AN ABSTRACT OF THE DISSERTATION OF

Alexandra A. Savotkina for the degree of Doctor of Philosophy in Geography presented on June 1, 2016.

Title: Nuclear Power Plant Siting in the Columbia River Basin: Current Trends, Effects of Climate Change, and Associated Uncertainties

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This PhD dissertation describes and evaluates a geographical analysis of candidate areas for siting nuclear plants utilizing a wet cooling tower in the Columbia River Basin (CRB). It focuses on the analysis of water availability for cooling and how it may be limited by climate change effects on river streamflow.

The CRB, which includes portions of OR, WA, ID and MT, is projected to require more sources of energy in the future. Oregon, Washington, and Idaho are projected to have a total energy shortfall of 58,676 MWe by 2050. Given the limitations on alternative low-carbon energy sources, nuclear power is a potential source of renewable low-carbon energy in the CRB.

This study applied siting criteria required by the Nuclear Regulatory Commission (NRC) and a GIS-based multicriteria decision analysis (MCDA) approach to identify candidate areas of the CRB appropriate for constructing nuclear reactors. Only 4.6% and 3.1% of the CRB were found to be suitable for siting small and large reactors, respectively. The two main candidate areas are Middle Columbia River, and Snake River plain. One of these regions already contains a nuclear power plant (Columbia Generating Station, WA), and the other site is currently under consideration for a nuclear plant (Payette County, ID). Water availability for cooling was the most important factor restricting nuclear power plants, but earthquake hazards and landslide

hazards were also significant limiting factors. The restricted area available means that future nuclear plants could meet only a portion of the projected future energy shortfall in the Pacific Northwest.

This study examined the possible effects of climate change on minimum streamflow requirements for siting nuclear power plants in the CRB, by analyzing projected future daily discharge data from several CMIP3 and CMIP5 climate models, downscaled using three different techniques under high (A1B/RCP8.5) and medium (B1/RCP4.5) emission scenarios. Projected future streamflow eliminated small clusters of potential sites in several parts of the CRB, while the two main candidate areas appeared to be relatively resilient to it, because of high initial streamflow.

Finally, the study discussed the uncertainty associated with the siting process for nuclear power plants, with the potential future effects of climate change on water availability necessary for cooling, and with overall public perceptions of nuclear power. While siting criteria and projected changes in streamflow may significantly reduce the number of potential sites, public opposition to nuclear power could entirely prevent construction of reactors within areas that are physically and economically suitable for siting.

Nuclear Power Plant Siting in the Columbia River Basin: Current Trends, Effects of Climate Change, and Associated Uncertainties

by

Alexandra A. Savotkina

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APPROVED:

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Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Alexandra A. Savotkina, Author

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Chapter 1. Introduction

This PhD thesis is a geographical analysis of potential sites for nuclear power plants in the Columbia River Basin (CRB), including an analysis of water availability for cooling and how water availability, and hence site selection, may be limited by climate change effects on river discharge. Chapter 1 provides an overview of this study. It establishes the disciplinary context of this study, reviews relevant prior literature, and describes the motivation for the study.

1.1. The geography of nuclear plant location: analysis of uncertainty and risk

This section describes how this study is related to the discipline of geography. It describes the logic and disciplinary context of the study.

1.1.1. Uncertainty and probabilistic risk assessment, and multi-criteria decision analysis

Uncertainty can be defined as lack of confidence in knowledge about a specific question (Kiparsky et al. 2012), or something that defines and limits our efforts to better understand extreme and rare events (Harrower 2003). Risk today is seen as a kind of uncertainty that can be measured or quantified probabilistically, and thus can be managed (Klüppelberg et al. 2014). Probabilistic risk assessment (PRA) which allows to account for and control uncertainty, is a quantitative approach toward system safety and reliability (Klüppelberg et al. 2014), that enables to evaluate risks associated with a complex technological entity (Kafka 2008).

In the United States Norman Rasmussen from MIT, on behalf of the Nuclear Regulatory Commission (NRC), assessed the risk associated with the operation of ten U.S. light water reactors. The results of this assessment were published in 1975 in form of the “Rasmussen Reactor Safety Study” and coded as WASH 1400 (Klüppelberg et al. 2014, Kafka 2008). The Rasmussen report was the first study that applied a probabilistic approach in the assessment of technical risks, and thus was a breakthrough in PRA. This study was an integrative application of the event tree and fault tree methodologies, both of which were known before, but had been applied separately in system reliability studies in various technologies. Although the Rasmussen report also received serious criticism (in particular, because of its heavy reliance on fault tree analysis, and large uncertainties associated with risk estimates), after the Three Mile Island accident in 1979 the NRC required PRA as a part of the licensing procedure for nuclear power plants (Klüppelberg et al. 2014, Kafka 2008).

Risk in PRA is determined by two factors: 1) the probability of the occurrence of an adverse consequence, and 2) the magnitude of a possible adverse consequence (Kafka 2008). Consequences here are expressed by numbers (e.g. number of potentially impacted people), and the likelihood of occurrence is expressed as probabilities or frequencies (i.e., the number of occurrences or the probability of occurrence per unit of time). PRA usually answers three basic questions related to: 1) the causes of possible faults within the entity, 2) the possible adverse consequences, and 3) the probability of the adverse consequences (Kafka 2008). For NPPs it is usual to perform PRAs for three different ranges: 1) Level 1 PRA estimates the frequency of accidents that cause core damage, 2) Level 2 PRA estimates the frequency of accidents that can lead to core damage and consequently to the release of radioactivity, and 3) Level 3 PRA estimates the impacts on public and the environment, based on the frequency of accidents that can lead to core damage and release of radioactivity (NRC 2013).

Multiple criteria decision analysis (MCDA) is a form of PRA. The aim of MCDA is to assist decision makers to choose, rank or sort alternatives within a finite set according to two or more criteria to make the best choice (Chen et al. 2008). In our study, we apply the MCDA approach to exclude a number of areas unsuitable for siting nuclear plants (near population zones, near faults, etc.) and thus reduce the probability of risk.

1.1.2. Location of hazardous facilities such as nuclear power plants

MCDA applies PRA to the process of facility location analysis. Facility location analysis is a form of applied, quantitative geographical analysis in which the objective is to locate a set of facilities to minimize risk based on the spatial patterns of probabilities and consequences of adverse outcomes.

Multi-criteria decision location analysis is especially useful for managing the spatial risks associated with hazardous facilities, such as nuclear power plants. A nuclear power plant is an electrical generating facility in which energy from the decay of uranium heats pressurized water to provide steam to power a turbine generator (Gerdes and Nichols 2008). A nuclear power plant is a potentially hazardous facility, because it is associated with probabilities of adverse consequences such as those related to core damage and release of radioactivity.

In our study we apply GIS-based MCDA (a form of PRA combined with location analysis) to the problem of identifying nuclear power plant locations. In summary, our research addresses three questions: 1) What areas of the Columbia River Basin are suitable for siting nuclear plants based on location analysis using probabilistic risk assessment and historical streamflow records? 2) How will the potential future effects of climate change on streamflow influence siting of nuclear plants in the Columbia River Basin? 3) How does uncertainty about past and future climate and other factors, such as public perceptions of nuclear power, affect the outcome of the analysis?

1.1.3. History and prior studies of nuclear power plant location in the CRB

A nuclear reactor first generated electricity on December 20, 1951 at the Experimental Breeder Reactor I at a site in Idaho, in the United States (DoE 2006). On June 27, 1954, the first nuclear power plant in the world designed for electricity production started operation at Obninsk in the former USSR, and was connected to the Soviet power grid (Kurchatov Institute 2010). Currently there are 440 operating (connected to the grid) nuclear reactors all over the world (as of March 1, 2016). The total installed capacity is 384,006 MWe (net). Another 65 reactors are under construction, and 173 are on order (World Nuclear Association 2016). According to the U.S. Energy Information Administration, as of December 1, 2015, there are 99 operating nuclear reactors at 61 nuclear power plants in the United States. In the Columbia Basin currently there is one operating nuclear plant (The Columbia Generating Station in south-central Washington). Another plant, the Trojan Nuclear Power Plant in southwestern Washington, was constructed in the early 1970s, and closed/demolished at the beginning of 2000s after the years of debates. After construction of the Trojan nuclear power plant, a 60-mile long seismic zone representing a possible fault or faults was identified within approximately 30 miles of the plant (Beaulieu and Peterson 1981). There is a plan for one more nuclear power plant to be built in the Columbia Basin. Alternate Energy Holdings, Inc. (AEHI), an American corporation, is working to build a new nuclear plant in Payette, Idaho (AEHI 2013). The site for the prospective nuclear plant has not yet been chosen.

A number of published studies have evaluated potential sites for energy facilities worldwide. These include solar farms in Spain (Sánchez-Lozano et al. 2014), wind farms in Turkey (Aydin et al. 2010), biogas plants in Finland (Höhn et al. 2014), nuclear plants in Malaysia (Basri and Ramli 2012), and various thermoelectric power sources, including nuclear plants, in the contiguous United States (Omitaomu et al. 2012, Mays et al. 2012)). Relatively few studies have examined suitable sites for locating energy facilities within the Columbia Basin. For example, Keeney (1980) described a case study related to identification of potential sites for nuclear plants with capacity of 3,000 MWe for the Washington Public Power Supply System in 1974. The region of interest included the entire state of Washington, and the basins of major rivers in Oregon and Idaho that flow to the Washington Rivers. This study identified the site in Washington currently occupied by the Columbia Generating Station, which first produced electricity in May 1984, and is operating today. Yates (2015) developed a methodology that takes scenarios and different variables such as politics, social impact, environmental impact, cost and types of materials, storage and wind turbine technologies, as input to a decision-making model for siting a wind farm in Oregon. Noll (2013) discussed a multi-criteria spatial decisions support system (MC-SDSS) tool that can facilitate multi-stakeholder engagement during site selection of a potential geothermal power generation facility in the Eastern Idaho.

Many studies have examined possible changes in runoff in response to climate change, including the Columbia Basin or its parts. Tohver et al. (2014) examined the nature of changing hydrologic extremes (floods and low flows) for about 300 river locations in the Pacific Northwest of the US (PNW) based on several climate models. The authors project decreases in summer low flows for most basins in the PNW with a few exceptions in the coldest sites, and increases in flood risk for transient and snow-dominated basins. Bürger et al. (2011) estimated future streamflow, including extremes (floods and low-flows) for the 2050s in the Columbia River headwaters (Canada), based on four regional climate models of the North American Regional Climate Change Assessment Program (NARCCAP). The authors predict a general warming of about 2°C in the future and slightly drier conditions, especially in late summer. Annual peak flow is not projected to increase, and August low flow is projected to decrease in all models. Chang and Jung (2010) assessed potential spatial and temporal changes in annual, seasonal, high and low runoff in the 218 subbasins of the Willamette River basin in Oregon for the 2040s and the 2080s. They projected increases in hydrological variability of the basin with reductions in summer runoff and increases in winter runoff, as well as increasing in high and low flow events, particularly in the Western Cascade basins.

As far as we can determine, no published studies have attempted to identify areas suitable for siting nuclear reactors in the Columbia Basin, and no studies have evaluated possible changes in potential candidate areas due to projected hydrological changes.

1.2. Motivation for locating nuclear power plants in the CRB

1.2.1. Current and projected energy consumption, demand, and shortfalls

1.2.1.1. Current energy consumption and demand

Currently, nuclear energy provides 19% of US electricity production and about 2.5% of energy production in the states (OR, WA, ID, MT) in the Columbia River Basin (CRB). For the region as a whole, energy consumption exceeds energy production by 268 trillion Btu (80 million MWh). Excluding MT, which is just a small part of the CRB, consumption is over two times more than production (1963 trillion Btu, or 576 million MWh). Energy consumption is projected to stay flat in OR, but grow by 311 trillion Btu, or 91 million MWh (10.5%) in ID, MT, and WA by 2025. By 2025, the total projected deficit of energy production relative to consumption in the four states is projected to be 1065 trillion Btu (312 million MWh).

Both depletion of fossil fuel resources and environmental concerns are generating rapidly increasing demand for low-carbon energy sources, primarily base-load (i.e., producing energy at a constant rate), including hydroelectric plants, geothermal plants, and nuclear plants. However, future gains in installed capacity for hydroelectric power will be limited to small dams, and will face opposition; development of geothermal power is limited to very few locations; and nuclear power is a feasible alternative to traditional fossil fuel. Despite its advantages, nuclear power has environmental challenges, which include management of radioactive waste, operating safety and risk of accidents, and reactor decommissioning.

Human society needs energy. In 2013, the United States generated about 4,058 million MWh of electricity, and consumed about 3,868 million MWh of electricity. About 67% of the electricity generated was from fossil fuel (coal, natural gas, and petroleum), with 39% attributed from coal. In 2013, energy sources and percent share of total electricity generation were: coal -

39%, natural gas - 27%, nuclear - 19%, hydropower - 7%, other renewables (biomass, geothermal, solar, wind) - 6%, petroleum - 1%, other gases < 1% (EIA 2014b) (Figure 1.1).

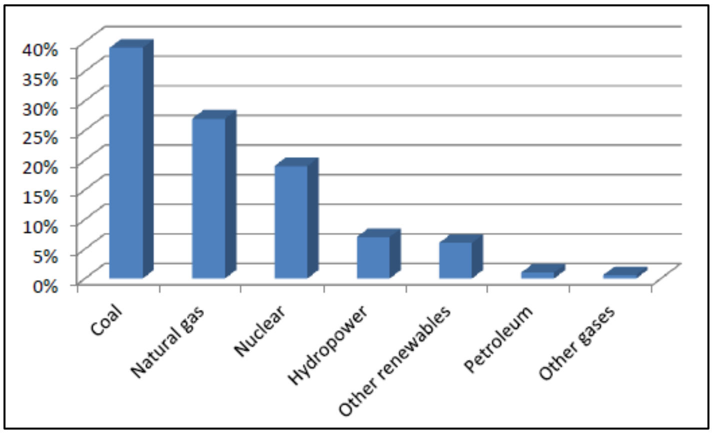


Figure 1.1. Percent share of total electricity generation in the U.S. by energy source, 2013. Graph based on the data taken from the report of U.S. Energy Information Administration (EIA 2014b).

Energy production and consumption for the main states in the Columbia River Basin (OR, WA, ID, MT) in 2013 are presented in the Figure 1.2.

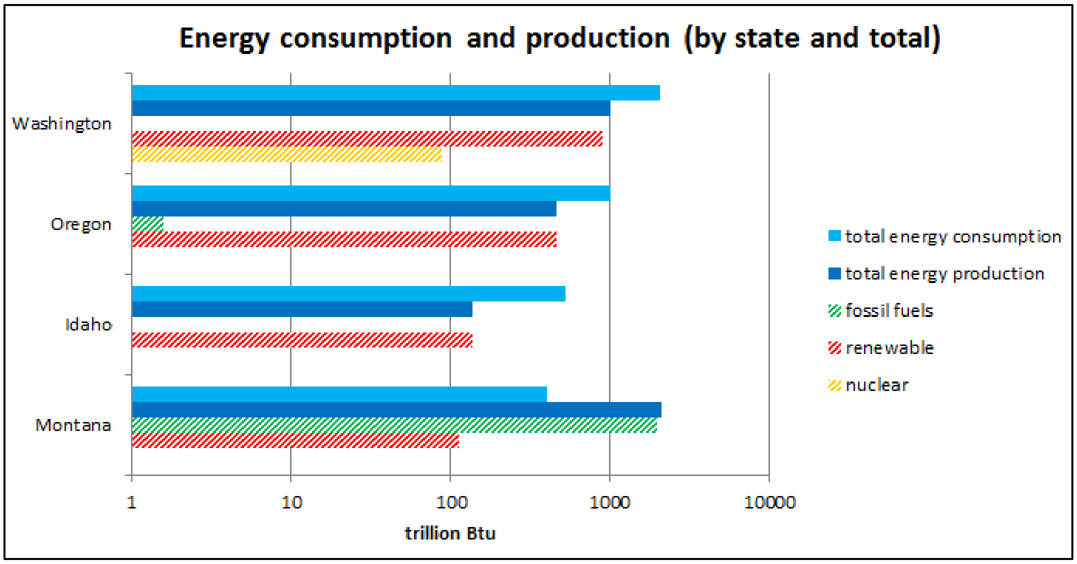


Figure 1.2. Energy production/consumption by state in 2013 (trillion Btu; 1 trillion Btu = 293,297 MWh). Source: US Energy Information Administration (info by state).

Energy production is less than half of energy consumption in Washington, Oregon, and Idaho. In 2013, energy consumption in Washington (2,039 trillion Btu, or 597.6 million MWh) was twice as large as production (1,003 trillion Btu, or 294 million MWh). In Oregon, energy generation was 458.8 trillion Btu (134.5 million MWh), and consumption was 996.7 trillion Btu (292 million MWh). In Idaho, in 2013, energy consumption (529.5 trillion Btu, or 155.2 million MWh) was four times larger than production (138.9 trillion Btu, or 40.7 million MWh). In Montana, production of electricity (1,105.2 trillion Btu, or 324 million MWh) is about three times larger than consumption (401.2 trillion Btu, or 117.6 million MWh).

The graph below (Figure 1.3) shows energy consumption and production for the period from 1960 to 2013 for each of the examined states. From both Figure 1.2 and 1.3 we can clearly observe that production of electricity is significantly smaller than its consumption in three states of the four: OR, WA, and ID. Montana, however, produces much more energy than it consumes, but the majority of it comes from fossil fuels (coal and crude oil) (EIA 2014a). Total consumption of energy in the region also exceeds production for all four states, and for the three states that occupy most of the CRB (ID, OR, WA).

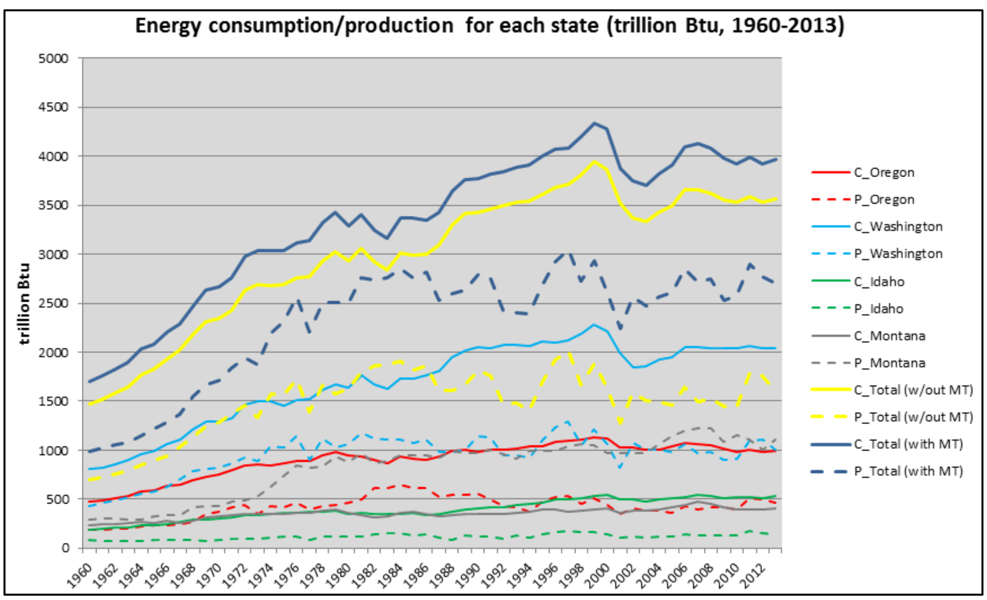


Figure 1.3. Energy consumption/production for each state in the CRB (trillion Btu; 1 trillion Btu = 293,297 MWh). ‘C’ in the legend means ‘Consumption’; ‘P’ means ‘Production’ (for example, ‘C_Oregon’ means ‘Consumption of energy in Oregon’). Montana is excluded because only a small part of the state (roughly 10%) is located within the Columbia River Basin. Source: US Energy Information Administration (info by state).

1.2.1.2. Future energy consumption and demand in the CRB

Table 1.1 and Figure 1.4 show energy consumption for each CRB state for the last 20 years, calculated annual growth rate, and projected energy consumption for the 2025 and 2050.

Table 1.1. Energy consumption in the CRB (source: US Energy Information Administration), trillion Btu, 1 trillion Btu = 293,297 MWh; annual growth rate, and projected consumption by state (calculated by author).

Total energy consumption, trillion Btu				
	Oregon	**Washington**	**Idaho**	**Montana**
1993	1,020.20	2,071.00	435.4	364.5
1994	1,033.80	2,061.60	450.2	368.6
1995	1,041.40	2,110.30	463.8	388.5
1996	1,085.60	2,094.40	497.5	394.7
1997	1,096.80	2,123.50	499.6	365.5
1998	1,108.10	2,195.10	504.4	388.1
1999	1,133.40	2,280.70	527.7	393.4
2000	1,117.30	2,211.50	540	407.5
2001	1,028.10	1,991.80	501.2	355.9
2002	1,023.70	1,846.90	496.5	379.1
2003	1,001.90	1,858.90	469.8	377.1
2004	1,000.00	1,919.50	502	399.1
2005	1,036.40	1,949.20	511	419.6
2006	1,072.10	2,056.10	524.2	439.2
2007	1,062.70	2,049.70	541.6	470.1
2008	1,047.70	2,042.70	537.7	457.2
2009	1,017.70	2,035.90	504.6	422.3
2010	979.8	2,034.50	518	395.3
2011	1,006.90	2,066.60	519.2	394.8
2012	978.5	2,043.20	513.2	388.4
2013	996.7	2,039.30	529.5	401.2
Annual growth rate				
1993-2013	0.02%	-0.02%	1.18%	0.85%
2003-2013	-0.21%	0.92%	0.65%	0.63%
Projected energy consumption, trillion Btu				
2025	999.1	2276.2	572.3	432.6
2050	1004.1	2861.8	672.9	506.1

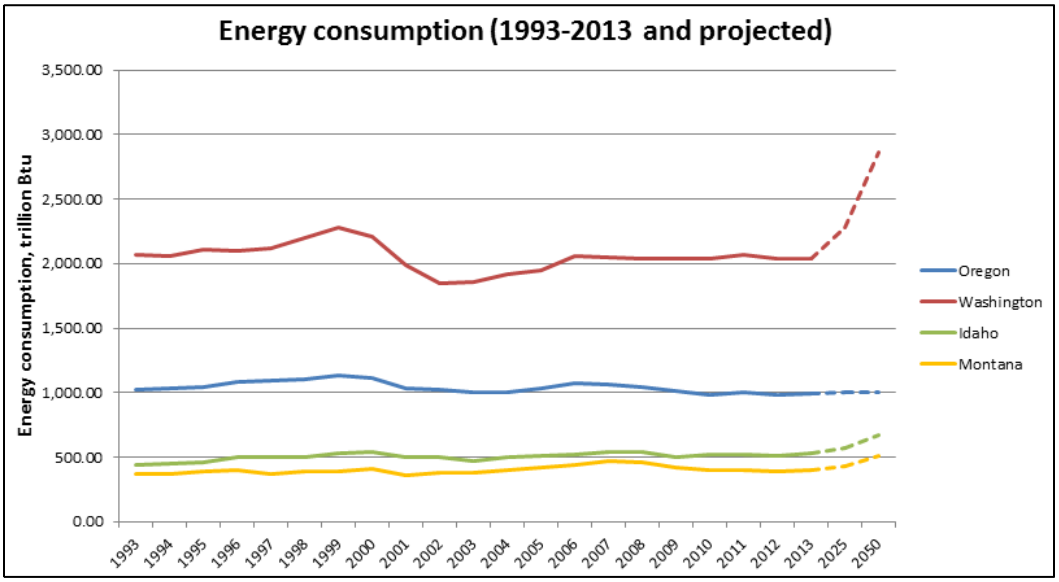


Figure 1.4. Energy consumption for each state for the last 20 years (source: US Energy Information Administration), trillion Btu, 1 trillion Btu = 293,297 MWh; and projected consumption (calculated by author).

Similarly, Table 1.2 and Figure 1.5 show total energy production for each state in the region for the last 20 years, and calculated annual growth rate, as well as projected energy production for the 2025 and 2050. These projections do not take into account possible energy storage.

Table 1.2. Energy production in the CRB (source: US Energy Information Administration), trillion Btu, 1 trillion Btu = 293,297 MWh; annual growth rate, and projected production by state (calculated by author).

Total energy production, trillion Btu				
	Oregon	**Washington**	**Idaho**	**Montana**
1993	418.1	941.5	126.2	916.3
1994	371.4	921.7	106.7	995.6
1995	469.2	1,093.4	139.9	989.2
1996	519.0	1,239.9	164.2	993.5
1997	531.8	1,295.8	179.3	1,038.2
1998	455.5	1,047.4	160.2	1,056.8
1999	511.2	1,209.4	167.7	1,048.9
2000	437.9	1,065.1	141.4	972.2
2001	351.1	817.4	105.0	965.0
2002	401.5	1,073.7	113.8	972.1
2003	385.3	1,006.3	109.6	967.9
2004	385.2	1,001.3	112.4	1,066.7

2005	364.6	976.5	121.1	1,145.1
2006	433.8	1,065.9	146.5	1,204.7
2007	397.5	968.2	125.6	1,219.6
2008	415.5	976.2	133.5	1,217.4
2009	416.9	901.5	134.5	1,081.0
2010	393.7	908.0	130.7	1,148.2
2011	513.7	1,101.3	176.7	1,104.2
2012	496.3	1,109.1	154.8	1,008.7
2013	458.8	1,003.3	138.9	1,105.2
Annual growth rate				
1993-2013	1.18%	1.12%	3.14%	0.82%
2003-2013	1.82%	-0.27%	2.73%	1.41%
Projected energy production				
2025	570	1147	192	1307
2050	894	1515	376	1855

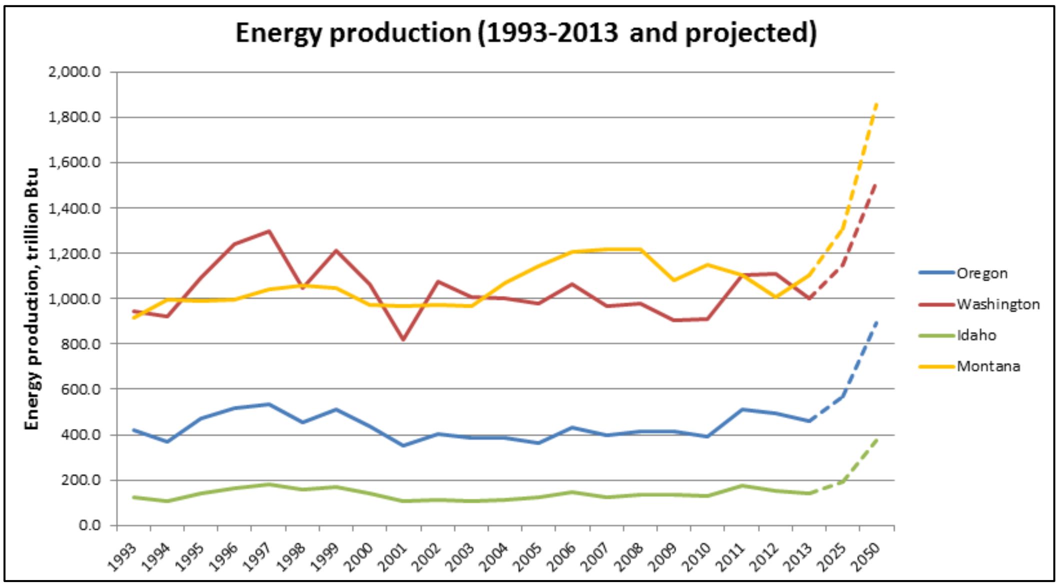


Figure 1.5. Energy production for each state for the last 20 years (source: US Energy Information Administration), trillion Btu, 1 trillion Btu = 293,297 MWh; and projected production (calculated by author).

For each of the examined states, we calculated the annual growth rate of electric power consumption/production for the past 10 and 20 years. Over the period 2003 to 2013, only Oregon had negative growth in energy consumption (-0.21%). Over the period 1993 to 2013, only Washington had slightly negative growth in energy consumption (-0.02%). For energy production, only Washington showed negative growth rate for the 2003 to 2013 period. Future energy consumption and production were projected based on the most recent positive annual rates of change for each state. The growth rates of electric power consumption for the period from 2003 to 2013 were 0.92% for Washington, 0.65% for Idaho, 0.63% for Montana. Oregon had the lowest annual growth (0.02%) over the period from 1993 to 2013. The growth rates of electric power consumption were 1.82% for Oregon, 2.73% for Idaho, and 1.41% for Montana over the period 2003 to 2013, and 1.12% for Washington over the period from 1993 to 2013.

The graphs provided in Figures 1.4 and 1.5 show energy production and consumption for the last 20 years and for the projected 2025 and 2050 years. On the consumption chart (Figure 1.4) we can clearly observe significant growth of consumption in Washington in 2025 and 2050 (because of the high calculated annual growth rate), and very low growth of consumption in Oregon (growth rate is very low for the last 20 years, and even negative for the last 10 years). Production chart (Figure 1.5) shows visible growth for the projected years for all four examined states. Although the numbers discussed above are just projections, they may be important in determining the future power generation infrastructure in the region and individual states.

1.2.2. Potential role of nuclear power plants in the CRB

Overall, based on the calculated annual growth rates and future values, energy production is projected to grow faster than energy consumption. Despite this projected narrowing of the gap between energy consumption and production, currently there is a huge deficit of produced energy in each state (besides MT, which occupies a small part of the Columbia Basin), and this deficit will persist into the future. Therefore, the region will need more sources of energy in the future.

1.2.2.1. Alternative future sources of energy in the CRB

Future sources of energy in the CRB/PNW include fossil fuels and low-carbon energy sources such as hydroelectricity, geothermal, nuclear, solar, wind, and tidal energy.

Fossil fuel resources are limited, and their combustion exerts a negative impact on the environment, because any process using fossil fuels produces carbon dioxide and other contaminants, such as nitrogen oxides, sulphur oxides and ash (Dresselhaus and Thomas 2001). In response to increasing regulations on air and water pollution, and policies promoting alternative energy sources, there is a growing need to site new power generating plants that use cleaner energy sources. Over the past decade, attempts to move away from fossil fuel sources have not achieved much success. However, in the 2011 State of the Union address, President Barack Obama announced a national clean energy standard goal of 80% clean energy by 2035 (EIA 2011). Clean energy is defined as an energy source that does not depend on fossil fuels and has a tolerable environmental impact (Dresselhaus and Thomas 2001). Both depletion of fossil fuel resources and environmental concerns are generating rapidly increasing demand for the development and deployment of a new, diversified generation of low-carbon technologies (Omitaomu et al. 2012).

Low-carbon energy sources include hydroelectricity, geothermal, nuclear, solar, wind, and tidal energy. Hydroelectric, geothermal, and nuclear plants are base-load power sources, which produce energy at a constant rate. Hydroelectric power plants can operate as base-load, load-following or peaking power plants; they also play an important role in flow regulation and irrigation (Masters 2004). Solar, wind, and tidal are intermittent energy sources, i.e., they are not continuously available due to some factor outside human control. Solar and wind energy require large areas and are limited geographically (Dresselhaus and Thomas 2001), and are often located far from load centers, in remote areas and off-shore, requiring large additional investments in long-distance transmission facilities (Kessides 2012).

Barring a breakthrough in electricity storage or related technologies, renewable technologies cannot fully replace the base-load generation lost as a result of coal and nuclear plant retirements (EIA 2014a). The World Nuclear Association states that "Sun, wind, tides and waves cannot be controlled to provide directly either continuous base-load power or peak-load power when it is needed. In practical terms they are therefore limited to some 10–20% of the capacity of an electricity grid, and cannot directly be applied as economic substitutes for coal or nuclear power, however important they may become in particular areas with favorable conditions." Energy storage is considered as a prominent solution for the problem of intermittency of renewable energy, such as solar and wind power plants (Daim et al. 2012), and seen an enabling technology for integrating variable renewable power into the electric grid, addressing grid reliability challenges (Kintner-Meyer et al. 2012). However, successful development and implementation of energy storage technologies in the grid market depend on significant reduction of the cost of technology, cooperation between the policy makers, utility companies, and battery manufacturers, along with a good understanding of where, when, and how the storage technology can be used (Liu 2013).

Although hydropower is probably the best option of base-load low-carbon energy sources, there is limited capacity to expand hydroelectric power production in the PNW region. According to different sources, 60% (Woo et al. 2013) to over 70% (Hamlet et al. 2010a) of energy production in the PNW comes from hydroelectric dams. In the CRB there are more than 370 hydroelectric dams, which can generate about 50–65% of the region’s electricity (Leonard et al. 2015). However, most sites for large hydro plants have already been taken, and new energy needs are not likely to be satisfied by construction of new dams.

In the future, hydroelectric power production may decline, because of political and economic pressures for dam removal (McClain et al. 2006). About 25% of the US dams are older than 50 years, and this number will increase to 85 percent by the year 2020 (Beck et al. 2012). Moreover, the structural instability of an aging dam increases the likelihood of failure and possible loss of human life (McClain et al. 2006). Additionally, social attitudes toward dam construction have changed, making dam removal more likely than dam construction (McClain et al. 2006). In particular, operation of some of the existing dams is being challenged, because of the environmental concerns connected with habitation of a variety of anadromous and resident fishes and wildlife species, and their migration within the region (Leonard et al. 2015, Mahler and Barber 2015).

Geothermal power is cost-effective and environmentally friendly, but its development is limited to very few locations (Dresselhaus and Thomas 2001), near tectonic plate boundaries, which have hot rocks below the earth and can produce steam over a long period of time.

1.2.2.2. Nuclear power as a future source of energy in the CRB

Nuclear energy is a feasible alternative to traditional fossil fuel. A nuclear power plant provides a lot of energy with small amount of uranium, and has a very small footprint compared to renewable technologies (Kessides 2012). The fission process does not emit CO_2, so from the standpoint of global warming, nuclear energy provides an ideal source (Dresselhaus and Thomas 2001), and is an effective greenhouse gases mitigation option (Sims et al. 2003). According to Finkbeiner (2009), nuclear power is a preferred energy generation option, because it has a lower carbon footprint than even most renewable energy sources. Nuclear power plants operate as base-load capacity: they can deliver low-carbon electricity in bulk, reliably and without intermittency (Kessides 2012), often operating for 18-24 months without shutting down (EPRI 2014).

Key environmental challenges of nuclear power include management of radioactive waste, operating safety and risk of accidents, and reactor decommissioning. While operating, nuclear plants produce radioactive fission products (Dresselhaus and Thomas 2001). One possible solution for safe and long-term disposal of high-level radioactive waste involves deep geological repositories (Sims et al. 2003). The issues here include understanding of the long-term effects in the waste itself and in the repository under various situations that might arise (floods, for example) (Daniel 2012, Dresselhaus and Thomas 2001). In some countries, like Russia or France, the spent nuclear fuel is recycled to produce new fuel (Ojovan and Lee 2013).

Decommissioning of nuclear power plants involves the demolition of buildings and other structures, including the parts near the reactor core that may have become radioactive. Radioactive decommissioning waste, in contrast to spent nuclear fuel, ranges from very low level to intermediate level radioactivity, but its volume is greater than the volume generated during operations (Samseth et al. 2012). Nevertheless, experts agree that currently after over 30 years of experience in decommissioning, nuclear facilities can be decommissioned safely and without unacceptable impacts on man or the environment (Laraia 2012).

Another big concern over the nuclear industry is related to the possible accidents caused by natural or human factors. Major reactor accidents of nuclear power plants are rare, yet the consequences are catastrophic (He et al. 2013, Kessides 2012), as demonstrated by the accident at Fukushima Daiichi Nuclear Plant in northern Japan in 2011. The Fukushima accident was a catastrophic event that significantly reduced public acceptance of nuclear energy across the globe (Kim et al. 2013).

Therefore, although nuclear energy has the potential to replace baseload fossil fuel electricity generation in many parts of the world (Sims et al. 2003), concerns related to fuel production, operating and decommission safety, and radioactive waste disposal are primary obstacles to the adoption or expansion of nuclear energy (Sims et al. 2003, Dresselhaus and

Thomas 2001). Public fears of nuclear energy must be respected, understood and alleviated if nuclear energy is to remain viable (Dresselhaus and Thomas 2001).

Research and technology can help address the key environmental challenges related to nuclear industry, by improving the operation of existing nuclear plants and the design and deployment of advanced nuclear plants (EPRI 2014). Most of the nuclear reactors currently in operation are medium- to large-scale plants sized at 500–1500 MWe, utilizing tested technologies (Kessides 2012). Construction of large-scale nuclear plants spans several decades, and has clearly stated safety-driven requirements related to their design and construction. At the same time, nuclear construction costs have escalated with time because of the growing complexity of large-scale reactors, increasing regulation, and construction delays (Kessides and Kuznetsov 2012, Kessides 2012). One promising direction for nuclear development might be to downsize reactors from the gigawatt scale (i.e. large reactors) to less-complex smaller units that are more affordable (Black et al. 2015, Kessides and Kuznetsov 2012, Kessides 2012). Although small modular reactors (SMRs, 350 MWe equivalent or less) can have higher specific capital costs as compared to large-scale reactors, they have a number of advantages, including small size and modular construction, substantially simpler designs (fewer systems), shorter construction times, reduced costs through accelerated learning effects, and less concerns about catastrophic events since they contain substantially smaller radioactive inventory (Kessides and Kuznetsov 2012, Kessides 2012).

1.3. Organization of the dissertation

This PhD dissertation is organized into 5 chapters. Chapter 1 is an introduction to the research, which discusses the geography of nuclear power plant location, including analysis of uncertainty and risk, and overall energy situation in the CRB and its states; current energy production and consumption; and projections to the future. It also introduces possible options of energy sources in the region, and presents nuclear power as one of the feasible alternatives, discussing its advantages and challenges. Chapter 2 examines the variety of criteria for siting nuclear reactors, and estimates the areas within the CRB that may be suitable for siting nuclear facilities through a GIS-based multicriteria decision analysis (MCDA) approach. MCDA, a form of PRA combined with location analysis, was used to exclude areas unsuitable for siting (near population zones, faults, etc.) and thus reduce the probability of events that can lead to accidents. In Chapter 3, effects of future climate change on streamflow in the CRB and implications for siting nuclear power plants are discussed. The magnitudes of the future variations in low-flow in the CRB were estimated using daily discharge data from several climate models statistically downscaled under medium and high emission scenarios, and the VIC hydrological model. Chapter 4 discusses uncertainties associated with the process of site selection and the process of estimating possible changes in streamflow, as well as the uncertainties related to the public attitudes towards nuclear power. Finally, Chapter 5 provides summary for the study, conclusions and recommendations to further work.

Chapter 2. Site selection process using historical streamflow records and GIS analysis based on existing maps

This study identified areas that are suitable for the location of nuclear power plants within the Columbia River Basin (CRB), which occupies most of the Pacific Northwest region (PNW). The CRB is likely to require more sources of energy in the future. Currently energy production in three main states of the CRB (WA, OR, ID) represents only about 45% of energy consumption, and this gap is likely to persist into the mid-21st century. Most energy production is from hydroelectric dams, which have limited potential for expansion to meet future energy demand. Nuclear power is a potential source of renewable low-carbon energy in the region. This study applied siting criteria required by the Nuclear Regulatory Commission (NRC), including hydrology, population density, seismology, and other factors to identify areas of the CRB appropriate for constructing nuclear reactors using a GIS-based multicriteria decision analysis (MCDA) approach. This process combined and transformed spatially referenced datasets (inputs) into a resultant base map (output) which identified two large candidate regions suitable for siting nuclear power plants: the Middle Columbia River and the Snake River plain. Limited availability of cooling water during the dry season was a principal factor that constrained site suitability. However, additional limitations may include frequent, severe flooding and risk of earthquakes. Further investigations and selection of potential/preferred sites for nuclear reactors should be focused around the two identified regions and thoroughly examine the three limitations.

2.1. Introduction

The objective of this study is to identify potential candidate areas for nuclear power plants in the Columbia River Basin (CRB), and to evaluate potential limits on nuclear power plant location due to low-flow limits on cooling water. In our study we also considered, to a lesser extent, limits related to flood hazard, and risk of accident from earthquakes.

The CRB provides an instructive study site for considering the potential for nuclear energy in the PNW because: (1) it includes a variety of hydroclimatic conditions, (2) a great deal of long-term streamflow data are available, and (3) the interest of private companies in establishing nuclear power plants in this basin (in particular, Alternate Energy Holdings, Inc. (AEHI) is working to build a new nuclear power plant in Payette county, ID). The CRB is also a challenging setting for nuclear energy because of potential limitations imposed by: (1) limited availability of water for cooling during dry season, (2) frequent, severe flooding and (3) high risk of major earthquakes.

The factors to be considered for siting nuclear plants include physical characteristics of a site, in particular hydrology, seismology, meteorology, and geology; population density, population distribution; unique physical characteristics of the proposed site; the nature and proximity of man-related hazards (NRC 2016). One of the crucial factors for siting nuclear power plants is the availability of water for cooling. In the CRB, due to a winter wet season which results in significant snow accumulation, peak flows typically occur in late spring or early summer as snow melts, and low flows occur at the end of the summer dry season, in August through October (Chang and Psaris 2013, Dittmer 2013). Thus, water availability in the CRB is limited by the relatively long dry season. Nuclear plant siting in the CRB, therefore, may be quite sensitive to water availability and expected future changes in water availability. Many areas in the CRB also are susceptible to floods, especially during the snow melting in late spring or early summer, and are likely to experience substantial increases in flooding in response to climate change (e.g. Tohver et al. 2014, Salathe et al. 2014). Flood risk may limit the location and safe operation of nuclear power plants in the region. The CRB region is also susceptible to earthquakes ranging from subduction earthquakes with magnitudes of 8 or greater, occurring about every 500 years on average, to smaller magnitude crustal earthquakes, which have a more compressed footprint but occur more frequently than megaquakes (Showstack 2014). In order to ensure safety related to construction and operation of a nuclear plant, areas where regional hazard mapping shows peak ground accelerations exceeding 0.30g at a probability of exceedance of 2% in 50 years (return period of 2,500 years) are excluded as potential sites (Rodwell 2002).

This study has the following objectives:

1) estimate minimum flow in the CRB based on historical streamflow records;

2) create maps showing candidate areas for construction of nuclear power plants;

3) evaluate potential future limits on nuclear power plant location due to low flow limits on cooling water;

4) discuss the uncertainties associated with the site selection process and assessment of potential future limits for siting.

The analysis considered all the siting criteria examined at the first step of site selection process (selection of candidate areas). Particular emphasis was placed on estimating water availability as a crucial part of the siting process.

2.2. Study area

The Columbia River Basin (CRB, Figure 2.1) has several advantages for this study: (1) the variety of hydroclimatic conditions, (2) the availability of long-term streamflow data, and (3) the interest of private companies in establishing nuclear power plants in this basin.

Figure 2.1. Study area – the Columbia River Basin (U.S. part).

The CRB occupies 670,000 km^2 of which 570,000 km^2 are in the United States. The CRB contains three types of watersheds: snowmelt dominant, transient, and rain-dominant. Snowmelt dominant watersheds are characterized by precipitation stored as snowpack causing low flows in winter and peak flows resulting from the melting of snowpack in late spring or early summer. Rain dominant watersheds are characterized by peak streamflow occurring in the cool season, November through January. Watersheds that experience two streamflow peaks, one from heavy precipitation in winter and the other from snowmelt, are called transient watersheds because they receive both snow and rain (Mantua et al. 2009). Future streamflow will respond to changes in climate, and different types of watersheds will respond to these changes differently. Thus, the variety of hydroclimatic conditions in the basin permits consideration of a variety of climate change effects on the future availability of cooling water for nuclear power plants.

The CRB has abundant data on historical streamflow, with over 600 stream gauges most of which have long-term historical data. These data permit comparatively reliable estimates of the availability of surface water for cooling nuclear power plants.

There is interest of private companies in establishing nuclear power plants in this CRB. In particular, Alternate Energy Holdings, Inc. (AEHI), an American corporation, is working to build a new nuclear power plant in Payette, Idaho (AEHI 2013). The site for the prospective nuclear plant is not chosen yet.

However, several factors may limit the location and safe operation of nuclear power plants in the CRB in the future: (1) limited availability of water for cooling in some periods of the year (mostly August through October), (2) high flood risk in some parts of the basin near surface water sources for cooling, and (3) the risk of major earthquakes, which may cause accidents or contamination from loss of cooling water or other damage to nuclear power plants.

2.3. Methodology

This analysis applied the screening criteria specified by the Nuclear Regulatory Commission (NRC 2016) to identify candidate areas for siting nuclear reactors of varying capacity in the CRB. The analysis considered all the criteria examined at the first step of site selection process (selection of candidate areas), including exclusionary criteria and avoidance criteria. Exclusionary criteria are used to eliminate areas not fitting certain criterion, avoidance criteria are used to eliminate feasible - but less favorable areas. The study particularly focuses on the water availability screening criterion as a crucial part of siting process, and develops a method to estimate minimum flow in the CRB based on historical streamflow records. Minimum flow calculations were based on data from existing gauges and estimates of flow from ungauged locations. Each of the applied siting criteria was mapped in ArcGIS, described, and used to create the resultant maps showing candidate areas for siting small/large nuclear reactors in the CRB. Maps for each criterion, as well as the resultant maps are provided in the results section.

2.3.1. Screening criteria for siting nuclear reactors

The nuclear energy industry in the US is regulated by the Nuclear Regulatory Commission (NRC). Siting and site evaluation processes for nuclear power plants must comply with a licensing process defined by the NRC. Criteria for siting nuclear power plants are described in the NRC regulations, Title 10, Part 100 (“Reactor Site Criteria”), which establishes approval requirements for proposed sites for stationary power and testing reactors (NRC 2016). The factors to be considered for siting nuclear plants include physical characteristics of a site, in particular hydrology, seismology, meteorology, and geology; population density, population distribution; unique physical characteristics of the proposed site; and the nature and proximity of human-related hazards (NRC 2016). Three levels of criteria are defined based on the severity of constraints imposed by underlying requirements (Table 2.1): exclusionary, avoidance, and suitability (Rodwell 2002, Mays et al. 2012). Exclusionary criteria are used to eliminate areas not fitting certain criterion, and are generally based on regulatory (national parks, high population densities) and/or plant design requirements. Avoidance criteria have the same site screening effect as exclusionary criteria but are more flexible in their application. They are utilized to identify broad areas with more favorable than unfavorable conditions, for example pumping distance from the source of water. If the process of selection the candidate areas results in an area too small for identification of an adequate number of potential sites, the avoidance criteria can be relaxed and the selection process repeated. Suitability criteria represent requirements that affect the relative environmental suitability or cost of developing the site, but do not represent unacceptable environmental stress, severe licensing problems, or excessive additional cost. Examples of suitability criteria are local topographic features, access considerations, important species habitat, and optimizing location of the site with respect to the load center.

The procedure for siting a nuclear power plant involves multiple steps (Table 2.1). This analysis was a Step 1 analysis only (selection of candidate areas). Steps 1 and 2 of the siting process are areal in nature, since screening of a relatively large region of interest is performed to identify candidate areas and a number of discrete "site-sized" parcels for evaluation as a potential nuclear power facility site. Comparison of individual sites on the basis of their relative suitability is the focus of Steps 3 and 4.

Table 2.1. Procedure for siting nuclear power plants (Rodwell 2002). For each of the steps, the starting point, the process employed at the step, the type of criteria to be used, the map scale likely to be most useful, the nature of the data sources, and the end product are indicated.

STEP	**1**	**2**	**3**	**4**
STARTING POINT	Region of Interest	Candidate Areas	Potential Sites	Candidate Sites
PROCESS	Area screening	Area screening	Site screening	Site selection: issue by issue analysis
CRITERIA E – Exclusionary A – Avoidance S - Suitability	E&A	E&A	Principally S; some redefinition of E&A boundaries	Principally S
RESULT	Candidate Areas	Potential Sites	Candidate Sites	Acceptable Sites or Preferred Sites
DATA SOURCES	Published 1:250,000 or smaller	Published 1:125,000 to 1:24,000	Published and reconnaissance 1: 24,000	Detailed on-site verification surveys 1:24,000 or larger

Since this chapter examines candidate areas within the region of interest (CRB), i.e. the first step of the siting procedure, at this stage we are interested only in exclusionary and avoidance criteria. In addition to the water availability criterion, which is the main focus of this study, among the exclusionary criteria we examined:

- geology/seismology (vibratory ground motion and capable faults),
- population density and distribution,
- flooding (100-year floodplain),
- protected lands (national parks, historic areas, wildlife refuges, etc.),
- wetlands and open waters,
- topography (land with a slope greater than 12%, land over 800 feet above the source of water), and
- landslide hazards,

as specified by the NRC regulations and described in the Siting Guide prepared by Electrical Power Research Institute (EPRI) (Rodwell 2002). Among the avoidance criteria we included pumping distance to the source of water (as a part of water availability criterion), and geology/seismology (part of faults). Mays et al. (2012) and Omitaomu et al. (2012) applied this set of criteria to estimate suitable areas for siting nuclear plants, advanced coal plants, concentrated solar steam plants, and compressed air energy storages within the contiguous United States.

In addition, we excluded land over 800 feet (~250 meters) above the source of water. Keeney (1980) described this criterion as a part of investigation of nuclear power plant site selection process being held in the state of Washington in the late 1970s, which resulted in the construction of the Columbia Generating Station. Relative height is an economic criterion, because pumping from the source of water at the high altitudes is an expensive task. Thus, screening criteria for water include consideration of both horizontal and vertical pumping distances from the water source.

2.3.2. Water availability criterion

2.3.2.1. Cooling requirements for nuclear reactors

In a nuclear plant, energy from decay of uranium heats pressurized water which is then used to produce steam in the steam generator. The condenser condenses steam to water and provides a pressure difference that drives the turbine. The water is needed to cool condensers of the turbine (Figure 2.2).

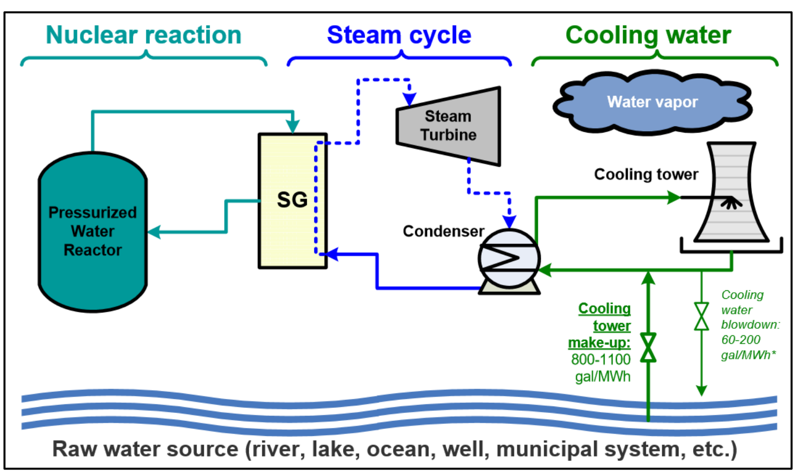


Figure 2.2. Water flow schematic for a nuclear plant utilizing a wet cooling tower (Gerdes and Nichols 2008).

There exist two basic cooling system configurations: once-through and recirculating (Figure 2.3). In a once-through cooling system, water from an external water source (e.g. river) passes through the steam cycle condenser and is then returned to the source at an elevated temperature with some level of contaminants (Walker et al. 2012, Gerdes and Nichols 2008), thus potentially impacting aquatic ecosystems (Macknick et al. 2012b). In a recirculating system, cooling water exits the condenser, goes through a fixed heat sink (cooling pond or cooling tower) and is then returned to the condenser (Gerdes and Nichols 2008). Heat is released to the environment through water evaporation. Once-through cooling technologies withdraw 10-100 times more water per unit of electric generation than cooling tower technologies (25,000-60,000 gal/MWh vs. 800-2,600 gal/MWh); but cooling tower technologies consume twice as much water as once-through cooling technologies (100-400 gal/MWh vs. 600-800 gal/MWh) (Macknick et al. 2012a; Gerdes and Nichols 2008). In a cooling tower, evaporation losses are the largest contributor to water consumption; blowdown rate is 25% of the total make-up cooling water flow (Gerdes and Nichols 2008). When water availability is low, a dry cooling system may be utilized. Dry cooling uses closed loop air cooling, eliminating evaporation losses. Cooling water make-up requirements in case of dry cooling systems can be almost eliminated, but process and steam make-up water requirements stay unaffected (Gerdes and Nichols 2008).

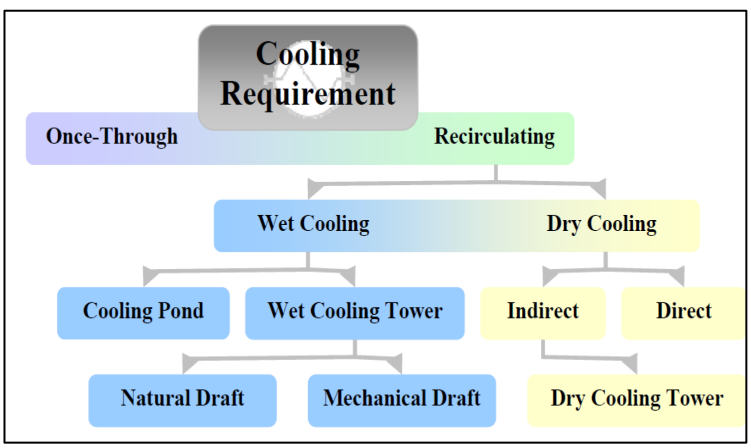


Figure 2.3. Cooling water system configurations (diagram reproduced from Gerdes and Nichols 2008).

Although most systems currently employ once-through cooling (Macknick et al. 2012b; Gerdes and Nichols 2008) and wet recirculating systems are roughly 40% more expensive than once-through systems (Gerdes and Nichols 2008), all new thermal generation is assumed to be equipped with recirculating cooling towers or dry-cooled systems (Walker et al. 2012; Macknick et al. 2012b), because of environmental concerns including fish kills at water intakes, damage to local marine ecology, thermal pollution, chemical pollution due to use of corrosion or scaling inhibitors, and metals pollution due to corrosion (Walker et al. 2012, Gerdes and Nichols 2008). At the same time, dry cooling systems are three to four times more expensive than wet recirculating systems (Gerdes and Nichols 2008), and their use is justified only when cooling water is not available or is very expensive (Yang et al. 2013).

Thus, in our research we will consider water requirements for the reactors which use recirculating wet cooling system: a small nuclear reactor with the capacity of 350 MWe, and a large nuclear reactor with the capacity of 1600 MWe.

2.3.2.1.1. Large reactor

The large nuclear reactor is a light-water reactor with a nominal output of 1600 MWe, representative of a single US Evolutionary Power Reactor (US EPR) or an advanced pressurized water reactor (APWR) (Mays et al. 2012). The power output is used to determine the necessary streamflow to supply makeup water for cooling. Plant cooling is provided by a closed-cycle mechanical draft cooling tower with makeup water required for evaporation and blowdown.

Based on the paper of Gerdes and Nichols (2008), we considered the following parameters for a large nuclear reactor:

- Reactor capacity: 1,600 megawatt electric (MWe),
- Type of cooling: wet cooling tower,
- Cooling tower make-up: 750 gallons/megawatt-hour (gal/MWh), which include blowdown and evaporated water.

