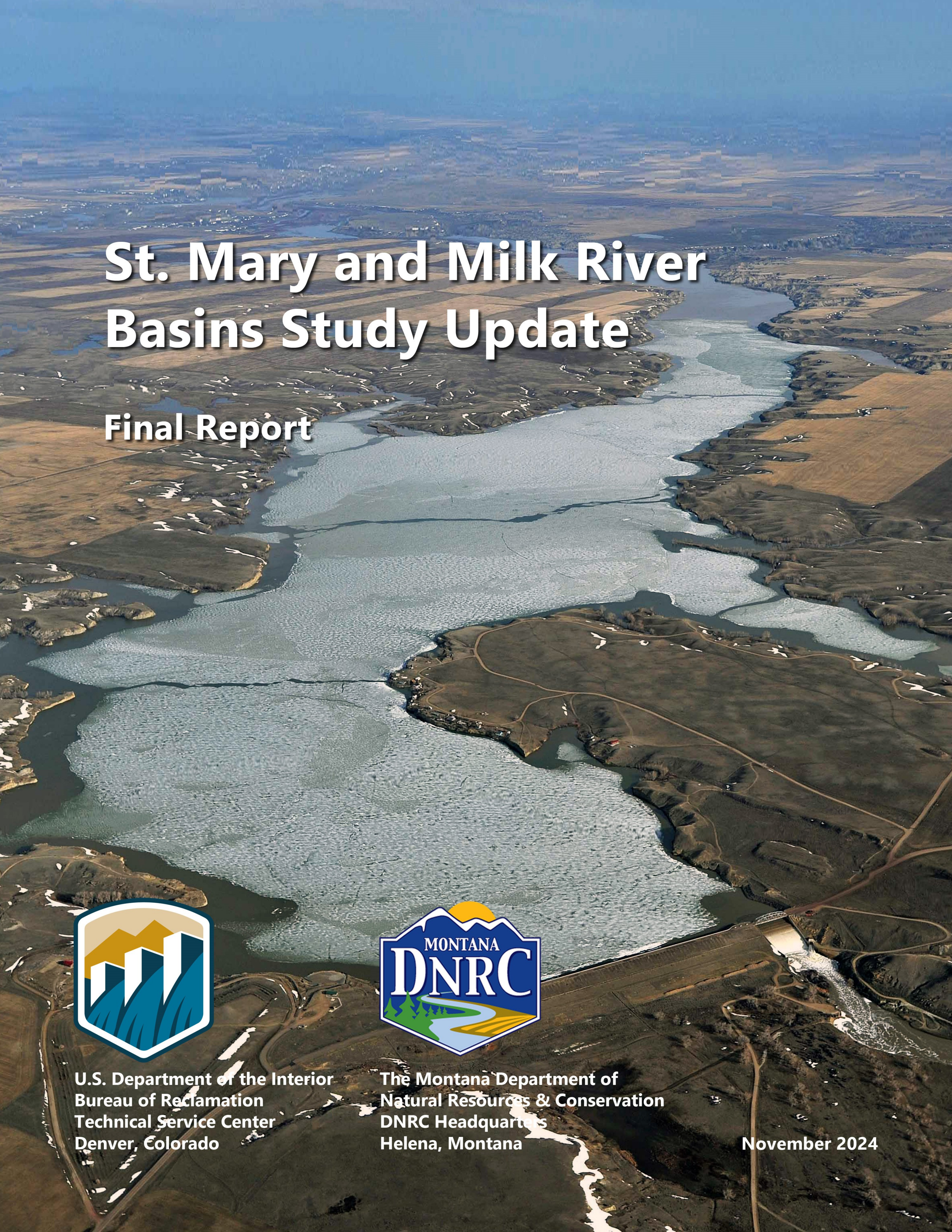

St. Mary and Milk River Basins Study Update

Final Report

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

MONTANA DNRC

The Montana Department of
Natural Resources & Conservation
DNRC Headquarters
Helena, Montana

November 2024

Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, Native Hawaiians, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Montana Department of Natural Resources and Conservation's mission is to help ensure that Montana's land and water resources provide benefits for present and future generations.

Cover Photo – Fresno Reservoir, Milk River basin, Montana (Larry Mayer; April 22, 2018).

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St. Mary and Milk River Basins Study Update, Final Report

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Acronyms and Abbreviations

2012 Basins Study	2012 St. Mary and Milk River Basins Study
ACI	Annual Crop Inventory
ACIS	Alberta Climate Information Service
AF	acre-feet
avg	average
AWC	available water capacity
Basins Study Update	St. Mary and Milk River Basins Study Update
BCBMO	Beaver Creek (Bowdoin) at Mouth
BCHMO	Beaver Creek (Havre) at Mouth
BFTM	right station
BGCMO	Buggy Creek at Mouth
BSCMO	Big Sandy Creek at Mouth
BTCIB	Battle Creek at International Boundary
CDL	Cropland Data Layer
cfs	cubic feet per second
CLCMO	Clear Creek at Mouth
CMIP5	Coupled Model Intercomparison Project Phase 5
COOP	Cooperative Observer Program
CRLE	complementary relationship lake evaporation
CT	central tendency
DCAHM	Dynamic Contributing Area Hydrology Model
DNRC	Department of Natural Resources and Conservation
DRI	Desert Research Institute
Eastern Crossing	Eastern Crossing of the International Boundary
EOWY	end of water year
ESA	Endangered Species Act
ET	evapotranspiration
F	Fahrenheit
FAO	Food and Agriculture Organization
FBIC	Fort Belknap Indian Community
FBIIP	Fort Belknap Indian Irrigation Project
FBIIPRes	proposed 60 KAF off-stream storage project strategy
FRRIB	Frenchman River at International Boundary
ft	foot/feet
Ft.	Fort

GCM	general circulation model
GHG	greenhouse gas
HD	hot-dry
Hist 1	historical drought 1
Hist 2	historical drought 2
HW	hot-wet
IB	International Boundary
ID	identification
IJC	International Joint Commission
KAF	thousand acre-feet
km	kilometer
kPa	kilo-pascals
LAD 1	the 1st ranked LAD event
LAD 2	the 2nd ranked LAD event
LAD 3	the 3rd ranked LAD event
LAD	Largest Annual Deficit
LAD Inst	largest instrumental average annual deficit
LBCMO	Little Box Elder Creek at Mouth
LCD	Largest Cumulative Deficit
LDCIB	Lodge Creek at International Boundary
LOCA	Locally Constructed Analogs
M&I	municipal and industrial
MC	Markov ChainMCA Montana Code Annotated
MBRFC	Missouri Basin River Forecast Center
MRWIB	Milk River at Western Crossing of the International Boundary
MT	Montana
NA	not applicable
NAIP	National Agriculture Imagery Program
NARR	North American Regional Reanalysis
NFKMR	North Milk River above St. Mary Canal
NIWR	net irrigation water requirement
NPC	nonparametric paleo-conditioning
NRCS	Natural Resource Conservation Service
NSE	Nash Suttcliffe Efficiency
OBSV	observed naturalized streamflow
OPAR	simulated streamflow using the calibrated model
PCA	principal component analysis
PCCMO	Porcupine Creek at Mouth

PKNN	predictive K-nearest neighbor
PM	Penman-Monteith
PPCMO	People's Creek at Mouth
PPR	Prairie Potholes Region
PRMS	Precipitation-Runoff Modeling System
RCP	Representative Concentration Pathway
Reclamation	Bureau of Reclamation
RKCMO	Rock Creek at Mouth
SECURE	Science and Engineering to Comprehensively Understand and Responsibly Enhance
SMRBB	St. Mary River near Babb
SWCSB	Swiftcurrent Creek at Sherburne
SWE	snow water equivalent
T	temperature
TDS	total dissolved solids
Treaty	Boundary Waters Treaty of 1909
U.S.	United States
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VIC	variable infiltration capacity
WD	warm-dry
WLCMO	Willow Creek at Mouth
WRCC	Water Rights Compact Commission
WW	warm-wet
WWCMO	Whitewater Creek at Mouth
WWCRA	West-Wide Climate Risk Assessment

Symbols

°	degrees
>	greater than
<	less than
≤	less than or equal to
–	minus
/	per
%	percent
+	plus[
§	section
*	times (multiplication)

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Introduction

About this Report/Report Purpose

The Bureau of Reclamation (Reclamation) partnered with the State of Montana (MT) Department of Natural Resources and Conservation (DNRC) to perform the St. Mary and Milk River Basins Study Update (Basins Study Update). The Basins Study Update is being carried out under Reclamation's WaterSMART (Sustain and Manage American Resources for Tomorrow) Program pursuant to the authority and mandates of the Science and Engineering to Comprehensively Understand and Responsibly Enhance (SECURE)Water Act, Subtitle F (Public Law 111-11). The Basins Study Update seeks to address the needs the of WaterSMART Program by achieving the following objectives:

- Assess current and projected future water supply; this study focuses on use of information characterizing the distant past (paleo), the recent past (historical), and projected future conditions.

- Assess current and projected future water demand.

- Evaluate water supply risks by analyzing simulated performance of water and power infrastructure and operations under paleo, historical, and future hydrology scenarios.

- Identify and evaluate potential strategies that may reduce any imbalances; development and evaluation of strategies includes outreach and involvement by stakeholders.

The United States (U.S.) Geological Survey (USGS) provided guidance and technical support for the Basins Study Update by developing paleo-reconstructed streamflow records, which Reclamation used to develop paleohydrology scenarios for the study. Figure 1 depicts the components of the Basins Study Update, which are focused on assessing water supply and demand, evaluating future risks to water supplies, and identifying and evaluating potential strategies in collaboration with basin stakeholders.

