the study region that have a small number of irrigated acres where this level of error would significantly affect the CI estimate. Therefore, we focus on counties that have at least some minimum amount of irrigated acres, and adjust the value to make sure results are robust to the exam cut-off. Our main cutoff was set at 15,000 acres. Results were not sensitive to adjusting this threshold up or down by a few thousand acres. The average CI across the four Census waves for each county are shown in Figure 2.1. A map showing the average CI across the four Census waves is shown in Figure 2.2.

Growing Season Length and Temperature

Heat, or temperature, uses the standard growing degree days (GDD) concept commonly applied to explain crop growth. Specifically, it is the temperature weighted sum of time spent between 8 and 32 degrees Celsius (C) during the typical growing season of April 1st to September 30th. Growing season length is the number of days during the calendar year where the minimum temperature was greater than 0 degrees C, which we refer to as frost free days (FFD). Scatter plots showing the overall trend between GDD, FFD and CI, respectively, are shown in Figures 2.3 and 2.4. Figure 2.5 shows a scatter plot between GDD and FFD to demonstrate that the two are not perfectly correlated.

Regression Model

Our empirical approach is a multivariate regression model estimated via ordinary least squares to measure the level of correlation separately between cropping intensity as dependent variable and GDD and FFD as explanatory variables. While GDD and FFD are somewhat correlated – warmer counties tend to have longer growing seasons – they are far from perfectly correlated. A major reason is the influence of coastal climates in Arizona, California, Oregon, and Washington. The moderating effects of the ocean result in cooler summer maximum temperatures and fewer days with frost than more inland counties. Based on findings from previous studies on climate change and agriculture (e.g. Schlenker and Roberts, 2009), there is reason to believe that temperature and growing season length affect cropping intensity in a nonlinear manner. Therefore, we estimate a multivariate regression model to disentangle the effect of GGD and FFD on cropping intensity and specify the model to permit the marginal effect of additional heat or another frost-free day to change as a function of the level of each variable. Additional explanatory variables include the size of the county in terms of total irrigated acres along with a set of dummy variables for the state the county is in and the wave of the census. A natural logarithmic transformation is used for CI, GDD, and FFD to allow for a more flexible non-linear, but still monotonic, relationship between these variables. Results from this regression analysis are discussed in the Legislative Report.

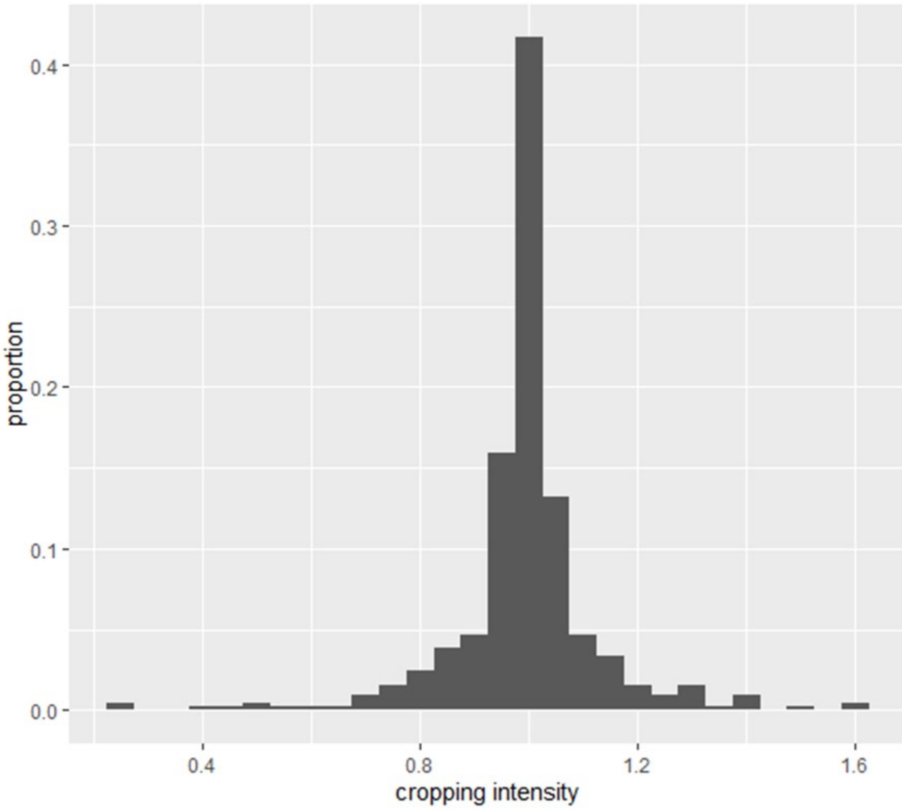


FIGURE 2. 1 HISTOGRAM OF CROPPING INTENSITY FOR ALL COUNTIES IN THE STUDY REGION WITH AT LEAST 15,000 IRRIGATED ACRES ACROSS FOUR WAVES OF THE CENSUS OF AGRICULTURE (2002, 2007, 2012, AND 2017).

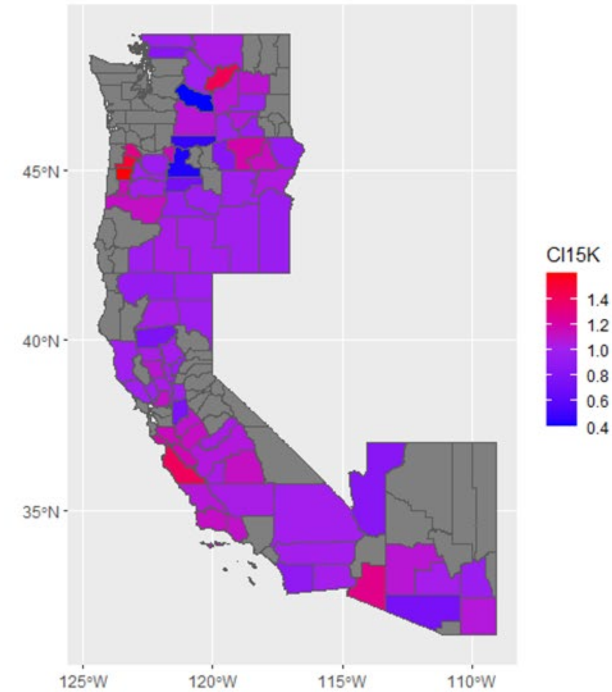


Figure 2. 2 Average value of cropping intensity by county across four waves of the Census of Agriculture.

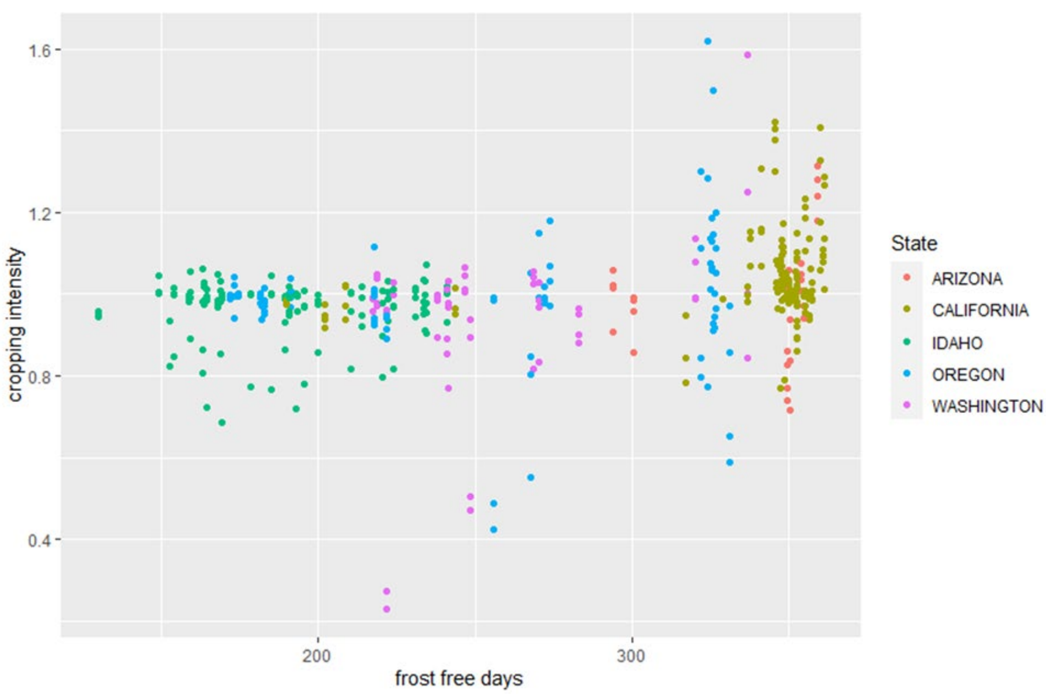


Figure 2. 3 Scatter plot of frost-free days and cropping intensity for all counties and four waves of the Census of Agriculture with color coding by state.

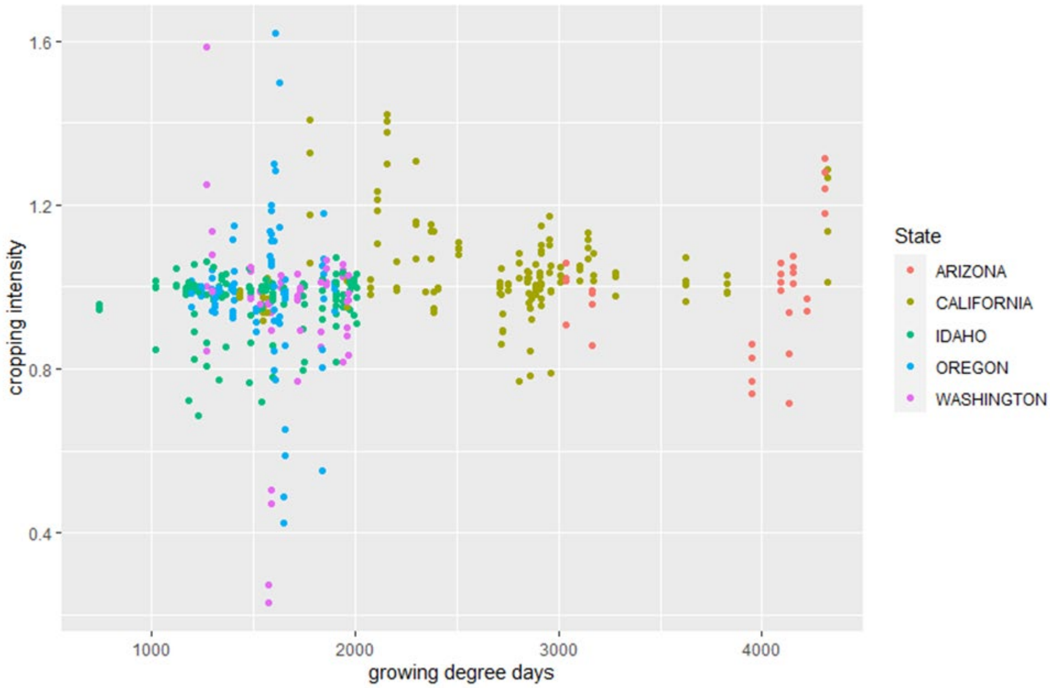


FIGURE 2. 4 SCATTER PLOT OF GROWING DEGREE DAYS AND CROPPING INTENSITY FOR ALL COUNTIES AND FOUR WAVES OF THE CENSUS OF AGRICULTURE WITH COLOR CODING BY STATE.

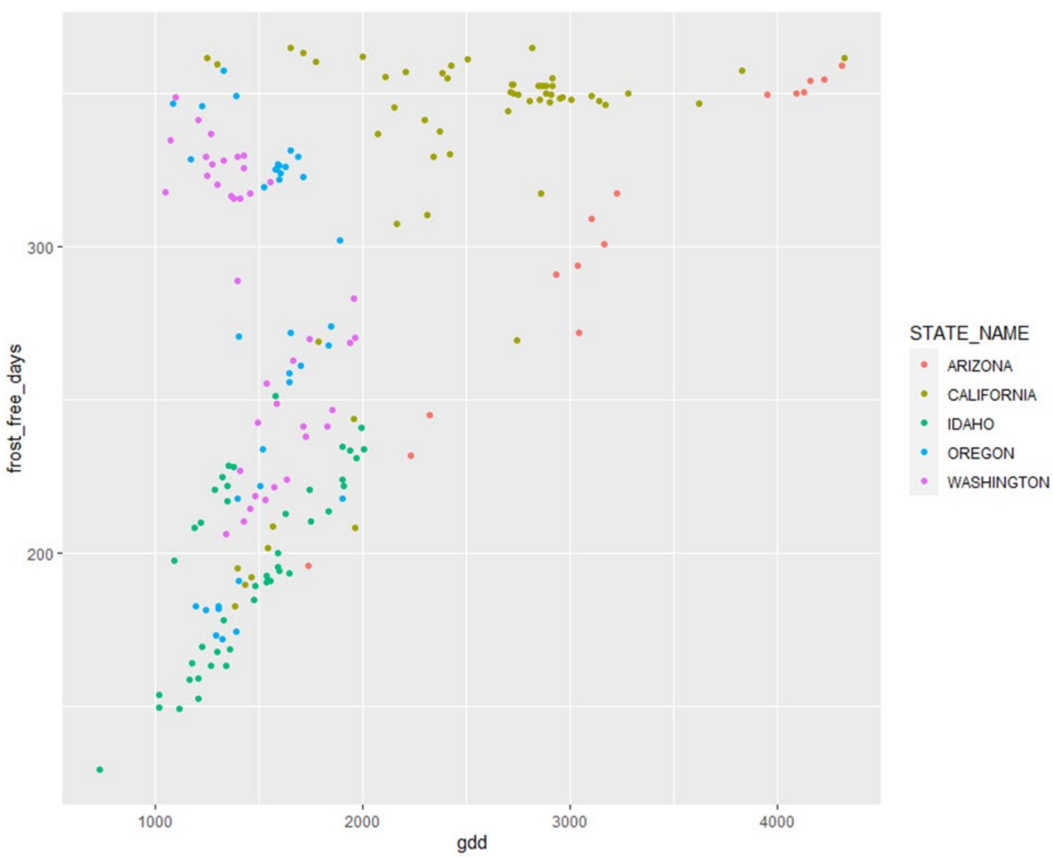


FIGURE 2. 5 SCATTER PLOT OF GROWING DEGREE DAYS AND FROST FREE DAYS.

Current Washington Double Cropping Extent Using Remote Sensing

Prior to 2021, the only available estimate of double cropping extent in Washington State was an estimate of 30,000 acres from the Washington State Department of Agriculture's Agricultural Land use Geodatabase. However, it is known that this information is not comprehensively collected or updated. Hence the available estimate are unreliable and potentially an underestimate. Understanding the potential to utilize satellite imagery to gather evidence for two harvest cycles in a given year as indicative of double cropping, a grant from Washington Water Research Center allowed to estimate current double cropping extent from satellite imagery. We utilized the Sentinel 2 optical data product (10 m spatial resolution with a 3-to-5-day revisit) from the European Space Agency's Copernicus Program's Sentinel mission (Drusch et al. 2012) to develop a time series of vegetation indices, and an empirical model to classify all irrigated annual crop fields in WA State as single cropped or double cropped. We utilized imagery for the time-period 2016 to 2019.

The analysis resulted in a double cropped area estimate in the range of 100,000 to 120,000 acres (3 to 4 times larger than prior estimates). We also conducted a workshop style meeting that included WSDA and WSU Extension personnel and identified the following as some key combinations of double crops for crop simulations (Green peas to sweet corn, green peas to green beans, triticale silage to field corn, timothy to sweet corn, timothy to dry beans, barley hay to field corn, grass seed to buckwheat, and potatoes to buckwheat). Some of these combinations were also highlighted in the response to surveys administered by Aspect Consulting.

Double cropping practice adoption survey administered by Aspect Consulting

Table 2. 2 Survey questions

1. Are you Currently Double Cropping?
If yes to (1) what crop combinations are you using?
2. Have you historically double-cropped?

If yes to (2) what combinations have you used in the past?
3. How long have you been double cropping/how recently have you started?
4. On fields that are double cropped, are there things that are different in terms of cropping systems or management (tillage, irrigation systems)?
5. Is the quantity of water rights available (having enough water to irrigate 2 crops as opposed to one) a limitation to double cropping?
6. If you have more frost free days (earlier start or later end) to the growing season, would you consider more double cropping or cover cropping?
7. Would your ability to double crop be limited by your water right's period of use?
8. If you have a longer and/warmer growing season in the future, and water is not limiting, would you be more likely to expand double cropping or shift to more profitable warm region crops that are not currently grown in WA, but grown in warmer places like CA?
9. Any other comments on this topic you'd like to share with the project team?

We received six survey responses to the questions (see Table 2.2), of which only one respondent indicated that they currently practice double cropping (Peas followed by sweet corn/sileage corn, Timothy followed by sweet corn/sileage corn, Blue grass followed by sweet corn/sileage corn, Wheat followed by buckwheat). Two respondents indicated that water right quantities are a limiting factor to adopting double cropping and three respondents noted that if water were not limiting and the growing season length increases, they would consider double cropping.

Survey responses can be summarized as indicating that current double cropping is limited due to high availability of land and limited availability of water rights quantity, suggesting that lack of water availability will likely limit the expansion of double cropping as growing seasons lengthen. The small respondent pool might not be representative of the grower population. Therefore, the responses should be interpreted with caution.

Quantification of Irrigation Water Demand under Double Cropping

Approach

Based on Sentinel 2 satellite imagery, seven double cropping combinations were selected (Table 2.3); being their parameterization/calibration performed in ten selected grids spread in six WRIAs: 32 Walla Walla, 33 Lower Snake, 36 Esquatzel Coulee, 41 Lower Crab, 37 Lower Yakima, and 31 Rock Glad; all located in Eastern WA (Figure 2.6).

Using the VIC-CropSyst model v3.0, the average evapotranspiration ratio between double cropping over the average sum of both single crop evapotranspiration, for all ten grids spreading throughout the entire historical period was estimated at ~44% as follows:

$$ET_{ratio} = \frac{\sum_{i=1}^{10} \left(ET_{double\ cropping}\right)}{\sum_{i=1}^{10} \left(ET_{single\ crop\ 1} + ET_{single\ crop\ 2}\right)} = 1.44 \qquad (17)$$

Therefore, our estimates suggest that the annual water demand for an acre of land that is double cropped is 44% greater than the demand if that same acre has a single crop. Next step, the single crop water demand of 1.37 acre-ft/acre was estimated as follows:

```
Avg_irrigation_demand_single_crops (acre-ft/acre) = sum(WIRA_1_DoubleCropAcre * WIRA_1_SingleCrop_1_Acre * WIRA_1_IrrigationDemand_SingleCrop_1,
                                                   WIRA_1_DoubleCropAcre * WIRA_1_SingleCrop_2_Acre * WIRA_1_IrrigationDemand_SingleCrop_2,
                                                   ...WIRA_i_DoubleCropAcre * WIRA_i_SingleCrop_j_Acre * WIRA_i_IrrigationDemand_SingleCrop_j,
                                                   ...WIRA_m_DoubleCropAcre * WIRA_m_SingleCrop_n_Acre * WIRA_m_IrrigationDemand_SingleCrop_n)
                                                 / sum(WIRA_i_DoubleCropAcre * WIRA_i_SingleCrop_j_Acre)
```

where *m* is the total number of WRIAs, *n* is the total number of single crops and, WRIA_*i*_IrrigationDemand_SingleCrop_*j* (acre-ft/acre) = irrigation demand of single crop *j* in WRIA *i*.

The average evapotranspiration ratio between double cropping over the average of the sum of both single crop evapotranspiration, i.e., 1.37 acre-ft/acre was multiplied by the average evapotranspiration ratio between double cropping over the average of the sum of both single crop evapotranspiration, i.e., 1.44; yielding the average irrigation demand of double cropping of 1.97 acre-ft/acre. The average irrigation demand of double cropping (1.97 acre-ft/acre) was multiplied by the ~120,976 acres, i.e., the current double cropping irrigated acres estimated in Eastern Washington for 2016, 2017 and 2018. Therefore, applying these water demand estimates to the acres that are currently double cropped suggests that our historical water demand values underestimate demand by ~238,323 acre-ft per year.

TABLE 2. 3 DOUBLE CROPPING NAME AND CODE USED IN THIS PROJECT.

Double cropping name	Double cropping code
Green peas - Sweet corn	4014
Grass hay - Dry beans	4015
Grass hay - Sweet corn	4016
Winter wheat - Buckwheat	4017
Potato - Buckwheat	4018
Corn - Triticalewinter	4023
Sod seed grass - Buckwheat	4027

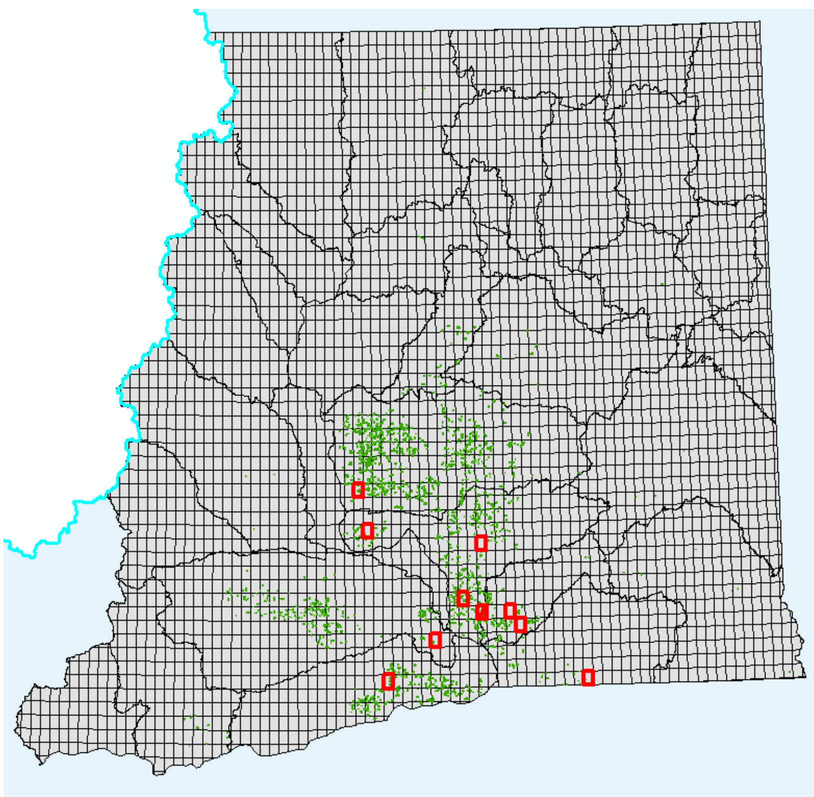


FIGURE 2. 6 EASTERN WASHINGTON STATE GRIDS SELECTION USED FOR DOUBLE CROPPING IRRIGATION WATER DEMAND UNDER DOUBLE CROPPING.

Module 3 – Seniority-Based Water Rights Interruption

Introduction

Washington State water law stipulates three forms of curtailment in the event of water shortage. The first two, curtailment in favor of instream flows and Yakima basin prorationing, are evaluated in the main 2021 Forecast report. Here we present a pilot study that focuses on the third form of curtailment, priority water calls. If senior water entitlements cannot be satisfied from the available streamflow, senior water right holders can call upon diverters with junior priority to temporarily suspend water withdrawals so that sufficient water flows to their points of diversion. Water calls are enforced by basin water masters or stream patrolmen who are assigned either to specific streams or to an entire basin. Water rights can be shutoff anywhere from a few days to weeks or months at a time, depending on flow conditions for the year. A water right is typically assigned to a class based on its priority date, which is printed on the water right document. The lower the class, the more senior the water right. In times of water shortage, calls are made on classes of water rights, with more junior (higher) classes curtailed before more senior (lower) classes. Most stream adjudications in Washington do not allow exceptions for junior irrigators who are situated along the stream such that curtailing their rights would have no effect on satisfying the needs of senior water users. However, some stream adjudications, of which Touchet is one, do exempt some junior irrigators from curtailment. For this module we assume that senior water users can only call on upstream junior water users.

The frequency of water calls and the quantities of water they affect are critical to our understanding of how water scarcity impacts water users both historically and in the future. Unfortunately, the importance of priority water calls to state-wide curtailment has largely gone unexamined due to lack of systematic record-keeping of water calls in a form that can be accessed electronically. Therefore, this module is intended to identify data needs and to provide a basic framework for building a more complete and useful module for the 2026 Forecast.

In preparation for the 2021 Forecast, a subset of the surface water modeling team at Washington State University met in December 2019 with water masters from Yakima, Okanogan, Methow, and Walla Walla basins at Ecology's Central Regional Office in Union Gap, WA. The purpose of the meeting was to elicit information about priority calls. The water masters were shown maps of each basin divided into subbasins and asked to indicate which streams are regulated. From this exercise, we developed a list of high priority streams to be the focus of a water call module. Following the meeting, we sent an email survey to water masters requesting detailed records of which classes of water right and when during the season those classes were curtailed. Only two responses were received, the first from the stream patrolman for Wenas Creek in Lower Yakima, and the second from the water master for Walla Walla. The data for Wenas Creek covered only the years 2019-2020. The Walla Walla data were more complete, with records spanning from 2003-2020. Curtailment in Walla Walla is complicated by the fact that half the watershed lies within Oregon state boundaries, and water rights there are under different jurisdiction. Owing both to data limitations and interstate water regulation, we focused our analysis on the Touchet River within the Washington portion of the Walla Walla basin. The objectives of the Touchet River pilot study were, under both historical and future climate conditions, to:

i. estimate water call frequency
ii. quantify curtailable irrigation demand by water right class, and
iii. estimate the water right class that would need to be curtailed to meet the needs of senior water rights.

Results from this module were then used to draw inferences about the contribution of water priority calls on the Touchet River to state-wide water right curtailment.

Methods

Touchet River Streamflow Bias Correction

Curtailment occurs when the water supply is insufficient to meet the needs of all water users. The first step in generating water supply input for the module was to create Touchet River naturalized flows. First, we routed VIC-simulated streamflow to the stream gauges at Bolles Rd., downstream of Coppei Creek, and Cummins Rd., near the mouth of the Touchet River (Fig. 2.7). Next, we added irrigation demands along the Touchet, simulated by VIC-CropSyst, back to the gauge flows. This process resulted in naturalized flow at the Cummins gauge over the period 2003-2015 and at the Bolles gauge over the period 2007-2015. We then bias-corrected the VIC-routed streamflow to the naturalized flows using the same bias-correction methodology previously reported (see the *Streamflow bias correction* sub-section under the *Modelling Water Supply* heading).

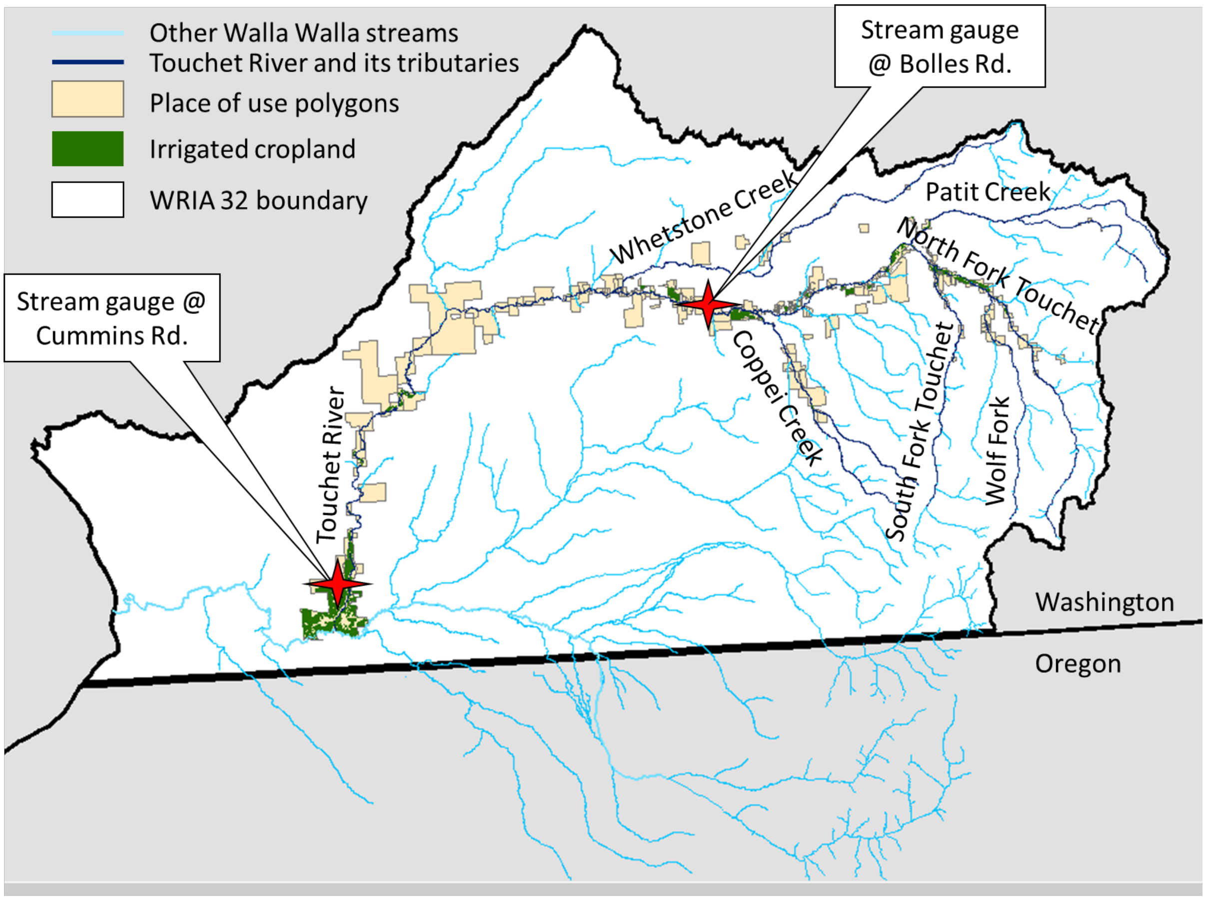


FIGURE 2. 7 STUDY AREA FOR THE TOUCHET RIVER WATER CALL CURTAILMENT MODULE. THE DARK BLUE LABELED STREAMS DELINEATE THE TOUCHET RIVER AND ITS TRIBUTARIES. THE RIVER DRAINS A PORTION OF WRIA 32 (WALLA WALLA) AND FLOWS INTO THE WALLA WALLA RIVER BELOW THE CUMMINS RD GAUGE.

Curtailment frequency

Curtailment frequency indicates how common it is for one or more classes of water right to be curtailed in a given week of the year. Historical curtailment frequencies for the period 2003-2020 were obtained from the Walla Walla water master. These data included the dates when water was shut off and turned back on, sometimes multiple times over the course of an irrigation season. When curtailment does occur, the call is normally made by the Touchet Eastside and Westside Irrigation District, which is a class 13 right near the Cummins gauge. This call typically comes when the flow at the Bolles gauge drops below 30 cfs (personal communication).

We used historical modified flow (bias-corrected historical flow with demands extracted) to identify a reasonable set of streamflow thresholds at the Cummins and Bolles gauges for triggering water calls at a weekly time step. A water call is triggered in the model whenever the following criterion is met:

$$Q_{mod} < Q_{min}$$

where Q_{mod} is modified flow (cfs) averaged over a week, and Q_{min} is the streamflow threshold. Threshold performance was evaluated by comparing the occurrence of water calls predicted by the threshold criterion with the observed occurrence of water calls. From this comparison, we calculated the rates of successfully identifying weeks with (true positivity rate) and without (true negativity rate) water calls (Eqs. 18-19). A sample calculation of threshold performance is given in Table 2.4, where the true positivity is 0.86 (6/7) and true negativity is 0.73 (8/11). After finding a reasonable set of thresholds, we applied them with future climate forcing to estimate future curtailment frequency. The frequency is reported in terms of the number of years out of 30 for which a water call is made in a given week of the year. The 30-yr time periods are consistent with all other sections of the 2021 Forecast, i.e. 1986-2015 for GridMet Historical, 1976-2005 for GCM historical, and 2026-2055 for GCM future.

$$\text{True positivity} = \frac{\sum(\text{Predicited=1 and Observed=1})}{\sum \text{Oberved=1}} \quad (18)$$

$$\text{True negativity} = \frac{\sum(\text{Predicted=0 and Observed=0})}{\sum \text{Observed=0}} \quad (19)$$

TABLE 2. 4 SAMPLE CALCULATION OF THRESHOLD PERFORMANCE DURING THE 2006 IRRIGATION SEASON USING A THRESHOLD OF 12 CFS.

2006 Irrigation Season	Q_{mod} (cfs)	Predicted Curtailment (Q_{min} = 12 cfs)	Observed Curtailment	Prediction Performance
5/28—6/3	286	0	0	True negative
6/4—6/10	111	0	0	True negative
6/11—6/17	312	0	0	True negative
6/18—6/24	115	0	0	True negative
6/25—7/1	68	0	0	True negative
7/2—7/8	53	0	0	True negative
7/9—7/15	1	1	0	False positive
7/16—7/22	0	1	0	False positive
7/23—7/29	8	1	0	False positive
7/30—8/5	20	0	0	True negative
8/6—8/12	7	1	1	True positive
8/13—8/19	6	1	1	True positive
8/20/2006	9	1	1	True positive
8/27/2006	0	1	1	True positive
9/3/2006	0	1	1	True positive
9/10/2006	11	1	1	True positive
9/17/2006	23	0	1	False negative
9/24/2006	36	0	0	True negative

Curtailable Water Demand Volume

The annual quantity of water that can be curtailed by class was determined by two independent methods. The first used the annual water quantities (acre-feet / yr) printed on water right documents accessed from Ecology's water rights tracking system (WRTS). The second used a combination of water right place-of-use polygons from the Geographic Water Information System (GWIS), the 2018 WSDA cropland data layer, and simulated irrigation demands from VIC-CropSyst. Both methods required the points of diversion to be mapped by stream position. This involved identifying all water rights located upstream of each right. The Touchet basin observes elements of the futile call doctrine (personal communication), which states that a junior water right cannot be called if doing so would be of no benefit to senior water users. For this exercise, we took this to mean that only junior rights upstream of a senior could be curtailed. The mapping process was carried out by plotting points of diversion along the Touchet, including its tributaries, and manually recording every upstream point for each downstream point. Annual quantity, irrigated area, and priority date attributes from the WRTS database were joined to points of diversion based on the document ID field (WR_DOC_ID). The class of each water right was determined from a crosswalk between class and priority date provided by the Walla Walla water master. The cumulative sum of curtailable water volume for class *i* up to the most senior class *j* was computed as:

$$\mathrm{Curtail}_{\mathrm{Cum}}(\mathrm{j}) = \sum_{\mathrm{i=j}}^{\mathrm{i=64}} \mathrm{V_i} \qquad (20)$$

where $\mathrm{Curtail}_{\mathrm{Cum}}$ is the cumulative curtailable water volume for classes equal or junior to *j*, and $\mathrm{V_i}$ is the total curtailable water volume for all water rights in class *i*. In accordance with futile call, a water right was considered curtailable only if there was one or more downstream rights senior to that right. Some rights have multiple points of diversion. In that case the water right was considered curtailable if the conditions for curtailment were met for any one of its diversion points.

In the quantification method based on WRTS, $\mathrm{V_i}$ was determined by summing the documented annual water quantities for all curtailable water rights in class *i*. In the second quantification method, $\mathrm{V_i}$ was calculated as the crop-specific, area-weighted irrigation depth simulated with VIC-CropSyst (d_c) multiplied by crop area (A_c) for all crops served by water rights of class *i*.

$$\mathrm{V(i)} = \sum \mathrm{A_c(i)} \cdot \mathrm{d_c(i)} \qquad (21)$$

The cropland area associated with each water right was determined from the intersection of the 2018 WSDA cropland data layer and the place-of-use polygons (from GWIS) for irrigation water rights along the Touchet River. The class of water right corresponding with each field was determined by matching the water right document ID from the place-of-use layer with the water right attributes from WRTS. The stream position of each field was determined from the location of point(s) of diversion corresponding to the place of use.