Water requirement for cooling the turbine of a large nuclear reactor, thus, amounts to 20,000 gallons per minute (gpm). This was calculated by multiplying reactor capacity (1,600 MWe) and cooling tower make-up (750 gal/MWh), and converting the result to gallons per minute. Additionally, it is assumed that cooling water makeup should be limited to taking no more than 10% of the available streamflow (Rodwell 2002, Mays et al. 2012). This limits the siting of reactor plants to the vicinity of streams with sufficient flow volumes, namely, to the streams with discharge equal to or over 200,000 gpm.

2.3.2.1.2. Small reactor

The small reactor is a light water reactor with a nominal output of 350 MWe, representative of a single small modular reactor (SMR) or a cluster of small reactors (Mays et al. 2012). As in the case of the large reactor, the power output is used to determine the necessary streamflow to supply makeup water for cooling, and plant cooling is provided by a closed-cycle mechanical-draft cooling tower with makeup water required for evaporation and blowdown.

SMRs have several advantages in comparison with the previous generation of nuclear reactors, namely, small size and modularity that allow major components to be standardized and fabricated in significant quantities on assembly lines. This gives the manufacturers greater ability to learn and control costs and results in a significant simplification of deployment (Cooper 2014). Although SMRs can have higher specific capital costs as compared to large-scale reactors, they have a number of advantages, including small size and modular construction, substantially simpler designs (fewer systems), shorter construction times, reduced costs through accelerated learning effects, and fewer concerns about catastrophic events, since they contain substantially smaller radioactive inventory (Kessides and Kuznetsov 2012, Kessides 2012).

We considered the following parameters for a small nuclear reactor:

- Reactor capacity: 350 MWe,
- Type of cooling: wet cooling tower,
- Cooling tower make-up: 850 gallons/megawatt-hour (gal/MWh), which include blowdown and evaporated water.

Water requirement for cooling the turbine of small nuclear reactor, thus, amounts to 5,000 gallons per minute (gpm). This was calculated by multiplying reactor capacity (350 MWe) and cooling tower make-up (850 gal/MWh), and converting the result to gallons per minute. Taking into account the common assumption that states would not permit more than 10% of the dependable flow to be withdrawn for a consumptive use (Rodwell 2002, Mays et al. 2012), streamflow magnitude necessary to satisfy the reactor's water requirement of 5,000 gpm, will be

50,000 gpm. These are just examples. Real nuclear reactors may have other parameters, and the total amount of water needed for cooling will differ.

2.3.2.2. Methodology for estimating water availability and sufficiency

One of the crucial factors for siting nuclear power plants is availability of the necessary amount of water for cooling condensers of the turbine. During the site selection phase it is important to assess the availability of the necessary amount of water to ensure further proper operation of the facility. Water from rivers is one of the options for cooling the condensers. For selecting appropriate sites, historical streamflow records as well as present conditions should be analyzed.

2.3.2.2.1. Calculating 7Q10 low-flows at gauged locations

Previously we defined minimum water requirements for two types of reactors. A small 350 MWe nuclear reactor requires at least 5,000 gpm of water, and a large 1600 MWe nuclear reactor requires at least 20,000 gpm of water. Our next task is to define the streams in the CRB with the discharge appropriate for siting nuclear reactors of two described capacities. The discharge, thus, should not be less than 50,000 gpm for a small nuclear reactor and 200,000 gpm for a large reactor. This minimum required discharge can be determined from standard low-flow statistics, which are used in a range of diverse applications, such as water-supply planning and design, waste-load allocation, reservoir storage design, and maintenance of quantity and quality of water for irrigation, recreation, and wildlife conservation.

According to the World Meteorological Organization, low flow is the "flow of water in a stream during prolonged dry weather". Low flows are normally derived from groundwater discharge or surface discharge from lakes, marshes, or melting glaciers. The lowest annual flow usually occurs in the same season each year (Smakhtin 2001). A commonly used low-flow statistic in the United States is the 7-day, 10-year low-flow (7Q10) (Riggs 1980). This statistic is based on an annual series of the smallest values of mean discharge computed over any seven consecutive days during the annual period. Thus, 7Q10 is the annual 7-day minimum flow with a 10-year recurrence interval (non-exceedance probability of 10 percent), or the average annual 7-day minimum flow that is expected to be exceeded on average in 9 out of every 10 years (Risley et al. 2008; Reilly and Kroll 2003). 7Q10 is the most dominant low-flow metric used by US agencies and researchers for many purposes, including siting facilities, particularly nuclear power plants (Rodwell 2002).

We calculated 7Q10 low-flow values for 622 gauges in the Columbia Basin (Figure 2.4). Daily data on each gauge were taken from the US Geological Survey (USGS) – National Water Information System (see Appendix 2 for the list of gauges). 7Q10 values were computed for all the gauges in the basin that had at least 10 years of daily streamflow observations. Within each calendar year, the annual minimum 7-day mean flow was calculated. The climatic year (October 1 to September 30) was used to define the starting and ending dates of annual periods for computation of the 7-day minimum flows. For quality assurance purposes there must have been at least 300 days of valid records within one year, otherwise the entire year was discarded. By collecting all annual minimum flow data together, the lower 10% quantiles were computed for each selected USGS gauge. A Python script (Appendix 1) was created to automate calculation tasks and apply them to all gauges of interest in the basin. This Python script can be easily used for calculating 7Q10 low-flows as well as any other low-flow statistics (7Q50, 7Q2, etc.) by changing some of the parameters in the code. The 10% quantile is statistically equivalent to the 10-year return threshold; it represents the low-flow value that is expected to occur once every 10 years. Because it is predicted to recur on average only once in 10 years, it is usually an indicator of low-flow conditions during drought (Mays et al. 2012; Omitaomu et al. 2012).

A stream network map of the CRB was created on the basis of the Digital Elevation Model (DEM) of the CRB, using ArcGIS. DEM was taken from the USGS web-site (http://viewer.nationalmap.gov). Stream gauge locations were plotted on the map (Figure 2.4).

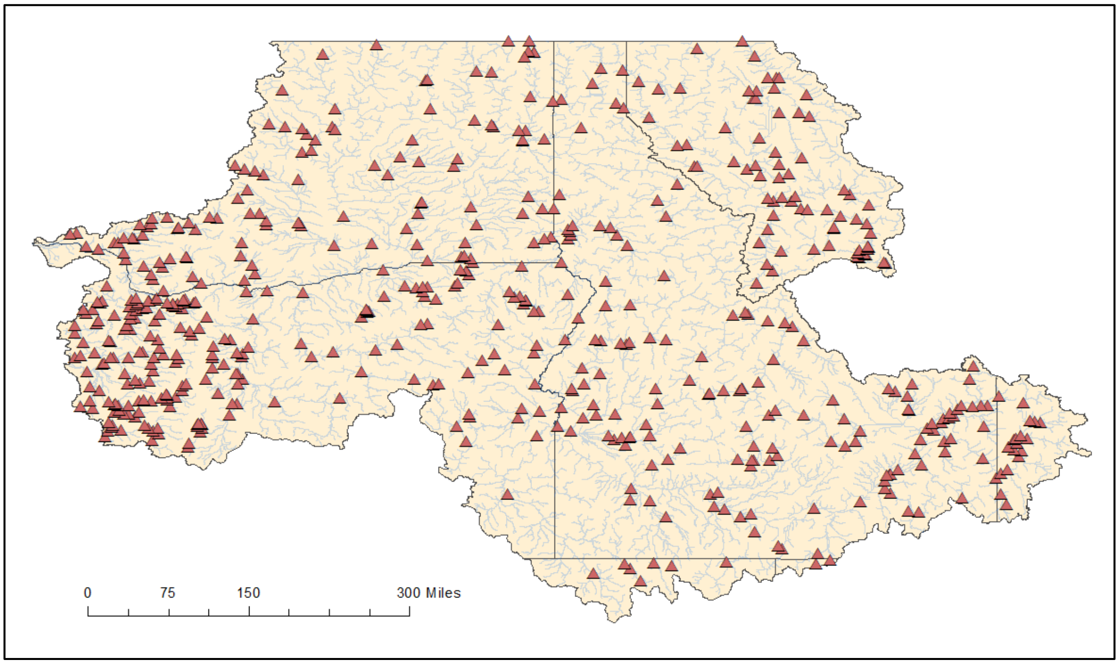


Figure 2.4. Stream network of the CRB and location of gauges (n = 622) for which 7Q10 low-flow was calculated. Sources: Gauges: US Geological Survey (USGS) – National Water Information System; stream network: created from the DEM taken at The National Map Viewer (http://viewer.nationalmap.gov).

7Q10 values were inserted into the attribute table for the CRB map in ArcGIS (Appendix 2). Initial flow maps were constructed based on flow characteristics estimated from gauged data, and defined water requirements for siting nuclear reactors.

2.3.2.2.2. Ungauged locations

Some catchments lack measured streamflow information. Low flows were estimated for these locations using the drainage-area ratio method. Flow-duration and low-flow frequency statistics can be estimated at ungauged stream sites using several methods. These include drainage-area ratio relation, use of miscellaneous flow measurements at the ungauged site (partial-record site method), and the regional regression equation method (a technique that assumes catchments with similar climatic, topographic, and geologic characteristics have similar streamflow responses) (Risley et al. 2008; Smakhtin 2001). Many of these methods are based on the assumption that catchments with similar climate, geology, topography, vegetation and soils have similar streamflow responses in terms of frequency and magnitude of low-flow events. A flow characteristic estimated at any gauged location in a region is assumed to be representative for the whole catchment above the gauge (Smakhtin 2001).

The drainage-area ratio relation is the preferred method for estimating low-flow statistics at an ungauged site on a stream with gauged record (Risley et al. 2008). The method was applied by Omitaomu et al. (2012), and Mays et al. (2012) to predict low-flow statistics for ungauged locations throughout the contiguous US. The drainage-area ratio method is usually used when the ungauged site is on the same stream (upstream or downstream) of the gauged site and the drainage-area ratio of the two sites is between 0.5 and 1.5. This method is based on the assumption that the unit area runoff of the ungauged basin is the same as that for the gauged site (Risley et al. 2008). If suitable upstream and downstream gauges are found, the flow per unit drainage area at the two neighboring gauges is averaged and multiplied by the drainage area of the ungauged location to estimate the flow. At ungauged catchments, methods to estimate daily streamflow time series typically require the use of a reference stream gauge, which transfers properties of the streamflow time series at a reference stream gauge to the ungauged catchment. The reference stream gauge is typically selected by choosing the nearest stream gauge (Archfield and Vogel 2010).

The method for estimating flow at ungauged locations is illustrated in Figure 2.5. A stream segment with unknown flow is represented by green circle, and the red triangle with 7Q10 low-flow equal to 323.8 cfs is the nearest (reference) gauge located on the same stream. The drainage area of the gauge is estimated from a DEM, and a point shapefile containing the gauge, and ArcGIS software functions to delineate the watershed and calculate the drainage area. A Python script (Appendix 1) was written to automate these geoprocessing tasks, which was applied to estimate flow at all ungauged stream segments.

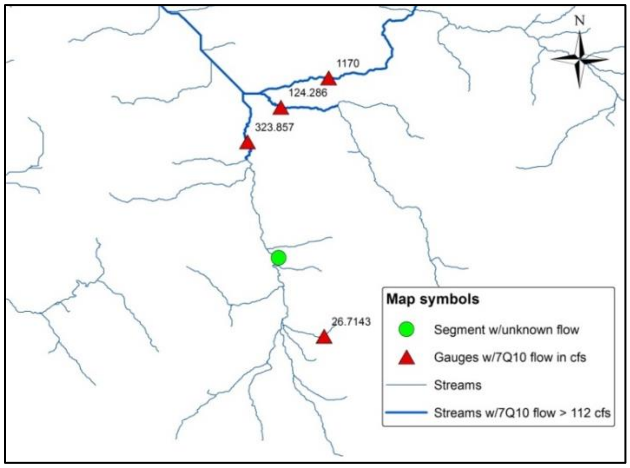


Figure 2.5. Calculating 7Q10 low-flow at the stream segment with unknown flow.

In the example (Figure 2.5) the drainage-area ratio of the two gauges was 0.67, which is between 0.5 and 1.5. Thus, the 7Q10 low-flow of the stream segment with unknown discharge was calculated as the 7Q10 low-flow of reference gauge (323.8 cfs) multiplied by the ratio (0.67). The estimated discharge of the ungauged stream segment was 216.7 cfs (97,262 gpm), which is enough for siting small nuclear reactors. The same method was applied for several other locations with unknown flow in the study area. Flow was calculated for only nine additional locations. These new locations (Figure 2.6) were inserted into the attribute table (Table 2.2) with calculated drainage area and 7Q10 low-flow.

Table 2.2. Locations with unknown flow inserted to the attribute table.

Gauges (622)

FID	Shape *	STAID	STANAME	DRAIN_SQK	LAT_GAGE	LNG_GAGE	STATE	low_fl_10
623	Point	11111111	location w/unknown flow	2058	0	0		142.51
624	Point	11111111	location w/unknown flow	1476.29	0	0		216.88
625	Point	11111111	location w/unknown flow	2442.36	0	0		277.39
626	Point	11111111	location w/unknown flow	1318.3	0	0		149.73
627	Point	11111111	location w/unknown flow	1538.45	0	0		116.53
628	Point	11111111	location w/unknown flow	2051.27	0	0		147.6
629	Point	11111111	location w/unknown flow	1313.12	0	0		180.69
630	Point	11111111	location w/unknown flow	1370.1	0	0		96.92
631	Point	11111111	location w/unknown flow	621.597	0	0		292.15

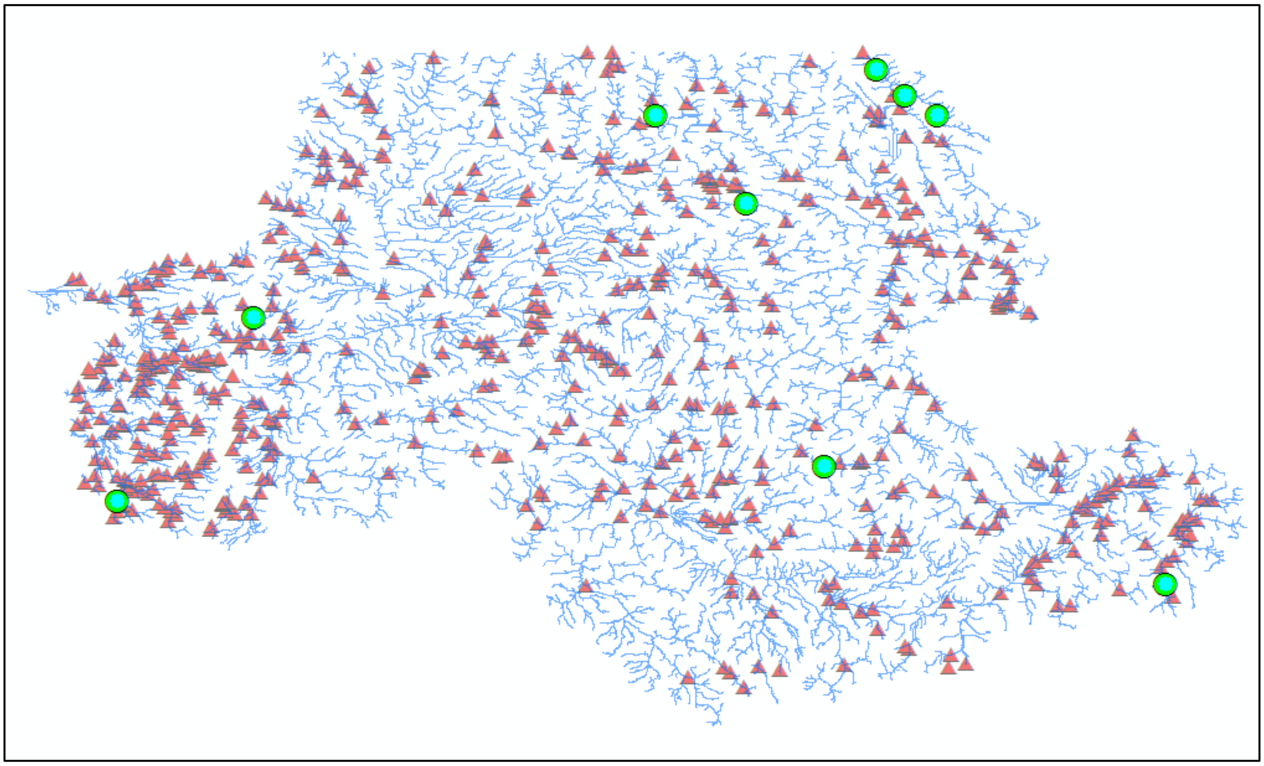


Figure 2.6. Stream network of the CRB, gauges (n = 622; red triangles), and ungauged locations for which discharge was calculated (n=9; green circles).

2.3.3. Other siting criteria

The first step in the process of selecting candidate areas is to select input datasets for each of the screening criteria. Datasets were selected that provide national or greater coverage with attributes matching the desired criteria.

Maps used in this analysis were consistent with the requirements for a Step 1 siting evaluation (Table 2.1), which specifies the use of maps at 1:250,000 or smaller scale. The scale of maps used for the analysis ranged from 1:12,000 (county level) or 1:24,000 (state level) to 1:1,000,000 (national level). Urban areas, landslides, and seismicity issues were analyzed using the national level maps (1:1,000,000). However, this analysis used maps at a larger scale (finer resolution) than required for some features. The river network layer, as well as slope and contour (relative height) layers, were created based on a 30-meter (1 arc-second, 7.5-minute) DEM, with a scale of 1:24 000. Protected land uses, and wetlands were identified using maps at 1:24,000 scale. The 100-year floodplains were identified from Federal Emergency Management Agency (FEMA) maps at 1:12,000.

Each input dataset or map was converted to a GIS layer. Some layers were a direct representation of available data (for example, protected areas), and some were a composite of information from multiple sources (for example, buffered faults, or buffered streams with certain calculated discharge). Slope and relative height were calculated from the DEM as raster layers, and processed manually.

The GIS layers, which represent areas that are excluded as nuclear power plant sites, were overlaid one by one. The GIS layers were applied in the following order: (1) water availability, including adequate streamflow, within 10 miles from the river for pumping water costs, (2) seismicity criterion (earthquakes/faults), (3) population, (4) landslides, (5) protected areas, (6) 100-year floodplain, (7) wetlands and open water, (8) slope and relative height criteria, and (9) land area requirements. The following criteria were selected for excluding areas for the siting of nuclear reactors:

- Areas that are more than 10 miles from cooling water makeup sources with at least 50,000/200,000 gpm (for small/large reactors);
- Areas with safe shutdown earthquake peak ground acceleration (2% chance in a 50-year return period) greater than 0.3g;
- Areas within 5 miles from capable faults over 12 miles in length;
- Areas with a population density greater than 500 people per square mile (including a 20-mile buffer);
- Areas with a moderate or high landslide hazard susceptibility;
- Protected lands (national parks, historic areas, wildlife refuges, etc.);
- Areas within a 100-year floodplain;
- Wetlands and open water;
- Areas with a slope greater than 12% (~7°);
- Areas whose elevation is more than 250 meters above the source of water used for cooling purposes;
- Land area required for each nuclear power plant.

The requirements for each criterion are based on the regulations established by regulatory bodies in the nuclear industry, and are described and discussed below.

2.3.4. Application of Geographic Information Systems (GIS)

GIS are computerized hardware and software systems that facilitate the entry, analysis, display, and overall management of mappable information (Blaschke et al. 2012, Rodwell 2002). GIS packages store geographic information as a set of data layers, where each layer represents a specific data theme, such as surface hydrology, topography, population distribution. The strength of GIS lies in its analytical capabilities, because it allows data computations that would be difficult and laborious, if possible at all, by using manual methods. Typical GIS operations include arithmetic operations (addition, subtraction, division, and multiplication of maps), logical/Boolean operations (comparison of two or more maps to return maximum, minimum, intersection, union, or other results), spatial operations (distance buffering, network modeling), topographic operations (slope, aspect, visibility) (Bonham-Carter 2014, Jovanović and Njeguš 2013, Rodwell 2002). The results of the analytical operations can be portrayed as high quality color maps and statistical reports to assist decision-makers in evaluating sites.

To identify suitable locations for siting nuclear facilities in the CRB, we adapted a GIS-based multicriteria decision analysis (MCDA) approach. GIS specialists from different science fields have developed this approach for many years for locating landfills (e.g. Gbanie et al. 2013, Yesilnacar et al. 2012), solar farms (e.g. Sánchez-Lozano et al. 2014), wind farms (e.g. Aydin et al. 2010), and power generating sites (Omitaomu et al. 2012). The MCDA approach is designed to quickly screen for candidate areas based on multiple criteria ranging from environmental and physical geological constraints to socioeconomic constraints. The GIS-based MCDA approach for siting plants can be described as a process that combines and transforms spatially referenced datasets (inputs) into a resultant map (output) (Omitaomu et al. 2012, Rodwell 2002).

There are several stages in the MCDA process to create a suitability map. In the first stage siting criteria are identified. During the second stage criteria are compiled onto base maps for the study area, and entered into GIS through digitization or reformatting of existing digital data. GIS operations are performed on map layers in a systematic, predetermined sequence. The result of this step is the creation of a set of issue maps, where each map evaluates candidate areas relative to a specific siting issue. Later issue maps are combined through a logical map overlay to create a composite map of candidate areas (Bonham-Carter 2014, Rodwell 2002).

In summary, this analysis involved: (1) identification of criteria for step 1 of the NRC regulations for nuclear power plant location, (2) identification of specifications for small and large nuclear reactors, (3) creation of maps displaying each criterion, and (4) application of a series of GIS operations and tools to combine these layers, producing (5) a final map of candidate areas appropriate for siting of small and large nuclear reactors.

2.4. Results

Results include maps of each of the criteria (Figures 2.7 to 2.17) and a final map showing the resulting available sites for nuclear power plants in the CRB (Figure 2.18).

2.4.1. Water availability for siting nuclear reactors

Only a portion of the CRB river network had 7Q10 low-flow exceeding 50,000 gpm or 200,000 gpm, appropriate for siting small and large nuclear reactors, respectively (Figure 2.7).

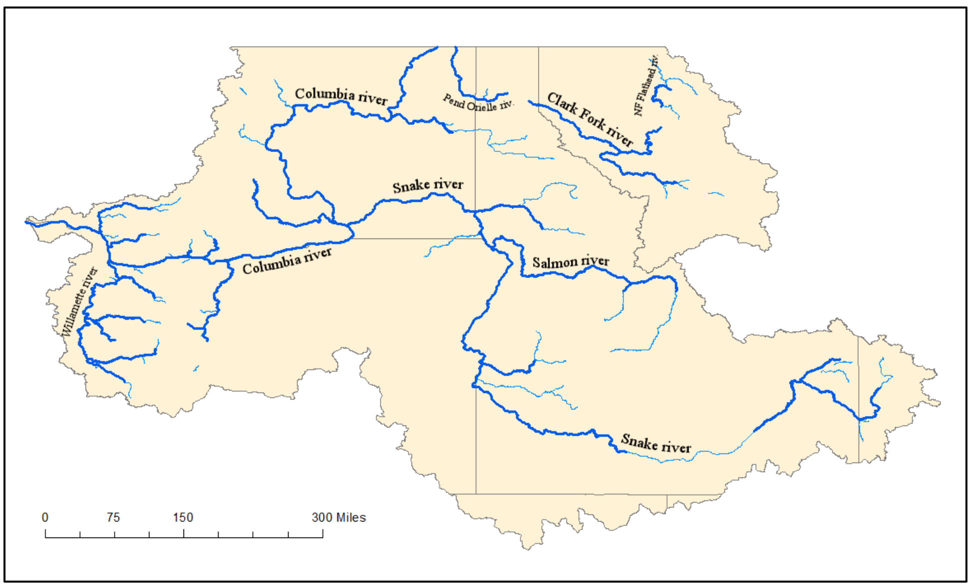


Figure 2.7. Map showing streams with 7Q10 low-flow exceeding 50,000 gpm (both thick and thin blue lines), and exceeding 200,000 gpm (thick blue lines). The map was created by merging a stream network map with a GIS layer attributed with 7Q10 low-flow values at stream gauges.

Of the 622 gauges analyzed, and 9 new ungauged locations with calculated flow, 182 (29%) locations had adequate flow for siting small reactors (over 50,000 gpm or 112 cfs), and 92 (15%) have enough flow for siting large reactors (over 200,000 gpm or 445 cfs).

Only a small proportion of the area of the CRB lies within 10 miles of rivers with adequate low flow for cooling for nuclear power plant location (Figures 2.8 and 2.9). Ten miles was considered to be within reasonable proximity to a cooling water source (Keeney 1980), allowing for pumping, thus, we used 10-miles buffers to create the maps.

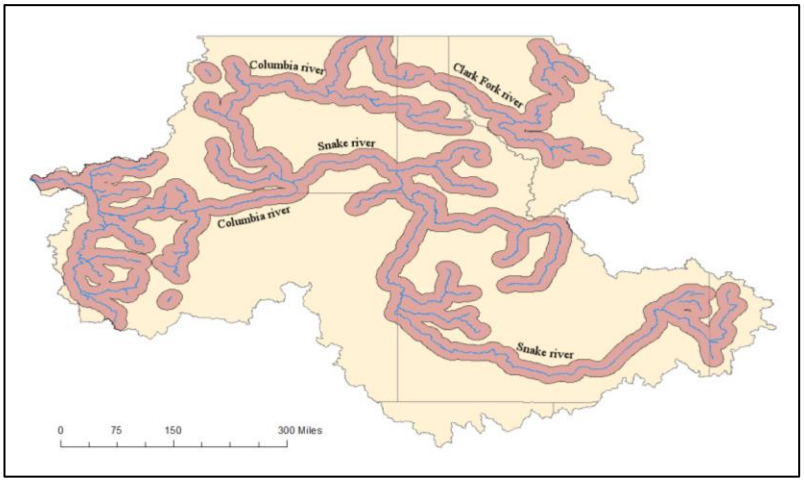


Figure 2.8. Buffers 10 miles for streams with 7Q10 low-flow over 50,000 gpm. This map was created using a 10-mile buffer around the river segments.

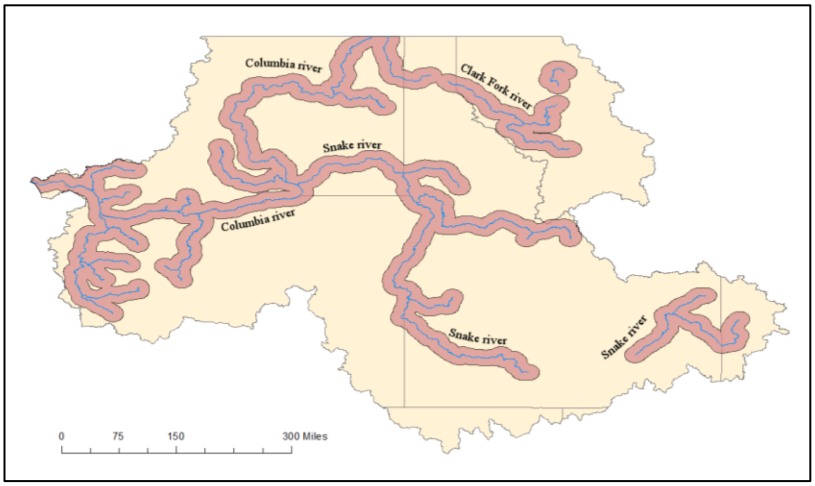


Figure 2.9. Buffers 10 miles for streams with 7Q10 low-flow over 200,000 gpm. This map was created using a 10-mile buffer around the river segments.

Based on these two screening criteria, potential sites for small and large nuclear reactors are distributed in the valleys of the largest rivers of the CRB, such as Columbia, Snake, Yakima, Spokane, Salmon, Willamette, and Flathead. The mainstems of these rivers have discharge exceeding 200,000 gpm, which is adequate for siting large nuclear reactors. An exception is the Snake River, where a long section of river in southern Idaho has lower flow than in the upstream and downstream areas (Figure 2.9). Flow in this section is adequate for siting small reactors only.

2.4.2. Results from applying other siting criteria

Maps were created to represent the following exclusionary criteria in the CRB: geology, seismic hazard, population, protected land uses and facilities, wetlands, slope, landslides, floods.

2.4.2.1. Geology/seismology criterion

Vibratory ground motion is an exclusionary criterion for siting nuclear reactors. The map below (Figure 2.10) shows 2% probability of exceedance in 50 years of peak ground acceleration located within the CRB. The probability of exceedance of 2% in 50 years roughly corresponds to a return period of 2,500 years (or a frequency of occurrence of once in 2,500 years).

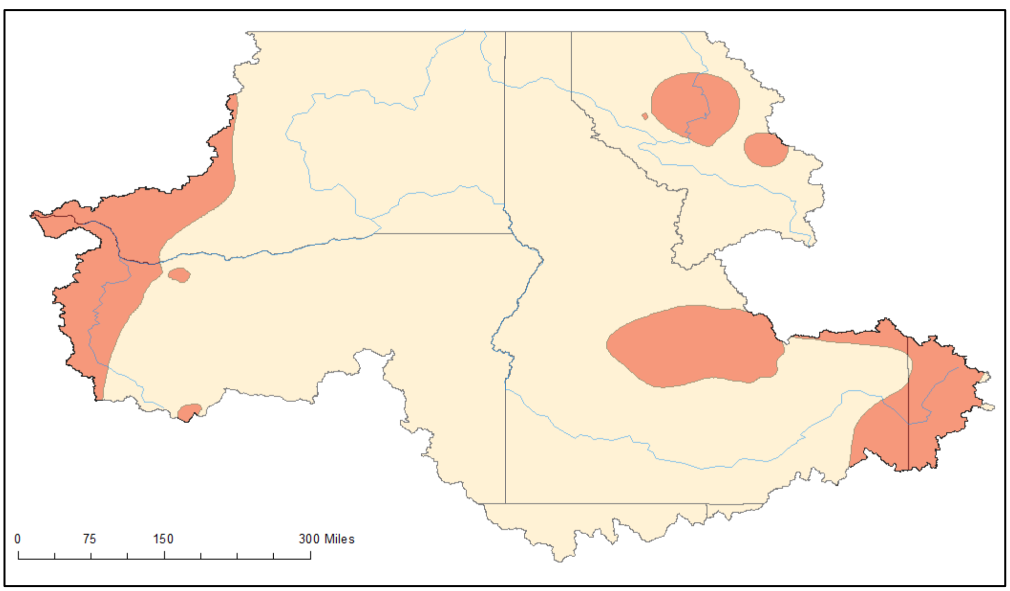


Figure 2.10. Areas with peak ground acceleration over 0.30g within the CRB (in orange). Source: U.S. Geological Survey (USGS) http://earthquake.usgs.gov/hazards/products/conterminous/

Rodwell (2002), referring to the EPRI's "Advanced Light Water Reactor Utility Requirements Document", in his report notes, that a maximum Safe Shutdown Earthquake is 0.30g. The Safe Shutdown Earthquake (SSE) is that earthquake which is based upon an evaluation of the maximum earthquake potential considering the regional and local geology and seismology and specific characteristics of local subsurface material. It is that earthquake which produces the maximum vibratory ground motion for which certain structures, systems, and components are designed to remain functional (NRC 2015). Areas where regional hazard mapping shows peak ground accelerations (PGAs) exceeding 0.30g at a probability of exceedance of 2% in 50 years should be excluded (Rodwell 2002).

The western parts of Oregon and Washington, the eastern part of the Snake River Basin in Idaho, upstream areas of the Salmon River in Idaho, and the central part of the Flathead River in Montana are areas with PGAs over 0.30g at a probability of exceedance of 2% in 50 years, which should be excluded from further analysis. Also, during selection of potential sites (next step of site selection process) exclusionary areas should be refined and plotted at sufficiently large scales such that boundaries are easily defined in the mapped areas.

2.4.2.2. Capable faults

Capable tectonic structures, in particular faults, are addressed both as an exclusionary and avoidance criterion. The 5-mile areas surrounding capable faults over 12 miles in length should be excluded from the further analysis during the first stage of site selection process, because these areas cannot be used for siting nuclear reactors (Keeney 1980).

According to the NRC, capable faults are those that had "movement at or near the ground surface at least once within the past 35,000 years or movement of a recurring nature within the past 500,000 years" (NRC 2015). USGS uses the following categories based on the estimated most recent date of movement of a fault:

- >1 = historic
- >2 = Holocene < 15,000 years
- >3 = late Quaternary < 130,000 years
- >4 = mid to late Quaternary < 750,000 years
- >5 = Quaternary < 1,600,000 years

It is difficult to match the NRC definition to the USGS system, because it overlaps categories 1 through 4 of the USGS system, which also does not indicate whether the movement was of a recurring nature. Thus, for the purposes of this study, all the faults which had movement at or near the ground surface within the past 15,000 years (categories 1 and 2) were excluded from further analysis, and faults, which had movement within the past 130,000 years and 750,000 years (categories 3 and 4) were placed in avoidance criteria (Figure 2.11).

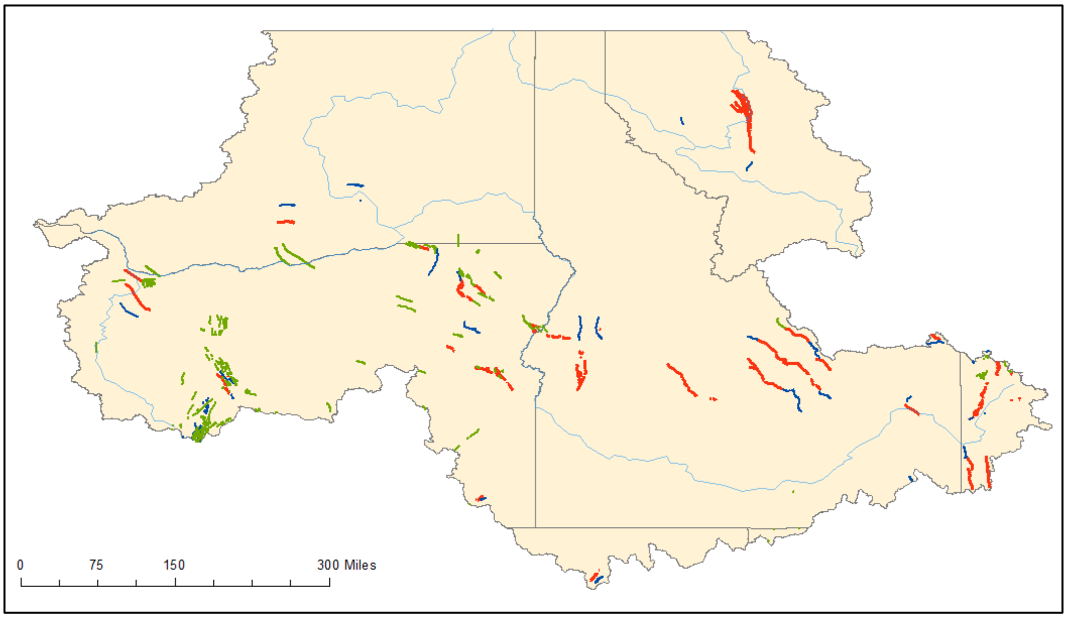


Figure 2.11. Faults in the CRB (red: historic and < 15,000 years; blue: < 130,000 years; green: < 750,000 years). Source: U.S. Geological Survey (USGS) http://earthquake.usgs.gov/hazards/products/conterminous/

2.4.2.3. Population

Population distribution and density are very important criteria in the process of site selection. In selecting a site for a nuclear power station, the applicant must demonstrate that the proposed site meets the following conditions codified at 10 CFR 100.21:

- Exclusion area surrounding the reactor in which the reactor licensee has the authority to determine all activities, including exclusion and removal of personnel and property,
- Low population zone (LPZ) which immediately surrounds the exclusion area,
- Population-center distance of at least 1.33 times the distance from the reactor to the outer boundary of the LPZ, where a populated center contains more than 25,000 residents.

In addition, NRC's Regulatory Guide 4.7 (NRC 2011) provides guidance that "a reactor should preferably be located such that, at the time of initial site approval and within about 5 years thereafter, the population density, including weighted transient population, averaged over any radial distance out to 20 miles (cumulative population at a distance divided by the circular area at that distance), does not exceed 500 persons per square mile." Under this guidance, a population center of 25,000 or more residents should be no closer than 4 miles from the reactor because a density of 500 persons per square mile within this distance would yield a total population of 25,000 persons. Similarly, a city of 100,000 or more should be no closer than 10 miles; a city of 500,000 or more should be no closer than 20 miles; and a city of 1,000,000 or more should be no closer than 30 miles (Table 2.3) (Rodwell 2002).

Table 2.3. Population criterion as presented in Rodwell's report. Source: Rodwell 2002.

Population Center Size	**Exclusionary Distance (miles)**
25,000	4
100,000	10
500,000	20
1,000,000	30

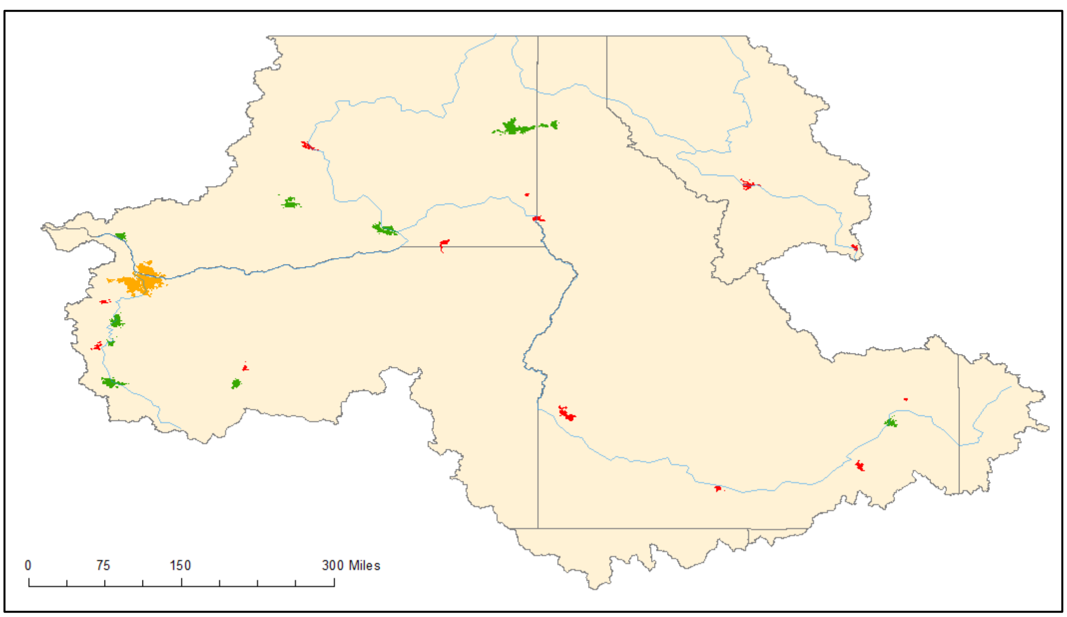


Figure 2.12. Urban areas in the CRB. Red: population 25,000–100,000. Green: population 100,000–500,000. Blue: population 500,000–1 mln. Orange: population >1 mln. Source: The National Map http://viewer.nationalmap.gov

Thus, buffered areas of corresponding size (Table 2.3) around urban areas with population over 25,000 (Figure 2.12) are excluded from the further analysis.

2.4.2.4. Landslides

Areas with moderate or high incidence or susceptibility to landslides (Figure 2.13) were excluded from site selection.

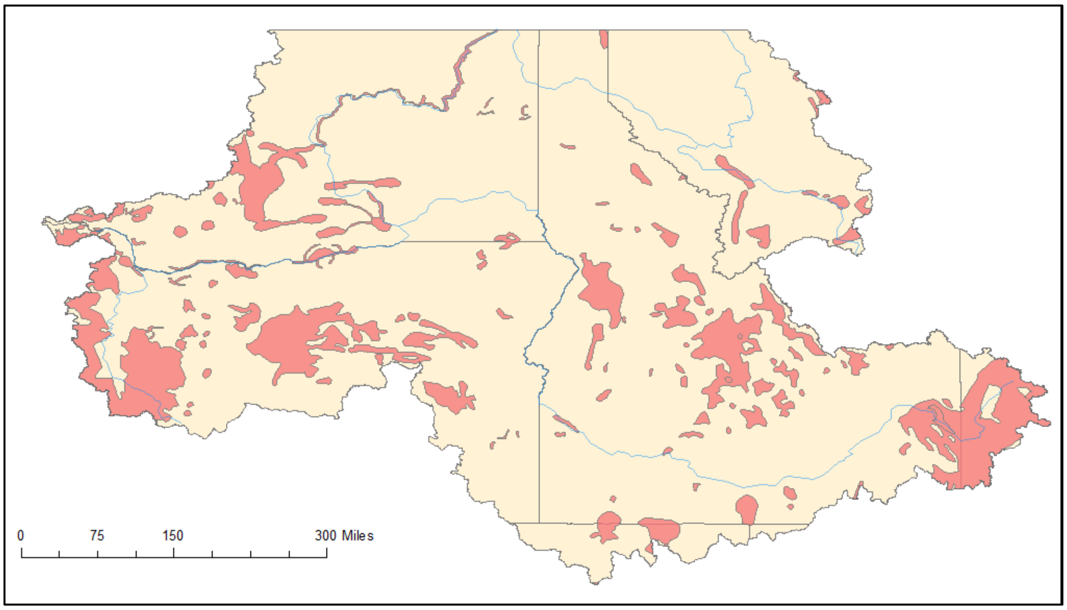


Figure 2.13. Areas with moderate/ high incidence or susceptibility to landslides in the CRB (in red). Source: U.S. Geological Survey (USGS) Landslide Hazards Program (2002).

2.4.2.5. Protected land uses

Land use areas that are protected by a Federal, state, or local agency, should be excluded from site selection. Regulatory Guide 4.7, Section B (NRC 2011) identifies the areas of public use that should be considered in this step. Nuclear power plants are excluded from (Figure 2.14):

- National Parks
- Wilderness Areas
- Native American Reservations
- National Forests
- National Wildlife Reserves or Preserves

- National Monuments
- National Conservation Areas
- National Scenic Areas

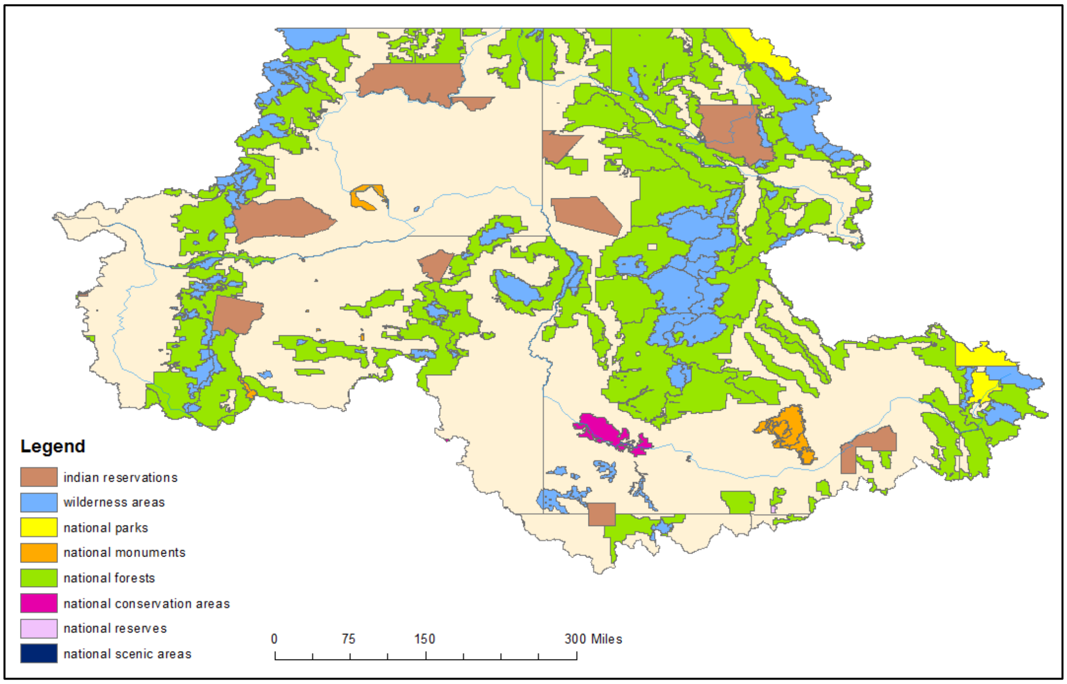


Figure 2.14. Protected lands within the CRB. Source: The National Map http://viewer.nationalmap.gov

2.4.2.6. Wetlands

According to the Executive Order No 11990, protection of wetlands requires that each federal agency "avoid to the extent possible the long and short term adverse impacts associated with the destruction or modification of wetlands and to avoid direct or indirect support of new construction in wetlands wherever there is a practicable alternative" (EPA 1977). Thus, wetlands and waterbodies (Figure 2.15) were excluded from further analysis.

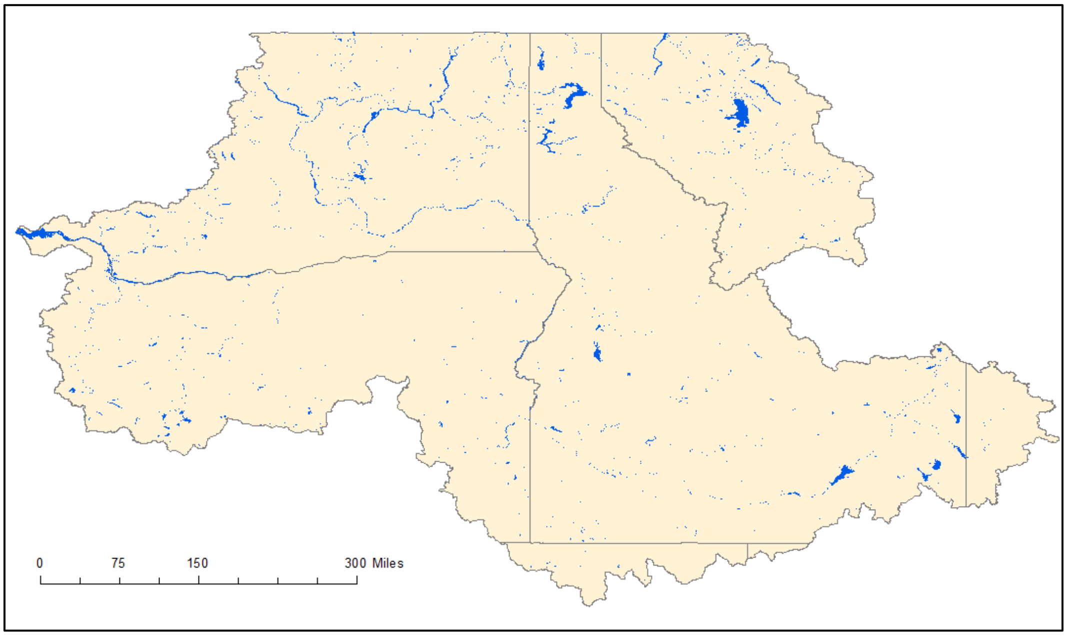
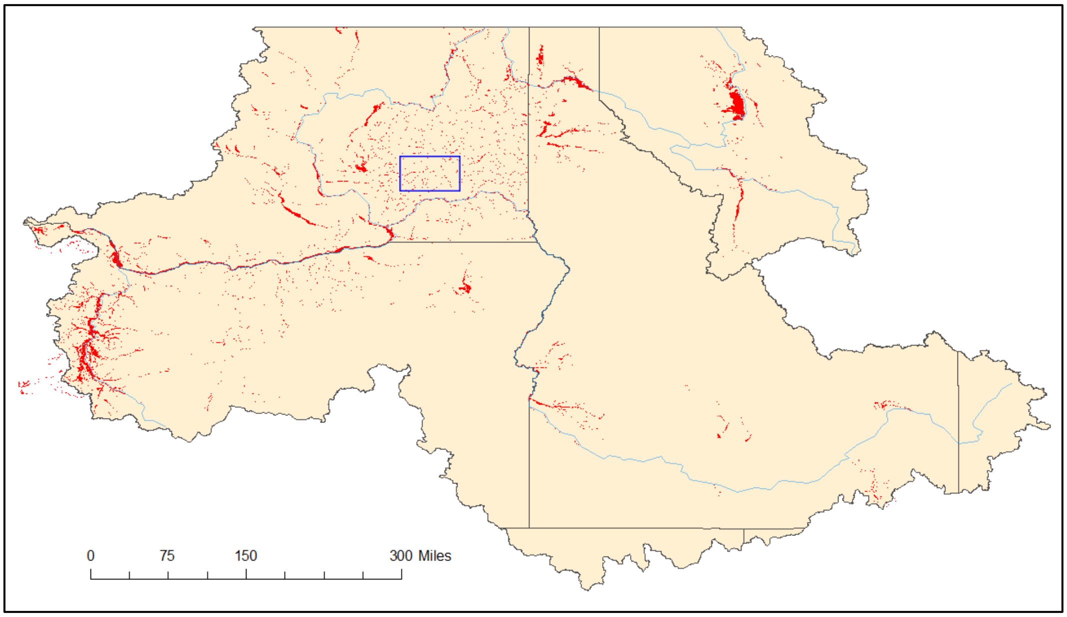


Figure 2.15. Waterbodies and wetlands in the CRB (in blue). Source: The National Map (http://viewer.nationalmap.gov), National Land Cover Database (NLCD) 2011, National Wetlands Inventory (http://www.fws.gov/)

2.4.2.7. Floods

According to the Federal Emergency Management Agency, flooding is a general and temporary condition of partial or complete inundation of normally dry land area, and floodplain consists of land area susceptible to being inundated by floodwaters from any source. The 100-year floodplain is the boundary of the flood that has a 1-percent chance of being equaled or exceeded in any given year. The 1-percent annual chance flood is also referred to as the base flood or 100-year flood (FEMA 2015). Areas within the 100-year flood plain are not appropriate for siting nuclear reactors, and were excluded from site selection (Figure 2.16).

According to NRC Regulatory Guide 4.7 (NRC 2011), the effects of a probable maximum flood, seiche, surge, or seismically induced flood such as might be caused by dam failures or tsunamis on station safety functions can generally be controlled by engineering design or protection of the safety-related structures, systems, and components identified in Regulatory Guide 1.29, Seismic Design Classification.

a) 

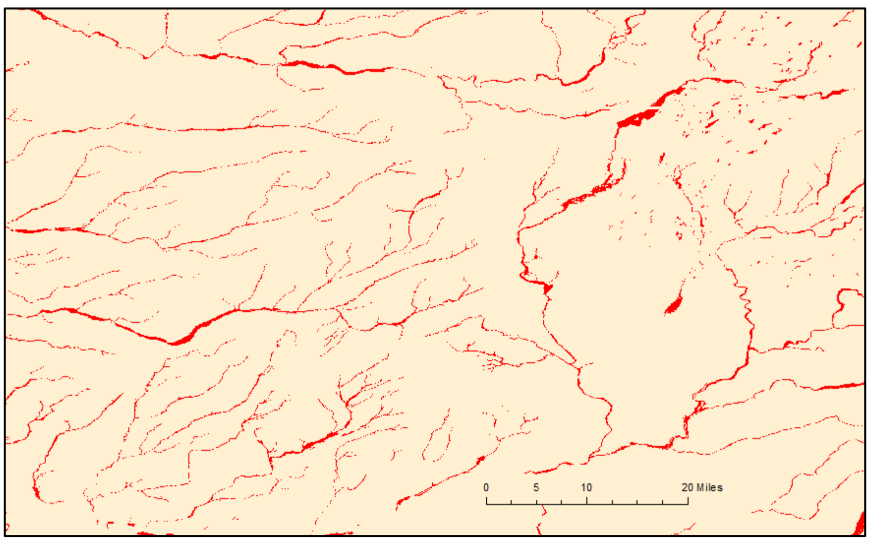
b) 

Figure 2.16. a) 100-year floodplain in the CRB (in red). The quality and availability of data vary by county; b) enlargement of area (on a) in blue frame) to show fine-scale floodplain features. Source: FEMA Geoplatform application (http://fema.maps.arcgis.com/)

2.4.2.8. Slopes and relative height

Areas characterized by mountainous terrain were excluded because of steep slopes, which are: 1) potentially unstable, 2) require more costly site preparation, 3) are significant impediments to emergency plan effectiveness (Mays et al. 2012, Rodwell 2002). Regions with slopes greater than 12% mean slope, or greater than 400 feet relief, were excluded (Figure 2.17).

Land over 800 feet (~250 meters) above the source of water was excluded due to economic reasons (pumping from the source of water at the high altitudes is an expensive task).

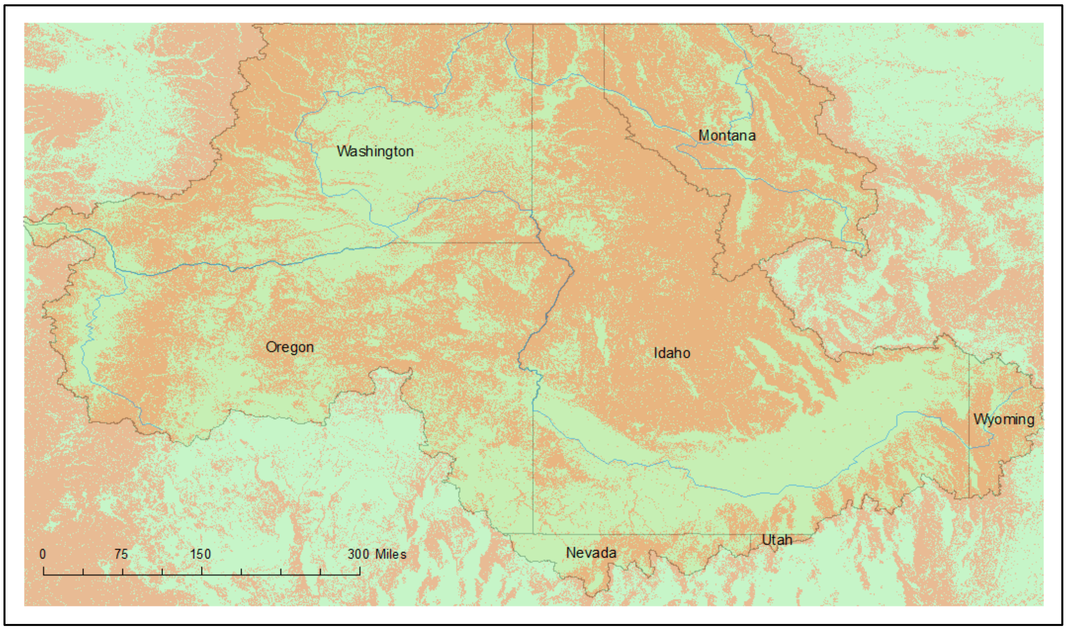


Figure 2.17. Slopes over 12% in the CRB (brown – slopes over 12%, green – up to 12%). Source of the DEM: The National Map Viewer (http://viewer.nationalmap.gov/viewer/)

2.4.2.9. Land requirements for nuclear power plants

Mays et al. (2012) state that the minimum footprint is 50 acres for a small nuclear plant, and 500 acres for a large nuclear plant.