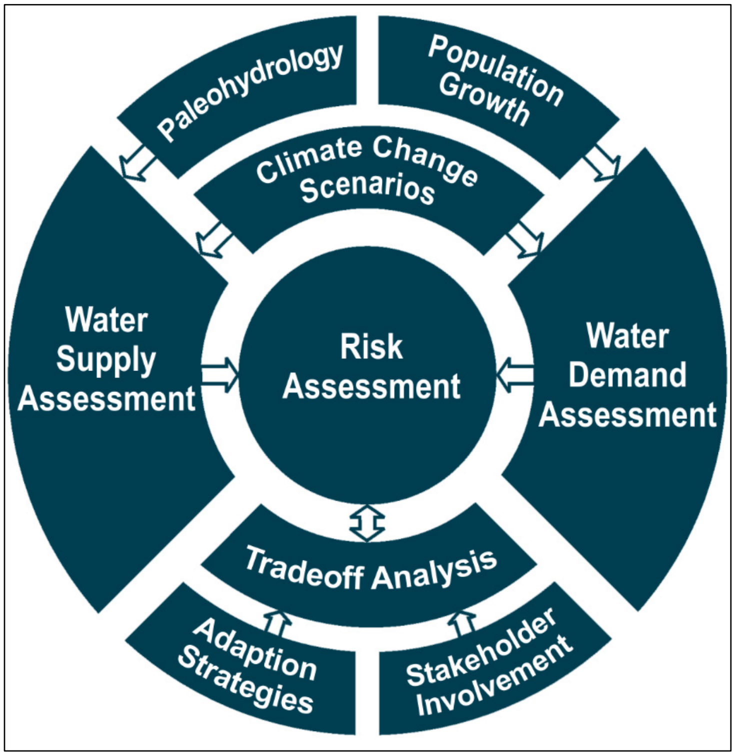


Figure 1.—Overview of the St. Mary and Milk River Basins Study Update components.

The Basins Study Update builds upon the 2012 St. Mary and Milk River Basins Study (2012 Basins Study) and supports the identified goals in the updated MT State Water Plan that was submitted to the 2015 MT Legislature (MT DNRC 2015). The MT State Water Plan lays out a path for managing MT's Water resources, including recommendations for DNRC to work with local water users and other government agencies to conduct basin studies and invest in the capacity to identify and evaluate the opportunities and challenges posed by large scale forces that will influence water supply and demand, such as energy development, demographic shifts, climate variability, reservoir operations, water management agreements, and federal actions related to threatened and endangered species.

The Basins Study Update summarizes how existing operations and infrastructure perform under future water supply scenarios and summarizes the effectiveness of adaptation and mitigation strategies for meeting the challenges of supplying adequate water in the future for these river basins. One important objective of this Basins Study Update is to improve the river system model that was developed in the 2012 Basins Study using the Riverware™ software (Zagona et al. 2001; Reclamation 2013). Improvements to the river system model (planning model) lay the foundation for evaluating historical and future projected water supply and demand. With these improvements, the planning model serves as a robust and credible decision support tool to evaluate and analyze the following:

- Potential changes in the region’s water supplies and demands
- Adaptive water management strategies
- Infrastructure deficiencies and needs
- Operational modifications
- Other watershed planning initiatives

Water supply and demand imbalances are expected to increase in the future. The purpose of this Basins Study Update is to bring current data, modeling tools, and approaches to evaluate these water supply and demand imbalances. Another purpose is to identify and evaluate adaptation strategies to provide adequate water supply to serve future needs.

Summary and Recommendations from the 2012 Basins Study Report

The 2012 Basins Study showed that the Milk River irrigators currently experience an average (avg) crop irrigation demand shortage of 36 percent. Most of the water shortages are attributed to insufficient supply to meet demand, but some of it is attributed to insufficient capacity in canals to deliver water even when available. The shortages are exacerbated by aging and deteriorating project facilities, shrinking reservoir storage capacity from sedimentation, reduced canal capacity, increased demand, and operational limitations. Furthermore, greater operational demands are placed on Reclamation’s Milk River Project facilities to meet other requirements including international treaty, compact, and water rights obligations; mitigation impacts to endangered and threatened species; municipal and water quality needs; recreational uses, and fisheries and wildlife.

The 2012 Basins Study recommended using and enhancing the new river system model to further analyze alternatives and combinations of alternatives to address supply and demand issues in the basins, including Tribal development and international apportionment.

Study Area

The study area encompasses the U.S. portion of the St. Mary River basin from its headwaters to the Canadian border where it flows into Alberta, as well as the entire Milk River basin including its portions located in Alberta and Saskatchewan (figure 2). The Basins Study Update portion of the St. Mary River drainage area is about 490 square miles. The St. Mary River begins in Glacier National Park, flowing northeast through the Blackfeet Reservation in MT into Canada to its confluence with Oldman River near Lethbridge, Alberta, on its way to Hudson Bay.

The Milk River basin drainage area is about 23,800 square miles. The Milk River originates in the foothills of the Rocky Mountains on the Blackfeet Reservation, flowing northeasterly into Canada near the Del Bonita Border Station on the Blackfeet Reservation at the Milk River at Western Crossing of the International Boundary (MRWIB). Shortly after flowing into Canada, the North Fork of the Milk River, which conveys imported water from the St. Mary Canal, joins with the Milk River main stem. The Milk River then flows through southern Alberta, Canada, before turning south and re-entering the U.S. at the Eastern Crossing of the International Boundary (Eastern Crossing) just upstream of Fresno Reservoir. Major tributaries to the Milk River main stem include Big Sandy, Peoples Creek and Beaver Creek flowing from the south, Lodge Creek and Battle Creek, and Frenchman River which flow into MT from the north out of Saskatchewan. Figure 3 shows the upper St. Mary River basin facilities map, encompassing the diversion and conveyance system for Reclamation's Milk River Project.

For most of its distance, the Milk River runs through short grass prairie: vast, rolling, high plains grasslands, interrupted by island mountain ranges like the Bears Paw and Little Rocky Mountains, and valleys like the Milk River basin and Missouri River basin. Potholes—remnants of glaciers—scatter the prairie, providing grassland-wetland habitat. The prairie potholes landscape also creates a highly complex hydrologic system in which there are large regions of the watershed that may be non-contributing to streamflow during all or parts of the year.

Other important wetland habitat is provided by the river's oxbows and sloughs. Habitat diversity in the region allows for a great number of wildlife and bird species. The region is a haven for birds. There are 10 MT Wildlife Management Areas in the Milk River basin. Several of them are associated with Milk River Project facilities, including Fresno Reservoir, Dodson Diversion Dam, Dodson South Canal, Nelson Reservoir, and Vandalia Diversion Dam. Bowdoin National Wildlife Refuge is also located in the Milk River basin near Malta, MT. Lakes in the St. Mary drainage also contain native populations of northern pike and sucker species as well as the only known population of trout-perch in MT. This habitat is shared with non-native populations of Yellowstone cutthroat trout, rainbow trout, brook trout, kokanee, and lake whitefish.

There are several species listed under the Endangered Species Act (ESA) which can be found in the St. Mary River and Milk River region. Endangered species include the black-footed ferret, whooping crane, pallid sturgeon, and interior least tern. Threatened species include the grizzly bear, piping plover, bull trout, and Canada lynx. The MT Department of Fish, Wildlife, and Parks has identified 27 Species of Special Concern in the St. Mary River and Milk River region.

Humans have occupied northern MT for at least 11,900 years, evidenced by finds of distinctive stone artifacts. Northern MT is rich in prehistoric and historic resources. Cultural resources include prehistoric archeological sites, Indian sacred sites, and other traditional and historic sites important to Native Americans. Many of the facilities of the Milk River Project itself are considered eligible for the National Register of Historic Places.

The five-county region, including counties of Glacier, Hill, Blaine, Phillips, and Valley, had a total population of 48,936 people in the 2020 census, compared to 47,608 in 2010. Native Americans make up a considerable portion of the population. In 2020, the populations of the reservations were: Blackfeet Reservation: 10,764; Rocky Boy's Indian Reservation: 3,639; and Fort Belknap Indian Reservation: 3,382 (U.S. Census Bureau 2020a).

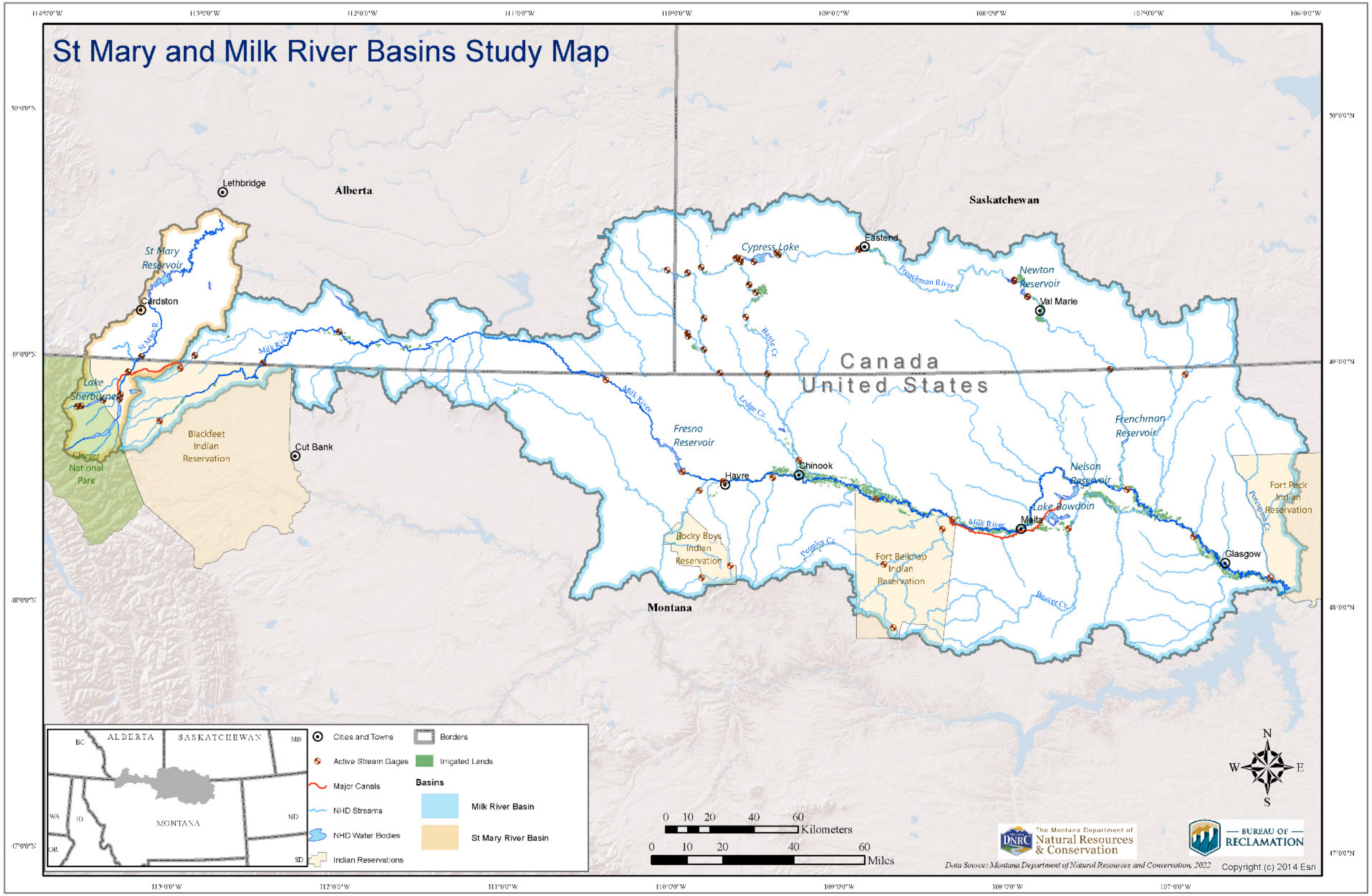


Figure 2.—St. Mary and Milk Rivers Basins Study Update overview.