The VIC-CropSyst quantification method was used to estimate the spatial and temporal variability of curtailable demand under both historical and future climate conditions. We calculated $\mathrm{Curtail}_{\mathrm{Cum}}(\mathrm{j})$ at weekly intervals over the course of the irrigation season for three locations along the Touchet River: the stream gauge at Bolles Rd., the stream gauge at Cummins Rd., and a location just upstream of the confluence of the North and South Fork Touchet Rivers. The weekly irrigation volumes were converted to an average flow rate (cfs) to give the weekly curtailable irrigation demand using the conversion factor of 1 cfs = 13.884 acre-feet / week. The curtailable irrigation demand represents forgone water withdrawals if classes *j* and junior are curtailed.

Change in Curtailed Water Right Class

Climate-induced changes in VIC-CropSyst modified flows are expected to cause changes to the classes of water rights curtailed to satisfy all senior water rights. We calculated the 30th, 20th, and 10th percentiles of modified flow by week of the growing season, under future and historical climate conditions. We then calculated the streamflow deficit as the difference between the top-performing, modified-flow threshold and the modified flow from each quantile. Finally, we used the curtailable irrigation demand values calculated according to section 2.3 to determine the most senior water right class that would need to be curtailed to overcome the deficit.

Results

Curtailment Frequency

The best-performing streamflow thresholds for observed gauge flow among the tested ranges were 4 cfs for the Cummins Rd. gauge, with a 62% true positivity rate and a 93% true negativity rate, and 35 cfs for the Bolles Rd. gauge, with an 85% true positivity rate and an 84% true negativity rate. The 35 cfs threshold is close to the threshold of 30 cfs indicated by the water master; however, the success rates of 30 cfs were 70% and 89% for positive and negative identification, respectively (see Table 2.5 for comparison). It should be noted that large amounts of flow data are missing prior to 2007 from the Bolles Rd. gauge. To compensate, we filled the missing data using data from the Cummins gauge. As a result, there was a relatively high degree of uncertainty in flow at the Bolles gauge from 2003 to 2006 over which 29 of the 47 weeks of curtailment were observed. The close relationship existing between streamflow at gauged locations and observed water calls is significant because it indicates human decision-making (e.g. a senior irrigator making a call and that call actually being enforced) closely follows measured streamflow. Using thresholds to predict future water calls was therefore a reasonable approach.

When we applied the same threshold method to the VIC-CropSyst modified flow, water calls were correctly identified most often using a 10 cfs threshold at the Cummins gauge, for which the success rates were 62% and 72% for positive and negative identification, respectively. The Cummins thresholds generally performed better than the Bolles thresholds. A potential reason for this is that a longer record of observed streamflow was available for reconstructing naturalized flow at the Cummins gauge, which is expected to make the bias-corrected streamflow data more reliable. Curtailment frequencies obtained under eight streamflow thresholds and both historical and future climate conditions are shown in Fig. 2.8. For simulated streamflow with historical climate forcing at the Cummins gauge (Fig. 2.8a, c, e, and g), the maximum July through September frequencies ranged from 9 to 17 years out of 30 for thresholds of 4 cfs to 12 cfs. At the Bolles gauge (Fig. 2.8b, d, f, and h), the corresponding range was 5 to 21 years out of 30 for thresholds of 30 to 45 cfs. The higher the threshold, the greater the frequency because the streamflow was more likely to dip beneath the threshold. In general, from week to week the future climate projections of curtailment frequency were slightly greater than curtailment with historical climate. The future-climate, July-through-September maximum frequencies were 9 to 17 years out of 30 at the Cummins gauge and 5 to 25 years out of 30 at the Bolles gauge.

Table 2. 5 Rate of correct identification of Touchet River water calls. The true positivity rate is the rate at which observed water call events at weekly intervals are correctly predicted by streamflow dropping below the threshold, and the true negativity rate is the rate at which lack of observed water call events is correctly predicted using the threshold. Rows are highlighted to indicate the best-performing thresholds using observed (gauge) flows at Cummins Rd. and Bolles Rd. gauges, and the best overall threshold using simulated flows.

Gauge	Flow Type	Threshold	True positivity rate (N=47)	True negativity rate (N=124)
Cummins	Gauge flow	4 cfs	0.617	0.927
Cummins	Gauge flow	6 cfs	0.851	0.681
Cummins	Gauge flow	10 cfs	0.936	0.426
Cummins	Gauge flow	12 cfs	0.957	0.234
Cummins	Gauge flow	15 cfs	0.979	0.000
Bolles	Gauge flow	30 cfs	0.702	0.887
Bolles	Gauge flow	35 cfs	0.851	0.839
Bolles	Gauge flow	40 cfs	0.915	0.734
Bolles	Gauge flow	45 cfs	0.979	0.516
Bolles	Gauge flow	50 cfs	1.000	0.363
Cummins	VIC-CropSyst modified	4 cfs	0.340	0.855
Cummins	VIC-CropSyst modified	6 cfs	0.426	0.823
Cummins	VIC-CropSyst modified	10 cfs	0.617	0.718
Cummins	VIC-CropSyst modified	12 cfs	0.681	0.653
Cummins	VIC-CropSyst modified	15 cfs	0.745	0.573
Bolles	VIC-CropSyst modified	30 cfs	0.255	0.952
Bolles	VIC-CropSyst modified	35 cfs	0.340	0.879
Bolles	VIC-CropSyst modified	40 cfs	0.404	0.798
Bolles	VIC-CropSyst modified	45 cfs	0.638	0.597
Bolles	VIC-CropSyst modified	50 cfs	0.851	0.452

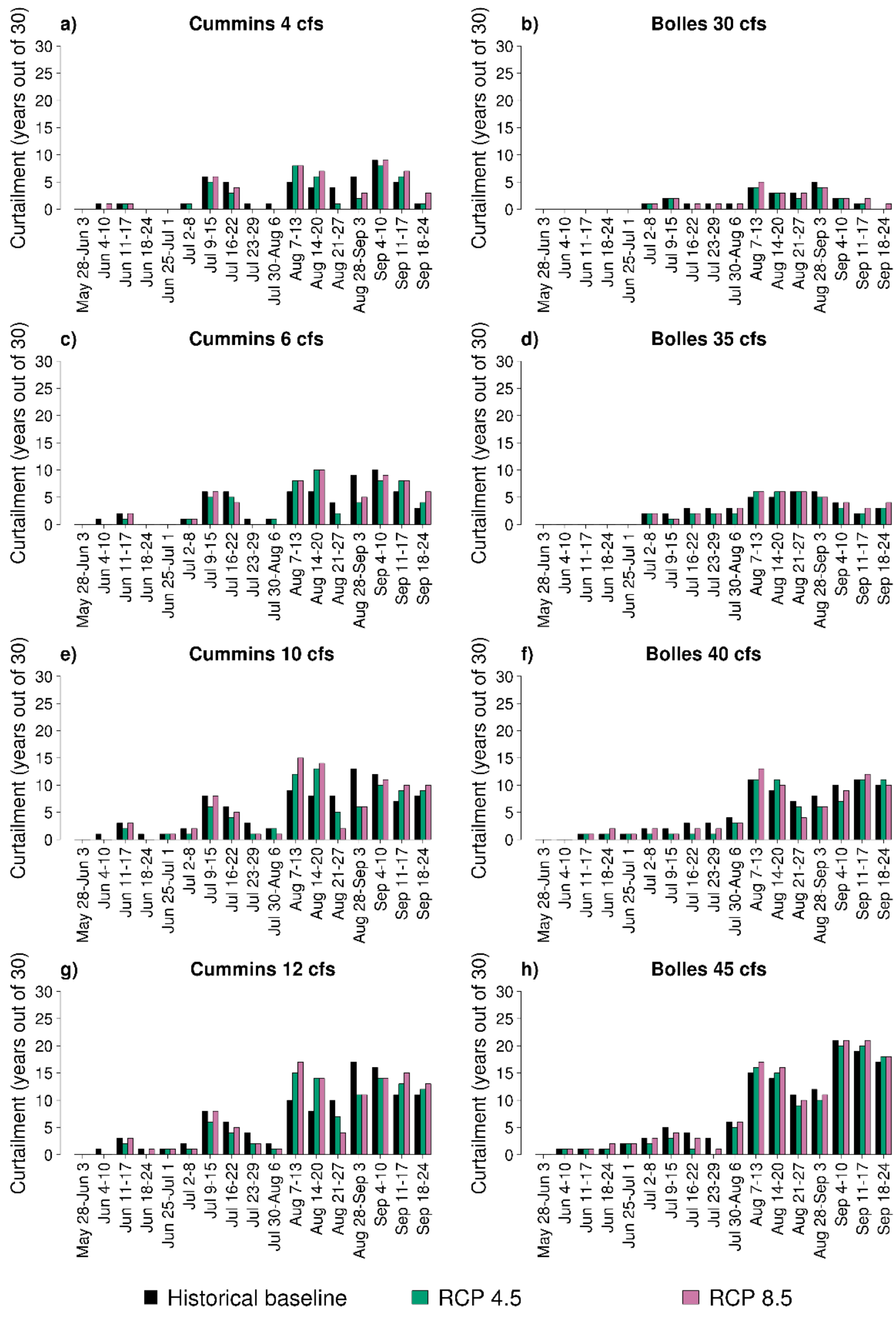


FIGURE 2. 8 FREQUENCY OF WATER CALLS ON THE TOUCHET RIVER FOR A RANGE OF VIC-CROPSYST MODIFIED-FLOW THRESHOLDS SET AT THE CUMMINS RD. (A, C, E, G) AND BOLLES RD. (B, D, F, H) STREAM GAUGES. THE BLACK BARS GIVE FREQUENCIES USING GRIDMET HISTORICAL CLIMATE DATA OVER THE PERIOD (1986-2015), THE GREEN BARS SHOW THE MEDIAN CURTAILMENT FREQUENCIES OBTAINED FROM 17 CLIMATE GCMS UNDER THE RCP 4.5 EMISSIONS PATHWAY OVER THE PERIOD 2026-2055, AND THE PINK BARS SHOW THE SAME FOR THE RCP 8.5 EMISSIONS PATHWAY.

Curtailable Irrigated Area and Annual Water Quantity

Approximations of annual water quantity and irrigated area for curtailable water rights were dramatically greater when using the quantities printed on water right documents. There are two primary causes of this. First, it could be that some water rights were historically perfected, but the irrigated area printed on the water right documents do not reflect the area of crop currently irrigated. For example, there are some place-of-use polygons that contain no cropland either irrigated or non-irrigated. The comparison of irrigated area obtained from both methods is shown in Fig. 2.9b. The second cause for differences in water quantities is that the CropSyst irrigation demands, typically less than 2 acre-ft/acre, tend to be much less than the water duty assumed in water appropriations, which are up to 6 acre-ft/acre. These large historical water duties were assigned when inefficient irrigation methods, like flood irrigation methods, were in common use. Additionally, CropSyst-estimated irrigation demands represent ideal demands, while actual irrigation applications are not typically optimized. Lastly, unlike other areas, several Walla Walla water rights authorize year-round water use -- a practice that CropSyst does not simulate. The combined result of larger water duties with greater cropland area was that annual quantities estimated from water entitlements were about 12x those estimated from the WSDA cropland data layer in combination with VIC-CropSyst (Fig. 2.9a).

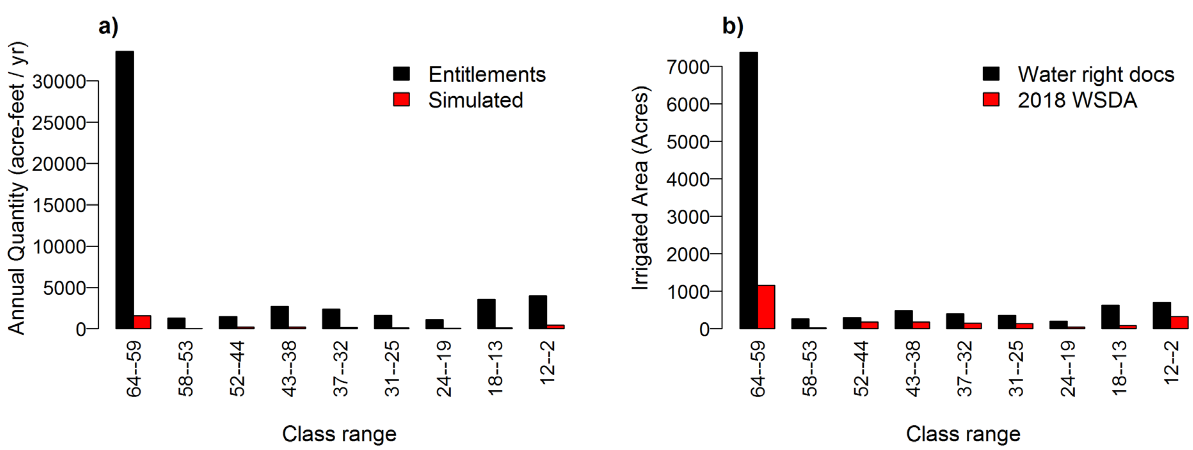


FIGURE 2. 9 COMPARISON OF ANNUAL CURTAILABLE QUANTITY (A) AND IRRIGATED AREA (B) FOR ALL OF TOUCHET RIVER AND ITS TRIBUTARIES BY WATER RIGHT CLASS. THE BLACK BARS GIVE THE ESTIMATE CALCULATED FROM THE 2018 WSDA CROPLAND DATA LAYER COMBINED WITH IRRIGATION DEMANDS FROM VIC-CROPSYST. A SET OF BARS IS SHOWN FOR EACH RANGE OF CLASSES, WITH THE HIGHER NUMBER INDICATING THE MOST JUNIOR CLASS IN THAT RANGE AND THE LOWER NUMBER INDICATING THE MOST SENIOR CLASS IN THAT RANGE.

Spatial and Temporal Variability of Curtailable Demand

The total quantity of water withdrawals impacted by a water call depends on both the stream position and the class of the right making the call. The greatest possible impact will come from a class 1 (most senior) water right positioned far downstream because it maximizes the number of upstream water rights that can be curtailed. Water withdrawals foregone by junior water rights augment river flow to the point of withdrawal by the calling senior water right. Depending on the quantity of foregone withdrawals compared to withdrawals by the calling right, downstream flows might also be augmented if the calling right can be satisfied with less than the total quantity of curtailed water. On the Touchet River, the majority of calls come from the Touchet Eastside and Westside Irrigation District, which diverts water near the Cummins gauge. The District has a class 13 water right that authorizes 8704 acre-feet of water per year. It can call on all upstream rights of class 14 and junior. Calls from the District have a greater impact on streamflow than any other water right owing to its downstream positioning and its relatively high priority. Because irrigation demands vary considerably over the irrigation season, a call placed later in the season when irrigation withdrawals are smaller will have a smaller effect on streamflow in terms of magnitude than a call placed when crop water requirements are at their peak. Figure 2.10 shows how the curtailable water demand varies by stream position, water right class, time of year, and climate.

The central plot in Fig. 2.10 shows points of diversion color-coded by water right class range. Three stream positions are highlighted. In order of downstream to upstream, these are: the gauge at Cummins Rd., the gauge at Bolles Rd., and at a point just downstream of the confluence of the North and South Fork Touchet Rivers with the mainstem Touchet. Under historical climate conditions, the curtailable demand peaked at 20 cfs, 12 cfs, and 7 cfs for water rights junior to class 13 upstream of Cummins, Bolles, and North/South Fork Touchet, respectively (Fig. 2.10a-c). Under future climate conditions, the corresponding peak demands increased to 22 cfs, 14 cfs, and 9 cfs (Fig. 2.10d-f). The difference between future and historical curtailable demands was most pronounced during the month of August (see Fig. 2.10g-i). A couple of interesting trends can be noted from these three plots. First, future irrigation demand was greater than historical during the month of June. This was due to the accelerated crop growth of annual crops under higher temperatures. After irrigation demand of annual crops peaked, typically in June, demand for the remainder of the irrigation season was controlled by hay and perennial crops. Since hay crops are harvested multiple times in a growing season, future-climate demands alternated between greater and less than historical-climate demands every 2-3 weeks, as the cycle of clipping and growing continued at different rates to the end of the season. Therefore, while there was a small difference between total curtailable demand over the course of the growing season, with cumulative demands somewhat greater under future than historical climate forcing, the main difference in curtailable demand was in the demand timing.

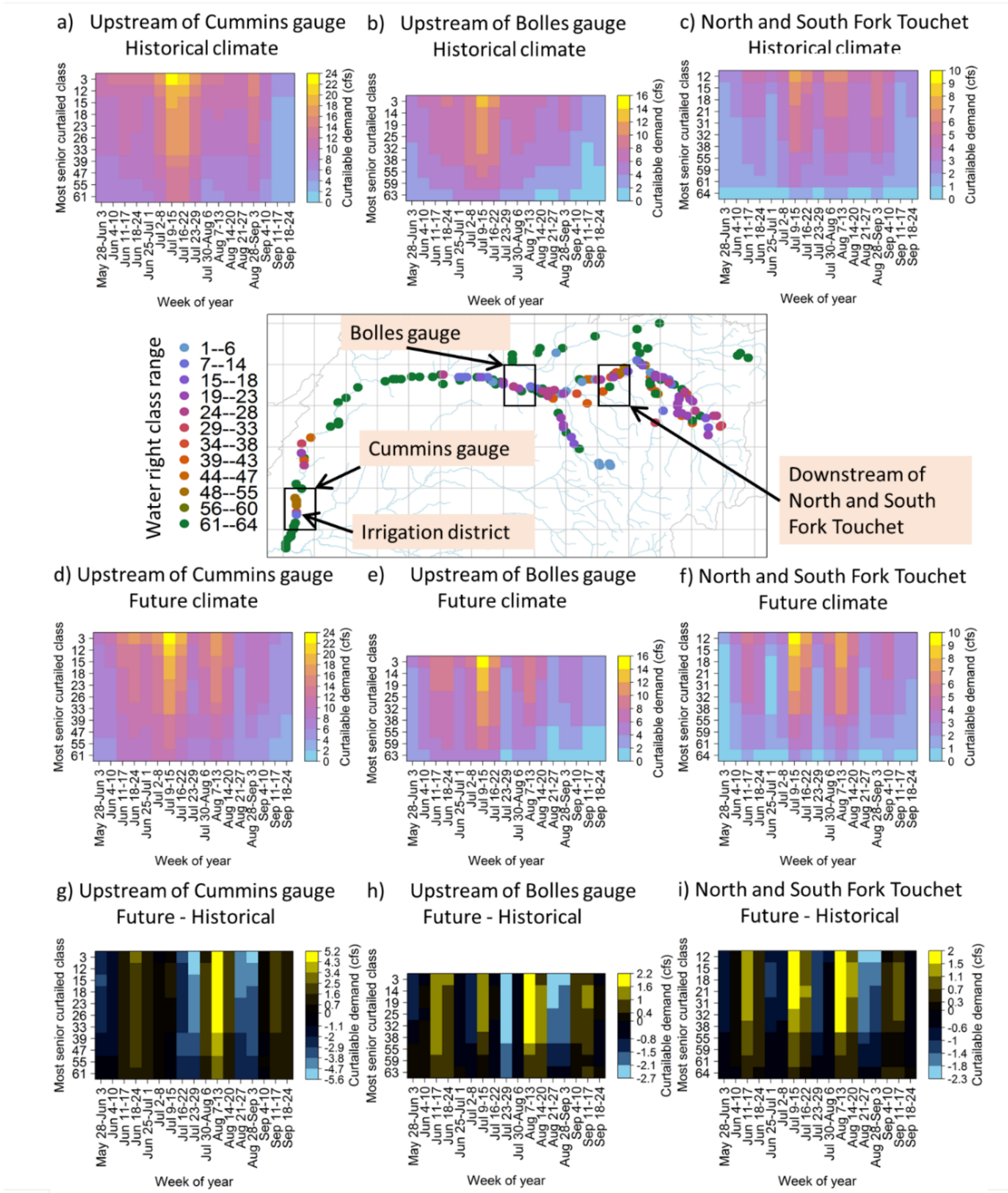


FIGURE 2. 10 CURTAILABLE IRRIGATION DEMAND ON THE TOUCHET RIVER BY CLASS AND WEEK OF YEAR UPSTREAM OF THREE LOCATIONS UNDER HISTORICAL (A-C) AND FUTURE (D-F) CLIMATE CONDITIONS, AND THE DIFFERENCE BETWEEN FUTURE AND HISTORICAL CLIMATE SIMULATIONS (G-I). THE LIGHT BLUE SHADING IN FIGS. G-I INDICATE TIME OF YEAR AND CLASSES WHERE CURTAILABLE DEMAND IS DECREASING IN THE FUTURE AND THE LIGHT YELLOW INDICATES THAT CURTAILABLE DEMAND IS INCREASING IN THE FUTURE. BLACK COLORATION SIGNIFIES NO CHANGE IN DEMAND BETWEEN HISTORICAL AND FUTURE CLIMATE. THE VERTICAL PLOT AXES GIVE THE CURTAILABLE IRRIGATION DEMAND OF RIGHTS EQUAL OR JUNIOR TO THE INDICATED CLASS DESIGNATION. SIMULATIONS WITH HISTORICAL CLIMATE FORCING USE THE 30-YEAR PERIOD 1986-2015 AND SIMULATIONS UNDER FUTURE CLIMATE USE THE MEDIAN OF 34 CLIMATE SCENARIOS: 17 GCMS X 2 RCP EMISSIONS PATHWAYS, OVER THE 30-YEAR PERIOD 2026-2055.

Change in Curtailed Classes in Response to Climate Change

The combined influence of climate on irrigation demand and water supply led to a small difference in modified flow simulated at the Cummins Rd. gauge (Fig. 2.11a, c, and e). However, even small differences in flow beneath the 10 cfs threshold sometimes resulted in large differences in curtailed classes when curtailing only class 64 rights was insufficient (Fig. 2.11b, d, and f). This is because the majority of curtailable volume comes from class 64 (about 61%), with all the remaining classes accounting for 39%. The greatest number of classes needed to be curtailed during the month of September, when both the flow deficits were large and the curtailable demands were low.

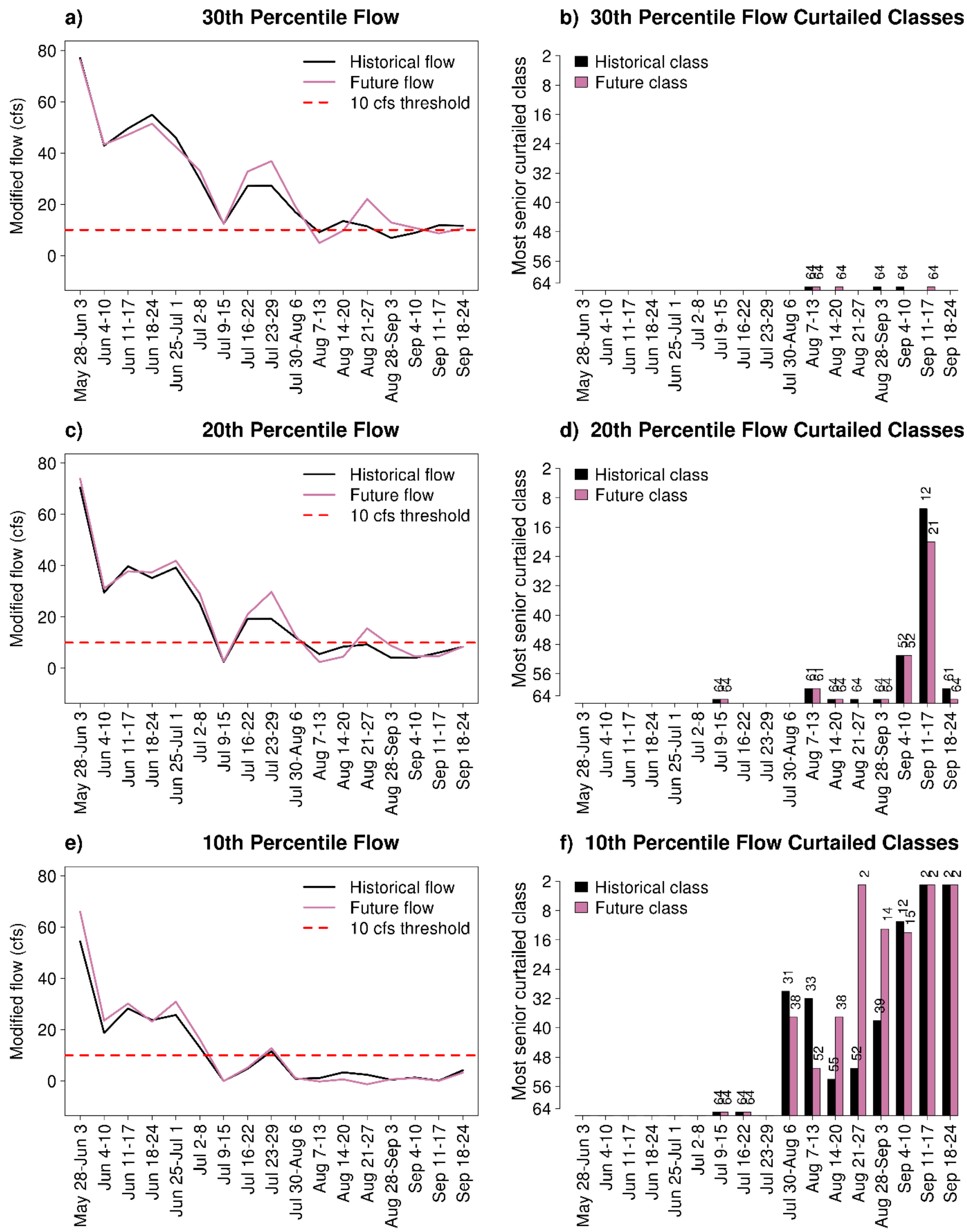


Figure 2. 11 VIC-CropSyst modified flows for Touchet at the Cummins Rd. gauge and corresponding curtailed water right classes. Panels a, c, and e show 30th, 20th, and 10th percentile weekly flows, respectively. Panels b, d, and f show the most senior curtailed class that must be curtailed to bring flow up to the 10 cfs threshold, using the lookup table from Figs. 2.10a and 2.10d. Simulations with historical climate forcing use the 30-year period 1986-2015 and simulations under future climate use the median of 34 climate scenarios: 17 GCMs x 2 RCP emissions pathways, over the 30-year period 2026-2055.

Discussion

In our simulations, water calls were significantly less frequent than interruptible curtailment in favor of instream flows in Methow and Okanogan, while they were slightly more frequent than interruptible curtailment in Colville (Fig. 2.12). However, the curtailable water demand of water rights along the Touchet exceeded that of other basins except for Okanogan (Fig. 2.13). This was the case even when accounting only for irrigation demand of class 64, the most junior water right class (2.13f). Similarly, the curtailable demand for Touchet class 3-64 curtailable water rights was greater as a fraction of total demand compared to Colville and Wenatchee, while it was comparable to Methow and Okanogan (see Fig. 2.14). The curtailable demand of class 64 only (2.14f) was similar to interruptible demand as a fraction of total demand in the Colville and Wenatchee basins.

From this analysis of Touchet curtailment, we can infer that future Forecast curtailment analyses could benefit from inclusion of water calls, especially in a basin like Walla Walla where they represent the primary form of curtailment. In applying the methodology detailed in this pilot study to Washington basins more broadly, care should be taken to ensure the regulatory practices are accurately represented. The Touchet basin is a special case where elements of futile call are observed. In contrast, there are no futile call provisions in most, if not all, other basins in Eastern Washington.

The relative importance of water calls in Methow and Okanogan is unknown at this time. In preparation for the 2026 Forecast there should be a concerted effort to collect data from water masters and stream patrolmen. Toward this end, we composed a simple electronic survey for stream patrolmen to use each time a call is made. The survey has six fields:

1) water master name
2) stream name and watershed
3) shutoff start date
4) shutoff end date
5) which classes or water right IDs were interrupted?
6) which class or water right ID made the call?

Beyond the Forecast, water call data will help Ecology to estimate how much water is being curtailed in the basins of Eastern Washington, knowledge of which may provide valuable insight for identifying solutions to water scarcity issues, including where to focus water supply projects and where to implement water banks. The survey questions are meant to facilitate record-keeping among stream patrolmen who do not already maintain log books or have some other organizational system. The collation of hand-written records and spreadsheets into a centralized electronic database would greatly enhance the value of existing data. Therefore, in addition to distributing the survey, we recommend persistent outreach to water masters who are willing to share their archived curtailment data.

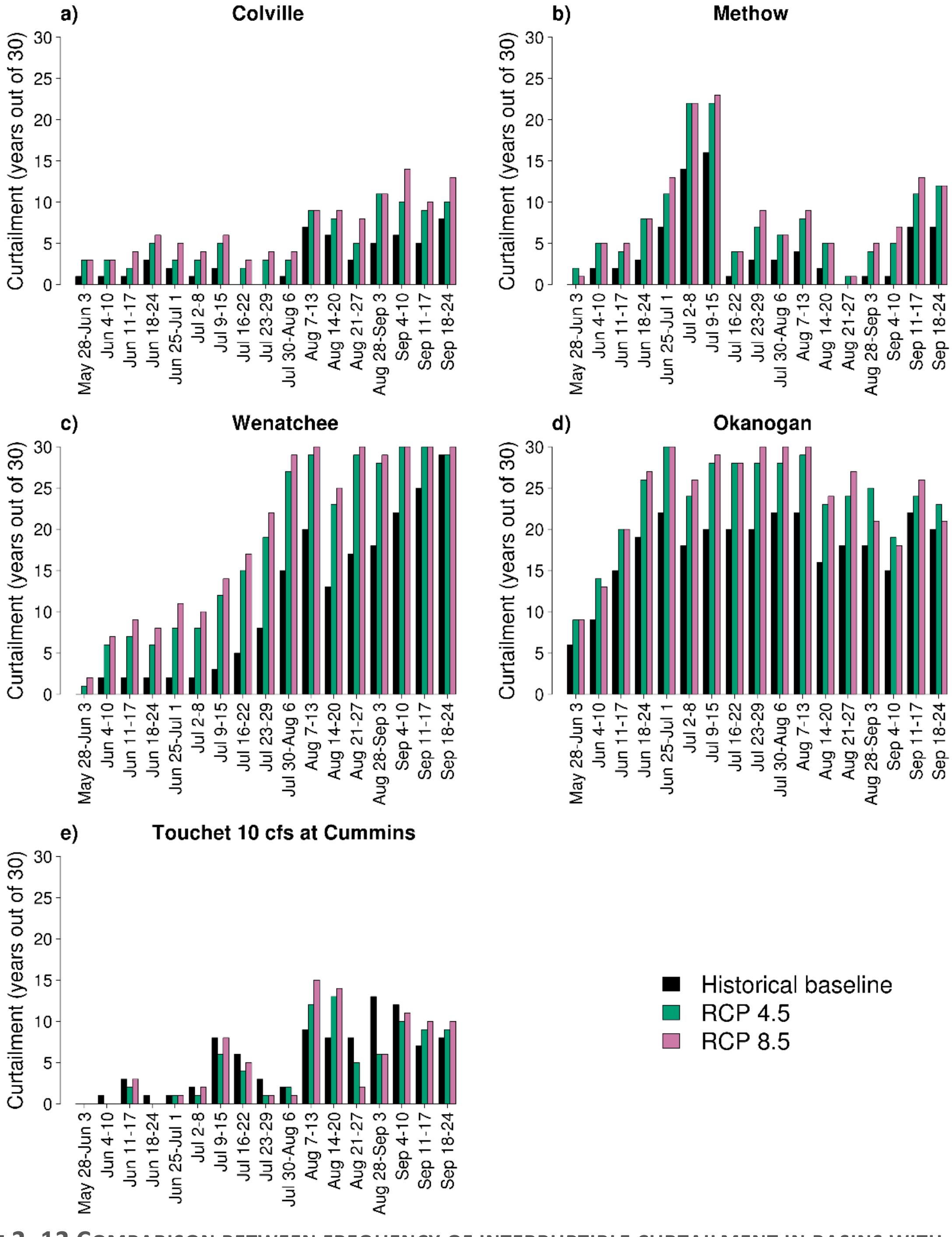


FIGURE 2. 12 COMPARISON BETWEEN FREQUENCY OF INTERRUPTIBLE CURTAILMENT IN BASINS WITH AN INSTREAM FLOW RULE (A-D) AND WATER CALLS ON THE TOUCHET RIVER USING A 10 CFS THRESHOLD AT CUMMINS (E). THE BARS FOR HISTORICAL BASELINE REPRESENT THE NUMBER OF YEARS WITH CURTAILMENT FOR THE GIVEN WEEK OVER THE PERIOD 1986-2015. THE GREEN AND PINK BARS REPRESENT THE MEDIAN NUMBER OF YEARS WITH CURTAILMENT FOR THE GIVEN WEEK OVER THE PERIOD 2026-2055, CALCULATED FROM 17 GCMS UNDER THE RCP 4.5 AND RCP 8.5 EMISSION PATHWAYS, RESPECTIVELY.

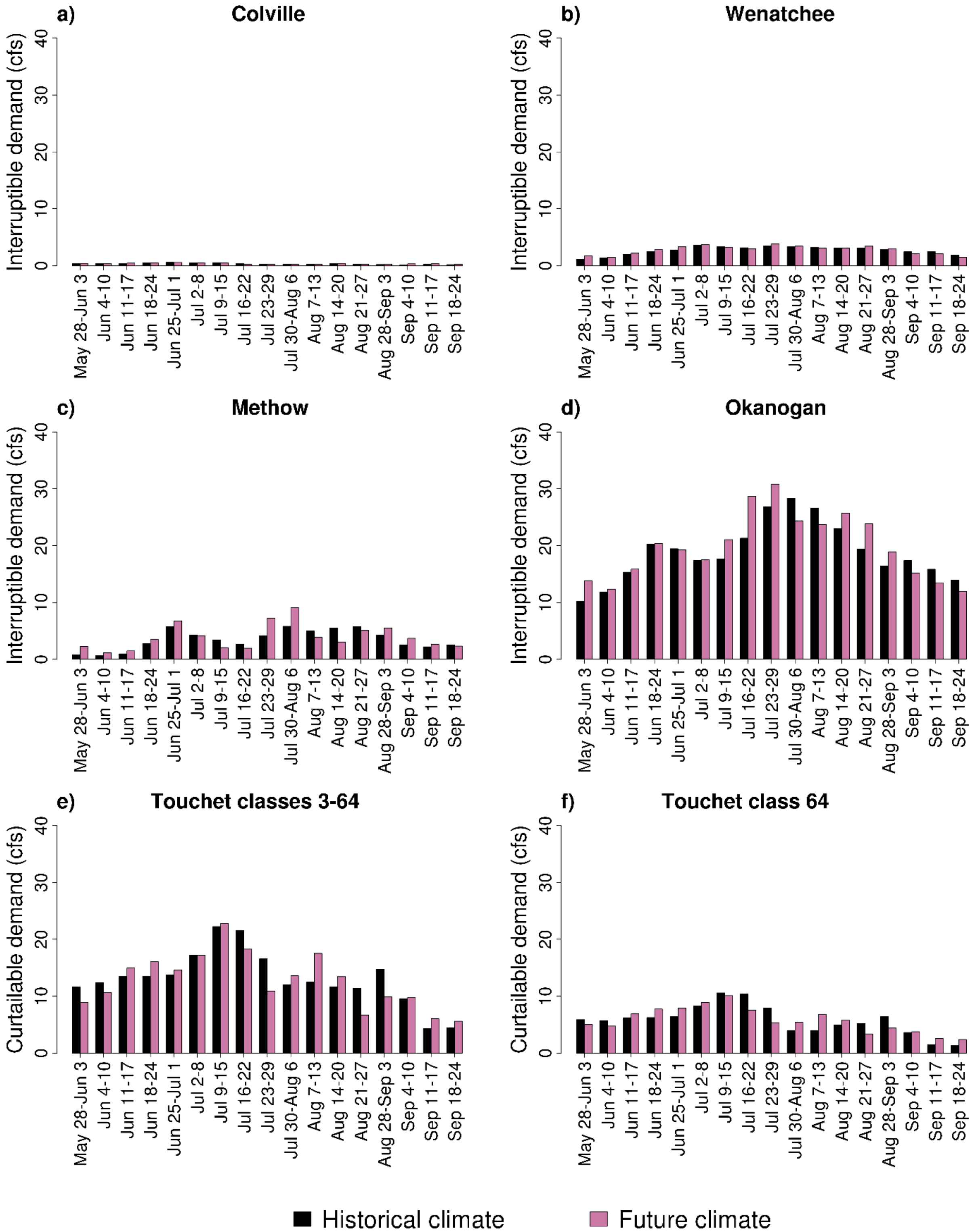


Figure 2. 13 Comparison between interruptible demand in basins with an instream flow rule (a-d) and curtailable demand on the Touchet River for the class range 3-64 (e) and for class 64 only (f).