2.4.3. Candidate sites for nuclear power plant locations in the CRB

By applying a series of GIS operations and tools to the raster map of the candidate areas created based on all the criteria defined previously, a final map displays candidate areas appropriate for siting small and large nuclear reactors considering the land size necessary for their construction (Figure 2.18). Approximately 4.6% of the US portion of the CRB may be suitable for siting small nuclear reactors and 3.1% may be suitable for siting large nuclear reactors, based on Step 1 requirements of the NRC regulations for nuclear power plant siting. Most of these candidate areas are contained within two major regions: Middle Columbia River, in south central Washington and the northern edge of Oregon, and the Snake River plain in southern Idaho.

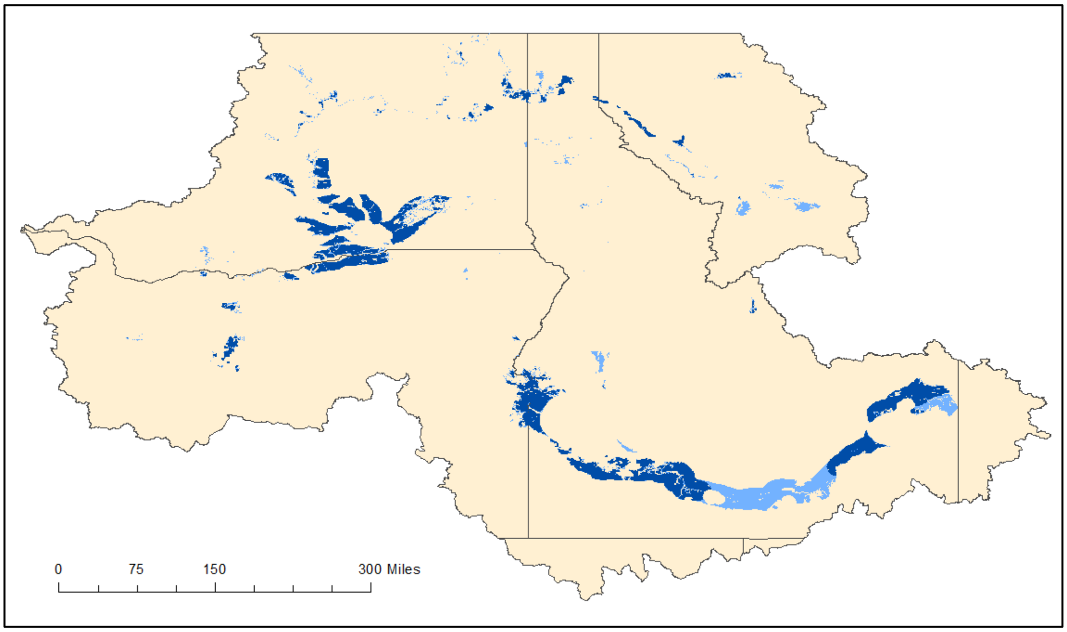


Figure 2.18. Candidate areas for siting small (light blue and dark blue) and large (dark blue only) nuclear reactors after applying all criteria.

2.5. Discussion

The objective of this part of dissertation is to assess areas suitable for siting nuclear power plants of different capacity in the Columbia Basin. In our study we applied commonly used GIS-based MCDA approach for selecting candidate areas, although made some changes to the methodology and analyzed criteria. Studies related to siting nuclear reactors examined a similar set of siting criteria; however, none of them applied relative height criterion (exclusion of land of certain height above the source of water due to economic reasons), which is especially important in such a mountainous region as the CRB. We analyzed the criteria in terms of suitability for siting nuclear plants with wet cooling towers, and additionally evaluated how the candidate area will change in case of plants with dry cooling towers. We also revealed that in addition to traditional 7Q10 low-flow analysis, 7Q50 analysis may also be required for assessing water sufficiency for siting the reactors.

2.5.1. Limitations of the study

Three major issues affecting nuclear power plant siting emerged from this study: potential future limits on nuclear power plant location due to: (1) low flow limits on cooling water, (2) flood hazard, and (3) risk of accident from earthquakes.

There is some spatial uncertainty about available water during minimum flow periods in some portions of the CRB, where flow estimates differ in upstream versus downstream river segments. There is also temporal uncertainty due to differences in 7Q10 and 7Q50 low-flow statistics at several gauges. Overall, low water availability may limit nuclear power plant siting in many parts of the Columbia Basin.

A second issue relates to the uncertainty of flooding in the candidate areas. Many parts of the Basin are likely to experience substantial increases in flooding in response to climate change. In particular, increases in precipitation intensity are projected for the windward slopes, and decreases are projected for the leeward slopes of the Cascades and Rockies (Salathe et al. 2014). Increasing in flood risk, in its turn, may limit the location and safe operation of nuclear power plants in the region.

A third source of uncertainty arises from the seismicity criterion for siting nuclear power plants. The CRB is susceptible to earthquakes. Consistent with NRC regulations, areas with peak ground accelerations exceeding 0.30g at a probability of exceedance of 2% in 50 years (return period of 2,500 years) were excluded from the list of potential sites (Rodwell 2002). In addition, nuclear plants are constructed to withstand environmental hazards, including earthquakes, without loss of capability to perform their safety functions (NRC 2015).

2.5.2. Water availability

2.5.2.1. Difference in upstream and downstream flow

Most of the mainstem tributaries in the Columbia Basin have adequate discharge for siting large and small nuclear reactors, based on 7Q10 low-flow statistics calculated using streamflow records for 2003 to 2013 from 622 USGS gauges. All of the major rivers have adequate discharge (exceeding 200,000 gpm) for siting large nuclear reactors throughout their mainstem lengths, except the Snake River. A long section of the upper Snake River has lower flow than in the upstream and downstream parts (Figure 2.19). Flow in this section is adequate for siting small reactors, but not for large reactors.

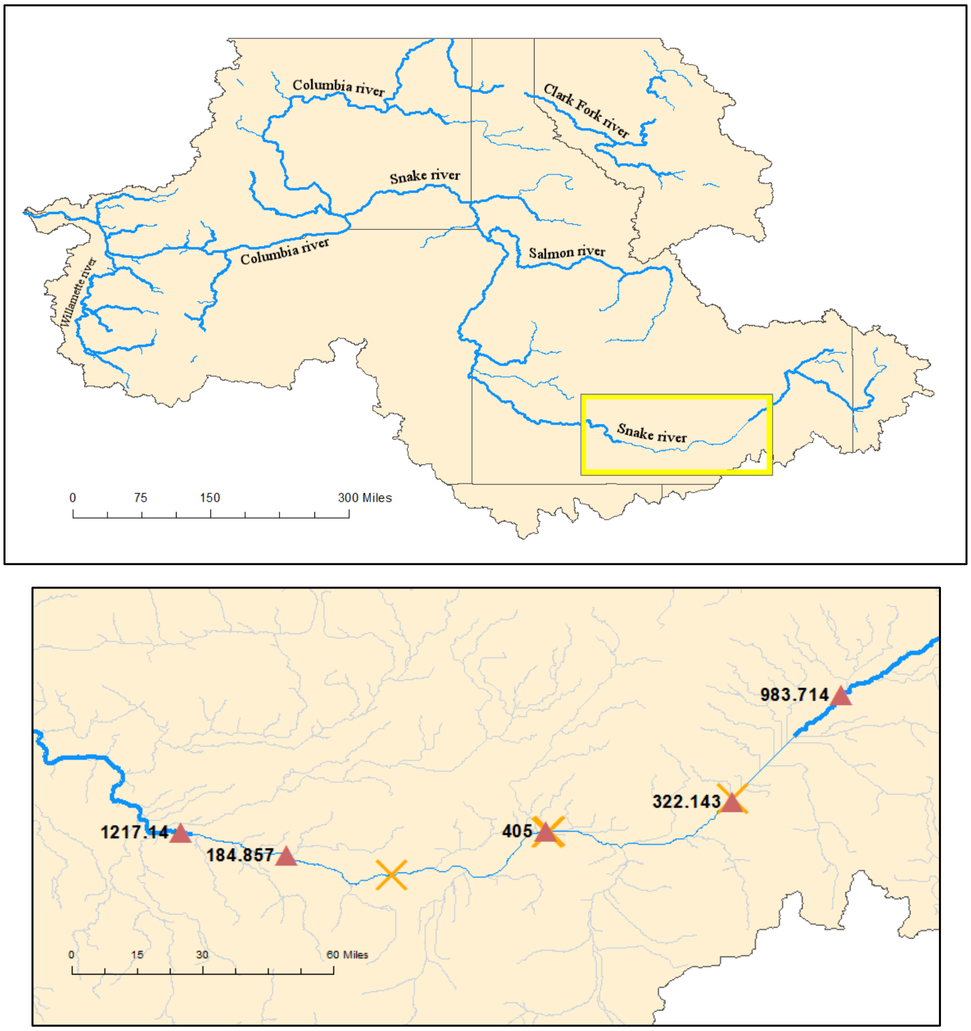


Figure 2.19. Snake River: section of the stream in the upper part with lower flow than in the upstream and downstream areas. Both thick and thin blue lines represent streams with 7Q10 low-flow exceeding 50,000 gpm; thick blue lines - exceeding 200,000 gpm. Orange crosses represent the dams.

Sections of other major tributaries also had significantly lower discharge than in the upstream and downstream parts of the same rivers. The middle part of the Deschutes River in Oregon had significantly lower low-flow (7Q10 of approximately 25-30 cfs) compared to the surrounding sections of this river (417 cfs in the upstream part; 497 cfs in the downstream part) (Figure 2.20).

Figure 2.20. Deschutes River: section of the stream in the upper part with lower flow than in the upstream and downstream areas. Both thick and thin blue lines represent streams with 7Q10 low-flow exceeding 50,000 gpm; thick blue lines - exceeding 200,000 gpm. Orange crosses represent the dams.

Low-flow values also decrease in the downstream sections, in comparison with the upstream, in the Clark Fork River in Montana (160 cfs upstream/100 cfs downstream/271 cfs – further downstream) (Figure 2.21), and the Falls River in Idaho (338 cfs upstream/72 cfs downstream) (Figure 2.22).

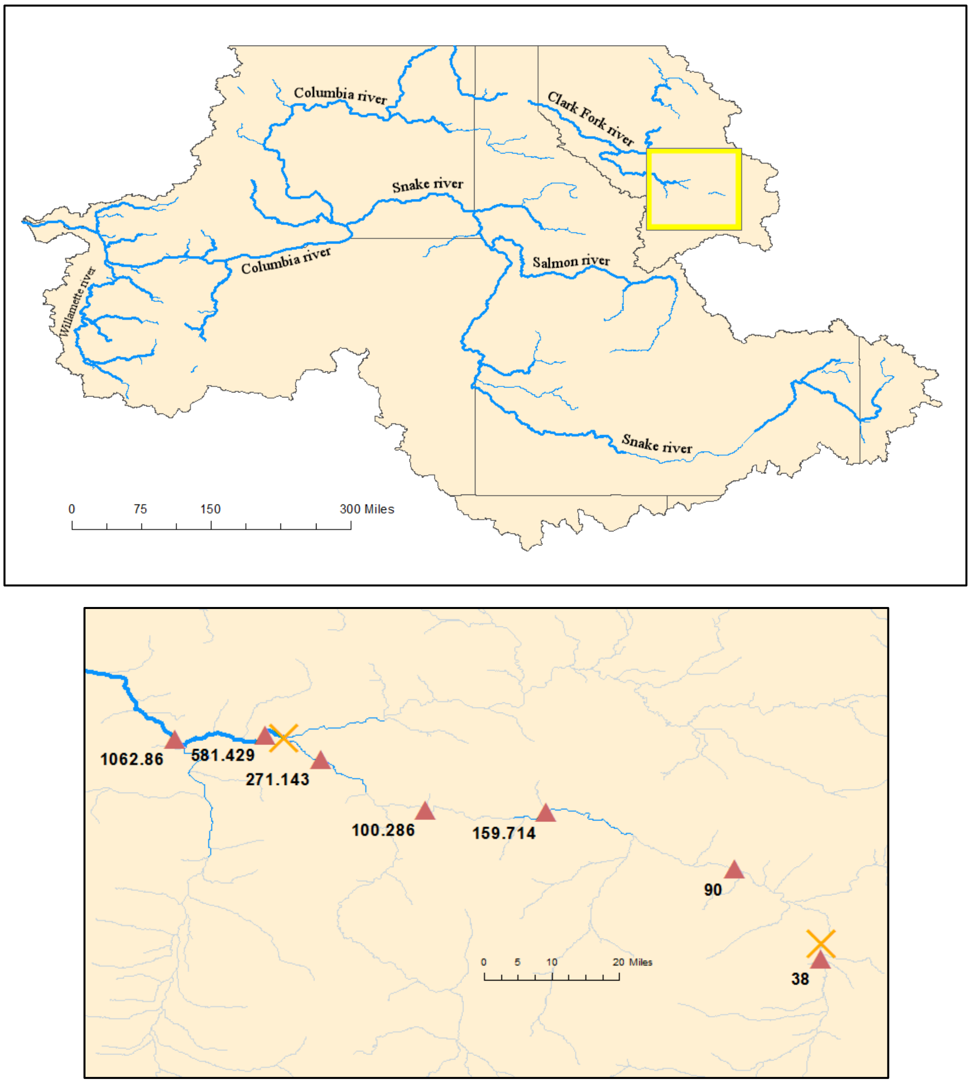
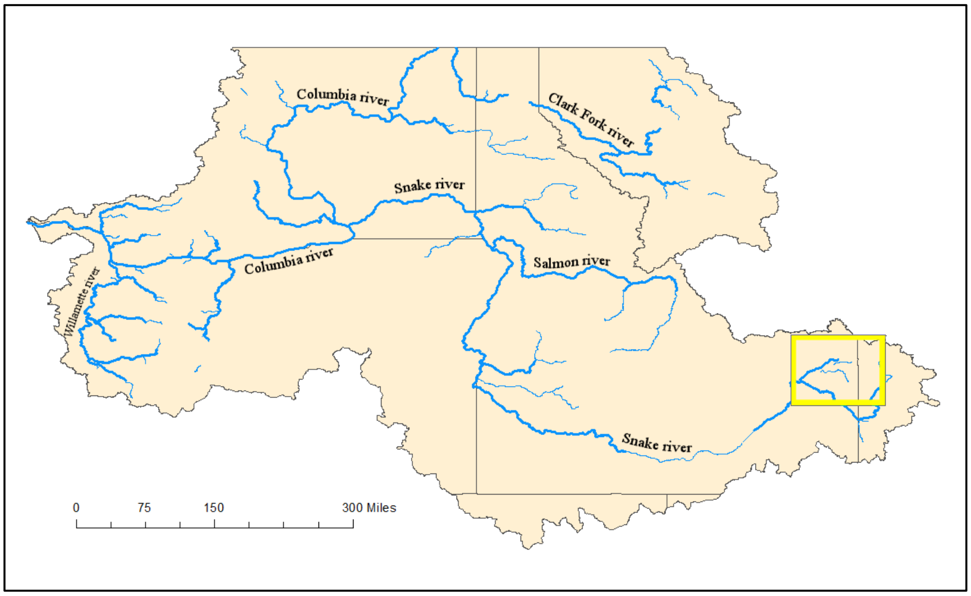


Figure 2.21. Clark Fork River: flow decrease in the downstream sections of the river, in comparison with the upstream. Both thick and thin blue lines represent streams with 7Q10 low-flow exceeding 50,000 gpm; thick blue lines - exceeding 200,000 gpm. Orange crosses represent the dams.



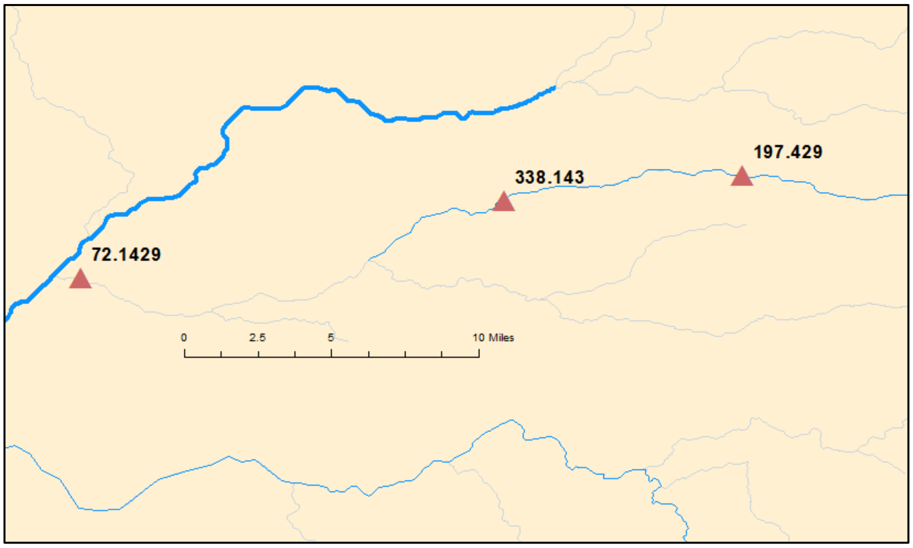


Figure 2.22. Falls River: flow decrease in the downstream sections of this river, in comparison with the upstream. Both thick and thin blue lines represent streams with 7Q10 low-flow exceeding 50,000 gpm; thick blue lines - exceeding 200,000 gpm. Orange crosses represent the dams.

Possible reasons for differences in streamflow between the downstream and upstream segments include dam operation in the area, or water withdrawal for irrigation purposes, as well as natural factors, such as the character of the valley floor (deep alluvial sediment vs. bedrock). Whatever the reasons for these very low 7Q10 values, the existence of the portions of the CRB where flow estimates differ in upstream versus downstream river segments leads to some spatial uncertainty about available water during minimum flow periods. In particular, it is debatable whether sections of a river should be considered as feasible candidate areas for siting nuclear reactors, if they are upstream of stream segments where flow is below the threshold. On the one hand, such sections can be considered as feasible candidate sites, because the local gauge record indicates that discharge is adequate for siting nuclear reactors. But on the other hand, very low 7Q10 values downstream of these areas may be connected with the operation of dams, or with water withdrawal for irrigation purposes. If so, it may be justifiable to exclude upstream areas from nuclear power plant siting, because taking water for cooling purposes will automatically reduce the flow downstream and leave farmers without water for irrigation. To understand this, we should, in particular, thoroughly analyze the water balance of the river.

2.5.2.2. 7Q10 and 7Q50 differences

Nuclear power plants have a lifetime of 50-60 years until decommissioning, but the analysis conducted here used minimum flow estimates based on only a 10 year record. 7Q10 is the dominant low-flow metric used by US agencies and researchers for many purposes, including siting facilities, particularly nuclear power plants (Rodwell 2002). This statistic has been used in studies related to site selection for different facilities (e.g., Omitaomu et al. 2012, Mays et al. 2012). However, several gauges have adequate discharge for siting nuclear plants according to 7Q10 low-flow statistics, but not according to 7Q50 statistics. Some of the years from the 50-year period show very low discharge values (less than 50,000 gpm which are needed for a small nuclear reactor) indicating that over the 50-year lifetime of a nuclear power plant there may not be enough water for cooling the condensers. These differences in 7Q10 and 7Q50 low-flow statistics at some gauges lead to some temporal uncertainty about available water during minimum flow periods.

Gauge 14187500 on the South Santiam River (Oregon) had very low low-flow in one of the 50 years of record. The average annual 7Q low-flow was 625 cfs (from 1963 to 2013, excluding 1966), but the 7Q low-flow value in 1966 was only 75 cfs, i.e. less than the required 112 cfs (Table 2.4, Figure 2.23).

Table 2.4. Gauge 14187500, South Santiam River, OR. Enough discharge (in cfs) for siting nuclear reactors according to 7Q10 low-flow statistics, but not according to 7Q50 low-flow statistics.

206.4286	1963	452.1429	1976	499.8571	1989	677.2857	2002
210	1964	544.7143	1977	575.8571	1990	573	2003
126.7143	1965	684.5714	1978	663.1429	1991	605.4286	2004
75	1966	625.7143	1979	544	1992	666	2005
442.8571	1967	733	1980	622.1429	1993	873.7143	2006
627.2857	1968	715.4286	1981	632.2857	1994	651	2007
804.7143	1969	689	1982	727.1429	1995	887.2857	2008
741.4286	1970	700.4286	1983	679.1429	1996	781.5714	2009
507	1971	596.7143	1984	742.8571	1997	815	2010
454	1972	595.8571	1985	669.4286	1998	822.2857	2011
642.5714	1973	613	1986	630.7143	1999	887.1429	2012
487.8571	1974	618	1987	631.8571	2000	863.1429	2013
477.7143	1975	599.8571	1988	622.4286	2001		

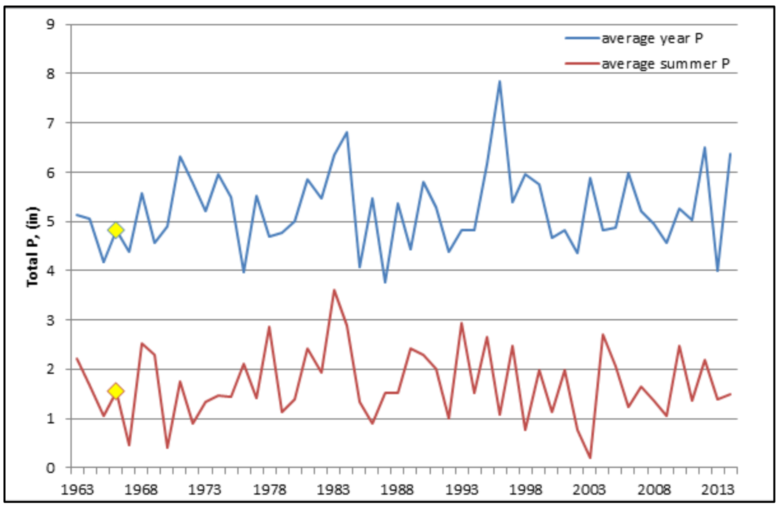


Figure 2.23. Annual average and summer average precipitation for Cascadia, OR (351433) station. Low-flow years are indicated by yellow dots. Source: The Carbon Dioxide Information Analysis Center (CDIAC), http://cdiac.ornl.gov/

Gauge 14159500 on South Fork McKenzie River (Oregon) had two very low 7Q low-flow values in the last 50 years. Average 7Q low-flow during the period 1963-2013 (excluding 1973 and 1977) is 279 cfs, while values in 1973 and 1977 were 108 cfs and 86 cfs respectively (Table 2.5, Figure 2.24).

Table 2.5. Gauge 14159500, South Fork McKenzie River, OR. Enough discharge (in cfs) for siting nuclear reactors according to 7Q10 low-flow statistics, but not according to 7Q50 low-flow statistics: a number of small 7Q10, but not in the last 45 years.

172.5714	1963	285.8571	1976	301.1667	1989	190.5714	2002
287.2857	1964	86.14286	1977	267.3333	1990	185.2857	2003
152.5714	1965	198.1429	1978	285.1429	1991	228.8571	2004
184.5714	1966	306.1429	1979	274.2857	1992	182.1429	2005
260	1967	253.1429	1980	235.5714	1993	337.5714	2006
201.7143	1968	225.4286	1981	246	1994	345.8571	2007
254.2857	1969	310.4286	1982	305.5714	1995	326	2008
283.4286	1970	264.1429	1983	305.7143	1996	393	2009
362.2857	1971	362.4286	1984	264.3333	1997	392.1429	2010
335.2857	1972	309.4286	1985	264.8571	1998	344.4286	2011
107.8571	1973	255.5714	1986	331.5714	1999	416.2857	2012
246.8571	1974	303.4286	1987	281.2857	2000	354	2013
250.2857	1975	271.5714	1988	256.6667	2001		

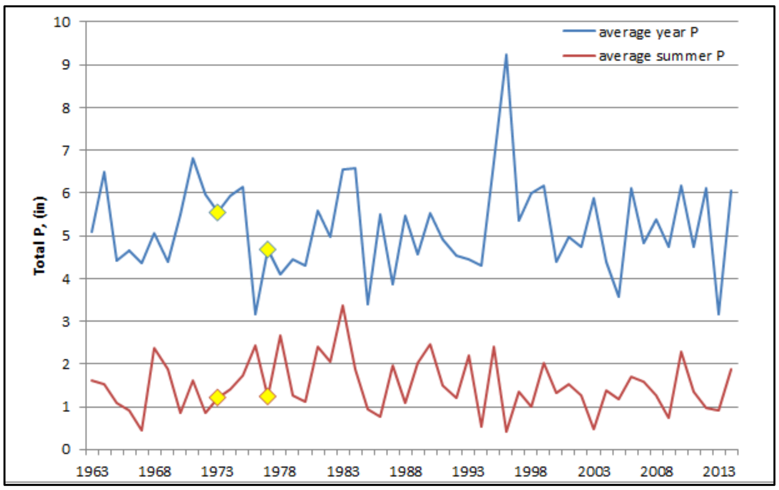


Figure 2.24. Annual average and summer average precipitation for McKenzie Brg Rs, OR (355362) station. Low-flow years are indicated by yellow dots. Source: The Carbon Dioxide Information Analysis Center (CDIAC), http://cdiac.ornl.gov/

Gauge 13077000 on the middle Snake River, Idaho, had several years with very small 7Q low-flow values in comparison with the average. The average annual 7Q low-flow was 1263 cfs (from 1963 to 2013, excluding “low” years), but 7Q low-flow values in 1963, 1966 and 1967 did not exceed 92 cfs (Table 2.6, Figure 2.25).

Table 2.6. Gauge 13077000, middle Snake River, ID. Enough discharge (in cfs) for siting nuclear reactors according to 7Q10, but not according to 7Q50 low-flow statistics. A number of small 7Q10, but not in the last 45 years.

92.14286	1963	3212.857	1976	357.8571	1989	293.7143	2002
603.1429	1964	179.2857	1977	372.5714	1990	352.7143	2003
2954.286	1965	191.7143	1978	312.8571	1991	345.5714	2004
53.14286	1966	433.2857	1979	322.7143	1992	322.1429	2005
68.85714	1967	385.8571	1980	290.5714	1993	339.8571	2006
245	1968	470	1981	299.2857	1994	352.4286	2007
264.4286	1969	878.1429	1982	298	1995	359.4286	2008
857.7143	1970	3101.429	1983	1078.571	1996	489.7143	2009
4020	1971	1775.714	1984	4454.286	1997	514.8571	2010
4945.714	1972	1620	1985	3430	1998	1838.286	2011
1574.286	1973	3991.429	1986	3485.714	1999	346.4286	2012
2521.429	1974	365	1987	350.5714	2000	385.5714	2013
4381.429	1975	327.5714	1988	328	2001		

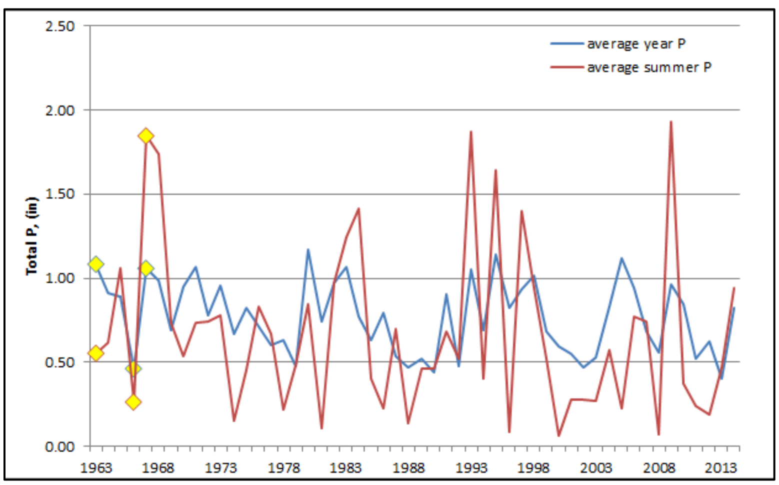


Figure 2.25. Annual average and summer average precipitation for Aberdeen Exp Stn, ID (100010) station. Low-flow years are indicated by yellow dots. Source: The Carbon Dioxide Information Analysis Center (CDIAC), http://cdiac.ornl.gov/

A similar picture can be found among the observations of the following gauges:

- 14145500, Middle Fork Willamette River, Oregon. Seven years starting from 1963 to 2013 (1963, 1964, 1972, 1977, 1980, 1987, 2001), but not in the last 10 years, have low-flow values less than necessary 112 cfs, with the average low-flow 296 cfs;
- 13011000, upper Snake River, Wyoming. Eight years (1963-1969, 1981) for the last 50 years have small low-flow values, but not in the last 30 years; the average low-flow 322 cfs;

- 12419000, Spokane River, Idaho. Two years for the period 1963-2013 (1966, 1967) have small low-flow values, with the average low-flow for the whole period 557 cfs;
- 12362500, Flathead River, Montana. Two years out of the last 50 years (1993, 1995) have small low-flow values, with the average low-flow for the whole period 418 cfs.

Figures 2.23-2.25, and similar graphs for the four above gauges do not show strong correlation between low-flow anomalies and precipitation anomalies: the lowest low-flows were not necessarily in the years with the lowest precipitation. However, in the western part of the CRB, some of the low-flow anomalies are more often explained by relatively low precipitation, in comparison with the eastern part (Snake River, Flathead River).

Only seven of 622 gauges in the CRB have enough discharge for siting nuclear plants according to 7Q10 low-flow statistics, but not according to 7Q50 statistics (Figure 2.26). Only one of these gauges (gauge 13077000 - Snake River at Neeley, ID) occurs within the candidate areas identified in the first step of site selection. Therefore this site, which is also notable for having lower flow than portions of the river upstream, merits further investigation about water availability for cooling, at later stages of the site selection process.

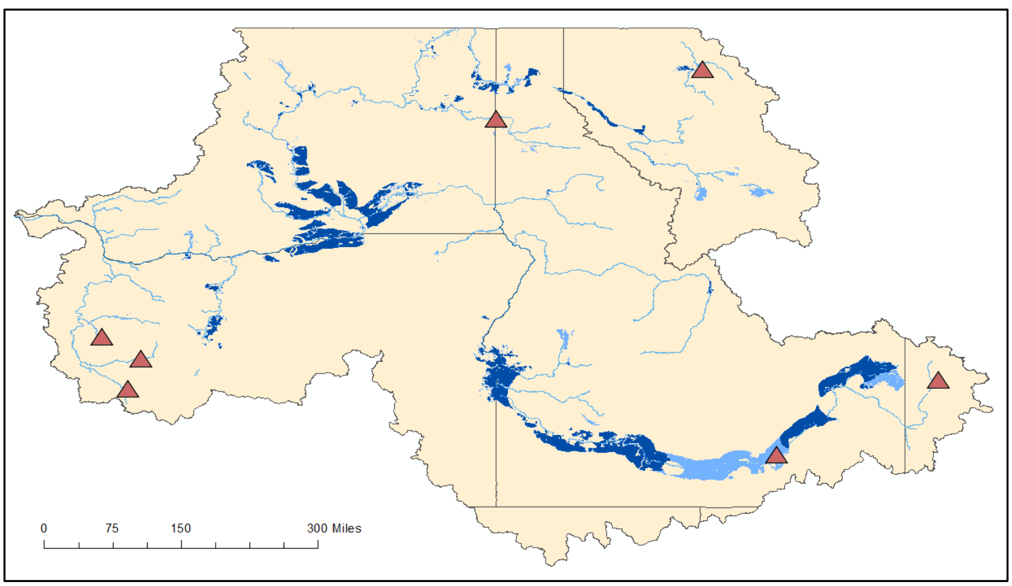


Figure 2.26. Gauges in the Columbia Basin with difference in 7Q10 and 7Q50 statistics (gauges have enough discharge for siting nuclear plants according to 7Q10 low-flow statistics, but not according to 7Q50 statistics).

Although 7Q10 is the most dominant low-flow metric used in studies related to siting facilities, 7Q50 analysis might be justified for nuclear power plants, whose lifetime is 50 years. The lack of long-term records may limit the ability to calculate 7Q50, but 7Q50 is desirable for gauges within the candidate areas identified from the first step of site selection process.

2.5.2.3. Pumping distance

In our study, ten miles was considered to be within reasonable proximity to a cooling water source, allowing for economics of pumping, following Keeney (1980). In some studies (for example, Mays et al. 2012), the recommended maximum pumping distance is 20 miles. We used the 10-mile distance, because: 1) we work with a relatively large-scale region; 2) a larger pumping distance increases the cost for construction and operation of a nuclear plant.

2.5.3. Floods

The largest floods in the PNW are generally driven by snowmelt during winter rain-on-snow events (Safeeq et al. 2015, McCabe et al. 2007). Peak flows are particularly sensitive to climate warming in this region, because snow typically falls near the 0°C freezing point, and a change in few degrees can mean the difference between snow and rain, or between snow accumulation and rapid melt (Safeeq et al. 2015, Abatzoglou et al. 2014b, McCabe et al. 2007). According to a variety of studies, many areas in the Pacific Northwest are likely to experience substantial increases in flooding in response to climate change (e.g. Tohver et al. 2014, Salathe et al. 2014). In particular, increases in precipitation intensity are projected for the windward slopes, and decreases are predicted for the leeward slopes of the Cascades and Rockies (Salathe et al. 2014). Flood risk, in its turn, may limit the location and safe operation of nuclear power plants in the region.

According to NRC Regulatory Guide 4.7 (NRC 2011), the effects of a probable maximum flood, seiche, surge, or seismically induced flood such as might be caused by dam failures or tsunamis on station safety functions can generally be controlled by engineering design or protection of the safety-related structures, systems, and components identified in Regulatory Guide 1.29, Seismic Design Classification. Although nuclear power plants are designed to withstand damages that can be caused by floods, during the site selection process the areas within the 100-year floodplain are excluded from the list of potential sites. Taking into account that this study did not examine flood effects in detail, further research is needed to determine whether particular sites would be susceptible to damage from flooding in the future.

2.5.4. Seismicity

2.5.4.1. Issues with seismicity and candidate areas

The PNW is vulnerable to major earthquakes because it is located along the Cascadia subduction zone, a 680-mile fault that runs 50 miles off the coast of the PNW, from Cape Mendocino in California to Vancouver Island in southern British Columbia (Hansen 2012). Megaquakes, subduction earthquakes with magnitudes of 8 or greater, occur about every 500 years on average, and smaller magnitude crustal earthquakes, which have a more compressed footprint, occur more frequently (Showstack 2014). In order to ensure safety related to construction and operation of a nuclear plant, areas where regional hazard mapping shows peak ground accelerations exceeding 0.30g at a probability of exceedance of 2% in 50 years (return period of 2,500 years) are excluded from the list of potential sites (Rodwell 2002). Therefore, the western part of the Willamette basin influenced by seismic Cascadia subduction zone and the very eastern part of the Snake basin located near the seismic Yellowstone caldera were excluded (Figure 2.10). In addition, areas within five miles of "capable" faults, which had movement at or near the ground surface within the past 15,000 years, were also excluded (Figure 2.11). However, subsequent steps in the site selection process require detailed analysis of any capable faults within 200 miles^2 of the site (Rodwell 2002). This includes investigation of the geologic structures surrounding a site to identify any structure that might cause a hazard, analysis of the earthquake history of area, and study of soil and rock properties (via field observations and laboratory tests). The faults screening criterion in this analysis was rather liberal and may allow sites, which would be excluded upon further analysis.

2.5.4.2. Interaction of seismicity with cooling water: example of Fukushima

Although nuclear power plants are designed to withstand environmental hazards, including earthquakes, without loss of capability to perform their safety functions (NRC 2015), earthquakes have disrupted the functioning of nuclear power plants by impeding cooling systems. The safe operation of a nuclear power station depends on its cooling systems, which remove the heat from the reactor during normal operation and residual decay heat when the reactor has been shut down. Overheating and eventual meltdown of fuel in reactor can happen if heat production exceeds cooling capacity, or if the cooling system is not removing the heat at the rate it was designed. Failures resulting from loss of the cooling mechanism are more common because of the fundamental design feature of most operating reactors (Srinivasan and Gopi Rethinaraj 2013).

The March 2011 earthquake in Japan affected the availability of cooling water and led to a nuclear accident at the Fukushima Dai-Ichi nuclear power station. The combined effect of the earthquake and subsequent tsunami damaged the connection of the plant to the electricity grid, and sea water flooded its backup diesel generators (Povinec et al. 2013, Srinivasan and Gopi Rethinaraj 2013, Revankar 2012). At the time of the accident, only three reactors were in operation, and the other three were shut down for planned maintenance. The earthquake automatically caused a shutdown as designed, and stopped fission reaction in three operating reactors. The residual decay heat from the core was supposed to be removed by a residual heat removal system or by an emergency core cooling system, but both of these require electricity. Because of the earthquake, all external power lines connecting the site to the electricity grid were damaged. This caused the total loss of all offsite power. Moreover, the tsunami flooded the backup diesel generators, which were installed at a lower elevation than the reactor buildings. Without power, the station’s cooling systems failed, and without cooling, the reactors overheated (Povinec et al. 2013, Srinivasan and Gopi Rethinaraj 2013, Revankar 2012).

Although this nuclear disaster was primarily caused by combined effects of the very strong earthquake and unusually high tsunami, a number of technical errors and delays in coordinated action led to a cascading series of accidents at Fukushima (Aoki and Rothwell 2013, Srinivasan and Gopi Rethinaraj 2013). In particular, nuclear plants in Japan, including Fukushima, were built to withstand earthquakes up to only magnitude 8, whereas the earthquake on March 11 was of magnitude 9. The earthquake hazard maps prepared by government agencies were mainly based on events occurring with a predictable frequency (around magnitude 8 or less) over a long period of time (Srinivasan and Gopi Rethinaraj 2013). The frequency and height of the tsunamis were also underestimated. Tsunami waves reached a maximum height of about 15 m in Fukushima, while the height of the seawater pump installation was designed for maximum water level of 5.7 m (Srinivasan and Gopi Rethinaraj 2013).

Therefore, it is very important to conduct deeper statistical analysis of probabilities of natural events that can cause serious destructive nuclear accidents. In particular, the assessment of accidents with very low probability of occurrence but with very high social costs should not be ignored (Srinivasan and Gopi Rethinaraj 2013, Revankar 2012). In addition, since many of the failures at Fukushima originated from disruption of power supply, it is clear that emergency backup generators should be installed in sufficiently high elevations or in watertight chambers (Povinec et al. 2013, Srinivasan and Gopi Rethinaraj 2013), if flooding is a serious risk.

The Fukushima accident also highlighted the dangers of clustered nuclear plants (Srinivasan and Gopi Rethinaraj 2013, Revankar 2012). Because of land constraints, Japan has generally chosen cluster siting, whereas in the United States most reactor complexes have one or two units. Therefore, the obvious siting approach for future plants should be to locate them inland, if possible, and away from highly seismic areas and coasts, to reduce the possibility of damage due to serious earthquakes, tsunamis and floods (Srinivasan and Gopi Rethinaraj 2013). However, in many countries mostly coastal sites have been chosen for cooling and logistic convenience.

Nuclear regulatory failures also contributed to the Fukushima nuclear accident (Srinivasan and Gopi Rethinaraj 2013, Wang and Chen 2012). In Japan, three agencies (The Nuclear Safety Commission of Japan (NSC), Nuclear Industrial Safety Agency (NISA), and Nuclear Safety Division) share regulatory responsibilities. During the Fukushima crisis, it was difficult to achieve coordination and consistency of responses among them (Srinivasan and Gopi Rethinaraj 2013). In addition, many issues related to the operation of the plant had been identified prior to the accident. The Fukushima plant was listed among the most trouble-prone nuclear facilities in Japan over last decade, and ranked among the five worst nuclear plants in the world between 2004 and 2008 (Wang and Chen 2012). Nevertheless, the NISA still allowed its operation, and even approved the Unit 1 reactor for an extension of operation for another 10 years in February 7, 2011, after the reactor ended its designed lifecycle (Wang and Chen 2012).

2.5.5. Candidate areas

2.5.5.1. Candidate areas and past/present/projected nuclear plants

The candidate areas for siting small and large nuclear reactors identified by this analysis overlap with areas where two of three nuclear power plants within the CRB are located (Figure 2.27). The Middle Columbia River candidate region overlaps with the Columbia Generating Station in Washington (Figure 2.28), and the Snake River plain candidate region overlaps with a projected nuclear power plant in Payette County, Idaho (Figure 2.29). Alternate Energy Holdings, Inc. (AEHI), an American corporation, is working to build a new nuclear power plant in this location (AEHI 2013).

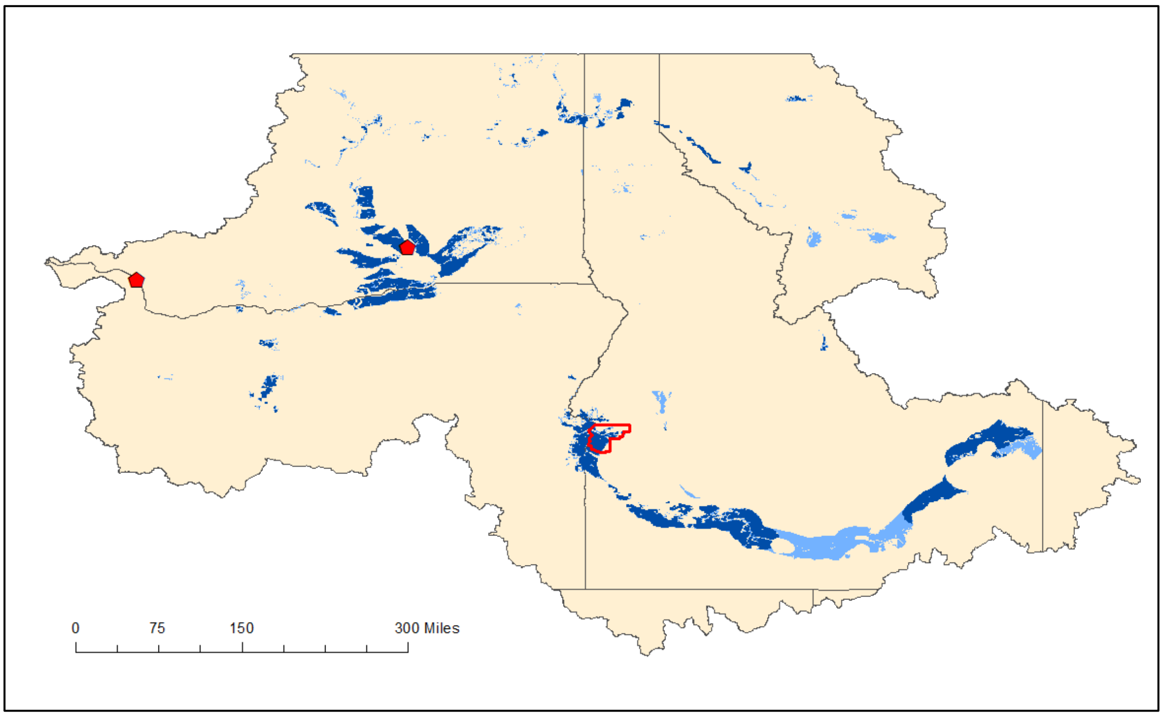


Figure 2.27. Candidate areas for siting small (light blue and dark blue) and large nuclear reactors (dark blue) in the CRB. Red points: Trojan nuclear power plant (NPP) (western part of the basin, border of OR and WA), Columbia Generating Station (WA). Red polygon: Projected NPP in the Payette county, ID.

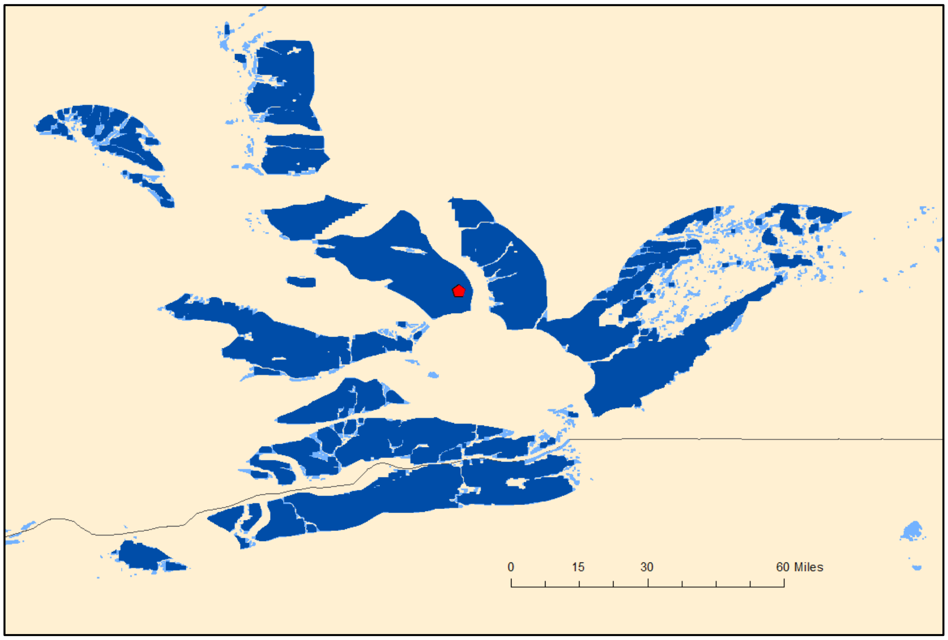


Figure 2.28. Middle Columbia River candidate region.

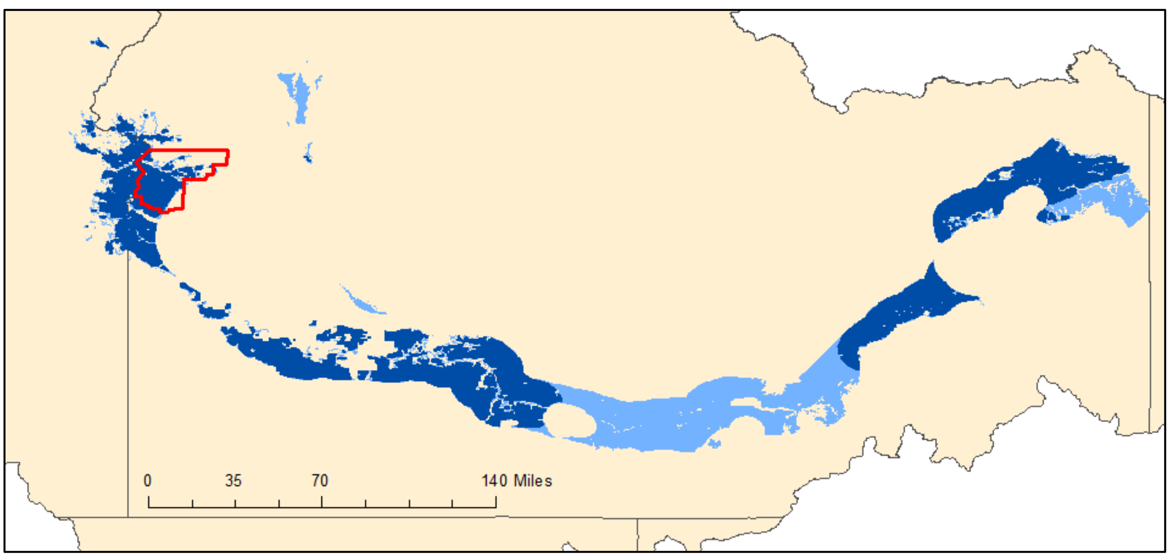


Figure 2.29. Snake River plain candidate region.

The majority of areas within both regions are appropriate for siting large and small nuclear reactors. Thus, this analysis corroborates the site selection process for these nuclear power plants, at least at the initial stage.

On the other hand, the Trojan Nuclear Power Plant in western Washington is not located within an area identified as suitable for nuclear power plant location in this analysis. The Trojan plant was constructed at the beginning of 1970s, and closed/demolished at the beginning of 2000s after the years of debates. After construction of the plant, a 60-mile long seismic zone representing a possible fault or faults was identified within approximately 30 miles of the plant (Beaulieu and Peterson 1981). In the analysis in this dissertation, the area where Trojan NPP was located was excluded from the analysis by the seismicity criterion.

2.5.5.2. General patterns of candidate areas relative to major hydroclimate subregions of the CRB

CRB has three types of watersheds within its territory: snowmelt dominant, transient, and rain dominant. Snowmelt dominant watersheds are characterized by precipitation stored as snowpack causing low-flows in winter and peak flows resulting from the melting of snowpack in late spring or early summer. Rain dominant watersheds are characterized by peak streamflow occurring in the cool season, November through January. Low-flows are observed during the summer and fall months, July through October. Watersheds that experience two streamflow peaks, one from heavy precipitation in winter and the other from snowmelt, are called transient watersheds because they receive both snow and rain (Mantua et al. 2009) (Figure 2.30).

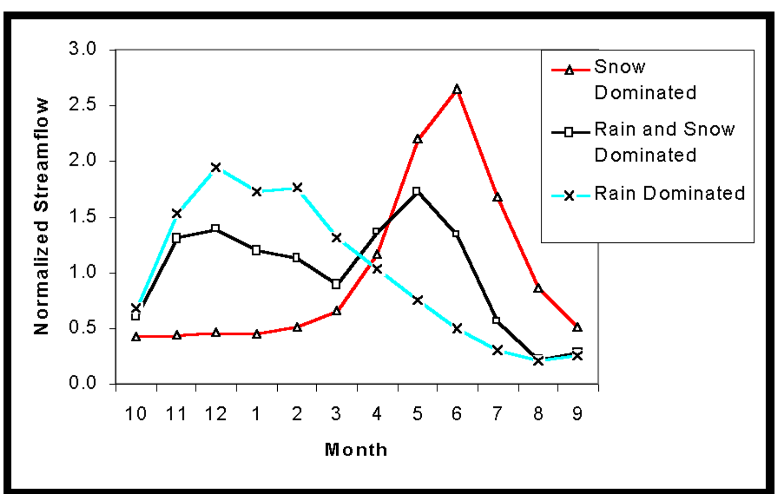


Figure 2.30. Streamflow patterns for different types of watersheds (Source: Hamlet et al. 2010b).

Historically, snowmelt dominant basins prevail in the headwaters of the CRB, extending south into the east side of Cascades in Washington and the higher elevation basins of the Rockies in Idaho and northern Montana. Transient basins predominate where mid-winter temperatures fluctuate around 0°C at mid-elevations of the Cascades and Rockies, in central Washington and Oregon and in southern and western Idaho. Rain-dominant basins are confined to the coastal stretches in Washington and Oregon, west of the Cascades and Coast ranges, and in large swathes of warmer regions in central and southern Oregon and smaller patches in southeast Washington and southwest Idaho (Hamlet et al. 2010b) (Figure 2.31).

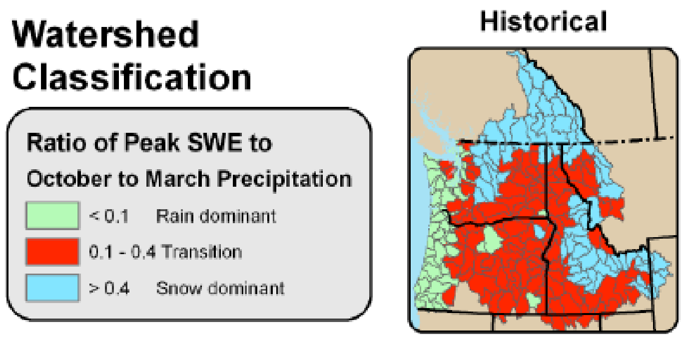


Figure 2.31. Types of the CRB watersheds (Source: Hamlet et al. 2010b)

According to this classification, the majority of streams appropriate for siting both small and large reactors according to our analysis, are located within the transient watersheds. The upper parts of the Snake River, Salmon River, Falls River and others in the eastern and northern parts of the CRB lay in the snowmelt dominant basins. The Willamette River and many of its tributaries are located in the rain-dominant watersheds.

2.5.6. Criteria ranking

In our study, we considered a range of criteria for siting nuclear plants using wet cooling towers. In this case, the first two applied criteria (water availability and seismicity) reduced the number of potentially suitable areas for siting to 28.2% (small reactors), and 20% (large reactors) (Figure 2.32). Other criteria added incrementally excluded just small amounts of additional area, reducing the total square of candidate areas within the CRB to 4.6% (small reactors), and 3.1% (large reactors) at the end of the selection process.

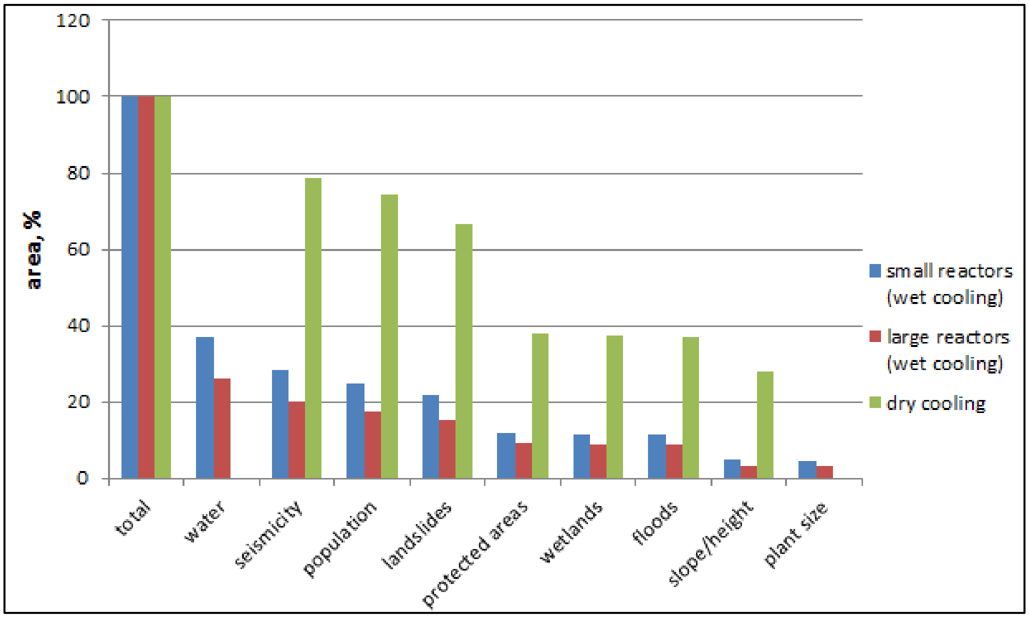


Figure 2.32. Histograms showing changes in the candidate areas after sequential application of different criteria. Blue (small reactors) and red (large reactors) histograms show selection of candidate areas based on all examined criteria; green histogram shows selection of candidate areas based on all criteria except water, relative height, and plant size.

Additionally, we conducted the similar analysis for the siting process which does not consider water availability criterion (Figure 2.32, green columns). Such siting process could be applied, in particular, to roughly estimate suitable lands for siting nuclear plants with dry cooling system. Final square of candidate areas according to this option reduced to 27.8% (Figure 2.33) at the end of the selection process, which is roughly the same percentage as in case of small reactors after applying just the first two criteria.