Bureau of Reclamation Milk River Project

Reclamation's Milk River Project is located in the St. Mary and Milk River basins and is one of Reclamation's five original projects authorized in 1902. It serves about 121,000 acres of irrigable lands. Major Reclamation-owned Project components include three major storage facilities, diversion dams, and a trans-basin canal (table 1).

Table 1.—Summary of major Reclamation Milk River Project facilities

Facility	Purpose	Description
Sherburne Dam	On-stream Storage Reservoir	Stores about 66,147 acre-feet (AF) of water on Swiftcurrent Creek, a tributary to the St. Mary River located near Babb, MT. Construction completed 1921.
Swiftcurrent Dike	Directs Swiftcurrent Creek into Lower St. Mary Lake above the St. Mary Diversion Dam	Earthen dike that diverts Swiftcurrent Creek flows – including releases from Sherburne Dam – into Lower St. Mary Lake above the St. Mary Diversion Dam. Diversion capacity is the maximum release from Sherburne Dam, including the flows of Swiftcurrent Creek. Construction completed 1915.
St. Mary Diversion Dam	Diverts water from the St. Mary River into the St. Mary Canal	Concrete weir and sluiceway structure that diverts water through a headgate into the St. Mary Canal on the west side of the St. Mary River. Located near Babb, MT. Construction completed in 1915. Construction of the replacement dam is estimated to be complete by 2030.
St. Mary Canal	Conveys water from the St. Mary River to the North Fork Milk River	29-mile-long trans-basin canal with a current capacity of 650 cubic feet per second (cfs). Includes two steel plate siphons (3,600-foot [ft] St. Mary Siphon and the 1,404-ft Halls Coulee Siphon) and 5 large concrete drop structures at the end of the canal with a total drop of 214 ft where it discharges into the North Fork Milk River. Located near Babb, MT. Operational in 1917, other features were added later.
Fresno Dam	On-Stream Storage Reservoir	Currently stores approximately 92,000 AF of water on the Milk River main stem. Original storage capacity was about 130,000 AF. Located 14 miles west of Havre, MT. Construction completed 1939.
Nelson Dikes	Off-Stream Storage Reservoir	Series of dikes that stores about 79,000 AF of water. Water is conveyed from the Milk River to Nelson Reservoir by the Dodson South Canal. Nelson Reservoir is located 19 miles northeast of Malta, MT. Construction completed 1917.

The St. Mary and Milk Rivers are linked by the St. Mary Canal, which diverts St. Mary River water that originates in Glacier National Park and conveys it to the more arid Milk River basin. The canal is owned and operated by Reclamation. Lake Sherburne, also a Reclamation facility, is the only major storage reservoir in the U.S. headwaters of the St. Mary River (table 2).

Table 2.—Major reservoirs in the St. Mary and Milk River basins

St. Mary and Milk River reservoirs	Basin	Maximum capacity	Additional information
Lake Sherburne	St Mary River Basin	66,147 AF	
Lower St. Mary Lake	St Mary River Basin	5,001 AF	
Fresno Reservoir	Milk River Basin	62,000 AF	
Lake Bowdoin	Milk River Basin	21,207 AF	
Nelson Reservoir	Milk River Basin	79,220 AF	Top of conservation pool
Frenchman Reservoir	Milk River Basin	2,801 AF	

The St. Mary River flows in a northeasterly direction into Alberta. Its waters are divided between the U.S. and Canada through the Boundary Waters Treaty of 1909 (Treaty). Congress authorized construction of the St. Mary facilities in 1905. Water is diverted by the St. Mary Diversion Dam just downstream from the outlet of Lower St. Mary Lake and upstream of the international boundary and is conveyed to the North Fork of the Milk River through a 29-mile canal, siphon, and drop system (figure 3). Lake Sherburne on Swiftcurrent Creek, a tributary of the St. Mary River, stores winter and high spring flows for later release to keep the St. Mary Canal running near full longer in the irrigation season. When the U.S. share is insufficient to meet St. Mary Canal diversion needs, stored U.S. share water is released from Lake Sherburne to make up the difference. When there is a U.S. share surplus, water from the Swiftcurrent drainage is stored in Lake Sherburne.

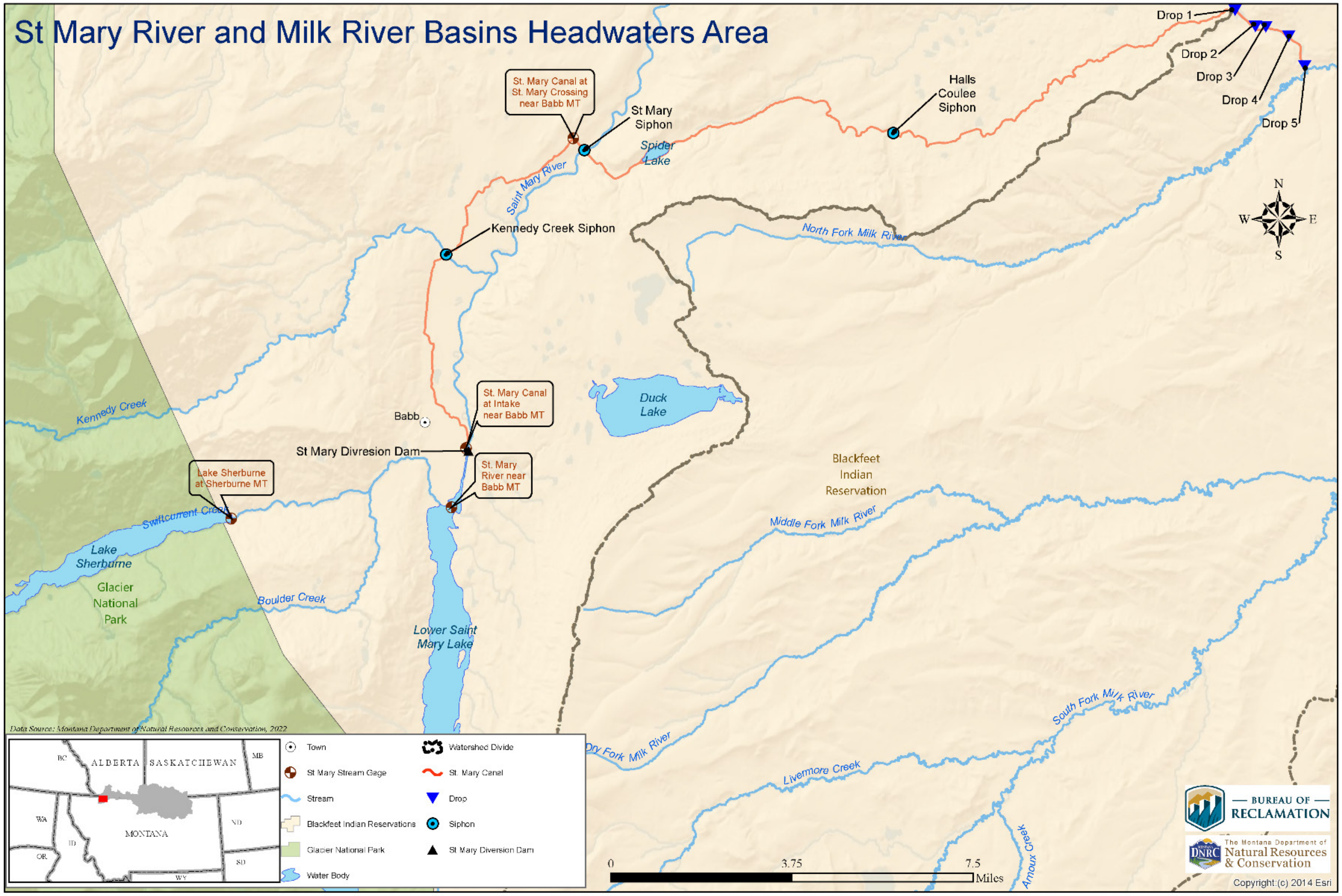


Figure 3.—St. Mary River facilities map.

In dry years, the St. Mary Canal supplies up to 95 percent of the flow in the Milk River, traveling up through Canada and returning to MT around Havre 216 miles away. Water flowing through the St. Mary Canal is stored in the Fresno Reservoir near Havre and supplies around 140,000 acres of irrigable land along the Hi-Line in eight irrigation districts. The Hi-Line runs east-west across the northern part of MT defined by the Burlington Northern Santa Fe rail line and State Highway 2. The system supports Reclamation pump contracts, private contracts, stock water, and the cities of Havre, Chinook and Harlem as well as provides water to the Fort Belknap and Blackfeet Indian communities, Town of Milk River and Coutts, Alberta, Sweet Grass in Toole County and the Bowdoin National Wildlife Refuge. The system also creates habitat for wildlife and recreational benefits.

Reclamation’s Fresno Dam, about 50 miles downstream from the Eastern Crossing, is the only on-stream storage reservoir on the Milk River (see figure 2). Major irrigation diversions from the river begin just below Havre, MT, and continue for about 400 miles downstream to the Milk River's confluence with the Missouri River near Nashua, MT. One of these diversions, the Dodson South Canal near Malta, supplies water to a large portion of Malta Irrigation District, Nelson Reservoir, and to the Bowdoin National Wildlife Refuge. Vandalia Diversion Dam is the downstream-most Reclamation facility on the Milk River main stem. It diverts irrigation water to 18,000 irrigated acres in the Glasgow Irrigation District near Glasgow, MT. The Milk River also supplies the municipal water needs of several communities including the City of Havre: the largest community in north-central MT with a population of 9,362 (U.S. Census Bureau 2020b).