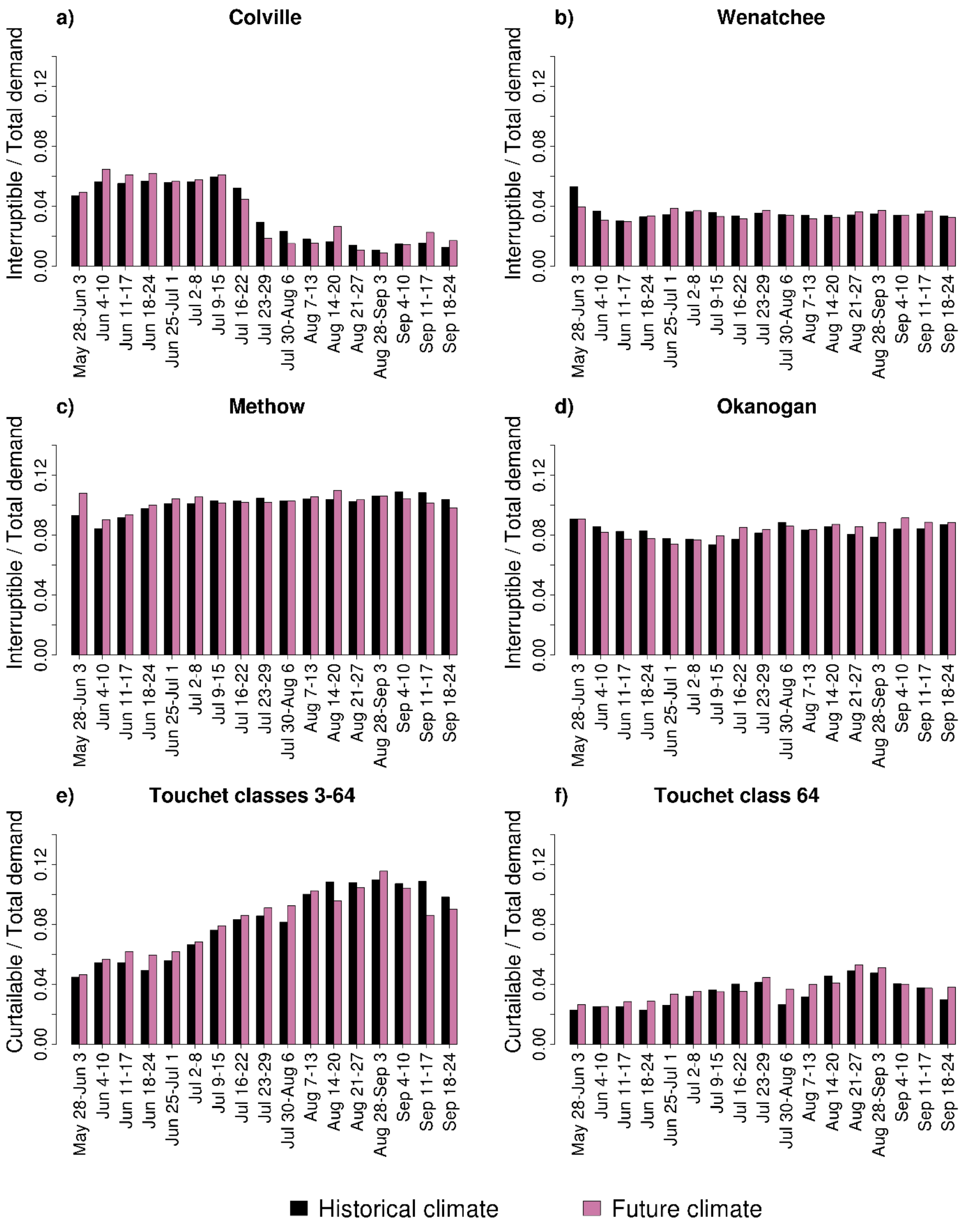


Figure 2. 14 Comparison between interruptible demand as a fraction of total demand in basins with an instream flow rule (a-d) and curtailable demand on the Touchet River as a fraction of total demand in WRIA 32, for the class range 3-64 (e) and for class 64 only (f).

Conclusion

Priority water calls are an important application of Western water law. Our study indicates the volume of water curtailed as a result of water calls on the Touchet River alone is comparable to, and often greater than, the interruption of water rights in favor of instream flow rules. However, we also found that water call frequencies were generally less than interruptible curtailment frequencies in other basins. These two results suggest that even if water shortages on the Touchet River occur less often than in basins like Methow or Wenatchee, when they do occur, a greater number of irrigated acres are impacted. A more complete curtailment module will therefore include water calls in at least the Walla Walla basin. Meanwhile, additional research is needed to establish the relative contribution of water calls in basins that also enforce curtailment in favor of instream flows. An emphasis on collecting water call data in Yakima, Okanogan, and Methow basins for the 2026 Forecast would help meet this need.

Module 4 – Estimating Low Flows

Introduction

Independent modeling-based research led by the University of Washington's Climate Impacts Group (REF) provides some interesting insights around expected changes in low flows under future climates. Which can help managers and policy makers determine where fish species and associated restoration efforts may be vulnerable to such changes in low flows.
Mauger and colleagues' study (Mauger et al., 2021), offers information on change in a range of streamflow metrics. The Forecast team focused on two of these, 7Q10 and 7Q2. The 7Q10 is a commonly used low-flow metric that quantifies the annual minimum 7-day average streamflow with a 10-year recurrence interval. This metric can be interpreted as presenting the value of the minimum flow (expressed as an average over seven days) that has a 10% chance of occurring any given year. Similarly, the 7Q2 quantifies the annual minimum 7-day average streamflow with a 2-year recurrence interval, or the minimum flow (expressed as an average over seven days) that has a 50% chance of occurring any given year.

Overview of Guillaume et al. 2021

Climate forcing data:

For historical period: PNNL historical (1990s): 1982-2011
WRF downscaled GCM projected climate (RCP8.5): access1.0, access1.3, bcc-csm1.1, canesm2, ccsm4, csiro-mk3.6.0, fgoals-g2, giss-e2-h, gfdl-cm3, mri-cgcm3, miroc5

Time periods:

GCM 1990s: 1982-2011

GCM 2040s: 2030-2059

GCM 2080s: 2070-2099

Model:
We are using the VIC version 4.2.d.(https://vic.readthedocs.io/en/vic.5.0.1/Development/ReleaseNotes/), which is the final release of classic VIC version 4 before version 5 (which uses the same physics and enables multiple drivers, and also have the capacity of running with image mode, i.e. space-before-time (all grid cells need to be finished at current simulation time-step before moving to the next time-step)).

Methods

Data Sources

Soil Properties

The following VIC soil properties (for each layer) has been updated from gNATSGO: Ksat (saturated hydraulic conductivity), bulk_density, Wcr (the fractional soil moisture at the critical point, set as 70% of the field capacity), Wpwp (the fractional soil moisture at the wilting point) and quartz (the quartz content of the soil. The layer thickness maintains the original soil parameter, i.e. 0.1 and 0.3 meter for first and second soil layer, and the thickness of the third layer is calibrated and varies. The soil properties for each layer are retrieved from gNATSGO dataset by using its “Soil Data Development Toolbox” (ArcTools for ESRI ArcMap) and the value is the average within VIC’s corresponding depth, i.e. 0-10 cm for the first layer, 10-40 cm for the second layer, and the third layer is the average between the depth of 40 to 190 cm. After getting the soil properties at 10 meter resolution, they are spatially aggregated with “mean mode” to VIC grid cells, i.e. 1/16th degree (~6 km).

Land Cover and Monthly LAI

We updated the land cover based on National Land Cover Database (NLCD) 2016 (Homer et al., 2020; Jin et al., 2019 ; Yang et al., 2018) (https://www.mrlc.gov/data/nlcd-2016-land-cover-conus) and MODIS yearly Land Cover Type at 500 m resolution (MCD12Q1.005) (Friedl et al., 2010). In the NLCD classification system the forest is separated into three subgroups: deciduous, evergreen, and mixed forest. By using the MODIS landcover with IGBP detailed classification system (https://lpdaac.usgs.gov/news/modisterra-land-cover-types-yearly-l3-global-005deg-cmg-mod12c1/), in each VIC gridcell the total fraction of NLCD forest (except mixed forest, which keep as it is) is divided into Evergreen Needleleaf, Evergreen Broadleaf, Deciduous Broadleaf, and

Deciduous Broadleaf Forest. The shrubland from NLCD is also divided into open and closed shrublands depending on the fraction defined in MODIS land cover. The “developed” class in NLCD is firstly reclassified as Pasture/Hay because of its major component of lawn; then among this the “Percent Developed Imperviousness” is deducted to produce a separate class “Impervious surface”.

The land cover types for VIC model runs include: 1 Evergreen Needleleaf Forest; 2 Evergreen Broadleaf Forest; 3 Deciduous Needleleaf Forest; 4 Deciduous Broadleaf Forest; 5 Mixed Cover Forest; 6 Woodland; 7 Wooded Grasslands; 8 Closed Shrublands; 9 Open Shrublands; 10 Grasslands; 11 Crop land (corn); 12 Impervious surface; 13 Pasture/Hay; and 14 Other lands.

The monthly leaf area index (LAI) for each land cover within VIC gridcell comes from PROBA-V based LAI 300m (version 1.0) (for every 10-days) products (Fuster et al., 2020[ML1]) and being averaged between the year 2015 to 2017.

Calibration over WA

We downloaded historical streamflow observations from USGS National Water Information System (NWIS) (https://waterdata.usgs.gov/nwis/sw; retrieved: 2020-05-04), which contains 1041 gauges within Washington state during the year 1902 to 2020. From these 1041 gauges we selected 218 gauges which has at least two year’s observations (Figure 2.15).

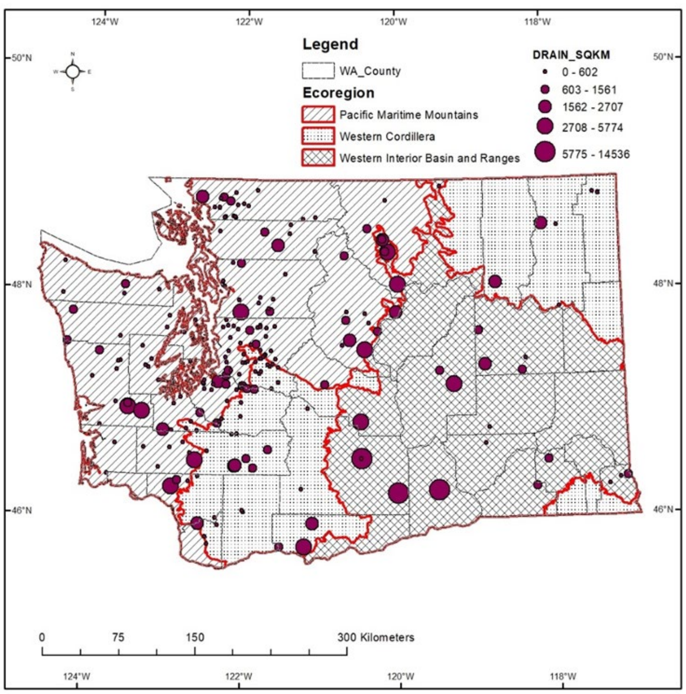


FIGURE 2. 15 GAUGES SELECTED FOR MODEL CALIBRATION AND THE BOUNDARY OF ECOREGION

Spatial and Temporal Aggregation

The original simulation was conducted for every three-hour simulation and total runoff (including surface runoff and baseflow) is aggregated to daily time step as the base for evaluations. Then, for getting the total runoff to each responding observation gauge, we aggregate the modeled output from VIC gridcells that are within (entirely or partially; if partially within, the contribution of this gridcell to the gauge is calculated with the fraction of the gridcell area in this basin) the drainage basin and assume there is no lag time between each gridcell and the gauge, i.e. the total runoff will instantly flow to the gauge.

To evaluate model performance over various soil parameter sets (next section), the following temporal simulated streamflow are compared with observations: daily mean flow, 7-day mean flow, annual minimum 7-day mean flow, annual peak flow (water year, i.e. from October to September), and monthly mean flow. For final soil parameter sets selection, we only used the model performance ranking on daily mean flow.

Soil Parameter Sets for Evaluation

According to soil physics, literature, and the earlier VIC calibration over the Columbia River Basin (Hamlet et al., 2013), we identify the range of soil parameter for calibration which is listed in Table 2.6.

TABLE 2. 6 THE RANGE OF SOIL PARAMETERS TO BE CALIBRATED

Parameter	Range	Unit
BI	0.001 – 0.4	N/A
DsMAX	0.01 – 30	mm/day
Ds	0.0001 – 1.0	fraction
Ws	0.01 – 1.0	fraction
D2	0.001 - 3	Meter

By using Latin-hypercube designs with “center” criteria (python package pyDOE, https://pythonhosted.org/pyDOE/randomized.html), we generate 40 sets for model runs (details can be found in Mauger et al., 2021).

Since the total drainage basins of observation gauges cannot cover the entire Washington State, we decide to use the ecoregion as calibration unit, i.e. we select the soil parameter sets for individual ecoregion. Instead of getting the best calibrated soil parameter set, we select the top 5 sets for each ecoregion and we used those 5 sets (simulations) to estimate the uncertainties due to parameter selection.

All 7Q2 and 7Q10 estimations are from the median of changes from these 5 sets of each model. And 7Q10 and 7Q2 are estimated with Generalised Extreme Value (GEV) distribution with L-moments fitting (Python package “lmoments3”) (Hewa et al., 2007).

Module 5 - Hydropower Demand Forecasting

Introduction

The importance of hydropower to the State of Washington’s energy portfolio and energy resiliency picture cannot be overemphasized. Hydroelectric generation has been Washington State’s primary energy source for electric generation for decades including our historic study period covering the years from 1990 to 2019. Hydroelectric generation is accountable for 60-85% of Washington State’s total electric industry generation throughout this 1990 to 2019 period (U.S. Energy Information Administration, 2020). Despite conservation efforts, it is expected that the demand for electricity will increase as the population in the Pacific Northwest increases and demands from electric vehicles and economic growth of high use industries such as data centers increase. Since Washington State passed both S.B. 5116 and H.B 1287, additional renewable replacement electricity will also be required. Senate Bill 5116 concerns the transition to 100% carbon free emissions by 2045 and to phase out coal power by the end of 2025 (S.B. 5116, Wash. 2019). An amendment passed to H.B. 1287 sets a goal for all passenger and light-duty vehicles with a model year of 2030 or later to be electric vehicles (H.B. 1287, Wash. 2021). Thus, in addition to coal, natural gas production (which accounted for 15% of Washington’s total electric generation in 2019) will also need to be replaced. In total, non-emitting power sources would need to replace 1,084,000 MWh of natural gas and 362,000 MWh of coal-fired generation, in addition to fulfilling demands for additional electricity by 2040.

The composition of the renewable and non-emitting energy supply portfolio that will be required to meet these additional electricity demands is not certain as economic, political, social, and technological factors are rapidly changing the options for energy production and storage. In addition to advancements in wind and solar, other energy emerging technologies continue to evolve. For example, in March 2021, Douglas County PUD began construction of an electrolysis pilot project at Wells Dam that will utilize hydropower for hydrogen production (Russo, 2021). Likewise, in April 2021, Grant County PUD and Energy Northwest, and Xcel-energy proposed a 320 MW advanced nuclear reactor. However, it should be noted that in support of the overall energy goal, Washington's SB 5116 states "…'non-emitting electric generation' does not include new large hydroelectric generation." The implication is that additional hydropower would need to be supplied through pump storage projects and/or efficiencies or other improvements made to existing hydroelectric generating facilities.

In addition to increased electricity demands, climate-induced changes in water supply hydrographs threatens to disrupt traditional hydroelectric power production. Hamududu and Killingtveit (2012) found that climate change could result in large variations in hydropower generation around the globe. The variable nature of climate change means that in some regions overall generation may increase (Oyerinde et al. 2016; Ali et al. 2018) decrease or stay essentially the same (Bombelli et al. 2019) depending on the emission scenario and time frame selected. Hamlet et al. (2010) predicted Columbia River Basin hydropower production would increase 4.7-5% during winter periods and decrease by 12.1-15.4% in summer by the 2040s based on A1B and B1 emission scenarios. These changes were based on predicted changes to the runoff and stream flow patterns because of the run-of-the-river power production at many of the Pacific Northwest (PNW) dams.

In the previous 2016 Columbia River Basin Long-Term Water Supply and Demand Forecast, preliminary hydropower efforts translated regional demands for electricity into the required flows necessary to generate said electricity using hydropower (Washington Department of Ecology, 2016). The 2016 results showed a change in hydropower demand of 6.19% to 21.65% between 2013 and 2035.

The primary objective of the hydropower module within the 2021 Long-Term Water Supply and Demand Forecast was to answer the following questions projected out to year 2040:

1) Will there be demand for additional hydropower?
2) Will there be demands from any new facilities?
3) What are the potential evaporation losses from new facilities?
4) Will there be a climate change impact on generation from existing hydropower facilities?

These questions were answered using two primary methods. The first being an extrapolation and regression of population, hydropower/pump storage generation, data center infrastructure, and electric vehicle use growth. The second method was a qualitative review of current journal, news, and informational articles.

A secondary objective was to evaluate how the latest climate change modeling efforts would impact the shift in supply of hydropower generation based on a facility-specific empirical relationship between hydropower facility weekly outflow and its respective weekly total generation. The regulated flows calculated by the RColSim model for the 2021 Long-Term Water Supply and Demand Forecast were used as the outflow inputs into the empirically generated equations.

Approach

Primary Objective

There are many intricacies regarding the forecast of hydropower generation demand within the Columbia Basin. Such intricacies made following a completely qualitative approach impossibly difficult when answering the primary objectives. Because of this, both qualitative and quantitative approaches were utilized to answer the primary objectives. A quantitative analysis was used to provide an answer to the question "will there be a demand for additional hydropower." The other three objectives were answered using a qualitative analysis of current literature, reports, and news articles.

Question 1

Objective one was broken down into three scenarios with each scenario following the first being a cumulation of the previous ones (population, electric vehicles, and data centers). Each scenario was calculated with high and low alternatives of hydropower demand from 2020 to 2040. The results for scenario one was calculated based off a relationship between total annual historic hydropower generation (U.S. Energy Information Administration, 2019) and annual postcensal estimates for the State of Washington (Office of Financial Management, 2022). The range of years used as the historic baseline was from 1990 to 2019. From the relationship between hydropower generation and annual postcensal estimates, a forecast of total annual statewide hydropower generation was produced from high and low population estimates forecasted from Washington State Office of Financial Management. A similar historic relationship and forecast method from scenario one was used to produce the ancillary generation demands (electric vehicle and data center growth) for scenarios two and scenario three.

Scenario two is the summation of hydropower demand with population growth and the adoption of electric vehicles with the assumption that all future electric vehicle charging will be provided by hydropower generation. A historical relationship was built between annual registration of electric vehicles (Washington State Department of Licensing, 2021) and postcensal population data from 2017 to 2020. Then, electric vehicle registration was forecasted from 2021 to 2040 using the previous high and low statewide annual population forecast. Once the electric vehicle forecast was developed, the annual amount of registered electric vehicles was multiplied by the annual MWh needed to power an electric vehicle. The assumption used to calculate annual MWh demand per vehicle is based off the average MWh/mi efficiency of 3.435×10^{-4} (U.S. Department of Energy, 2022) and the average Washington State driver driving 10,959 miles in a year (U.S. Department of Transportation, 2019).

Scenario three is the hydropower demand culmination of scenario two summed with the expected expansion of data centers in Washington. Data center information regarding the number of data centers in Washington was used from 2021. Data center growth was then projected out annually from a count of 66 data centers in 2021 (Cloud and Colocation, 2021) to 150 and 200 datacenters for the respective low and high alternatives in 2040. An assumption was made that on average a data center requires 9MW of power per year or 78840 annual MWh's (Washington State Department of Commerce, 2018).

Question 2

Question 2 was solved using a more qualitative analysis. It is easy to say that there will be an increased future electricity demand and that these could be met from new facilities given the results from question one. However, a review of S.B. 5116 changes the prospect of using new on-stream hydroelectric facilities to meet these demands. The assumption in our analysis is that S.B. 5116 will impact management of hydropower facilities such that future demand can only be met with the addition of pump storage projects and/or more conservation and turbine efficiency measures. As conservation and improved turbine efficiency was used to meet the initial 15% targets, it is unclear how much more can be done in this area, but the assumption was that it would be relatively small.

Question 3

A brief review of the Goldendale Pump Storage Project proposed by Rye Development was done to understand the potential evaporation losses from new facilities. This was done due to difficulty in attaining conclusive pan evaporation data for much of the Columbia Basin. Pan evaporation data was sourced from Western Regional Climate Center for the State of Washington (WRCC, 2022). Upon review of the pan evaporation data, it was decided that spatial and temporal distribution of the pan evaporation data would not allow us to make any conclusive estimates towards how evaporation might impact hydropower into the future. These results helped us understand the difficulty of knowing climate change impacts on losses from existing hydropower reservoir facilities.

Question 4

Originally, we believed that we could answer this goal through equating projected reservoir levels/surface area and open-water evaporation equations to losses in generation. This approach turned out to be problematic and the uncertainty surrounding the estimated losses too large to be of value to the Forecast. Rather than a quantitative approach to addressing this question, we implemented a secondary objective to help understand the potential impact of climate change on generation from existing hydropower facilities.

Secondary Objective

The secondary objective was a significantly different approach to our previous process related to answering Question 4 of the primary objective. Here, we obtained and analyzed the historical water year data for each of the hydropower facilities which was used to determine empirical formulas between weekly average outflow (cfs) and weekly total facility generation (Mwh). This data was accumulated and processed from the USGS NWIS (U.S. Geological Survey National Water Inventory System), EIA (Energy Information Agency), and USACE (U.S. Army Core of Engineers) Dataquery 2.0. From the Dataquery 2.0 engine, the parameters used were one day power total and flow out daily average. A list of the hydropower facilities, their location, date range for their data, and data source can be seen in Table 2.7. These 11 sites were chosen as they represent most hydropower facilities within the Columbia River Basin with a nameplate capacity greater than 624 MW (Figure 2.17). Not only do these facilities have a larger capacity to generate power but make up a relatively diverse spatial range of hydropower facilities within the CRB (Columbia River Basin). Furthermore, it was assumed that due to the nature that many of these rivers are run-of-the-river (RoR) they would be representative of how other RoR facilities would operate within the CRB.

The data for all 11 hydropower facilities went through quality control to remove null and repeating date and observation values. Once the quality control was complete, weekly outflow (cfs) was plotted against total weekly generation (Mwh) for each of the 11 hydropower facilities (Figure 2.18). Using this information, we developed non-linear relationships for each facility with NumPy's polynomial regression line of best fit function. Using the 2021 forecasted flows produced from the RColSim model, we performed an empirical analysis using the predicted outflows and the non-linear relationships to predict future generation at each of the eleven facilities.

Table 2.7 List of hydropower facilities, their location, data date range, and data source used for empirical and forecasting analysis.

Facility	Type	River	Hydraulic Capacity (kcfs)	Date Range (WY)	Data Source
Boundary	Gravity	Pend Orielle	55	2002-2020	USGS, EIA
Grand Coulee	Gravity	Middle Columbia	280	1986-2015	USACE
Chief Joseph	Run of River	Middle Columbia	219	2004-2020	USACE

Facility	Type	River	Hydraulic Capacity (kcfs)	Date Range (WY)	Data Source
Rocky Reach	Run of River	Middle Columbia	220	1986-2015	USACE
Wanapum	Run of River	Middle Columbia	161	1986-2015	USACE
Priest Rapids	Run of River	Middle Columbia	162	1986-2015	USACE
Lower Granite	Run of River	Lower Snake	130	1986-2015	USACE
Lower Mon.	Run of River	Lower Snake	130	1986-2015	USACE
Ice Harbor	Run of River	Lower Snake	106	1986-2015	USACE
McNary	Run of River	Lower Columbia	232	2004-2020	USACE
Dalles	Run of River	Lower Columbia	375	2004-2020	USACE

Daily outflow and total generation for 10 of the 11 hydropower facilities listed in Table 2.7 were acquired from the USACE Dataquery 2.0 database. For the Boundary Dam location, daily outflow was acquired from USGS stream gauge 12399500 Columbia River at International Boundary and monthly total power generation was acquired from the EIA. For all 11 hydropower facilities, daily total generation and daily average outflow was summed and averaged respectively to a weekly scale. Weekly averages were determined based on the same weekly period as the regulated flows developed from RColSim which outputs weekly data using the ISO 8601 date time convention.

Unique patterns in generation versus outflow for many of the 11 hydropower facilities were observed (Figure 2.18). Many of these plots had patterns where the data forked (i.e., Lower Monument) or there were multiple relationships between generation and outflow (i.e., McNary). Establishing and separating these patterns was done by plotting the figures with a third variable, water year week or water year, using a continuous color range to label the points using the Plotly's express 3d library and function. Having established any potential weekly and annual patterns within the data sets, conditional arguments were used to label data points such that a regression line could be fitted to the appropriate point cluster patterns (Figure 2.19). Point clusters were denoted by 1) the latest point annually where there was a noticeable shift in the discharge generation relationship and 2) any discharge generation pattern associated with a range of weeks within the first condition. Outlying data was excluded, this was data that occurred outside the most recent operations for the facility. This outlying data was excluded with the assumption that the data would not represent the most current hydropower facility management practices given facility infrastructure updates and fish ecosystem requirements. This resulted in up to three temporal conditions. The conditional arguments used to separate data patterns can be seen in Table 2.8. As seen in Figure 2.19, individual regression lines were fit to each of the delineated discharge generation patterns.

The respective regulated flow discharge data from the RColSim model was used as an input into the empirically developed regression lines. RColSim regulated flow results were acquired from 17 bias removed, statistically downscaled GCM's (global circulation model) inputs, with results for 2 RCP's. For this analysis the RCP's used were 4.5 and 8.5 respectively (Washington Department of Ecology, 2021). Total CRB outflow for the RCP scenarios and date periods can be seen in Figure 2.16. Prior to input of the RColSim regulated flows into the empirically based regression models, two adjustments were made to limit the input of values into the formulas. Average weekly RColSim flows that exceeded their respective hydropower facilities hydraulic capacity were set equal to that respective hydraulic capacity. The hydraulic capacity related to the regression lines produced can be seen in Figure 2.19. The second adjustment was limiting the minimum weekly CFS from the RColSim output to the minimum observed average weekly values used to produce the regression lines. Both adjustments were done to remove the result of negative and or unrealistic generation outputs. The bias removed regulated flow results from the RColSim model at each respective hydropower facility were used as inputs into the empirical analysis.

Bias removed GCM's were a result of taking the weekly annual median, min, and max values of the historic (WY 1976-2005), future, and baseline historic periods of each GCM. After which, the median, min, and max future periods were divided by their respective historic period and then multiplied by their respective historic baseline period. Bias adjustment was done to remove the high and low bias of each GCM output. After each GCM was adjusted, the median max, min, and median values were found for each water year week between all 17 GCM's at each of the 11 facilities.

Two sets of future time series as well as a historical baseline were used as the dependent variables to determine total weekly generation. The future time series include water years 2025-2055 and 2055-2085 with RCP's 4.5 and 8.5 and water years 2085-2015 for the historical baseline. The generational time series data were then used to compare modeled baseline historic generation to observed historic generation to understand the overall accuracy of the model. Along with this, future generation time series data were compared with modeled baseline historic generation and observed generation time series data to understand potential impacts of climate change into the future under different RCP scenarios.

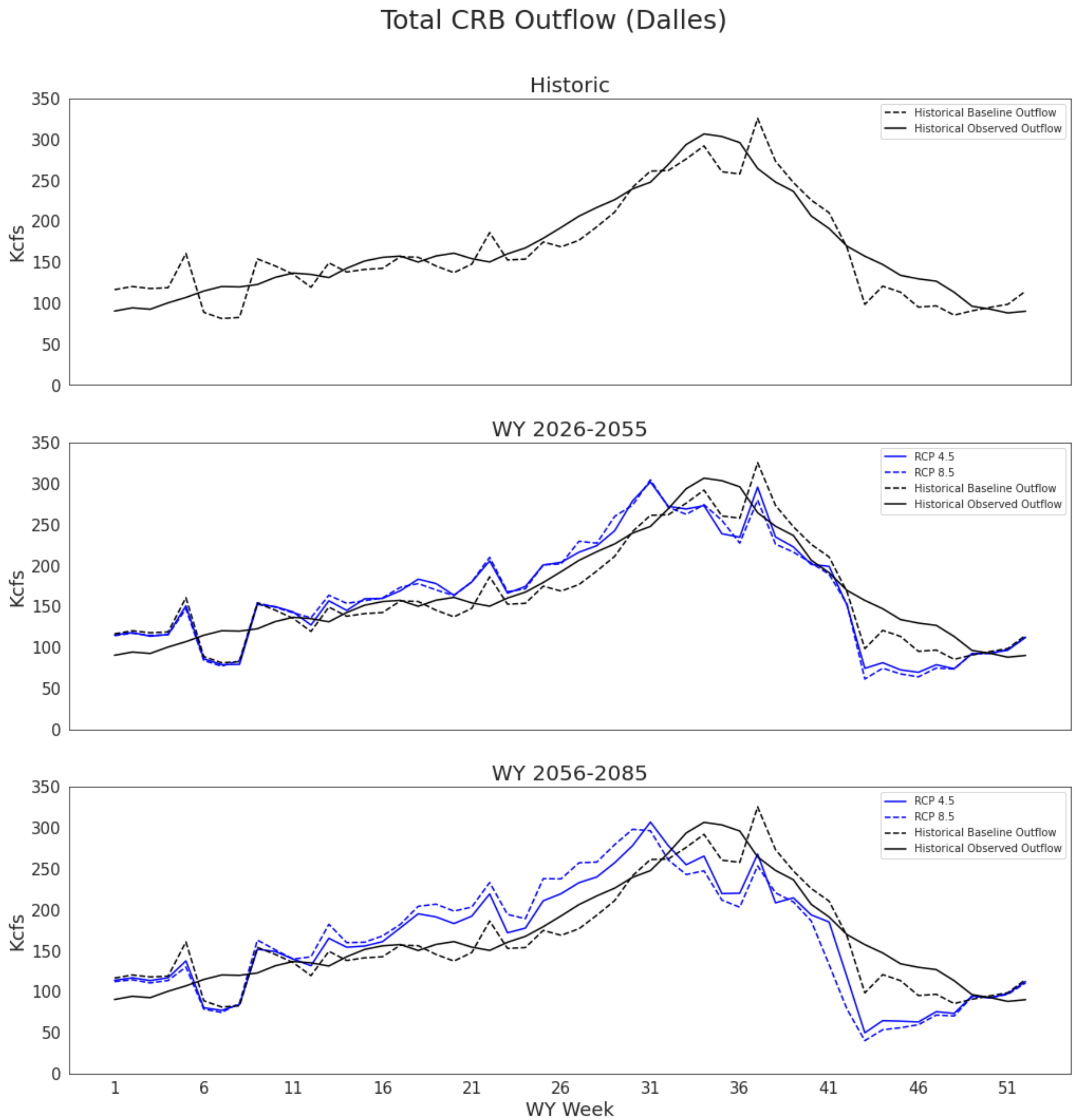


FIGURE 2. 16 MEDIAN CRB OUTFLOWS AT THE DALLES HYDROPOWER FACILITY COMPUTED USING THE AVERAGE OBSERVED OUTFLOW MEDIAN MODELED BASELINE HISTORIC OUTFLOW, AND THE MEDIAN RCP 4.5 AND 8.5 SCENARIOS FOR EACH FUTURE PERIOD

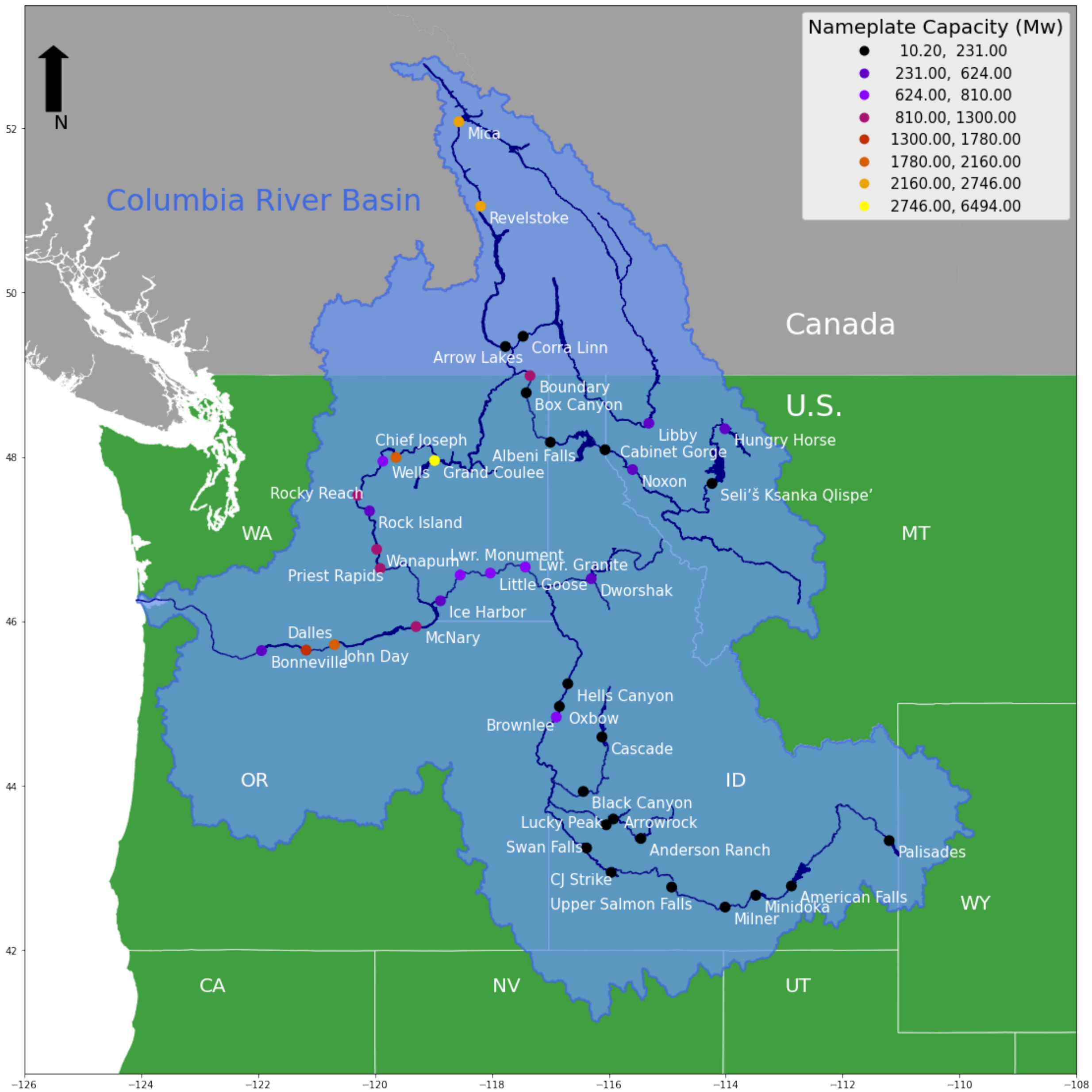


FIGURE 2. 17 MAP OF THE CRB WITH MAJORITY OF HYDROPOWER FACILITIES FOUND WITHIN BASIN. NAMEPLATE CAPACITY SEPARATED USING NATURAL BREAKS.