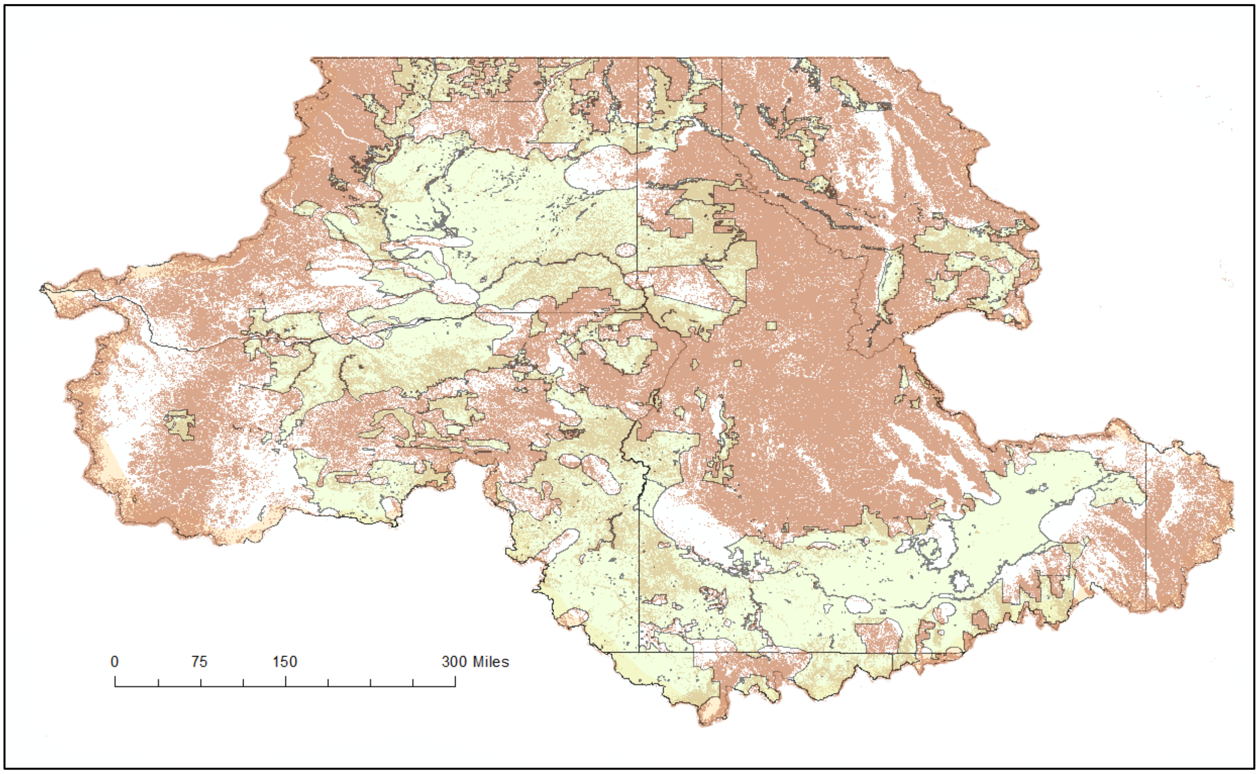


Figure 2.33. Candidate areas (light green) selected based on all criteria besides water availability and relative height (vertical distance from the water source). Slope criterion is presented on a separate (underlying) layer (slopes greater than 12% are shown in brown).

Thus, water availability is a dominant factor limiting nuclear power in the CRB. Another criterion which visibly reduced the number of potential sites is protected areas (Figure 2.14). At the same time, wetlands and 100-year floodplain slightly changed the candidate area, and may be considered the least dominant, although very important, criteria for this study.

2.6. Conclusion

Human society needs energy. The Columbia River Basin is not an exception, even though estimates indicate that energy production in the region is growing faster than energy consumption. Currently energy production in the Pacific Northwest represents only about 68% of energy consumption, and it is mostly provided by hydroelectric dams. Hydroelectric capacity may decline as a result of dam removal and very limited sites for construction of additional dams. Thus, new sources of renewable low-carbon energy in the CRB may be needed. Nuclear power plants can become one of the solutions, as indicated by a projected nuclear power plant in Payette County, Idaho.

This study identified candidate areas for nuclear power plants in the CRB using a multi-criteria decision analysis approach in GIS based on a set of criteria (including hydrology, population density, seismology, etc.). The analysis developed a method to estimate minimum flow in the Columbia Basin based on the historical records, and demonstrated that water availability was a crucial part of siting process. Although most major tributaries and the mainstem of the Columbia River have adequate discharge for siting both small and large nuclear reactors, application of other siting criteria eliminated all but two “candidate regions”. These regions are located within the middle part of the Columbia River, and upper–middle part of the Snake River, where the only nuclear power plants in the CRB are already currently located (Columbia River Generating Station) or projected (in Payette County, Idaho). Continued investigations of possible sites for nuclear reactors should be focused around these two regions. Limitations for nuclear power plants in the CRB include: (1) lack of water for cooling during the dry season, (2) frequent, severe flooding and (3) risk of earthquakes. There is some spatial uncertainty about available water during minimum flow periods in some portions of the CRB, where flow estimates differ in upstream versus downstream river segments. There is also temporal uncertainty due to differences in 7Q10 and 7Q50 low-flow statistics at several gauges; one location designated as suitable based on minimum flow over a decade did not meet the screening criterion for minimum flow over 50 years, which is the lifetime of a nuclear power plant. Overall low water availability limited nuclear power plant siting in a significant part of the Columbia Basin (63% for small reactors, and 74% for large reactors). In the future, minimum flow will vary due to climate change, which may alter precipitation and runoff patterns and modify the shapes of the identified candidate regions. In addition, although this research took into account flooding and seismicity, further studies are needed to examine potential flood and earthquake effects in detail.

Chapter 3. Effects of future climate change on streamflow in the CRB and implications for siting nuclear power plants

This study examined the potential future effects of climate change on the minimum streamflow requirements for siting nuclear power plants in the Columbia River Basin (CRB). Future climate change is expected to alter minimum water flow in the CRB potentially affecting site suitability for nuclear power plants, which require water for cooling. This study used projected future daily discharge data from several CMIP3 and CMIP5 climate models, downscaled using three different techniques under high (A1B/RCP8.5) and medium (B1/RCP4.5) emission scenarios, to determine how future variations in low-flow in the CRB might affect nuclear power plant siting. Three CMIP3 models and two CMIP5 models generally predict similar future streamflow, although the CMIP3 models overall predict a drier future. Despite predicted drying, modeled future streamflow did not significantly affect candidate areas for siting nuclear reactors identified in a previous analysis (Chapter 2 of this dissertation). Projected future streamflow eliminated small clusters of potential sites located in the western, northern, and central parts of the CRB (North Santiam basin, Yakima basin, NF Payette basin, etc.), and decreased the area of two main candidate areas by 2.9% (small reactors) and 13.9% (large reactors). Because of high initial streamflow, these two main candidate areas (the Middle Columbia River and the Snake River plain) appear to be relatively resilient to projected changes in low-flow, even if future climate is drier than predicted by the models.

3.1. Introduction

Climate change is expected to lead to a significant warming of the planet over the coming decades. Earth's average temperature has risen by 0.7°C over the past century, and is projected to rise another 1.8°C to 5.4°C in the future (Mote et al. 2014b). In the Pacific Northwest of the US (PNW) minimum nighttime temperature increased by 0.6-0.8 °C from 1901 to 2012, and the freeze-free season lengthened by an average of 9 days from 1950 to 2012 (Abatzoglou et al. 2014b). Long term warming has been modulated by interdecadal variability associated with the El Nino-Southern Oscillation and the Pacific-North American pattern, with relatively cool periods from 1910 to 1925 and 1945 to 1960 and relatively warm periods around 1940 and since the mid-1980s. Warming trends were found in every season and time period except for spring of

1980 to 2012. Anthropogenic forcing is a significant predictor of, and the leading contributor to, long-term warming; solar and volcanic forcing were nonsignificant predictors (Abatzoglou et al. 2014b).

Therefore, increasing global mean surface temperature is an indicator of climate change, and humans are largely responsible for it, although natural variability does also play an important role. Increase in temperature will be accompanied by changes in other aspects of the climate system, such as atmospheric circulation and precipitation. Resulting changes in hydrological fluxes (streamflow, evapotranspiration) and storages (snow water equivalent, soil moisture) are likely to change the flow regime of many rivers around the world (BPA 2014).

Hydrologic response to climate change will depend upon the dominant form of precipitation in a particular watershed, as well as other local characteristics including elevation, aspect, geology, vegetation, and changing land use. The Columbia River Basin (CRB) includes three main types of hydrologic regimes: snowmelt dominant, transient, and rain dominant. Climate change is likely to change the existing hydrologic regime patterns in terms of streamflow levels and timing, and also to increase the frequency of extreme hydrologic events – floods and droughts (Chang and Jung 2010), because increased heating leads to greater evaporation and thus surface drying, but at the same time air moisture-holding capacity increases exponentially with air temperature, producing more intense precipitation events (Trenberth 2011). Annual streamflow in the PNW has declined in the past 60 years, and the timing of snowmelt-dominated streamflow has advanced (Abatzoglou et al. 2014a). Since 1950, area-averaged snowpack on April 1 in the Cascade Mountains decreased by about 20%, spring snowmelt occurred 0 to 30 days earlier depending on location, late winter/early spring streamflow increased by as much as 20% relative to annual flow, and summer flow decreased 0% to 15% relative to annual flow (Mote et al. 2014b).

Climate change will continue and is likely to accelerate, leading to more severe changes in hydrology. In recent years it has become increasingly important to take into account possible future variations of streamflow in the light of climate change when selecting sites for energy facilities. Several studies have explored how future climate change will influence streamflow in the CRB (Mantua et al. 2009, Bürger et al. 2011, Tohver et al. 2014, Ficklin et al. 2015), and one study examined how future climate change will influence hydropower production (Hamlet et al.

2010a). However, to the best of our knowledge, no studies have examined how future streamflow will affect water availability for cooling, which influences site selection for nuclear power plants. Therefore, this chapter examines how projected climate change effects on hydrology influence nuclear power plant siting based on the water availability criterion. We use projected future streamflow in the Columbia Basin based on existing climate models to predict future changes in low-flow and how it will affect water availability for siting nuclear reactors of different capacity.

3.2. Background

3.2.1. Previous studies of hydrologic response to climate change in the CRB

Many studies have estimated future streamflow, and in particular hydrologic extremes (including low-flow) for part or all of the CRB. The majority of these studies use global climate models based on phase 3 of the Coupled Model Intercomparison Project (CMIP3), and significantly fewer use CMIP5, because this is a more recent project.

In an evaluation of the sensitivity of freshwater habitat of Pacific salmon to climate change in Washington, Mantua et al. (2009) found that basins strongly influenced by transient runoff are most sensitive to climate change, and they predicted widespread reductions in summer low flows for rain dominant and transient runoff river basins, with an increase in the duration of the summer low flow period in all watershed types.

Bürger et al. (2011) estimated future streamflow, including extremes (floods and low-flows) for the 2050s in the Columbia River headwaters (Canada), based on four regional climate models of the North American Regional Climate Change Assessment Program (NARCCAP), and a fully distributed, physically based Water Balance Simulation Model (WaSim) as a hydrological model. The authors employed a two-step downscaling (dynamical followed by statistical), and verified the results against observed streamflow. The authors predict a general warming of about 2°C in the future and slightly drier conditions, especially in late summer. All models projected a one-month shift of the seasonal hydrograph, with maximum flow occurring in June instead of July. Annual peak flow is not projected to increase, and August low flow is projected to decrease in all four models.

Tohver et al. (2014) examined the nature of changing hydrologic extremes (floods and low flows) under natural conditions for approximately 300 river locations in the Pacific Northwest based on several global climate models (from CMIP3), statistically downscaled under two emission scenarios (A1B and B1), and a physically based hydrologic model (VIC model). The authors project decreases in summer low flows for most basins in the PNW with a few exceptions in the coldest sites such as the headwaters of the CRB. Decreases in low flows are driven by loss of snowpack, drier summers, and increasing evapotranspiration in the simulations. Low-flow values are projected to decrease most notably in rain-dominant and transient basins located west of the Cascades. Low flow statistics in snow-dominant basins were relatively insensitive to projected increases in temperature.

Relatively few studies use CMIP5 climate models. Ayers et al. (2016) compared hydrologic projections for the Upper Colorado River Basin based on CMIP5 to projections based on CMIP3. The authors used 21 CMIP5 and 18 CMIP3 GCMs (collected into one CMIP5 ensemble and one CMIP3 ensemble, respectively), and the Soil and Water Assessment Tool (SWAT) model to simulate the impacts of end-of-century climate change. Hydrologic simulations from CMIP5 inputs indicated wetter conditions than simulations based on CMIP3 inputs, yet drier conditions than the historical climate. Even with projected increases in precipitation, snowmelt was projected to decrease dramatically throughout the Upper Colorado River Basin for both ensembles. Ficklin et al. (2015) also evaluate the differences between projections based on high emission scenarios of CMIP3 and CMIP5 and assess their effects on expected hydrologic impacts in several snowmelt-dominant regions, including CRB. In the CRB, CMIP3 and CMIP5 provided comparable hydrologic projections, because of similar underlying climate signals.

Few papers discuss the influence of future changes in streamflow on the energy sector (primarily, hydropower) in the CRB. Hamlet et al. (2010a) evaluate potential changes in hydropower production and changes in energy demand in the light of climate change in the PNW. They used composite temperature and precipitation scenarios, which are spatial (regional) and temporal (monthly) averages of climatic changes simulated by 20 GCMs for three future time periods (2010-2039, 2030-2059, and 2070-2099) and two emissions scenarios (A1B and B1). Annual hydropower production in the Columbia Basin is projected to decline slightly by the

2050s, with increases in the winter and declines in summer. Population growth is expected to increase both heating and cooling energy demand.

3.2.2. Main concepts

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. This organization reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change (IPCC 2016). One of the main IPCC activities is the preparation of comprehensive Assessment Reports (ARs) which are based on scientific, technical and socio-economic knowledge on climate change, its causes, potential impacts and response strategies. Since the IPCC was established, five reports have been released: AR4 in 2007 and AR5 in 2013-2014.

Climate models provide the basis for important components of IPCC reports. The IPCC's AR5 draws on phase 5 of the Coupled Model Intercomparison Project (CMIP5), while IPCC’s AR4 draws on the CMIP3. The Coupled Model Intercomparison Project (CMIP) is a suite of coordinated experiments with participation from a range of modeling groups from all over the world. For this project, each modeling group performs the exact same experiment on their model using the same external forcing (i.e., increasing greenhouse gas and aerosol emissions) to facilitate an inter-model comparison (PCMDI 2016).

CMIP3 is a global model analysis conducted for the fourth IPCC assessment (AR4). Issued in 2007, CMIP3 represented the largest and most comprehensive international global coupled climate model experiment and multi-model analysis effort ever attempted. It included participation of 17 modeling groups from 12 countries and compared 24 climate models (Meehl et al. 2007). CMIP5 is a new set of coordinated climate model experiments (issued in 2013-2014). CMIP5 was based on the results of the previous CMIPs (in particular, CMIP3), but also included new features, such as more comprehensive models and a broader set of experiments. In particular, the CMIP5 strategy included two types of climate change modeling experiments based on two time scales. Although long-term (century-scale) prediction experiments were conducted in previous CMIPs, near-term (decadal scale) experiments were new to CMIP5 (Taylor et al. 2012, PCMDI 2016). CMIP5 also added simulations of carbon cycle and atmospheric chemistry in some of the long-term models. More than 20 modeling groups performed CMIP5 simulations using more than 50 models (Taylor et al. 2012). CMIP5 included more complete descriptions of the experiment conditions, and an expanded list of model output (total data volume is 3 PB, 100 times more than in CMIP3).

3.2.2.1. Global Climate Models

Global climate models (GCMs) are mathematical models that represent physical processes in the atmosphere, ocean, cryosphere, and land surface (Trzaska and Schnarr 2014). GCMs represent many important features of the Earth's climate system based on atmospheric and ocean circulation. Many GCMs have been constructed by modeling groups all over the world (Taylor et al. 2012, Meehl et al. 2007).

GCM simulations are the most advanced methods to investigate the response of the global climate system to increasing greenhouse concentrations. Most GCMs provide information at coarse spatial scales exceeding 100 km (Mearns et al. 2014), and do not represent some of the physical processes at smaller scales, such as clouds. Spatial resolution of the CMIP3 climate models typically varied from 200 to 300 kilometers (at mid-latitudes). In CMIP5, models were of higher spatial resolution ranging from 100 to 200 kilometers (Walsh et al. 2014). However, natural systems subjected to climate impacts operate at finer spatial scales (Wilby et al. 2004). The problem of estimating climate changes on local/regional scales, based on results from large-scale GCMs, is referred to as "downscaling." For example, estimating impacts of climate change on hydrologic systems such as river basins requires information at finer spatial scales than GCMs provide.

3.2.2.2. Downscaling techniques

Downscaling techniques are used to transfer coarse scale GCM outputs to finer spatial resolutions (Trzaska and Schnarr 2014, Mearns et al. 2014). There are generally two classes of downscaling methods: statistical and dynamical downscaling (Trzaska and Schnarr 2014, Hamlet et al. 2010b), although some authors define simple downscaling methods (i.e. delta method) as a third class (Mearns et al. 2014).

In climate impact assessments, statistical downscaling is usually based on relating temperature (T) and precipitation (P) data at approximately 200 km resolution, simulated by a global climate model, to finer scale information, such as that needed to drive a hydrologic model or other application model. For example, daily data at 1/16th degree resolution are needed to drive the VIC hydrologic model. Statistical downscaling involves the establishment of empirical (quantitative) relationships between large-scale atmospheric predictions and local surface variables (Mearns et al. 2014, Trzaska and Schnarr 2014, Hamlet et al. 2010b, Wilby et al. 2004).

One of the key assumptions in using a statistical downscaling approach is the assumption of stationarity, i.e. it is assumed that although the climate is changing, defined statistical relationships do not change (Trzaska and Schnarr 2014, Wilby et al. 2004). Another assumption states that GCMs should accurately simulate climate variables observed in the past as well as their future evolution. Additionally, to apply statistical downscaling we should have high-quality observational data, because this approach uses observational (historical) data to correct for model bias (Mearns et al. 2014). Bias is any discrepancy of interest (temperature, precipitation, etc.) between a model output characteristic and the corresponding "true" (observed) value (Ehret et al. 2012). Since the output of climate models is affected by biases to a degree that excludes its direct use, bias correction (the correction of model output towards observations in a post-processing step) is often necessary (Ehret et al. 2012).

The Delta method is the simplest approach within the statistical downscaling group. In the Delta method, differences between simulated future and simulated historical periods are added to historical monthly or daily observations (Mearns et al. 2014, Hamlet et al. 2010b). The advantage of the Delta method is that it preserves observed patterns of temporal and spatial variability from the gridded observations, and comparison between future scenarios and observations can be easily interpreted (Hamlet et al. 2010b). The limitation of the Delta method is that potential changes in the variability or time series behavior of variables (e.g. T, P extremes) are not captured by the approach, and only changes in monthly means are captured (Hamlet et al. 2010b).

In the Bias Correction and Statistical Downscaling (BCSD) technique, monthly P and T output from GCMs is first bias-corrected (using quantile-mapping), then spatially disaggregated to higher resolution (Wood et al. 2002, Wood et al. 2004, Maurer and Hidalgo 2008). While the BCSD method traditionally has been used to downscale climate data at monthly scales, the method can be extended to operate on daily timescales (Abatzoglou and Brown 2012). To get daily values, historical months are selected randomly, and each day in the selected month is rescaled identically (using a multiplicative factor for P and an additive factor for T) to match the projected monthly total P and average T (Maurer and Hidalgo 2008). For BCSD the stationarity assumption is usually used in the context of saying that the large-scale P and T patterns and fine-scale P and T patterns will be the same as in the past.

The Hybrid Delta (HD) approach, created by Climate Impacts Group, combines the strengths of the Delta and BCSD approaches (Hamlet et al. 2010b). In the HD approach, after output from GCMs is bias corrected and spatially disaggregated to higher resolution, the historical record is remapped to interpolated GCM data, and monthly data is disaggregated to a daily time step (Tohver et al. 2014, Hamlet et al. 2010b). The method preserves the time series behavior and spatial correlations from the gridded T and P observations (a key advantage of the delta method), but transforms the entire probability distribution of the observations at monthly time scales based on the bias corrected GCM simulations (a key advantage of the BCSD method) (Tohver et al. 2014, Hamlet et al. 2010b).

Multivariate Adaptive Constructed Analogs (MACA) is another more recent statistical method for downscaling GCMs (Integrated Scenarios 2016, Abatzoglou and Brown 2012). This method is considered to be slightly preferable in regions of complex terrain due to its use of a historical library of observed coarse-resolution and corresponding high-resolution climate anomaly patterns, and a multivariate approach (Abatzoglou and Brown 2012, Maurer and Hidalgo 2008). MACA is advantageous over other statistical downscaling methods because: 1) the analog approach overcomes the limitations of interpolation based methods and yields more accurate spatial patterns; 2) it uses daily output from GCMs (unlike BCSD, which uses monthly), and thus captures simulated changes in extreme events, and 3) it does not assume that future GCM distributions are stationary with respect to historical records, and 4) it can be used for more than just T and P (Integrated Scenarios 2016, Abatzoglou and Brown 2012). Among the limitation of MACA is its negligence of model biases and inability to address no-analog situations that may arise in a future climate (Abatzoglou and Brown 2012).

In the dynamical (or regional) downscaling, a high-resolution (typically 10–50 km) regional climate model (RCM) is nested into a GCM, which provides the forcing at the boundaries, to derive smaller-scale information (Mearns et al. 2014, Ehret et al. 2012, Hamlet et al. 2010b). It physically resolves processes that occur at scales smaller than the driving GCM (Abatzoglou and Brown 2012), thus is not constrained by the historical record and can simulate novel scenarios (Mearns et al. 2014, Trzaska and Schnarr 2014). Other advantages of dynamical downscaling include: 1) RCMs physically simulate many variables that are not statistically downscaled, 2) since RCMs are physically based, they can resolve some local scale processes not included in GCMs (rain shadows, convection, etc.), 3) RCMs can save output at fine temporal resolution (minute, hourly, daily). However, unlike statistical downscaling, it is computationally intensive, and archives are often limited to a few models, whereas statistical archives will have many models and realizations. Output from RCMs is biased both due to the GCM bias (input) and RCM bias. Therefore, RCM output often needs some form of bias correction before it can be used in applications (specifically hydrology applications sensitive to T/P bias).

3.2.2.3. Emission scenarios

Emission scenarios are used to describe how concentrations of greenhouse gases could evolve between 2000 and 2100, depending on various hypotheses (IPCC 2000). They represent a wide range of key future characteristics, such as demographic change, economic development, and technological change.

In CMIP3, four main scenarios are used – A1, A2, B1, B2. Each represents a distinct future with a specific combination of population growth and policies related to alternative energy systems and conventional fossil fuel sources. The A1 scenario in general assumes rapid economic growth, population that peaks at mid-century and then declines, and rapid introduction of new technologies. The A1 scenario is divided into 3 sub-scenarios based on energy technology: A1FI (fossil-fuel-intensive), A1T (non-fossil), and A1B (balanced between the two). The A2 scenario assumes continuously increasing population, self-reliance and preservation of local identities, regionally oriented economic development, and slower technological change than in other scenarios. The B1 scenario assumes population that peaks at mid-century and then declines, rapid changes in economic structures, introduction of clean technologies, and global solutions to economic, social, and environmental sustainability, including improved equity. The B1 scenario includes stabilization of greenhouse gas concentration by the end of the 21st century. The B2 scenario assumes continuously increasing population at a rate lower than A2, local solutions to economic, social, and environmental sustainability, intermediate levels of economic development, and less rapid and more diverse technological change than in B1 (IPCC 2000, Walsh et al. 2014, Hamlet et al. 2010b). The projected CO_2 concentrations for these emission scenarios are presented in Figure 3.1.

In CMIP5, a new approach to scenarios of projected greenhouse gas concentrations was adopted. CMIP5 simulations are driven by so called “representative concentration pathways” (RCPs), which are not based on emissions, but instead depict trajectories of increased radiative forcing resulting from changing concentrations of greenhouse gases (van Vuuren et al. 2011). RCPs do not assume any particular climate policy actions, unlike CMIP3 scenarios. For CMIP5, four RCPs are based on a range of projections of future population growth, technological development, and societal responses. For example, the radiative forcing in RCP8.5 increases throughout the twenty-first century before reaching a level of about 8.5 W/m^2 at the end of the century. In addition to this “high” scenario, there are two intermediate scenarios. RCP4.5 is analogous to the B1 scenario from AR4, and RCP6.0 is analogous to the A1B scenario from AR4. A "peak-and-decay" scenario, RCP2.6, assumes that radiative forcing reaches a maximum near the middle of the 21st century before decreasing to an eventual nominal level of 2.6 W/m^2 (Taylor et al. 2012, Walsh et al. 2014, van Vuuren et al. 2011).

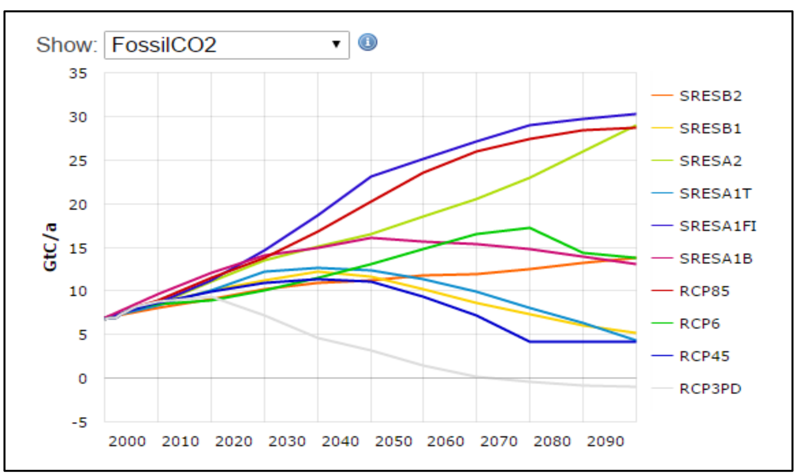


Figure 3.1. Historical and projected fossil CO_2 concentrations for different scenarios (Meinshausen et al. 2011).

3.2.2.4. Hydrologic models

The effect of climate change on future hydrology can be estimated using GCM outputs and hydrologic models. First, future climate change projections representing information at coarse scales over 100 km are obtained from a GCM. Then, these projections are downscaled from the global to the regional scale. Then the downscaled future climate is used as input to run a hydrologic model.

The variable infiltration capacity (VIC) hydrologic model (Liang et al. 1994, Liang et al. 1996) was used in Climate Impacts Group (CIG) and Integrated Scenarios of the Future Northwest Environment (IS) project reports used in this study. VIC is a large-scale, semi-distributed hydrological model. The VIC model has been used in numerous studies of the hydrologic effects of climate variability and change at regional and global scales (e.g., Elsner et al. 2010; Hamlet et al. 2010b). The VIC model explicitly considers the effects of vegetation, topography, and soils on the exchange of moisture and energy between land and atmosphere (Zhao et al. 2013). The key characteristics of the grid-based VIC are the representation of multiple vegetation types, multiple soil layers with variable infiltration, and non-linear base flow (Zhao et al. 2013, Elsner et al. 2010, Gao et al. 2009, Maurer 2007). Water and surface energy balances are computed within each grid cell, typically at resolutions ranging from a fraction of a degree to several degrees of latitude and longitude (Elsner et al. 2010, Maurer 2007). Water balance variables include evapotranspiration, runoff, baseflow, soil moisture, and snow water equivalent (Hamlet et al. 2010b). Potential evapotranspiration is calculated using a Penman Monteith approach (Hamlet et al. 2010b). Initially the model included two soil layers, but more recent versions have specified a thin top soil layer (5–15 cm), which significantly improved evapotranspiration estimates (Zhao et al. 2013, Liang et al. 1996).

VIC can be applied at multiple spatial scales and can be temporally discretized to simulate hourly, daily, monthly and yearly time scales (Hamlet et al. 2010b). Both CIG and IS implemented the VIC hydrologic model at the daily time step and a spatial resolution of 1/16th degree latitude by longitude, or approximately $30km^2$ per cell (Hamlet et al. 2010b, Mote et al. 2014a). The VIC model was driven by daily inputs of precipitation, maximum and minimum air temperature, and wind speed.

3.3. Methodology

This research is based on data obtained from the existing projects of the Climate Impacts Group (CIG) and Integrated Scenarios of the Future Northwest Environment (IS). CIG is an interdisciplinary research group studying the impacts of natural climate variability and global climate change within the University of Washington, USA (CIG 2016). The Integrated Scenarios (IS) project is an effort to understand the projections of climate change on the Northwest's resources, in particular hydrology. IS involves Oregon State University, University of Idaho, University of Washington, Conservation Biology Institute, Northwest Climate Science Center, Climate Impacts Research Consortium, and Regional Integrated Sciences and Assessments (Integrated Scenarios 2016). CIG data are based on the phase 3 of the Coupled Model Intercomparison Project (CMIP3), while the Integrated Scenarios project data are based on the phase 5 (CMIP5). In this research, we consider three climate models (CNRM-CM3, ECHAM5, and ECHO-G) and two scenarios (A1B and B1) used to create daily streamflow data in the CIG project, and two models (CNRM-CM5 and CCSM4) and two scenarios (RCP4.5 and RCP8.5) used to create daily streamflow data in the IS project.

3.3.1. Data sources from Climate Impacts Group and CMIP3

This study used CIG data based on the CMIP3 multi-model dataset. To calculate future streamflow for the rivers of the Columbia Basin, CIG used the VIC hydrologic model and 10 global climate models, downscaled into regional datasets under two emissions scenarios (A1B and B1). Global climate models were those whose 20th century simulations had the smallest bias in temperature and precipitation and that simulated the most realistic annual cycle in these parameters (Hamlet et al. 2010b). Climate models were downscaled using three methods: two statistical downscaling approaches described above, and a new technique, which is a hybrid between the two existing methods, exploiting the relative strengths of each. This study used two of the three approaches, BCSD and Hybrid Delta.

3.3.1.1. Calculation of 7Q10 values using daily data based on BCSD approach

This study calculated projected 7Q10 low-flow values for three 30-year periods using BCSD daily discharge data: 2010-2039, 2040-2069, and 2070-2099, following procedures described in Chapter 2. Briefly, for each USGS gauge, the annual 7-day minimum was calculated for every year of the record, and the 7Q10 is defined as the value that is exceeded in 90% of years, i.e., the lowest 10% quantile. A Python script (Appendix 1) was created to automate calculation tasks for all gauges of interest in the basin. The climatic year (October 1 to September 30) was used to define the starting and ending dates of annual periods for computation of the 7-day minimum flows.

A subset of the 622 gauges in the CRB was examined for this study. These gauges were located within or near candidate areas defined in Chapter 2, and their daily projected discharge data were included in the CIG report. Future projected 7Q10 low-flow was calculated for a total of 55 gauges (Figure 3.2, Appendix 3).

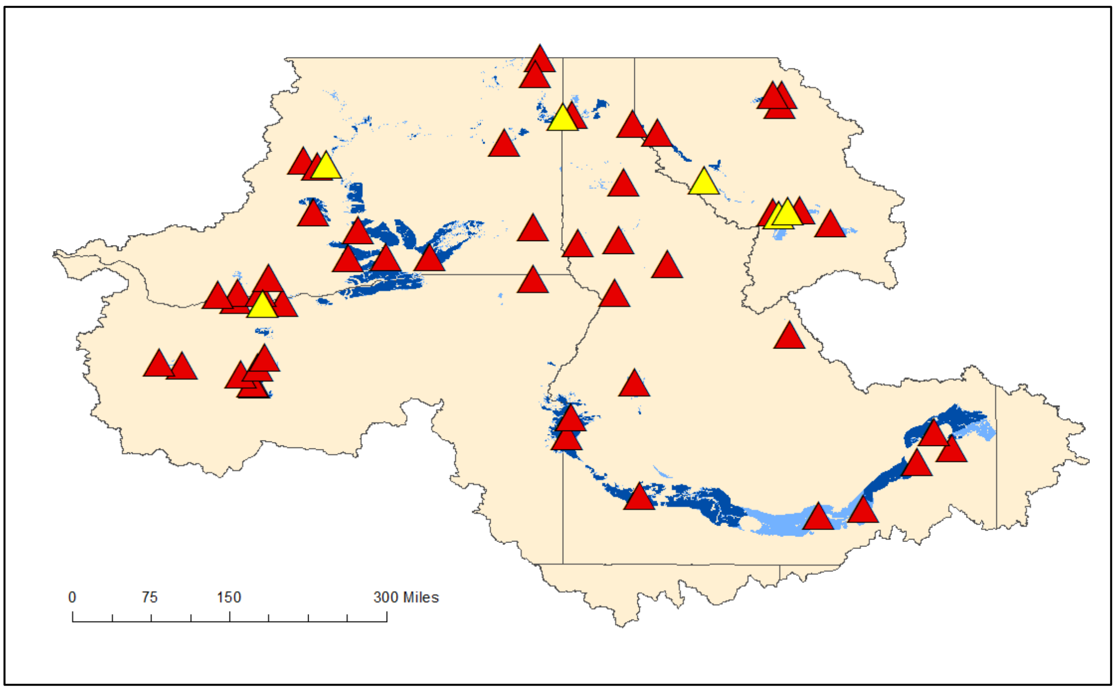


Figure 3.2. Final set of gauges (n=55) for which projected 7Q10 low-flow was calculated. Red and yellow triangles show gauges having data in CIG report and red triangles – in IS report.

This study calculated 7Q10 values for three future time periods based on VIC model runs for two scenarios (A1B and B1) for each of three GCM models (CNRM-CM3, ECHAM5, and ECHO-G). These models had the best combined rankings for 20th century bias and North Pacific variability (Hamlet et al. 2010b). This produced results for three time periods, three models, and two emission scenarios, resulting in 18 sets of 7Q10 values based on the BCSD downscaled GCM data.

3.3.1.2. 7Q10 values based on the Hybrid Delta approach

In this study we used 7Q10 values provided by CIG (Hamlet et al. 2010b) based on the daily data from the HD approach, for the three 30-year periods - 2010-2039, 2030-2059, 2070-2099, for total of 55 gauges in the CRB (Figure 3.2). Projected 7Q10 values calculated by CIG were entered in the attribute table in ArcGIS, mapped, and compared with the calculated 7Q10 values based on the daily discharge data from BCSD approach (see section 3.1.1).

3.3.2. Data sources from Integrated Scenarios and CMIP5

Future streamflow data also were obtained from the Integrated Scenarios project based on the CMIP5 multi-model dataset. This project used VIC hydrologic model to obtain projected daily discharge data. The VIC model was applied to the output from several GCMs, downscaled into regional datasets under two emissions scenarios (RCP 8.5 and RCP 4.5). The project used global climate models that provided both monthly and daily climate data for temperature, precipitation, etc. (Integrated Scenarios 2016). Model output was downscaled using the MACA statistical downscaling method. This study used daily discharge data for two models (CCSM4 and CNRM-CM5) and the RCP 8.5 and RCP 4.5 emission scenarios. These models rank among the top five GCMs based on how well they simulate historical climate of the Pacific Northwest (Integrated Scenarios 2016), and among those for which daily discharge data are provided. Climate projections from a random set of models yield results similar to those from the best models (Integrated Scenarios 2016).

3.3.2.1. Calculation of 7Q10 values using daily data based on MACA approach

This study calculated projected 7Q10 low-flow values for three 30-year periods used above: 2010-2039, 2040-2069, and 2070-2099, based on daily streamflow data from the IS project. Calculations followed methods used for BCSD, see section 3.1.1 above. We used the list of gauges from the CIG's report, for which we calculated 7Q10 values based on CMIP3. There was no information for several gauges from that list, although, as the analysis revealed, these gauges can be ignored as they are located near (downstream) the gauges with existing data (Figure 3.2).

3.3.3. Summary of calculations

In summary, this study used three different datasets to determine future 7Q10 low-flow values for a subset of gauges near candidate sites identified in Chapter 2 (Table 3.1).

Table 3.1. Major characteristics of datasets for projected 7Q10 statistics for future streamflow used in this study.

	(1)	(2)	(3)
Daily projected streamflow provided by	**CIG**		**IS**
Model comparison experiment	CMIP3		CMIP5
GCM models used in this study	CNRM-CM3, ECHAM5, and ECHO-G		CNRM-CM5 and CCSM4
Scenarios	A1B and B1		RCP8.5 and RCP4.5
Hydrologic model	VIC		VIC
Downscaling approach	BCSD	HD	MACA
7Q10 calculated by	**Author**	**CIG**	**Author**
For time periods:			
– early 21st century	2010-2039	2010-2039	2010-2039
– mid 21st century	2040-2069	2030-2059	2040-2069
– late 21st century	2070-2099	2070-2099	2070-2099
Final number of obtained datasets	18	18	12

3.3.4. Changes in streamflow requirements

According to the U.S. Census Bureau, by 2050 the US population will increase to 400 million people. The population of Oregon, Washington, and Idaho is projected to increase by 32 to 161 percent by 2050, depending on which projection series (low/medium/high) is chosen (Houston et al. 2003).

Freshwater withdrawals for public and domestic uses and industrial and commercial uses are projected to increase by up to 70 percent by 2050 (Houston et al. 2003). To account for expected increases in human consumption of water, this study reduced the allowable water withdrawals for nuclear power plant cooling as a proportion of streamflow. Candidate areas for nuclear reactors were selected (in Chapter 2) based on the condition that the power plant should not withdraw more than 10% of the available streamflow at a given location. To approximate the increased demand on water supplies in the future, the new condition specified that a power plant should not withdraw more than 5% of the available flow as of 2050 and beyond, consistent with a rule adopted by Mays et al. (2012) for an analysis of thermoelectric plants.

The water requirement for cooling the turbine of small nuclear reactor is 5,000 gallons per minute (gpm). If water withdrawals are limited to 10% of streamflow, a stream must have a discharge of 50,000 gpm (112 cfs). If water withdrawals are limited to 5% of streamflow, a stream must have a discharge of 100,000 gpm (223 cfs). For large nuclear reactors, which require 20,000 gpm for cooling, the minimum discharge required is 200,000 gpm (445 cfs) using a 10% rule, and 400,000 gpm (891 cfs) using a 5% rule. The 5% assumption was applied only to the predictions for the 2050s and beyond, and the 10% assumption was used for predictions for the 2010-2039 period. Thus, for selection of gauges with 7Q10 values lower than needed for siting nuclear reactors, we considered the following streamflow thresholds:

- for 2020s period: 50,000 gpm (112 cfs) for small reactors and 200,000 gpm (445 cfs) for large reactors;
- for 2050s period: 100,000 gpm (223 cfs) for small reactors and 400,000 gpm (891 cfs) for large reactors;
- for 2080s period: 100,000 gpm (223 cfs) for small reactors and 400,000 gpm (891 cfs) for large reactors.

3.3.5. Evaluation of projected 7Q10 values for the candidate areas

The 7Q10 values calculated from projected 21st century streamflow at the gauges, which were identified as suitable for the siting of nuclear reactors based on the analysis in Chapter 2, were evaluated to see if they will still meet the criterion for cooling water availability in the future. The gauges which were eliminated as a result of projected changes in streamflow were depicted on maps of the CRB for each of the three 21st century periods (centered on the 2020s, 2050s, and 2080s).

The resulting changes in site availability were applied to the siting procedure following methods described in Chapter 2, and the resulting changes in candidate areas for nuclear reactors were depicted in maps of the CRB. The used projections were averages for the analyzed models within CMIP3 or CMIP5 projects.

Five climate models used in this study were compared using a subsample of gauges. The results for different future periods, downscaling approaches, and emission scenarios were presented on scatterplots. Additionally, spatial patterns of CMIP3 and CMIP5 models agreement were depicted on maps.

To examine the overall spatial pattern of projected streamflow changes, this study examined how streamflow predictions based on the averages of CMIP3 and CMIP5 models changed between the historical 7Q10 period (2003-2013) and future periods (centered on the 2020s, 2050s, and 2080s). Ratios of 7Q10 values were calculated for each gauge for each projected future period, relative to the historical period. These values were depicted on maps of the CRB. The historical data were 7Q10 values for 2003-2013, that were used for estimating water availability for siting nuclear reactors in the Chapter 2 of this dissertation.

To show how projected streamflow declines interacted with water availability thresholds for nuclear power plants, the 7Q10 values for selected gauges were plotted as a function of time.

3.4. Results

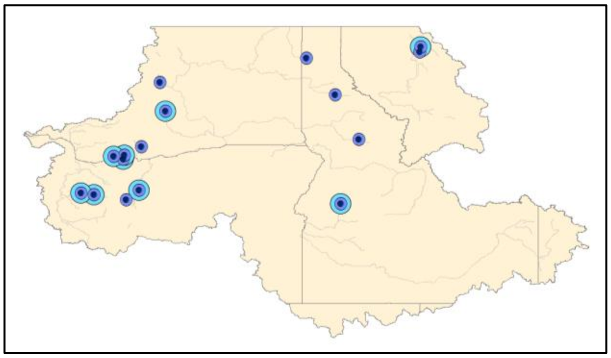
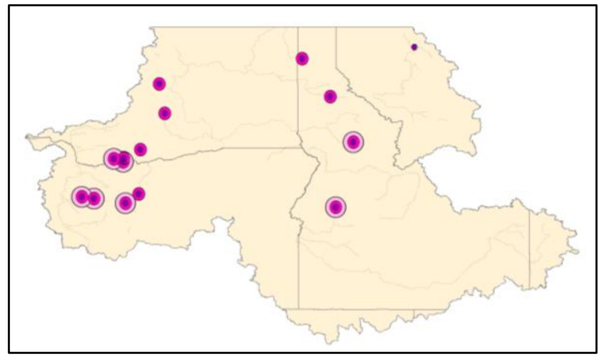
3.4.1. Effect of 21st century projected streamflow on gauges near small reactor sites

Climate change is projected to decrease low-flow below the threshold for siting small nuclear reactors in several parts of the CRB, which were identified as candidate areas in Chapter 2, based on CMIP3 GCMs (CNRM_CM3, ECHAM5, ECHO_G) (Figures 3.3 and 3.4) and based on CMIP5 GCMs (CCSM4 and CNRM-CM5) (Figure 3.5).

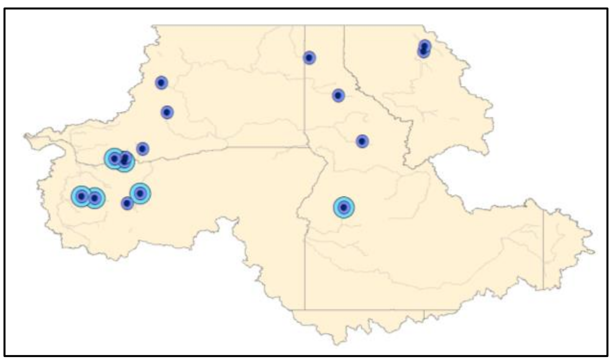
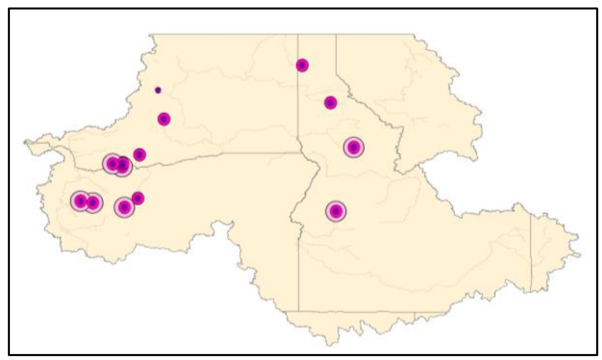
A1B scenario

BCSD approach **HD approach**

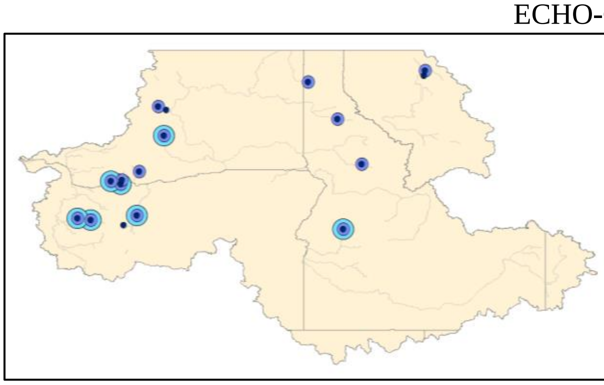
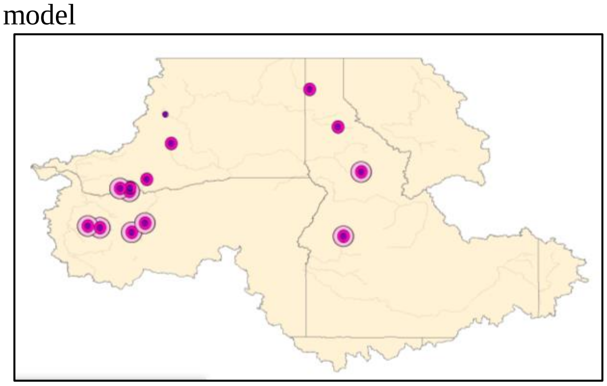
CNRM-CM3 model

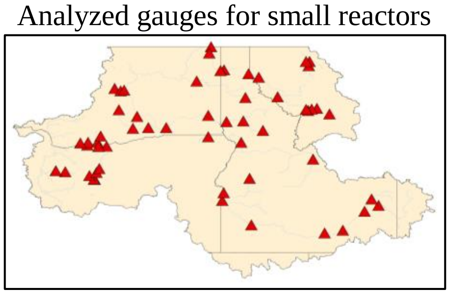
ECHAM5 model

ECHO-G model

Analyzed gauges for small reactors



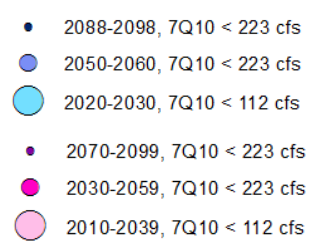
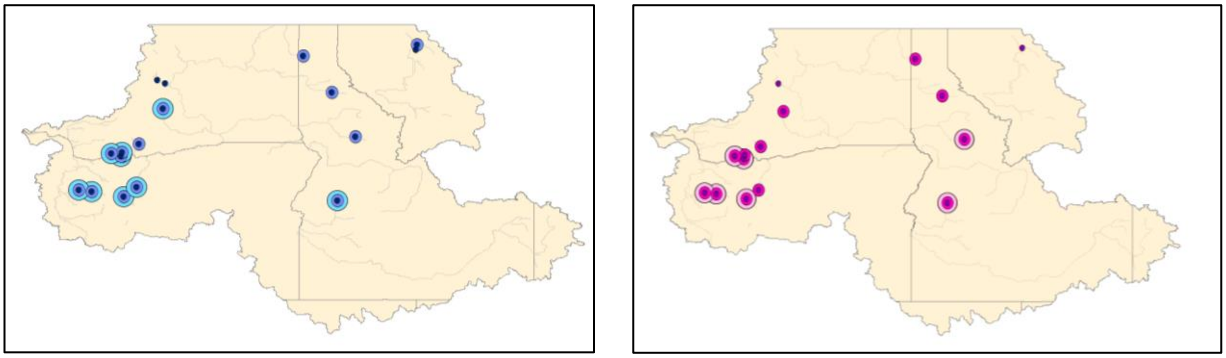


Figure 3.3. Results for A1B scenario, CNRM_CM3, ECHAM5, ECHO_G models, small reactors.

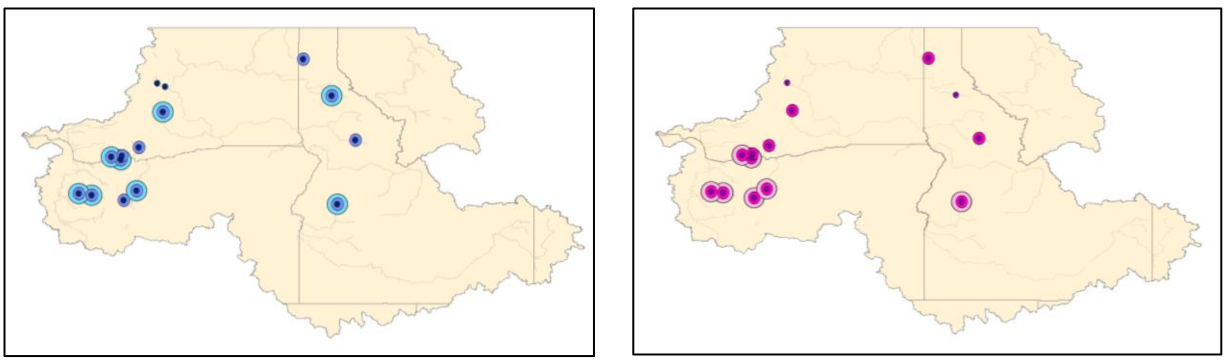
B1 scenario

BCSD approach **HD approach**

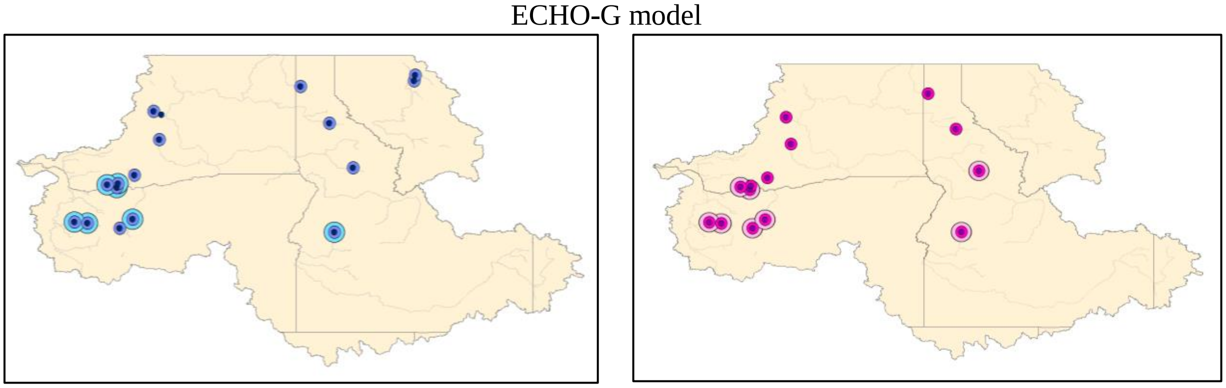
CNRM-CM3 model



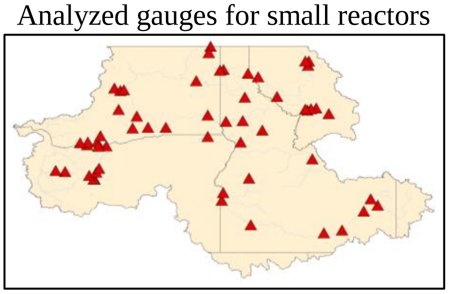
ECHAM5 model



ECHO-G model



Analyzed gauges for small reactors



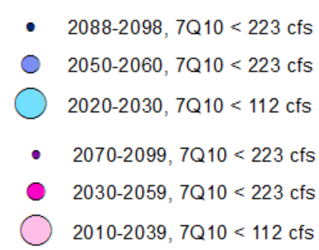


Figure 3.4. Results for B1 scenario, CNRM_CM3, ECHAM5, ECHO_G models, small reactors.

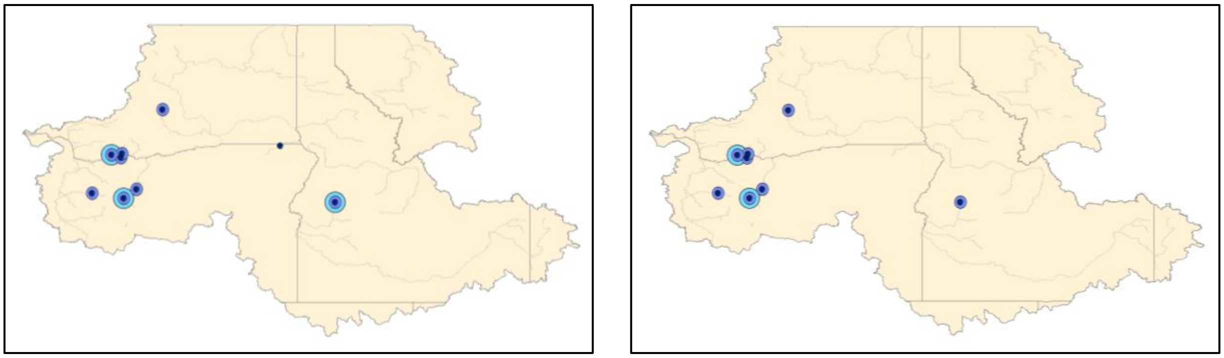
Based on CMIP3 GCMs (CNRM_CM3, ECHAM5, ECHO_G), climate change is projected to decrease low-flow below the threshold for siting small nuclear reactors in several parts of the CRB, which were identified as potential sites in Chapter 2 (Figures 3.3 and 3.4). These areas are on the west side of the Columbia Basin (western Oregon and Washington): the North Santiam River in the Willamette Basin, some tributaries of the Deschutes River, some tributaries in the downstream section of the Columbia River (Wind River, Klickitat River, Hood River, and White Salmon River), upstream sections of the Wenatchee and Yakima Rivers. All three models, both scenarios, and both datasets (BCSD and HD) show similar patterns (Figures 3.3 and 3.4).

Decreases in low-flow below the threshold for siting a small nuclear reactor are projected to occur throughout most of the 21st century in western Oregon and Washington and in south central Idaho. Gauges on the North Santiam River in western Oregon, and Wind River in the Columbia Gorge are projected to fall below the threshold in all three simulated periods in the 21st century. Gauges in the northern part of Idaho (upper sections of the Priest River, St. Joe River, and Lochsa River, and upper reaches of the NF Payette River in central Idaho, also fall below the threshold for two or more periods. A tributary of the Flathead River in Montana also falls below the threshold, particularly for the BCSD downscaling approach.

Overall, future streamflow estimated based on BCSD downscaling of CMIP3 models are just slightly “drier” (more gauges/periods with low 7Q10) than those based on HD downscaling for all three models and both emission scenarios (Figures 3.3 and 3.4). In particular, in northwest Montana, streamflow is projected to fall below the threshold based on the BCSD dataset in five of six model/scenario combinations (except ECHAM5/B1), but for only one time period (the 2080s) and two model/scenario combinations (CNRM-CM3/A1B and B1) in HD dataset (Figures 3.3 and 3.4).