Other Facilities

There are few large-scale irrigation facilities in the Milk River basin besides those on the main stem of the river. One important project is the State of MT owned Frenchman Dam, located on Frenchman River. It was constructed in 1953 with an original storage capacity of about 7,600 AF. The structure is in poor condition and sedimentation has reduced the storage capacity by about 60 percent. It provides irrigation water for about 2,801 acres.

There is a private off-stream storage facility on Lodge Creek called North Chinook Reservoir with about 5,000 AF of storage capacity. There is little to no data available for this facility; however, water demands from this facility are captured in the irrigated acreage represented in this Basins Study Update. This facility is not further modeled in any detail.

Challenges

Water management challenges in the St. Mary and Milk River basins are consistent with those across the western U.S., namely having to do with variable hydrology, increasing water demands, aging infrastructure and impacts of sedimentation, administration of available water for a variety of needs, and environmental concerns. For example, water shortages in the region are caused by periodic severe droughts and development of more irrigated lands than the available water supply can support in most years. Further, a severe drought in the Milk River basin in 2012 was preceded by major flooding in 2011, representing new and unprecedented variability that is likely to become more common in the future. Details of existing water management challenges are more fully described below and provide motivation for basin studies such as this one.

Aging Infrastructure

Aging, under-designed canals are not able to supply enough water to irrigators even when an adequate water supply is available. This is exacerbated by lack of crop diversity which concentrates irrigation demands into a short time window. Diversions from the St. Mary Canal supply over half of the Milk River Project's water in an avg year and up to 95 percent in extreme drought years. The St. Mary Canal System—through which St. Mary River water is transferred to the Milk River—is aging and needs rehabilitation to ensure an adequate water supply for the Milk River basin (Reclamation 2004). As figure 3 shows, most of the structures of the 100-year old St. Mary Canal have exceeded their design life and need major repairs or replacement.

As an example of the consequences of aging critical infrastructure, on May 17, 2020, a concrete drop structure (Drop 5) failed on the St. Mary Canal, northwest of the town of Cut Bank in northern MT, within the Blackfeet Indian Reservation. When the structure failed, the St. Mary Canal, which conveys water 29 miles to the Milk River, could not deliver water until October 15, 2020, when the drop structure was rebuilt.

Sedimentation

Sedimentation is decreasing the storage capacity of Fresno and Frenchman Reservoirs, further reducing the amount of water that can be delivered to irrigators and other users. Moreover, future demands are projected to increase, particularly under various future climate scenarios, leading to even more demands competing for a limited water resource.

Water Shortages

Water shortages in the St. Mary River and Milk River basins have been well documented. Shortages may be caused by various factors including periodic severe droughts and water supply and demand imbalances. During the spring, the Milk River Project irrigation districts meet with Reclamation to set water allotments for the upcoming season. In years where water shortages are anticipated, allotments for all project water users are reduced so that shortages are equitably shared. According to the 2012 Basins Study, existing irrigation water shortages avg about 71,000 AF per year, which is about 36 percent of the total amount of water needed for optimal crop growth. Updated results from this study show similar results, with an annual avg water shortage of 77,000 AF per year, about 37 percent of the amount of water needed for optimal crop growth. This is defined as unmet crop need which is termed "irrigation depletion shortages." These frequent irrigation depletion shortages affect the irrigators' willingness to invest in necessary equipment and infrastructure to diversify crops. The lack of crop diversity then further contributes to water shortages, as project facilities were not designed to meet current peak irrigation demands (Reclamation 2004). See the "Water Demands Assessment" section for more information.

Aging, deteriorating, and outdated design of facilities may also contribute to water shortages even when an adequate water supply is available. The St. Mary Canal capacity is about 600 cfs, down from its original design capacity of 850 cfs due to active landslides along the canal.

On avg, the U.S. does not use approximately 38,500 AF of its apportioned flow of the St. Mary River due to storage and diversion limitations of existing facilities. The IJC 1921 Order also limits the U.S. ability to use its share. In the Milk River basin, Canada surpluses on avg about 33,000 AF of its share of Milk River to the U.S. Canada is investigating alternatives to provide storage facilities on the Milk River to capture more of its share. Fresno Reservoir current capacity is at 90,000 AF down from its original storage capacity of 127,200 AF, which further contributes to water shortages, while also reducing flood control and recreational benefits. Water shortages are projected to increase in the future. Results from this study project a 15 to 18 percent increase in irrigation depletions by 2050.

Water Rights Adjudication

Federal reserved water rights were established by a 1908 U.S. Supreme Court decision (Winters versus U.S.) on a case concerning the Fort Belknap Indian Reservation. Known as the Winters Doctrine, the ruling found that when a federal reservation was created, enough water had implicitly been set aside for its purpose by the federal government. The MT Legislature established the Reserved Water Rights Compact Commission (WRCC) in 1979 as part of the statewide stream adjudication process. The Reserved Water Rights Compact Commission was authorized to negotiate settlements with federal agencies and Indian Tribes within the State of MT. Water compacts in the St. Mary and Milk River basins have been completed for the Blackfeet, Rocky Boy's, Fort Belknap and Fort Peck Reservations; U.S. Fish and Wildlife Service (Bowdoin National Wildlife Refuge Complex); and the National Park Service (Glacier National Park).

The MT water rights are guided by the prior appropriation doctrine (first in time is first in right). A priority date is generally established when the water was first put to beneficial use. Priority dates are especially important in dry years. When there is insufficient water to meet all the demands, senior water rights holders may operate to the exclusion of junior water rights holders. From a water rights perspective, the Milk River basin is unique because of the Treaty with Canada, the existence of federal reserved water rights for three Indian Reservations, and the significant role of Milk River Project water rights. The MT water rights only apply to the U.S. share of internationally apportioned waters. This includes the St. Mary River, Milk River and their tributaries. In general, federal reserved water rights (through compacts with the U.S.) have the earliest priority dates, followed by Reclamation's Milk River Project water rights, which encompass most of the land irrigated from the Milk River mainstem. Most all of the other water rights are junior to these rights. During extreme drought, the only water in the Milk River downstream from the Eastern Crossing is Milk River Project water diverted via the St. Mary Canal from the St. Mary River.

Adjudication of all MT water rights is an on-going legal process to determine who has valid water rights, how much water can be used and who has priority so that enforceable decrees may be issued.

International Apportionment

Waters of the St. Mary and Milk Rivers are divided between the U.S. and Canada through the Treaty and further defined by the 1921 International Joint Commission (IJC) Order. According to the Order,

> "between the 1st of April and 31st of October, inclusive, annually, the United States is entitled to a prior appropriation of 500 cubic feet per second of the waters of the Milk River, or so much of such amount as constitutes three-fourths of its natural flow, and that Canada is entitled to a prior appropriation of 500 cubic feet per second of the flow of St. Mary River, or so much of such amount as constitutes three-fourths of its natural flow."

The USGS and Environment Canada are tasked with administering international apportionment of the two rivers and their tributaries. Protocol for the division of these international rivers is described in the Procedures for the Division of the Waters of the St. Mary and Milk Rivers (USGS and Water Survey Division, Meteorological Service of Canada 2018). A Letter of Intent, initiated in 1991 and updated in 2001, provides for additional flexibilities in the division of St. Mary and Milk River basins water. The IJC International St. Mary and Milk Rivers Study (currently underway at the time of publication of this report) is exploring options to improve access to apportioned waters by each country, in recognition of climate change and challenges to apportionment since the original 1921 Order was issued. The effort includes a desire to achieve long-term resilience in accessing the shared waters of the St. Mary and Milk Rivers. (please see the following web address for additional details on the IJC https://www.ijc.org/en/smmr). In addition, this Basins Study Update explores one strategy for the accounting of apportioned shares, described in the "Risk Assessment with Strategies" section.

Environmental Challenges

There are a variety of environmental issues in the study area. In the St. Mary River basin, climate change is resulting in glacial retreat in Glacier National Park (USGS 2017). Although glacial retreat is not likely to measurably impact water supplies, it is an indicator that future water supplies and timing may impact operations of the St. Mary Diversion and storage facilities.

The St. Mary Diversion Dam has been identified as detrimental to bull trout by impeding fish passage at the dam and entrainment into the St. Mary Canal. The bull trout is listed as threatened under the ESA. Issues that affect bull trout also affect the west slope cutthroat trout population, which is listed as a Species of Special Concern by the State of MT. The Swiftcurrent Dike, which directs Swiftcurrent Creek into Lower St. Mary Lake has contributed to erosion problems and sedimentation in Lower St. Mary Lake. Sedimentation has resulted in reduced storage and water availability.

In the Milk River basin, there are several species listed as endangered under the ESA. Piping plover are found in the Nelson Reservoir and Bowdoin National Wildlife Refuge areas. An agreement among Reclamation, U.S. Fish and Wildlife Service and the irrigation districts allows for modified reservoir operations, thereby avoiding designation of Nelson Reservoir as critical habitat. Pallid Sturgeon are found in the Missouri River and are known to use the Milk River downstream from Vandalia Diversion Dam. There are numerous fish species identified as Species of Special Concern located in the Milk River. Most of the populations are isolated by upstream and downstream diversion dams in the Milk River. Diversion and storage facilities divide the Milk River into roughly six distinctive segments that impact fish and wildlife habitats:

- Above Fresno Reservoir
- Fresno Reservoir to Lohman Diversion Dam
- Lohman Diversion Dam to Paradise Valley Diversion Dam
- Paradise Valley Diversion Dam to Fort Belknap Diversion Dam
- Fort Belknap Diversion Dam to Dodson Diversion Dam
- Dodson Diversion Dam to Vandalia Diversion Dam
- Vandalia Diversion Dam to the mouth of the Milk River at the Missouri River Confluence

There are also numerous weirs associated with municipal intakes that further segment the river.

Water Quality

Water quality and erosion are concerns in the St. Mary and Milk River basins. Higher flows from the St. Mary diversions into the Milk cause increased bank and channel erosion in Alberta, contributing to sediment load, which settles in Fresno Reservoir. According to the North-Central MT Regional Feasibility Study (Reclamation 2004), Fresno Reservoir has lost about 29 percent of its storage capacity to sedimentation. The MT Department of Environmental Quality (DEQ) has identified impairments in the Milk River including flow alterations, nutrients, habitat alterations, suspended solids and salinity, mercury and metals (DEQ 2016).