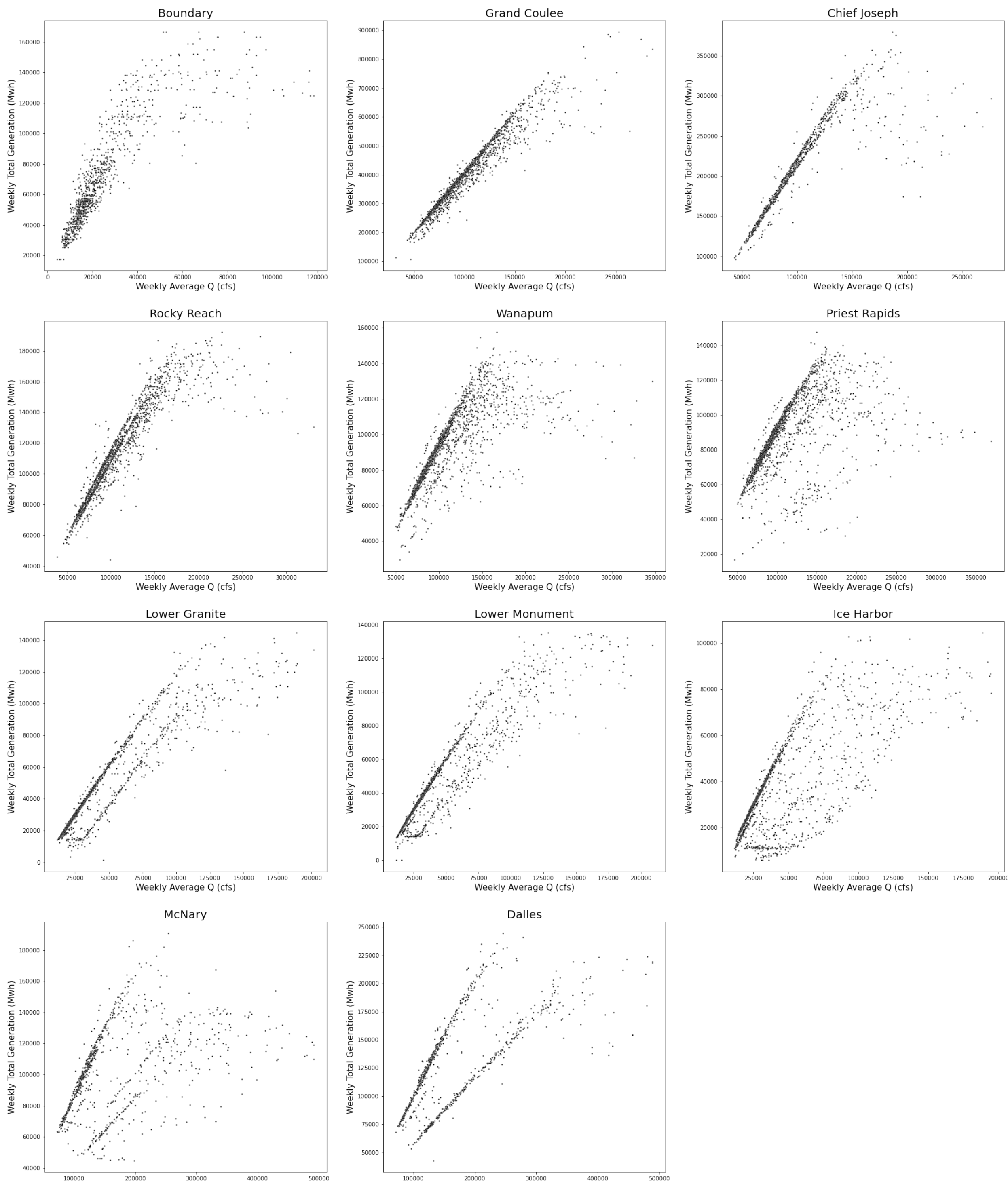


FIGURE 2. 18 DISCHARGE VERSUS GENERATION PLOTS FOR 11 HYDROPOWER FACILITIES USED IN THE ANALYSIS PRIOR TO EXCLUDING DATA POINTS.

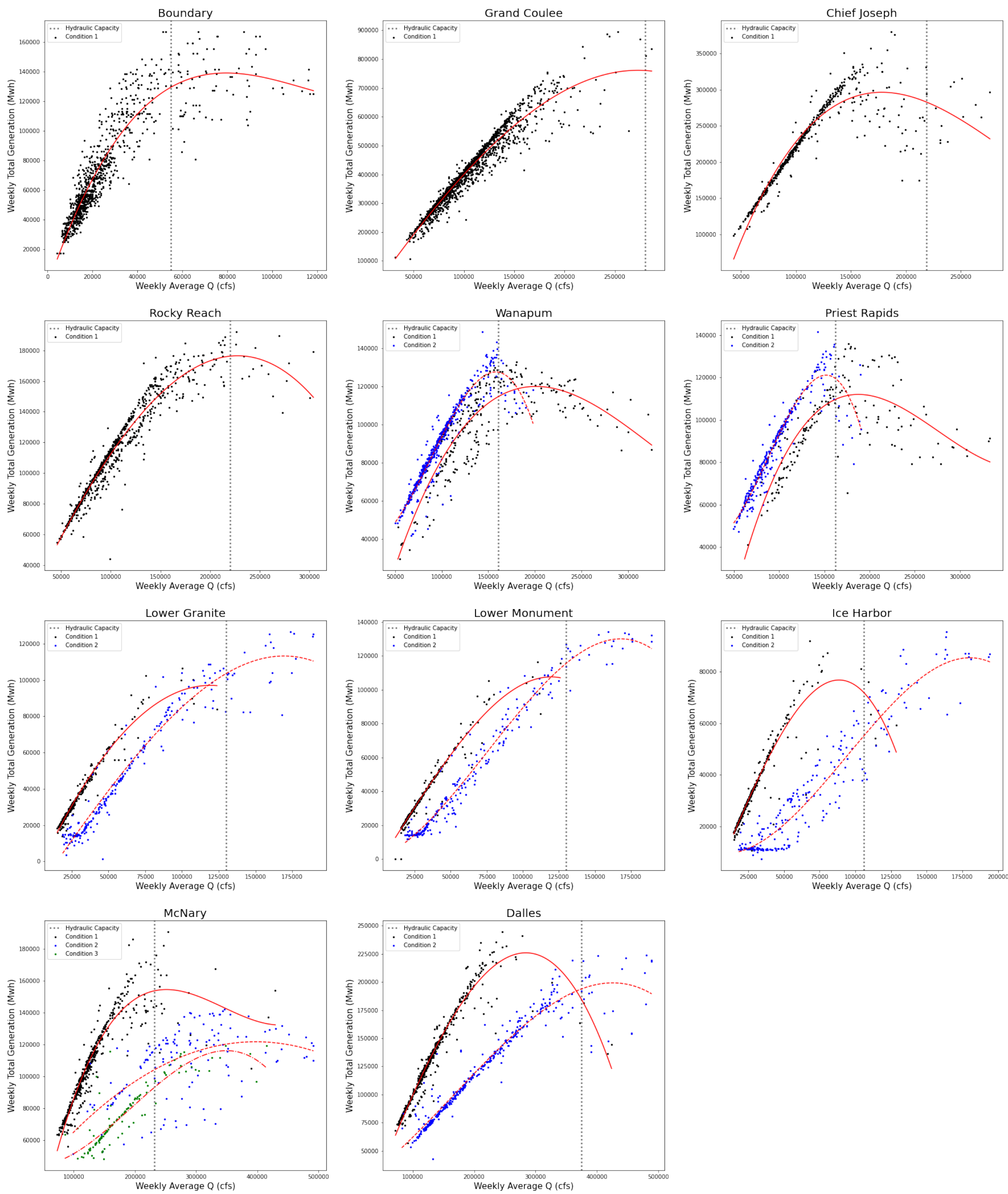


FIGURE 2. 19 REGRESSION ANALYSIS PLOTS INCLUDING HYDRAULIC CAPACITY FOR RESPECTIVE HISTORIC OPERATING CONDITIONS FOUND FOR THE ELEVEN HYDROPOWER FACILITIES.

TABLE 2. 8 CONDITIONAL ARGUMENTS USED TO DELINEATE OPERATING CONDITIONS FOR THE ELEVEN HYDROPOWER FACILITIES.

Facility	Excluded Condition	Condition 1	Condition 2	Condition 3
Boundary	Years < 2002	Years >= 2002		
Grand Coulee	Years < 1985	Years >= 1985		
Chief Joseph	Years < 2011	Years >= 2011		
Rocky Reach	Years <= 1999 and weeks 32-37 for 2001-2005	Years >= 2000		
Wanapum	Years >= 2000 and 2014	Weeks 30-48	Weeks 1-29 and 49-52	
Priest Rapids	Years >= 2006 and 2014	Weeks 30-48	Weeks 1-29 and 49-52	
Lower Granite	Years <= 2004	Weeks 1-27 and 49-52	Weeks 28-48	
Lower Monument	Years <= 2004	Weeks 1-27 and 49-52	Weeks 28-48	
Ice Harbor	Years <= 2004	Weeks 1-27 and 49-52	Weeks 28-48	
McNary	Weeks >= 30 during 2004-2008	Weeks 1-27 and 49-52	Weeks 28-38	Weeks 39-48
Dalles		Weeks 1-27 and 49-52	Weeks 28-48	

Results

Objective 1

Question 1

As was presented in the Legislative Report for question 1, we expect there to be more demand for generation of electricity into 2040. Table 2.9 shows an increase in electricity demand within all three of the scenarios for both the low and high alternatives. As a reminder, the “low” and “high” alternatives are calculated based on the range of existing projections in population growth (all scenarios), in expected adoption of electric vehicles (scenarios 2 and 3), and expected expansion of data centers (scenario 3). For the high alternative in scenario 1 there are increases in total demand and hydroelectric demand of 29% and 14%, respectively. If scenario 3 occurs, demands for total annual electricity could increase up to 47% which translates to an increase of average hydroelectric power demand of 34%. This varies greatly from just the scenario 1 projections.

Table 2. 9 Expected changes in demand for electricity and hydropower by 2040 in the Columbia River Basin.

		Generation Demand (KWh)			Percent Change	
		2019	2040 - Low	2040 - High	2040 - Low	2040 - High
Scenario 1 - Population growth	Total	106,463,608	117,410,322	137,592,463	10	29
	Hydroelectric	66,026,861	69,175,073	75,468,376	5	14
Scenario 2 - Population growth + Electric vehicles	Total	106,463,608	118,697,840	140,746,676	11	32
	Hydroelectric	66,026,861	72,329,286	76,755,894	10	16
Scenario 3 - Population growth + Electric vehicles + Data centers	Total	106,463,608	130,523,840	156,514,676	23	47
	Hydroelectric	66,026,861	88,097,286	88,581,894	33	34

Question 2

As mentioned above, S.B. 5116 significantly reduces the prospect of using new on-stream hydroelectric facilities to meet future electric demands by essentially eliminating new hydropower facilities from qualifying for renewable energy status. Given this, coupled with the various fish-related impediments associated with bringing new power, water demands for new hydropower facilities was considered unlikely.

Question 3

A demand for off-channel pump storage projects will likely exist unless some breakthrough battery technology drives the costs of electricity storage down significantly. As such, there will be additional water demands needed to replace evaporation and seepage losses. To put this into perspective, the proposed early-stage Goldendale Pump Storage Project would generate 25.5 thousand MWh for approximately 12-20 hours. The Sierra Club opposes the project because it will require 2.93 billion gallons of Columbia River water initially to fill and as much as 1.2 million gallons each year to make up for water lost through evaporation and leakage. The surface areas of the upper and lower storage reservoirs are anticipated to be 61 and 63 acres, respectively. When put into traditional storage volume units, it is about 9,000 ac-ft to fill and about 3.7 ac-ft per year in losses. Thus, evaporation losses would be rather small and would likely be able to be mitigated unless some mega Banks Lake type projects are proposed.

Question 4

As indicated in our approach, we were unable to address this question directly. While it is rational to believe that increased air temperatures, earlier runoff, and longer summer periods would result in additional evaporation from existing facilities, quantifying the actual impacts of these factors was not feasible within the scope of this project. Correlation of future air temperatures to future water temperatures was not simulated so future evaporation estimates would be suspect. Given that, at nearly full pool, a 1-inch increase in annual evaporation from Lake Roosevelt would result in an additional demand of 6,800 acre-feet, the implications to system could be significant. So, the secondary objective was added to understand the potential impacts of climate change on power generation.

Secondary Objective

As expected, the result of this analysis demonstrated that there is in general a strong relationship between weekly average outflow (Q cfs) below each of the hydroelectric facilities and their weekly total generation (Mwh). The desire to produce power and reduce total dissolve gas issues by keeping spillway discharges as small as possible would lead one to expect that this would be the case. These relationships fit well within 2nd and 3rd degree polynomial regressions when accounting for operational conditions. The R squared values for these regression plots ranged from .65 to .96 except for an outlying R squared score of .34 that occurred for the condition 2 regression at McNary. The regression formula for each condition and their respective R squared valued can be found in Tables 2.10 and 2.11, respectively.

TABLE 2. 10 R SQUARED VALUES FOR POLYNOMIAL REGRESSION LINES.

Facility	Condition 1	Condition 2	Condition 3
Boundary	0.87		
Grand Coulee	0.94		
Chief Joseph	0.87		
Rocky Reach	0.94		
Wanapum	0.76	0.92	

Facility	Condition 1	Condition 2	Condition 3
Priest Rapids	0.65	0.91	
Lower Granite	0.96	0.94	
Lower Monument	0.95	0.96	
Ice Harbor	0.89	0.91	
McNary	0.89	0.34	0.79
Dalles	0.95	0.93	

TABLE 2. 11 POLYNOMIAL REGRESSION FORMULAS FOR WEEKLY TOTAL GENERATION OF EACH CONDITION FOR THE HYDROPOWER FACILITIES, WHERE X IS WEEKLY AVERAGE OUTFLOW.

Facility	Condition 1	Condition 2	Condition 3
Boundary	$1.25e^{-10}x^3 - 4.27e^{-5}x^2 + 4.42x - 5.36e^{+3}$		
Grand Coulee	$-1.21e^{-11}x^3 - 4.22e^{-6}x^2 + 5.02x - 4.78e^{+4}$		
Chief Joseph	$2.6e^{-11}x^3 - 2.31e^{-5}x^2 + 5.75x - 1.42e^{+5}$		
Rocky Reach	$-3.54e^{-12}x^3 - 1.95e^{-6}x^2 + 1.44x - 8.56e^{+3}$		
Wanapum	$7.85e^{-12}x^3 - 7.7e^{-6}x^2 + 2.15x - 6.39e^{+4}$	$-6.76e^{-11}x^3 + 1.8e^{-5}x^2 - .616x - 4.29e^{+4}$	
Priest Rapids	$1.25e^{-11}x^3 - 1.04e^{-5}x^2 + 2.57x - 8.81e^{+4}$	$-7.3e^{-11}x^3 + 1.9e^{-5}x^2 - .772x + 5.1e^{+4}$	
Lower Granite	$-9.6e^{-11}x^3 - 9.5e^{-6}x^2 + .96x - 1.4e^{+3}$	$-1.3e^{-11}x^3 - 1.3e^{-7}x^2 + 1.17x - 1.75e^{+4}$	
Lower Monument	$-3.55e^{-11}x^3 + 8e^{-7}x^2 + 1.34x - 3.14e^{+3}$	$-4.23e^{-11}x^3 + 9.61e^{-6}x^2 + .35x + 1.6e^{+2}$	
Ice Harbor	$-5.68e^{-11}x^3 - 5.23e^{-8}x^2 + 1.35x - 2.63e^{+3}$	$-3e^{-11}x^3 + 8.48e^{-6}x^2 - .134x + 1.01e^{+4}$	
McNary	$7e^{-12}x^3 - 7.20e^{-6}x^2 + 2.3x - 7.9e^{+4}$	$-6.42e^{-7}x^2 + .51x + 2.03e^{+4}$	$-4.75e^{-12}x^3 + 2.76e^{-6}x^2 - .186x + 4.71e^{+4}$
Dalles	$-4.7e^{-12}x^3 - 5.53e^{-7}x^2 + 1.47x - 3.7e^{+4}$	$-2.9e^{-12}x^3 + 1.46e^{-6}x^2 + .33x + 1.73e^{+4}$	

Discussion

Primary Objective

Our study found that there will be a need for additional hydropower within the 2040 study period. In our analysis hydropower demand increased from 66 GW in 2019 to a range of 69-88 GWs for the low demand under scenario one and the high demand for the third scenario, respectively (Table 2.9). However, a recent study by Energy and Environmental Economics, Inc. (E3) sponsored by Puget Sound Energy, Avista, NorthWestern Energy, and the Public Generating Pool (a trade association representing 10 consumer-owned utilities in Oregon and Washington) showed hydropower production remaining constant at 35 GW annually through 2050 (E3, 2019). The apparent discrepancy between our demand versus the hydropower production evaluated in the E3 study is that our study evaluated demand rather than explore the financial and policy issues related to generation. As was acknowledged in the Legislative Summary, this is an important distinction in that hydropower generation may not be able to meet future electricity demands. The E3 study also validates an earlier assumption we made about the finite limits to conservation and efficiency improvements in the future.

Given the nature of the hydropower facilities within the CRB, i.e. being mostly run of the river with almost negligible storage capacity, they must generate power based on the flow going through the facility. The implication of this is demand for hydropower exists outside of the capacity to generate hydropower given seasonal flows. In such cases, other sources of power will need to be utilized. Moreover, in terms of the Forecast, when S.B. 5116 is considered, it is difficult to envision a feasible scenario that would allow additional water storage for release during periods when additional generation capacity exists. Consequently, while demand for hydropower will increase in the future, the system's ability to respond to that demand through increased generation will likely be limited to small tweaks in operations.

Climate change will likely impact the evaporation from reservoir pools but the evidence to accurately predict these quantities is not sufficiently developed for meaningful analysis. The Forecast runoff model indicates a hydrograph shift resulting in longer summer conditions that reasonably could lead to more water demand system wide. Understanding the impacts on storage operations both at Grand Coulee and other upstream storage facilities (e.g., Mica and Libby) could help in these efforts but more data collection surrounding lake evaporation would also be needed.

Secondary Objective

In understanding the role of climate change on hydropower production, it is thought that the seasonality of the CRB plays an important role in hydropower facility management. For example, weeks 28 through 38 generally accounts for a period of high run off where flows often exceed the hydraulic capacity of the hydropower facilities. Consequently, when looking at total river flow versus hydropower production, there are inherent discrepancies where higher flows may not translate to higher hydropower generation. Furthermore, operations appear to have shifted over time presumably in response to fish recovery efforts. Accounting for such patterns includes removing historic data that no longer accurately represents current facility management. By removing past outlying data, more accurate regression lines were fitted based on the most current management decisions for the hydroelectric facilities. Because the relationship between outflow and generation is not linear, the generation output is not an equal shift up or down relative to outflow. The general shape of the outflow and generation plots can best be seen both in Figure 2.19 and Figure 2.20 where 2^{nd} and 3^{rd} degree polynomial lines are fitted to operation conditions for each facility.

The outflow and generation relationship for The Dalles shown in Figure 2.19 is an example of the general shape for the distribution of points when plotting outflow versus generation. The solid red line depicting generation versus flow for Condition 1 (weeks 1-27 and 49-52 in a water year calendar – Sept 30 through Apr 6 and Sep 7 through Sep 28) likely reflects management decisions to generate less power during periods of extremely high flows (sometimes exceeding the 375 kcfs capacity of the powerhouse). This could be the result of several reasons such as insufficient electricity demand in the BPA system, efforts related to fish recovery efforts, or other management decisions resulting in dramatic drop-off in power production at flows greater than 300 kcfs. Care must be exercised when interpreting changes in this data sparse region as it would be incorrect to suggest that as flows decrease from 375 kcfs to 325 kcf that power production increases. Better understanding of how real-time decisions are made at each generation facility are needed although tracking down the decisions in a historical context was not feasible. The results of this distribution on generation can be seen in Figure 2.20. Figure 2.20 also exemplifies the need for conditional formatting to separate the different observed patterns in data due to seasonal shifts in outflow or fish management. For the case of The Dalles, it was assumed that the multiple relationships were due to different operational management from flow seasonality.

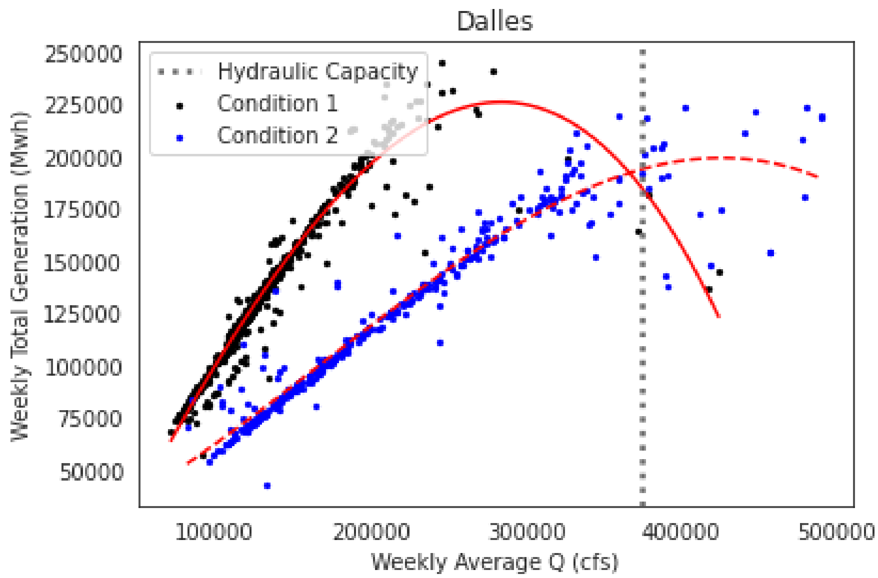


FIGURE 2. 20 WEEKLY TOTAL GENERATION VERSUS WEEKLY AVERAGE OUTFLOW FROM THE DALLES HYDROPOWER FACILITY (WY 2004-2020).

Figure 2.22 provides the results for both modeled baseline historic generation developed from the polynomial regression model as well as observed historic generation for each of the 11 hydropower facilities. Included in Figure 2.22 is also baseline historic outflows and observed historic outflows. While there are more than 11 hydropower facilities in our study area, our selection of facilities was done to ensure that major river reaches were represented.

From Figures 2.21 and 2.22 it is observed that historic modeled generation is like that of observed generation, following the same seasonal pattern based on outflow and showing similarity in magnitude. This seasonal pattern includes high seasonal runoff during the May and June resulting in an increase in historic and modeled historic hydropower generation. Also observed is the hydrograph and generation shapes for each facility respective of their location to other facilities and location within the CRB. For example, the facilities on the Snake River (Lower Granite, Lower Monument, and Ice Harbor) show a much less interrupted/managed hydrograph due to both the nature of them being RoR facilities and not down stream of any gravity fed facilities that may impact flow in and out of their system, such as what can be observed at and below the Grand Coulee hydropower facility. This cannot be said for facilities down stream of Grand Coulee on the Columbia River where, while they are RoR facilities, their hydrograph is often dominated by Grand Coulee and Chief Joseph Operations.

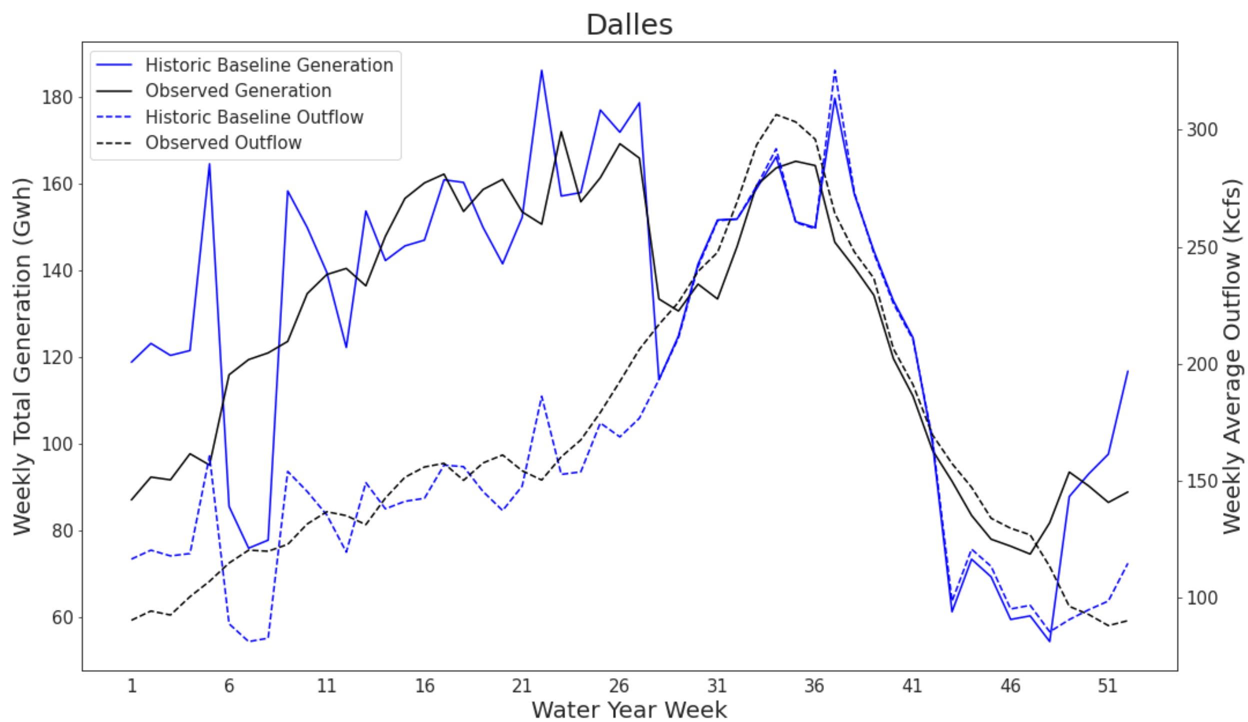


FIGURE 2. 21 HISTORIC MODELED AND OBSERVED GENERATION AND OUTFLOW FOR THE DALLES HYDROPOWER FACILITY.

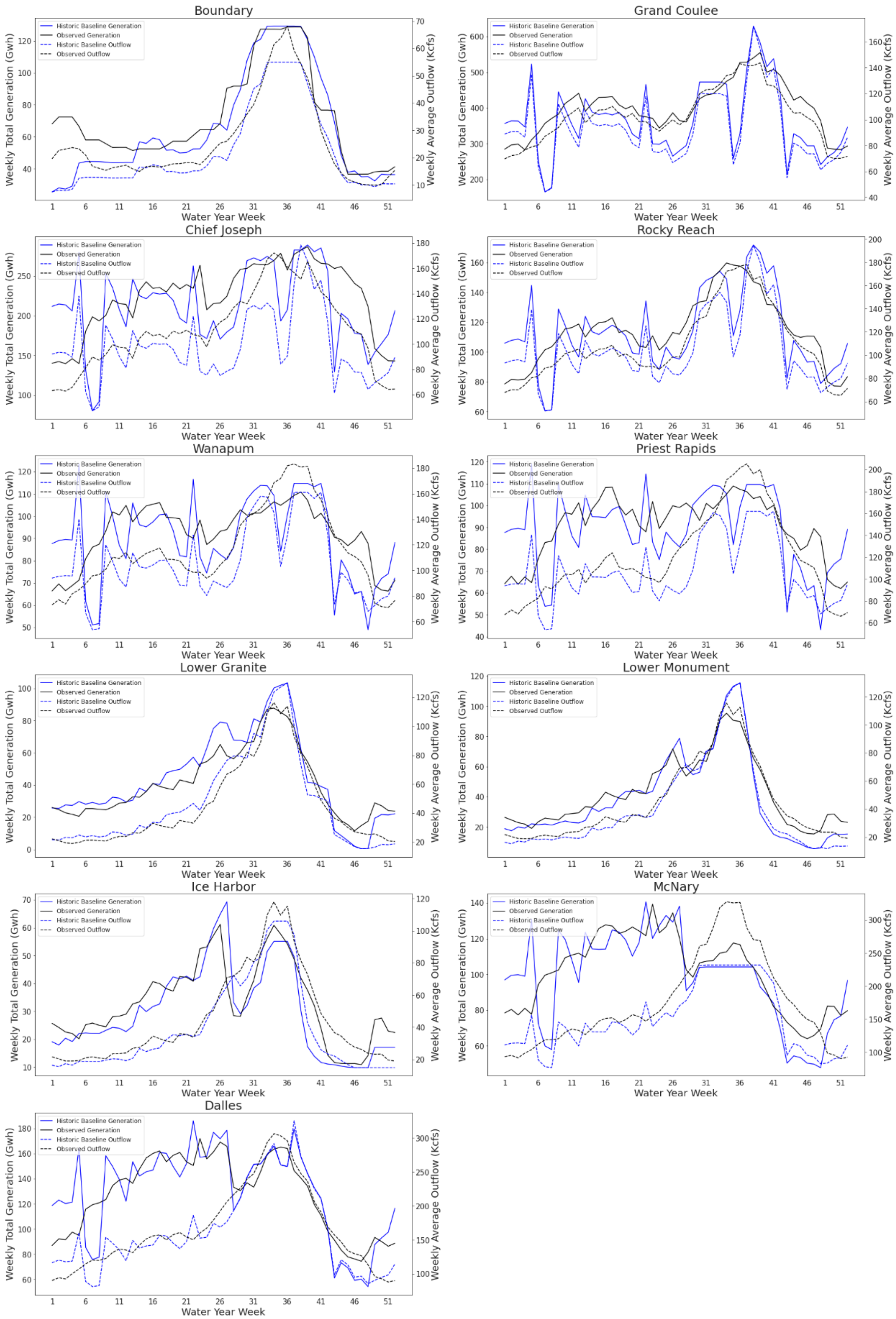


FIGURE 2. 22 HISTORIC MODELED AND OBSERVED GENERATION AND OUTFLOW FOR THE 11 HYDROPOWER FACILITIES.

In Figure 2.23, it can be observed for all the facilities except for Rocky Reach and Lower Granite, during WY 2026-2055 there is a shift forward in time for when peak generation occurs. There is also more variable generation during the fall months for both RCP 4.5 and 8.5 within the 2026-2055 period compared to what has historically been observed. This observation is especially true for the Middle Columbia hydropower facilities. During the spring and summer months (after peak runoff) and into September, modeled generation for both RCP’s is significantly lower than the observed generation during those seasons.

A similar pattern developed for the later period, 2056-2085. However, the 2056-2085 period has more exaggerated modeled median weekly generations with even greater variability during the fall weeks especially at the hydropower facilities located below Grand Coulee. Peak generation shifts further ahead into the water year occurring closer to mid-April compared to the historic peak which occurred late spring. Generation further decreases than what was observed in the 2026-2055 period (Figure 2.23). There is also more of an observed difference between the RCP’s during the fall season as well, except for the hydropower facilities below Grand Coulee on the Middle Columbia River, where generation within RCP 8.5 is lower than that of modeled generation within the RCP 4.5 simulation.

Within Figures 2.23 and 2.24, the impacts of the hydraulic capacity limits set within the empirical model can be observed, particularly for the McNary Hydropower facility. These flat lines occurred during weeks 28-38 which falls within condition two for McNary Dam. During the 28–38-week period, high weekly average flow occurs however generation is limited to only produce power within the range of McNary’s hydraulic capacity of 232 kcfs. Power can still be produced with flows greater than McNary’s hydraulic capacity however, past this point it is necessary for flow to be spilled and not ran through the facilities turbines. From Figure 2.19 it appears that generation does exceed past hydraulic capacity not only for McNary Dam but the other 10 hydropower facilities.

Table 2.12 provides the high, median, and low values of annual monthly average total generation for observed historical, and modeled 2040 and 2070 values under RCP 4.5 and 8.5 respectively. Within Table 2.12 there may be some skewing of historic annual monthly median total generation values due to dataset incompleteness. Only 7 of the 11 facilities have a complete 30-year average spanning from WY 1986-2015. These values are summed for each month and for the entire study site which includes all 11 facilities. Looking at this table is of particular importance when wanting to understand the impact of keeping or removing the Lower Snake River dams.

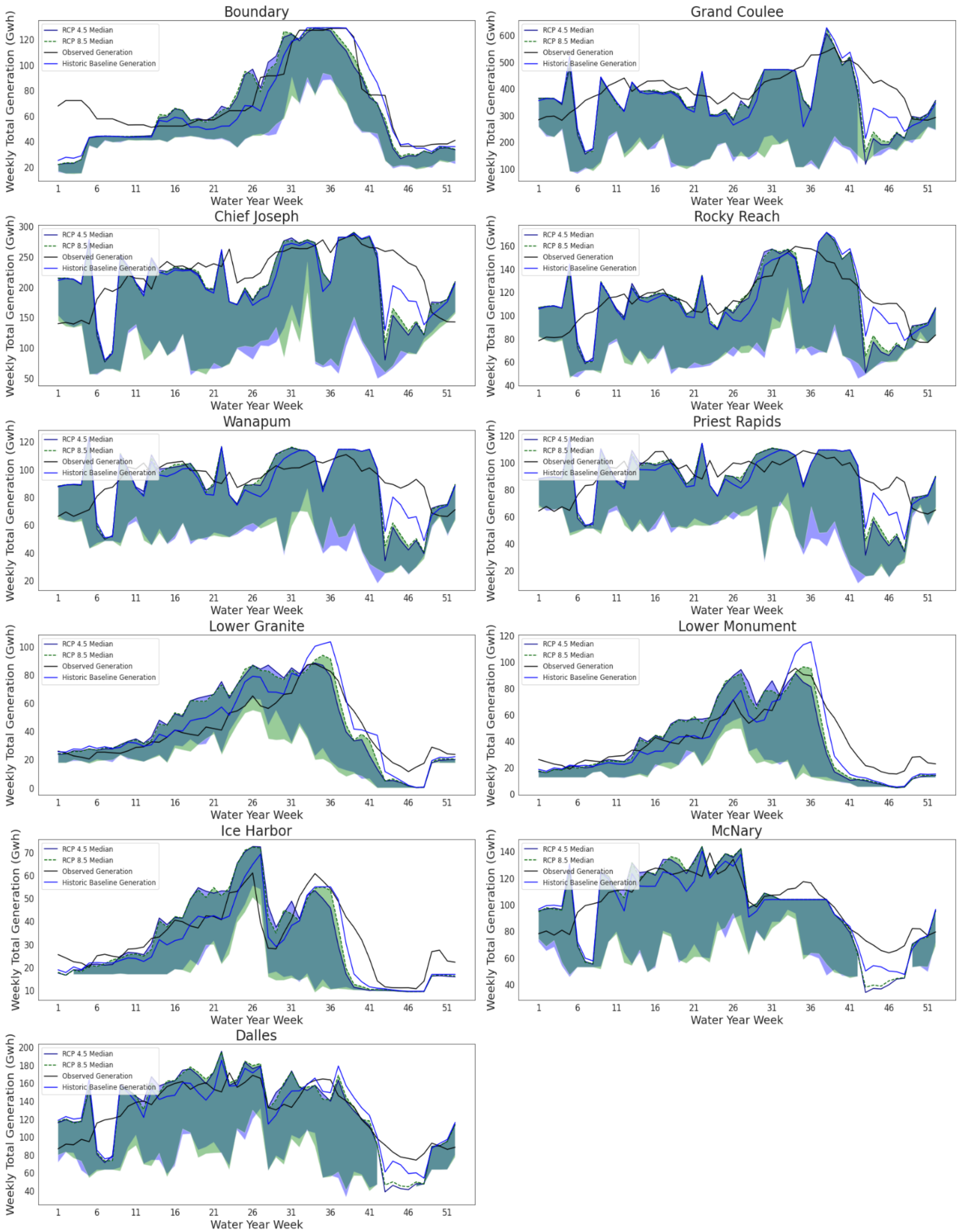


FIGURE 2. 23 2025-2055 RCP 4.5 AND 8.5 ANNUAL MEDIAN AND WEEKLY MINIMUM WEEKLY TOTAL GENERATION OUTPUTS COMPARED TO OBSERVED HISTORIC ANNUAL WEEKLY TOTAL GENERATIONS.