CNRM_CM5 model

RCP8.5 scenario | RCP4.5 scenario



CCSM4 model

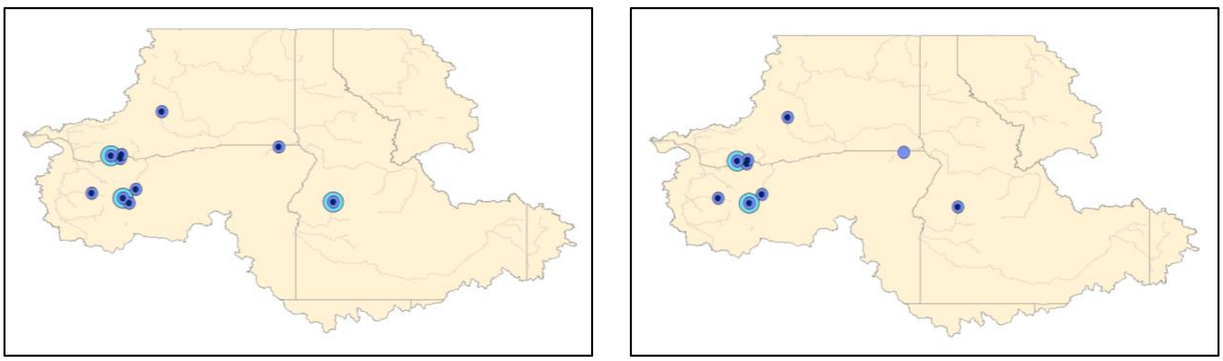


Figure 3.5. Results for RCP 4.5 and RCP 8.5 scenarios, CNRM_CM5 and CCSM4 models, small reactors

Based on CMIP5 GCMs, climate change is projected to decrease low-flow below the threshold for siting small nuclear reactors in several parts of the CRB (Figure 3.5), but fewer than indicated by the CMIP3 models. Most of the gauges with reduced low-flow are located in the western part of the Columbia Basin. The 7Q10 values fell below the threshold required for a small nuclear reactor for all three future time periods at only two sites: Wind River and the Metolius River (Deschutes tributary), both in the western part of the Columbia Basin. On the North Santiam River, only one gauge fell below the 7Q10 threshold based on the CMIP5 model, compared to two in the CMIP3 models, and only starting 2050s, compared to the 2020s in the CMIP3 models, for both scenarios. In Idaho, only one gauge fell below the 7Q10 threshold for siting a small nuclear reactor in the 21st century, compared with 4 in the CMIP3 models, and these declines occurred later in the century. This gauge is located in the upstream NF Payette

River in central Idaho. One gauge fell below the threshold based on the CMIP5 models but not in the CMIP3 models: this is the Grande Ronde River on the Oregon-Washington border.

3.4.2. Effect of 21st century projected streamflow on gauges near large reactor sites

Climate change is projected to decrease low-flow below the threshold for siting large nuclear reactors in several parts of the CRB, which were identified as potential sites in Chapter 2, based on CMIP3 GCMs (CNRM_CM3, ECHAM5, ECHO_G) (Figures 3.6 and 3.7) and based on CMIP5 GCMs (CCSM4 and CNRM-CM5) (Figure 3.8). Fewer gauges were analyzed for climate change effects on large vs. small nuclear reactors, because fewer gauges were identified as suitable for locating large reactors in Chapter 2.

A1B scenario

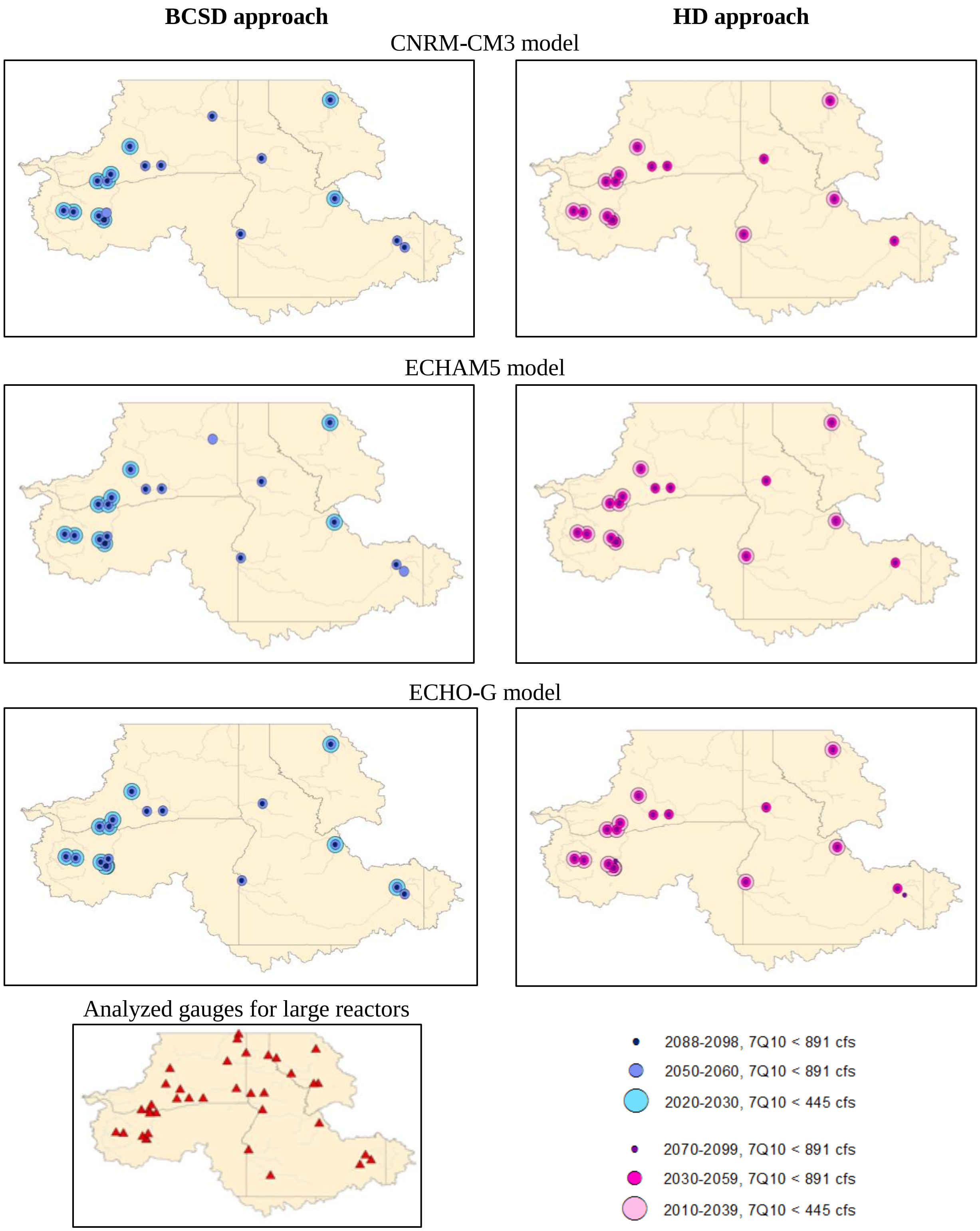
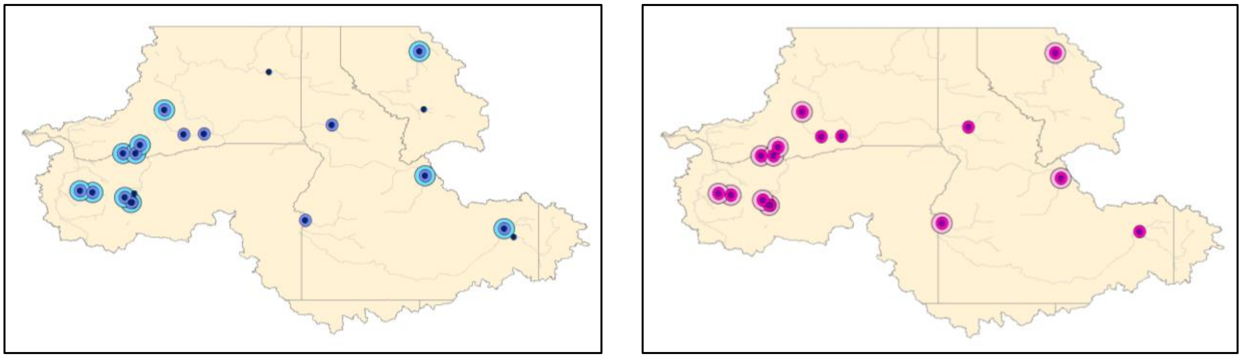


Figure 3.6. Results for A1B scenario, CNRM_CM3, ECHAM5, ECHO_G models, large reactors

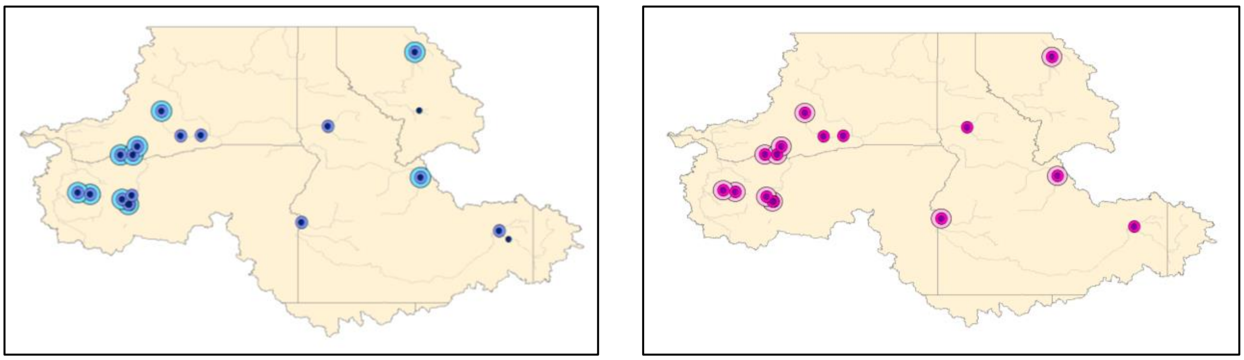
B1 scenario

BCSD approach **HD approach**

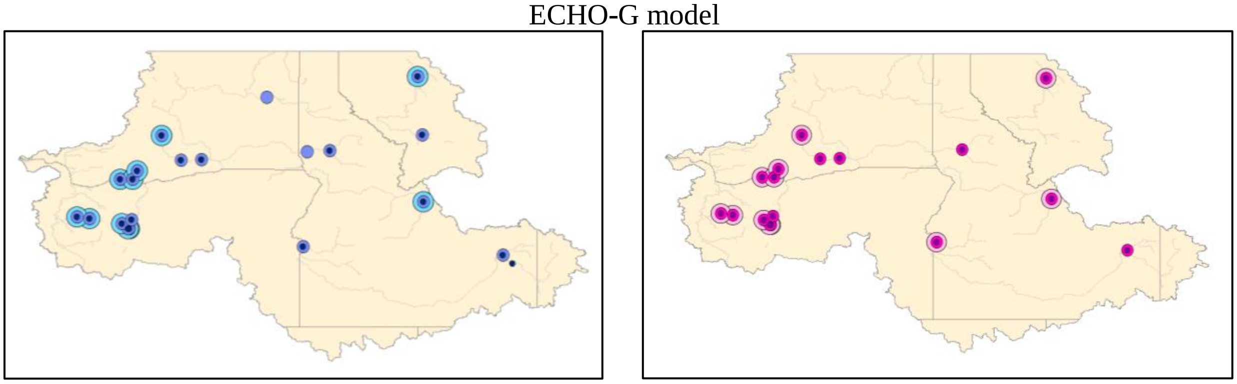
CNRM-CM3 model



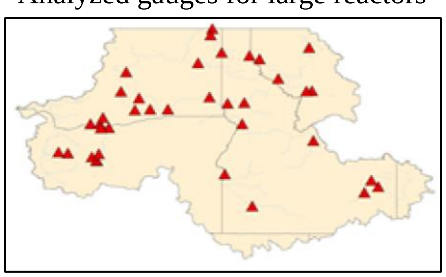
ECHAM5 model



ECHO-G model



Analyzed gauges for large reactors



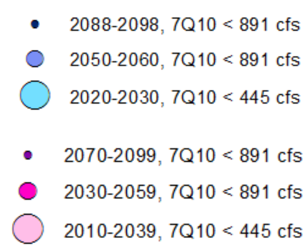


Figure 3.7. Results for B1 scenario, CNRM_CM3, ECHAM5, ECHO_G models, large reactors

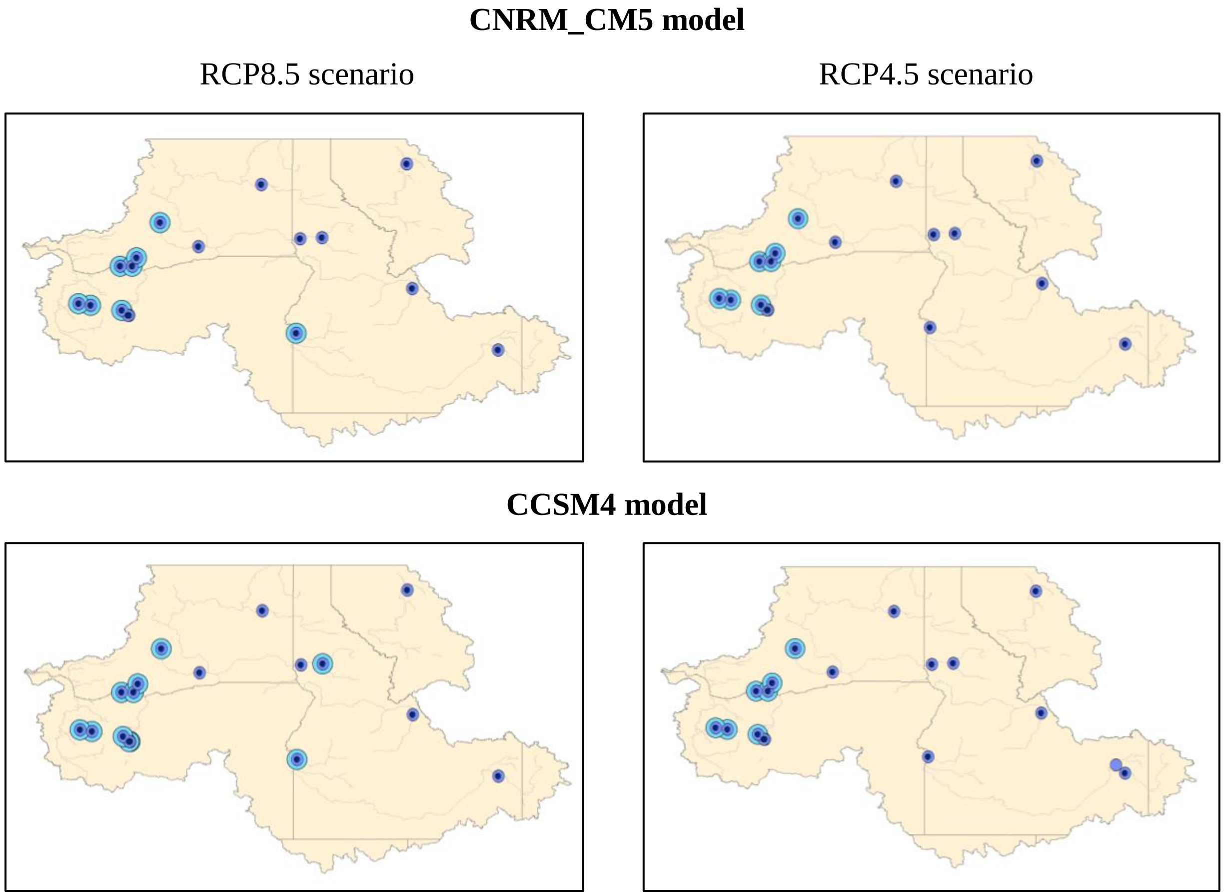


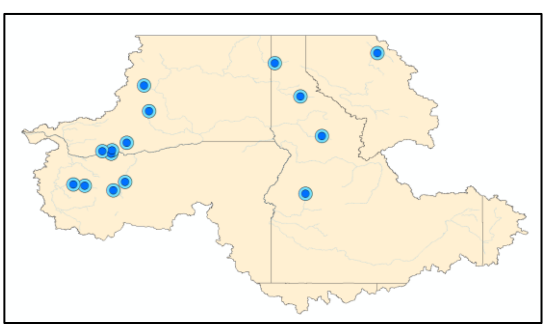
Figure 3.8. Results for RCP 4.5 and RCP 8.5 scenarios, CNRM_CM5 and CCSM4 models, large reactors

Gauges where streamflow is projected to fall below the threshold 7Q10 for siting large reactors are distributed more evenly over the Columbia Basin than in the case of small reactors. Nevertheless, gauges where large reactor siting is precluded based on projected 21st century streamflow are somewhat concentrated in the western CRB. These are the same gauges identified as falling below the threshold for small reactors: on the North Santiam, Deschutes, and Yakima Rivers and nearby tributaries of the Columbia River. Thus, several approaches and models indicate that the Yakima River will not have adequate water for cooling nuclear power plant condensers during the 21st century.

In the reminder of the CRB, 21st-century streamflow (7Q10) is projected to fall below the threshold 7Q10 for siting large reactors at sites downstream of those sites, where 21st century streamflow is projected to fall below the threshold for siting small reactors. These include the Clearwater River in the northern Idaho, whose tributary, the Lochsa River, fell below the threshold for siting small reactors, and the Spokane River, whose tributary, the St. Joe River, fell below the threshold for siting small reactors. In addition, 21st-century streamflow (7Q10) is projected to fall below the threshold 7Q10 for siting large reactors on the lower Payette River in southwestern Idaho, on the Salmon River in the central-eastern Idaho, and on the upper Snake River and its tributary, the Henry's Fork River in southeastern Idaho (Figures 3.6, 3.7, and 3.8).

3.4.3. Effect of 21st century projected streamflow on small reactor sites

When the projected 21st century streamflow values are applied to the process of siting nuclear power plants used in Chapter 2, they have the effect of eliminating portions of the candidate areas for locating small nuclear reactors (Figures 3.10 and 3.11). Candidate areas were excluded that lie within or near (and influenced by) the streams with gauges where 7Q10 values were projected to fall below the threshold for locating small nuclear reactors in at least one of the three 21st century time periods. Modified candidate areas based on projections from the CMIP3 models (Figure 3.10) and CMIP5 models (Figure 3.11) are shown. The used projections are averages for the analyzed models within CMIP3 or CMIP5 projects, respectively (Figure 3.9). Projections based on CMIP5 models differ slightly between the RCP4.5 and RCP8.5 scenarios. A small area surrounding part of the Grande Ronde River near the Oregon-Washington border (in green, Figure 3.11) is excluded based on RCP8.5 but not for RCP4.5. Because of broad agreement among all models, the choice of model does not significantly influence the areas that are excluded for siting small nuclear power plants based on projected 21st century streamflow.

(a)


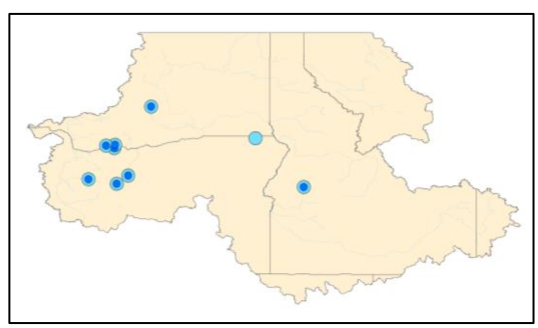
(b)


Figure 3.9. Models averages for CMIP3 project (a) and CMIP5 project (b). Big light blue circles represent A1B/RCP8.5 scenarios; small dark blue circles represent B1/RCP4.5 scenarios. The maps show gauges with low 7Q10 values in at least one of the three projected time periods. The map, therefore, presents the “worse” case, reflecting maximum amount of the areas (gauges), which showed low 7Q10 values.

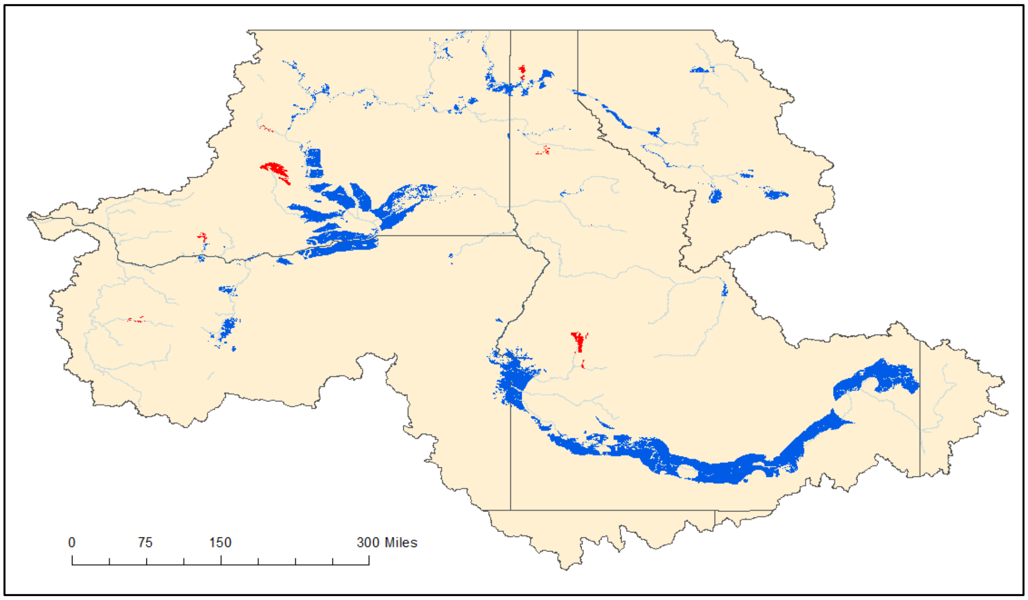


Figure 3.10. Candidate areas based on projected 7Q10 low-flow for small reactors for CMIP3 models (in blue). Areas which were considered suitable based on 20-th century streamflow, but where 21st century streamflow is projected to fall below the threshold for siting small nuclear reactors, are shown in red.

Only a small portion (maximum 3.26% depending on the models ensemble and scenario) of the candidate areas is excluded based on projected 21st century streamflow. These include areas surrounding the upper Yakima River in the Middle Columbia River candidate region, and areas near the upper NF Payette River in the Snake River plain candidate region. However, climate change projections for 21st century streamflow eliminate candidate sites for small nuclear reactor siting in western Oregon (along North Santiam River in the Willamette Basin), in southwest Washington, in central-western Washington (Wenatchee River), and in northern Idaho (Priest River and St Joe River). Despite elimination of small candidate areas, the two main candidate regions identified as suitable for siting small nuclear reactors in Chapter 2 are not affected by climate change effects on projected 21st century streamflow.

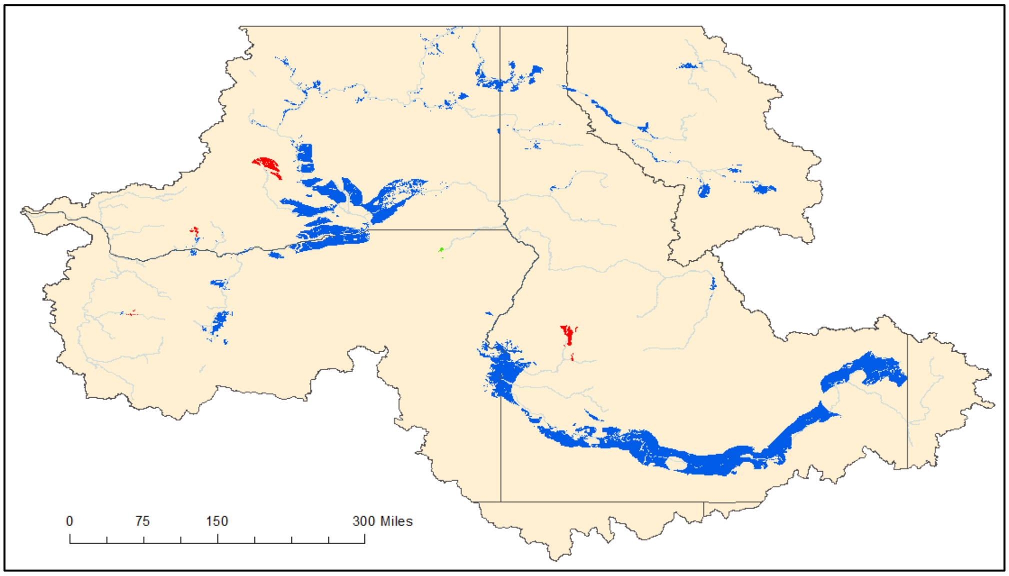


Figure 3.11. Candidate areas based on projected 7Q10 low-flow for small reactors for CMIP5 models (in blue or blue/green). In red: areas removed for both scenarios, in green: area removed for RCP8.5 and existing for RCP4.5 (upstream Grande Ronde River).

3.4.4. Effect of 21st century projected streamflow on large reactor sites

Application of the projected 21st century streamflow values to the process of siting nuclear power plants used in Chapter 2 has the effect of eliminating several portions of the candidate areas for locating large nuclear reactors (Figures 3.13 and 3.14). Projected 21st century streamflow based on the CMIP3 models (Figure 3.13) eliminates more candidate areas for siting large reactors compared to the CMIP5 models (Figure 3.14).

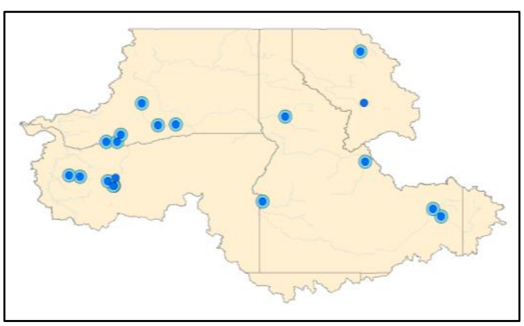
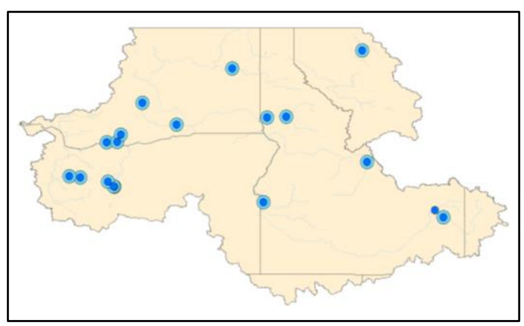
(a)  (b) 

Figure 3.12. Models averages for CMIP3 project (a) and CMIP5 project (b). Big light blue circles represent A1B/RCP8.5 scenarios; small dark blue circles represent B1/RCP4.5 scenarios. The maps show gauges with low 7Q10 values in at least one of the three projected time periods. The map, therefore, presents the “worse” case, reflecting maximum amount of the areas (gauges), which showed low 7Q10 values.

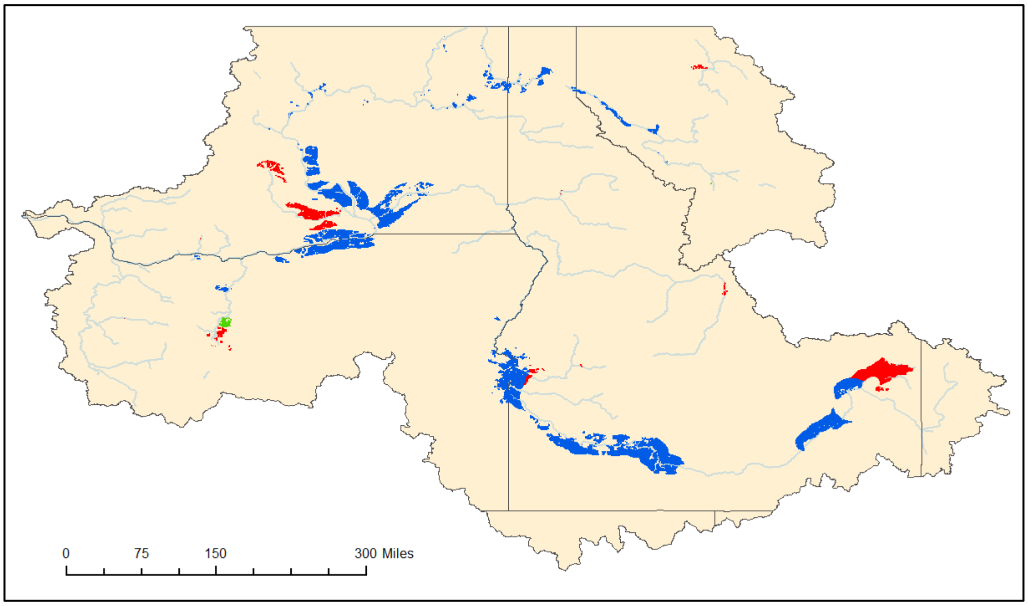


Figure 3.13. Candidate areas based on projected 7Q10 low-flow for large reactors for CMIP3 models (in blue or blue/green). In red: areas removed for both scenarios, in green: areas removed for B1 scenario and existing for A1B scenario (part of Deschutes River).

Projected 21st century streamflow eliminates larger portions of candidate areas for large reactors than for small reactors (up to 18.5% depending on the models ensemble and scenario). Based on the CMIP3 models, excluded areas include the entire Yakima River in the Middle Columbia River candidate region, the Henrys Fork River in the Snake River plain candidate region, and areas near the lower Payette River (Figure 3.13). Projected 21st century streamflow based on the CMIP3 models also eliminates candidate areas for large reactors surrounding the central Deschutes (based on B1 scenario only), Flathead, and central Salmon Rivers (Figure 3.13). Projected 21st century streamflow based on the CMIP5 models eliminates smaller areas compared to the CMIP3 models (Figures 3.13 and 3.14). A smaller portion of the Yakima River is excluded; the Henrys Fork River in the Snake River plain candidate region is excluded only based on RCP4.5 scenario in CMIP5 compared to CMIP3 models. Two main candidate regions – the Middle Columbia River and the Snake River plain – remain largely intact, despite projected reductions in 21st century streamflow.

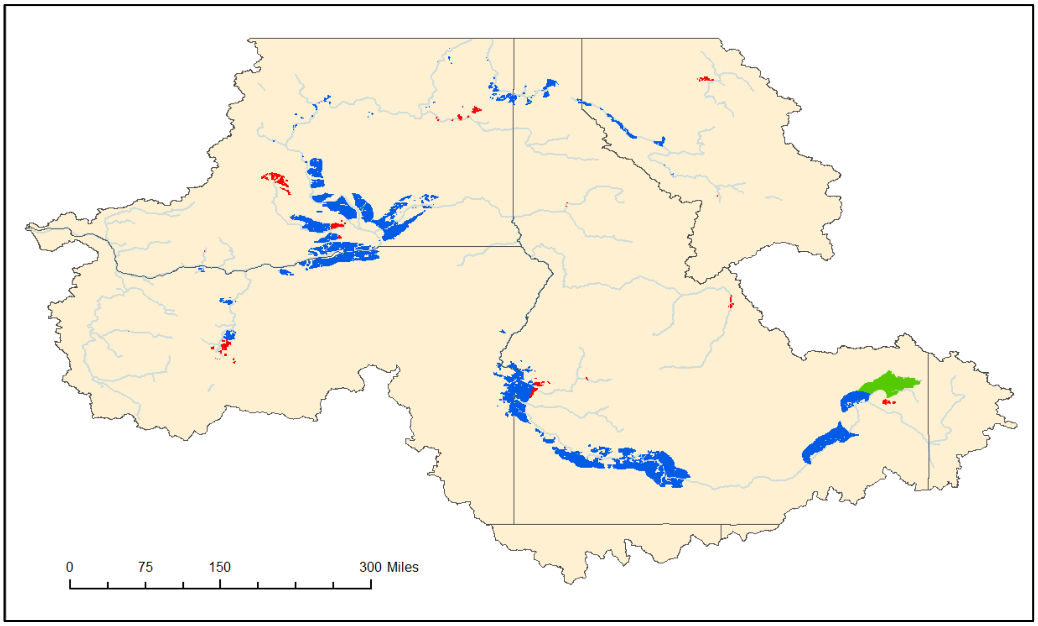


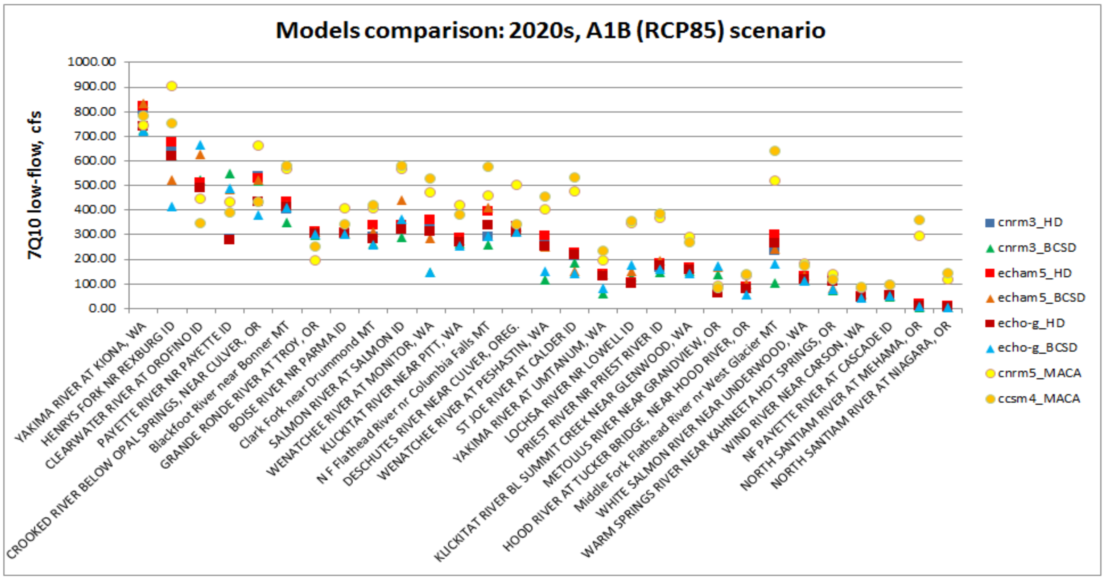
Figure 3.14. Candidate areas based on projected 7Q10 low-flow for large reactors for CMIP5 models (in blue). In red: areas removed for both scenarios, in green: areas removed for RCP4.5 scenario and existing for RCP8.5 scenario (Henrys Fork River).

3.4.5. Model comparison

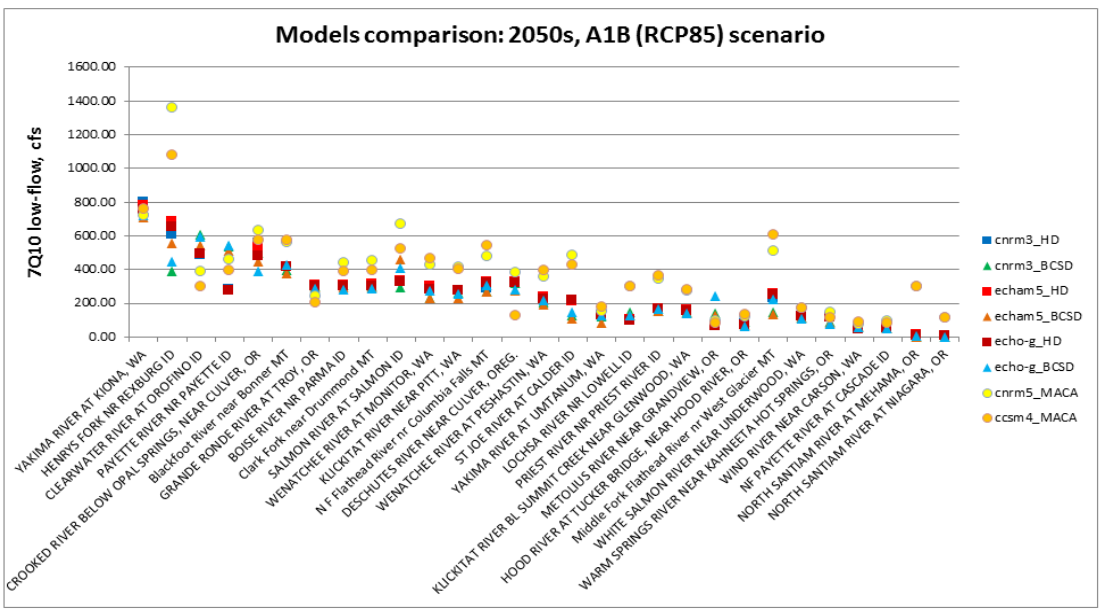
Projected streamflow based on the five climate models generally provide consistent 7Q10 values for a subsample of 28 gauges with 7Q10 values below 1000 cfs, for both the A1B/RCP 8.5 scenarios (Figure 3.15) and the B1/RCP 4.5 scenarios (Figure 3.16). Agreement is quite high among the three CMIP3 models, for both BCSD and HD downscaling approaches. Agreement is also high between the two CMIP5 models. Overall, 7Q10 values calculated from CMIP5 model output are higher than those calculated from CMIP3 model output (Figures 3.15 and 3.16).

A1B (RCP8.5) scenario

(a)



(b)



(c)

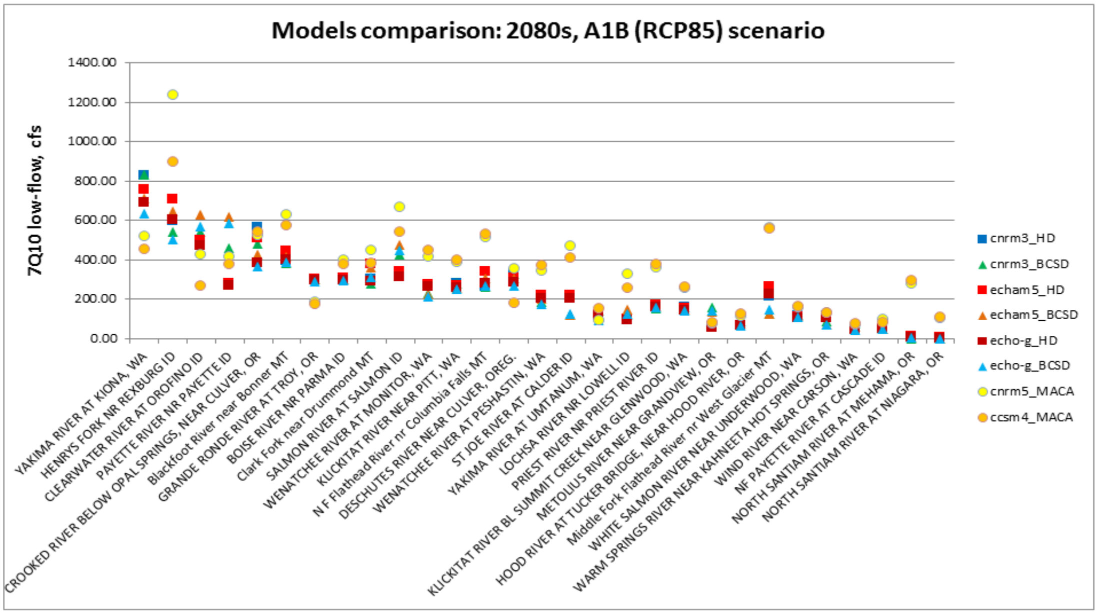
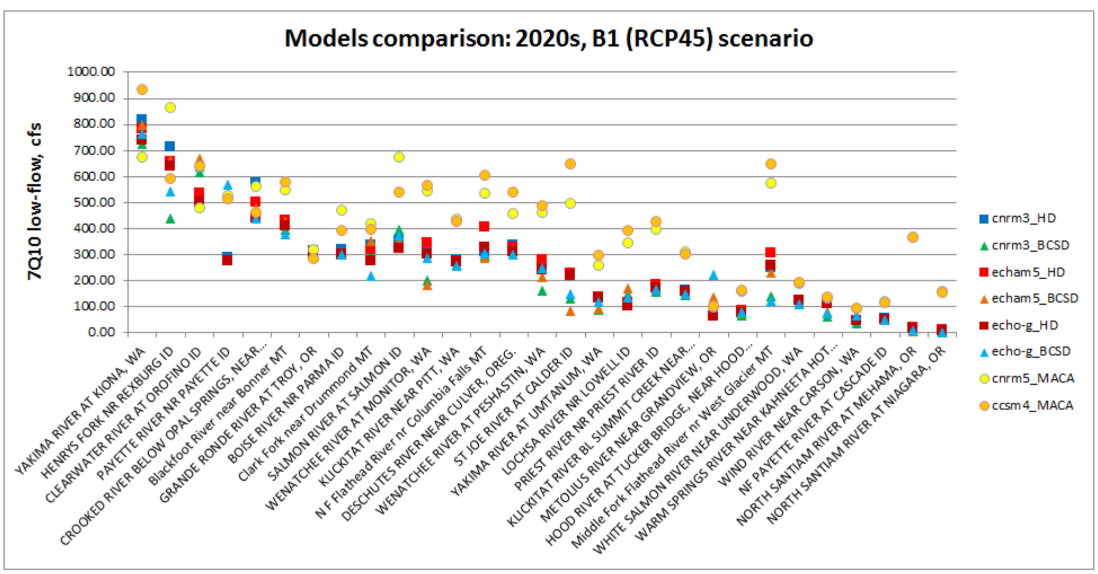


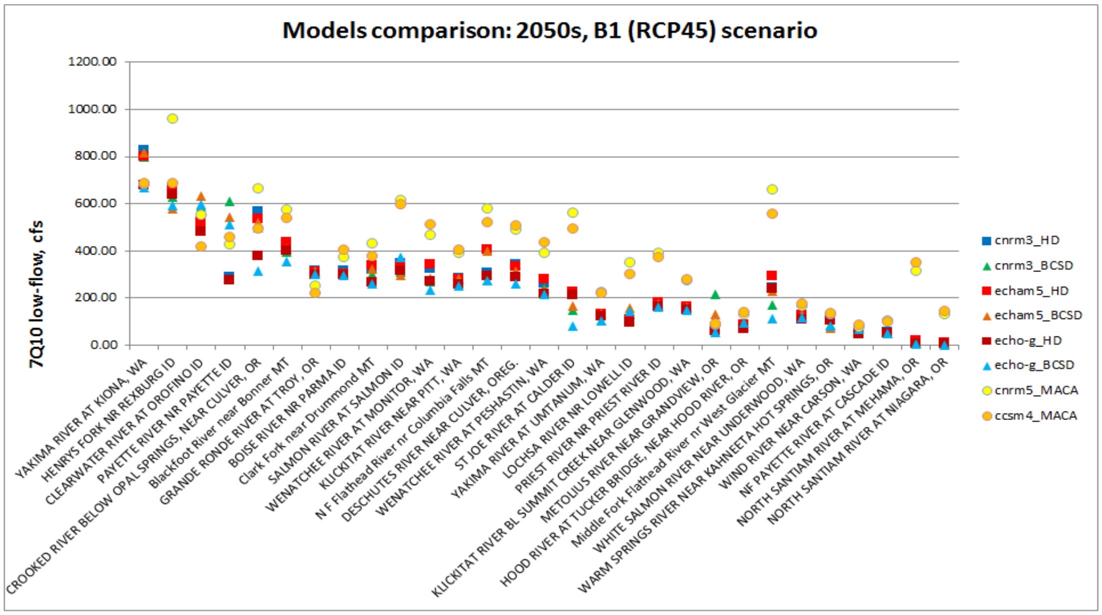
Figure 3.15. Scatterplots show 7Q10 low-flow values for A1B/RCP8.5 ('high') scenarios, 5 climate models, and three future time periods (2020s (a), 2050s (b), 2080s (c)). Three CMIP3 models (CNRM-CM3, ECHAM5, ECHO-G), downscaled using two approaches (BCSD, HD), were used. Two CMIP5 models (CCSM4 and CNRM-CM5), downscaled using MACA approach, were used.

B1 (RCP4.5) scenario

(a)



(b)



(c)

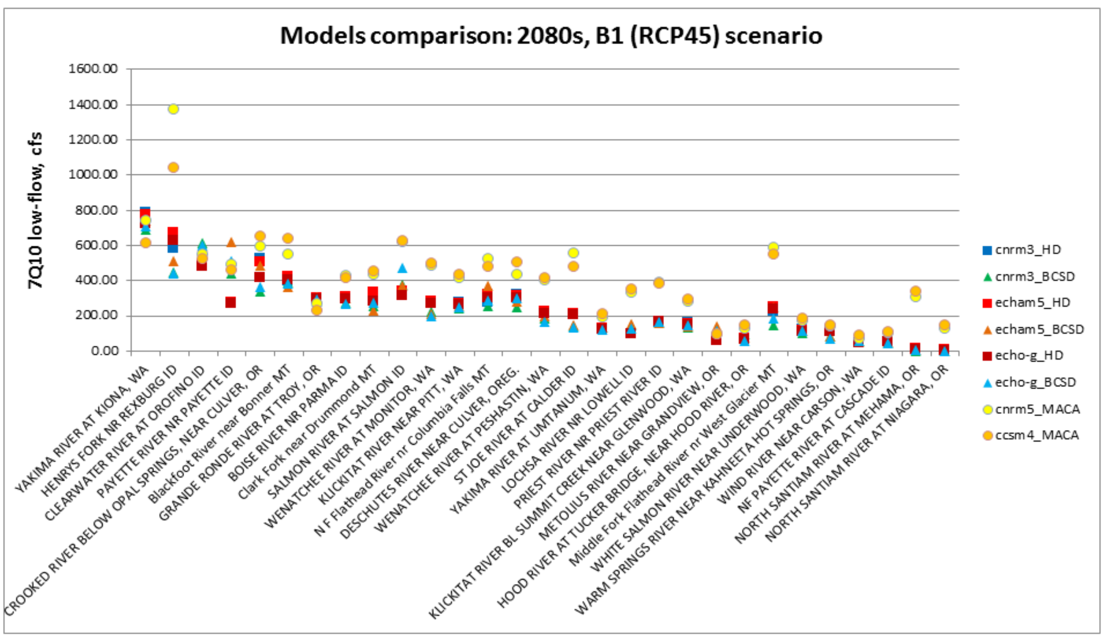


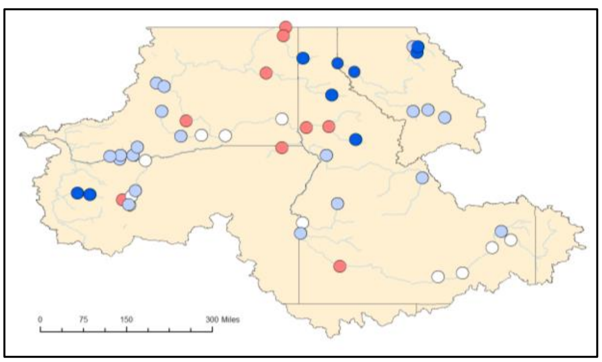
Figure 3.16. Scatterplots showing 7Q10 low-flow values for B1/RCP4.5 (‘medium’) scenarios, 5 climate models, and three future time periods (2020s (a), 2050s (b), 2080s (c)). Three CMIP3 models (CNRM-CM3, ECHAM5, ECHO-G), downscaled using two approaches (BCSD, HD), were used. Two CMIP5 models (CCSM4 and CNRM-CM5), downscaled using MACA approach, were used.

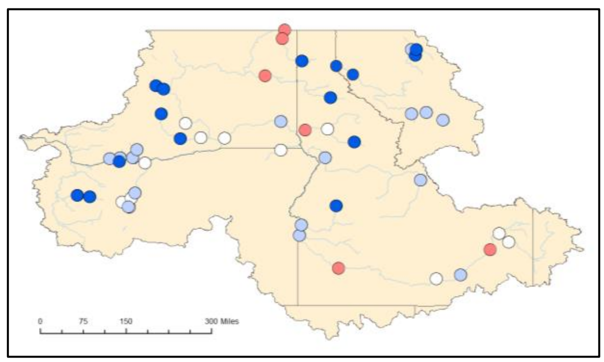
3.4.6. Spatial patterns of model agreement: CMIP5 vs. CMIP3

Although CMIP5 model projections of streamflow for the 21st century were generally higher than those from CMIP3 models, this was not true everywhere. In the North Santiam River in Oregon and in the north-eastern part of the CRB (Idaho, Montana), the CMIP5 streamflow projections led to 7Q10 values that were more than twice as high as those calculated from CMIP3 output, for the same periods (Figure 3.17). In these areas, CMIP3 models produced very small 7Q10 values – as low as 2 to 15 cfs. The 7Q10 values calculated based on streamflow projections using CMIP5 models were within +/- 20% of those calculated from CMIP3 model output in the northern and central part of the CRB, and along the Snake River (Figure 3.17).

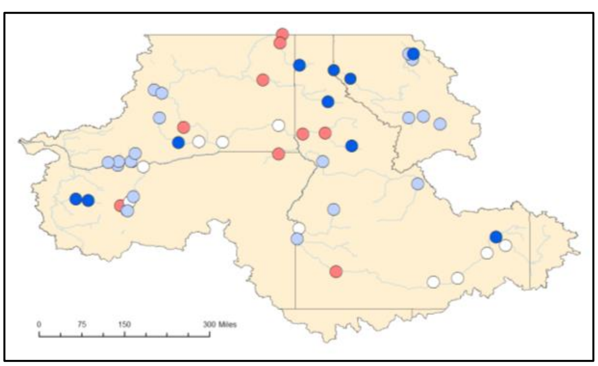
A1B (RCP8.5) **B1 (RCP4.5)**

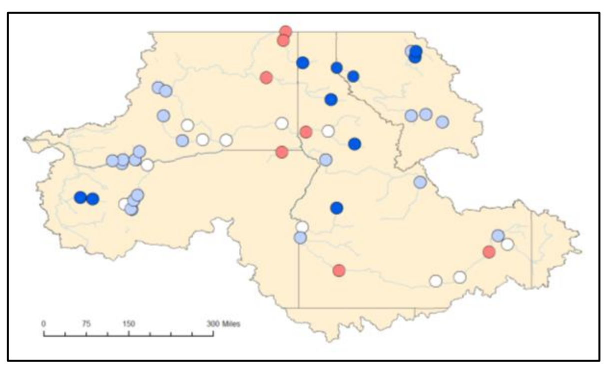
2020s



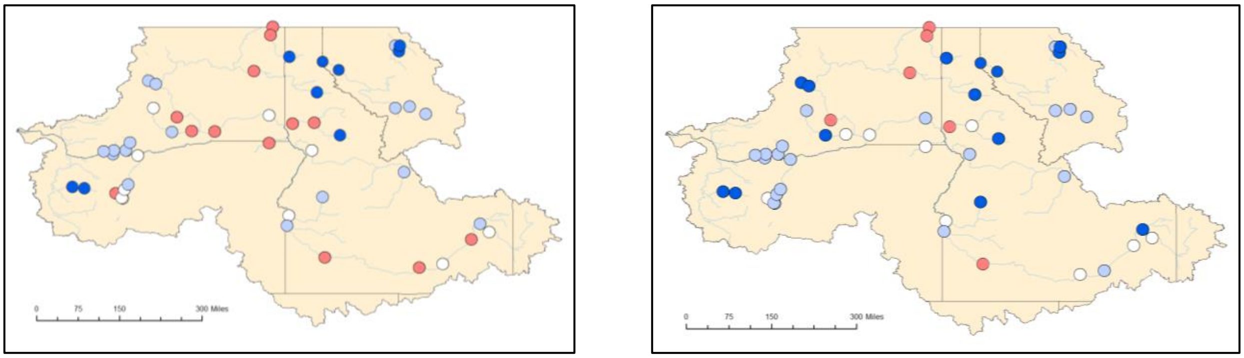


2050s





2080s



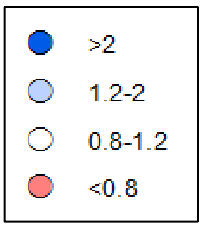


Figure 3.17. Ratios CMIP5 models/CMIP3 models show how much 7Q10 values differed in CMIP5 versus CMIP3 model projections. Two pairs of scenarios and three time periods are examined. ‘CMIP5 models’ is an average of low-flow values based on CCSM4 and CNRM-CM5 models using the MACA downscaling; ‘CMIP3 models’ is an average of low-flow values based on CNRM-CM3, ECHAM5 and ECHO-G models downscaled using both BCSD and HD approaches.

3.4.7. Spatial patterns of projected streamflow changes

Based on streamflow simulations using the averages of CMIP3 and CMIP5 models, the 7Q10 low-flow values decrease in almost all parts of the Columbia Basin during the 21st century (Figures 3.18 and 3.19). Future streamflow simulated using the CMIP3 models (Figure 3.18) is lower than streamflow simulated using the CMIP5 models (Figure 3.19).

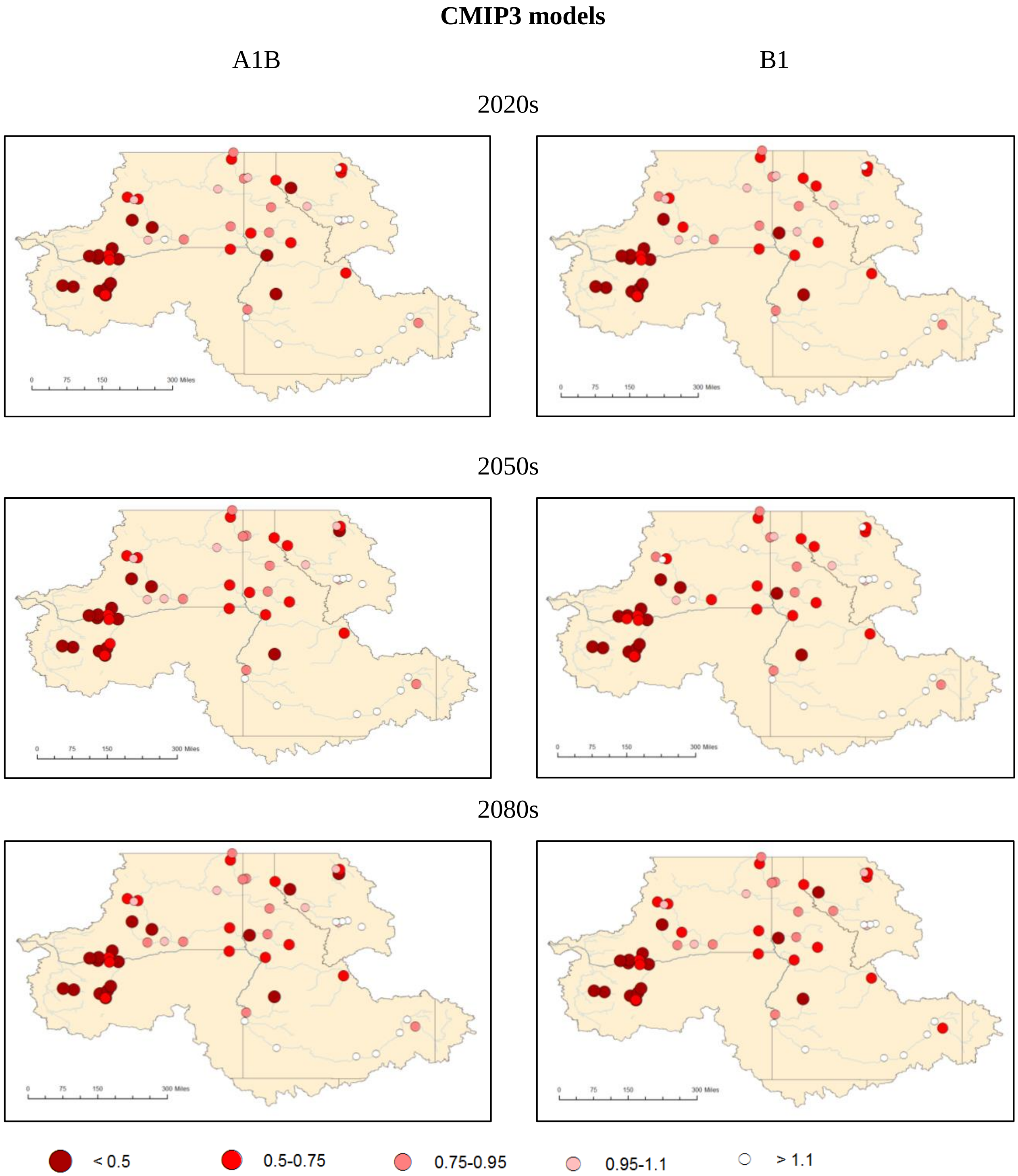


Figure 3.18. Ratios future vs. historical 7Q10 values for CMIP3 models, A1B and B1 scenarios. Lower ratios (larger, darker symbols) indicate more intense low-flow extremes in the future.