Scenarios and Analysis

The Basins Study Update incorporates newly developed data and tools to quantify water supply and demand and for evaluating strategies to address imbalances. Reclamation and MT DNRC used a scenario approach to develop water supply and demand data for a range of plausible conditions. These scenarios may be considered storylines because the likelihood of any individual scenario coming to fruition is small, but collectively they are useful to test how the river basins may be impacted by difference scenarios. Figure 4 illustrates the scenarios developed for the Basins Study Update showing the variability in streamflow under different scenarios.

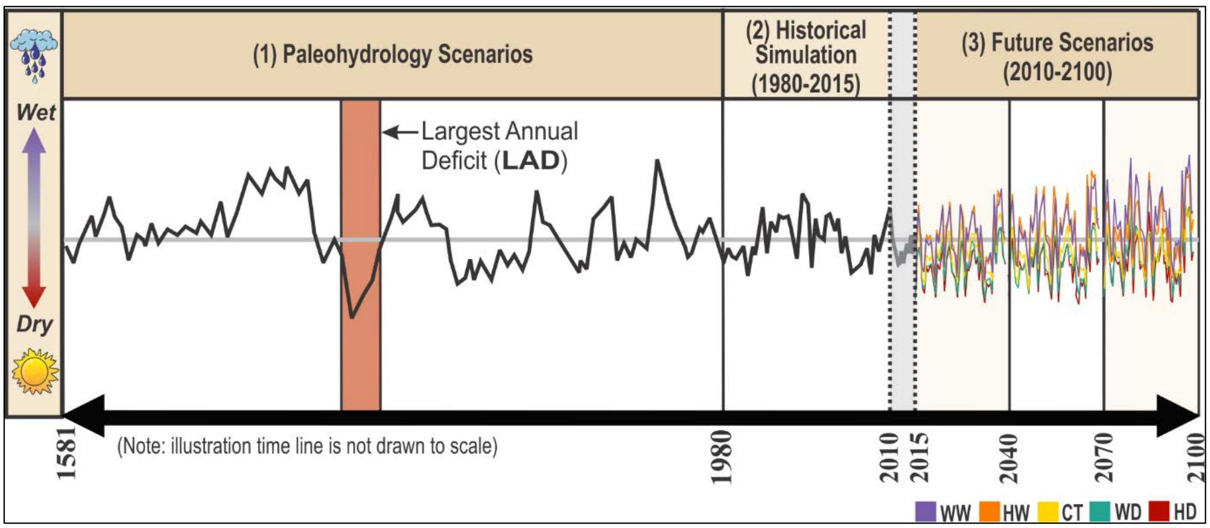


Figure 4.—Illustration of scenario approach for St. Mary and Milk River Basins Study Update.

Details of the different scenario types are provided below.

Water supply scenarios:

- may be described as scenarios of streamflow, reservoir inflows, and local inflows that are simulated by hydrologic and statistical models. Groundwater and surface water interactions were modeled by altering return flows based on aquifer characteristics.

Water demand scenarios:

- may be described as scenarios of evaporative demands from reservoirs, agricultural demands via crop evapotranspiration (ET), and phreatophyte demands via riparian vegetation ET; they also incorporate population estimates for municipal and industrial (M&I) water use.

- Scenarios of water supply and demand encompass three types: paleohydrology (spanning years from as early as 1018 to as late as 2008), historical reference (encompassing years 1980 to 2015), and projected future scenarios under three planning horizons: the 2020s (which encompasses years 2010–2039), the 2050s (which encompasses years 2040–2069), and the 2080s (which encompasses years 2070–2099).

Paleohydrology:

- Paleohydrology was developed from tree rings to provide a record of hydrologic conditions over the past 1,000 years, as far back as 1018 in the St. Mary Basin (Martin and Pederson 2022; Reclamation 2021). The study team developed daily streamflow timeseries over 35-year periods (consistent with the historical reference period) that encompass extreme droughts that were identified from tree rings over water years 1581–1999 (418 years), which is the common period of record for streamflow reconstructions in the study area.

The managed river systems are most impacted by single annual drought events due to the limited carryover storage of water from one year to the next. Therefore, periods with the largest avg annual deficit (LAD) in the paleohydrology record were identified the in the paleohydrology record (refer to "Water Supply Assessment" section, table 9)—collectively, these are called "paleo drought events".

Historical simulations:

- The Basins Study Update simulated the historical reference period from 1980 to 2015 to represent historical hydrologic conditions over that period.

Future scenarios:

- Future scenarios based on general circulation model (GCM) projections were developed and provide the best estimate of what could occur over the coming century with respect to climate dynamics and warming. For this study, each scenario for a particular time horizon is considered an equally likely future planning scenario. These scenarios include five climate timeseries developed for the region that represent a range of projected changes in temperature (less warming to more warming) and precipitation (from decreases to increases) for three future time horizons, the 2020s, the 2050s, and the 2080s and these are called warm-wet (WW), hot-wet (HW), a middle range central tendency (CT), warm-dry (WD), and hot-dry (HD).

For these scenario types, the study team used the St. Mary and Milk Rivers planning model to simulate river and reservoir operations, with and without strategies in place, and assuming 2022 operating policies. Model results provide information on agricultural water deliveries, managed river flows, and reservoir levels. The study team compared results from future scenarios to both historical reference simulations and to paleohydrology scenario simulations to answer whether projected future conditions may be outside the range of conditions seen over the last 418 years.

The analyses provided in this report reflect the use of best available datasets and data development methodologies at the time of the study. It is important to acknowledge the uncertainties inherent within projecting future planning conditions for water supply and demand. For example, projections of future climate, population, water demand, and land use contain uncertainties that vary geographically and temporally depending on the model and methodology used. Trying to identify an exact impact at a particular place and time remains difficult, despite advances in modeling efforts. Accounting for these uncertainties, Reclamation and its stakeholders used a scenario planning approach that encompasses the estimated range of future planning conditions.

Collaboration and Outreach

Basin studies costs are equally shared between Reclamation and non-Federal partners. Reclamation and MT DNRC were partners in this Basins Study Update. In addition, Reclamation contracted with the USGS Northern Rocky Mountain Science Center and MT State University, Bozeman to develop paleohydrology scenarios (Reclamation 2021; SECURE Water Act Report) for the Basins Study Update and provide guidance for their application. In addition, collaboration and outreach with stakeholders and tribes are key components of these studies.

Interrelated Activities

In addition to the Basins Study Update, other water management activities are occurring in the St. Mary and Milk River basins. These interrelated activities affected some of the Basins Study Update strategies.

Blackfeet Tribe Water Rights Settlement

The 2009 MT Legislature passed a Compact settlement between the Blackfeet Tribe, the U.S., and the State of MT (§85-20-1501:1511, MT Code Annotated [MCA]). The Compact quantifies the reserved water right for the Blackfeet Tribe including water rights in the St. Mary and Milk River basins. The Compact was first introduced in Congress in 2010 and signed into law by President Obama on December 16, 2016. On April 20, 2017, Blackfeet Tribal members voted to approve the Compact. Interior Secretary Zinke executed the Compact on June 12, 2018.

Part of the settlement includes conveying 5,000 AF of the Tribe's St. Mary water right through the St. Mary Canal. The St. Mary and Milk Rivers planning model incorporated this provision of the settlement.

The settlement authorized an appraisal study to identify alternatives to develop water of the St. Mary River for the Tribe. In addition, a feasibility study was authorized to evaluate rehabilitation of the St. Mary Diversion Dam and Canal and increase storage in Fresno Reservoir. The St. Mary and Milk Rivers planning model could be used for the authorized studies.

Fort Belknap Indian Community (FBIC) Water Rights Settlement

The 2001 MT Legislature passed a Compact settlement between the Fort Belknap Indian Community (FBIC) and the State of MT (§85-20-1001, MCA). The Compact quantifies the reserved water rights for the FBIC, including water rights in the Milk River basin. Federal legislation to ratify the compact is actively moving through Congress at the time of this report.

Water right quantities and projects identified in the Compact were included in the St. Mary and Milk Rivers planning model. The Compact requires mitigation of the expected impacts when the FBIC develops their water right. Several potential mitigation options were modeled during the Basins Study Update. Results are included in the "Water Supply Risk Assessment with Strategies" section. The St. Mary and Milk Rivers planning model can continue to be a tool used during eventual implementation of the Compact.

International Joint Commission (IJC) Study

The Treaty between the U.S. and Great Britain is for the apportionment of the waters between the U.S. and Canada including the shared waters of the St. Mary and Milk River basins. The International Joint Commission (IJC) was established by the Treaty to provide direction for the measurement and apportionment of the water and resolve disputes.

The IJC has funded a study to explore options to improve access to apportioned waters by each country. The study was started in November 2021. The study will consider different options including non-structural solutions such as changes to the accounting procedures. The study is expected to last four years. The Study Board is relying on experts and existing tools developed for the St. Mary and Milk River basins. Some of the options likely to be evaluated under the IJC study were included in the Basins Study Update. The IJC Study Team may use the St. Mary and Milk Rivers planning model as tool for evaluating options in the IJC study.

Water Supply Assessment

Water supply across the St. Mary and Milk River basins is variable, with most of the Milk River basin water supply coming from the St. Mary River basin. Understanding of historical and projected future water supply informs the amount of water supply available to the U.S. and to Canada, as well as how much water may be available for deliveries to the Milk River Project and other users. Even small changes in annual precipitation can have large effects downstream; when coupled with the variability from extreme events, these changes make managing these resources a challenge. Future changes in precipitation patterns, warmer temperatures, and the potential for more extreme rainfall events are very likely to exacerbate these challenges (Conant et al. 2018).

The “Water Supply Assessment” section summarizes potential changes in hydroclimate across the study area, incorporating scenarios of projected future climate as well as scenarios of drought developed from tree-ring analysis. To evaluate potential hydrologic changes, a hydrologic modeling framework was developed to address the complexities in the regional hydrologic landscape, including depression storage and processes associated with cold regions such as glaciers and frozen soils.

The following subsections detail the approaches used for developing projected future climate scenarios, paleohydrology scenarios, and surface hydrology assessment. Following the discussion of approaches, this section summarizes how water supply may be different in the future compared with a historical reference, and then the comparison is brought into context by reviewing reconstructed streamflow via tree-ring information. Supporting details and discussion are included in “Appendix B. Water Supply Development.”