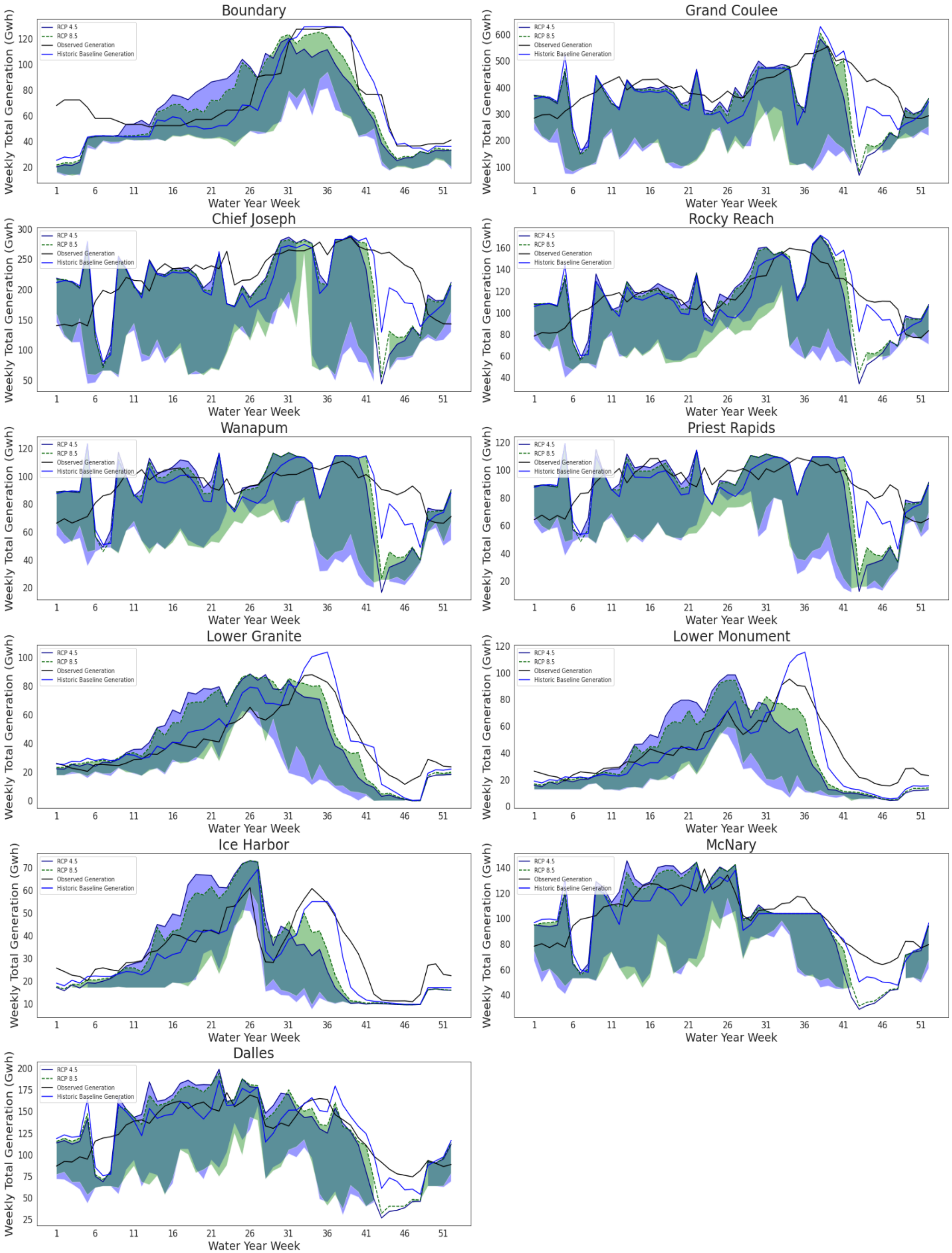


FIGURE 2. 24 2055-2085 RCP 4.5 AND 8.5 ANNUAL MEDIAN AND WEEKLY MINIMUM WEEKLY TOTAL GENERATION OUTPUTS COMPARED TO OBSERVED HISTORIC ANNUAL WEEKLY TOTAL GENERATIONS.

TABLE 2. 12 TOTAL STUDY POWER PRODUCTION WITH HISTORIC OBSERVED AND MODELED FUTURE SCENARIOS (GWH/MONTH).

Period		Historic	2040		2070	
RCP			4.5	8.5	4.5	8.5
Oct	High	6481	6373	6428	6451	6322
	Median	4665	4627	4623	4621	4578
	Low	3464	3195	3182	3069	2807
Nov	High	9649	9653	9791	9681	9678
	Median	5265	5165	5116	5056	5130
	Low	2720	2562	2582	2562	2413
Dec	High	7767	8125	8177	8231	8421
	Median	5054	5130	5195	5168	5320
	Low	3247	2896	2960	2854	2828
Jan	High	7308	8157	8002	8401	8858
	Median	5372	5673	5691	5731	5932
	Low	3010	2899	2901	2816	2800
Feb	High	7919	8452	8295	8548	8576
	Median	5185	5607	5585	5787	6087
	Low	2401	2459	2485	2433	2475
March	High	10323	10647	10587	10647	10683
	Median	6675	7124	7091	7250	7428
	Low	3182	3796	3754	4316	4591
	High	8290	8430	8412	8485	8484

Period		Historic	2040		2070	
April	Median	5484	6115	6162	6307	6440
	Low	2295	2979	3184	3739	3909
May	High	9854	10094	10029	10100	10158
	Median	8257	8413	8409	8270	8086
	Low	3902	3983	4270	4416	4521
June	High	8615	8609	8588	8566	8510
	Median	6891	6623	6485	6342	6137
	Low	2870	2681	2484	2441	2114
July	High	8101	7813	7672	7495	7307
	Median	5251	4862	4670	4206	3509
	Low	2268	2081	1945	1972	1748
Aug	High	8441	7936	7841	7512	6898
	Median	4365	3373	3216	3041	2813
	Low	2518	2547	2521	2494	2440
Sept	High	4806	4718	4628	4693	4640
	Median	3929	4026	4045	4095	4115
	Low	3088	3082	3109	3054	2897

Looking specifically at the three lower Snake River facilities included in our study, Table 2.13 provides the high, median, and low values of monthly median total generation for observed historical, and modeled 2040 and 2070 values under RCP 4.5 and 8.5, respectively. Assuming Little Goose behavior is similar to the other three hydropower facilities (Lower Granite, Lower Monument, and Ice Harbor), it is observed from Table 2.14 that the Snake River hydropower facilities are projected to change, sometimes significantly, depending on season in their hydropower generational output under both RCP scenarios for both the 30-year averages of 2040 and 2070. High, median, and low observations of generation worsen from November to May. There is generally a decline over time and under the separate RCP scenarios of high, median, and low monthly annual median totals from observation period values. The characteristics of overall higher generation especially in the late fall and winter can also be seen when looking at Figure 2.23 and Figure 2.24 which shows a clear increase during those seasons for the Snake River hydropower facilities. This observation falls into the general theme of the results from this analysis in that there is a temporal shift forward in when peak hydropower generation is available and a reduction of available hydropower generation in early spring to mid-summer. Generation of hydropower for the Snake River hydropower facilities decreases greatly during the Spring and Summer months with improvements in generation output during the mid to late Fall and Winter. This can also be said for the other facilities used in this analysis. It is important to understand that most of these facilities are run of the river systems with very little storage capacity. It can be inferred that the limiting factor would then be 'when is there an actual demand for hydropower generation and will that demand align with the above noted seasonal shifts generation production' which does not include the complexity of overall facility management and fish ecosystem health.

TABLE 2. 13 TOTAL SNAKE RIVER POWER PRODUCTION WITH HISTORIC OBSERVED AND MODELED FUTURE SCENARIOS (GWH/MONTH).

Period		**Historic**	**2040**		**2070**	
RCP			**4.5**	**8.5**	**4.5**	**8.5**
	High	535	512	544	511	497
Oct	Median	259	244	245	239	228
	Low	195	195	194	195	193
	High	779	808	851	822	827
Nov	Median	365	361	359	355	337
	Low	261	258	257	257	253
	High	937	1089	1125	1143	1155
Dec	Median	314	339	352	346	383
	Low	205	201	201	198	199
		952	1089	1111	1133	1159

Period		Historic	2040		2070	
	High					
Jan	Median	410	525	529	546	614
	Low	229	240	249	238	236
	High	1058	1072	1077	1077	1080
Feb	Median	536	683	690	770	872
	Low	307	337	347	324	349
	High	1399	1405	1402	1404	1406
March	Median	862	1055	1057	1118	1158
	Low	482	579	637	661	674
	High	1104	1104	1104	1104	1104
April	Median	694	824	856	842	856
	Low	316	379	463	467	384
	High	1371	1371	1371	1371	1371
May	Median	1149	1097	1095	1012	866
	Low	420	317	348	292	202
	High	1096	1091	1070	1048	992
June	Median	732	577	494	415	326
	Low	186	135	151	128	110
	High	747	572	576	470	403
July	Median	239	190	164	153	122
	Low	87	82	82	77	70
	High	373	325	349	302	248
Aug	Median	104	96	93	91	85

Period		Historic	2040		2070	
	Low	78	78	78	78	78
	High	386	363	366	358	318
Sept	Median	212	202	196	194	182
	Low	191	191	191	191	191

TABLE 2. 14 PERCENT OF SNAKE RIVER MODELED GENERATION VALUES FROM THE HISTORIC OBSERVED GENERATION.

Period RCP		Historic	2040 4.5	8.5	2070 4.5	8.5
	High	535	96%	102%	96%	93%
Oct	**Median**	259	94%	95%	92%	88%
	Low	195	100%	99%	100%	99%
	High	779	104%	109%	105%	106%
Nov	**Median**	365	99%	98%	97%	92%
	Low	261	99%	99%	99%	97%
	High	937	116%	120%	122%	123%
Dec	**Median**	314	108%	112%	110%	122%
	Low	205	98%	98%	97%	97%
	High	952	114%	117%	119%	122%
Jan	**Median**	410	128%	129%	133%	150%
	Low	229	105%	108%	104%	103%
	High	1058	101%	102%	102%	102%
		536	127%	129%	144%	163%

Period		Historic	2040		2070	
Feb	Median					
	Low	307	110%	113%	105%	114%
	High	1399	100%	100%	100%	100%
March	Median	862	122%	123%	130%	134%
	Low	482	120%	132%	137%	140%
	High	1104	100%	100%	100%	100%
April	Median	694	119%	123%	121%	123%
	Low	316	120%	147%	148%	122%
	High	1371	100%	100%	100%	100%
May	Median	1149	95%	95%	88%	75%
	Low	420	76%	83%	70%	48%
	High	1096	100%	98%	96%	91%
June	Median	732	79%	68%	57%	45%
	Low	186	72%	81%	69%	59%
	High	747	77%	77%	63%	54%
July	Median	239	79%	68%	64%	51%
	Low	87	94%	93%	88%	79%
	High	373	87%	94%	81%	67%
Aug	Median	104	92%	89%	88%	82%
	Low*	78	100%	100%	100%	100%
	High	386	94%	95%	93%	83%
Sept	Median	212	95%	93%	91%	86%
	Low*	191	100%	100%	100%	100%

**No change in low values for August and September are an artifact of the procedure and are an overestimate.*

Conclusions

Passage of the Clean Energy Transformation Act (CETA) by the Washington State Legislature in 2019 will undoubtedly change the mix and demands for reliable energy sources such as hydropower. The elimination of baseload power supplies in favor of carbon neutral electricity alternatives will create a need for reliable and continuous power production. Coupled with the impacts of climate change, this study demonstrated the resiliency of the hydropower system to deliver an increase in 30-year average weekly peak totals of 12 GWh under the 2040 4.5 RCP, 11 Gwh under the 2040 8.5 scenario and 10-9 GWh under the 2070 4.5 and 8.5 RCP scenarios respectively but, timing/extremes will play a somewhat predictable role in when and the magnitude of which power will be generated.

Primary Objective

In addressing the four questions related to this objective, it must be understood that supply for hydropower generation does not equate to demand of hydropower generation and accounting for new legislature will reduce the role in future hydroelectric facilities. It is expected that with population growth, technology such as required registration of electric vehicles and increased data centers, paralleled with an increasing dependence on electricity that need for hydropower generation would increase. Our study provided a rough estimate of that demand with historical hydropower generation, population, vehicle registration and data center estimates in the State of Washington. Showing an overall increase as low as 5% and as high as 47% into 2040 from the 2019 hydroelectric generation demand value of 66 GW. How the State of Washington is able to make up these increases in demand depends on the introduction and reliability of renewable energy as there is little question to the impact climate change will have on the resilience of hydroelectric facilities regarding the magnitude and timing of seasonal flow as well as the increase from potential evaporation losses on current facilities.

Secondary Objective

There is a strong relationship between outflow below hydropower facilities and the total generation they produce even though spills occur during high flow months and at other times when they were not producing power at maximum capacity. Using this relationship, an empirical relationship was developed between generation dependent on outflow. R squared values ranging from .65 to .96 were observed when fitting the polynomial regression lines to the observed data. We were able to model future generation given our polynomial based empirical formulas. Inputs for the empirically based formulas were results from the regulated flow analysis of the RColSim model which utilized 17 GCM's to run simulations of baseline historic flow data and future flow data to forecast stream flow at a weekly total into 2085. The high R squared values show a strong correlation between generation and outflow, there is an instance where a low R squared value occurs. For condition two at the McNary facility, an R squared value of .34 is observed. Condition two is during weeks 28-38 which is historically during the spring runoff. It is believed that this low R squared value is a characteristic of the variability in observed generation demand for that period of weeks.

The seasonal pattern in the modeled historical baseline generation matched poorly with that of the observed generation. The average peak for the baseline generation was 16 GWh larger and occurred on average 3 weeks prior to the observed generation. For the 2025-2055 period there was a shift forward in peak generation. Peak generation occurred on average 3 to 4 weeks before average observed peak. Average peak generation was also greater than that of average observed historic peak ranging from 192 to 190 GWh's greater than the historical observed average peak. For the 2055-2085 period a similar pattern was observed with peak generation occurring 4 to 5 weeks earlier than the observed peak. Average peak generation for this period was 189 to 188 GWh's for the 4.5 and 8.5 RCP scenarios respectively.

TABLE 2. 15 SHIFT IN MAGNITUDE OF PEAK AND WHEN PEAK OCCURS (WEEKS) FROM THE OBSERVED HISTORICAL GENERATIONAL DATA BASED ON MODELED OUTPUTS.

	Historic Observed	Historic Baseline Modeled	2040		2070	
RCP			4.5	8.5	4.5	8.5
Week*	32.5	-3	-4	-4	-4	-5
Generation (GWh)	179	+16	+12	+11	+10	+9

**Average weekly maximum value and occurrence was taken between WY weeks 22-52*

An overall temporal shift forward in peak generation as well as increased magnitude of generation means that more generation will occur earlier than what has been historically observed. There will be a potential for even more generation during fall and late winter when demand for hydroelectric power is not at its greatest.

Hydropower facility management involves a multitude of stakeholders who are beholden to providing generation when demand requires it as well as ensuring the fisheries within the CRB stay intact. While working with the observed data for the hydropower facilities, it was noticed that throughout time there were shifts in generation and outflow. It is difficult distinguish whether these shifts were due to management practices or changes in flow regime. Hydropower facilities are limited in generation by not only their generation capacity but hydraulic capacity which ensures that total dissolved gasses below the hydropower facilities from outflow will not endanger fish. Often, forecasting for fish management occurs on a short-term basis meaning that the distinguished flow conditions are not a thorough example of management. Along with this, there are a myriad of other limitations to this analysis including the introduction of legislation which impacts hydropower facility management such as S.B. 5116 or the further introduction of solar or wind powered generation.

Given the results of this study, it can be concluded that hydropower generation within Washington State and the greater Columbia River basin is sensitive to the impact of climate change. More variable periods of generation during the fall with a forward shift in peak generation means a lack of reliability of generation output with peak generations occurring further from when demand is generally at its highest. Furthermore, forecasted Spring and Summer seasonal generation output was observed to be less than that of historically observed generation for the same seasonal periods. If demand for electricity increases as forecasted, this may pose a potential problem for incorporating management practices for fish in combination with fulfilling an increase in electricity demand.

Module 6 – Evaluating Trends in Groundwater Levels

Overview of Approach

The 2021 groundwater module expands on the 2016 report by conducting a trend and vulnerability analysis across Eastern Washington. This section describes additional methods and results in support of the findings presented in the Legislative Report and includes a discussion on groundwater data availability.

Methodological Details

Trends in Groundwater Levels

Site Selection

Data Access

Information about wells and measurements of groundwater levels were primarily acquired from the Washington State Department of Ecology's (Ecology) online database, the Environmental Information Management (EIM) system. The depth to groundwater parameter was queried based on two study ID's representing Ecology's annual/semi-annual groundwater monitoring program for the Ecology Central Regional Office Groundwater Database (CRGWDB) and the Ecology

Eastern Regional Office Groundwater Database (EROGWDB). Each county in the study area was also queried for all study ID's. Additional groundwater level data were also obtained from the Walla Walla Basin Watershed Council, the Washington State Department of Natural Resources and the U.S. Geological Survey. The depth to groundwater level was converted to groundwater level elevations using the datum information reported for each well. In addition to the depth to groundwater measurements from the EIM database were the well types, well locations, land-surface elevations, and the well completion depths. The type of wells used for this research were irrigation wells, monitoring wells, and domestic water supply wells.

Selection Criteria

The water-level data were filtered by selecting wells from a "historical" time period, 1975-2020, and a "recent" time period, 2000-2020. A minimum of 10 spring high measurements were required for the historical time period, with at least eight occurring since 2010. A minimum of eight spring high measurements were required for the recent time period, following guidance by the Environmental Protection Agency to have at least eight data points to compute a trend using the Sen slope (EPA, 2009). An exception was made for the Walla Walla and Palouse subareas where a minimum of five spring high measurements were used as the criteria because the wells in these subareas did not meet the selection criteria of a minimum of eight, but are known to be important groundwater-dependent regions. Spring high groundwater level measurements were used as the representative equilibrium or static condition after drawdown in the summer and recharge in the winter. The spring high measurements were identified as the shallowest depth-to-water observations between February and May of any given year.

Groundwater Subareas

Groundwater subareas were defined to create watershed–equivalent boundaries, as geographic boundaries with similar hydrogeologic characteristics and groundwater hydraulic connectivity. Only regions that contained wells that met the selection criteria were used to delineate groundwater boundaries based on a combination of preexisting groundwater boundaries and Water Resources Inventory Areas (WRIA), when existing groundwater boundaries were not available. Geographic boundaries delineated by Vacarro et al., (2009) in the Yakima Basin were used to define five subareas in the Yakima Basin including the Roslyn, Kittitas, Selah, Yakima, and Toppenish Basins. Groundwater management areas established under WAC 173-100 defined the Odessa and Quincy subareas. The Palouse Groundwater Basin followed the boundaries outlined by the Palouse Basin Aquifer Committee. The Spokane boundary was based on the boundary of the Spokane Rathdrum Prairie Aquifer outlined in a shape file provided by the City of Spokane (City of Spokane, 2020). The Northern CPRAS subarea was defined by merging four WRIAs (Foster, Moses Coulee, Grand Coulee, and Upper Crab-Wilson) clipped to the extent of the CPRAS aquifer. The remaining subareas were defined directly by WRIAs.

Hydrograph Review

Hydrographs were constructed for each of the wells that met the selection criteria. Each hydrograph was qualitatively reviewed for abnormalities indicative of factors such as airline breaks. Any hydrograph with an abnormality was reviewed by the Ecology regional office that had collected the original data. The trends of the hydrographs of the wells that had airline breaks and other factors noted as abnormalities were adjusted based on the recommendations by the office of Ecology responsible for the monitoring of these wells. In some instances, outlier points were removed, which occasionally resulted in a well being removed from analysis if it no longer met the required minimum number of observations. The adjustments were made by averaging the trends before and after each break in observations and using the average trend to readjust the water-levels after the breaks. The trend was then re-computed for the overall trends used for the remainder of the analysis.

Figure 2.25 shows an example of a well containing airline breaks. Figure 2.25 contains the full record of depth to water for the historical time period considered herein. Airline breaks are visible in 1993 and 2007, indicated by the jumps in depth to water. The calculated trends on either side of the breaks are consistent. The trend before and after the airline break in Figure 2.26 is -7.86 ft/yr and -6.92 ft/yr, respectively. The average of these values is used to reset the post-break depth to water values for a continuous record from which the overall trend is recalculated.

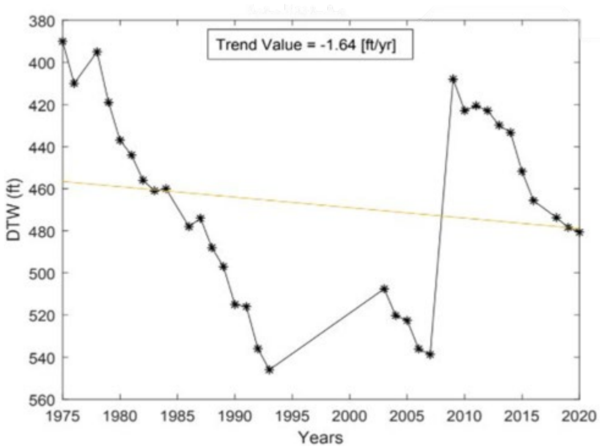


FIGURE 2. 25 SAMPLE HYDROGRAPH OF DEPTH TO WATER (FT) UNDER REVIEW FOR WELL ID AHP747. THIS FIGURE SHOWS THE FULL HISTORICAL RECORD FOR THE WELL. AIRLINE BREAKS ARE VISIBLE IN 1993 AND 2007

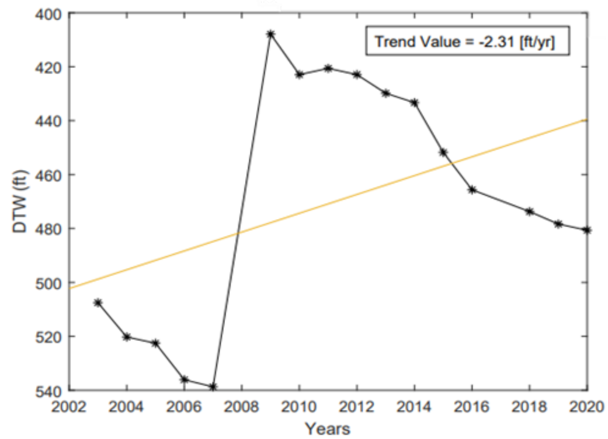


FIGURE 2. 26 SAMPLE HYDROGRAPH OF DEPTH TO WATER (FT) UNDER REVIEW FOR WELL ID AHP747. THIS FIGURE SHOWS THE RECENT PERIOD ONLY. THE YELLOW LINE SHOWS A TREND COMPUTED FROM A LINEAR REGRESSION. THE REPORTED TREND VALUE IN THE BOX AT THE TOP OF BOTH FIGURES IS CALCULATED WITH THE SEN SLOPE ESTIMATOR, INDICATING THE ADVANTAGE OF THE SEN SLOPE ESTIMATOR IN CALCULATING TRENDS WHERE UNDETECTED OUTLIERS OR OTHER ABNORMALITIES MAY BE PRESENT.

Separation by Aquifer Layer

The well log for each well was reviewed to determine the depth of the screened interval. The screened interval depth was then compared to the USGS CPRAS model's (Burns et al., 2011) aquifer layers to determine which aquifer layer (Overburden, Saddle Mountains, Wanapum, Grande Ronde) the well was screened in. Only wells identified as being screened in a single aquifer of the CPRAS were selected for further analysis.

Evaluating Point Trends

Long-term trends were computed for all hydrographs. The magnitude of the trends was computed using the non-parametric Sen slope estimator (Sen, 1968). The Sen slope estimator is a linear regression method that selects the median slope among all lines through pairs of two-dimensional sample points. The Sen slope method was chosen due to its low sensitivity to outliers. The low sensitivity is demonstrated in Figure 2.26), where the yellow line shows the trend based on a simple linear regression. The linear regression results in a positive trend, which is not representative of the data. The Sen slope shows a negative trend value prior to the airline break adjustment. The trend if -8.14 ft/yr from 1975 - 1993, -7.82 ft/yr between 2003 and 2007, and -6.92 ft/yr from 2009 to 2020.

A trend comparison was conducted for the historical time period (1975-2020) to evaluate the number of data points to require while still maximizing spatial coverage. The comparison was between a minimum of 10 and a minimum of 20 spring high measurement, with at least eight falling after 2010. Table 2.16 shows the mean and standard deviation for each option across all subareas and all layers. The difference between the means is insignificant to the 95% confidence level, therefore the criteria of a minimum of 10 spring high measurements was chosen for the historical time period to maximize the number of well locations included in the analysis. After consultation with Ecology Water Resources staff, the results presented herein are based solely on the recent trends (2000-2020) to be more representative of current conditions.

TABLE 2. 16 STATISTICAL COMPARISON OF ALL TRENDS FOR A MINIMUM OF 10 WITH AT LEAST 8 POINTS AFTER 2010 VERSUS A MINIMUM OF 20 SPRING HIGH MEASUREMENTS.

	Minimum 10	Minimum 20
Total number of wells	470	247
Mean	-1.20	-1.49
Standard deviation	2.35	2.23

The Mann-Kendall (MK) test was used to determine whether the trends of the selected wells had a significant monotonic upward or downward trend. The MK trend test, originally developed by Mann (1945) and Kendall (1975), is a nonparametric test used for identifying the significance of trends without stating whether the trends are linear or non-linear (Wu et al., 2008). The hypothesis testing of the MK test was conducted using a 95% confidence level. The box plots of trends in the aquifer pages of the Legislative Report are based on the significant and insignificant trends across all point locations by subarea by aquifer layer. Figure 35 in the Legislative Report shows the location of all the final wells included in the analysis, separated by aquifer layer. Figure 2.31 shows box plots of the significant trends only for each subarea and aquifer layer.

Trend Interpolation

The individual point trends were interpolated within each subarea and for each aquifer layer to provide trend surfaces that covered a larger spatial area than the individual points. While the interpolated trend surfaces represent trends over the areas between individual points, it is important to note that the interpolated coverage has not been validated by point data within these gap areas. The inverse distance weighting (IDW) method (Cressman 1959; Shepard 1968; Barnes 1973) was used for the interpolation using a fixed radius of six miles and bounded by each subarea. The interpolation was done separately for each subarea within each aquifer layer. The interpolated trend surfaces in Figures 36-37 and shown in the aquifer pages of the Legislative Report are based on all trends (i.e. significant and non-significant trends).

Future Changes in Available Saturated Thickness

Groundwater vulnerability is defined based on changes in the amount of groundwater available for pumping, which is defined herein as the available saturated thickness. The available saturated thickness is quantified as the distance between the spring high water level and the pump intake location (Figure 8, Legislative Report). The pump intake location is estimated as 20 feet above the bottom of the well, with the well depth for each study well taken from the associated well log. A well was excluded from further analysis if the well depth was shallower than 20 feet. The vulnerability levels were based on an average of the point trends per subarea per aquifer layer of the significant trends only and only for subareas with a minimum of three well locations with significant trends. The point trends, pump intake locations, and 2020 spring high water levels were averaged by subarea by aquifer layer and the vulnerability was then calculated from the averaged values.

The changes in available saturated thickness are a result of changing spring high water levels, while the pump intake location is constant. The changes are compared to a baseline available saturated thickness in the year 2020. Figure 2.32 shows the spread and median behavior of the available saturated thickness for each point location prior to averaging by subarea. The figure shows that some subareas, such as the Yakima Basin, have a wide range of available saturated thickness across the wells included in the subareas. This contrasts with subareas such as the Palouse Basin in the Grande Ronde and Quincy Basin in the Wanapum that have more similar available saturated thickness across the wells included.

A trend projection was used to estimate the water level in 2020 if spring high water level measurement were not available. The recent trend was projected to 2020 starting in the last year of observed data. For all wells, future changes in available saturated thickness were estimated by projecting the recent trend calculation forward from 2020 into the future. The percent change in available saturated thickness in 2040 was calculated by projecting the trend to 2040, computing the available saturated thickness in 2040 and calculating the percent change from 2020. The trends were also projected forward until a 25%, 50%, and 75% reduction in available saturated thickness was achieved. Vulnerability for the latter change estimate was based on the number of years until each percent change threshold was reached.

Groundwater vulnerability was evaluated based on the future changes in available saturated thickness. This method allows for vulnerabilities to be driven by a combination of the severity of a trend and the water available for pumping based on the well depth. Figure 38 in the Legislative Report shows the most vulnerable subarea across all aquifer layers, such that the vulnerable subareas in the figure are representing different aquifer layers. The figure is based on the number of years to a 25% reduction in available saturated thickness, showing a total of 11 subareas with approximately 60 years or less until this metric is reached.

The Walla Walla in the Overburden layer and the Okanogan subareas have the fewest number of years to a 25% reduction in available saturated thickness, with approximately 10 years each. The high degree of vulnerability in both cases is driven by a small average available saturated thickness as opposed to a steep decline trend. The average available saturated thickness in 2020 is 40 feet and 34 feet for Walla Walla and Okanogan, respectively, and the average significant trend for each is -1.0 ± 2.3 ft/yr and -0.8 ± 0.5 ft/yr for each. In the case of the Walla Walla, Figure 2.26d) shows the spread of the trend values used to calculate the average includes both positive and negative trends and was based on a total of four locations across the whole subarea. The six wells used to calculate the average significant trend in the Okanogan have a small spread around the median. The Quincy Basin in the Wanapum layer has approximately 30 years to a 25% reduction in available saturated thickness, also driven by a small average available saturated thickness, despite a small negative trend.

Rock Glade and Eastern Benton in the Wanapum and the Yakima Basin in the Saddle Mountains are considered the next most vulnerable, with approximately 20 years to 25% decline to average available saturated thickness. The vulnerability in these subareas and layers are driven primarily by steeper average declines. The Yakima Basin has a large spread in average available saturated thickness (Figure 2.32c) from close to zero feet to over 400 feet depending on the well site. High vulnerability in Eastern Benton County is based on wells clustered in the Black Rock area (see figure 35 of the Legislative Report). The Red Mountain subarea in the Saddle Mountains and Northern CPRAS in the Grande Ronde both have approximately 30 to 40 years to 25% decline in average available saturated thickness. Both have significant trends ranging from close to 0 ft/yr to ~-5 ft/yr, with a positive value included in the Northern CPRAS. They also have a similar spread of average available saturated thickness, primarily between 300-400 ft, with Northern CPRAS having some larger values including an outlier.

The Odessa subarea in the Grande Ronde has the largest number of wells with a significant trend (60) contributing to the approximately 40 years to 25% reduction in average available saturated thickness. The significant trend values have a large spread from the most negative to most positive value, but are predominantly negative. The average available saturated thickness primarily ranges between 200 and 800 feet, with some larger extreme and outlier values. The Extended Toppenish in the Saddle Mountains also has approximately 40 years to 25% reduction in average available saturated thickness. The significant trends in this subarea range from slightly positive to about -5 ft/yr with a large spread of average available saturated thickness.

The Palouse Basin has approximately 60 years to 25% reduction in average available saturated thickness in the Grande Ronde. The spread in both the significant trend values and average available saturated thickness in this subarea is relatively small. The negative trends are close to -1 ft/yr, with the vulnerability driven primarily by small available saturated thickness.

Selah in the Grande Ronde and Spokane in the Beyond CPRAS region also have at least three wells with significant trends. The Selah has a small spread of negative significant trends that are close to 0 ft/yr with average available saturated thickness ranging close to 500-1000 ft, resulting in more than 100 years to 25% reduction in average available thickness. The Spokane subarea in the Beyond CPRAS region only has positive significant trends, therefore the vulnerability analysis was not conducted.

Additional Data Collection

To expand upon Ecology's existing groundwater level monitoring network within the CPRAS in areas where declining trends in groundwater levels have been documented and/or where groundwater level monitoring data is sparse, identification and selection of new groundwater level monitoring sites was completed. The expanded groundwater level data set will be used in future Water Supply and Demand Forecasts and will be uploaded to Ecology's Environmental Information Management (EIM) Database so they may be publicly available for use by others in additional studies.

The process to identify potential monitoring locations included a data gaps analysis that produced focused areas for detailed review of existing groundwater well logs for sites likely to provide good quality water level data. Outreach to well owners was then undertaken to obtain permission to access candidate wells for water level monitoring. A Quality Assurance Project Plan (QAPP) was prepared to guide field procedures and fulfill data quality assurance requirements for upload to EIM.

Working in cooperation with local entities, including Conservation Districts, WDNR, and WDFW assisted both the selection of sites and outreach to landowners based on local presence and existing relationships with landowners. This reinforces the value of projects that are implemented at the local level (WRIA, conservation district, and structurally isolated aquifers) to increase the coverage of available groundwater monitoring data throughout the CPRAS area. The identification of regional data gaps and water level trend analysis implemented at the scale of the CPRAS, such as the effort discussed here, will aid future efforts to focus on funding and outreach strategies to implement additional groundwater monitoring in areas where the risk from declining groundwater levels is greatest, or least understood.

GIS Data Gaps Analysis

To identify areas that would benefit from additional groundwater level monitoring, a geospatial gap analysis compared spatial density of groundwater rights, groundwater well locations, and existing monitoring sites. It included assessments of GIS coverages for existing Ecology, U.S. Geological Survey (USGS), and WA Department of Natural Resources (DNR) groundwater level monitoring networks, along with the density of groundwater rights, and primarily identified priority areas that met the following criteria:

- Publicly available current groundwater monitoring data is sparse or not available
- Reliance on groundwater is high

Additional criteria were also considered:

- Existing data show declining groundwater
- Identified as water level monitoring data gap in the previous 2016 Water Supply and Demand Forecast (Hall et al., 2016)

Results of the data gaps analysis are shown in Figure 2.27 below. Discussion of sources and representation of the data in the GIS is discussed below.