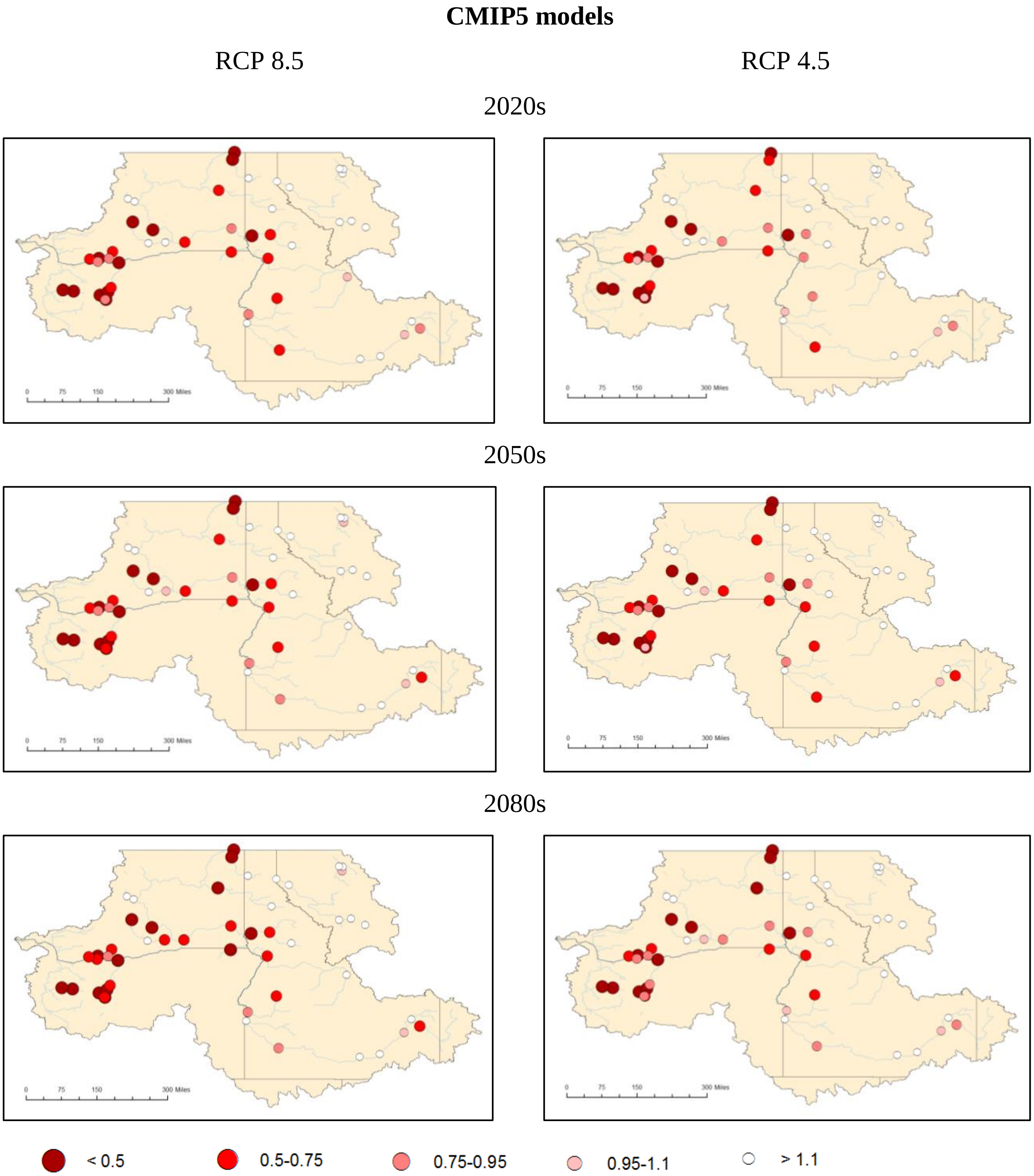
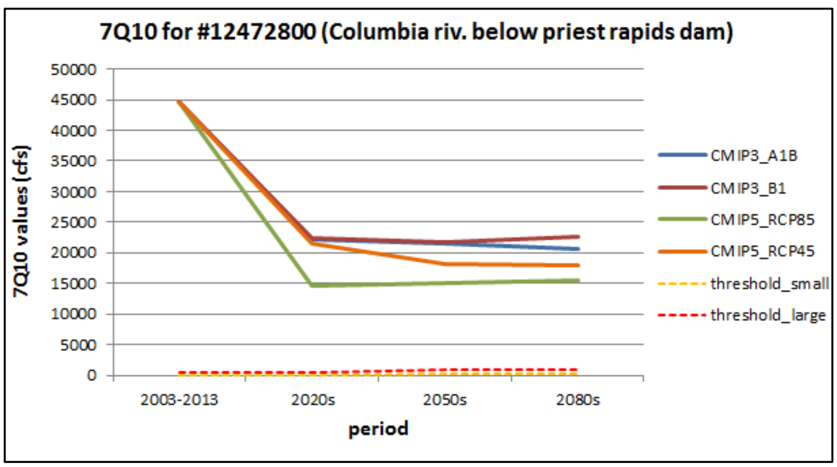


Figure 3.19. Ratios future vs. historical 7Q10 values for CMIP5 models, RCP4.5 and RCP8.5 scenarios. Lower ratios (larger, darker symbols) indicate more intense low-flow extremes in the future.

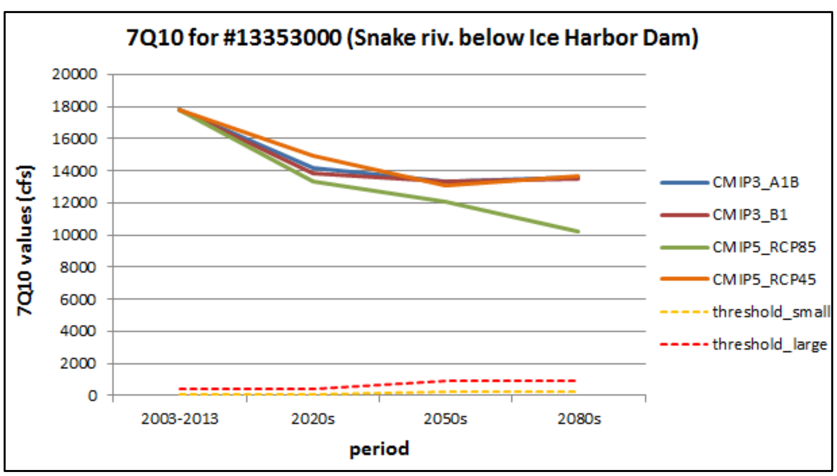
The largest decreases in 7Q10 values in the 21st century are predicted to occur in the western part of the CRB. The 7Q10 values calculated from projected 21st century streamflow are predicted to remain constant, or even to increase, at some gauges in the future (Figures 3.18 and 3.19).

3.4.8. Effects of projected changes in low-flow on two main candidate regions

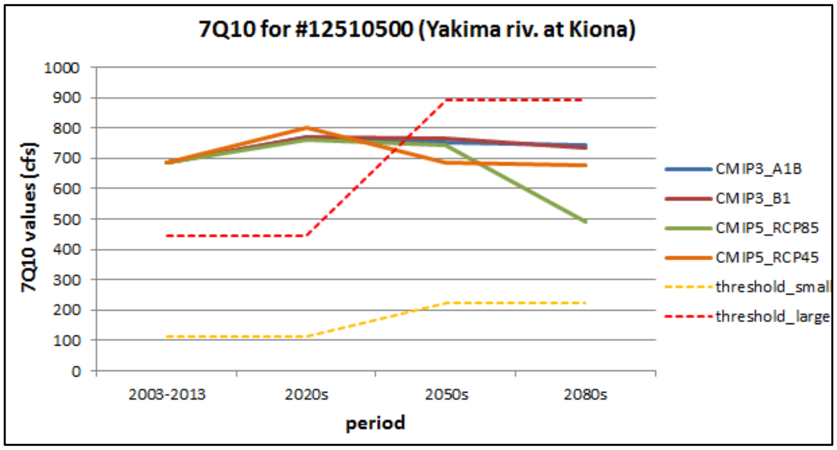
Despite projected decreases in streamflow 7Q10 values associated with 21st-century climate change, the high discharge at the two main candidate areas for siting nuclear power plants buffers them from climate change effects. The suitability of gauges along the main stem of the Columbia River and the Snake River is unaffected by climate change-related reductions in streamflow, although gauges along their tributaries (Yakima River, Payette River) become limited to large nuclear reactors only (Figures 3.20-3.21).



(a)

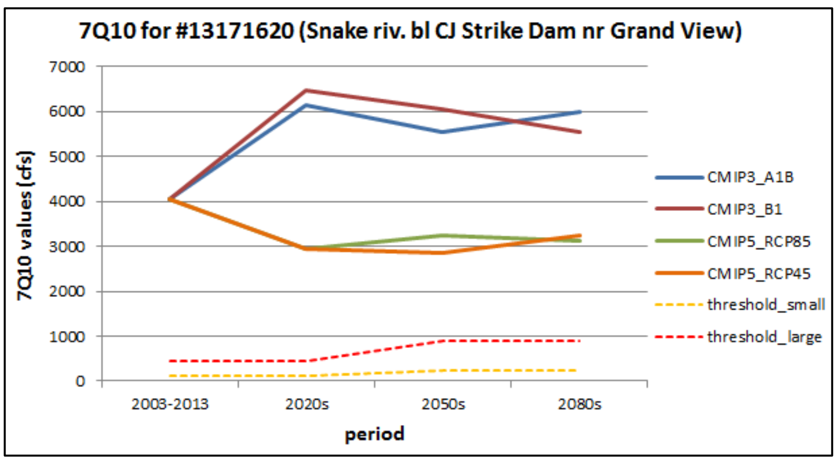


(b)

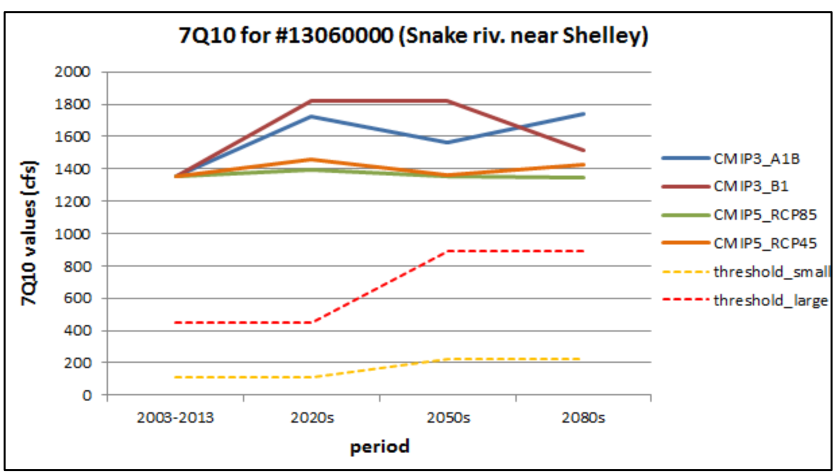


(c)

Figure 3.20. Projected 7Q10 values for three gauges within the Middle Columbia River candidate region. The 7Q10 values are averages for all analyzed models within CMIP3 or CMIP5 projects. (a) and (b) gauges on the Columbia River, where discharge exceeds the thresholds for siting both small and large reactors throughout the 21st century. (c) a gauge on the Yakima River, where discharge exceeds the thresholds for siting small reactors only.



(a)



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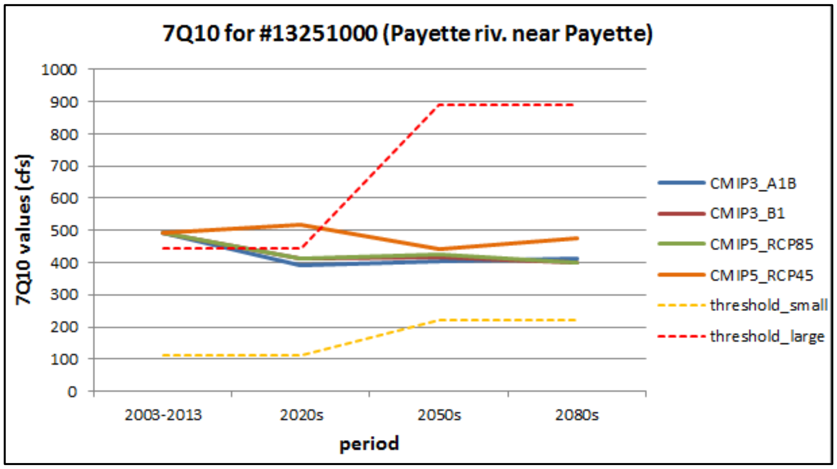
(c) 

Figure 3.21. Projected 7Q10 values for three gauges within the Snake River plain candidate region. The 7Q10 values are averages for all analyzed models within CMIP3 or CMIP5 projects. (a) and (b) gauges on the Snake River, where discharge exceeds the thresholds for siting both small and large reactors throughout the 21st century. (c) gauge on the Payette River, where discharge exceeds the thresholds for siting small reactors only.

3.5. Discussion

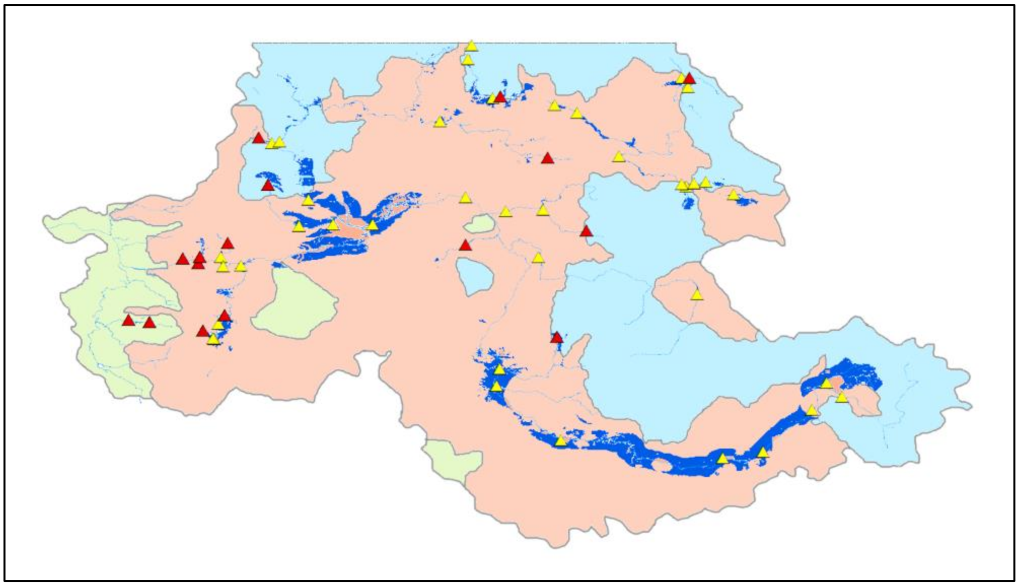
The two largest candidate areas for siting nuclear reactors in the CRB were not significantly affected by projected 21st century streamflow based on simulated future climate from global circulation models (GCMs). Two large candidate areas for small and large reactors identified in Chapter 2, in the mid-Columbia River and the Snake River plain, were robust to simulated future streamflow. However, projected 21st century declines in low-flow had the effect of eliminating most of the small areas that had been identified as suitable, especially for small reactors, in Chapter 2. Expected climate change effects on streamflow eliminated almost all candidate sites for nuclear power in the CRB, except the two main candidate regions in south central Washington and south central Idaho.

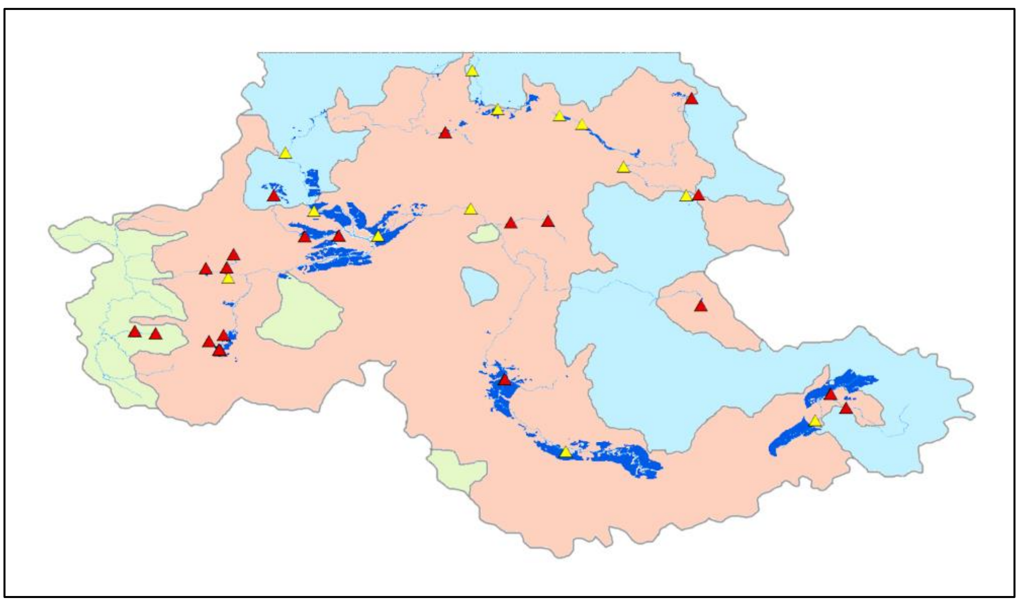
Although simulated climate change effects on 21st century minimum streamflow varied among the models and scenarios, these differences were mostly small. Therefore, the models and scenarios provided a fairly consistent picture of how future minimum streamflow affected site eligibility for nuclear power plants based on the water availability criterion. Although the 7Q10 low-flow values are predicted to decrease overall in the Columbia Basin in the 21st century, even large decreases at some of the gauges do not disqualify these locations as sites for nuclear reactors in the future. This is because water availability for cooling purposes depends upon a threshold discharge (for example, 112 or 223 cfs in the case of small reactors), and rivers with high discharge can experience large declines in flow without falling below the threshold value.

Models and scenarios used in this study produced fairly consistent results, and these models seem to be representative of GCM-based simulations in general. Simulations were based on three GCMs (CNRM-CM3, ECHAM5, and ECHO-G) and two scenarios (A1B and B1) from the CMIP3 model comparison experiment, and two GCMs (CNRM-CM5 and CCSM4) and two scenarios (RCP8.5 and RCP4.5) from the CMIP5 experiment. The CMIP3 models were selected because they had low 20th century bias and North Pacific variability (Hamlet et al. 2010b). The two CMIP5 models were highly ranked for their ability to simulate historical climate of the Pacific Northwest (Integrated Scenarios 2016). Ensemble of CMIP5 models predicted consistently higher streamflow than that of CMIP3 models for most sites during all future periods and according to both emission scenarios. Nevertheless, climate projections from a random set of models in CMIP5 yielded results similar to those from the best models (Integrated Scenarios 2016). Therefore, we conclude that our results are representative of what would have been found if we had used a larger set of models.

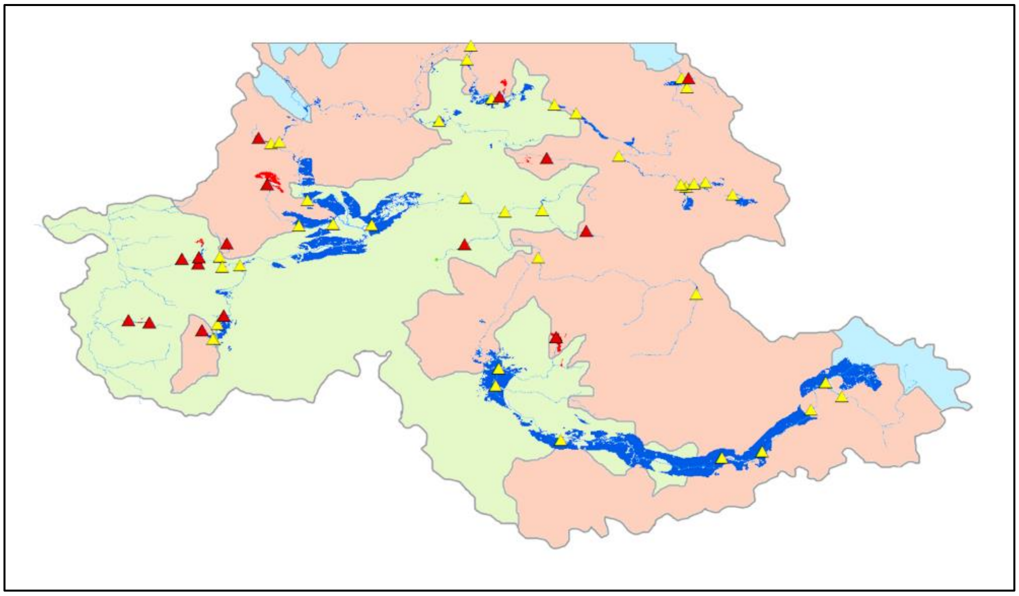
The projected spatial patterns of decreases in minimum streamflow (7Q10) are consistent with expected changes in rain-dominated, transition, and snow-dominated river basins. Large declines in low-flows in the 21st century are predicted to occur in the western portion of the CRB, in rain-dominant basins, such as middle part of North Santiam River (Figure 3.22; see also Figures 3.18 and 3.19). Rain-dominant areas are likely to receive more rain in the future, increasing winter streamflow. Thus, rain-dominated basins are likely to have more floods in winter, but they also may have more severe droughts in summer, because increasing temperature and evapotranspiration reduces soil moisture and late summer baseflows (Hamlet et al. 2010b, Tohver et al. 2014).

Historical


(a)


(b)

2080s, B1 scenario



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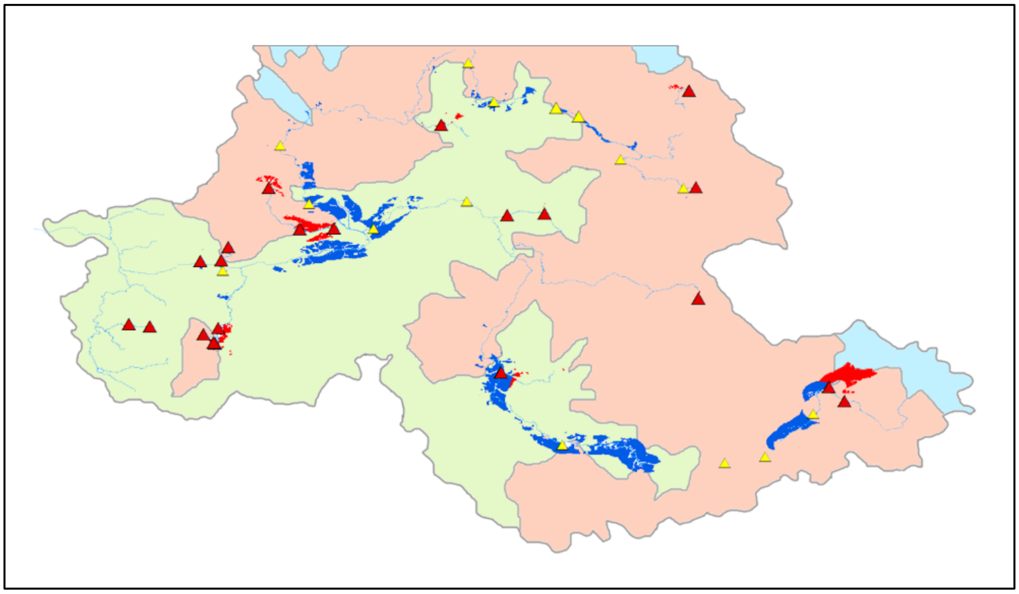
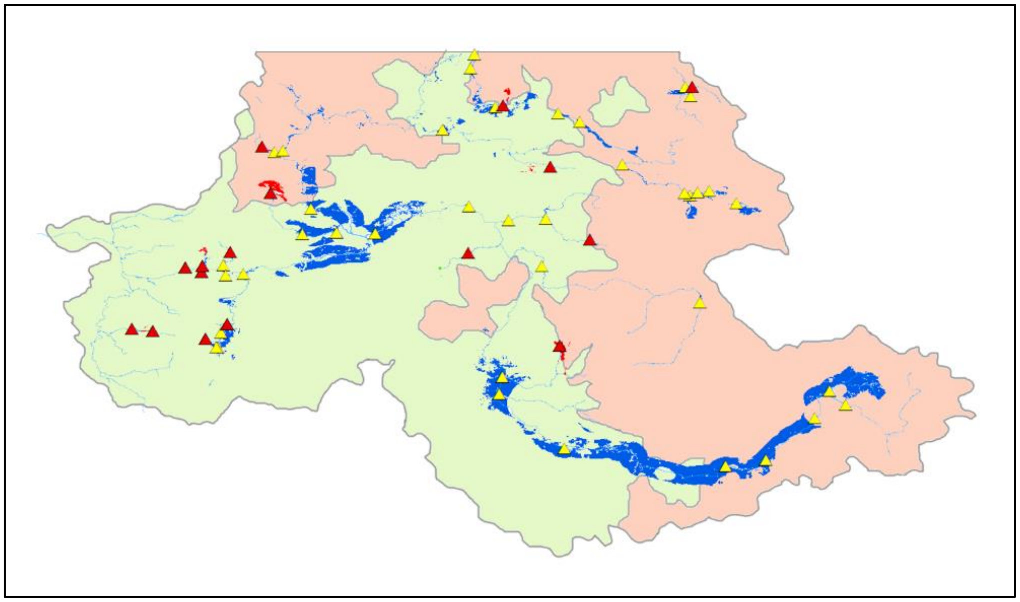


(d)

2080s, A1B scenario

(e)



(f)

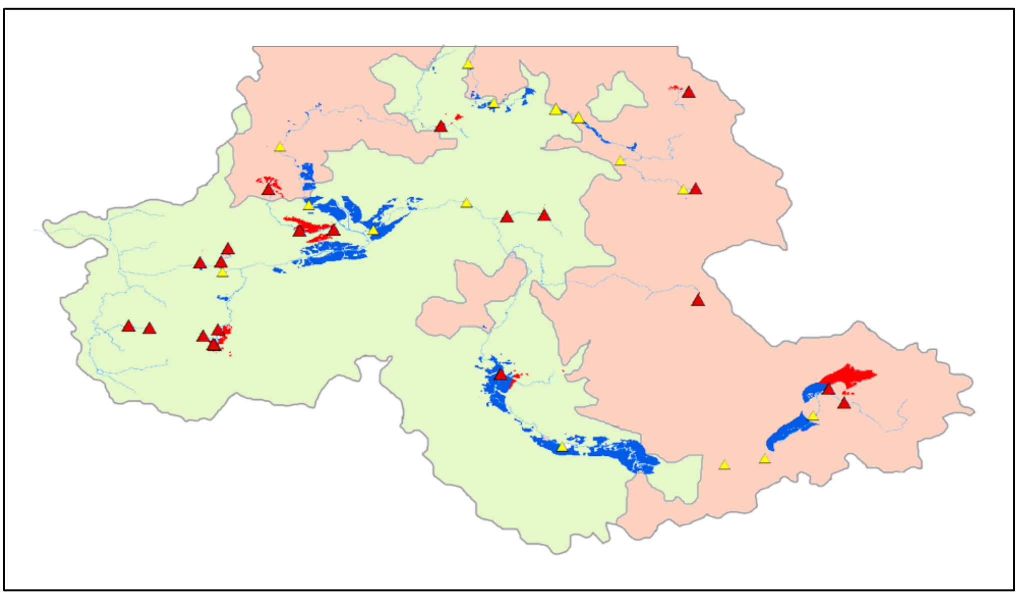


Figure 3.22. Analyzed gauges and candidate areas for siting small reactors (a, c, e) and large reactors (b, d, f) in relation to the types of basins, during historical period (a, b) and projected 2080s (c-f) (green = rain-dominant, red = transition, blue = snow-dominant). Map of the basins was reproduced from Hamlet et al. (2010b), and is based on the ratio of peak SWE to October to March precipitation, where the ratio < 0.1 = rain-dominant, 0.1-0.4 = transition, and > 0.4 = snow-dominant. Yellow+red triangles show all gauges analyzed for small (a, c, e) and large (b, d, f) reactors, red triangles show gauges with low-flow below the threshold for at least one future period/scenario (see also Figures 3.2, 3.9, and 3.12). Blue polygons represent the candidate areas. Red polygons represent excluded parts of the candidate areas based on the low projected flow.

Large declines in low-flows in the 21st century also are predicted to occur in the western portion of the CRB, in transition basins (Figure 3.22; see also Figures 3.18 and 3.19).

Streamflow in transition basins depends on snow accumulation and melt, which are very sensitive to small changes in temperature (Jennings and Jones 2015). Higher winter temperatures are projected to cause more precipitation to fall as rain instead of snow, which would decrease snow accumulation, lead to earlier snowmelt and alter the timing of runoff (Chang and Jung 2010, Mote et al. 2014b). By 2050 snowmelt in the Cascade Mountains is projected to shift three to four weeks earlier than the 20th century average, and summer flows are projected to decline substantially (Mote et al. 2014b). The largest declines are expected to occur in basins with significant snow accumulation, where warming will increase winter streamflow and advance the timing of spring snowmelt. The reduction in available snowpack (and thus water) is expected to increase the risk of drought during normally dry summers. As climate warms, transition basins will become rain-dominant basins, with more severe summer low flow periods and more frequent days with intense winter flooding (Mantua et al. 2009) (Figure 3.22, c-f).

In contrast, projected 21st century streamflow indicates that low-flow may not change, or may increase, in some transition and snow-dominated basins (Figures 3.18, 3.19, and 3.22). This result is consistent with expected effects of climate change on snow accumulation and melt. The lowest flows in the coldest basins often occur in the winter, when water is stored as snow. With changes in climate, more precipitation will fall as rain in the winter months and contribute to runoff, increasing 7Q10 values (Hamlet et al. 2010b). This explanation applies primarily to headwater basins in the Columbia and Snake Rivers. Another possible explanation for the projected increase in 7Q10 values at some gauges located in transition basins (such as the Snake River at Neeley, Snake River at Minidoka, and the Boise River near Parma) is that USGS 7Q10 values for the historical period reflect the real discharge including management operations, while simulated future streamflow does not consider the effects of reservoir management on flows.

The two main candidate areas were robust to projected changes in low-flow in the 21st century; about 2.77% (average for small reactors) and 13.25% (average for large reactors) of these two candidate areas were eliminated as a result of predicted decreases in streamflow. These candidate areas are robust to streamflow change because they are adjacent to major rivers (Columbia, Snake) with high discharge. Gauges on the Columbia and Snake Rivers are likely to have enough flow for small and large reactors, even if future climate is drier than predicted by models and scenarios used in this analysis. In contrast, the Payette River in Idaho and the Yakima River in Washington may not be able to provide adequate flow for even small nuclear reactors in the future.

The Middle Columbia candidate area appears to be the most robust to projected changes in low-flow of all candidate areas for nuclear reactors in the CRB. This is because of the high discharge values (and 7Q10 values) of the Columbia River and its tributaries. In contrast, in the Snake River plain candidate region, only the Snake River mainstem has high discharge (and 7Q10) values, while its tributaries (Boise, Henrys Fork, and Payette Rivers) have lower discharge, and projected 7Q10 values that are near the threshold values mentioned previously. However, the candidate areas associated with these tributaries are rather small, so even if they are eliminated, the Snake River plain candidate region will decrease only slightly, by about 10% of its total area.

Finally, it should be noted that this analysis refers only to step 1 of NRC regulations for nuclear reactor siting. Candidate regions should be analyzed thoroughly during further stages of the site selection process, and uncertainties associated with future water availability should be considered.

3.6. Conclusion

Increasing global mean surface temperature is an indicator of climate change, which will affect many parts of the world, including the Columbia River Basin, potentially affecting water availability for location of facilities such as nuclear power plants. Shifts in precipitation, increased risk of drought, reduced snowpack, and changes in the timing of snowmelt in spring are likely to influence the patterns of discharge in the rivers of the CRB. This study showed that streamflow will decrease at most gauges in the basin, where 20th-century streamflow was adequate for nuclear power plant siting (as shown in Chapter 2).

For assessing changes in low-flow discharge in the Basin, we calculated 7Q10 values based on daily streamflow projections that were driven by output from several global circulation models, which were part of the CMIP3 and CMIP5 model comparison experiments, with high (A1B/RCP8.5) and medium (B1/RCP4.5) emission scenarios, downscaled using three different techniques. Results indicated that CMIP3 models overall predicted a drier future for the analyzed locations than CMIP5 models, although outcomes from three CMIP3 models are consistent with each other, and with output from two CMIP5 models.

Projected 21st century minimum streamflow (7Q10) decreased at most analyzed locations, but these changes did not have a significant impact on candidate areas for siting nuclear reactors defined in Chapter 2. The reductions of candidate areas are noticeable when comparing results for small vs large reactors. Only 2.9% of candidate areas for small reactors were eliminated, but 13.9% of candidate areas for large reactors were eliminated as a result of predicted decreases in streamflow. Overall, for both small and large reactors, future changes in streamflow mostly affected small clusters of potential sites located in the western, northern, and central parts of the CRB (North Santiam basin, Yakima basin, NF Payette basin, etc.). However, future streamflow did not significantly affect two main candidate areas along the Middle Columbia and Snake Rivers.

In summary, although climate is changing, and the water availability may be significantly influenced by these changes in the CRB, many areas remain appropriate for siting nuclear reactors. As much as 4.5% of the CRB is projected to be suitable for siting small reactors, and 2.7% of the area – for siting large reactors. These candidate areas have changed just slightly in comparison with the historical period (4.6% and 3.1%, respectively).

Chapter 4. Uncertainty associated with the site selection process for nuclear plants

This study discussed the uncertainty associated with the siting process for nuclear power plants, including siting criteria, the potential future effects of climate change on water availability necessary for cooling, and overall public perceptions of nuclear power. The effect of each type of uncertainty in this chapter is evaluated relative to its effects on omission and commission of potential sites for nuclear power plants. Although siting criteria and possible changes in climate and hydrology significantly limit the number of areas suitable for siting, public opposition to nuclear power is able to entirely prevent construction of reactors in sites that are physically and economically suitable for nuclear power plants. Public support for nuclear power has increased and decreased over the past 50 years in response to nuclear accidents. Public acceptance increased during periods without accidents, and declined after nuclear power plant accidents, particularly Three Mile Island (1979), Chernobyl (1986), and Fukushima (2011). The very low probability of an accident, combined with the very high negative consequences, make it difficult to quantify and assess risk, contributing to uncertainty and lack of public confidence. Future climate and hydrologic projections also cause deep uncertainty, as they predict the future that cannot be verified before it comes. Many factors contribute to this uncertainty, including global climate model structure, emission scenarios, downscaling process, and hydrologic model structure. The least uncertainty is related to the selection of sites using historical records, because they can be verified, in particular, by the maps of larger scale and/or by the field observations.

4.1. Introduction

Uncertainty can be defined as lack of confidence in knowledge about a specific question (Kiparsky et al. 2012), or something that defines and limits our efforts to better understand extreme and rare events (Harrower 2003). Uncertainty arises from both an imperfect understanding of the studied events and processes, which are unknowable or very difficult to predict, as well as the imperfect data used (Malczewski 2006, Harrower 2003). Power plants and other facilities are subject to large uncertainties, because they generally function for years or decades, and the environment in which they operate may change substantially within this period (Snyder 2006).

This chapter reviews three principal sources of uncertainty affecting nuclear power plant location: those associated with (1) the site selection process; (2) predicting future climate and hydrology; and (3) public perceptions of nuclear power. Site selection is a process of selecting a location for a new facility. Changes in future climate and hydrology may influence the future viability of sites selected today. Public opposition to nuclear power plants may prevent their construction even if they are physically and economically feasible. This chapter describes these sources of uncertainty and assesses how they affect the siting of nuclear power plants.

Chapter 2 identified potential sites for nuclear power plants using GIS-based site selection methods. The uncertainties in the field of GIS-based site selection for hazardous facilities, such as nuclear power plants, may arise from many sources. They may be connected with the data used, such as map scale or inaccuracies in maps used for analysis, for example, due to the absence of sharp boundaries in the real world (Chang et al. 2008). Uncertainties may also arise concerning the examined siting criteria and the way they were applied or, conversely, concerning criteria that were omitted for one or another reason. Uncertainties may be associated with the facility design parameters used for analysis. Uncertainty may arise in the routing of hazardous wastes from the hazardous facilities to selected disposal facilities (uncertainty associated with location–transportation problems) (Snyder 2006, Killmer et al. 2001). Keeney (1980) identifies uncertainties associated with the possible environmental impacts, future costs (economic impacts), and the likelihood of accidents and their impacts. Uncertainties also are related to the government decisions and actions, which may change during the life cycle of a facility. For example, a future federal governmental decision requiring the installation of some additional safety equipment on all facilities of a certain type could have a significant differential impact on the candidate sites being considered now (Keeney 1980). Thus, it may be necessary to consider the possibilities of the various government actions in evaluating current siting decisions.

Chapter 3 demonstrated that climate impacts are likely to influence the hydrology and water systems of the Columbia Basin in the future. However, because of the uncertainty, it is hard to predict the precise form of these changes. Potential impacts of climate change on hydrology are commonly assessed by driving hydrological models with climate projections derived from GCMs. The general procedure for assessing the impacts of climate change on water resources is to choose a climate change projection, which is a combination of a GCM driven by an emission scenario, downscale climate projections from global to finer regional-scale, generate hydrologic predictions using hydrologic models and climate change simulations, and compare model simulations from both current and future climates (Vano et al. 2014, Schnorbus and Cannon 2014, Bae et al. 2011, Elsner et al. 2010). Each of these processes involves its own uncertainties. Climate and hydrologic system are influenced by inherently stochastic elements, such as population growth, deforestation trends, changes in agriculture and other large-scale processes, through their influence on greenhouse gases and thus radiative forcing of climate warming. But even given a known emissions trajectory, the response of the climate system is challenging or impossible to predict (Kiparsky et al. 2012). There also exists an uncertainty associated with the remoteness of the period for which climate/hydrologic simulations are projected. Thus, the projected impacts of climate change on river streamflow are associated with large uncertainties. For a complete analysis of uncertainty in runoff projections, it is important to investigate the contributions of all existing sources.

A major source of uncertainty about nuclear power plant siting is associated with public attitudes towards nuclear power. Public opinion about nuclear facilities has long played an important role in the US, and attitudes towards nuclear plants changed over time. In recent years, the Fukushima accident in Japan also significantly lowered the level of public acceptance of nuclear energy worldwide (Kim et al. 2013). Nevertheless, some authors argue that nuclear energy is still a safe alternative and that the Fukushima disaster resulted from insufficient safety regulations in Japan, a problem that does not exist in the United States (Stoutenborough et al. 2013).

Finally, the effects of uncertainty may be evaluated based on the concepts of omission and commission errors. Omission errors involve the failure to identify sites that should have been included to the list of candidate areas/suitable sites. Errors of commission involve the selection of sites that are not suitable. In this chapter, the effect of each type of uncertainty is evaluated relative to its effects on omission and commission of potential sites for nuclear power plants.

4.2. Uncertainties associated with site selection process using historical streamflow records and GIS analysis based on existing maps

4.2.1. Low-flow statistics: 7Q10 vs. 7Q50

Our assessments have shown that several gauges have enough discharge for siting nuclear plants according to 7Q10 low-flow statistics, but not according to 7Q50 statistics (Chapter 2). Length of record used as basis for low-flow statistics, therefore, may affect the outcome. To reduce the uncertainty associated with the length of record, it is worth calculating not only 7Q10 low-flow statistics commonly used for site selection purposes, but also the statistics for the longer record (if it exists) for comparison. Differences in low-flow statistics between 10-yr and 50-yr periods may be connected with human-related issues (e.g. dam construction), or natural phenomena (e.g. local drought period). These reasons should be investigated thoroughly in each case, and used to guide decisions about the inclusion of such gauges (and stream segments) to the list of potential sites.

Calculating long-term statistics (such as 7Q50) may often be problematic, because of the lack of long-term records for a range of the gauges, and is desirable for at least those gauges which appear within the candidate areas after the first step of site selection process (and will be examined in detail during selection of candidate sites/preferred sites during further stages).

4.2.2. Scale of maps used for analysis

The scale of all the maps used for the selection of candidate areas differs and ranges from 1:12,000 (county level) and 1:24,000 (state level) to 1:1,000,000 (national level). While selecting the maps, we followed the principle of quality and accuracy, and used the data from official open public sources (USGS, FEMA, etc.) Thus, the final choice depended on data availability, but not all of the maps had identical scale, although the maps of different scales were appropriate for conducting initial site selection analysis (it must be 1:250 000 or smaller for selecting candidate sites). Data at the scale 1:24,000 and larger can be used during the further steps of site selection (selection of potential sites and candidate sites), while other criteria will require searching for the new data of the larger scale. These new data will allow refining the boundaries of the candidate areas determined during the initial analysis.

Use of maps of different scale in the siting analysis produces uncertainties. Small scale data inherently are less accurate and less detailed than large scale data, and the use of small scale data for large scale analysis can produce errors. Large scale data, as a rule, are too detailed for small-scale analysis, and for this reason in most cases we generalized them (e.g. floodplains, slopes, etc.) Therefore, the best option for siting analysis is to have maps of similar scale. The necessary maps and data in this case may be retrieved from the local agencies, federal organizations, etc. upon the request.

Despite uncertainties arising from the difference in map scales, it is important to remember, that we this analysis was only the initial stage of the site selection process. The candidate areas will be refined during the further stages using larger scale maps.

4.2.3. Accuracy of maps (shapefiles, rasters)

GIS resultant map of candidate areas is only as good as the underlying data. As it was mentioned previously, while selecting the underlying maps, we followed the principle of quality and accuracy, and used the data coming from the official open public sources (USGS, FEMA, etc.). Nevertheless, these official data may contain inaccuracies; they may include some unnecessary features, or lack some important features, especially if they are outdated. To reduce the uncertainty associated with the accuracy of maps, at the stage of selection of candidate sites/preferred sites, field surveys are necessary to refine the boundaries of the candidate areas at certain locations.

4.2.4. Sensitivity of the analysis to selected types of reactors and corresponding water requirements

In our research we consider minimum water requirements for two different types of reactors with different capacities: a small nuclear reactor with a capacity of 350 MWe, and a large nuclear reactor with a capacity of 1600 MWe. The parameters for each type are described in Chapter 2. The design parameters determine how much water is needed for cooling the condensers, and, accordingly, what discharge should have the nearby stream. However, reactor parameters are approximate, and final parameters will differ depending on reactor design and customer requirements, as will the associated requirements for cooling water and stream discharge. Hence, the outcome of the analysis will change if the site selection process involves different types of reactors (with different water requirements). Nevertheless, the described methodology for calculating low-flow values may be used by substituting exact parameters of actual reactor.

4.2.5. Criteria used and not used in the analysis

For selecting candidate areas, we considered a set of siting criteria, including physical characteristics of a site (hydrology, seismology, meteorology, and geology), population density, population distribution, and the nature and proximity of human-related hazards. In our analysis, the water availability (discharge) criterion was applied first, and it excluded about 63 to 74% of the CRB area (for small and large reactors, respectively). Applying the first two criteria (water availability and seismicity) excludes all but 28.2% of the CRB (for small reactors), and 20% (for the large ones). The final candidate areas represented 4.6% of the CRB area for small reactors and 3.1% of the CRB area for large reactors. Overall, the order in which the criteria are applied does not affect the shape and size of the final candidate areas. However, application of all the siting criteria excluding water availability (i.e., for siting nuclear plants with dry cooling system) produces a final candidate area that represents 27.8% of the CRB (Figure 2.33, Chapter 2).

This study considered water resources stored in streams widely represented across the entire Columbia River Basin, although water from the sea and from lakes may also be used for cooling purposes. Groundwater supply sources also can be included in the evaluation as independent sources or as supplemental sources to the surface water supply, but this is usually done only when surface water limitations preclude site selection (Rodwell 2002).

Another issue is the spatial coverage of the stream gauging network. Water requirements for the reactors used in this analysis restricted site selection to rather large rivers, which had relatively good coverage by gauges.

However, there exists an uncertainty associated with the siting criteria that were not used during the initial analysis, but should be used during the further stages of siting process and will influence the choice of the candidate sites/preferred sites. These criteria include water quality, sedimentations rates, migratory species effects, soil stability, transportation access, land rights, social and legal constraints on water availability, emergency planning issues, and some others.

4.2.6. Errors of omission/commission

Using 7Q10 low-flow metrics as the dominant in studies related to siting facilities may produce errors of commission, including the locations where gauges have adequate discharge for siting according to 7Q10 low-flow statistics, but not according to 7Q50 statistics. Therefore, it is desirable to use 7Q50 statistics in addition to 7Q10, and investigate the locations with the difference in statistics in terms of water availability for cooling, at later stages of the site selection process.

The use of small scale data for large scale analysis can produce errors. These are both errors of omission (we omit site(s) that could be used for constructing nuclear reactors) and errors of commission (we select site(s) for constructing that in fact is (are) not suitable), because the boundaries of the objects on the small scale maps are too coarse for the maps of larger scales. Large scale data, as a rule, are too detailed for small-scale analysis, and for this reason in most cases we generalized them (e.g. floodplains, slopes, etc.). Map generalization also produces some errors, which may be both errors of omission and commission.

Errors of omission, such as when official data contain inaccuracies (include unwanted features, or lack features), seem to be more serious than the errors of commission. The latter are likely to be fixed during further steps of siting process, while the former (the omitted sites lying outside the defined candidate areas) most probably will not be examined during the further stages, because the site selection process does not include a step to consider errors of omission from previous steps.

Since the streams in the CRB have relatively good coverage by gauges, based on the estimates of discharge at ungauged locations, there do not appear to be errors of commission based on lack of coverage of the stream gauging network.

4.3. Uncertainties associated with the assessment of climate change influence on water resources and defined candidate areas

4.3.1. Climate projections

Key sources of uncertainty coming from climate model projections include uncertainties of GCMs themselves, uncertainties from emission scenarios, and uncertainties from natural climate variability (for example, El Niño Southern Oscillation).

4.3.1.1. GCM structure

According to a number of studies, climate model structure is a primary source of uncertainty for the evaluation of hydrologic impacts (Vano et al. 2014, Bae et al. 2011, Chang and Jung 2010, Graham et al. 2007, Wilby and Harris 2006). As GCMs are simplifications of the real world they exhibit some level of bias relative to the ‘real’ climate system (Ekström et al. 2015).

All of the GCMs are subject to two main types of uncertainties. First, because scientific understanding of the climate system is not complete, a model may not include an important process, which is currently unknown or cannot be modeled (Walsh et al. 2014, Ekström et al. 2015). Second, many physical processes occur at finer temporal/spatial scales than models can resolve. GCMs cannot resolve processes such as turbulent mixing, radiational heating/cooling, and small-scale physical processes such as cloud formation and precipitation, chemical reactions, and exchanges between the biosphere and atmosphere (Walsh et al. 2014). Different GCMs may simulate quite different changes in climate in response to the same radiative forcing, simply because of the way certain processes and feedbacks are modelled (Hawkins and Sutton 2009). Moreover, all climate models use the same knowledge base, and are based on the common basic methodologies. Thus it is likely that all models share common biases, making the overall uncertainty larger than differences across models (Hallegatte et al. 2012). Hence, multiple models should be used to display uncertainty in simulated future conditions.

For our research, we used five different models (CMIP3 models: CNRM-CM3, ECHAM5, and ECHO-G, and CMIP5 models: CCSM4 and CNRM-CM5), and two pairs of scenarios (A1B-B1 and RCP4.5-RCP8.5). CMIP3 models were chosen as the three “best” models based on the best combined rankings for 20th century bias and North Pacific variability, according to the CIG’s report (Hamlet et al. 2010b). The two CMIP5 models were highly ranked for their ability to simulate historical climate of the Pacific Northwest (Integrated Scenarios 2016).

4.3.1.2. Emission scenarios

Uncertainty about future emissions also affects the modeling of future climate change, but it is less than uncertainty in model structure (Chang and Jung 2010, Wilby and Harris 2006). In the IPCC AR4, the increasing concentrations of greenhouse gases (A1B, B1 and others, as described in chapter 3) were determined through emission scenarios. In the IPCC AR5, emissions are represented differently: as representative concentration pathways (RCP4.5, RCP8.5, and others) which provide information about trajectories for the main forcing agents (greenhouse gases, air pollutants, and land use change) (Ekström et al. 2015, Vano et al. 2014, Moss et al. 2010). Absolutely credible projections of future emissions do not exist, and several emission scenarios should be included in an investigation of future possible changes in streamflow. Emission scenarios were chosen following the selection criteria applied in CIG and IS reports. They represent medium to high scenarios (A1B and RCP8.5), associated with increasing greenhouse gases through the end of the 21st century, and lower scenarios (B1 and RCP4.5), characterized by stabilization of greenhouse gases concentration by the end of the 21st century.

4.3.1.3. Internal Variability

Internal variability is the ability of climate models to represent future climate variation. It is the natural variability of the climate system that occurs in the absence of external forcing, and includes processes inherent to the atmosphere, the ocean, and the coupled ocean-atmosphere system (Deser et al. 2012b). Internal variability occurs at interannual, interdecadal, and longer time scales (over periods as long as 50 years) due to the chaotic nature of the climate system, including impacts due to changes in the sun activity or volcanic activity. The role of natural variability becomes more obvious at the regional scale, because regional patterns of natural variability can have a large impact on the climate (Ekström et al. 2015, Deser et al. 2012a). For example, in the Pacific Northwest, climate is greatly influenced by El-Niño Southern Oscillation and Pacific North-American pattern, which define seasonal trends in temperature on multidecadal scale.

The uncertainty due to natural variability is unlikely to be reduced as models improve or as greenhouse-gas trajectories become more accurate, because these uncertainty are a consequence of the chaotic nature of large-scale atmospheric circulation patterns (Deser et al. 2012b). Some authors argue that regardless of anthropogenic forcing of large-scale climate, internal climate variability will be a prime contributor to uncertainty in near-term climate projections at regional scales for the next several decades (Abatzoglou et al. 2014b).

4.3.2. Downscaling process

Uncertainties also arise from the process of downscaling used to achieve higher resolutions from coarser large-scale GCMs. Uncertainties can arise between future scenarios downscaled using dynamical versus statistical methods or among different statistical downscaling methods (Wilby and Harris 2006). For our research, we used daily streamflow values from three different statistical methods: BCSD and Hybrid Delta (CMIP3), and MACA (CMIP5), as described in Chapter 3.

A key assumption in statistical downscaling is stationarity, which states that although the climate is changing, defined statistical relationships do not change (Trzaska and Schnarr 2014, Wilby et al. 2004). This assumption causes uncertainty: if historical patterns of hydrology are changing and those assumptions of stationarity are no longer viable, relying on existing behaviors under nonstationarity may no longer result in the same reliability for water resources (Kiparsky et al. 2012). However, for BCSD and HD methods, the stationarity assumption is usually used in the context of saying that the large-scale P and T patterns and fine-scale P and T patterns will be the same as in the past. The MACA approach does not assume that future GCM distributions are stationary with respect to historical records (Integrated Scenarios 2016, Abatzoglou and Brown 2012).

The MACA approach uses daily output from GCMs (unlike BCSD and HD, which use monthly outputs). The MACA approach thus captures simulated changes in extreme events (Abatzoglou and Brown 2012), while BCSD and HD cannot resolve the sequencing of extreme events (Jung et al. 2012). In this regard, MACA output data contain less uncertainty than those coming from BCSD and HD downscaling techniques, or more uncertainty, if modeling is not capable of accurately predicting the future at the daily time scale. Although the analog MACA approach overcomes the limitations of interpolation-based methods (e.g. BCSD method) and thus yields more accurate spatial patterns, it neglects the model biases and is unable to address no-analog situations that may arise in a future climate (Abatzoglou and Brown 2012).

All statistical downscaling approaches are sensitive to the choice of calibration period: observational data should be of a high quality, and the training sample for calibration should be large enough (Mearns et al. 2014), as there is high uncertainty for values outside of calibration range.

Uncertainty in climate models is compounded by downscaling. Although downscaling provides information at finer scales, a tradeoff is that uncertainty and error are difficult to quantify (Trzaska and Schnarr 2014). Downscaling does not reduce the uncertainty in future climate change at local scale. Downscaling does not help with the uncertainty if global climate models disagree (Hallegatte et al. 2012).

4.3.3. Hydrologic models

The hydrologic model used in this research is the variable infiltration capacity (VIC) model (Liang et al. 1994, Liang et al. 1996). The VIC model is a large-scale, semi-distributed land hydrological model, which balances both water and surface energy within the grid cell, typically at resolutions ranging from a fraction of a degree to several degrees latitude by longitude (Elsner et al. 2010, Maurer 2007). The VIC model has been used in numerous studies of the hydrologic effects of climate variability and change on regional and global scales (e.g. in the Northwest, Elsner et al. 2010; Hamlet et al. 2010b). The VIC model explicitly considers the effects of vegetation, topography, and soils on the exchange of moisture and energy between land and atmosphere (Zhao et al. 2013). For each grid cell, the model calculates water balance variables such as evapotranspiration, runoff, baseflow, soil moisture, and snow water equivalent (Hamlet et al. 2010b).

VIC can be applied to multiple spatial scales and can be temporally discretized to hourly, daily, monthly and yearly time scales. The key characteristics of the grid-based VIC are the representation of multiple vegetation types, multiple soil layers with variable infiltration, and non-linear base flow (Zhao et al. 2013, Dan et al. 2012, Elsner et al. 2010, Maurer 2007). Early simulations with the VIC model were conducted using two soil layers. Later, it was determined that the specification of a thin top layer (5–15 cm) in the model significantly improved evapotranspiration predictions (Zhao et al. 2013, Liang et al. 1996). Potential evapotranspiration is calculated using a Penman Monteith approach (Hamlet et al. 2010b). Land use in the VIC hydrology model is static, being set at the level of the late twentieth century (Maurer 2007). This may lead to uncertainty in hydrologic predictions as a result of land cover change in response to climate change, or land conversion (such as agriculture to urban).

Both CIG and IS have implemented the VIC hydrologic model at 1/16th degree latitude by longitude resolution, or approximately 30 km^2 per cell (Hamlet et al. 2010b, Mote et al. 2014a), instead of 1/8th degree implemented in many studies (Hamlet et al. 2010b). Use of a finer spatial resolution better resolves smaller watersheds and reduces associated uncertainty.

The time period used for calibration was water year 1975 to 1989; a separate period was used for model validation (1960 to 1974). Although uncertainty arises from the choice of calibration/validation periods, the chosen 15-year periods are relatively long, encompassing a range of wet, dry, and average years to test VIC model performance under these conditions.

4.3.4. Future land cover

Land cover changes, such as urbanization, irrigated agriculture, grazing, reclamation, dust on snow, changing fire regimes through fire suppression, and deforestation affect land surface-atmosphere interactions and consequently alter thermodynamic and dynamic characteristics of the atmosphere, leading to different climate processes and patters. They play an important role in the climate system and hydrology through the impacts of these changes on atmospheric temperature, atmospheric pressure, evapotranspiration, humidity, cloud cover, circulation, and precipitation (Mahmood et al. 2014, Vano et al. 2014, Deng et al. 2014). There is great uncertainty associated with future land cover. It is hard to predict how forest cover or agriculture will change, or whether there will be more wildfires or not, and how all these changes will influence future climate and hydrology.