Descriptions of Surface and Groundwater Supplies

Streamflow in the headwaters of the St. Mary River consists of rainfall, snowmelt, glacier melt, and baseflow. The St. Mary River originates within Glacier National Park in MT and flows northeast into Alberta, Canada (see figure 2). The Milk River basin is in the Northern Glaciated Plains province, with headwaters in the Rocky Mountains near the U.S./Canada border. The surficial geology includes glacial drift and localized outwash deposits from the recent Pleistocene continental glacial periods. The lower Milk River valley fills the ancestral Missouri River valley, which was shifted south to the present location as a result of the glacial affects. Alluvial terrace deposits extend from the Continental Divide, Bears Paw Mountains, Sweet Grass Hills, and Little Rocky Mountains.

The St. Mary River and Milk River in MT are managed for various resources including irrigation, M&I use, flood control, ecological resources, and recreation. Reclamation, MT DNRC, and private entities all manage water supplies within the study area. Reclamation manages water deliveries to the Milk River Project primarily for irrigation. Reclamation also manages surface water from its dams for flood control purposes and environmental purposes, such as cottonwood regeneration and instream flows for ESA listed fish species. Typical of plains watersheds in the region, the Milk River has greater variability from year to year than does the St. Mary River. The Milk River basin produces less water because it has a far smaller high-elevation drainage area than the St. Mary River basin.

Groundwater is a limited resource in the St. Mary River and Milk River basins, used primarily for domestic and stock water purposes. Wells used for these two purposes generally pump less than about 1.5 AF per year per well. Springs and wells with sources from alluvial deposits in coulees are used widely throughout the Milk River basin. While they may be developed locally, they are not considered productive aquifers. Thick alluvial and glacial deposits found in buried valleys are considered productive aquifers in both MT and Alberta. Bedrock aquifers are present across the watershed and are developed as the primary water sources away from the Milk River Valley alluvium and other main drainages.

Overall, groundwater recharge is primarily derived from seepage from streams, infiltration of precipitation and snowmelt in topographically high outcrop areas, and leakage through confining units. Other recharge sources include irrigation water lost by percolation through fields and leakage from ditches. On a regional scale, deep groundwater and alluvial aquifers are connected. Shallow aquifers discharge at springs and seeps along the valley bottom and in the active channel of rivers. Groundwater from sandstone aquifers discharge in topographically lower areas by upward leakage to shallower aquifers and streams.

In addition to local domestic and stock water use, groundwater is also used to supplement the surface water supply for the city of Havre and is the main supply for the city of Malta. The only widespread groundwater use for agricultural irrigation is in the Turner, MT, area near the U.S./Canadian border. Joining of wells for sprinkler irrigation systems to serve about 125 acres is a common practice in this area. Because entire U.S. portion of the Milk River basin is closed to new surface water irrigation, groundwater may become a more important source for new uses in the future. However, a groundwater modeling study performed by Petre et al. (2019) exploring groundwater use in the Milk River Aquifer found that existing water use is sustainable, but larger water use scenarios are not.

Changes in groundwater due to climate change have not been specifically studied in the St. Mary or Milk River basins. However, surface water is connected to alluvial aquifers, which includes alluvium of the ancestral Missouri River throughout the basin. The Milk River is also a regional discharge area for bedrock aquifers such as the Judith River and Eagle formations. Therefore, effects of climate change on precipitation and surface water runoff could affect both recharge to and discharge from groundwater. Warmer climate conditions could reduce groundwater recharge. Increased ET would result in more water consumed by plants, thereby reducing groundwater recharge. Less precipitation and possibly fewer irrigation return flows due to direct evaporation from the soil also might reduce recharge to groundwater. In addition, riparian areas might consume more water due to increased ET, thereby reducing groundwater flows to surface water or recharge to groundwater. Increased ET is dependent on temperature and changes to riparian vegetation and might be offset by increased precipitation, with the timing of precipitation being an important factor. A reduction in volume and change in timing of surface water runoff could reduce recharge to groundwater via return flows from application of surface water to farmland. Less water available for irrigated agriculture could result in less recharge, thereby reducing groundwater availability and discharge to surface water bodies such as the Milk River.

Assessment Approach

Water supply was assessed in this Basins Study Update by evaluating historical streamflow, projected future streamflow, as well as reconstructed streamflow from the distant past (about 1,000 years) from tree rings. Development of water supply scenarios across this broad time horizon allows for greater understanding of variability and potential future conditions, beyond that which may be understood by evaluating the instrumental (gaged) records alone. These scenarios of water supply may be thought of as storylines for testing water operations strategies, infrastructure changes, and institutional changes in the managed river system. Water supply scenarios, along with complementary water demand scenarios, were collectively evaluated in St. Mary and Milk Rivers planning model to understand impacts of these scenarios (refer to “Risk Assessment” section).

Hydrologic Modeling Framework

Physical hydrologic processes that are uniquely important in the St. Mary and Milk River basins compared with other watersheds in the western U.S. include glacier processes, frozen soils, snow redistribution, and depression storage. The Prairie Potholes Region (PPR) in the north-central U.S. extends north into central Canada and spans much of the Milk River basin. The PPR watersheds have low-slope surface drainage networks including lakes and wetlands, resulting in storage conditions that vary in time. Consequently, significant portions of a watershed within the PPR could be considered non-contributing for some portion of time, as depression storage fills, not leaving enough water for runoff (figure 5). Physically-based surface hydrology models often do not represent these diverse and complex hydrologic processes that are important in St. Mary and Milk River basins. Due to these complexities, a new hydrologic modeling framework called the Dynamic Contributing Area Hydrology Model (DCAHM) was developed for the Basins Study Update, specifically designed for intended use in planning, design, and operational decisions.

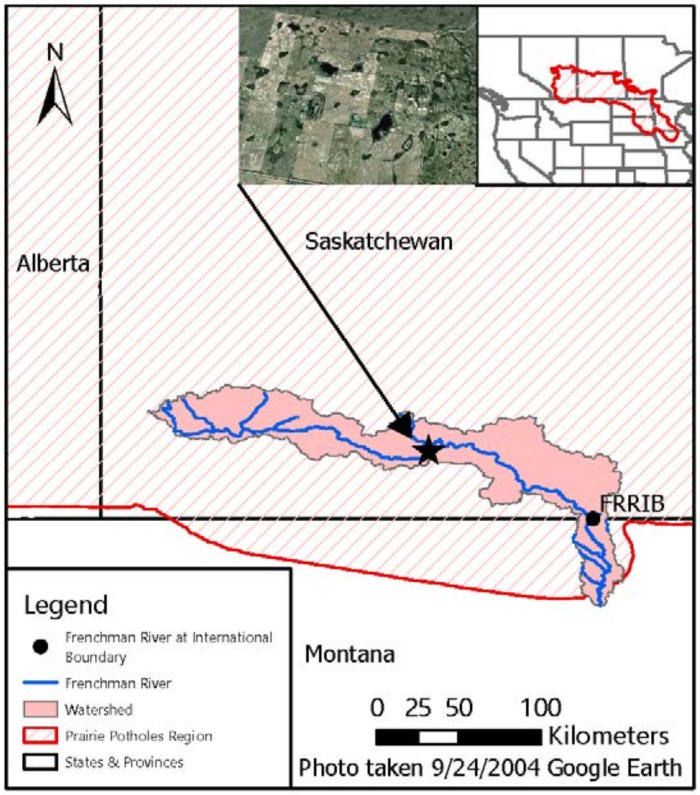
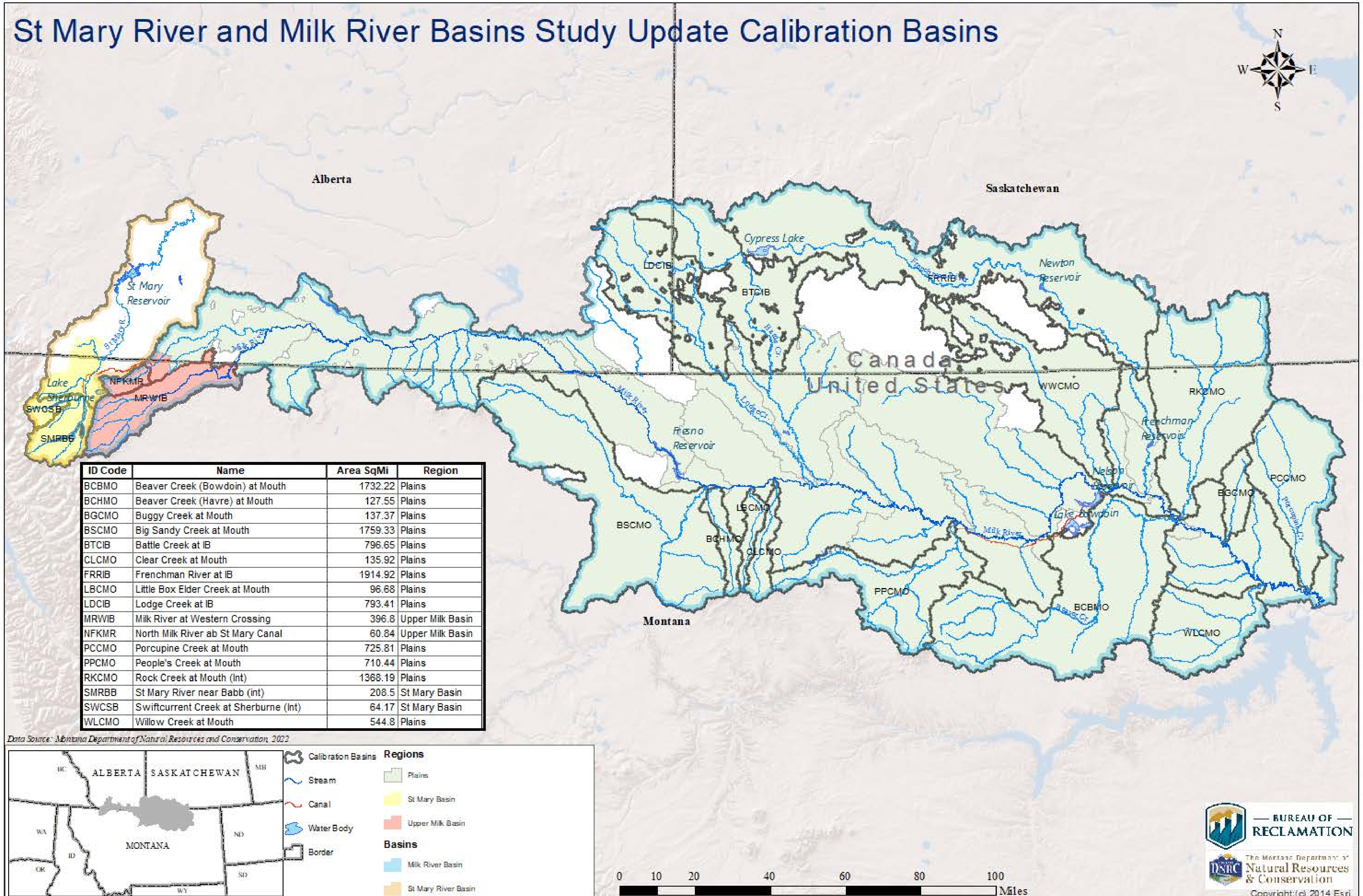


Figure 5.—Illustration of Prairie Potholes Region as a portion of St. Mary and Milk River Basins Study area.