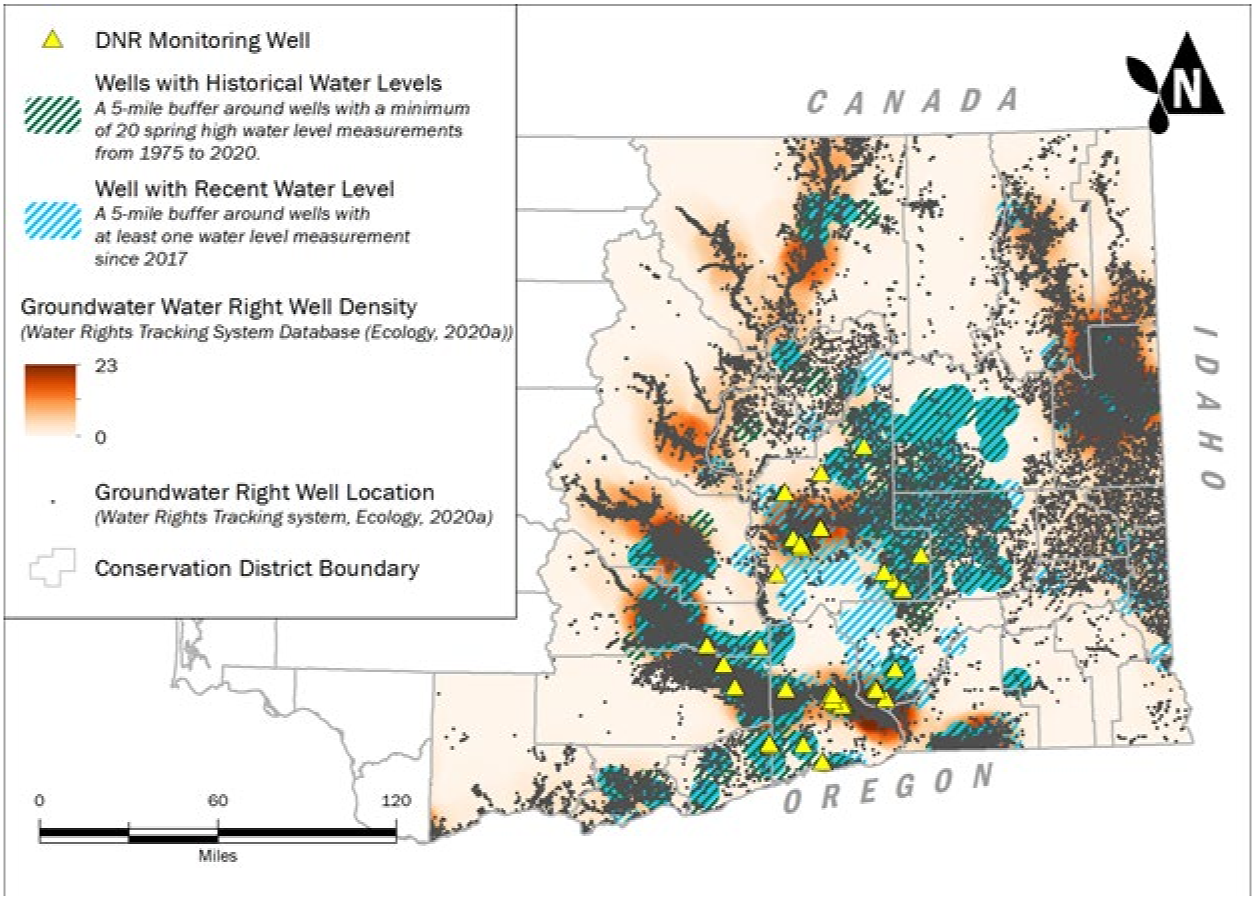


Figure 2. 27 Data Gaps Analysis. Current and historic water level monitoring is juxtaposed with water use as represented by groundwater rights points of withdrawal. Data Sources: Water Rights Tracking System (Ecology, 2020a), EIM, Study ID: GWDB (Ecology, 2020b), US *GS NWIS (USGS, 2020), and DNR personal communication (DNR,2019).*

Groundwater Right Density

Proximity to high groundwater use areas was indicated by density of groundwater points of withdrawal permitted for use in the Water Rights Tracking System Database (Ecology, 2020a).

Current Groundwater Monitoring Coverage

The current ground water monitoring coverages were represented in the GIS by data from the following data sources:

- Ecology - EIM groundwater level data from Eastern and Central Regions downloaded from the EIM Database under the GWDB study ID (Ecology, 2020b)
- USGS - groundwater level data retrieved from the National Water Information System (NWIS) (USGS, 2020)
- DNR – groundwater levels measured annually in Washington State Department of Resources owned wells by DNR Staff (DNR, 2019).

These data were represented in the GIS analysis with 5-mile buffer around each of the well locations. Locations with "recent data" were represented by filtering locations to show only locations with at least one spring high water level measurement since the beginning of 2017. Locations with robust historical data sets were represented by locations with a minimum of 20 spring high water level measurements from 1975 to 2020.

Priority Areas

Several priority areas were identified in the data gaps analysis to focus the area of new site selection and well logs for wells located in those areas were obtained from Ecology's online Well Report Viewer for well log review. The locations of wells in the priority areas are displayed in Figure 2.28. The well log review is discussed in the following section.

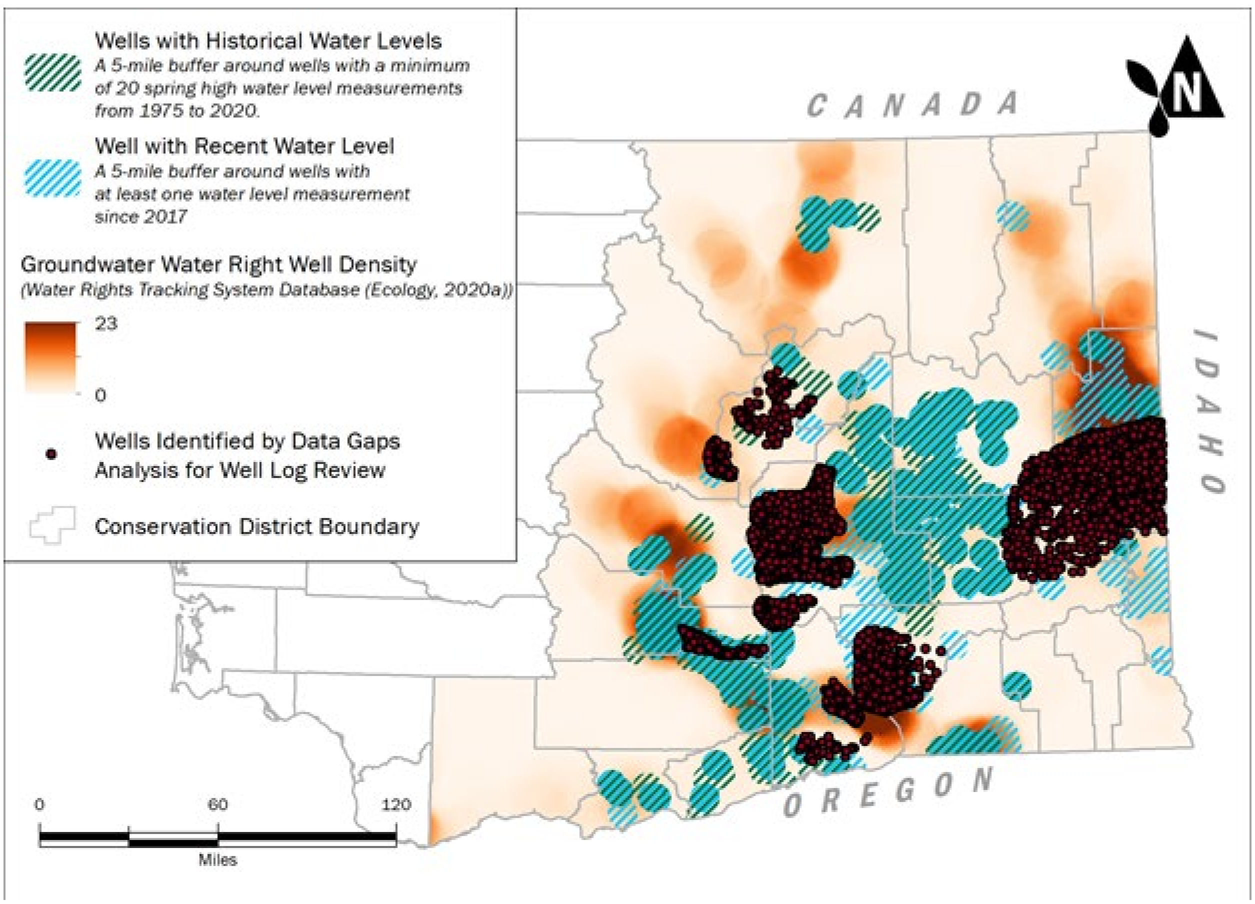


FIGURE 2. 28 LOCATION OF WELLS IDENTIFIED IN DATA GAPS ANALYSIS FOR WELL LOG REVIEW.

Well log Review

Once priority areas were identified by the GIS data gaps analysis, well logs were obtained from Ecology's online Well Report Viewer and reviewed for monitoring suitability. Drilling notes and geologic descriptions were evaluated, and the wells were prioritized based on records that had sufficient detail to differentiate between the major basalt formation of the CPRAS (Overburden, Saddle Mountain, Wanapum, and Grande Ronde). The well locations were compared to the USGS CPRAS Three-Dimensional Geologic Framework Model (Burns et al., 2011) to estimate the deepest aquifer formation penetrated by the well. Well construction details were evaluated and compared to geologic descriptions, and priority was given to cased wells having open intervals within a single basalt group (i.e. not cross-connecting aquifers), primarily the Wanapum and Grande Ronde groups.

The initial data gaps analysis yielded over 4,000 well logs in PDF format. To filter the list of well logs, an automated process was developed utilizing Amazon's AWS Textract software service. Amazon Textract uses Optical Character Recognition (OCR) technology to automatically detect printed text, handwriting, and numbers in a scan or rendering of a document. Domestic wells were not considered due to complexity introduced by increased sanitation and decontamination considerations. OCR technology was utilized to scan thousands of well log documents and identify logs with boxes that were checked indicating they were domestic wells.

The well log review process was standardized for efficiency and consistency. A series of true/false questions identified wells based on the completeness and detail of the well log. Well log quality was tested by noting descriptions and well construction details that support differentiation of geologic formations, flow zones, and Aquifer Units. Below is a table providing descriptions of the selection criteria questions.

TABLE 2. 17 DESCRIPTIONS OF THE WELL SELECTION CRITERIA QUESTIONS

True/False Question	Description
Domestic?	Yes or if false, note the proposed well use i.e., irrigation, stock water, frost protection, etc.
Open To Basalt?	Does the well log specifically document penetration of basalt?
Aquifer Support?	Does the soil/rock description support differentiation of aquifer/formation (ie. Saddle Mountain, Wanapum Grande Ronde)?

Member Support?	Does the soil/rock description support differentiation of members?
Flow Zone Support?	Does the soil/rock description support differentiation of individual water-bearing interflow zones?
Casing Info?	Does the well log contain construction information? i.e., casing length, diameter, and transitions in size, screened interval, surface seal, etc.
Aquifer Isolation?	Does the well's open interval isolate a single aquifer/formation and not cross connect aquifers? (ie. Saddle Mountain, Wanapum Grande Ronde)
Member Isolation?	Does the well's open interval isolate a single member?
Flow Zone Isolation?	Does the well's open interval capture a single water-bearing interflow zone?
New Well?	Does the well log document new construction? If false, note if the well log documents deepening, decommissioning, reconditioning, etc.

The well log review resulted in a final list of 128 monitoring candidates which met the following criteria:

- Well use is not domestic
- Well is open to Wanapum or Grande Ronde Basalt aquifers based on comparison to layers in the CPRAS Three-Dimensional Geologic Framework Model (Burns et al., 2011)
- Well construction open interval isolates a single basalt group (i.e. not cross-connecting aquifers), primarily the Wanapum and Grande Ronde formations.

These locations are shown below in Figure 2.29

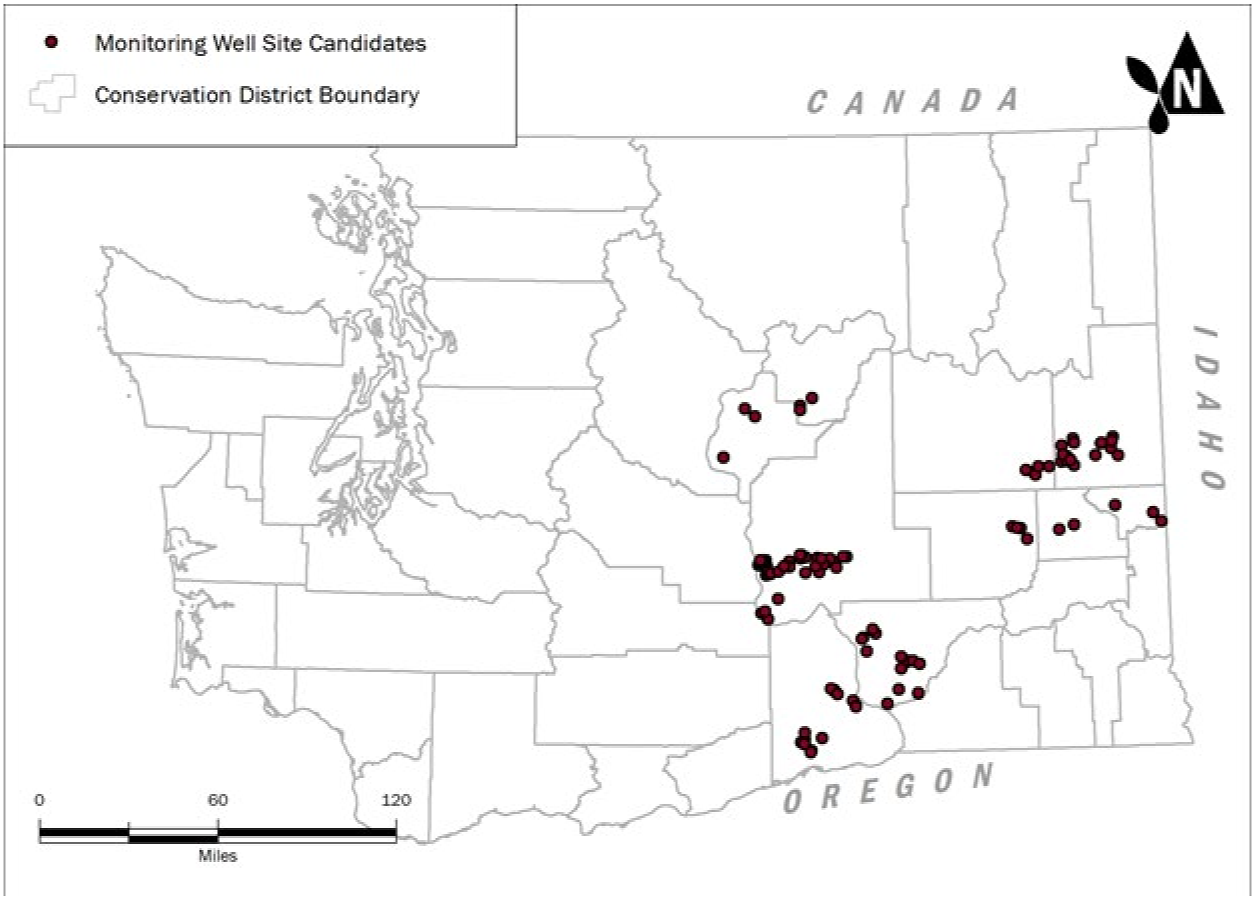


FIGURE 2. 29 MAP SHOWS LOCATIONS OF POTENTIAL MONITORING WELL SITE CANDIDATES IDENTIFIED THROUGH WELL LOG REVIEW.

Sites were compared to EIM records under the GWDB study ID to confirm monitoring status. If recent measurements were found during the search, the well was excluded as a candidate. There are many wells with historic data under the GWDB study ID where monitoring has ceased. However, we found in discussions with Ecology staff that monitoring often ceased because it was no longer feasible due to issues such as airline breaks or access. Modification of wells to improve suitability for monitoring was not part of the scope of this study.

Well Owner Outreach

To initiate participation in the monitoring program, outreach to owners of the final list of monitoring well candidates shown above in Figure 2.29 to provide the invitation to participate in the project and assess permission for site access. Well ownership information was obtained from Ecology's well log database and County-level parcel ownership data to identify current owners and contact information for outreach. Outreach included letters mailed to well owners which include a description of the project, access agreements, contact info for project contacts, and a return envelope with postage

Unfortunately, response to initial outreach in Grant, Franklin, and Spokane Counties was poor. Only one well owner responded and agreed to participate in the monitoring program. Their participation included five wells across two sites in Franklin and Grant Counties. The location of these sites is shown below in Figure 2.30.

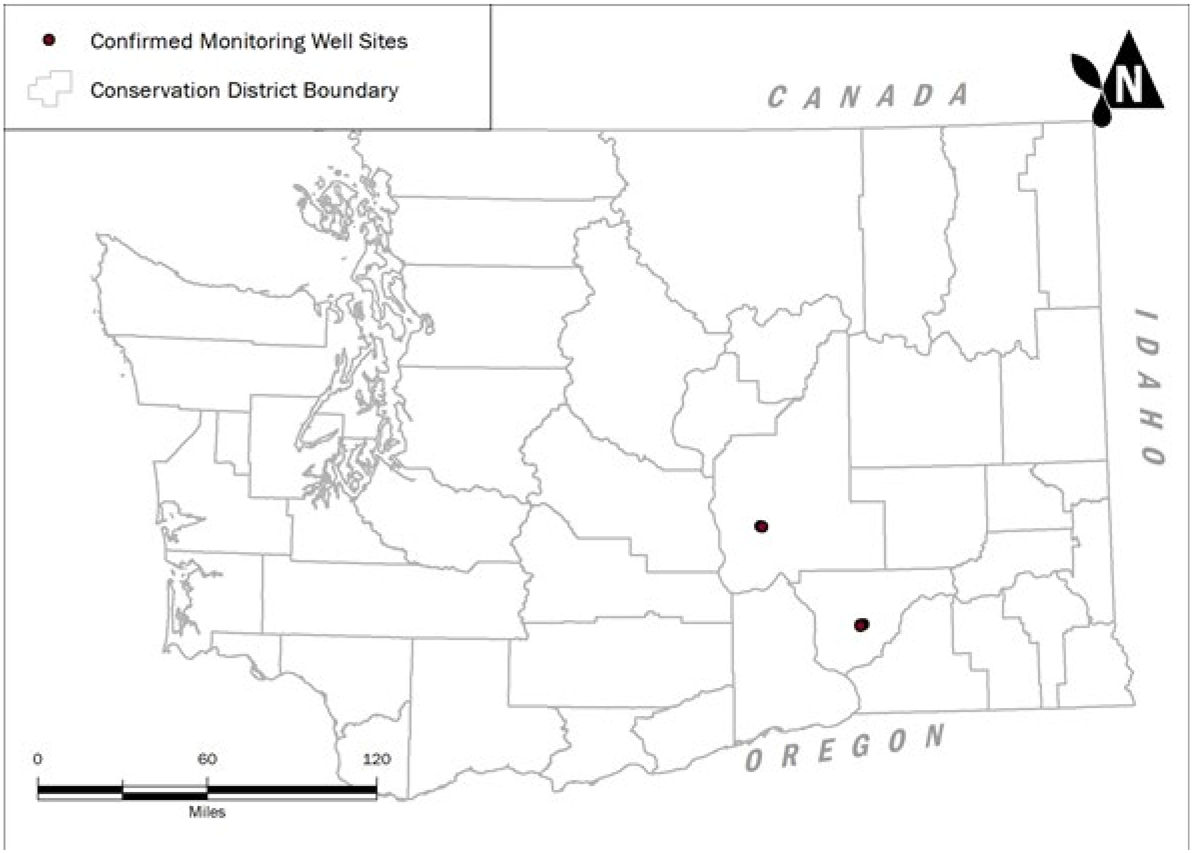


FIGURE 2. 30 MAP SHOWS LOCATIONS OF CONFIRMED NEW MONITORING WELL SITES.

Because initial outreach response was poor, subsequent outreach to owners identified through the data gaps analysis and well log review was undertaken in partnership with Conservation Districts. The Conservation District's relationships with landowners and local presence provided increased participation. Further outreach effort is needed and is ongoing through a separate grant funded from the United States Bureau of Reclamation (USBR). Monitoring these wells will be conducted by Conservation District staff under a separate QAPP. The data will be submitted to the EIM database under a separate study ID.

Data Collection

Procedures for initial site visits and water level data collection are documented in an Ecology approved Quality Assurance Project Plan (QAPP; Turk et al., 2021). The QAPP documents the data quality assurance requirements for upload to Ecology's EIM database. Groundwater level monitoring began in Spring of 2021 and includes two annual measurements collected during the spring and fall (pre- and post-irrigation season). The timing of the water level measurements in the spring provides a measure of the static water level when it is least affected by local dynamic pumping effects (spring pre-irrigation) and to track post irrigation season recovery through the winter.

None of the five selected wells were suitable locations to deploy a pressure transducer/data logger, so only manual water level measurements will be collected.

The data will be processed and converted to depth below ground surface and uploaded to the EIM Database under a new Study ID being created for the project.

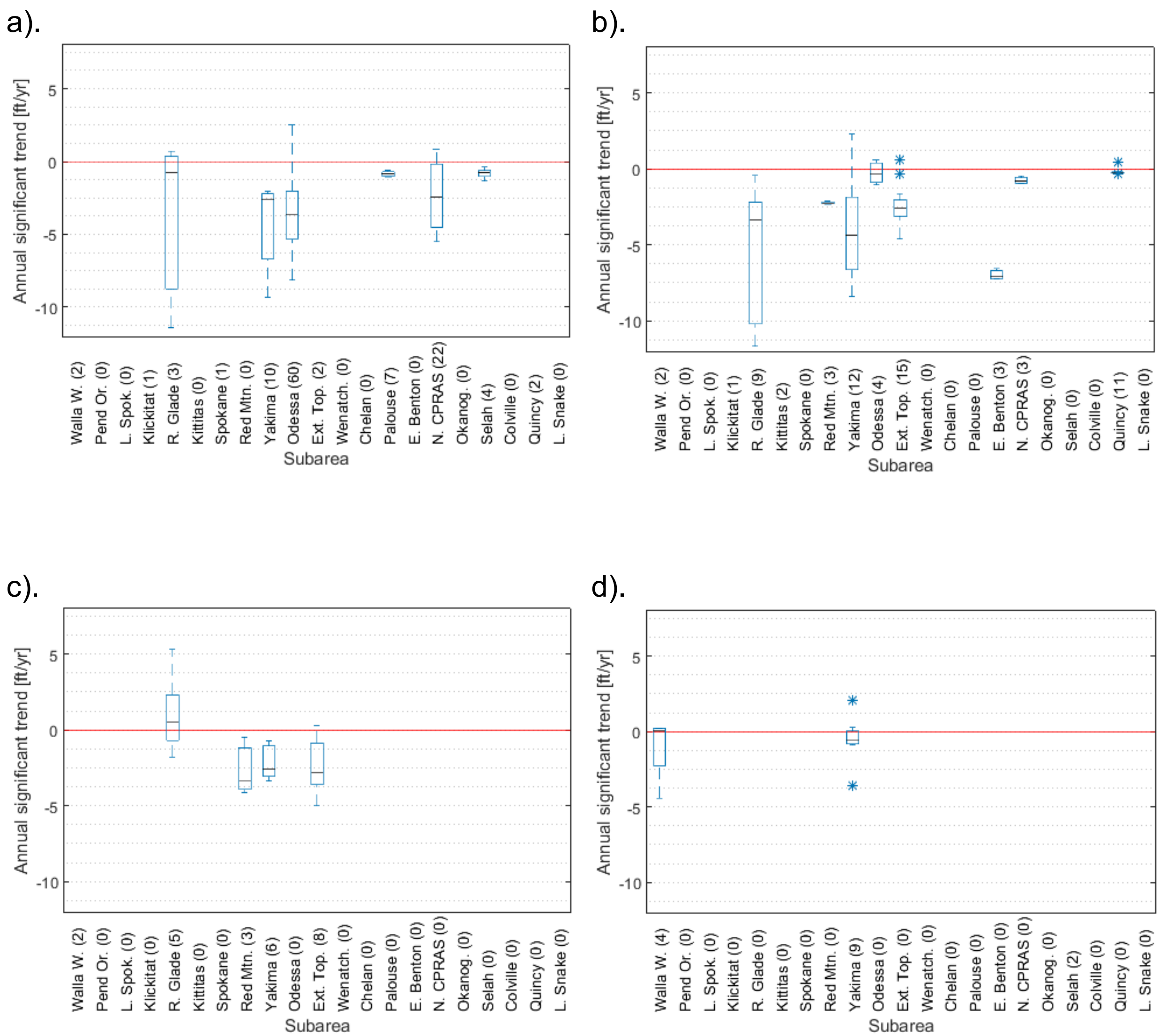
Data Outreach

The data gaps analysis highlighted a number of regions in Eastern Washington with a high number of issued groundwater permits, but limited monitoring capacity. Outreach was conducted to state agencies and conservation districts in an effort to identify additional sources of groundwater data that may be publicly available.

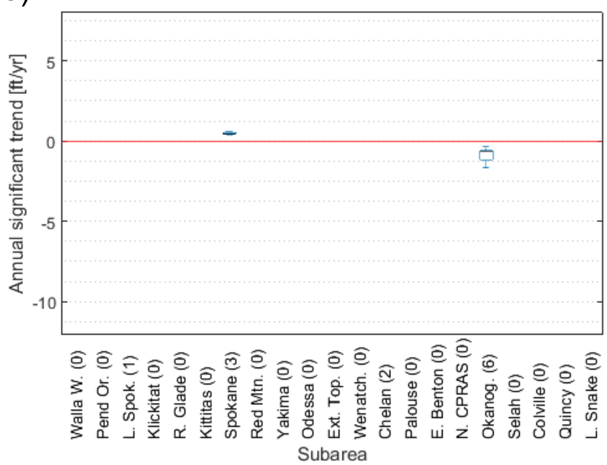
Conversations with the Washington State Departments of Health (DOH), Natural Resources (DNR), Commerce, Agriculture (WSDA), and Fish & Wildlife (WDFW). All agencies agreed to the importance of accessible groundwater monitoring data. DNR provided data for 63 wells, 12 of which met the selection criteria. These data were inadvertently excluded from the analysis but will be incorporated in future Forecasts. Other agencies collected groundwater data for specific projects, but they were for discrete time periods during the project duration alone and therefore did not meet our minimum data requirements for length of record. DOH maintains the Sentry Internet Washington State Water System Data managed by the Office of Drinking Water. Voluntary, monthly water level reporting has been added to the Water Use Efficiency forms and are accessible on Sentry. These data will be incorporated into future Forecast reports as possible.

Foster Creek Conservation District directed us to pre-existing data that were already included in EIM, but the length of record was too short for inclusion.

Additional Figures

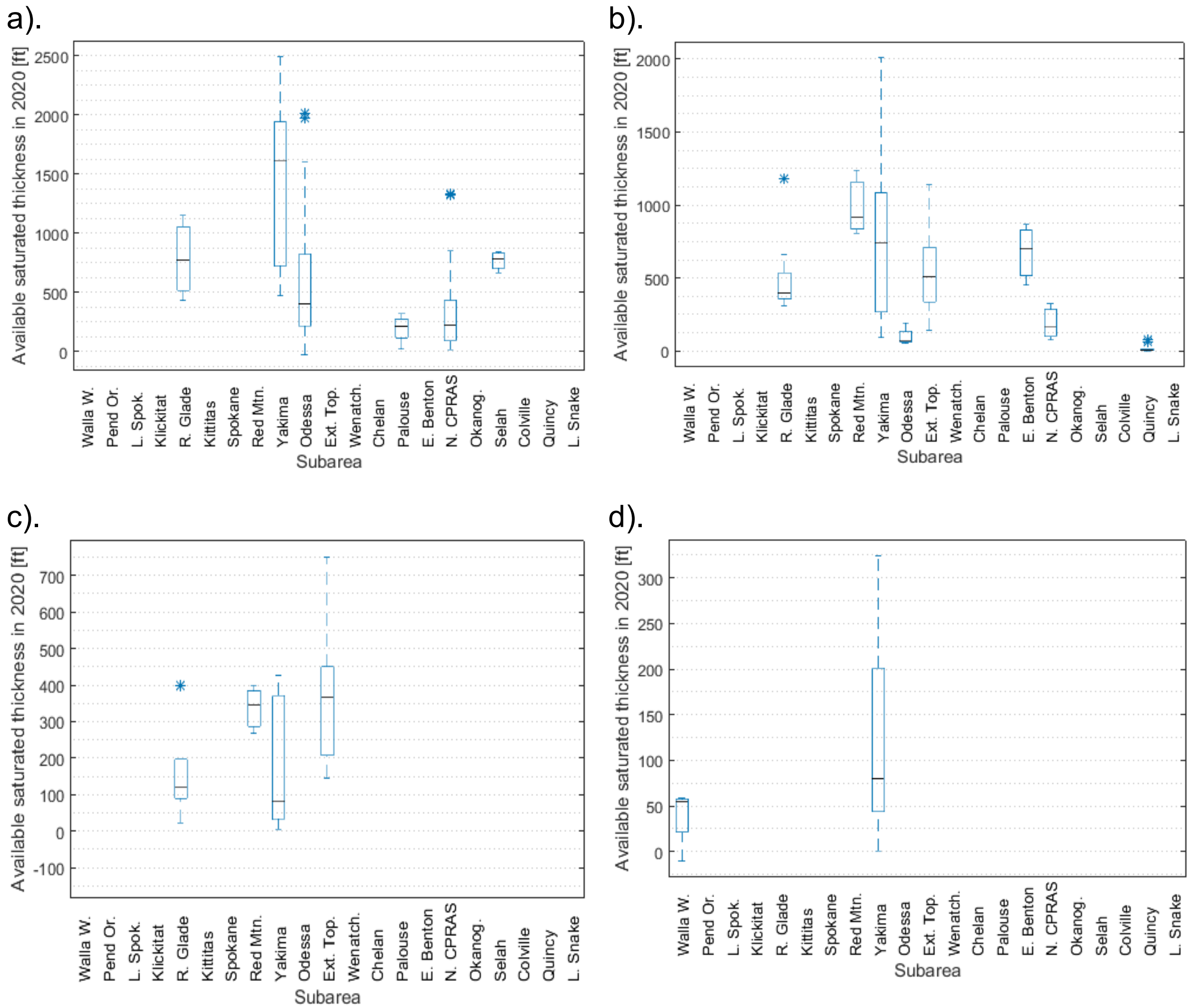


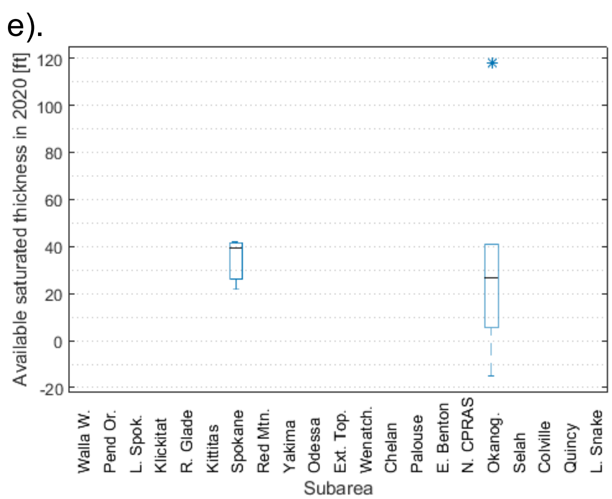
e).



The black lines represent the median significant trend for each subarea. The bottom and top of each box represents the 25th and 75th percentiles, respectively. The dashed lines terminate in the most extreme lower and upper values that are not considered outliers. Outliers are represented by asterisks. The number of wells used to create the boxplots follows the subarea name on the x-axis in parentheses. A minimum of three wells with significant trends within each subarea was required such that missing boxes represent subareas with two or fewer wells with significant trends within them. The horizontal red line marks the zero trendline, where values above represent increasing water levels and values below it show decreasing water levels.

Figure 2. 31 Summary of the significant trends by subarea in the Grande Ronde (a), Wanapum (b), Saddle Mountains (c), and Overburden (d) aquifer layers the and Beyond CPRAS (e) region.





The black lines represent the median available saturated thickness for each subarea. The bottom and top of each box represents the 25th and 75th percentiles, respectively. The dashed lines terminate in the most extreme lower and upper values that are not considered outliers. Outliers are represented by asterisks. Available saturated thickness is only included in this figure for the subareas containing a minimum of three wells with significant trends.

Figure 2. 32 Summary of the available saturated thickness in 2020 by subarea in the Grande Ronde (a), Wanapum (b), Saddle Mountains (c), and Overburden (d) aquifer layers the and Beyond CPRAS (e) region.

SECTION 3 – Outreach Efforts that Informed the 2021 Long-Term Water Supply and Demand Forecast

Outreach Efforts

Many of the members of the Forecast team that developed this 2021 Columbia River Basin Long-Term Supply and Demand Forecast, as well as our Office of Columbia River partners, had already developed past Forecasts. As such, they are keepers of valuable feedback received on the 2016 Forecast in the intervening years, feedback that informed the planning and design of this 2021 Forecast. In addition to the multiple presentations that Forecast team members have given at multiple scientific and management venues, the team has maintained close communications with regional groups that have provided insights and data, as well as perspectives on Forecast-related needs and priorities. Recent examples of these presentations and conversations focused on the Long-Term Water Supply and Demand Forecasts include some focused on sharing the 2016 results (a-k, below), and others focused on preliminary results from the 2021 Forecast (l-r, below):

a. Public meetings to present preliminary results of the 2016 Forecast and to collect actionable feedback to improve the 2016 Forecast and plan for the 2021 Forecast (Richland, Wenatchee, and Spokane, June 2016).
b. Columbia River Policy Advisory Group Meetings (January 29, 2015 and August 4, 2016).
c. Water Resources Advisory Committee Meetings (March 16, 2015 and July 11, 2016).
d. Presentation to Bonneville Power Administration and Chelan Public Utility District representatives (May 5, 2015).
e. Eastern Washington County Commissioners Policy Advisory Group meetings (June 11, 2015 and July 15, 2016).
f. Discussion of the Columbia River Treaty with the Bonneville Power Administration and the Office of Columbia River (July 7, 2015).
g. State agency outreach meeting (August 4, 2016)
h. Presentation at the Columbia Basin Development League's Annual Conference (November 3, 2016).
i. Presentation at the Water Rights Transfers Seminar hosted by The Seminar Group (Seattle, November 10, 2016).
j. Presentation at the Lake Roosevelt Forum's Conference (November 15, 2016).
k. Presentation at the Washington Small Fruit Conference (December 2, 2016).
l. Presentation at the Water Utility Water Use Efficiency Reporting Webinar (February 18, 2021).
m. State Agency Outreach Caucus meetings (July 31, 2017, February 13, 2018, October 2, 2018, March 26, 2020, November 19, 2020, and May 26, 2021).

n. Columbia River Policy Advisory Group meetings (September 7, 2017, December 6, 2017, June 3, 2021).
o. Presentation to the Walla Walla Water 2050 Strategic Plan Advisory Committee (February 4, 2021).
p. Working session with the Washington State Department of Fish and Wildlife (March 8, 2021).
q. Virtual public meetings to present preliminary results of the 2021 Forecast and to collect actionable feedback to improve the 2021 Forecast and plan for the 2026 Forecast (June 8, 2021, June 17, 2021).
r. Presentation to the Washington State Water Resources Association (December 2, 2021).