4.3.5. Different future periods

There is an uncertainty associated with the remoteness of the period for which climate/hydrologic simulations are projected. Overall, the more remote the future, the greater the uncertainty in streamflow and 7Q10 low-flow values associated with a future period. In our case, for example, predictions for 2020s or 2050s are likely to be more credible than projections for 2080s.

Additionally, the relative importance of the three sources of uncertainty in climate predictions – climate models, scenarios, and internal variability – varies with prediction lead time and with spatial and temporal averaging scale (Hawkins and Sutton 2009). For more remote periods (many decades or longer), the dominant sources of uncertainty at regional or larger spatial scales are model uncertainty and scenario uncertainty. For nearer time periods (a decade or two), the dominant sources of uncertainty on regional scales are model uncertainty and internal variability. Overall, the importance of internal variability increases at smaller spatial scales and shorter time scales (Hawkins and Sutton 2009).

4.3.6. Errors of omission/commission

Uncertainty associated with changes in future hydrology involves both errors of omission and errors of commission. Depending on the model and scenario chosen, decisions about site selection may exclude potential sites which in fact will be suitable (errors of omission), or conversely, may include some locations which in fact will turn out to be inappropriate (errors of commission).

4.4. Uncertainties associated with public attitudes towards nuclear power

Site selection for hazardous industry facilities, particularly for the nuclear power plants, depends on a number of factors. Availability of necessary natural resources and conditions are important, but often not a determining factor. Politics and public opinion in many cases play a significant role. To understand the uncertainties associated with public attitudes and politics, it is worth tracing the history of these important factors, and their role in the nuclear industry during different historical periods.

In the early days of the U.S. nuclear power development (1950s), public attitudes toward the technology were highly favorable, as the few opinion polls on the subject revealed. Press coverage of nuclear power was also overwhelmingly positive (Walker and Wellock 2010). However, in the late 1950s and early 1960s, the public became more alert to, and anxious about the hazards of radiation, stemming largely from a major controversy over radioactive fallout from nuclear weapons testing. The public became increasingly troubled about the risks of exposure to radioactivity from any source, including nuclear power. Yet, by the late 1960s, environmental concerns about industrial pollution, the deteriorating quality of the natural environment, and the growing demand for electricity, which was doubling every 10 years, placed nuclear power in an advantageous position as an air-pollution-free energy source.

In the 1970s and 1980s, the nuclear industry in the USA experienced significant growth, and then declined. Early growth was accompanied by a reformed regulatory system and especially by the creation of the Nuclear Regulatory Commission (NRC), which tightened safety standards and added criteria for site selection. By 1974, there were 54 operating reactors in the United States with another 197 on order. This period was one of great enthusiasm for nuclear power. The U.S. Atomic Energy Commission (1974) predicted that by the end of the twentieth century half of all U.S. electricity generation would come from nuclear power (Davis 2012). Instead, reactor orders fell precipitously after 1974. Over the next several years not only were new reactors not being ordered, but utilities began suspending construction on existing orders. Part of the explanation is that demand for electricity decreased and concern grew over nuclear issues, such as reactor safety, waste disposal, and other environmental considerations (DoE 2006). Beginning in the 1970s, it also became more difficult to site nuclear power plants. Communities began challenging nuclear power projects in federal and state courts, leading to extended construction delays and changing public attitudes about nuclear power (Davis 2012).

The first serious accident in the history of the nuclear power occurred on March 28, 1979, at the Three Mile Island Nuclear Station (TMI), Unit 2, near Harrisburg, PA. As a result of a series of mechanical failures and human errors, the accident uncovered the reactor’s core and melted about half of it (Walker and Wellock 2010). Although not a single person was injured, the accident intensified U.S. public concerns about nuclear safety (DoE 2006). Public opinion polls taken after the TMI accident showed significant erosion in support for nuclear power. One survey found that for the first time, the number of respondents who opposed building more nuclear units exceeded those who favored new plants. However, polls indicated that the public did not want to abandon nuclear power or close existing plants (Walker and Wellock 2010).

According to Bolsen and Cook (2008), there were three distinct stages in attitudes toward nuclear power from the early 1970s to the early 1980s. These stages were: the early 1970s, when

Americans were enthusiastic about the growth of nuclear power; a second stage of ambivalence following TMI when a less enthusiastic plurality of citizens consistently supported nuclear growth; and a third stage, emerging in the early 1980s, when a decisive majority of Americans opposed building more nuclear power plants (Figure 4.1).

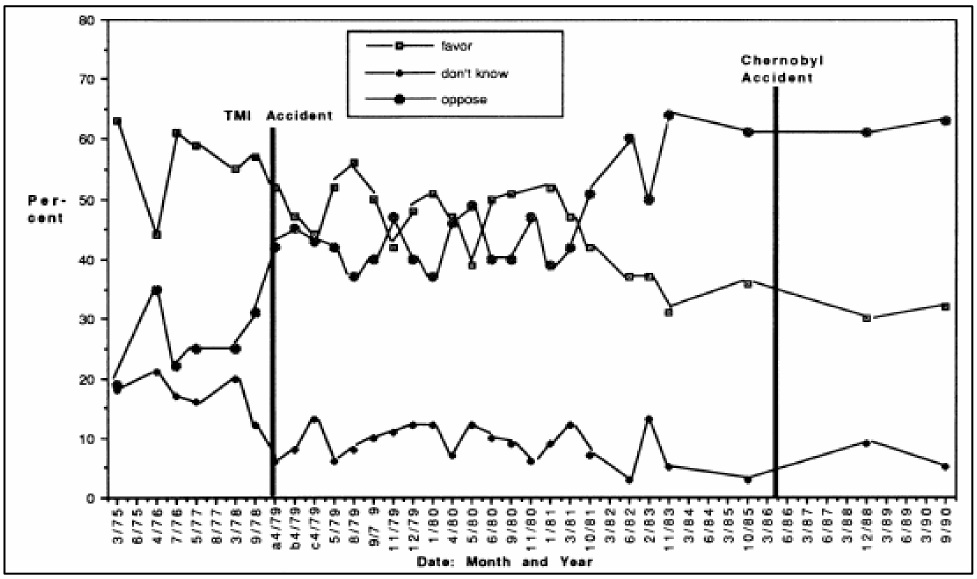


Figure 4.1. Public attitudes toward building nuclear plants in the United States. Source: Bolsen and Cook (2008).

While the NRC was still deliberating over and revising its requirements in the aftermath of TMI, another event shook the industry and further undercut public support for nuclear power. On April 26, 1986, Unit 4 of the nuclear power station at Chernobyl in the USSR underwent a violent explosion that destroyed the reactor and blew the top off it, spewing massive amounts of radioactivity into the environment. Cities and countries near the plant suffered from a high rate of radioactive fallout, but countries farther away like the Netherlands, Germany, France, and Great Britain also measured an increased level of radioactivity in the air, water, and soil (de Boer and Catsburg 1988). In virtually all polls taken immediately after the accident at Chernobyl nuclear power plant, U.S. public support for nuclear power declined and concerns about nuclear safety increased (Rosa and Dunlap 1994).

According to Bolsen and Cook (2008), by July of 1986, two months after the disaster at Chernobyl, only 24 percent of Americans supported the construction of more nuclear plants while 69 percent opposed (Figure 4.1). Surveys a year or so later, however, showed signs that nuclear power was regaining some of its lost ground, leading de Boer and Catsburg (1988) to hypothesize that the large changes toward increased opposition in public opinion are likely to be temporary.

It is one thing to have an opinion about the construction of nuclear power plants in the abstract; it is another to be confronted with the prospect of having a plant built nearby. Only a minority of Americans polled between 1983 and 1991 have supported total elimination of nuclear power (Rosa and Dunlap 1994). The most frequently chosen option, attracting sizable pluralities to majorities, favored the status quo: let the existing nuclear plants operate but do not build any more. Polling data of 1983-1991 showed that, on the one hand, solid majorities of the public opposed the construction of more nuclear plants and were likewise opposed to their local siting; on the other, equally solid majorities believed that nuclear power should be and will be an important energy source in the nation's future (Rosa and Dunlap 1994). Americans supported the idea of leaving the nuclear option open, perhaps as a trump card against possible future energy shortages; but when it came to the specific means for achieving that opinion - the siting and construction of nuclear power plants – they were solidly opposed (de Boer and Catsburg 1988).

Opposition of the U.S. public to nuclear power found expression in the case of specific nuclear power plants. In 1989, New York Governor Mario Cuomo and the Long Island Lighting Company closed the Shoreham Nuclear Power Plant because of public opposition and long-standing concerns about how nearby residents would be evacuated in the event of an emergency. The plant was 100 percent completed and had been connected to the grid, yet was never used to produce a single kilowatt hour of commercial electricity (Davis 2012).

Currently there are 104 nuclear power reactors at 65 sites in the US, and all of these reactors were ordered prior to 1974 (Davis 2012). In September 2007, the U.S. NRC received the first new license application for building a new nuclear power reactor in almost three decades, and during the following year, it received 16 license applications for a total of 24 proposed reactors. Natural gas prices were at their highest level ever in real terms. It was a period of renaissance for the nuclear power (Davis 2012).

While public attitudes toward nuclear energy were slow to rebound from the Three Mile Island and Chernobyl disasters, polls (e.g. Gallup and Pew Research Center) consistently found public support growing through the 1990s and 2000s (Stoutenborough et al. 2013). In the 2000s, with growing concerns related to climate change, nuclear power started to be reframed as a solution to a problem, rather than the source of a problem (He et al. 2013, Kessides 2012). However, the nuclear accident at Fukushima nuclear plant in Japan in 2011 again undermined public acceptance of nuclear energy (Kim et al. 2013, He et al. 2013, Ramana 2011). The Fukushima accident reversed the renaissance period and raised new questions concerning the security of potential locations for hazardous industrial facilities. A Washington Post-ABC poll conducted in April 2011 (immediately after the Fukushima accident) found that 64 percent of Americans opposed the construction of new reactors (Ramana 2011).

The Fukushima nuclear accident was a catastrophic incident that significantly lowered the level of public acceptance of nuclear energy across the globe (Kim et al. 2013). Nevertheless, while plenty of people do not support nuclear power, many argue that it is still a safe alternative and that the Fukushima disaster resulted from insufficient safety regulations in Japan, a problem that does not exist in the United States (Stoutenborough et al. 2013). The longer range prospects for nuclear power might be brighter than the near-term, post-Fukushima outlook (Kessides 2012).

In any case, the uncertainties associated with the public attitudes make the big part of the overall uncertainties related to the siting of nuclear reactors. Public attitudes may permit or prevent the construction of a nuclear plant within a candidate area selected based on siting criteria. This could be considered an “error” of omission, because in some sense candidate areas that are feasible for siting nuclear power plants are excluded by public opinion.

4.5. Summary and conclusion

In this chapter we discussed three main sources of uncertainty influencing nuclear plants siting associated with: (1) site selection process; (2) variations in hydrology due to climate change; and (3) public attitudes towards nuclear power. While siting criteria and projected changes in hydrology may significantly reduce the number of potential sites, public opposition to nuclear power could entirely prevent construction of reactors within areas that are physically and economically suitable for siting.

Public opinion is the biggest source of uncertainty associated with locating nuclear plants. Knowledge significantly influences public perceptions of nuclear energy, and surveys show that people who are more knowledgeable about nuclear power are more supportive of it (Stoutenborough et al. 2013). Thus, to deal with public attitudes it is important to educate the public about the nuclear power, its benefits and possible caveats. Another issue associated with this kind of uncertainty is the lack of transparency of the nuclear regulatory process for the public (Srinivasan and Gopi Rethinaraj 2013). To address this issue at any stage of the lifetime of a nuclear facility (site selection, operation, consequences after accidents, decommissioning), it is important to organize public hearings, hold public meetings, and share information in a transparent manner.

Deep uncertainty also arises from the future climate and hydrologic projections, as they predict the future that cannot be verified before it comes. Although this uncertainty is unavoidable, this does not mean that climate projections are useless. In many cases, climate model information provides understanding of what changes can be expected (Hallegatte et al. 2012). There are many methodologies for decision making under deep uncertainty, e.g. robust decision-making (many model runs are analyzed to distinguish future conditions), cost-benefit analysis (probabilities are attributed to the different scenarios, and "best" strategy is determined), or real option (the choice is not between "act" and "not act", but between "act now" and "act later with more information") (Hallegatte et al. 2012).

Less uncertainty is associated with the selection of sites using historical records, because they can be verified, in particular, by the maps of larger scale and/or by the field observations. The boundaries of the areas defined during selection of candidate areas, are refined further, while selecting potential sites, candidate sites, and, lastly, preferred sites.

This study provides a limited evaluation of sources of uncertainty in the process of site selection and prediction of the future climate and hydrology. Future work may include more detailed analysis of the sources of uncertainty and their management for nuclear power plant location.

Chapter 5. Conclusions

This study applied decision analysis to identify sites suitable for nuclear power plant location in the Columbia River Basin (CRB).

Chapter 1 established the disciplinary context of the study, and reviewed relevant prior literature. It summarized energy consumption, demand, and projected future energy shortfalls in the Columbia River Basin, which revealed a huge projected deficit of energy in the future. The chapter identified the following research questions: 1) What areas of the Columbia River Basin are suitable for siting nuclear plants based on location analysis using probabilistic risk assessment and historical streamflow records? 2) How will the potential future effects of climate change on streamflow influence siting of nuclear plants in the Columbia River Basin? 3) How does uncertainty about past and future climate and other factors, such as public perceptions of nuclear power, affect the outcome of the analysis?

The analysis presented in **Chapter 2** applied a multi-criteria decision analysis (MCDA) approach (a form of probabilistic risk assessment combined with location analysis) to select candidate areas for nuclear reactors of different capacity within the Columbia River Basin. To exclude areas unsuitable for siting, we used the probability of occurrence of events that can lead to accidents. A key variable was the probability of occurrence of low-flow events, which limit the cooling water available to a nuclear power plant utilizing a wet cooling tower. This probability (expressed by 7Q10 statistics) varied throughout the CRB and depending on the length of the historical time period considered (decade or half-century). The novel contributions in Chapter 2 include: (1) lack of a similar published analysis, and (2) assessment of the probabilities of water availability using historical stream gauge records.

The study revealed two main candidate regions suitable for NPP location, and several smaller clusters of candidate areas. One currently operating nuclear plant (Columbia Generating Station) is located within the Middle Columbia River candidate region (Washington), and another nuclear power plant is being planned in the Snake River plain candidate region (Payette county in Idaho). No large candidate areas were identified in Oregon.

According to our analysis, the projected deficit of energy in the CRB (for states of Oregon, Washington, and Idaho) by 2050 will be 514 million MWh (for 2013 this number was 576 million MWh), or 58,676 MWe of power. The growth of energy production during these 50 years is projected to be 347 million MWh (or 39,612 MWe of power). This energy increase and the future energy deficit must be compensated by construction of new energy sources, importing energy, or reducing energy demand. To meet the projected increase in electricity demand (39,612 MWe) in the CRB by 2050 would require the construction of 25 large reactors (or 113 small reactors). To meet the projected 2050 deficit of 58,676 MWe would require the construction of another 37 large reactors (or 168 small reactors). Thus, nuclear power can solve only a portion of the energy problem in the CRB region, because the defined candidate areas are not sufficient to locate this number of nuclear reactors.

The influence of future climate change on the probability of occurrence of events that can lead to accidents was addressed in **Chapter 3**. The analysis was based on the daily discharge data from the VIC hydrologic model run using output from five GCMs (CNRM-CM3, ECHAM5, and ECHO-G from CMIP3; CNRM-CM5 and CCSM4 from CMIP5), statistically downscaled using three different approaches (BCSD and Hybrid Delta for the CMIP3 models, and MACA for CMIP5 models) under medium (B1 and RCP4.5) and high (A1B and RCP8.5) emission scenarios, for three future periods (2020s, 2050s, 2080s). The simulated future hydrology of the CRB eliminated many of the smaller areas identified in Chapter 2, while the two main candidate regions remain almost the same. In other words, the two main locations for NPP siting in the Columbia Basin appeared to be robust to future climate change effects on water availability, given the limitations of GCMs, emission scenarios, downscaling approaches, etc.

Probabilistic risk assessment applied in Chapter 2 and Chapter 3 involved the magnitude of a specific adverse consequence (e.g. potential low-flows), and the probability of occurrence of this consequence. However, many uncertainties were involved including: (a) consequences not considered in the analysis, (b) probabilities not estimated correctly. **Chapter 4** identified major uncertainties including limits of the data for site selection, future climate and hydrology, and public attitudes towards nuclear power. Public opinion is the biggest source of uncertainty associated with siting nuclear facilities. While criteria for site selection and projected changes in hydrology may significantly reduce the number of suitable areas, public opposition to nuclear power could entirely prevent construction of reactors within areas that are physically and economically suitable for siting. Deep uncertainty also arises from the future climate and hydrologic projections, because they predict the future that cannot be verified before it comes.

Smaller uncertainty is associated with the selection of sites using historical records, because they can be verified.

Risk in PRA is determined by two factors: 1) probability of the occurrence of an adverse consequence, and 2) magnitude of possible adverse consequence (Kafka 2008). The MCDA procedure that we used in our analysis involved specific consequences such as potential earthquakes, floods, loss of cooling water, landslides. The probability of risky events was assessed via calculating 7Q10 statistics (for low-flow risks), via estimating peak ground acceleration rates (for earthquake risks), the steepness of slopes (for landslide risks), and 100-year floodplain zones (for flood risks).

Among the overall limitations of the outcome of an MCDA approach, as a form of probabilistic risk assessment, is the lack of some consequences in the NRC regulations. For example, climate change as a phenomenon does not appear to be a part of these consequences, although potentially the influence of climate change may cause the occurrence of events that can lead to accidents (e.g. droughts, or floods).

Also, there are uncertainties which affect the probabilities used during the selection of candidate sites. For example, the MCDA approach in this study did not consider the long-term probability of occurrence of 7Q10 low-flow statistics, which is uncertain because of climate change, but also because of other factors affecting water availability (for example, land cover).

5.1. Future work

This analysis focused on the selection of candidate areas for siting nuclear reactors in the CRB using the first stage of the site selection process specified by the US Nuclear Regulatory Commission. Future work is needed on the further steps of siting process, which involve selection of potential sites, candidate sites, and, lastly, preferred sites. These steps refine boundaries of exclusion areas using larger scale maps. Also, these steps involve additional criteria (e.g. water quality, sedimentations rates, transportation access, land rights, emergency planning issues, and others). The candidate areas defined in this study are only the “starting point” for nuclear power plant siting.

The analysis of the future projections was focused on expected future changes in water availability necessary for cooling. We considered other siting criteria as stationary, although understanding they also may change in the future; however, these changes were out of scope of this research. Future work may include investigations of the influence of climate change on the other criteria (such as population distribution, floods, and landslides).

Additionally, this study provides a limited evaluation of sources of uncertainty in the process of site selection and prediction of the future climate and hydrology. Future work may include more detailed analysis of the sources of uncertainty and their management for nuclear power plant location.

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APPENDICES

Appendix 1. Python code created for calculating 7Q10 low-flow values

low_flow_calc

```
gaugeData = open('file name')
gaugeDataList = gaugeData.readlines()

averages_list = []
charge = []
for item in gaugeDataList:
    charge.append(item[0 : ])

idx_items = 0
while idx_items < len(charge) - 7:
    sum_items = 0
    for item in charge[0 + idx_items : 7 + idx_items]:
        sum_items += float(item)
    aver_flow = float(sum_items) / 7
    averages_list.append(aver_flow)
    idx_items += 1

min_average = min(averages_list)
print min_average
```

Appendix 2. List of gauges for which historical 7Q10 low-flow was calculated

FID	Shape *	STAID	STANAME	DRAIN_SQK	LAT_GAGE	LNG_GAGE	STATE	low_fl_10
0	Point	13077700	GEORGE CREEK NEAR YOST, UTAH	20.1726	41.918529	-113.48166	UT	1.3
1	Point	13079000	CLEAR CREEK NEAR NAF, IDAHO	51.8328	41.966862	-113.28666	UT	0.4
2	Point	13174500	OWYHEE R NR GOLD CREEK, NV	527.5683	41.688794	-115.84480	NV	0.05
3	Point	13078000	RAFT RIVER AB ONEMILE CREEK NR MALTA ID	1059.469	42.063611	-113.45138	ID	0.291429
4	Point	13105000	SALMON FALLS CREEK NR SAN JACINTO NV	3629.59	41.944722	-114.68861	NV	10.7143
5	Point	13162225	JARBIDGE RV BLW JARBIDGE, NV	76.1346	41.890461	-115.42868	NV	1.35714
6	Point	13082500	GOOSE CREEK AB TRAPPER CREEK NR OAKLEY ID	1632.673	42.126111	-113.93555	ID	0.942857
7	Point	13175100	OWYHEE RV NR MOUNTAIN CITY, NV	1014.325	41.860458	-115.98926	NV	3.22857
8	Point	13083000	TRAPPER CREEK NR OAKLEY ID	133.1838	42.165833	-113.98361	ID	5.1
9	Point	13177800	S F OWYHEE R NR WHITEROCK, NV	2790.847	41.799898	-116.48427	NV	5.75714
10	Point	13161500	BRUNEAU RIVER AT ROWLAND NV	986.1309	41.933237	-115.67452	NV	2.08571
11	Point	13176000	OWYHEE RIVER AB CHINA DIVERSION DAM NR OWYHEE N	1173.884	41.921108	-116.06955	NV	11.4286
12	Point	13025000	SWIFT CREEK NEAR AFTON, WY	70.7274	42.726111	-110.89777	WY	26.7143
13	Point	13073000	PORTNEUF RIVER AT TOPAZ ID	1523.439	42.625556	-112.08805	ID	54.7143
14	Point	13075000	MARSH CREEK NR MCCAMMON ID	907.9749	42.63	-112.22596	ID	12
15	Point	13092000	ROCK CREEK NR ROCK CREEK ID	211.221	42.356303	-114.30419	ID	4.57143
16	Point	13063000	BLACKFOOT RIVER AB RESERVOIR NR HENRY ID	863.4066	42.815278	-111.50666	ID	7.78571
17	Point	13081500	SNAKE R NR MINIDOKA ID (AT HOWELLS FERRY)	48830.41	42.672778	-113.50027	ID	405
18	Point	13077000	SNAKE RIVER AT NEELEY ID	40151.53	42.7675	-112.87944	ID	322.143
19	Point	13092747	ROCK CREEK AB HWY 30/93 XING AT TWIN FALLS ID	664.3553	42.5625	-114.49472	ID	29.8571
20	Point	13075500	PORTNEUF RIVER AT POCATELLO ID	3353.598	42.871667	-112.46805	ID	16.5714
21	Point	13027500	SALT RIVER AB RESERVOIR NR ETNA WY	2206.336	43.079722	-111.03722	WY	323.857
22	Point	13075910	PORTNEUF RIVER NR TYHEE ID	3342.839	42.944722	-112.54444	ID	38
23	Point	13023000	GREYS RIVER AB RESERVOIR NR ALPINE WY	1161.929	43.142778	-110.97666	WY	124.286
24	Point	13167500	EF BRUNEAU RIVER NR HOT SPRING ID	1304.077	42.55675	-115.51022	ID	0
25	Point	13022500	SNAKE RIVER AB RESERVOIR NR ALPINE WY	8867.073	43.196111	-110.88944	WY	1170
26	Point	13108150	SALMON FALLS CREEK NR HAGERMAN ID	5632.912	42.696389	-114.85527	ID	19.2857
27	Point	13075983	SPRING CREEK AT SHEEPSKIN RD NR FORT HALL ID	53.6661	43.0425	-112.55	ID	213.286
28	Point	13068501	BLACKFOOT RIVER AND BYPASS CHANNEL NR BLACKFOO	2753.508	43.13047	-112.47720	ID	1.57714
29	Point	13068500	BLACKFOOT RIVER NR BLACKFOOT ID	2753.494	43.130556	-112.47666	ID	1.3
30	Point	13069500	SNAKE RIVER NR BLACKFOOT ID	31558.4	43.125192	-112.51914	ID	983.714
31	Point	13018750	SNAKE RIVER BL FLAT CREEK NR JACKSON WY	6884.45	43.372222	-110.73861	WY	981.429
32	Point	13062500	SNAKE RIVER AT BLACKFOOT ID	28139.67	43.1975	-112.36916	ID	921.429
33	Point	13153500	MALAD RIVER NR BLISS ID	8322.071	42.863235	-114.90200	ID	79.5714
34	Point	13032500	SNAKE RIVER NR IRWIN ID	13424.32	43.350833	-111.21888	ID	765.429
35	Point	13152500	MALAD RIVER NR GOODING ID	8607.503	42.886389	-114.80305	ID	0
36	Point	13066000	BLACKFOOT RIVER NR SHELLEY ID	2324.469	43.262778	-112.04777	ID	35.7143
37	Point	13168500	BRUNEAU RIVER NR HOT SPRING ID	6958.448	42.771111	-115.72027	ID	31.5714
38	Point	13018300	CACHE CREEK NEAR JACKSON, WY	27.90146	43.452153	-110.70409	WY	2.88571
39	Point	13018350	FLAT CREEK BELOW CACHE CREEK, NEAR JACKSON, WY	333.0387	43.458333	-110.79611	WY	26.1429
40	Point	13169500	BIG JACKS CREEK NR BRUNEAU ID	631.6308	42.784895	-115.98425	ID	0
41	Point	13016450	FISH CREEK AT WILSON, WY	183.3435	43.50076	-110.8716	WY	28.4286
42	Point	13057940	WILLOW CREEK BL TEX CREEK NR RIRIE ID	1472.161	43.441667	-111.72833	ID	9.5
43	Point	13015000	GROS VENTRE RIVER AT ZENITH WY	1608.247	43.557222	-110.76277	WY	0
44	Point	13060000	SNAKE RIVER NR SHELLEY ID	26342.95	43.413056	-112.135	ID	1350
45	Point	13014500	GROS VENTRE RIVER AT KELLY, WY	1571.78	43.622222	-110.625	WY	114.429
46	Point	13016305	GRANITE C AB GRANITE C SUPPLEMENTAL, NR MOOSE,	39.5442	43.603818	-110.80548	WY	1.37143
47	Point	13016240	LAKE CR BEL GRANITE CR SUPPLEMENTAL, NR MOOSE,	57.7953	43.61354	-110.77965	WY	0
48	Point	13013650	SNAKE RIVER AT MOOSE, WY	4311.2	43.654056	-110.71547	WY	595.857
49	Point	13058000	WILLOW CREEK NR RIRIE ID	1654.143	43.583333	-111.74583	ID	0
50	Point	13142500	BIG WOOD RIVER BL MAGIC DAM NR RICHFIELD ID	3981.529	43.24796	-114.35643	ID	0.605714
51	Point	13037500	SNAKE RIVER NR HEISE ID	14858.54	43.6125	-111.66	ID	1085.71
52	Point	13150430	SILVER CREEK AT SPORTSMAN ACCESS NR PICABO ID	184.9266	43.322222	-114.10666	ID	47.7143
53	Point	13057155	SNAKE RIVER AB EAGLE ROCK NR IDAHO FALLS ID	24688.22	43.604722	-112.05861	ID	1300
54	Point	13140800	BIG WOOD RIVER AT STANTON CROSSING NR BELLEVUE I	1899.155	43.32917	-114.31917	ID	10.1286
55	Point	13141000	BIG WOOD RIVER NR BELLEVUE ID	1947.981	43.328042	-114.34177	ID	10.8571
56	Point	13148500	LITTLE WOOD RIVER NR CAREY ID	801.7371	43.39	-113.99972	ID	0.197143
57	Point	13132520	BIG LOST RIVER BL INEEL DIV NR ARCO ID	4281.379	43.515833	-113.08194	ID	0
58	Point	13011900	BUFFALO FORK AB LAVA CREEK NR MORAN WY	851.8032	43.838056	-110.44111	WY	78.5714
59	Point	13141500	CAMAS CREEK NR BLAINE ID	1624.693	43.332778	-114.54194	ID	1.27143
60	Point	13011500	PACIFIC CREEK AT MORAN WY	404.0775	43.850278	-110.51777	WY	21
61	Point	13181000	OWYHEE RIVER NR ROME OR	19916.13	42.866389	-117.64916	OR	58

FID	Shape *	STAID	STANAME	DRAIN_SQK	LAT_GAGE	LNG_GAGE	STATE	low_fl_10
62	Point	13052200	TETON RIVER AB SOUTH LEIGH CREEK NR DRIGGS ID	869.7069	43.781389	-111.20916	ID	143.143
63	Point	13132535	BIG LOST R AT LINCOLN BLVD BRIDGE NR ATOMIC CITY	4743.366	43.573889	-112.94333	ID	0
64	Point	13011000	SNAKE RIVER NR MORAN WY	1964.2	43.858333	-110.58583	WY	255.286
65	Point	13038500	SNAKE RIVER AT LORENZO ID	14979.16	43.735278	-111.87805	ID	372.857
66	Point	13132500	BIG LOST RIVER NR ARCO ID	3869.123	43.582222	-113.27055	ID	0
67	Point	13057000	SNAKE RIVER NR MENAN ID	23703.15	43.752778	-111.97916	ID	1407.14
68	Point	13147900	LITTLE WOOD RIVER AB HIGH FIVE CREEK NR CAREY ID	645.9073	43.491572	-114.05920	ID	13.4286
69	Point	13159800	CANYON CR AT OREGON TRAIL XING NR MOUNTAIN HOME	184.2651	43.261111	-115.7025	ID	0.068571
70	Point	13055340	SF TETON RIVER NEAR REXBURG ID	2764.828	43.835	-111.77777	ID	0
71	Point	13056500	HENRYS FORK NR REXBURG ID	8336.927	43.825833	-111.905	ID	472.143
72	Point	13190500	SF BOISE RIVER AT ANDERSON RANCH DAM ID	2532.608	43.341562	-115.47869	ID	246.857
73	Point	13139500	BIG WOOD RIVER AT HAILEY ID	1624.031	43.517222	-114.32166	ID	78
74	Point	13132565	BIG LOST RIVER AB BIG LOST RIVER SINKS NR HOWE ID	4975.601	43.72333	-112.875	ID	0
75	Point	13055250	NF TETON RIVER NR SUGAR CITY ID	62.9883	43.8875	-111.75778	ID	0
76	Point	13055198	NORTH FORK TETON RIVER AT TETON ID	2301.44	43.897968	-111.67774	ID	53.2857
77	Point	13055000	TETON RIVER NR ST ANTHONY ID	2294.463	43.927135	-111.61607	ID	268.571
78	Point	13050500	HENRYS FORK AT ST ANTHONY ID	4807.364	43.966944	-111.6725	ID	788.571
79	Point	13186000	SF BOISE RIVER NR FEATHERVILLE ID	1660.134	43.495833	-115.30805	ID	100.714
80	Point	13010065	SNAKE RIVER AB JACKSON LAKE AT FLAGG RANCH WY	1222.287	44.098889	-110.6675	WY	195.429
81	Point	13046995	FALLS RIVER AB YELLOWSTONE CANAL NR SQUIRREL ID	835.1658	44.061944	-111.15194	ID	333.286
82	Point	13049500	FALLS RIVER NR CHESTER ID	1324.234	44.018333	-111.56666	ID	72.1429
83	Point	13047500	FALLS RIVER NR SQUIRREL ID	799.9791	44.068611	-111.24138	ID	197.429
84	Point	13047600	FALLS RIVER NR ASHTON ID	873.6606	44.056111	-111.35861	ID	338.143
85	Point	13046000	HENRYS FORK NR ASHTON ID	2865.313	44.069722	-111.51055	ID	742.571
86	Point	13119000	LITTLE LOST RIVER NR HOWE ID	1809.41	43.886014	-113.10083	ID	19.1429
87	Point	13112000	CAMAS CREEK AT CAMAS ID	947.232	44.002778	-112.22111	ID	0
88	Point	13114000	BEAVER CREEK NR CAMAS ID	1012.135	44.007222	-112.2242	ID	0
89	Point	13046680	BOUNDARY CREEK NR BECHLER RANGER STATION Y.N.P.	220.1688	44.185278	-111.00777	WY	54
90	Point	13202000	BOISE RIVER NR BOISE ID	6959.264	43.527669	-116.05955	ID	166.286
91	Point	13135500	BIG WOOD RIVER NR KETCHUM ID	354.4434	43.786297	-114.42505	ID	0
92	Point	13127000	BIG LOST RIVER BL MACKAY RES NR MACKAY ID	1979.611	43.939167	-113.64833	ID	45.2857
93	Point	13185000	BOISE RIVER NR TWIN SPRINGS ID	2154.389	43.659444	-115.72722	ID	258.857
94	Point	13200500	ROBIE CREEK NR ARROWROCK DAM ID	41.6601	43.629917	-115.99970	ID	0.008571
95	Point	13205500	BOISE RIVER AT BOISE ID	7101.839	43.609056	-116.20845	ID	86.1429
96	Point	13204640	COTTONWOOD CREEK BEL FIVEMILE CR NR BOISE ID	15.3846	43.628611	-116.11083	ID	0
97	Point	13200000	MORES CREEK AB ROBIE CREEK NR ARROWROCK DAM ID	1028.84	43.648056	-115.98972	ID	6.8
98	Point	13120000	NF BIG LOST RIVER AT WILD HORSE NR CHILLY ID	297.2691	43.933611	-114.1125	ID	14.7143
99	Point	13113500	BEAVER CREEK AT DUBOIS ID	627.8292	44.186021	-112.23637	ID	0
100	Point	13206000	BOISE RIVER AT GLENWOOD BRIDGE NR BOISE ID	7182.155	43.660556	-116.27916	ID	199
101	Point	13120500	BIG LOST RIVER AT HOWELL RANCH NR CHILLY ID	1143.906	43.998333	-114.02111	ID	47.7143
102	Point	13118700	LITTLE LOST RIVER BL WET CREEK NR HOWE ID	1104.002	44.138611	-113.24527	ID	5.21429
103	Point	13116500	MEDICINE LODGE CREEK NR SMALL ID	679.8448	44.258889	-112.41	ID	12
104	Point	13196500	BANNOCK CREEK NR IDAHO CITY ID	12.2436	43.807283	-115.77510	ID	0.18
105	Point	13042500	HENRYS FORK NR ISLAND PARK ID	1325.219	44.416667	-111.39472	ID	71
106	Point	13116000	MEDICINE LODGE CREEK AT ELLIS RANCH NR ANGORA ID	408.5901	44.291183	-112.50256	ID	9.17143
107	Point	13113000	BEAVER CREEK AT SPENCER ID 12N-36E-23A	319.6791	44.355336	-112.17997	ID	0
108	Point	13212500	BOISE RIVER AT NOTUS ID	9842.887	43.722383	-116.79375	ID	94
109	Point	13183000	OWYHEE RIVER BELOW OWYHEE DAM OR	28159.19	43.654444	-117.25583	OR	6.54286
110	Point	13215000	MALHEUR R BE WARMSPRINGS RES NR RIVERSIDE OR	2786.962	43.574444	-118.20972	OR	0
111	Point	13213000	BOISE RIVER NR PARMA ID	10124.23	43.781667	-116.97277	ID	229.714
112	Point	13039500	HENRYS FORK NR LAKE ID	244.3383	44.595	-111.34916	ID	0.3
113	Point	13247500	PAYETTE RIVER NR HORSESHOE BEND ID	5743.841	43.943333	-116.19666	ID	675
114	Point	13250000	PAYETTE RIVER NR LETHA ID	7318.918	43.896111	-116.62777	ID	182.143
115	Point	13249500	PAYETTE RIVER NR EMMETT ID	7067.407	43.930556	-116.44277	ID	448.571
116	Point	13235000	SF PAYETTE RIVER AT LOWMAN ID	1163.229	44.085278	-115.62222	ID	190.714
117	Point	13297330	THOMPSON CREEK NR CLAYTON ID	75.6405	44.270278	-114.51666	ID	1.94286
118	Point	13295000	VALLEY CREEK AT STANLEY ID	376.3872	44.2225	-114.93111	ID	53.2857
119	Point	13297355	SQUAW CREEK BL BRUNO CREEK NR CLAYTON ID	185.6556	44.290833	-114.47166	ID	6.17143
120	Point	13297350	BRUNO CREEK NR CLAYTON ID	16.551	44.2975	-114.48138	ID	0.041429
121	Point	13296500	SALMON RIVER BL YANKEE FORK NR CLAYTON ID	2090.915	44.268333	-114.73277	ID	287.714
122	Point	13238000	PAYETTE RIVER NR BANKS ID	3080.059	44.085448	-116.09984	ID	400.286
123	Point	13237920	MIDDLE FORK PAYETTE RIVER NR CROUCH ID	874.8054	44.108611	-115.98222	ID	65.1429

FID	Shape *	STAID	STANAME	DRAIN_SQK	LAT_GAGE	LNG_GAGE	STATE	low_fl_10
124	Point	13298500	SALMON RIVER NR CHALLIS ID	4632.931	44.378532	-114.25589	ID	435.714
125	Point	13246000	NF PAYETTE RIVER NR BANKS ID	2392.131	44.113781	-116.10790	ID	205
126	Point	13220000	MALHEUR RIVER AT LITTLE VALLEY NEAR HOPE,OREG.	7826.062	43.899326	-117.50796	OR	8.27143
127	Point	13250600	BIG WILLOW CREEK NR EMMETT ID	126.7146	44.074703	-116.48553	ID	1.77143
128	Point	13214000	MALHEUR RIVER NEAR DREWSEY, OR	2451.443	43.784602	-118.33158	OR	0.548571
129	Point	13233300	MALHEUR RIVER BELOW NEVADA DAM NEAR VALE OR	12021.36	43.9875	-117.21889	OR	0.472857
130	Point	13251000	PAYETTE RIVER NR PAYETTE ID	8534.454	44.042222	-116.92527	ID	492.571
131	Point	13236500	DEADWOOD RIVER BL DEADWOOD RES NR LOWMAN ID	283.6323	44.291944	-115.64194	ID	0.51
132	Point	13226500	BULLY CREEK AT WARMSPRINGS NEAR VALE,OREG.	1394.481	44.019326	-117.46074	OR	0
133	Point	13217500	NORTH FORK MALHEUR RIVER AT BEULAH OR	1157.341	43.9075	-118.15333	OR	0.02
134	Point	13308500	MF SALMON RIVER NR CAPEHORN ID	358.0902	44.409072	-115.18371	ID	51
135	Point	13216500	N FK MALHEUR R AB BEULAH RES NR BEULAH,OREG.	885.3129	43.948214	-118.17436	OR	20.5714
136	Point	13266000	WEISER RIVER NR WEISER ID	3751.663	44.27	-116.77222	ID	74.2857
137	Point	13302005	PAHSIMEROI RIVER AT ELLIS ID	2143.219	44.691667	-114.04694	ID	97.1429
138	Point	13265500	CRANE CREEK AT MOUTH NR WEISER ID	732.0762	44.291389	-116.78222	ID	0.985714
139	Point	13264500	CRANE CREEK NR MIDVALE ID	605.8872	44.355443	-116.61904	ID	0
140	Point	13245000	NF PAYETTE RIVER AT CASCADE ID	1593.936	44.524893	-116.04679	ID	146
141	Point	13261000	LITTLE WEISER RIVER NR INDIAN VALLEY ID	206.7201	44.492472	-116.39711	ID	4.01429
142	Point	13275000	BURNT RIVER AT HUNTINGTON, OREG.	2832.758	44.358217	-117.27323	OR	6.48571
143	Point	14060000	CRESCENT CR AT CRESCENT LAKE NR CRESCENT,OREG.	147.6	43.502903	-121.97336	OR	0
144	Point	13309220	MF SALMON RIVER AT MF LODGE NR YELLOW PINE ID	2696.614	44.721667	-115.01638	ID	302
145	Point	14055500	ODELL CREEK NEAR CRESCENT,OREG.	96.8598	43.547346	-121.96253	OR	15.5714
146	Point	13305000	LEMHI RIVER NR LEMHI ID	2412.171	44.94	-113.63916	ID	84.2857
147	Point	14063000	LITTLE DESCHUTES RIVER NEAR LA PINE,OREG.	2285.511	43.68901	-121.50280	OR	24.8571
148	Point	13258500	WEISER RIVER NR CAMBRIDGE ID	1540.317	44.579444	-116.64333	ID	34
149	Point	14056500	DESCHUTES R BL WICKIUP RES NR LA PINE,OREG.	1151.622	43.685953	-121.68808	OR	16.4286
150	Point	14054500	BROWN CREEK NEAR LA PINE,OREG.	52.8894	43.712897	-121.80391	OR	22
151	Point	14144800	MIDDLE FORK WILLAMETTE RIVER NR OAKRIDGE OREG	669.3398	43.597066	-122.45671	OR	172.286
152	Point	14054000	DESCHUTES R BL CRANE PRAIRIE RES NR LA PINE,OREG	670.4811	43.753452	-121.78364	OR	1.74286
153	Point	14057500	FALL RIVER NEAR LA PINE,OREG.	124.2126	43.796508	-121.57280	OR	82.5714
154	Point	14037500	STRAWBERRY CR AB SLIDE CR NR PRAIRIE CITY,OREG.	18.2376	44.341548	-118.65661	OR	1.4
155	Point	14036860	JOHN DAY R AT BLUE MTN HOT SPGS NR PRAIRIE CITY,O	104.3073	44.35794	-118.57605	OR	25.1429
156	Point	14053000	CHARLTON CR AB CRANE PRAIRIE RES NR LA PINE,OREG	39.9933	43.780674	-121.83614	OR	0
157	Point	13274200	BURNT RIVER NEAR BRIDGEPORT, ORE.	1682.593	44.543493	-117.68715	OR	5.97143
158	Point	14144900	HILLS CR AB HILLS CR RES, NR OAKRIDGE,OREG.	136.7514	43.680401	-122.3706	OR	16.4286
159	Point	13305310	LEMHI RIVER BELOW L5 DIVERSION NEAR SALMON, ID	3134.748	45.132778	-113.79888	ID	17.5714
160	Point	14078000	BEAVER CREEK NEAR PAULINA,OREG.	1166.969	44.163751	-119.92331	OR	0.121429
161	Point	14050000	DESCHUTES RIVER BL SNOW CR NR LA PINE,OREG.	323.3997	43.814006	-121.77697	OR	65.2857
162	Point	14052000	DEER CR AB CRANE PRAIRIE RES NR LA PINE,OREG.	45.2007	43.804841	-121.83947	OR	0
163	Point	14050500	CULTUS RIVER AB CULTUS CR NR LA PINE,OREG.	39.2742	43.818173	-121.79558	OR	34.7143
164	Point	14051000	CULTUS CR AB CRANE PRAIRIE RES NR LA PINE,OREG.	85.0986	43.821229	-121.82391	OR	0
165	Point	13273000	BURNT RIVER NEAR HEREFORD, OR	803.43	44.503772	-118.17743	OR	0.03
166	Point	14145500	M F WILLAMETTE R AB SALT CR., NR OAKRIDGE, OREG	1016.985	43.722068	-122.43865	OR	265.143
167	Point	14064500	DESCHUTES R AT BENHAM FALLS NR BEND,OREG.	4522.208	43.930117	-121.41197	OR	417.429
168	Point	13302500	SALMON RIVER AT SALMON ID	9709.622	45.183611	-113.89527	ID	537.143
169	Point	13313000	JOHNSON CREEK AT YELLOW PINE ID	561.9358	44.961667	-115.5	ID	52.5714
170	Point	14038530	JOHN DAY RIVER NEAR JOHN DAY, OR	1009.755	44.418489	-118.90634	OR	13.7143
171	Point	14146500	SALMON CREEK NEAR OAKRIDGE,OREG.	302.6502	43.762346	-122.37282	OR	105.857
172	Point	13242500	LAKE FORK PAYETTE RIVER BL LID CANAL NR MCCALL ID	157.4532	44.895308	-116.04060	ID	0.294286
173	Point	13240000	LAKE FORK PAYETTE RIVER AB JUMBO CR NR MCCALL ID	125.5698	44.913611	-115.99722	ID	7.92857
174	Point	14147500	N FK OF M FK WILLAMETTE R NR OAKRIDGE,OREG.	640.6209	43.758179	-122.50949	OR	108.714
175	Point	14152500	COAST FORK WILLAMETTE RIVER AT LONDON, OREG.	184.7169	43.64151	-123.08590	OR	9.08571
176	Point	13239000	NF PAYETTE RIVER AT MCCALL ID	375.6537	44.907222	-116.11916	ID	14.7143
177	Point	14080500	CROOKED RIVER NEAR PRINEVILLE, OR	6904.596	44.113182	-120.79557	OR	7.32857
178	Point	13306385	NAPIAS CREEK BELOW ARNETT CREEK NEAR LEESBURG,	105.2055	45.20556	-114.13389	ID	5.72857
179	Point	13310700	SF SALMON RIVER NR KRASSEL RANGER STATION ID	853.1325	44.986944	-115.725	ID	85.2857
180	Point	14154500	ROW RIVER ABOVE PITCHER CREEK NEAR, DORENA, ORE	546.8105	43.735957	-122.87340	OR	11.5714
181	Point	14148000	MF WILLAMETTE RIVER BLW N FORK, NR OAKRIDGE, OR.	2409.197	43.801235	-122.56088	OR	805.714
182	Point	13286700	POWDER RIVER NEAR RICHLAND,OREG.	3512.036	44.777661	-117.29268	OR	1.85714
183	Point	13275300	POWDER RIVER NEAR SUMPTER, OREG.	427.3182	44.6721	-117.99549	OR	0.015714
184	Point	14153500	COAST FORK WILLAMETTE R BLW COTTAGE GROVE DAM	274.9752	43.720678	-123.04979	OR	31.1429
185	Point	14070500	DESCHUTES RIVER BELOW BEND,OREG.	4809.92	44.082895	-121.30781	OR	22.7143

FID	Shape *	STAID	STANAME	DRAIN_SQK	LAT_GAGE	LNG_GAGE	STATE	low_fl_10
186	Point	13251500	WEISER RIVER AT TAMARACK ID	94.1184	44.946686	-116.38281	ID	2.55714
187	Point	14073001	TUMALO CREEK NEAR BEND, OR	124.1262	44.087617	-121.37281	OR	0
188	Point	13254500	LOST CREEK NR TAMARACK ID	75.9402	44.954719	-116.46642	ID	0.185714
189	Point	14156500	MOSBY CR AT MOUTH, NR COTTAGE GROVE,OREG.	246.3003	43.776234	-122.99979	OR	3.57143
190	Point	14155500	ROW RIVER NEAR COTTAGE GROVE, OR	696.4029	43.792901	-122.99146	OR	86.2857
191	Point	13277000	POWDER RIVER AT BAKER CITY, OR	899.8533	44.768208	-117.83160	OR	3.61429
192	Point	13306500	PANTHER CREEK NR SHOUP ID	1348.842	45.306028	-114.39286	ID	43.8571
193	Point	13288200	EAGLE CREEK ABV SKULL CREEK, NR NEW BRIDGE, OR	403.7085	44.880438	-117.25379	OR	41.8571
194	Point	13290190	PINE CREEK NR OXBOW OR	772.0587	44.952397	-116.87416	OR	17.2857
195	Point	13310199	MIDDLE FORK SALMON RIVER AT MOUTH NR SHOUP ID	7450.978	45.293611	-114.59638	ID	595.429
196	Point	13307000	SALMON RIVER NR SHOUP ID	16172.04	45.3225	-114.44	ID	768.429
197	Point	14150800	WINBERRY CREEK NEAR LOWELL,OR	113.3136	43.914292	-122.68867	OR	3.67143
198	Point	14040500	JOHN DAY R AT PICTURE GORGE, NR DAYVILLE,OREG.	4366.206	44.520699	-119.62609	OR	6.37143
199	Point	14159200	SO FK MCKENZIE RIVER ABV COUGAR LAKE NR RAINBOW	414.2997	44.047067	-122.21782	OR	181.857
200	Point	14150300	FALL CR. NEAR LOWELL, OREG.	304.9047	43.970682	-122.63867	OR	15.7143
201	Point	14151000	FALL CREEK BLW WINBERRY CREEK, NEAR FALL CREEK,	481.0788	43.944293	-122.77479	OR	44
202	Point	14150000	MIDDLE FORK WILLAMETTE RIVER NEAR DEXTER, OREG.	2605.191	43.945681	-122.83729	OR	966.143
203	Point	14075000	SQUAW CREEK NEAR SISTERS,OREG.	147.8871	44.233727	-121.56698	OR	21.5714
204	Point	14157500	COAST FORK WILLAMETTE RIVER NEAR GOSHEN, OR	1663.972	43.980403	-122.96647	OR	117.714
205	Point	14152000	MIDDLE FORK WILLAMETTE RIVER AT JASPER, OR	3491.435	43.998182	-122.90591	OR	1074.29
206	Point	14159500	SOUTH FORK MCKENZIE RIVER NEAR RAINBOW, OR	539.5959	44.135958	-122.24839	OR	182.143
207	Point	14159000	MCKENZIE R AT MCKENZIE BRIDGE, OREG.	904.5936	44.179012	-122.13033	OR	781
208	Point	14159110	MCKENZIE RIVER ABOVE SOUTH FORK, NEAR RAINBOW, O	1362.46	44.166376	-122.25653	OR	0
209	Point	14162500	MCKENZIE RIVER NEAR VIDA, OR	2402.694	44.124849	-122.47062	OR	1828.57
210	Point	14163900	MCKENZIE RIVER NEAR WALTERVILLE, OR	2808.228	44.069849	-122.77118	OR	974.429
211	Point	14162200	BLUE RIVER AT BLUE RIVER, OR	227.6181	44.162348	-122.33311	OR	44.8571
212	Point	14164700	CEDAR CREEK AT SPRINGFIELD, OR	25.1064	44.059348	-122.91966	OR	0.234286
213	Point	14163150	MCKENZIE RIVER BLW LEABURG DAM, NR LEABURG, OR	2668.18	44.123738	-122.62757	OR	989.429
214	Point	14161500	LOOKOUT CREEK NEAR BLUE RIVER, OR	62.4241	44.209571	-122.25673	OR	7.27143
215	Point	14163000	GATE CREEK AT VIDA,OREG.	124.4484	44.145683	-122.57201	OR	11.8571
216	Point	14164900	McKENZIE RIVER ABV HAYDEN BR, AT SPRINGFIELD,OR	2960.256	44.071237	-122.96452	OR	1801.43
217	Point	14161100	BLUE RIVER BELOW TIDBITS CREEK, NR BLUE RIVER, OR	118.3653	44.217904	-122.26506	OR	7.32857
218	Point	14087380	CROOKED RIVER BLW OSBORNE CANYON, NR OPAL CITY,	11766.85	44.426897	-121.23287	OR	91.4286
219	Point	14158850	MCKENZIE R BLW TRAIL BR DAM NR BELKNAP SPRINGS, O	480.1356	44.2679	-122.04978	OR	559.857
220	Point	14167000	COYOTE CREEK NEAR CROW, OREG.	248.4081	44.02179	-123.25592	OR	0
221	Point	14165000	MOHAWK RIVER NEAR SPRINGFIELD, OR	460.1817	44.092903	-122.95730	OR	20.5714
222	Point	14165500	MCKENZIE RIVER NEAR COBURG,OREG.	3453.444	44.112347	-123.04703	OR	2112.86
223	Point	14046000	NORTH FORK JOHN DAY RIVER AT MONUMENT, OR	6553.41	44.813758	-119.43165	OR	44.8571
224	Point	14158790	SMITH R AB SMITH R RES NR BELKNAP SPRGS,OREG.	40.5711	44.334567	-122.04700	OR	2.64286
225	Point	14166500	LONG TOM RIVER NEAR NOTI, OREG.	226.5246	44.049845	-123.42621	OR	8.34286
226	Point	14044000	M FK JOHN DAY R AT RITTER, OREG.	1354.981	44.888764	-119.14136	OR	17.4286
227	Point	14087400	CROOKED RIVER BELOW OPAL SPRINGS, NEAR CULVER,	11810.18	44.492341	-121.29837	OR	1210
228	Point	14158500	MCKENZIE RIVER AT OUTLET OF CLEAR LAKE, OR	237.0771	44.360955	-121.99561	OR	159.429
229	Point	14076500	DESCHUTES RIVER NEAR CULVER, OREG.	6943.026	44.498729	-121.32115	OR	497
230	Point	14088000	LAKE CREEK NEAR SISTERS,OREG.	56.6019	44.426228	-121.72616	OR	22.8571
231	Point	13320000	CATHERINE CREEK NEAR UNION, OREG.	269.262	45.155417	-117.77493	OR	11.4286
232	Point	14169000	LONG TOM RIVER NEAR ALVADORE,OREG.	660.5496	44.123457	-123.29981	OR	18
233	Point	14046778	BRIDGE CR ABV COYOTE CANYON NR MITCHELL, OR	691.1163	44.726799	-120.30196	OR	1.38571
234	Point	14046500	JOHN DAY RIVER AT SERVICE CREEK, OR	13313.44	44.793747	-120.00667	OR	26.5714
235	Point	13316500	LITTLE SALMON RIVER AT RIGGINS ID	1492.905	45.413056	-116.32527	ID	113.571
236	Point	12342500	West Fork Bitterroot River nr Conner MT	820.0926	45.724918	-114.28147	MT	43.1429
237	Point	12323240	Blacktail Creek at Butte MT	298.7946	45.994649	-112.53668	MT	5.04286
238	Point	12323250	Silver Bow Cr bl Blacktail Cr at Butte MT	322.8354	45.996871	-112.56280	MT	12.1429
239	Point	13327500	WALLOWA RIVER AT JOSEPH,OREG.	131.7114	45.337375	-117.22739	OR	12.4286
240	Point	13329500	HURRICANE CREEK NEAR JOSEPH, OREG.	76.8204	45.337373	-117.29267	OR	12
241	Point	14185000	SOUTH SANTIAM RIVER BELOW CASCADIA, OR	458.1774	44.391792	-122.49758	OR	35.8571
242	Point	14187000	WILEY CREEK NEAR FOSTER, OR	134.7498	44.372348	-122.62313	OR	5.1
243	Point	14090350	JEFFERSON CREEK NEAR CAMP SHERMAN, OR	72.0855	44.571506	-121.63922	OR	47.2857
244	Point	14166000	WILLAMETTE RIVER AT HARRISBURG, OR	8895.176	44.270401	-123.17370	OR	3800
245	Point	14172000	CALAPOOIA R AT HOLLEY OREG	268.0263	44.351236	-122.78730	OR	15.5714
246	Point	14091500	METOLIUS RIVER NEAR GRANDVIEW, OR	818.0802	44.626227	-121.48394	OR	1197.14
247	Point	14187200	SOUTH SANTIAM RIVER NEAR FOSTER,OR	1444.943	44.412347	-122.68869	OR	649.286