Hydrologic model simulations using projected future climate scenarios (further described below) were compared with hydrologic model simulations forced with the historical meteorology to evaluate implications of climate change on unimpaired streamflow. The time period used as the basis for historical analysis as well as the basis of comparison for projected future simulations is calendar years 1980 to 2015. Modeling of water management ("Risk Assessment" section) and evaluation of strategies ("Risk Assessment with Strategies" section) focus on the time period including water years 1981 to 2015.

The hydrologic model framework was implemented at a subbasin scale, for each of the subbasins illustrated on figure 6. The accompanying table 3 summarizes the subbasins and provides the subbasin identifier that is referenced in results figures later in this report.



ID Code	Name	Area SqMi	Region
BCBMO	Beaver Creek (Bowdoin) at Mouth	1732.22	Plains
BCHMO	Beaver Creek (Havre) at Mouth	127.55	Plains
BGCMO	Buggy Creek at Mouth	137.37	Plains
BSCMO	Big Sandy Creek at Mouth	1759.33	Plains
BTCIB	Battle Creek at IB	796.65	Plains
CLCMO	Clear Creek at Mouth	135.92	Plains
FRRIB	Frenchman River at IB	1914.92	Plains
LBCMO	Little Box Elder Creek at Mouth	96.68	Plains
LDCIB	Lodge Creek at IB	793.41	Plains
MRWIB	Milk River at Western Crossing	396.8	Upper Milk Basin
NFKMR	North Milk River ab St Mary Canal	60.84	Upper Milk Basin
PCCMO	Porcupine Creek at Mouth	725.81	Plains
PPCMO	People's Creek at Mouth	710.44	Plains
RKCMO	Rock Creek at Mouth (Int)	1368.19	Plains
SMRBB	St Mary River near Babb (int)	208.5	St Mary Basin
SWCSB	Swiftcurrent Creek at Sherburne (Int)	64.17	St Mary Basin
WLCMO	Willow Creek at Mouth	544.8	Plains

Figure 6.—Hydrologic model calibration basins within the study area.

Table 3.—Summary of hydrology model calibration basins within the study area

Calibration basins*	Description	USGS Identification (ID; if applicable)	Location
BCBMO	Beaver Creek (Bowdoin) at Mouth	06167500	Plains
BCHMO	Beaver Creek (Havre) at Mouth	06140000	Plains
BGCMO	Buggy Creek at Mouth	06172200	Plains
BSCMO	Big Sandy Creek at Mouth	06139500	Plains
BTCIB	Battle Creek at International Boundary	06149500	Plains
CLCMO	Clear Creek at Mouth	06142400	Plains
FRRIB	Frenchman River at International Boundary	06164000	Plains
LBCMO	Little Box Elder Creek at Mouth	06141600	Plains
LDCIB	Lodge Creek at International Boundary	06145500	Plains
MRWIB	Milk River at Western Crossing of the International Boundary	06133000	Upper Milk Basin
NFKMR	North Milk River above St. Mary Canal	06133500	Upper Milk Basin
PCCMO	Porcupine Creek at Mouth	06175000	Plains
PPCMO	People’s Creek at Mouth	06154550	Plains
RKCMO	Rock Creek at Mouth	06171000	Plains
SMRBB	St. Mary River near Babb	05017500	St. Mary Basin
SWCSB	Swiftcurrent Creek at Sherburne	05014500	St. Mary Basin
WLCMO	Willow Creek at Mouth	06174000	Plains
WWCMO	Whitewater Creek at Mouth	not applicable (NA)	Plains

* Items in this column are acronyms with their definitions provided in the “Description” column.

A calibration and validation workflow process was developed over a historical period of record 1980 to 2015 (calendar years). As part of the calibration process, simulated streamflow was compared with naturalized streamflow by way of identified metrics. A daily naturalized streamflow dataset was developed by MT DNRC using twice-monthly natural flow records from the IJC, as well as through observed gage records and consumptive use estimates. Calibration points and associated methods for developing naturalized flow records are summarized in "Appendix B. Water Supply Development."

The calibration and validation workflow process was also developed with the goal of evaluating climate change impacts based on downscaled GCM projections as part of this water supply assessment. Further details of the model calibration and validation approach are provided in "Appendix B. Water Supply Development."

The study area was also discretized into three regions, named the St. Mary Basin, the Upper Milk Basin, and the Plains, as illustrated on figure 7. The gray regions represent regions not included in the hydrologic modeling. Discussion of watershed delineations is provided in "Appendix B. Water Supply Development." The gray region to the north of the blue-shaded St. Mary River basin is the part of the St. Mary watershed downstream from the Canadian border, so simulated streamflows do not impact the study area. The gray region in the Milk River basin represents those areas that are closed basins and do not contribute streamflow to the Milk River. In development of the hydrologic model framework, we determined the subbasins within these regions have similar hydrologic characteristics and thereby have consistent hydrologic model parameters within these regions. Also, as summarized later in the "Paleohydrologic Analysis and Scenarios" section, three reconstructions of annual streamflow based on tree rings were used as the basis for analysis, one in each of these three hydrologically distinct regions. Results summarized in the "Water Supply Assessment" section are grouped according to these three regions.

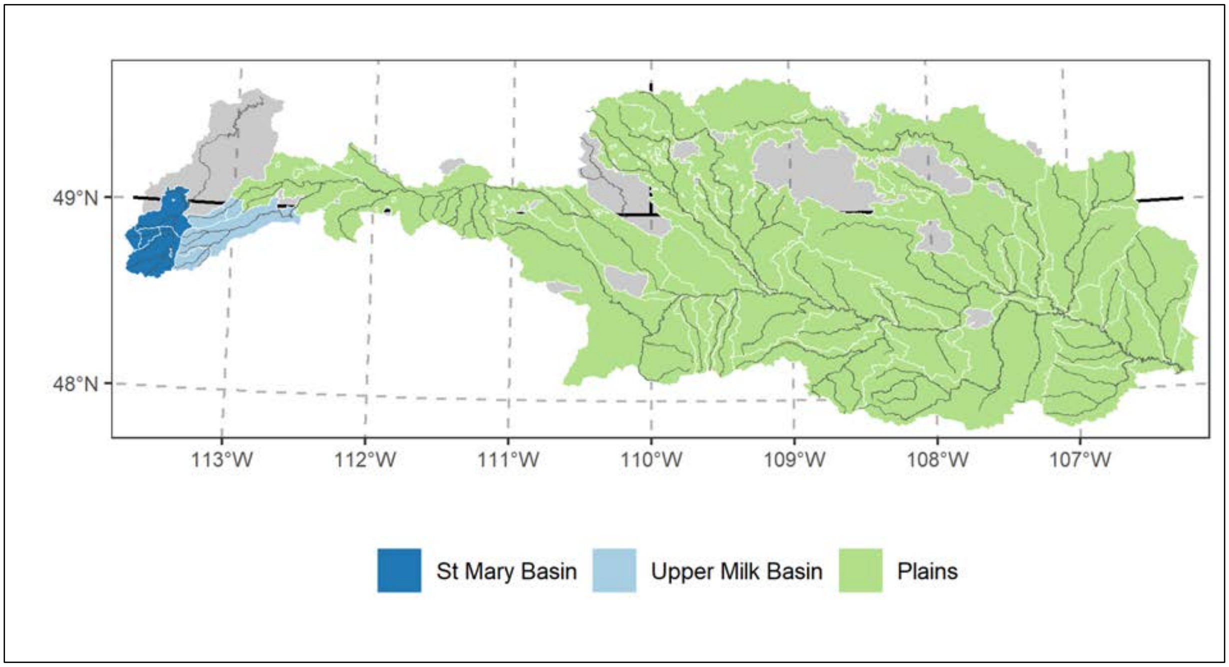


Figure 7.—Hydrologically similar regions within the St. Mary and Milk River basins.

Projected Future Climate Scenarios

Weather and climate conditions are a primary driver of water supply and demand. Projections of future climate conditions help to inform what water supply and demands may look like in the future. The scientific community's primary approach for characterizing future climate consists of using GCMs to simulate future climate conditions, including temperature, precipitation, and other relevant climate variables. The GCMs are used to simulate future climate conditions over the globe, including the global climate response to changes in greenhouse gas (GHG) and aerosol concentrations in the atmosphere. Numerous climate projections have been developed through coordinated efforts by the international climate science community. Projections from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) were used in this Basins Study Update.

This Water Supply Assessment relies on downscaled climate projections that are served as part of the Downscaled Climate and Hydrology Projections archive at: http://gdodcp.ucllnl.org/downscaled_cmip_projections. This database of climate and hydrologic projections was developed by Reclamation and several collaborators, and covers the lower 48 States, including Canadian portions of the Columbia River basin and St. Mary and Milk River basins. Climate projections are downscaled to a finer spatial and temporal scale needed for water management studies.

A subset of the full ensemble of CMIP5 projections are used in this study, based on projections using two GHG emissions scenarios, namely CMIP5 Representative Concentration Pathway (RCP) 4.5, and CMIP5 RCP 8.5. This subset, comprised of 64 individual projections, is consistent with work done for the Fourth National Climate Assessment (USGCRP 2018).