In addition, team members participated in multiple conversations with irrigation district, agricultural, municipal, tribal, and state and federal agency professionals to identify relevant datasets not yet incorporated into the modeling and updated analyses, as well as to inform the definition of scenarios modeled and metrics presented in this 2021 Forecast. And the team has integrated results from the Forecast into presentations for multiple user groups who might find this information relevant, including the 2018 Hermiston Farm Fair and Trade Show, a presentation to a delegation of the Dutch Embassy in 2018, and presenting to participants in the 2020 Washington State University Pesticide Recertification Courses.

Public Meetings

As with previous Forecasts, the team hosted two public meetings where we presented and discussed preliminary results, and we requested actionable feedback from participants representing a range of interests, including agency and legislative staff, Tribes, non-governmental organizations, irrigation districts and interested private citizens. These meetings were held virtually on June 8 and 17, 2021 (q, above). The draft Legislative Report was simultaneously available online, and comments from the interested public were accepted during a month-long public comment period, from June 2 to July 1, 2021. These comments were compiled, and where applicable, informed the final version of the 2021 Legislative Report. Many of the comments provided useful insights into what could improve the utility of future Forecasts for a variety of stakeholders, and these comments will inform the design and approaches for the 2026 Forecast. These comments are provided in Table 3.1, along with the Forecast team's responses to each individual comment. In addition, the team received additional comments focused on other projects or activities carried out or being planned by the Office of Columbia River or other programs within the Washington State Department of Ecology, which were either outside the scope and purpose of the Columbia River Long-Term Water Supply and Demand Forecast or addressed projects at a scale incompatible with this Forecast. These comments were also compiled, with individual responses, and in some cases may inform future Forecasts, as the science, methodologies and approaches used continue to evolve (Table 3.2).

Responses to Public Comments

All comments were received from the interested public during the two public workshops held in June 2021, and during the month-long public comment period held throughout the month of June 2021. Team responses, provided in the Forecast Team's Response column, ranged from clarification of different parts of the analysis, to descriptions of elements being considered for future Forecasts. The team received other comments that referred to projects and decisions of the Office of Columbia River but were not specific to the 2021 Forecast. These comments are included, with responses, in Table 3.2. Note that page numbers in the Public Comment column refer to the draft that was available for review, and may be different to the page numbers in the final 2021 Forecast Legislative Report.

Table 3. 1 Comments received that are specific to the 2021 Water Supply and Demand Forecast.

PUBLIC COMMENT	FORECAST TEAM'S RESPONSE
What constitutes the water supply figures? The numbers seem low, i.e. Columbia River main stem flows alone are much higher than the figures presented.	The water supply figures the comment alluded to just showed the amount of supply generated over the eastern Washington portion of the Columbia River Basin. The Legislative Report also contains supply figures for the entire Columbia River Basin (see Table 4 in the Legislative Report). Expected impacts of climate change on the entire Columbia River Basin are similar to those detailed for the eastern Washington portion.

<table>
<tr><td>What, if any, investigation has occurred for alternative methods of irrigation and differences (higher/lower demand) for the methods? Germany, in particular, has employed an alternative method that has significantly reduced their irrigation needs.</td><td>While the Forecast did represent different irrigation technologies as they currently exist, it has not looked at how to integrate different methods for new conservation in irrigated systems. The team has carried out some related work in the Yakima Basin to provide insights about downstream availability and prorationing, and we see that as irrigation methods become more efficient the losses change (runoff, reduced deep percolation, for instance). This makes the dynamics of the effect of conservation methods very complex at broader scales, and the Forecast team has not had the resources to address this level of detail yet. This is now discussed in the Legislative Report under Limitations (page 23 in the Legislative Report), and some resources are provided that discuss these complexities (see Box 3 in the Legislative Report). Exploring this issue is noted as a recommendation for the 2026 Forecast (see Next Steps—Building Towards the 2026 Forecast in the Legislative Report).</td></tr>
<tr><td>Are there potential pathways or scenarios that could be modeled to look at potential effects on water supply/demand that could then be used to incentivize water conservation?</td><td rowspan="4">Ecology did not specifically direct the research team to ignore conservation. The 2021 Forecast did not explore scenarios related to water conservation efforts because conservation is a complex issue to address at the watershed scale and incorporate into water supply and demand modeling (see response to the previous comment, above). Sometimes conservation only has local stream flow benefits that cannot be captured at a watershed scale. The Forecast team will consider scenarios or options that could help inform water conservation efforts when planning for the 2026 Forecast (see Next Steps—Building Towards the 2026 Forecast in the Legislative Report).</td></tr>
<tr><td>The Forecast does not assume any irrigation or residential water conservation or efficiencies as part of its analysis.</td></tr>
<tr><td>Why did Ecology require a supply/demand forecast framework that ignores water conservation, but assumes uneconomical and environmentally damaging water projects?</td></tr>
<tr><td>Why did Ecology require the draft Forecast to ignore water conservation and efficiencies?</td></tr>
</table>

Table ES-3, page ES-6, assumes "The "median agricultural water demand + residential water demand + planned water supply projects" scenario adds the 250,000 ac-ft of additional water that could be available for out-of-stream uses by 2040 through water development projects." Why are only 250,000 acre-feet of water assumed, when the FPEIS for the Yakima Plan alone, projected over 450,000 acre feet of water storage projects, additional water storage is proposed within the Alpine Lakes Wilderness, and new storage dams are also proposed in the Walla Walla Basin?	The estimate of an additional 250,000 ac-ft of additional water was provided by the Office of Columbia River, as a conservative, good-faith effort at estimating what amount the water supply projects currently approved, permitted or in construction could provide for out-of-stream uses in eastern Washington by 2040. The time limitation on this estimate (2040) and the purpose of the water (out-of-stream uses only) determine that this is not an estimate of all proposed and planned projects in the region. We recognize that there are other proposed water supply development projects being evaluated or planned. We also recognize that these projects may have other purposes beyond providing water for agricultural uses by 2040 (for example, instream flows). We have attempted to clarify this by stating "It is important to note that this amount does not reflect the entirety of all ongoing and planned water supply projects, which also consider water supply needs of instream and other out-of-stream uses, as well as planning horizons that exceed 2040" (page 19 of the Legislative Report).
Did the draft Forecast take into consideration other water storage projects that are not authorized for study, but which Ecology is spending money on, such as potential sites for new small surface water storage site in the upper Yakima River Basin or the North Fork Cowiche Creek Reservoir?	
The draft Forecast should include all the proposed water storage dams that Ecology has spent money studying since 2006.	
Why has Ecology requested that only 250,000 acre-feet of new water supply projects be considered available by 2040 for this Forecast?	

Page 32 states, “It is worth highlighting that there are other factors that could lead to future agricultural water demand that is greater than we estimated. We assumed a constant irrigated acreage in the region. However, additional water supply development could increase the land base for irrigated agriculture (see the Potential Impacts of Planned Water Supply Projects section). These estimates also do not include possible increases in agricultural water demand due to double cropping, though estimates of these practices in the recent past range from 3% to 6% of total irrigated acres in Washington State (see the Potential Impacts of Double-Cropping section). We also assumed no changes in irrigation efficiency or other water conservation measures, which could counteract some of these factors, leading to lower water demands.” We are concerned with the above assumption that “additional water supply development could increase the land base for irrigated agriculture” while assuming “no changes in irrigation efficiency or other water conservation measures.” Many of the Columbia River Basin WRIAs are over allocated with water “rights” exceeding water supplies. This has resulted in ESA-listed fish species and inadequate “minimum” instream flows. In addition, in 2018, Ecology was preparing an EIS for a new reservoir at Switzler Canyon in southern Benton County, which would be used to expand crops grown in the Horse Heaven Hills. The final Forecast should list ALL new water storage supply dams that Ecology has spent funds studying that would	

be used to increase the land base for irrigated agriculture.	
In reference to Table 8, it is revealing that the Forecast assigns ALL 250,000 acre-feet of water due to “planned water supply projects” to out-of-stream uses, rather than working toward fish restoration by increasing instream flows. Why does the draft Forecast make this assumption?	The estimate of 250,000 acre-feet of water provided by the Office of Columbia River was specific to additional water that would be available for out-of-stream uses focused on agricultural demands. It therefore by definition does not include water allocated to increase instream flows. It is important to note that this amount does not reflect the entirety of all ongoing and planned water supply projects, which also consider water supply needs of instream and other out-of-stream uses, as well as planning horizons that exceed 2040 (page 19 of the Legislative Report).
While there are many specific questions that need to be address concerning the 2021 Forecast, a fundamental concern is why the Department of Ecology directed the Forecast team to ignore water conservation and efficiency (as it is not mentioned at all in the Forecast Executive Summary) and why the Department of Ecology directed the Forecast team to ignore the aggressive water storage projects pursed by the Office of Columbia River including in the Yakima River Basin, the Walla Walla River Basin, and the Alpine Lakes Wilderness which vastly exceed the limited 250,000 acre feet estimated on page 32.	See responses to comments about water conservation measures and about the estimate of 250,000 ac-ft of additional water for out-of-stream uses above.
Is Crab Creek influenced by return flows from agriculture? Are you taking into account flow addition water through Crab Creek?	By definition, water supply in the 2021 Forecast does not take into account irrigation, irrigation losses, or irrigation return flows (see Definitions of Water Supply and Water Demand Terms in the Legislative Report). Return flows are captured, to the extent the model can, during curtailment modeling. The 2021 Forecast did not include curtailment modeling for Crab Creek.

<table>
<tr><td>Why on page 112 of the Forecast (page 116 in the final Legislative Report) is the bar chart summary at the top of the page blank for increasing curtailment for WRIAs 37-39?</td><td rowspan="3">Water in the Yakima River Basin (WRIAs 37-39) is managed differently than in other Washington watersheds (see Box 2 in the Legislative Report for details). The Forecast team provided results on prorationing in these WRIAs, but due to the management differences to the other WRIAs where curtailment was modeled, these WRIAs were not ranked relative to the others for curtailment in the summary bar chart. We added labels in the bar chart summaries, where appropriate, making it clear when the WRIA was not ranked based on a particular variable. In terms of the Yakima River Basin specifically, we have included a note in the caption, and refer the reader to the proration results as well (see page 120 in the Legislative Report for the proration results).</td></tr>
<tr><td>The analysis of the Yakima River Basin WRIA's 37, 38, and 39, on page 112, shows a blank for "Increasing Curtailment Frequency." If the Forecast used Yakima RiverWare, where is this curtailment information located?</td></tr>
<tr><td>Why does the WRIA Summary chart on page 112 have a blank for the curtailment bar?</td></tr>
</table>

Page 116 of the Forecast chart shows that the magnitude of curtailment in the Yakima WRIAs is less by 2040 and that “Proration rates higher than 70% of entitlements should not have significant adverse effects on agricultural production in the Yakima region, and hence were ignored.” Doesn’t this suggest that senior irrigation districts could get by with 70% of their allotment during drought years, freeing up water to share with the proration?	The expectation that there will not be significant adverse effects over the long term with prorations greater than 70% reflects water supply development and conservation plans under the Yakima Basin Integrated Plan (YBIP), as well as water irrigation districts' ability to self-mitigate those impacts. That being said, some crop impacts are expected any time less than 100% of water supply is available, which may manifest itself in crop yield or fruit size and quality.These issues become particularly challenging if droughts occur in sequential years. The updated figure caption for Yakima prorationing contains the following rationale for concentrating on proration rates less than 70% consistent with YBIP: "Periodic proration rates higher than 70% of entitlements do not typically have significant adverse effects on agricultural production in the Yakima region because irrigation districts have water-sharing mechanisms in place to cope with minor water restrictions" (see page 120 in the Legislative Report). This statement is based on the understanding that these are naturally variable systems, and that options exist for managing the occasional dry year. However, managing for 70% of entitlements year after year would likely have very different implications and adverse impacts over the long term for both agricultural production (quantity and quality) and for the necessary irrigation infrastructure.
Page 49 states: “Due to the differences in how curtailments occur in the Yakima River Basin, our modeling results do not show seasonality of curtailment. The annual average prorationing rate in the Yakima River Basin is not projected to change much, though the frequency of prorationing is expected to increase three-fold, from around 20% of years historically to close to 60% of years by 2040.” Have there been any historical Yakima River Basin droughts in which Senior Irrigators did not receive their full allotment?	In the Yakima irrigation districts where there is a mix of junior and senior water rights, senior water right holders will not receive their full allotment in years where there is prorationing. An agreement exists that states that all water right holders in each irrigation district receive the same fraction of their full allotment.

How do we interpret the curtailment plots? Is it that there's a lot of seasonal variation in terms of benefits (and none in other times?)? And is it crop specific?	To help provide clearer information on the expected changes in curtailment, the final report focuses on curtailment frequency, and includes two paired figures. The first quantifies the historical baseline of curtailment, and the second shows the expected change by 2040s from that historical baseline. See, for example, Figure 33, and paired Figures 41 and 42.
Does the river flow rate determine river temperature?	There is a clear relationship between river temperature and flow. However, addressing impacts of changes in flow on temperatures was beyond the scope of the 2021 Forecast.
Is the irrigation demand similar for the entire basin?	Agricultural water demand varies throughout the Columbia River Basin. Some watersheds within the basin are expected to experience decreases in demand, and others are expected to experience increases (see Figure 23 for the expected changes in Washington's watersheds; though agricultural water demands outside of Washington are included in the modeling, watershed-level results are not provided outside of Washington). There is also variation within a watershed. Generally, much of the demand occurs in the lower elevation portions of the watersheds, though the Forecast results do not provide this level of resolution.
For WRIAs along the Columbia that draw water from the Columbia, did you say the water rights interruption models DO or DO NOT account for water being withdrawn from the Columbia?	Mainstem interruptible water rights are curtailed separately from interruptibles within the tributaries and WRIAs. In the Forecast, irrigation demands are withdrawn from the Columbia River mainstem in all of their listed points of diversion before running the water rights interruption model.
As a ranch/farmland owner in Klickitat/Clark Counties, I am finding this portion of your presentation particularly enlightening/confirming......very much appreciated. For future presentations, I will be particularly interested in learning positive irrigation alternatives as I noted earlier.	Comment noted.

Long-term resident, and watching impacts of climate change I feel there will be some dramatic forced or voluntary changes in how water use will be implemented across the state. This info is very important and informative. But we need to know more about human factor- actions taken or needed to be taken. It's going to be hard to judge how things will turn out.	The team agrees that the human factors, including what actions are taken, can have significant impact on the outcomes. These actions are hard to predict, and complex to integrate into the modeling. The team is considering a scenario approach for the 2026 Forecast that could allow us to model specific sets of actions and provide some insights as to what the outcomes would be under those specific scenarios.
Uninterruptibles, on west Walla Walla River. The amount of interruptibles seems small. Were we included? Where are the other acres that aren't interruptible?	The figure the comment refers to is only showing acreage under Forage and High Value Perennials crops. Within acres with those crops, the number shown is the number of acres categorized as interruptible, based on priority date relative to instream flow rules, in Ecology's Water Right Tracking System (WRTS). There are often priority calls on junior water rights as streams dry up, and there are often more places curtailed, but the team is still working on how to include these in the analysis. Unfortunately, this local variation of junior water right curtailment is not a detailed enough data set and needs further ground truthing.
The US Supreme Court decided the water divide between WA and OR [in the Walla Walla watershed], and they said it has to be done on an equitable basis based on water rights, including mainstream and tributaries. There's precedent as to how management is to be done, based on Supreme Court, so you can't willy-nilly exclude some. So you have to include them all.	Water supply and demand results in the Walla Walla and other watersheds that cross Washington state lines are only presented for the Washington portion of the watershed (the WRIA) as required by RCW 90.90.040. However, curtailment modeling in the Walla Walla considered the whole watershed, including both the Oregon and Washington portions. In planning for the 2026 Forecast the team will consider whether presenting all results for the whole watershed or different portions of it would be more informative.
Interested in the branches downstream [in the Walla Walla watershed] and is emphasizing that things need to look at the whole - mainstem and branches in WA and OR. Neither can take it all.	

Are the low flow requirements by virtue of the fish and senior water rights holders? Is there more information about how to communicate this information to policy makers?	Low flow requirements are codified by the Washington Administrative Code (WAC), and are instream water rights with a specific priority date. All water users that are junior to instream flows can be subject to interruption in favor of instream flows when these flows are not met. These codified requirements are included in the 2021 Forecast in an effort to evaluate where and when fish species who depend on these flows might be vulnerable to changes in water supply. In addition, the team included information from a separate analysis focused on changes in low flows, to help communicate the importance of instream water for fish populations: changes in anticipated 7Q10 and 7Q2 flows ((see Figures 29-32, and Considerations for Fish for each WRIA under the Forecast Results for Individual WRIAs section).
The precautionary principle should be followed and a range of forecasts involving reduced irrigated agriculture and deforestation with a goal of optimum instream flows to restore fish runs. In addition, while the Forecast does include references to fish and instream flows, the Forecast fails to mention any analysis or consideration of wildlife. This is a critical failure that does not provide the Washington State legislature with sufficient information needed to have confidence that Ecology has produced an adequate 2021 Forecast. The Forecast must include projections of wildlife populations.	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. The team is considering focusing on "what if" scenarios in the 2026 Forecast. Such an approach would more readily lend itself to evaluating options such as those described in this comment. It is important to note that there will likely be limitations to the number of "what if" scenarios the team can adequately examine in the 2026 Forecast. The request of wildlife population projections are likely better provided by wildlife experts, as water supply and demand may not be the driving factors affecting these populations.
The Forecast does not address impacts to wildlife resulting from long-term "demand" for more out-of-stream uses.	

Do you have other data for historical flow plots?	The historical flow plots are provided in the Forecast Results for Individual WRIAs section as context to help understand the possible consequences of expected changes in supply and demand. The team used data from the most downstream gage for which data are available in each WRIA. Data for additional gages may be available from the U.S. Geological Survey or Washington Department of Ecology.
How do you deal with/trust data generated through use of climate models which are known to be inaccurate?	There are two main tactics the team used to help determine to what extent the model results can be trusted: first, to quantify the uncertainty as much as possible and second, to compare with observational data. By using outputs from 17 climate models under two emissions scenarios, we can quantify a range of possible outcomes, which provides a measure of uncertainty. When that range of possible outcomes all point to the same direction of change (e.g., all future projections are greater than the historical baseline), that tends to increase confidence in the direction of change that is expected in the future. We know there is uncertainty around future precipitation and temperature. We also know, based on comparisons between model outputs for past conditions and the associated observations, that the uncertainty is much greater for precipitation. Streamflow and supply respond to precipitation, and thus this is an important source of uncertainty. However, we can have more confidence in variables that respond to temperature, such as declining snowpack and the resulting shift in timing of water supply; this is where decision-making can be more confident in relying on results. Agricultural demand will be impacted by both precipitation and temperature, but temperature is expected to play a larger role, based on what other studies have found, and we can evaluate that. However, human management will be the most important determinants (planting dates, the Columbia River Treaty changes, etc.) of how impacts will play out in future. In planning for the 2026 Forecast, the team is considering whether to explore other “what if” scenarios, beyond using different global climate model (GCM) scenarios.

Human decision-making will be important for storage flows and will be dependent on snow levels. And sooner than later we’re going to have our questions answered by looking at the Colorado River and how it’s managed. For border watersheds it may be more important to look at the entire watershed instead of just the WRIA.	The Forecast modeling of water supply and agricultural water demand uses both watershed and WRIA boundaries. In the case discussed in this comment during the public meetings, the Walla Walla, results only show the Washington portion of the watershed (that is, the WRIA), but the curtailment analyses do include the entire watershed. We welcome any thoughts on how best to communicate these complexities, which occur not only in watersheds that cross the Washington state borders, but also watersheds where irrigation is supplied from the Columbia River mainstem, which have big demands and small supply, as the supply only quantifies water sourced in the WRIA.
I believe the Forecast would be wise to adopt a "what if" scenario outlook instead of forecasting based on computer modeling of climate change. Computer modeling has proven to be very unreliable up until now and has tended to drive extreme decision-making untethered to reality. "What if" scenarios are good preparation for possibilities such as extended drought periods or even extended cooler, wetter periods.	The team is considering an approach focused on "what if" scenarios in planning for the 2026 Forecast. It is important to note that, should this approach be adopted, there will be limitations to the number and range of scenarios that can be considered based on available data to quantify those scenarios, as well as uncertainty as to the likelihood of each scenario actually occurring in the future.
I think your "what if" scenarios would be very beneficial. It will be interesting to watch future temperatures (if I live long enough :). I don't have the confidence you have that they will continue to rise. I've been around long enough to have been told temperatures will drop and now temperatures will rise...all through computer "modeling." Thanks for your answers and all this team's hard work on this project.	

How is the snowpack modeled? Mid and lower elevation snowpack is likely to reduce/disappear. High elevation may grow with more spring precipitation. Is it modeled as one mass or by accumulation by elevation?	VIC, the model in the integrated VIC-CropSyst modeling system that quantifies snowpack dynamics, is a spatially explicit model that represents different elevations, so we can simulate different snow zones. We run a full energy-balance snow model that looks at melting, runoff, aspect, slope, etc. to fully capture the dynamics in each cell.
Lower elevation and higher temperatures, is it affecting flows?	*Note: This comment was made during the public meetings, and the response reflects the team's verbal response at the time. We recognize that in this summary table it is out of context. However, we hope the response may still be useful to readers.* The lower elevation watersheds with higher winter temperatures are less vulnerable to warming-induced changes in streamflow because snowmelt contributes a relatively small proportion of the total runoff. Since seasonality of streamflow is strongly related to snowpack, the watersheds most vulnerable to shifts in streamflow timing are those where the mean winter temperature is near 0° Celsius and any additional warming could significantly increase the proportion of precipitation falling as rain rather than snow. These vulnerable, transitional watersheds are generally at higher elevations, such as the eastern slope of the Cascades.
How have we compared demand for the subbasins within Yakima Basin?	The relevant maps presented in the Water Supply and Demand for Washington's Watersheds section provide demand values for each subbasin in the Yakima Basin. The associated 2021 Long-Term Water Supply & Demand Forecast Data Access Website (https://arcg.is/0CqnP01) has the underlying data for each of the three Yakima Basin WRIAs.

Please elaborate on the changes between interactions between surface and groundwater in regards to the direction of flow.	The VIC model captures shallow subsurface dynamics at the local scale but does not capture deeper groundwater dynamics and flow, or the connection between surface water in channels and the groundwater table. The team is prioritizing such integration in key locations for future Forecasts (see the Next Steps—Building Towards the 2026 Forecast section).
Page ES-3 states: "Is the availability of water to meet all instream and out-of-stream demands vulnerable to expected changes in climate and population growth in eastern Washington? The answer is definitely yes." This is the wrong question and results in a wrong framework for the Forecast. As shown by the last century plus of irrigated agriculture in Eastern Washington, there is NO LIMIT to out-of-stream irrigation demands (which always come at the expense of instream demands). The draft Forecast fails to set out alternative futures. Instead, it not only assumes steady demand, but refuses to incorporate water conservation measures or alternative crop mixes that might allow a rebalancing between out-of-stream and instream uses.	The team is considering focusing on "what if" scenarios in the 2026 Forecast. Such an approach would more readily lend itself to evaluating alternative futures such as those described here. It is important to note that there will likely be limitations to the number of "what if" scenarios the team can adequately examine in the 2026 Forecast. For the team's response to comments about water conservation measures, please see responses to comments specifically asking about water conservation earlier in this Table.
I saw a couple of mentions of the RCP 8.5. Given that even the upcoming IPCC report is dropping it because it is beyond the worst-case scenario, is it worth continuing to factor it in to the data sets?	The team continues to simulate both RCP 4.5 and 8.5 because it is important to see how much these levels of emissions matter. This approach provides a range, and posits the opportunities should decisions lead to certain levels of emission reduction. Where the RCP makes a difference, the results under RCP 4.5 and 8.5 are shown separately so those differences can be considered.

Without metrics for industry and other water users, it seems disingenuous to note agriculture as the biggest contributor to water demand.	This is a fact that the team cites from other data and not a result of the Forecast analysis (see Table 2 in the Legislative Report). Also, note that agriculture is the largest consumptive water user in the Columbia River Basin, not necessarily the largest user overall. This is an important distinction.
Did I miss the inclusion of new industry as a demand for water? We have continued requests for significant water use from the industry that is being recruited... Commercial and industrial uses need to be accounted for, as we, a water utility, do when considering capacity.	We did not include commercial or industrial water demands in this analysis, or in previous analyses, but hope to do so in the future.
The best studies & forecasts are those that acknowledge their limitations. The report's academic boundaries should be transparent. During the June 8 webinar, the WSU presenters indicated that commercial/industrial needs were not represented in the supply & demand study. This is only implied in the report (p. 62, "Improve the accounting of non-residential use, namely commercial and industrial use" in the 2026 Forecast). So that legislators clearly understand that this forecast does not reflect water demand for these user categories, we encourage Ecology to expressly state that exclusion in the report.	A description of limitations in included in the final report. See the Forecast Limitations section.
Did out-of-stream also include commercial/industrial?	No; other than agricultural demand, only residential uses (i.e., water used in or around homes) were included in this study. We have included some additional text in the final report to help make sure this is clear to readers: "Residential water use refers to water that is used in or around the home, and does not include water used for industrial or commercial purposes." (see page 20 in the Legislative Report).

In the future, a brief exploration of other Columbia River-connected items would be helpful (i.e. status of the Columbia River Treaty negotiations, updates from the river-connected irrigation districts, river port summaries) as each of those topics will, ultimately, also be effected by water supply levels as well.	The exploration of other Columbia River-connected items will be considered for future Forecasts. However, it is important to note that the team will focus efforts on those items that are feasible and a priority to integrate into the Forecast, especially if other items are described elsewhere.
On page 72, which focuses on WRIA 29A and 29B (Wind and White Salmon Rivers), the historical flows graph features the Klickitat River, which is in WRIA 30. It would be more appropriate to use historical flow data from either the White Salmon or Wind Rivers if flow data is available.	This was an error and has been corrected in the Legislative Report (see the historical flows for the White Salmon River on page 76).
How does the shift in precipitation timing impact instream flows?	The coupled models that we use would capture the effects of any precipitation shifts as projected by the global climate models on all of the hydrologic fluxes and stores, including instream flow.
Did the draft Forecast assume minimum stream flows would continue to be the baseline, or did the draft Forecast consider using optimum stream flows?	The modeling scope of work was to simulate water supply and demand as the system is currently regulated, so the team incorporated current regulations on minimum instream flows. Future work, in collaboration with the Washington State Department of Fish and Wildlife, could examine the effects of changing minimum flows.
The final Forecast should identify all stream reaches within the Columbia River Basin for which minimum instream flows for fish have not been met since 2016.	The Forecast provides information at the WRIA level, not the tributary reach level, as well as focusing on what is expected to change by 2040s. For WRIAs for which the Washington Department of Fish and Wildlife has provided fish periodicity tables and for which the team were able to calibrate the streamflow outputs, we have included modeled estimates of historical and future streamflows at the WRIA scale, which users can compare to instream flow rules where appropriate.

WDFW appreciates the multiple opportunities to review and provide input on the Draft 2021 Columbia River Basin Long-Term Water Supply and Demand Forecast. We understand that instream demands are challenging to forecast but we feel more analysis is needed in this area. In the current document, instream flow rules serve as a proxy for instream demand. However, many watersheds in the Columbia River Basin are without instream flow rules. This leaves watersheds without information about instream demands. Additionally, instream flow rules are set to protect select fish species, they do not represent the flow required by all instream life. We look forward to working with Ecology and its partners early in the 2026 process to ensure a more thorough examination of instream demand is presented.	The team looks forward to continuing the conversations with individuals from WDFW and other partners to build on the work done to represent instream flows in the 2021 Forecast. See the Next Steps—Building Towards the 2026 Forecast section in the Legislative Report (page 64).
The Washington Irrigation Guide (WIG) is mentioned on page 63 and links to a September 1997 USDA-NRCS document at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_035205.pdf. This irrigation guide is now nearly a quarter century old. A revised draft has been prepared, but not released. The draft Forecast cannot rely on a 25 year-old guide for projections decades into the future. We request that the final Forecast utilize updated and revised irrigation guide tables.	The mention of the WIG in the draft Legislative Report was not a recommendation of its use. It was mentioned simply to clarify that the type of information that new approaches based on remotely sensed data can provide updates for, and was a simple reference to how improvements could be incorporated. Note that edits to the Legislative Report in response to other comments have led to a shortening of the relevant section of the Report, and the WIG is no longer mentioned.

The Forecast should also include an analysis of expected increase in flooding assuming this key finding that wet periods are getting wetter.	The Forecast team will consider ways that floods might be analyzed when planning for the 2026 Forecast.
The Forecast should also include an analysis of existing reservoir management and impacts on in-stream flows assuming less snowpack, which could result in fuller reservoirs in winter due to less spring snow melt needing to be captured.	Existing reservoir management is captured in the integrated modeling. The team is considering focusing on developing "what if" scenarios in future Forecasts, and such changes in reservoir management could be considered with that approach. It is important to note that there will likely be limitations to the number of "what if" scenarios the team can adequately examine in the 2026 Forecast.
"An average decrease of -2.2% (± 0.6%) in agricultural water demand is expected in eastern Washington by 2040." This affirms the finding from the 2016 Forecast, namely that the state should plan on DECREASES in agricultural water demand. This should inform the Washington Legislature and Congress to be wary of Ecology lobbying efforts that would result in uneconomical and environmentally damaging new water projects.	The intent of the Forecast is to provide information on anticipated changes in water demand, to inform a wide variety of discussion and decisions relating to water management. Note that the estimated decrease in agricultural demand in the future is very small, and is based on scenarios where many factors, particularly related to human responses to climate change impacts, are not considered. Changes already planned would be sufficient to lead to an increase in agricultural demand by 2040. In addition, this overall slight decrease is the net effect of increases and decreases. This variation occurs through time, with the early season expecting increases and the late season expecting decreases under current

Page 31 states: "The agricultural water demand results across the entire Columbia River Basin highlight the following: Demand for agricultural irrigation water across the entire Columbia River Basin is expected to decline slightly, on average, by 2040 (-1.6% ± 0.7%) and continue declining through 2070 (-3.8% ± 0.9%; Table 6). This slight decline is consistent for low, median and high demand years (Table 6). When the focus narrows to the Washington portion of the Basin, results suggest the decrease in agricultural water demand is somewhat larger. These 11 declines are more noticeable in high demand years (-3.0% ± 0.7% and -6.8% ± 0.9% for 2040 and 2070, respectively; Table 6)." COMMENT: Again, the finding that a decrease in agricultural water demand in the Columbia River Basin within Washington remains a significant finding that should temper the clamor for new irrigation storage dams.	conditions, as well as across the region, with some WRIAs expecting increases and others expecting decreases. The changes in seasonality and the variations across the region emphasize the vulnerabilities we face. The intent of the Forecast is to provide information on these variations, and include what is known to be changing, to inform decision-makers who have authority to decide on water management policy.

Page ES-9 states: “Reduced irrigation due to curtailment generally caused reductions in yields of forage and high value perennial crops. The magnitude of the yield reduction for crops experiencing curtailment was generally greater under future (2040) conditions than under historical (1986-2015) conditions. The forecast reductions in yield were on the order of 20-25% larger than under historical conditions, though at one location, in the Okanogan (WRIA 49) loss in yields could triple." COMMENT: This fails to acknowledge the Washington Academy of Sciences critique of the Washington Department of Agriculture's 2015 Drought and Agriculture report and fails to include the following: "The economic effects of the 2015 drought described in this interim report are based on gross rather than net revenue lost. This can account for an incongruity between the estimated gross revenue lost stated in this report and the fact that net farm income for Washington in 2015 was higher than in any of the previous four years by a significant amount."	This report does not attempt to calculate price effects from reduced supply due to drought. This is primarily because of significant uncertainty over how priority calls and curtailment are implemented. This iteration of the Forecast included curtailment modeling that helped fill this knowledge gap. This will allow the team to consider including price effects in future Forecasts.
The Forecast needs to address decreased agricultural production and decreased water demand from increased pest infestations due to climate change.	Addressing the effects of pest infestations on water demand would require significant research and synthesis that is currently beyond the scope of the Forecast. In addition, significant uncertainty would need to be considered, as growers will respond to changes in pest infestations in ways that the team is currently unable to predict.

Page 6 states: "Similar to the 2016 Forecast, the 2021 Forecast assumed groundwater is not limiting (though we evaluate this assumption via the groundwater trends analysis; see the Water Supply Forecast for Washington's Aquifers section)." What is the basis for Ecology assuming that groundwater is not limiting? Why did Ecology insist on this assumption?	Ecology has not insisted on this limitation. For example, in the Odessa area the team assumed that groundwater sources would be replaced by surface water. The reason why this assumption that groundwater is not limiting was made in much of the rest of the region is because the team does not currently have the modeling capacity to examine the role of declining groundwater on the system. We hope to overcome this obstacle in future Forecasts. In the interim, as the sentence being quoted also states, the groundwater trends analysis is starting to elucidate to what extent these assumptions are reasonable.
Groundwater data doesn't seem to address Franklin County or Grant County. Can you comment on that?	Strict criteria were used to select wells that were used for the groundwater trends analysis (see the Evaluating Groundwater Trends section), and existing data in these counties may not have met those criteria for the time period of interest, or for some reason not been compatible with the data used. The team continues to look for additional data to broaden and deepen the analysis, so please get in touch if you know of additional data in these counties or elsewhere in Washington.
Why is there an increase in water level in Quincy areas vs decline in Odessa subarea?	The trends analysis did not extend to exploring the drivers of these trends. Generally, these patterns could be due to an increase in recharge at the surface, water levels rebounding after a decrease in pumping, or possibly the impacts of artificially stored groundwater related to U.S. Bureau of Reclamation infrastructure.
Groundwater withdrawals vary greatly across the extended Toppenish.	Comment noted.

For Quincy subarea in Grande Ronde aquifer layer, how are you looking for additional data? Particularly for long term?	The team is discussing data availability with a number of state agencies, Conservation Districts, and other groups who might have more data. As part of the Forecast, the team is working to add new monitoring locations in areas where groundwater monitoring is currently limited and there is a high density of permitted groundwater rights. The team is looking for well owners who are willing and open to monitoring with their approval. See the SECTION 3 – Evaluating Trends in Groundwater Levels in this Technical Supplement for further detail about areas targeted for additional data collection and the requirements for data collection and use.
Is raw data available underlying the Aquifer pages?	The data underlying all the Legislative Report figures is available online on the 2021 Long-Term Water Supply & Demand Forecast Data Access Website (https://arcg.is/0CqnP01). In addition, all the water level analysis is based on publicly available data, as is the well depth information. Ecology and USGS data sources used in this study are publicly available from the USGS NWIS Database (https://waterdata.usgs.gov/nwis/gw) and Ecology's EIM database (https://apps.ecology.wa.gov/eim/search/default.aspx, study ID: GWDB).
Given the variability of vulnerability within the Yakima and the Extended Toppenish, would it make sense to study each in more detail?	The groundwater subareas used in the 2021 Forecast were delineated based on a groundwater connectivity perspective at a coarse scale. It was beyond the scope of this Forecast to calculate vulnerabilities at a finer scale. However, the team will consider smaller subareas for the 2026 Forecast.
The vulnerability here raises some questions, especially since groundwater vulnerability is based on saturated thickness (b). The b is thin in the Overburden, so it makes it seem like a big problem, but it's due to that thin layer.	The team included the average saturated thickness by layer and subarea in the vulnerability tables in the Forecast Results for Aquifer Layers section (see Average Available Saturated Thickness in 2020 in the Vulnerability tables).