FID	Shape *	STAID	STANAME	DRAIN_SQK	LAT_GAGE	LNG_GAGE	STATE	low_fl_10
248	Point	12343400	East Fork Bitterroot River nr Conner MT	984.969	45.883253	-114.06563	MT	50.7143
249	Point	14042000	CAMAS CREEK NR LEHMAN,OREG.	156.6126	45.17097	-118.73247	OR	0.357143
250	Point	14042500	CAMAS CREEK NEAR UKIAH, OREG.	312.1182	45.156805	-118.82053	OR	2.94286
251	Point	14092500	DESCHUTES RIVER NEAR MADRAS, OR	20857.07	44.725952	-121.24699	OR	3610
252	Point	14170000	LONG TOM RIVER AT MONROE, OR	1021.562	44.3129	-123.29648	OR	10.2
253	Point	12323710	Willow Creek nr Anaconda, MT	35.5581	46.064648	-112.89365	MT	0.028571
254	Point	14046890	PINE CREEK NEAR CLARNO, OR	168.5637	44.910407	-120.44086	OR	0.107143
255	Point	12323670	Mill Creek nr Anaconda, MT	102.4056	46.082981	-112.91698	MT	6.71429
256	Point	13330000	LOSTINE RIVER NEAR LOSTINE, OR	185.1021	45.438758	-117.42740	OR	16.7143
257	Point	14093000	SHITIKE CREEK NEAR WARM SPRINGS, OR	270.144	44.764286	-121.23643	OR	31
258	Point	12323720	Willow Creek at Opportunity, MT	80.9658	46.106037	-112.81226	MT	2.88571
259	Point	12323600	Silver Bow Creek at Opportunity MT	887.463	46.107703	-112.80559	MT	9.88571
260	Point	14185900	QUARTZVILLE CREEK NEAR CASCADIA, OREG.	258.1965	44.540124	-122.43591	OR	16.5714
261	Point	12323700	Mill Creek at Opportunity, MT	110.1186	46.11437	-112.82198	MT	0.278571
262	Point	14092885	SHITIKE CR BL WOLFORD CANYON NR WARM SPRGS,ORE	194.3604	44.772063	-121.30533	OR	17.1429
263	Point	13292000	IMNAHA RIVER AT IMNAHA, OR	1622.087	45.562378	-116.83431	OR	55.7143
264	Point	13329765	WALLOWA RIVER NEAR ENTERPRISE, OR	665.7885	45.475	-117.3875	OR	0
265	Point	14090400	WHITEWATER RIVER NEAR CAMP SHERMAN, OR.	60.759	44.719006	-121.64034	OR	37.4286
266	Point	13329770	WALLOWA R ABV CROSS CNTRY CANAL, NR ENTERPRISE,	705.4182	45.488203	-117.40379	OR	102.714
267	Point	12344000	Bitterroot River near Darby MT	2718.683	45.972142	-114.14147	MT	104.286
268	Point	12323760	Warm Springs Creek near Anaconda MT	402.2136	46.133537	-112.91420	MT	18.8571
269	Point	14187500	SOUTH SANTIAM RIVER AT WATERLOO, OREG.	1645.005	44.498456	-122.82342	OR	573
270	Point	14092750	SHITIKE CR, AT PETERS PASTURE, NR WARM SPRINGS, O	57.4803	44.750395	-121.63339	OR	19.1429
271	Point	14180300	BLOWOUT CREEK NEAR DETROIT, OR	66.6477	44.6529	-122.13090	OR	2.8
272	Point	12323840	Lost Creek near Anaconda MT	68.60414	46.16187	-112.89254	MT	0
273	Point	14097100	WARM SPRINGS RIVER NEAR KAHNEETA HOT SPRINGS, O	1361.541	44.856509	-121.14977	OR	194.286
274	Point	12323750	Silver Bow Creek at Warm Springs MT	1200.983	46.17937	-112.78142	MT	20
275	Point	12323770	Warm Springs Creek at Warm Springs MT	413.9685	46.180301	-112.78594	MT	5.14286
276	Point	13337500	SF CLEARWATER RIVER NR ELK CITY ID	675.7767	45.825278	-115.52722	ID	10.8571
277	Point	14188610	SCHAFER CREEK NEAR LACOMB, OR	2.5848	44.619567	-122.46591	OR	0.03
278	Point	12323800	Clark Fork near Galen MT	1690.272	46.208259	-112.76726	MT	38.2857
279	Point	13330300	LOSTINE RIVER AT BAKER ROAD, NEAR LOSTINE, OR	237.9852	45.537645	-117.48101	OR	10.4571
280	Point	13330500	BEAR CREEK NEAR WALLOWA, OR	184.5828	45.526811	-117.55241	OR	6.81429
281	Point	14178000	NO SANTIAM R BLW BOULDER CRK, NR DETROIT, OR	557.6805	44.706789	-122.10118	OR	318.714
282	Point	12323850	Lost Creek near Galen, MT	160.47	46.218537	-112.77392	MT	1.41429
283	Point	13317000	SALMON RIVER AT WHITE BIRD ID	34780.62	45.750278	-116.32388	ID	2721.43
284	Point	13323500	GRANDE RONDE RIVER NEAR ELGIN, OREG.	3238.863	45.512361	-117.92743	OR	0.008571
285	Point	14179000	BREITENBUSH R ABV FRENCH CR NR DETROIT, OR.	272.5416	44.752622	-122.12896	OR	96.2857
286	Point	14096300	MILL CREEK, NR BADGER BUTTE, NR WARM SPRINGS, OR	68.0463	44.861506	-121.62756	OR	29
287	Point	12332000	Middle Fork Rock Cr nr Philipsburg MT	315.1476	46.184493	-113.50247	MT	10
288	Point	14181750	ROCK CREEK NEAR MILL CITY, OR	35.2233	44.71207	-122.42758	OR	1.51429
289	Point	14171000	MARYS RIVER NEAR PHILOMATH, OR	392.5557	44.526232	-123.33454	OR	10.1286
290	Point	14034800	RHEA CREEK NEAR HEPPNER,OREG.	297.1287	45.261243	-119.62391	OR	0.201429
291	Point	14181500	NORTH SANTIAM RIVER AT NIAGARA, OR	1170.957	44.752622	-122.29841	OR	746.571
292	Point	12325500	Flint Creek near Southern Cross MT	140.0499	46.23298	-113.29978	MT	3.5
293	Point	13331450	WALLOWA RIVER BELOW WATER CANYON, NR WALLOWA,	1598.676	45.6082	-117.6163	OR	89
294	Point	12346500	Skalkaho Creek near Hamilton MT	226.2825	46.161033	-113.94869	MT	16.1429
295	Point	14096850	BEAVER CREEK, BLW QUARTZ CR, NR SIMNASHO, OR.	374.6232	44.958727	-121.39422	OR	21.7143
296	Point	13331500	MINAM RIVER NEAR MINAM, OR	618.9291	45.619867	-117.72658	OR	38.1429
297	Point	14173500	CALAPOOIA RIVER AT ALBANY, OR	957.5633	44.620677	-123.12898	OR	14.5857
298	Point	14174000	WILLAMETTE RIVER AT ALBANY, OR	12574.71	44.638733	-123.10676	OR	4007.14
299	Point	14095500	WARM SPRINGS RIVER NEAR SIMNASHO, OR	277.0434	44.969282	-121.47728	OR	85.1429
300	Point	14188800	THOMAS CREEK NEAR SCIO, OR	284.2524	44.712067	-122.77008	OR	9.05714
301	Point	14034480	BALM FORK NEAR HEPPNER, OR	68.049	45.332073	-119.54113	OR	0
302	Point	14034470	WILLOW CREEK ABV WILLOW CR LAKE, NR HEPPNER, OR	176.229	45.340683	-119.51585	OR	0
303	Point	14022200	NORTH FORK MCKAY CREEK NEAR PILOT ROCK,OREG.	125.487	45.506518	-118.61691	OR	0.412857
304	Point	14034500	WILLOW CREEK AT HEPPNER, OREG.	251.7876	45.350406	-119.55002	OR	1.88571
305	Point	14034608	WILLOW CREEK AT MORGAN STREET, AT HEPPNER, OR	381.5253	45.36124	-119.5603	OR	0.681429
306	Point	14184100	NORTH SANTIAM R AT GREENS BRIDGE, NR JEFFERSON,	1894.58	44.7079	-122.97287	OR	579.143
307	Point	14181900	LITTLE N SANTIAM RIVER ABV EVANS CR, AT ELKHORN,O	137.1402	44.835678	-122.35480	OR	0
308	Point	14182500	LITTLE NORTH SANTIAM RIVER NEAR MEHAMA, OR	286.8498	44.791511	-122.57897	OR	17
309	Point	12324200	Clark Fork at Deer Lodge MT	2591.439	46.397705	-112.74281	MT	38

FID	Shape *	STAID	STANAME	DRAIN_SQK	LAT_GAGE	LNG_GAGE	STATE	low_fl_10
310	Point	14183000	NORTH SANTIAM RIVER AT MEHAMA, OR	1696.206	44.788733	-122.61786	OR	817
311	Point	14189000	SANTIAM RIVER AT JEFFERSON, OR	4606.429	44.715122	-123.01231	OR	1502.86
312	Point	14022500	MCKAY CREEK NEAR PILOT ROCK,OREG.	463.3668	45.549019	-118.77442	OR	0.025714
313	Point	13332500	GRANDE RONDE R AT RONDOWA, OREG.	6702.233	45.726534	-117.78409	OR	196.857
314	Point	13336500	SELWAY RIVER NR LOWELL ID	4959.467	46.086667	-115.51388	ID	238.571
315	Point	12347500	Blodgett Creek near Corvallis MT	67.52609	46.269366	-114.23704	MT	2.41429
316	Point	13324300	LOOKINGGLASS CREEK NEAR LOOKING GLASS, OR.	198.8784	45.731808	-117.86493	OR	46.5714
317	Point	14208000	CLACKAMAS RIVER AT BIG BOTTOM, OREG.	359.4249	45.01651	-121.92063	OR	220.286
318	Point	14023500	MCKAY CREEK NEAR PENDLETON,OREG.	501.4044	45.609297	-118.79970	OR	0
319	Point	14020300	MEACHAM CREEK AT GIBBON, OR	456.3927	45.688743	-118.35662	OR	6.05714
320	Point	14189500	LUCKIAMUTE RIVER NEAR HOSKINS, OREG.	89.9118	44.71623	-123.50399	OR	6.5
321	Point	14190000	LUCKIAMUTE R AT PEDEE OREG	300.7251	44.742897	-123.42482	OR	8.95714
322	Point	14190500	LUCKIAMUTE RIVER NEAR SUVER, OR	603.4942	44.783175	-123.23454	OR	13.7143
323	Point	14198400	BULL CREEK NEAR WILHOIT, OR	1.827	44.961511	-122.38424	OR	0.03
324	Point	12324590	Little Blackfoot River near Garrison MT	1071.465	46.519651	-112.79337	MT	11.2857
325	Point	12329500	Flint Creek at Maxville MT	532.7172	46.463816	-113.23978	MT	25.2857
326	Point	14032000	BUTTER CREEK NEAR PINE CITY, OREG.	743.7969	45.54429	-119.31223	OR	1.32857
327	Point	13338500	SF CLEARWATER RIVER AT STITES ID	3027.002	46.086389	-115.97666	ID	52.5714
328	Point	14020000	UMATILLA RIVER ABOVE MEACHAM CREEK, NR GIBBON,	341.4267	45.719577	-118.32329	OR	33.5714
329	Point	12330000	Boulder Creek at Maxville MT	182.4732	46.472149	-113.23395	MT	4.51429
330	Point	13337000	LOCHSA RIVER NR LOWELL ID	3053.417	46.150833	-115.58722	ID	177.143
331	Point	14209000	OAK GROVE FORK ABOVE POWERPLANT INTAKE, OR.	321.0075	45.071232	-121.94063	OR	203.857
332	Point	14101500	WHITE RIVER BELOW TYGH VALLEY,OREG.	1080.376	45.241509	-121.09506	OR	93.8571
333	Point	14020850	UMATILLA R AT W RESERVATION BNDY NR PENDLETON,	1143.864	45.671519	-118.73664	OR	21.7143
334	Point	14025000	BIRCH CREEK AT RIETH,OREG.	736.9956	45.652631	-118.88026	OR	0
335	Point	14208700	OAK GROVE FORK NEAR GOVERNMENT CAMP, OREG.	141.3036	45.11373	-121.81507	OR	39
336	Point	14021000	UMATILLA RIVER AT PENDLETON,OREG	1658.608	45.672075	-118.79276	OR	24.2857
337	Point	14198500	MOLALLA R AB PC NR WILHOIT, OREG.	252.1674	45.009567	-122.48036	OR	16.8571
338	Point	14026000	UMATILLA RIVER AT YOAKUM,OREG.	3303.03	45.677631	-119.03444	OR	39.1429
339	Point	12324680	Clark Fork at Goldcreek MT	4590.105	46.590486	-112.92866	MT	90
340	Point	13333000	GRANDE RONDE RIVER AT TROY, OR	8556.385	45.945702	-117.45100	OR	409.714
341	Point	14010000	SOUTH FORK WALLA WALLA RIVER NEAR MILTON,OREG.	160.0857	45.829857	-118.16995	OR	82.5714
342	Point	12350250	Bitterroot River at Bell Crossing nr Victor MT	4982.504	46.443256	-114.12371	MT	0
343	Point	14209500	CLACKAMAS RIVER ABOVE THREE LYNX CREEK, OR	1266.116	45.124843	-122.07341	OR	551.429
344	Point	14192000	MILL CREEK AT SALEM, OREG.	291.4308	44.934564	-123.01787	OR	19.7143
345	Point	14191000	WILLAMETTE RIVER AT SALEM, OR	18821.76	44.944286	-123.04287	OR	5854.29
346	Point	14010800	NORTH FRK WALLA WALLA RIVER NR MILTON FREEWATE	90.0972	45.88458	-118.20273	OR	3.54286
347	Point	12331500	Flint Creek near Drummond MT	1273.599	46.628819	-113.15145	MT	7.9
348	Point	14190700	RICKREALL CREEK NEAR DALLAS,OREG.	72.7542	44.915117	-123.38510	OR	0.681429
349	Point	14134000	SALMON RIVER NEAR GOVERNMENT CAMP, OREG.	21.5424	45.266507	-121.71785	OR	12.5714
350	Point	14011000	NO FK WALLA WALLA RIVER NR MILTON, OREG.	110.8683	45.902079	-118.28301	OR	1.65714
351	Point	14201500	BUTTE CREEK AT MONITOR,OREG.	153.0756	45.10151	-122.74620	OR	3.75714
352	Point	14201300	ZOLLNER CREEK NEAR MT ANGEL, OR	38.8514	45.100398	-122.82176	OR	0.032857
353	Point	14048000	JOHN DAY RIVER AT MCDONALD FERRY, OR	19785.97	45.587628	-120.40949	OR	31.2857
354	Point	14199704	NATE CREEK TRIBUTARY NEAR COLTON, OR	1.7082	45.205233	-122.41200	OR	0.075714
355	Point	12335500	Nevada Cr ab Reservoir, nr Helmville, MT	314.1036	46.778269	-112.76754	MT	3.78571
356	Point	14013000	MILL CREEK NEAR WALLA WALLA, WA	151.983	46.007916	-118.11856	WA	21.1429
357	Point	12331800	Clark Fork near Drummond MT	6511.738	46.712152	-113.33090	MT	159.714
358	Point	14201340	PUDDING RIVER NEAR WOODBURN, OR	819.297	45.151231	-122.80426	OR	8.48571
359	Point	12351200	Bitterroot River near Florence MT	6139.801	46.633256	-114.05094	MT	374.286
360	Point	14192500	SOUTH YAMHILL RIVER NEAR WILLAMINA, OREG.	335.0718	45.047059	-123.50399	OR	5.71429
361	Point	14013500	BLUE CREEK NEAR WALLA WALLA, WA	44.8569	46.057638	-118.14022	WA	0.128571
362	Point	13339500	LOLO CREEK NR GREER ID	625.491	46.371667	-116.1625	ID	18.1429
363	Point	12334510	Rock Creek near Clinton MT	2313.95	46.722427	-113.68315	MT	60
364	Point	14210000	CLACKAMAS RIVER AT ESTACADA, OR	1763.227	45.299843	-122.35397	OR	702.286
365	Point	14200000	MOLALLA RIVER NEAR CANBY, OR	842.6178	45.244288	-122.68731	OR	45
366	Point	14202000	PUDDING RIVER AT AURORA, OR	1261.469	45.233176	-122.75009	OR	12.5
367	Point	14136500	SANDY RIVER BELOW SALMON RIVER NEAR BRIGHTWOOD	625.6593	45.383175	-122.04563	OR	0
368	Point	14015000	MILL CREEK AT WALLA WALLA, WA	249.9192	46.076248	-118.27357	WA	0
369	Point	14013700	MILL CREEK AT FIVE MILE RD BR NR WALLA WALLA, WA	240.2559	46.085693	-118.22829	WA	18.4286
370	Point	14033500	UMATILLA RIVER NEAR UMATILLA, OR	5971.813	45.90291	-119.32696	OR	1.34286
371	Point	14103000	DESCHUTES RIVER AT MOODY, NEAR BIGGS, OR	27772.14	45.622068	-120.90256	OR	4105.71

FID	Shape *	STAID	STANAME	DRAIN_SQK	LAT_GAGE	LNG_GAGE	STATE	low_fl_10
372	Point	14194000	SOUTH YAMHILL RIVER NEAR WHITESON,OREG.	1288.593	45.168728	-123.20816	OR	9.54286
373	Point	13342295	WEBB CREEK NEAR SWEETWATER ID	76.9581	46.326667	-116.83222	ID	0
374	Point	14018500	WALLA WALLA RIVER NEAR TOUCHET, WA	4294.051	46.027634	-118.72971	WA	1.24286
375	Point	14137002	SANDY RIVER BELOW MARMOT DAM, NEAR MARMOT, OR	677.2293	45.39956	-122.13731	OR	0
376	Point	14137000	SANDY RIVER NEAR MARMOT, OR	674.2395	45.399564	-122.13730	OR	241.286
377	Point	14138800	BLAZED ALDER CREEK NEAR RHODODENDRON, OREG.	21.2886	45.452618	-121.89146	OR	1.2
378	Point	13334450	ASOTIN CREEK BELOW CONFLUENCE NEAR ASOTIN, WA	269.8056	46.273611	-117.29138	WA	19.1429
379	Point	14138720	BULL RUN RIVER AT LOWER FLUME NR BRIGHTWOOD, OR	13.1031	45.470952	-121.86535	OR	13
380	Point	14194150	SOUTH YAMHILL RIVER AT MCMINNVILLE, OR	1357.946	45.205672	-123.18260	OR	11.6714
381	Point	14193000	WILLAMINA CREEK NEAR WILLAMINA, OR	166.815	45.142891	-123.49427	OR	9.54286
382	Point	14141500	LITTLE SANDY RIVER NEAR BULL RUN, OREG.	59.8653	45.415398	-122.17147	OR	10.1429
383	Point	14198000	WILLAMETTE RIVER AT WILSONVILLE, OREG.	21862.08	45.299009	-122.75120	OR	5142.86
384	Point	13342340	SWEETWATER CREEK AT MOUTH AT SWEETWATER ID	216.6525	46.369167	-116.79555	ID	0.597143
385	Point	14139700	CEDAR CREEK NEAR BRIGHTWOOD, OREG.	20.1186	45.458175	-122.03174	OR	6.08571
386	Point	13335050	ASOTIN CREEK AT ASOTIN, WA	840.6135	46.34072	-117.05599	WA	23
387	Point	14139800	SOUTH FORK BULL RUN RIVER NEAR BULL RUN, OR	40.7034	45.444564	-122.10952	OR	0
388	Point	13334700	ASOTIN CR BLW KEARNEY GULCH NR ASOTIN, WASH.	441.2709	46.326269	-117.15266	WA	17.2857
389	Point	14140000	BULL RUN RIVER NEAR BULL RUN, OR	278.091	45.437342	-122.17897	OR	21.7143
390	Point	14140001	BULL RUN RIVER NEAR BULL RUN, OR	278.0101	45.437342	-122.17953	OR	0
391	Point	12335100	Blackfoot R ab Nevada Cr nr Helmville MT	1273.574	46.919104	-113.01561	MT	68.5714
392	Point	14197900	WILLAMETTE RIVER AT NEWBERG, OR	21563.02	45.284563	-122.96148	OR	6065.71
393	Point	13340000	CLEARWATER RIVER AT OROFINO ID	14268.92	46.478333	-116.2575	ID	594.286
394	Point	12334550	Clark Fork at Turah Bridge nr Bonner MT	9520.545	46.826037	-113.81426	MT	271.143
395	Point	14138870	FIR CREEK NEAR BRIGHTWOOD, OR	14.02431	45.480119	-122.02563	OR	1.78571
396	Point	14207500	TUALATIN RIVER AT WEST LINN, OR	1832.925	45.350676	-122.67620	OR	163.571
397	Point	14211010	CLACKAMAS RIVER NEAR OREGON CITY, OR	2436.125	45.379287	-122.57731	OR	663.143
398	Point	14142500	SANDY RIVER BLW BULL RUN RIVER, NR BULL RUN, OR	1117.501	45.449009	-122.24508	OR	266
399	Point	14211000	CLACKAMAS RIVER NEAR CLACKAMAS, OREG.	2420.275	45.393177	-122.53286	OR	590.286
400	Point	14138850	BULL RUN RIVER NEAR MULTNOMAH FALLS, OR	124.4574	45.498174	-122.01230	OR	37.1429
401	Point	14138900	NORTH FORK BULL RUN RIVER NEAR MULTNOMAH FALLS,	21.6828	45.494286	-122.03591	OR	8.71429
402	Point	13342450	LAPWAI CREEK NR LAPWAI ID	698.0922	46.426554	-116.80515	ID	1.32857
403	Point	12352500	Bitterroot River near Missoula MT	7249.828	46.831868	-114.054	MT	407.714
404	Point	13341050	CLEARWATER RIVER NR PECK ID	20665.06	46.500278	-116.3925	ID	2442.86
405	Point	13340500	NF CLEARWATER RIVER AT BUNGALOW RANGER STATION	2586.016	46.631302	-115.50875	ID	491.429
406	Point	14118500	WEST FORK HOOD RIVER NEAR DEE,OREG.	247.0014	45.598451	-121.63590	OR	92.4286
407	Point	14113200	MOSIER CREEK NEAR MOSIER, OR	107.4582	45.649008	-121.37729	OR	0.76
408	Point	13342500	CLEARWATER RIVER AT SPALDING ID	24064.79	46.448498	-116.82737	ID	2544.29
409	Point	12338300	NF Blackfoot R ab Dry Gulch nr Ovando MT	811.4193	46.979938	-113.09116	MT	73
410	Point	12340000	Blackfoot River near Bonner MT	5925.355	46.89965	-113.75648	MT	214.286
411	Point	12340500	Clark Fork above Missoula MT	15591.48	46.877147	-113.93232	MT	581.429
412	Point	14206950	FANNO CREEK AT DURHAM, OR	80.7422	45.403452	-122.75481	OR	1.22857
413	Point	14211315	TRYON CREEK NEAR LAKE OSWEGO, OR	17.11965	45.43123	-122.67259	OR	0.235714
414	Point	14120000	HOOD RIVER AT TUCKER BRIDGE, NEAR HOOD RIVER, OR	721.8369	45.655396	-121.54840	OR	162.286
415	Point	14211400	JOHNSON CREEK AT REGNER ROAD, AT GRESHAM, OR	39.7521	45.486509	-122.42175	OR	0.828571
416	Point	12353000	Clark Fork below Missoula MT	23353.03	46.86909	-114.12677	MT	1062.86
417	Point	14211499	KELLEY CREEK AT SE 159TH DRIVE AT PORTLAND, OR	12.2553	45.476787	-122.49842	OR	0.038571
418	Point	14211500	JOHNSON CREEK AT SYCAMORE, OR	68.4882	45.47762	-122.50786	OR	0.934286
419	Point	13341570	POTLATCH RIVER BEL LITTLE POTLATCH CR NR SPALDIN	1511.338	46.498611	-116.76194	ID	0.082857
420	Point	14211550	JOHNSON CREEK AT MILWAUKIE, OR	137.3274	45.452897	-122.64315	OR	10.1
421	Point	14196000	HASKINS CREEK BLW RESERVOIR, NR MCMINNVILLE, OR	18.2943	45.310946	-123.34983	OR	0.027143
422	Point	14017000	TOUCHET RIVER AT BOLLES, WA	941.6691	46.274307	-118.22190	WA	17.5714
423	Point	14142800	BEAVER CREEK AT TROUTDALE, OR	28.8396	45.519287	-122.38898	OR	0.184286
424	Point	14113000	KLICKITAT RIVER NEAR PITT, WA	3365.91	45.756511	-121.21007	WA	487
425	Point	14197000	NORTH YAMHILL R AT PIKE, OREG.	169.3692	45.36928	-123.25538	OR	2.35714
426	Point	14206900	FANNO CREEK AT 56TH AVE, AT PORTLAND, OR	6.2253	45.487896	-122.73481	OR	0.014286
427	Point	14194300	NORTH YAMHILL RIVER NEAR FAIRDALE, OREG.	25.0803	45.365112	-123.37899	OR	2.12857
428	Point	14211720	WILLAMETTE RIVER AT PORTLAND, OR	28936.87	45.518452	-122.66787	OR	7375.71
429	Point	14125500	LITTLE WHITE SALMON RIVER NEAR COOK, WA	340.956	45.723451	-121.63396	WA	107.429
430	Point	14123500	WHITE SALMON RIVER NEAR UNDERWOOD, WA	1000.348	45.752064	-121.52701	WA	470.857
431	Point	14112500	LITTLE KLICKITAT RIVER NEAR WAHKIACUS, WA	724.8429	45.843734	-121.06007	WA	7.7
432	Point	14143500	WASHOUGAL RIVER NEAR WASHOUGAL, WA	277.6302	45.623173	-122.29759	WA	54.4286
433	Point	14128500	WIND RIVER NEAR CARSON, WA	556.7868	45.726784	-121.79479	WA	131.143

	FID	Shape *	STAID	STANAME	DRAIN_SQK	LAT_GAGE	LNG_GAGE	STATE	low_fl_10
	434	Point	14203000	SCOGGIN CREEK NEAR GASTON, OREG.	112.6143	45.458725	-123.15566	OR	0.424286
	435	Point	14203500	TUALATIN RIVER NEAR DILLEY, OR	324.7677	45.474837	-123.12427	OR	56.8571
	436	Point	14202980	SCOGGINS CREEK BL HENRY HAGG LK NR GASTON,OREG	100.5021	45.46928	-123.20010	OR	5.5
	437	Point	13340600	NF CLEARWATER RIVER NR CANYON RANGER STATION ID	3354.622	46.840466	-115.62070	ID	198.571
	438	Point	12510500	YAKIMA RIVER AT KIONA, WA	14536.2	46.253467	-119.47807	WA	685.286
	439	Point	14111400	KLICKITAT RIVER BL SUMMIT CREEK NEAR GLENWOOD,	1967.008	45.962345	-121.10229	WA	487.286
	440	Point	14127000	WIND RIVER ABOVE TROUT CREEK NEAR CARSON, WA	277.0038	45.808449	-121.90869	WA	63
	441	Point	13344500	TUCANNON RIVER NEAR STARBUCK, WA	1117.466	46.505422	-118.06633	WA	36.4286
	442	Point	12383500	Big Knife Creek near Arlee MT	17.6706	47.147428	-113.97427	MT	3.44286
	443	Point	12508990	YAKIMA RIVER AT MABTON, WA	13857.67	46.231242	-119.99948	WA	732.143
	444	Point	13346800	PARADISE CR AT UNIVERSITY OF IDAHO AT MOSCOW ID	45.8334	46.731832	-117.02433	ID	0.072857
	445	Point	14212000	SALMON CREEK NEAR BATTLE GROUND, WA	46.8315	45.773727	-122.44565	WA	0
	446	Point	12381400	South Fork Jocko River near Arlee MT	150.9471	47.195486	-113.85065	MT	2.71429
	447	Point	13348000	SOUTH FORK PALOUSE RIVER AT PULLMAN, WA	237.7636	46.732386	-117.18100	WA	1.22143
	448	Point	12387450	Valley Creek near Arlee MT	41.8257	47.1702	-114.23067	MT	0
	449	Point	14205400	EAST FORK DAIRY CREEK NEAR MEACHAM CORNER, OR	87.53999	45.680669	-123.07122	OR	6.28571
	450	Point	12513500	ESQUATZEL COULEE AT ELTOPIA, WA	1417.032	46.46236	-119.01222	WA	0
	451	Point	14222500	EAST FORK LEWIS RIVER NEAR HEISSON, WA	323.8893	45.836781	-122.46620	WA	39.4286
	452	Point	12413875	ST. JOE RIVER AT RED IVES RANGER STATION ID	275.0648	47.056029	-115.3532	ID	34.2857
	453	Point	14110000	KLICKITAT RIVER NEAR GLENWOOD, WA	933.597	46.088733	-121.25952	WA	296.286
	454	Point	14219000	CANYON CREEK NEAR AMBOY, WA	167.4252	45.939834	-122.31704	WA	22.5714
	455	Point	12377150	Mission Cr ab Reservoir nr ST Ignatius MT	32.1768	47.322987	-113.97954	MT	5.71429
	456	Point	12388400	Revais Cr bl West Fork nr Dixon MT	60.8409	47.266317	-114.40678	MT	3.21429
	457	Point	14121300	WHITE SALMON R BL CASCADES CR NR TROUT LAKE, WA	77.2596	46.10373	-121.60869	WA	61.4286
	458	Point	13345000	PALOUSE RIVER NR POTLATCH ID	818.1477	46.91517	-116.95099	ID	1.72857
	459	Point	12388200	Jocko River at Dixon MT	1002.155	47.31187	-114.29762	MT	76.4286
	460	Point	14216000	LEWIS RIVER ABOVE MUDDY RIVER NEAR COUGAR, WA	594.6237	46.060391	-121.98453	WA	220
	461	Point	14220500	LEWIS RIVER AT ARIEL, WA	1898.358	45.951779	-122.56399	WA	1097.14
	462	Point	13351000	PALOUSE RIVER AT HOOPER, WA	6378.825	46.758483	-118.14884	WA	10.5571
	463	Point	13349210	PALOUSE RIVER BELOW SOUTH FORK AT COLFAX, WA	2045.603	46.88961	-117.37018	WA	4.2
	464	Point	12369200	Swan River near Condon MT	197.0991	47.422436	-113.67092	MT	18.1429
	465	Point	14216500	MUDDY CREEK BELOW CLEAR CREEK NEAR COUGAR, WA	349.524	46.075669	-121.99869	WA	100.571
	466	Point	14219800	SPEELYAI CREEK NEAR COUGAR, WA	32.7789	46.007611	-122.34731	WA	0.51
	467	Point	12513000	ESQUATZEL COULEE AT CONNELL, WA	602.1369	46.663473	-118.86333	WA	0
	468	Point	14107000	KLICKITAT RIVER ABOVE WEST FORK NEAR GLENWOOD,	393.7545	46.264844	-121.24507	WA	62.1429
	469	Point	12388700	Flathead River at Perma MT	21787.5	47.367432	-114.58512	MT	3744.29
	470	Point	12354000	ST. REGIS RIVER NEAR ST. REGIS, MT	828.4186	47.296874	-115.12263	MT	60
	471	Point	12354500	Clark Fork at St. Regis MT	27819.99	47.301874	-115.08736	MT	1425.43
	472	Point	12375900	South Crow Creek near Ronan MT	19.7226	47.4916	-114.02677	MT	4.35714
	473	Point	12505000	YAKIMA RIVER NEAR PARKER, WA	9588.034	46.497072	-120.44284	WA	0.957143
	474	Point	14223500	KALAMA RIVER BELOW ITALIAN CREEK NEAR KALAMA, W	513.7263	46.044836	-122.81538	WA	181.429
	475	Point	12512550	PROVIDENCE COULEE NEAR CUNNINGHAM, WA	137.5749	46.802919	-118.81638	WA	0
	476	Point	12414900	ST MARIES RIVER NR SANTA ID	705.7197	47.176297	-116.49266	ID	34.5714
	477	Point	12512500	PROVIDENCE COULEE AT CUNNINGHAM, WA	72.9441	46.822086	-118.81111	WA	0
	478	Point	12500450	YAKIMA RIVER ABOVE AHTANUM CREEK AT UNION GAP,	9018.442	46.534294	-120.46728	WA	864.429
	479	Point	12502500	AHTANUM CREEK AT UNION GAP, WA	446.0225	46.53596	-120.47339	WA	8
	480	Point	12414500	ST JOE RIVER AT CALDER ID	2678.972	47.27464	-116.18904	ID	202.857
	481	Point	14245000	COWEMAN RIVER NEAR KELSO, WA	306.0081	46.128169	-122.83844	WA	27
	482	Point	12501000	SF AHTANUM CREEK AT CONRAD RANCH NR TAMPICO, W	64.6416	46.510955	-120.91646	WA	2.3
	483	Point	12422990	HANGMAN CREEK AT STATE LINE ROAD NEAR TEKOA, WA	327.9006	47.202676	-117.04073	WA	0.184286
	484	Point	12500500	NORTH FORK AHTANUM CREEK NEAR TAMPICO, WASH.	180.1116	46.564288	-120.91701	WA	5.7
	485	Point	12372000	Flathead River near Polson MT	16725.67	47.680216	-114.24678	MT	3502.86
	486	Point	14232500	CISPUS RIVER NEAR RANDLE, WASH.	825.2712	46.447057	-121.86397	WA	234.571
	487	Point	12413140	PLACER CREEK AT WALLACE ID	38.7846	47.462994	-115.93711	ID	0.77
	488	Point	12413125	CANYON CREEK AB MOUTH AT WALLACE, ID	56.9538	47.4725	-115.91472	ID	9.31429
	489	Point	12415140	ST JOE RIVER NEAR CHATCOLET ID	4476.38	47.360278	-116.69055	ID	379.143
	490	Point	12413360	EF PINE CREEK ABV GILBERT CR NEAR PINEHURST ID	8.9712	47.440278	-116.17527	ID	0.205714
	491	Point	12413130	NINEMILE CREEK AB MOUTH AT WALLACE, ID	29.6613	47.47944	-115.91944	ID	2.25714
	492	Point	14243500	DELAMETER CREEK NEAR CASTLE ROCK, WA	50.9355	46.263444	-122.96733	WA	1.8
	493	Point	14243000	COWLITZ RIVER AT CASTLE ROCK, WA	5774.026	46.274833	-122.91455	WA	2768.57
	494	Point	12389500	Thompson River near Thompson Falls MT	1651.865	47.591881	-115.22959	MT	80
	495	Point	14241500	SOUTH FORK TOUTLE RIVER AT TOUTLE, WA	309.8862	46.322055	-122.69705	WA	64.4286
	496	Point	12413150	SF COEUR D ALENE RIVER AT SILVERTON ID	280.0088	47.491594	-115.95516	ID	30.1429

FID	Shape *	STAID	STANAME	DRAIN_SQK	LAT_GAGE	LNG_GAGE	STATE	low_fl_10
496	Point	12413150	SF COEUR D ALENE RIVER AT SILVERTON ID	280.0088	47.491594	-115.95516	ID	30.1429
497	Point	12390700	Prospect Creek at Thompson Falls MT	470.2338	47.586046	-115.35515	MT	35.1429
498	Point	14242500	TOUTLE RIVER NEAR SILVER LAKE, WA	1236.823	46.336222	-122.72538	WA	330.429
499	Point	12492500	TIETON RIVER AT CANAL HEADWORKS NEAR NACHES, WA	622.1133	46.670953	-121.00396	WA	0
500	Point	14240525	NF TOUTLE RIVER BELOW SRS NEAR KID VALLEY, WA	378.9126	46.371775	-122.57899	WA	164.714
501	Point	12413370	EF PINE CREEK ABV NABOB CR NEAR PINEHURST ID	74.1688	47.476667	-116.22166	ID	4.22857
502	Point	14233500	COWLITZ RIVER NEAR KOSMOS, WA	2652.842	46.466222	-122.10898	WA	560.143
503	Point	14233400	COWLITZ RIVER NEAR RANDLE, WA	2651.465	46.470111	-122.09870	WA	590
504	Point	14247500	ELOCHOMAN RIVER NEAR CATHLAMET, WA	170.2674	46.221221	-123.34234	WA	15.2857
505	Point	12491500	TIETON RIVER AT TIETON DAM NEAR NACHES, WA	485.2269	46.662618	-121.12480	WA	1
506	Point	14242580	TOUTLE RIVER AT TOWER ROAD NEAR SILVER LAKE, WA	1292.231	46.333722	-122.84011	WA	317.286
507	Point	12494000	NACHES RIVER BELOW TIETON RIVER NEAR NACHES, WA	2439.412	46.745402	-120.76924	WA	24.4286
508	Point	14225500	LAKE CREEK NEAR PACKWOOD, WA	45.5733	46.596225	-121.57008	WA	2.88571
509	Point	12413210	SF COEUR D ALENE AT ELIZABETH PARK NR KELLOGG ID	470.6469	47.53139	-116.0925	ID	56.1429
510	Point	14231000	COWLITZ RIVER AT RANDLE, WA	1377.963	46.532333	-121.95676	WA	293.857
511	Point	12413445	PINE CREEK BELOW AMY GULCH NEAR PINEHURST ID	189.7065	47.514444	-116.24194	ID	11.4286
512	Point	14226500	COWLITZ RIVER AT PACKWOOD, WA	730.7316	46.61289	-121.67925	WA	228
513	Point	12413355	SF COEUR D'ALENE RIVER ABV PINE CR NR PINEHURST ID	535.6566	47.548333	-116.21972	ID	66.7143
514	Point	12413470	SF COEUR D ALENE RIVER NR PINEHURST ID	738.004	47.551944	-116.23638	ID	86.8571
515	Point	12413860	COEUR D ALENE RIVER NR HARRISON ID	3760.38	47.478611	-116.73305	ID	234.286
516	Point	12484500	YAKIMA RIVER AT UMTANUM, WA	4139.169	46.862626	-120.48006	WA	605.571
517	Point	12413500	COEUR D ALENE RIVER NR CATALDO ID	3127.093	47.55464	-116.32405	ID	232.286
518	Point	12413000	NF COEUR D ALENE RIVER AT ENAVILLE ID	2325.166	47.568889	-116.25333	ID	174.714
519	Point	14237500	WINSTON CREEK NEAR SILVER LAKE, WA	98.3448	46.48233	-122.5215	WA	1.3
520	Point	14237000	KLICKITAT CREEK AT MOSSYROCK, WA	9.3213	46.520663	-122.46983	WA	0
521	Point	12359800	S F Flathead R ab Twin C nr Hungry Horse MT	2999.681	47.979115	-113.56092	MT	0
522	Point	12374250	Mill Cr ab Bassoo Cr nr Niarada MT	50.7897	47.829664	-114.69763	MT	1.01429
523	Point	14238000	COWLITZ RIVER BELOW MAYFIELD DAM, WA	3594.313	46.510385	-122.61622	WA	2422.86
524	Point	12464770	CRAB CREEK AT ROCKY FORD ROAD NEAR RITZVILLE, WA	1181.602	47.30265	-118.36914	WA	7.5
525	Point	14235500	WEST FORK TILTON RIVER NEAR MORTON, WA	43.0938	46.610942	-122.24455	WA	4.62857
526	Point	12411000	NF COEUR D ALENE R AB SHOSHONE CK NR PRICHARD ID	867.4833	47.706111	-115.97916	ID	48.4286
527	Point	14236200	TILTON RIVER AB BEAR CANYON CREEK NEAR CINEBAR,	360.9936	46.595384	-122.45955	WA	46.7143
528	Point	12467000	CRAB CREEK NEAR MOSES LAKE, WA	5347.965	47.189309	-119.26585	WA	7.52857
529	Point	14249000	GRAYS RIVER ABOVE SOUTH FORK NEAR GRAYS RIVER,	102.8898	46.393162	-123.47875	WA	17.8571
530	Point	12361000	Sullivan Creek near Hungry Horse MT	183.8952	48.029118	-113.70370	MT	18
531	Point	14250500	WEST FORK GRAYS RIVER NEAR GRAYS RIVER, WA	40.284	46.385106	-123.55958	WA	5.64286
532	Point	12370000	Swan River near Bigfork MT	1715.115	48.024396	-113.97982	MT	279.857
533	Point	12488000	BUMPING RIVER NEAR NILE, WA	192.1041	46.872614	-121.29258	WA	0
534	Point	12464800	COAL CREEK AT MOHLER, WA	158.5431	47.40682	-118.31887	WA	0.032857
535	Point	12465000	CRAB CREEK AT IRBY, WA	2707.411	47.360424	-118.85000	WA	0.262857
536	Point	12488500	AMERICAN RIVER NEAR NILE, WA	205.1703	46.977616	-121.16869	WA	30.1429
537	Point	12419500	SPOKANE R AB LIBERTY BRIDGE NR OTIS ORCHARD WA	10519.55	47.682121	-117.08575	WA	0
538	Point	12419000	SPOKANE RIVER NR POST FALLS ID	10162.14	47.702957	-116.97797	ID	324
539	Point	12420500	SPOKANE RIVER AT GREENACRES, WA	10762.29	47.6774	-117.15215	WA	0
540	Point	12483800	NANEUM CREEK NEAR ELLENSBURG, WA	177.6996	47.126792	-120.48090	WA	9.2
541	Point	12470500	ROCKY FORD CREEK NEAR EPHRATA, WA	1089.135	47.31264	-119.44558	WA	27.4286
542	Point	12424000	HANGMAN CREEK AT SPOKANE, WA	1785.244	47.652669	-117.44965	WA	1.48571
543	Point	12422500	SPOKANE RIVER AT SPOKANE, WA	11100.44	47.659335	-117.44910	WA	545
544	Point	12416000	HAYDEN CREEK BL NORTH FORK NR HAYDEN LAKE ID	55.7487	47.822525	-116.65459	ID	2.55714
545	Point	12465500	WILSON CREEK AT WILSON CREEK, WA	1125.391	47.430423	-119.10390	WA	0
546	Point	12365700	Stillwater River at Lawrence Park, at Kalispell	1520.109	48.21746	-114.31318	MT	26
547	Point	12366080	Whitefish River nr mouth at Kalispell, MT	486.2709	48.226628	-114.29235	MT	37.8571
548	Point	12431000	LITTLE SPOKANE RIVER AT DARTFORD, WA	2121.289	47.784614	-117.40438	WA	82.8571
549	Point	12431500	LITTLE SPOKANE RIVER NEAR DARTFORD, WA	2243.791	47.781	-117.49633	WA	341
550	Point	12479500	YAKIMA RIVER AT CLE ELUM, WA	1299.046	47.191231	-120.94702	WA	38
551	Point	12366000	Whitefish River near Kalispell MT	451.9431	48.320241	-114.27846	MT	58.8571
552	Point	12479000	CLE ELUM RIVER NEAR ROSYLN, WA	524.2203	47.244562	-121.06786	WA	0
553	Point	12362500	S F Flathead River nr Columbia Falls MT	4318.159	48.356631	-114.03761	MT	532
554	Point	12365000	Stillwater River near Whitefish MT	1440.35	48.318852	-114.38735	MT	95.1429
555	Point	12433000	SPOKANE RIVER AT LONG LAKE, WA	16019.22	47.836553	-117.84134	WA	1061.29
556	Point	12465400	WILSON CREEK BELOW CORBETT DRAW NEAR ALMIRA, W	870.2856	47.66293	-118.93057	WA	0
557	Point	12476000	KACHESS RIVER NEAR EASTON, WA	164.196	47.261226	-121.20342	WA	0

FID	Shape *	STAID	STANAME	DRAIN_SQK	LAT_GAGE	LNG_GAGE	STATE	low_fl_10
558	Point	12433200	CHAMOKANE CREEK BELOW FALLS NEAR LONG LAKE, WA	468.6498	47.861553	-117.85885	WA	19.2857
559	Point	12392155	LIGHTNING CREEK AT CLARK FORK ID	326.1928	48.151667	-116.18166	ID	1.88571
560	Point	12474500	YAKIMA RIVER NEAR MARTIN, WA	141.138	47.321224	-121.33620	WA	0
561	Point	12462500	WENATCHEE RIVER AT MONITOR, WA	3372.32	47.499291	-120.42452	WA	252.143
562	Point	12358500	Middle Fork Flathead River nr West Glacier MT	2939.194	48.495244	-114.01011	MT	333.571
563	Point	12433542	BLUE CR AB MIDNITE MINE DRAINAGE NR WELLPINIT, WA	15.6591	47.924328	-118.08942	WA	0
564	Point	12302055	Fisher River near Libby MT	2185.286	48.355512	-115.31488	MT	47.8571
565	Point	12303100	Flower Creek near Libby MT	29.1384	48.344674	-115.60655	MT	3.77143
566	Point	12458000	ICICLE CREEK ABV SNOW CR NR LEAVENWORTH, WASH.	499.3668	47.540954	-120.72008	WA	54.5714
567	Point	12459000	WENATCHEE RIVER AT PESHASTIN, WA	2587.774	47.583178	-120.61953	WA	295.571
568	Point	12395000	PRIEST RIVER NR PRIEST RIVER ID	2459.905	48.20852	-116.91464	ID	177
569	Point	12452990	ENTIAT RIVER NEAR ENTIAT, WA	1074.745	47.663185	-120.25063	WA	68.4286
570	Point	12303500	Lake Creek at Troy MT	538.218	48.446888	-115.87711	MT	76.2857
571	Point	12452890	MAD RIVER AT ARDENVOIR, WA	236.2014	47.73679	-120.3687	WA	7.85714
572	Point	12396000	CALISPELL CREEK NEAR DALKENA, WA	176.3037	48.244347	-117.34161	WA	5.07143
573	Point	12452500	CHELAN RIVER AT CHELAN, WA	2414.854	47.834581	-120.01312	WA	4.18571
574	Point	12392300	PACK RIVER NR COLBURN ID	313.983	48.419929	-116.50158	ID	18
575	Point	12434590	SANPOIL RIVER ABOVE JACK CREEK AT KELLER, WA	2167.94	48.084325	-118.69140	WA	13
576	Point	12457000	WENATCHEE RIVER AT PLAIN, WASH.	1545.47	47.7629	-120.66620	WA	193.714
577	Point	12452800	ENTIAT RIVER NEAR ARDENVOIR, WA	526.3533	47.818462	-120.42314	WA	45.4286
578	Point	12394000	PRIEST RIVER NR COOLIN ID	1570.182	48.451861	-116.90048	ID	58.4286
579	Point	12456500	CHIWAWA RIVER NEAR PLAIN, WA	445.7034	47.837346	-120.66231	WA	68.1429
580	Point	12305500	BOULDER CREEK NR LEONIA ID	143.7462	48.598273	-116.09268	ID	0
581	Point	12454000	WHITE RIVER NEAR PLAIN, WASH.	386.0433	47.874008	-120.87037	WA	75.2857
582	Point	12311000	DEEP CREEK AT MORAVIA ID	342.7551	48.629997	-116.38701	ID	11
583	Point	12449950	METHOW RIVER NEAR PATEROS, WA	4644.765	48.077364	-119.98507	WA	218.857
584	Point	12301300	Tobacco River near Eureka MT	1084.973	48.893576	-115.08794	MT	31.4286
585	Point	12408500	MILL CREEK NEAR COLVILLE, WA	213.9156	48.578793	-117.86664	WA	5.07143
586	Point	12434110	WEST FORK SANPOIL RIVER NEAR REPUBLIC, WA	760.833	48.45877	-118.75169	WA	0
587	Point	12433890	SANPOIL RIVER AB 13 MILE CREEK NEAR REPUBLIC, WA	580.5891	48.47738	-118.73003	WA	0
588	Point	12409000	COLVILLE RIVER AT KETTLE FALLS, WA	2601.777	48.594346	-118.06248	WA	33
589	Point	12449500	METHOW RIVER AT TWISP, WA	3424.684	48.365145	-120.11619	WA	200.429
590	Point	12448998	TWISP RIVER NEAR TWISP, WA	632.7072	48.369867	-120.14869	WA	14.5714
591	Point	12397100	OUTLET CREEK NEAR METALINE FALLS, WA	134.6058	48.844922	-117.28774	WA	8.7
592	Point	12396900	SULLIVAN CREEK AB OUTLET CR NR METALINE FALLS, W	181.3059	48.846311	-117.28690	WA	13.2857
593	Point	12398000	SULLIVAN CREEK AT METALINE FALLS, WA	370.1421	48.860198	-117.36413	WA	31
594	Point	12451000	STEHEKIN RIVER AT STEHEKIN, WA	830.5974	48.32958	-120.69176	WA	159.571
595	Point	12448500	METHOW RIVER AT WINTHROP, WA	2683.633	48.473479	-120.17730	WA	169.286
596	Point	12448000	CHEWUCH RIVER AT WINTHROP, WA	1357.697	48.47709	-120.18647	WA	40.1429
597	Point	12447383	METHOW RIVER ABOVE GOAT CREEK NEAR MAZAMA, WA	950.6574	48.573754	-120.38509	WA	0
598	Point	12439300	TONASKET CREEK AT OROVILLE, WA	157.2813	48.942942	-119.41367	WA	0
599	Point	12447390	ANDREWS CREEK NEAR MAZAMA, WA	58.10103	48.822925	-120.14592	WA	3.21429
600	Point	12398600	PEND OREILLE RIVER AT INTERNATIONAL BOUNDARY	0	0	0		6063.57
601	Point	14218000	LEWIS RIVER NEAR COUGAR	0	0	0		572.571
602	Point	12395500	PEND OREILLE RIVER AT NEWPORT	0	0	0		4838.57
603	Point	12396500	PEND OREILLE RIVER BELOW BOX CANYON NEAR IONE	0	0	0		5895.71
604	Point	13090000	SNAKE RIVER NR KIMBERLY	0	0	0		184.857
605	Point	13094000	SNAKE RIVER NR BUHL	0	0	0		1217.14
606	Point	13339000	CLEARWATER RIVER AT KAMIAH	0	0	0		986.143
607	Point	13353000	SNAKE RIVER BELOW ICE HARBOR DAM	0	0	0		17814.3
608	Point	13343600	SNAKE RIVER BELOW LOWER GRANITE DAM	0	0	0		15571.4
609	Point	12331900	Clark Fork near Clinton	0	0	0		100.286
610	Point	12452500	CHELAN RIVER AT CHELAN	0	0	0		0
611	Point	14074630	DESCHUTES RIVER AT LOWER BRIDGE NR TERREBONNE	0	0	0		31.5714
612	Point	14246900	COLUMBIA RIVER @ BEAVER ARMY TERMINAL NR QUINCY	0	0	0		91628.6
613	Point	14105700	COLUMBIA RIVER AT THE DALLES	0	0	0		75857.1
614	Point	13317660	SNAKE RIVER BL MCDUFF RAPIDS AT CHINA GARDENS	0	0	0		10785.7
615	Point	13315000	SALMON RIVER NR FRENCH CREEK	0	0	0		2092.86
616	Point	13171620	SNAKE RIVER BL CJ STRIKE DAM NR GRAND VIEW	0	0	0		4040
617	Point	13290450	SNAKE RIVER AT HELLS CANYON DAM	0	0	0		7577.14
618	Point	12472800	COLUMBIA RIVER BELOW PRIEST RAPIDS DAM	0	0	0		44585.7
619	Point	12453700	COLUMBIA RIVER AT ROCKY REACH DAM	0	0	0		37485.7
620	Point	12399500	COLUMBIA RIVER AT INTERNATIONAL BOUNDARY	0	0	0		39471.4
621	Point	12355500	N F Flathead River nr Columbia Falls MT	4030	0	0		278.571
622	Point	12355000	Flathead River at Flathead British Columbia	0	0	0		75

Appendix 3. Final set of gauges for which projected 7Q10 low-flow was calculated

STAID	STANAME
12331800	CLARK FORK NEAR DRUMMOND MT
12340000	BLACKFOOT RIVER NEAR BONNER MT
12340500	CLARK FORK ABOVE MISSOULA MT
12352500	BITTERROOT RIVER NEAR MISSOULA MT
12353000	CLARK FORK BELOW MISSOULA MT
12354500	CLARK FORK AT ST. REGIS MT
12355500	N F FLATHEAD RIVER NR COLUMBIA FALLS MT
12358500	MIDDLE FORK FLATHEAD RIVER NR WEST GLACIER MT
12362500	S F FLATHEAD RIVER NR COLUMBIA FALLS MT
12391400	CLARK FORK BL NOXON RAPIDS DAM NR NOXON MT
12391950	CLARK FORK RIVER BELOW CABINET GORGE DAM ID
12395000	PRIEST RIVER NR PRIEST RIVER ID
12395500	PEND OREILLE RIVER AT NEWPORT
12396500	PEND OREILLE RIVER BELOW BOX CANYON NEAR IONE
12398600	PEND OREILLE RIVER AT INTERNATIONAL BOUNDARY
12414500	ST JOE RIVER AT CALDER ID
12433000	SPOKANE RIVER AT LONG LAKE, WA
12453700	COLUMBIA RIVER AT ROCKY REACH DAM
12459000	WENATCHEE RIVER AT PESHASTIN, WA
12462500	WENATCHEE RIVER AT MONITOR, WA
12472800	COLUMBIA RIVER BELOW PRIEST RAPIDS DAM
12484500	YAKIMA RIVER AT UMTANUM, WA
12508990	YAKIMA RIVER AT MABTON, WA
12510500	YAKIMA RIVER AT KIONA, WA
13037500	SNAKE RIVER NR HEISE ID
13056500	HENRYS FORK NR REXBURG ID
13060000	SNAKE RIVER NR SHELLEY ID
13077000	SNAKE RIVER AT NEELEY ID
13081500	SNAKE R NR MINIDOKA ID (AT HOWELLS FERRY)
13171620	SNAKE RIVER BL CJ STRIKE DAM NR GRAND VIEW
13213000	BOISE RIVER NR PARMA ID
13245000	NF PAYETTE RIVER AT CASCADE ID
13251000	PAYETTE RIVER NR PAYETTE ID
13302500	SALMON RIVER AT SALMON ID
13317000	SALMON RIVER AT WHITE BIRD ID
13333000	GRANDE RONDE RIVER AT TROY, OR
13337000	LOCHSA RIVER NR LOWELL ID
13340000	CLEARWATER RIVER AT OROFINO ID
13342500	CLEARWATER RIVER AT SPALDING ID

13343600	SNAKE RIVER BELOW LOWER GRANITE DAM
13353000	SNAKE RIVER BELOW ICE HARBOR DAM
14076500	DESCHUTES RIVER NEAR CULVER, OREG.
14087400	CROOKED RIVER BELOW OPAL SPRINGS, NEAR CULVER, OR
14091500	METOLIUS RIVER NEAR GRANDVIEW, OR
14092500	DESCHUTES RIVER NEAR MADRAS, OR
14097100	WARM SPRINGS RIVER NEAR KAHNEETA HOT SPRINGS, OR
14103000	DESCHUTES RIVER AT MOODY, NEAR BIGGS, OR
14105700	COLUMBIA RIVER AT THE DALLES
14111400	KLICKITAT RIVER BL SUMMIT CREEK NEAR GLENWOOD, WA
14113000	KLICKITAT RIVER NEAR PITT, WA
14120000	HOOD RIVER AT TUCKER BRIDGE, NEAR HOOD RIVER, OR
14123500	WHITE SALMON RIVER NEAR UNDERWOOD, WA
14128500	WIND RIVER NEAR CARSON, WA
14181500	NORTH SANTIAM RIVER AT NIAGARA, OR
14183000	NORTH SANTIAM RIVER AT MEHAMA, OR