Would having the saturated thickness help in interpreting? For instance, when the saturated thickness layer is thin, like in the Overburden.	
Part of the conversation on vulnerability need to be on declines in basalt. Ecology has looked at trends and part of the story is that there are declines, but there also connections between units that aren't well defined. There's not a lot of uniformity within the units.	This is a point that the team is interested in exploring further for 2026. However, evaluating vertical and hydraulic connectivity across and within layers was beyond the scope of this 2021 Forecast. The need to explore this further is highlighted in this 2021 Forecast Technical Supplement.
Were the wells used for monitoring domestic, permit exempt wells or permitted wells?	They were primarily designated monitoring wells and permitted irrigation wells. For more details see SECTION 3 – Evaluating Trends in Groundwater Levels in this Technical Supplement.
In the future, there will be a -50% change in 10 years in groundwater? What do we need to be doing differently? 10 years will go by fast. What can we do?	The options vary based on the aquifer layer; the number of options decrease and costs generally increase for deeper layers. So there is not a single "silver bullet" that can be used to address groundwater declines. Water conservation strategies may be options to reduce overall demand. Managed aquifer recharge/aquifer storage and recovery can be used in some areas. Other areas may be able to increase the use of surface water to meet demands. Understanding users' needs and management constraints are important components when developing viable strategies, though strategy development was beyond the scope of the Forecast.

For the Overburden layer, do you have anything in that central area for individual wells?	All results are based on individual well data, the majority of which is publicly available through the Department of Ecology's Environmental Information Management System (EIM) and the US Geological Survey's National Water Information system (NWIS). We included all easily accessible wells that met our selection criteria (see SECTION 3 – Evaluating Trends in Groundwater Levels for methodological details). In those areas where there are gaps we either did not have access to the necessary data or the data did not meet our selection criteria. The intent was to use these data to understand the broader patterns of changes in groundwater levels, so results are aggregated for particular areas. Readers interested in individual well data can access these data at https://ecology.wa.gov/Research-Data/Data-resources/Environmental-Information-Management-database and https://waterdata.usgs.gov/nwis.
Do you anticipate some renewal of the supply of water in the Wanapum and Grand Rhonde as the surface water irrigation comes to the Odessa region?	We do expect some modest recharge, although the magnitude, depth and timing of this recharge is uncertain. This is something that could be explored in a future Forecast with groundwater modeling.
How can we help provide groundwater data in the future?	The best option is to contact the Department of Ecology's Water Resources representative for your region (Central Regional Office in Union Gap or Eastern Regional Office in Spokane). Municipal water systems can also contact the Department of Health. You are also welcome to contact the Forecast groundwater module team (sasha.richey@wsu.edu, jturk@aspectconsulting.com, smcclure@aspectconsulting.com).
Is snowmelt the primary source of recharge for the basalt aquifers?	Depending on the location, recharge can occur from snowmelt and other forms of precipitation, interflow between aquifers, irrigation infrastructure and associated return flows, Pleistocene glacial meltwater, or surface water where it intersects with basalt layers.

Moxee Valley declines: Also connected to water conservation and conveyance loss remedies. So, not just a function of withdrawal.	Comment noted. It is beyond the scope of this report to attribute the exact cause of declines.
Your modeling/forecast does not take into account any water conservation for municipal/residential use. Is there a way to include it?	This was our first major effort to upgrade the methodology for the residential water component of the Forecast since 2011. We focused on improving the temporal and special resolution of water demands in this Forecast, but did not collect information on municipal/residential water conservation efforts specifically. We are interested in exploring conservation and how it may affect residential demand in the future, and would hope to partner with the Dept. of Health (who maintains reports on water utility use efficiency) to make use of their extensive data archives related to water conservation measures in this sector. Some of the work that has occurred in parallel to this Forecast by a WSU graduate student has made inroads on understanding changes in residential outdoor water use, which we could also help use to inform 2026 Forecast efforts.
How were residential demands represented? Per capita demands?	Information on municipal water demands were collected from existing comprehensive water system reports. These reports are published by larger water utilities (available at the Washington State Department of Health) and contain a wealth of information about historical and projected future demands. Historical domestic water demands were obtained from county-level estimates in USGS Water Use Reports that are published every five years. Demand information was quantified as (1) total water demands (ac-ft/yr), (2) consumptive water demands (ac-ft/yr) and (3) as per capita demands (ac-ft/yr/person).
Will the actual data be available?	Yes, the data underlying all the figures in the 2021 Forecast Legislative Report is available online through the 2021 Long-Term Water Supply & Demand Forecast Data Access Website (https://arcg.is/0CqnP01). Additional data are also included in this 2021 Technical Supplement.

Page 21 states: "We calculated per capita water use using historical water demand data that we collected from 45 municipalities and 21 counties in eastern Washington. We aggregated the per capita water use estimates from the municipal and county levels for each WRIA as the area-weighted average. We then calculated current residential water demand at each level by multiplying recent per capita water use by the corresponding population size for that level." COMMENT: Did the calculations also include future daily 5,000 gallon exempt-well withdrawals?	The per capita demands used for domestic water demand assessments were aggregated data as reported by each county, which only speaks generally about the types of water use that could be included in this category. Our future assessments did not include a future daily 5,000 gallon exempt well withdrawal. Instead of assuming maximum withdrawals in the future, this assessment uses historical water use data to make predictions about likely per capita water demands in the future, and combines them with projections of population growth. Significant changes to water use from policy changes, for example, would not be captured in this type of assessment.
The draft Forecast makes no mention of the fact that the groundwater permit exemption provided in RCW 90.44.050 allows certain uses of groundwater to be established without first obtaining water right permits. One such use includes single homes or groups of homes that use no more than 5,000 gallons per day.	This residential demand assessment focuses broadly on the volume of water demanded by residents in eastern Washington, only making minimal distinction between the types of water users (i.e., domestic versus municipal). While these two broad categories cover a range of different water provider or self-supply provision options, a finer resolution analysis of these sub-categories was not included in this Forecast and therefore we also did not include any in-depth discussion of all the various policy or legal mechanisms by which water could be obtained for residential water use.
The draft Forecast estimates that "Total residential consumptive demand for eastern Washington will reach over 232,410 ac-ft per year by 2040, compared to close to 187,428 ac-ft per year in 2020. This represents an increase of approximately 24% (Table 9)." Why did the draft Forecast fail to take into consideration needed changes to the 5,000 gallons per day well exemption?	Our future assessments did not include a future daily 5,000 gallon exempt well withdrawal. Instead of assuming maximum withdrawals in the future, this assessment uses historical water use data to make predictions about likely water demands in the future. Significant changes to water use from policy changes, for example, would not be captured in this type of assessment.

The Washington state portion of the Columbia River Basin cannot meet existing water right allocations or instream flows, much less "unmet water requirements." The Forecast should review the Northwest's response to the demand in the 1970s by BPA, public and private utilities and chambers of commerce demanding massive new coal and nuclear powered electrical generating plants to meet an artificial electrical "demand" that appeared to have no limits. Fortunately, the Northwest rejected this expensive and dangerous "model," and instead adopted a soft-energy path approach built around energy conservation, alternative energy sources, and least-cost pricing. This was possible because of the tremendous energy wastage in the region along with faulty price signals. We request that the final Forecast include a soft-water path analysis that addresses the tremendous water wastage in Eastern Washington, including less than robust water metering, the 5,000 gallon domestic-well exemption, the Wapato Irrigation Project (known as the most wasteful and inefficient irrigation district run by the Bureau of Indian Affairs), and the water wastage by Senior Irrigation Districts with no incentive to conserve.	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years, and as such, does not include a particular path forward. The team is considering an approach focused on "what if" scenarios in planning for the 2026 Forecast. This approach would allow the team to evaluate alternate paths being considered, that could inform the type of soft-water path analysis mentioned here. It is important to note that there will likely be limitations to the number of "what if" scenarios the team can adequately examine in the 2026 Forecast.

What is the impact of no-till, cover crops and double cropping on late season water demand?	No-till is primarily employed in dryland agricultural areas in the Basin, so the impact to water demand for irrigation should be essentially non-existent, and has not been addressed in the Forecast. Some irrigated areas include some direct seeding; however, this has not been quantified in this Forecast. The team focused on using remote sensing and imagery to assess double and cover-cropping. The challenge has been to distinguish these two practices. There was an increase in double cropping about 10 years ago, and the team is evaluating whether anecdotal comments that an increase in double cropped acres might be happening again are accurate and to what extent.
Is there significant carbon storage benefit achieved through region-scale cropping-mix changes? For example, cover crops were mentioned. If cover cropping changes are adopted, how would this propagate through the water demand analysis?	Change in crop mix evaluated in this Forecast were projected based on trends observed in the past. This Forecast therefore did not assess changes that could occur due to carbon incentives in the future (such as increased cover cropping, for example, should programs such as the Sustainable Farms and Field Program be funded). Such changes could be accounted for in future Forecasts.
I was surprised by the increased curtailments for the vast majority of the growing season regardless of crop mix changes. As technologies improve and agriculture becomes more water efficient (60 percent less use in the last 50 years or so), I would expect the same level of effective innovation in cropping and irrigation moving forward, particularly as water scarcity becomes a concern.	Curtailments are heavily influenced by the natural water supply, and the future trend is toward more water in fall and winter and less water during most of the irrigation season due to less snowpack and earlier snowmelt, which leads to the increased curtailment results. Technological improvements and changes in agriculture (beyond what can be expected given recent trends in crop mix) are not included in the 2021 Forecast. The team is considering focusing on “what if” scenarios in the 2026 Forecast. Such an approach would more readily lend itself to evaluating options such as those described here. It is important to note that there will likely be limitations to the number of “what if” scenarios the team can adequately examine in the 2026 Forecast. Also, see below response for how crop mix changes were projected.

Why does the draft Forecast fail to include an alternative of moving irrigation water from high water demand crops, such as irrigated hay for export to Asia, to less intensive crops or to residential needs?	The Forecast focused on changes in crop mix that can be expected in the future based on understanding the trends in the recent past. These trends are driven by complex socio-economic conditions occurring both within the region and globally. The policy-based alternative suggested by this comment is one of many ideas that could be used in future Forecasts, if "what if" scenarios are scoped for the 2026 Forecast, rather than trying to project trends into the future. It is important to note that there will likely be limitations to the number of "what if" scenarios the team can adequately examine in the 2026 Forecast.
The final Forecast should provide an estimate of the total annual acre feet of water equivalent of crops exported overseas out of the Columbia Basin.	This is outside the scope of the Forecast. However, users could combine the estimates of agricultural water demand produced in this Forecast with other data on exports of crops to explore this question.
The final Forecast should explain what is meant by "current double cropping acreage could add a notable amount to the above agricultural water demand values." Is current double cropping having an impact now?	The historical agricultural water demand values are based on single-crop acreages, as insufficient data were available to make informed assumptions about double cropping. In parallel, the team, in partnership with the Washington Department of Agriculture and others, initiated a study to fill this data gap in future Forecasts. Though these results were not available in time to integrate them into the modeling of agricultural demand for this 2021 Forecast, the team estimated the additional water that fields that are currently double cropped would require (see the Potential Impacts of Double Cropping in the Legislative Report).
With the changes in power demand, did you look at the flattening of demand over the seasons for things like cars and server farms, and how bulk users demand would change flow management in the Columbia? Right now we are managing for peak demands during summer and winter, but what about larger consistent demands?	The 2021 Forecast did not evaluate within season differences. In addition, the estimates for changes in power demand estimated here do not include an evaluation of whether hydropower could increase to meet these demands. Therefore, no information on how this would or could change flow management in the Columbia River were included.

On the energy side, there are concerns (from the Bonneville Power Administration) about capacity in the future, with changes in the electric grid, energy leaving the grid more frequently (if updated nationally), and given what’s happening in California. Having a regional approach is helpful here, but we need to be looking at outside demand more (it is renewable and high value), so we can’t plan all our growth through it. Many utilities are trying to address these issues on their own. Certain utilities, such as Douglas Public Utility District (PUD), are investing in Hydrogen Production facilities to provide energy in the transportation sector or perhaps store power for use later, to meet the higher demands of the summer season. Other projects involving "pumped storage" try to store energy over shorter periods such as a single day and have been utilized very effectively in the Southwest and even in China.	We looked at pump storage power but not at the possibility of hydrogen production. Grant County PUD is also looking at modular nuclear power, which might be a water user to some extent. If Douglas PUD has a report on hydrogen production, we would love to get a copy.
The Columbia River Treaty provided the lower Columbia River with water storage for what are primarily "run of the river" dams, with little actual reservoir storage except behind the Grand Coulee Dam. BC Hydro will further "grow out" the full use of their storage dams as they build their complete suite of turbines to generate power, allowing more water to be released earlier in the water year as the power is needed.	Comment noted.

I am a ranch/farmland owner in Klickitat and Clark counties. I am disappointed that this information seems to communicate that nothing must change relative to water usage.	The Forecast is not intended to make prescriptions for policies or actions that should change, but rather to provide the relevant information around expected changes (such as due to climate change impacts), and the associated vulnerabilities in water availability to those who decide on policies and actions.
Are there currently any projects underway to increase water storage above or below ground? Are any in the planning or construction stage?	There are currently both above ground and below ground storage projects underway across eastern Washington. For example, the Yakima Basin Integrated Plan has a storage goal of 450,000 acre-feet. In addition, OCR is working with some mid-Columbia municipalities on aquifer storage and recovery efforts to increase groundwater storage. The Office of Columbia River is exploring many types of storage options (surface water, groundwater, existing storage modifications) to retime water supplies to help meet future demands. So far, only aquifer storage projects have been fully completed.
In summary, why did Ecology require a supply/demand framework that ignores conservation, but assumes uneconomical and environmental damaging water projects?	Ecology did not specifically direct the research team to ignore conservation. The 2021 Forecast did not explore scenarios related to water conservation efforts because conservation is a complex issue to address at the watershed scale and incorporate into water supply and demand modeling. The team made assumptions when there was insufficient data or appropriate methodologies to estimate, with some degree of confidence, what the future could hold. The team is considering an approach focused on "what if" scenarios in planning for the 2026 Forecast. It is important to note that, should this approach be adopted, there will be limitations to the number and range of scenarios that can be considered based on available data to quantify those scenarios, as well as uncertainty as to the likelihood of each scenario actually occurring in the future. However, such an approach would allow a range of alternative scenarios of water use.

Again, the Forecast assumes endless demand for water rather than providing a range of rational water use. Why?	The team made assumptions when there was insufficient data or appropriate methodologies to estimate, with some degree of confidence, what the future could hold. The team is considering an approach focused on "what if" scenarios in planning for the 2026 Forecast. It is important to note that, should this approach be adopted, there will be limitations to the number and range of scenarios that can be considered based on available data to quantify those scenarios, as well as uncertainty as to the likelihood of each scenario occurring in the future. However, such an approach would allow a range of alternative scenarios of water use.
It is now 2021. Hydrological continuity between ground water and surface water has been known for decades. Why has Ecology failed to prioritize research and understanding of these interactions?	Surface water supply models do not readily interact with detailed groundwater models. The team is prioritizing such integration for future Forecasts (see the Next Steps—Building Towards the 2026 Forecast section).
Page 1 states: "The water supply delivery systems in the Columbia River Basin were built to reliably deliver water under 20th century conditions." This is incorrect. Please amend this sentence to read: "Due to over appropriated river basins and unrealistic water "demands," the water supply delivery systems in the Columbia River Basin have been unable to reliably deliver water under 20th century conditions."	This introductory statement refers to the intent and purpose that drove the building of the delivery infrastructure and not as an assessment of effectiveness or a justification of these delivery systems.
Page 12 and Figure 5 fail to provide a clear picture of the amount of water that would be dedicated to instream or out-of-stream uses. The Forecast should provide a separate table of the instream and out-of-stream acre-feet provided by each project.	Figure 5 is included in the Forecast to provide a broad-scale view of the projects that the Office of Columbia River has or is funding. The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years, and as such, does not include a detailed quantification of the intended uses of water from each project.

On page 59 it states: "The possibility for re-negotiation of the international Columbia River Treaty and unquantified tribal water rights could also change the amounts and timing of water available to meet instream needs in the Columbia River Mainstem within Washington State (and beyond). These factors have the potential to impact future water supplies in ways that are difficult to predict." Rather than simply dismiss the Columbia River Treaty as difficult to predict, the Forecast should lay out the status of the current negotiations with the parties' positions to inform the Washington Legislature of possible outcomes.	The team's intent was to add value to other resources and information available to the State Legislature and the public related to this topic, and within the scope of the 2021 Forecast. The team considered that what would be informative and within the scope of the Forecast would be quantitative assessments of what proposed changes being considered in the Columbia River Treaty negotiations could mean to water supply and demand by 2040s. However, insufficient detailed information is publicly available on these negotiations to support a robust analysis. This point was added to the Legislative Report (see the Forecast Limitations

Depending on the outcome, it seems possible the federal Columbia River Treaty with Canada could turn out to be a more prominent unknown variable during this forecast period than is ascribed in the draft document. Earlier this week, a bipartisan group of Washington/Oregon lawmakers, led on Washington's behalf by Rep. McMorris Rodgers & Sen. Murray, submitted a letter to the Biden administration asking that the negotiations, which dwindled in late 2020, be made a priority. Ecology may wish to consider incorporating a brief, dedicated section about the treaty's status & how it could influence the Columbia River supply. This should be quickly achievable with a minimal amount of additional work. Currently, the treaty is mentioned only four times throughout the document, in context of hydropower (pp. 35 & 37), tribal water (p. 59), & reservoir operations (p. 63). Water supply allocation (including tribal water on both sides of the border, since tribal interests weren't considered in the original treaty) is expressly represented in the basis-of-negotiation document. The Legislature should understand this is an important externality.	section). The team is considering a "what if" scenario approach for future Forecasts. Such an approach could better support the requested analysis under conditions of insufficient quantitative information on the negotiations. It is important to note that there will likely be limitations to the number of "what if" scenarios the team can adequately examine in the 2026 Forecast.
The final Forecast should clarify the difference between Ecology supposed effort to aggressively pursue new water supplies for agricultural irrigated use during drought years and the likely outcome that new water supplies will be used for agricultural irrigated use during non-drought years, increasing the pressure on anadromous fish runs and instream flows.	The team is considering an approach focused on "what if" scenarios in planning for the 2026 Forecast. This approach would allow the team to evaluate different decisions around allocation of additional water supply due to water development projects. It is important to note that there will likely be limitations to the number of "what if" scenarios the team can adequately examine in the 2026 Forecast.

Just to follow-up, is Ecology now saying that increased irrigation water wastage and inefficiencies are to be encouraged; and is Ecology now saying that there will be no increase in water withdrawal quantities from the Alpine Lakes Wilderness under its Icicle Basin program?	No. The comments made around irrigation efficiency during the public sessions were related to the complexities of accurately capturing the watershed-level effects of irrigation efficiency measures. These comments do not imply that water wastage or inefficiencies are to be encouraged. The Forecast does not develop policy prescriptions, nor does it determine decisions by the Department of Ecology or other entities.
In summary, it appears that Ecology has directed a forecast that will be used to justify aggressive pursuit of additional water storage projects, while disregarding needed water conservation, water efficiency, and water banking. Upper Watershed restoration is a vital and necessary component to providing cool, clean water and shouldn't be ignored!	Responses provided to individual topics are included in comments above.

Table 3. 2 Comments received that referred to projects and decisions of the Office of Columbia River but were not specific to the 2021 Forecast. All comments were received from the interested public during the two public workshops held in June 2021 and during the month-long public comment period held throughout the month of June 2021. This Table includes the subset of the comments received that were focused on other projects or activities carried out or being planned by the Office of Columbia River (OCR) or other divisions in the Washington State Department of Ecology. These projects or activities were either outside the scope and purpose of the 2021 Columbia River Forecast or addressed projects at a scale incompatible with this Forecast. Specific details are provided in the OCR's and Forecast Team's Response column. Note that page numbers in the Public Comment column refer to the draft that was available for review, and may be different to the page numbers in the final 2021 Forecast Legislative Report.

PUBLIC COMMENT	OCR's and FORECAST TEAM'S RESPONSE
Friends of Toppenish Creek submitted detailed comments that concern the disproportionate impact that concentrated animal feeding operation (CAFO) dairies have on Lower Yakima Valley groundwater. They request that this relation be described in detail in the Forecast.	It is beyond the scope of this Forecast to evaluate either the volume of water withdrawals or the water use associated with those withdrawals. We can consider the importance of quantifying these specific withdrawals for the 2026 Forecast; however, the scale at which the Forecast provides results does not match the scale of individual operations.
The final Forecast should list all potential hydro and non-hydro reservoirs that Ecology has studied since 2006 in the Columbia River Basin, along with the expected evaporation amounts from each reservoir.	Comment noted. This will be considered for the 2026 Forecast.

The final Forecast shall also list all existing reservoirs, as well as potential hydro and non-hydro reservoirs that Ecology has studied since 2006 in the Columbia River Basin, along with the existing and expected generation of methane from such reservoirs, as methane is a powerful climate changing gas.	Comment noted. This will be considered for the 2026 Forecast.
The Forecast should examine what happens to the $130+ million investment in the Cle Elum Fish Passage Project if low flows and temperature result in no sockeye salmon returns to the Cle Elum River, as happened during the 2015 drought year?	The Forecast is focused on assessing water quantity metrics, quantifying where and when water is available and needed. In addition, the scale of the Forecast is watershed level or broader, so the proposed project-specific analysis is outside the scope of the Forecast.

The Lake Cle Elum Fish passage project, costing in the vicinity of $131+ million dollars to restore sockeye runs, which had been destroyed by the construction of the Cle Elum dam, is dependent for its success on sockeye returning up the Columbia River. With an anticipated completion date around 2024 of the Cle Elum Fish Passage Project, Ecology promises to reopen almost 30 miles of upstream spawning and rearing habitat which, in turn, would restore salmon, steelhead, and other fish populations in the Cle Elum River. As noted above, Ecology refuses to consider that temperature blockages in the Columbia River, caused in part by the lower Snake River dams, may prevent sockeye salmon from returning to the Cle Elum River during drought high summer temperature years. This puts at risk the millions of dollars invested in the Cle Elum Dam Fish Passage project. The Washington Legislature should support removal of the lower Snake River dams.	The Forecast has focused on assessing water quantity metrics, quantifying where and when water is available and needed. In addition, the scale of the Forecast is watershed level or broader, so the proposed project-specific analysis is outside the scope of the Forecast. Finally, the Forecast does not develop policy prescriptions, nor does it determine decisions by the Department of Ecology or other entities.

The Washington Legislature requested that before Washington state taxpayer money is spent on Yakima Basin projects, a benefit/cost analysis should be prepared. That analysis was prepared by the Water Research Center, dated December 15, 2014. According to its executive summary: “Net benefits for out-of-stream use of individual water storage projects implemented with no other projects implemented are negative, with some exceptions under the 19 most adverse climate and water market conditions. Based on moderate climate and market outcomes, storage infrastructure projects implemented alone and without proposed IP instream flow augmentation result in the following estimated out-of-stream net present value and B/C ratios, none of which passes a B-C test: o Bumping Lake Expansion: NB=-$371 million; B/C ratio of 0.18. o Cle Elum Pool raise: NB= -$6 million; B/C ratio of 0.62. Under the most adverse climate scenario and moderate market conditions, NB=$5 million with a B/C ratio is 1.35. It is also the most likely of the storage projects to satisfy a BC test under moderate climate based on the sum of out-of-stream and instream use value. o Keechelus to Kachess Conveyance: NB= -$110 million; B/C ratio of 0.20. o Kachess Drought Relief Pumping Plant: NB= -$107 million; B/C ratio of 0.46. Under the most adverse climate considered, Keechelus to Kachess Conveyance and Kachess Drought Relief Pumping Plant together provide net benefits of $6	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. As such, the Forecast does not include evaluation for any particular project. However, results from this Forecast could be used by other groups who wish to perform this evaluation.

million and a B/C ratio of 1.02. o Passive Aquifer Storage and Recovery: NB=-$82 million; B/C ratio of 0.35. o Wymer Dam and Reservoir: NB= -$1,217 million; B/C ratio of 0.09. o Due to diminishing economic returns to water in the basin, increasing the number of IP storage projects reduces the value of each water storage project implemented" https://wrc.wsu.edu/documents/2014/12/ybip_bca_execsumm_swwrc_2014. pdf/. We request that this executive summary be included in the Forecast for the benefit of the Washington State Legislature as a reminder of just how uneconomical the Department of Ecology's aggressive pursuit of water supply projects has been.	
The Forecast should take into consideration the breaching of the four lower Snake River Dams. This is a necessity not only to reverse the drastic decline in salmon runs, but to aid in the lowering of Columbia River temperatures to alleviate temperature blockages of sockeye salmon returning to Lake Cle Elum.	Comment noted. This will be considered for the 2026 Forecast.

Page 37 states: Climate Change Impacts on Evaporative Losses “Water losses due to evaporation and seepage from off-channel pump storage facilities are expected. For instance, the Goldendale Pump Storage Project proposed by Rye Development would generate 25,500 MWh for up to 20 hours. The Sierra Club opposes the project because it is estimated that it will require 2.93 billion gallons of Columbia River water initially to fill, and as much as 1.2 million gallons each year to make up for water lost through evaporation and leakage, which is equivalent to about 9,000 ac-ft to fill and 3.7 ac-ft per year in losses. Other pump storage projects like Shell’s Pearl Hill Project are closed-loop systems where water will be stored in a large tank. Evaporation losses would be negligible (assuming the tank is enclosed), although there could be additional small losses when the water is released back to the downstream pond. Therefore, evaporation losses from new facilities would likely be fairly small, though projects with larger surface area to volume ratios might result in larger losses.” While we appreciate Ecology noting that the Sierra Club is on record opposing the Goldendale Pump Storage Pump Storage Project, Ecology fails to include that there is large opposition to the construction of other Ecology water supply projects, including a new Bumping Lake Dam, a Wymer Dam, a Lake Kachess Pumping Plant Project, as well as expansion of water storage projects in the Alpine Lakes	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. The example of the Goldendale Pump Storage Project is simply to illustrate the magnitude of evaporative losses of this type of project. Neither policy recommendations nor information on the acceptance or opposition to particular projects is within the scope of the Forecast, therefore individual project comment letters are not included as part of this comment response..

Wilderness. Please include the attached group-letters as part of these comments.	

Ecology should provide more background from the May 12, 2020, State Audit Office Performance Audit, "Assessing Success of the Walla Walla Watershed Management Partnership Pilot," and how Ecology intends to address the audit's findings: 1. The Partnership did not explicitly identify improving streamflow as a core goal despite clear statutory intent, and board members agree that streamflow did not improve; 2. The Partnership met most statutory requirements, but did not create and use an accountability framework that could have helped it evaluate and adapt its activities to ensure success; 3. The Partnership lacked sufficient funds to implement strategies necessary to improve streamflow, but failed to fully exercise its authority to pursue additional revenue; 4. Returning management of the Walla Walla watershed to Ecology could offer better access to funding for needed infrastructure projects 5. Significant streamflow improvements in the Walla Walla watershed require greater cooperation between Washington and Oregon Although a Walla Walla River Bi-State Study update was prepared in 2019, there is no information as to whether the state of Idaho has been involved. This should be included as anadromous fish returning to Idaho are impacted by projects involving the Columbia and Walla Walla Rivers.	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. The comment is therefore outside the scope of this Forecast.

It is shocking, but not surprising that after years of pretending that the Kachess Drought Relief Pumping Plant would be funded by irrigation districts, Ecology has finally admitted that this project would be funded by the Office of Columbia River (i.e., state taxpayers). This is important information for the Washington State Legislature. Also of concern is that Ecology lobbied the Washington State Legislature and Congress hard for authorization for the Keechelus-to-Kachess (K-K) Conveyance Project after an inadequate Yakima Plan programmatic EIS was issued. Only after the project was authorized and with completion of the Supplemental EIS for the Kachess Drought Relief Pumping Plant and Keechelus-to-Kachess Conveyance Project, did Ecology abandon the K-K Conveyance Project. Ecology must stop requesting authorizations for projects without full SEPA review. Why did Ecology lobby the State Legislature and Congress to authorize a K-K Conveyance Project that was then abandoned?	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. The requested information on a specific project is outside the scope of this Forecast.

I recently read a story that the state is considering giving control of the Columbia River Basin Water to a private investment company made up of former Goldman Sachs executives. How is this possible? Especially as I read on your website that you recognize that climate change will have a major affect on our watershed? Water should not be owned by a company and especially not a hedge fund or investment company. It's clear that the very people who've spent years denying climate change exists, realize too that water will soon be a lucrative commodity. They'll charge our fisheries to use the basin. Place tolls on shipping and buy up agricultural areas to create corporate farms they give precedence to with water. And they'll sell our water or ship it back East. This is unacceptable. It should not even be considered.	This comment refers to a specific water banking proposal. The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. The requested information on a specific project is outside the scope of this Forecast.

In October 2019, Yakima Workgroup members and interested stakeholders held a full-day planning workshop that "celebrated 10 years of working together and focused on planning needs for the next 10 years. It was an opportunity to recognize the significant progress and investments made on watershed scale ecosystem health and improving critical infrastructure that supports a sustainable agricultural economy." Ecology should review and summarize this planning effort to determine whether it is consistent with the draft Forecast.	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. This information is now available to carry out the requested review and comparison, which are themselves outside the scope of this Forecast.

Within the Yakima River Basin (WRIA's 37, 38, 39), proratable irrigation districts conceded that they could manage with 70 percent of their allotment during drought years, showing the tremendous amount of wastage in their systems. No such concern was exhibited by senior irrigation districts, with their 100 percent of water allotment during drought years, results in no incentive to undertake water conservation measures. 8 P.L. 103-424 (Yakima Plan Phase II), passed in 1994, required water conservation plans be developed for each irrigation district. What have been the water conservation savings from each of these water conservation plans for each Yakima irrigation district? What is the status of water metering on each Yakima irrigation district?	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. Evaluation of water conservation savings under specific conservation plans and water metering within individual irrigation districts is outside the scope of the Forecasts.
P.L. 96-162, passed by Congress in 1979, directed: "That the Secretary Yakima River of the Department of the Interior is authorized and directed to conduct a feasibility study of the Yakima River Basin Water Enhancement Project, which shall include an analysis by the United States Geological Survey of the water-supply data for the Yakima River Basin." Please identify and provide a summary of this USGS study.	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. The feasibility study described is outside of the scope of this Forecast.

Why does the Forecast not address obvious problems with increased temperature, which has already caused significant adverse impacts to Columbia River salmon runs?	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. Though there are interactions between changes in water temperature and changes in flows, the Forecast's scope is limited to the latter changes.
The Forecast should review Ecology’s failure to meet the Congressionally set water conservation targets set in 1994.	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. Evaluation of water conservation targets under a specific federal conservation plan is outside the scope of the Forecast.
The Bureau of Reclamation awarded a WaterSMART grant in 2017 to the Kittitas Reclamation District and partners, Trout Unlimited and Mammoth Trading to continue their analysis of water banking and market based reallocation of water within Kittitas County. Continued “analysis” is not sufficient, nor does it represent a commitment by Ecology to an aggressive water efficiency, water conservation, and water banking program. What have been the results of this grant?	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. The WaterSMART grant described is outside the scope of the Forecast.

In reference to table 11, This does not appear to be a complete listing of “unmet water demand.”	The estimates provided in Table 11 are good-faith estimates of documented unmet demands. Demands that are not fully quantified or documented were not included. These unmet water demand values are also subject to fine-scale variation that is not fully captured in these estimates. If there are specific, existing datasets of additional unmet demands that the team should consider for future Forecasts, please contact the team leads.
Ecology should provide a listing of each WRIA that has over-allocated water rights, with an estimate of the acre-feet represented by over-allocated water rights.	The Forecast provides an assessment of water supply and demands for each WRIA, including adopted instream flow rules, under historical and future conditions. The extent to which water supply does not meet water demand in some locations and during some years is captured in the individual WRIA/watersheds through the curtailment modeling. See the *Forecast Results for Individual WRIAs* section.

The proposed Lake Kachess Pumping Plant Project, which would drain an additional 200,000 acre feet from Lake Kachess still does not have a competed environmental impact statement or design plan, or any firm agreement as to who will pay for this project or how impacts to bull trout will be addressed. Previous efforts to place plastic and hay bales at the mouth of Box Canyon Creek in Lake Kachess to assist with bull trout passage resulted in failure as the plastic and hay bales used were strewn all over the Lake Kachess mud flats. Recent attempts to place woody debris in Box Canyon Creek have likewise been a failure. Proposals to reconfigure Gold Creek above Lake Keechelus to enhance bull trout remain controversial. Why did Ecology lobby to have the Washington State Legislature and Congress authorize this project without a completed EIS process?	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. As such, the Forecast does not include evaluation for any individual project.

In addition, Ecology has proposed the construction of an off-channel mid-basin dam near the confluence of Lmuma Creek and the Yakima River to create a new reservoir called Wymer Reservoir in the Yakima River Basin with a storage capacity of up to 162,500 ac-ft. A new Wymer dam would flood critical shrub-steppe habitat used by sage grouse. There is not possible mitigation for the loss of this habitat. In addition, as noted below the Water Research Center's benefit-cost analyses, prepared in response to the Washington State Legislature, demonstrated that this project does not have a positive B/C ratio. Concerning a new Bumping Lake dam, the replacement of the existing Bumping Lake dam with a new dam downstream would increase the storage capacity of the reservoir from 33,700 ac-ft to 190,000 ac-ft, while flooding out ESA designated bull trout habitat and ancient forests along the shoreline valued at $1,8 billion dollars. The Forecast should acknowledge that the above water supply projects are uneconomical and environmentally damaging.	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. As such, the Forecast does not include evaluation for any individual project.

The demand analysis for WRIAs 37, 38, and 39 remains inadequate. The Forecast should disclose the amount of Yakima River Basin water that is exported, particularly in the form of hay/alfalfa that is sent overseas to Asia.	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. Evaluating the destination of products produced within any eastern Washington WRIA (and those products' water uses) is outside the scope of the Forecast.
The Forecast does not acknowledge that in a mere two centuries, after thousands of years of occupation by Native Americans, we have managed in the Columbia River Basin to clear-cut our way through much of the region's Ancient Forests, fill in a large percentage of our wetlands and estuaries, dam its rivers, and bring one of the world's most abundant fisheries to the brink of extinction. In addition, the Forecast does not acknowledge that that salmon runs in the Northwest are not predictable from year to year.	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. The requested context is much broader than this purpose, both in topic and scale, and is therefore outside the scope of this Forecast.

The Icicle Sub-watershed is the largest sub-watershed in WRIA 45, covering 136,916 acres. Yet the WIRA 45 summary makes no mention of Ecology's aggressive pursuit of new water supplies within the Alpine Lakes Wilderness. See: https://www.co.chelan.wa.us/natural-resources/pages/icicle-work-group. This continues a disturbing trend of Ecology's failure to disclose controversial, uneconomical, and environmental damaging water project proposals that the State Legislature continues to fund with little oversight or investigation, except for the performance audit carried out by the State Audit Office on the Walla Walla Watershed Management Partnership Pilot. It also demonstrates how nothing is off-limits to Ecology's aggressive pursuit of new water supplies, including within this state's Congressionally designated Wilderness Areas. The Forecast should disclose Ecology's Icicle Work Group plans to increase water storage projects within the Alpine Lakes Wilderness.	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. In addition, the Forecast does not develop policy prescriptions, nor does it determine decisions by the Department of Ecology, the State Legislature or other entities.
The Department of Ecology continues to aggressively pursue additional water storage in the Alpine Lakes Wilderness	

The Forecast does not address a needed recovery plan for Columbia River salmon, including options for breaching the four lower-Snake River dams, or possible outcomes from the Columbia River Treaty.	The purpose of the Forecast is to provide a system-wide, quantitative assessment of how future environmental and economic conditions and human responses are likely to influence water supplies and demands over the next 20 years. As such, addressing any species-specific planning needs is outside the scope of the Forecast. For responses on the breaking of the Snake River dams and the Columbia River Treaty, please see comments that respond to these topics specifically, above and in Table 1.

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