The available ensemble (or group) of 64 CMIP5 Locally Constructed Analogs (LOCA)-downscaled climate projections was used to inform five projected future climate scenarios for each of three future planning horizons: 2020s, 2050s, and 2080s. Together the five climate scenarios reflect the range of potential future climate conditions across the ensemble for a select future planning horizon. Narrowing to five projected future climate scenarios allows for a more manageable set of scenarios with which to evaluate water supply and demand imbalances, while still representing the range of projected future change.

Climate scenarios for this water supply assessment were developed using an approach that involves perturbing historical observed climate (precipitation and temperature) based on the projected change in simulated monthly climate by GCMs, computed based on a chosen future planning horizon and a reference historical period (figure 8; refer to "Appendix B. Water Supply Development" and Reclamation 2010 for a detailed description of methods). In this Basins Study Update, the reference historical period used as a basis for developing future climate scenarios is 1980 to 2015.

This climate scenario approach preserves the sequencing of historical climate, which is advantageous for studies evaluating potential changes in the characteristics of notable climate events in the historical record. This approach corresponds well with use of paleohydrology information to develop re-sequenced future climate scenarios based on transition probabilities computed from the paleo-reconstructed streamflow record. One weakness of this approach is the inability to evaluate the potential future rate of change in temperature or precipitation or the projected timing of reaching a given threshold.

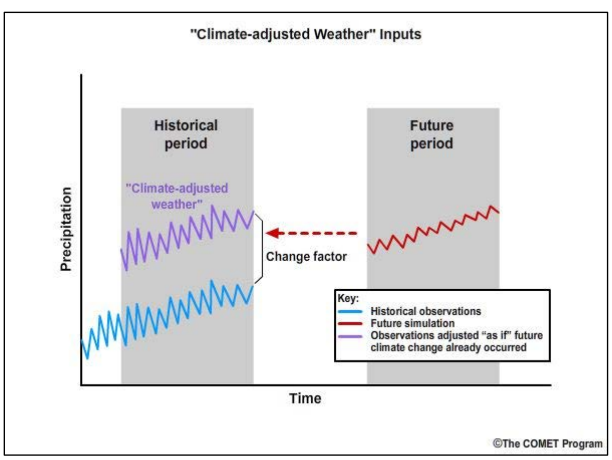


Figure 8.—Illustration of projected future climate scenario development approach. Source: the COMET Program (2012).

The five developed climate scenarios bracket the range of potential futures, from less to more warming and drier to wetter conditions. These scenarios are labelled: WW, WD, HW, HD, and CT. Scenarios were developed for each of three future time horizons:

- 2020s (spanning water years 2010–2039)
- 2050s (spanning water years 2040–2069)
- 2080s (spanning water years 2070–2099)

Figure 23 provides an illustration of the individual climate projections that inform each of the five types of climate scenarios, in this case for the 2080s future time horizon.

We acknowledge that at the publication date of this report (2024), we are already well into the 2020s future time horizon used in this “Water Supply Assessment” section. The challenge with near-term planning horizons is that the historical period used as a basis for comparison ends in 2015, while the latest broadly available downscaled GCM projections begin in 2006. The period of overlap is often confounding for climate change analysis, which requires evaluation of long periods (typically at least 30 years) in order to distinguish climate change from natural climate variability. Therefore, we keep the 2020s planning horizon as such and not as a period over which we may compare historical climate with what was projected over the same period from GCMs. We cannot expect GCMs to reproduce near-term climate due to natural climate variability simulated by the GCMs.

Projected Future Hydrology Scenarios

Projected future climate scenarios of precipitation and temperature were used directly as input to the hydrologic modeling framework to develop projected future hydrologic scenarios. The hydrology model, described earlier, incorporates optimization of model parameters for each year simulation, including the scaling coefficient used to identify the watershed area contributing to streamflow. This approach recognizes that model parameters are time-varying and calibrated based on comparison of simulated and observed naturalized streamflow. This poses a challenge when inputting projected future climate scenarios of precipitation and temperature into the modeling framework. To address this challenge, we employed a similar approach as applied for historical model verification (described in detail in appendix B). That is, based on antecedent conditions of precipitation and temperature, a principal component analysis (PCA) was performed to identify historical years similar to each year of the future climate scenarios to be simulated. The calibrated model parameters from the analog historical years were used in the future scenario simulations. Six historical analog years were selected and simulated for each future scenario year. A statistical resampling of the resulting streamflow simulations was performed, and the avg of the 1000-simulation ensemble was calculated to become the resulting future scenario daily streamflow timeseries.

Paleohydrologic Analysis and Scenarios

Tree-ring-based reconstructions of past streamflow that pre-date gage-based records have been utilized in several basin studies, including the Colorado River Basin Water Supply and Demand Study (Reclamation 2012c) and the Missouri Headwaters Basins Study (Reclamation and MT DNRC 2021). These long streamflow records help to expand the timeframe over which water managers and decision makers can evaluate water supplies, short- and long-term variability, and potential changes in hydrology associated with changing climate conditions. Streamflow reconstructions also provide a robust long-term perspective from which to evaluate projected changes to future water supplies under various climate scenarios.

Tree rings are used to develop chronologies, or timescale information about wet and dry years. Since inter-annual streamflow variability is also closely related to climatic conditions over the course of the water year, tree-rings record provide valuable information on the drivers of streamflow that can be used to estimate streamflow variability over time. The general approach to reconstructing streamflow involves the statistical correlation of growth patterns in tree-rings to variability in an observed streamflow record. This allows for the development of a statistical reconstruction model that can then be used to estimate annual flow from annual growth rings.

With the oldest tree-ring records in the general region of the study area dating back to as early as 200 B.C.E., very long estimates of streamflow are possible for some rivers and gage locations that are particularly favorable for reconstruction. The northern Rockies region contains a broad network of tree-ring records that represent a variety of tree growth sensitivities to climate including high elevation trees that reflect high snow years as reduced width of annual growth rings and lower elevations trees that grow wider rings during years with more winter and spring precipitation (figure 9). As a result, paleohydrologic records for the St. Mary and Milk rivers can be expected to reflect streamflow variability resulting from a diversity of hydrologically important climate factors (Martin and Pederson 2022).

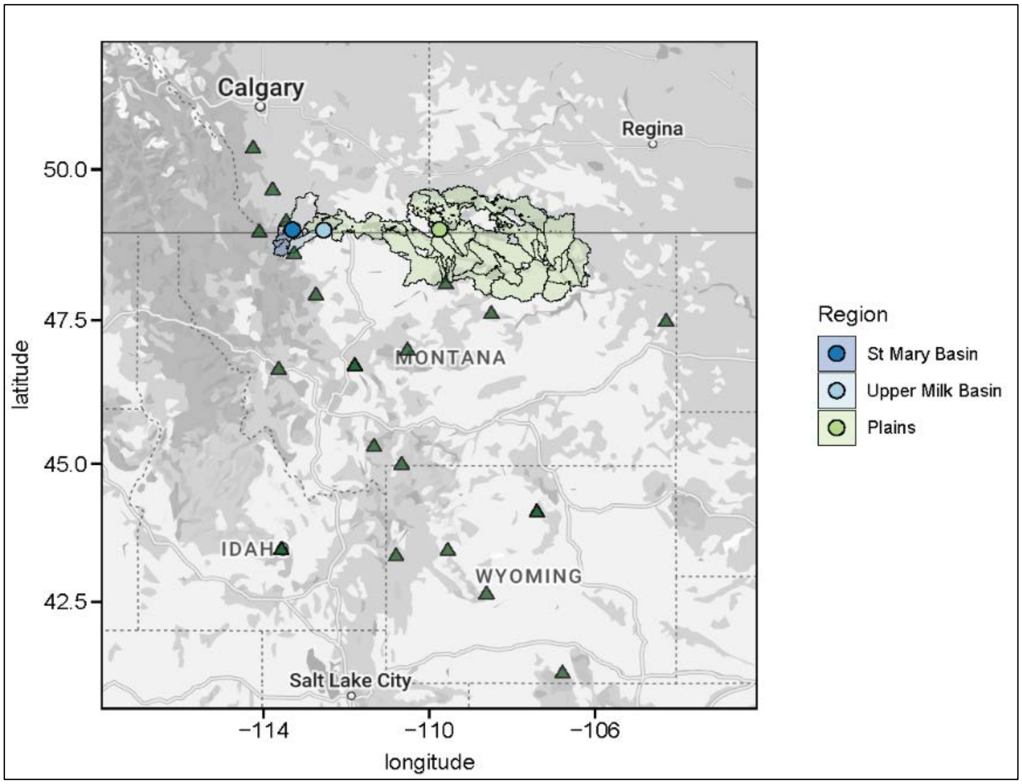


Figure 9.—Map of the study area showing the eight gage locations (points) with streamflow reconstructed, the HUC 8 watersheds within the St. Mary and Milk basins, and the tree-ring network used to reconstruct water-year streamflow (green triangles).

To simplify the integration of streamflow reconstructions into Reclamation's modeling exercises, this network of records was reduced to three key gaging locations within the most hydrologically distinct regions of the study area. This simplified network of locations is represented by the St. Mary River at the International Boundary, the MRWIB, and Lodge Creek at International Boundary (LDCIB). These locations correspondingly reflect streamflow contributions in the mountain headwaters of the St. Mary River basin, the foothills contributions to the mainstem Milk River, and the contributions of the Canadian prairie basins to the lower Milk River. Further, these reconstruction locations correspond with the hydrologically distinct regions illustrated on figure 7 and determined through parameterization of the hydrologic modeling framework.

A primary feature of interest in the paleohydrologic records examined here was the occurrence of drought events in the past that exceed those during the instrumental era. This is because evidence of drought conditions that exceed those previously experienced by water managers in the basin suggests the potential for low water supply stresses on infrastructure and operating protocols that are outside the envelope of experience for both water managers and end users. In comparing droughts of the past to those evident in the naturalized flow records, we first defined a drought event as:

> "An event beginning with (and including) two or more consecutive years of streamflow below the median flow level that is ended only by (and excluding) two or more consecutive years of streamflow above the median flow level and may include one or more individual wet years within the drought only when bounded on both sides by dry years."

This definition, depicted on figure 10 using the Dustbowl drought on the Milk River as an example, is the same used for Reclamation's 2021West-Wide Climate and Hydrology Assessment and very similar to that used in the recent Missouri Basin Impacts Assessment (Reclamation 2019) and Missouri Headwaters Basins Study (Reclamation and MT DNRC 2021). Additional details describing methodology and major drought events in the paleohydrology record are provided in appendix F.

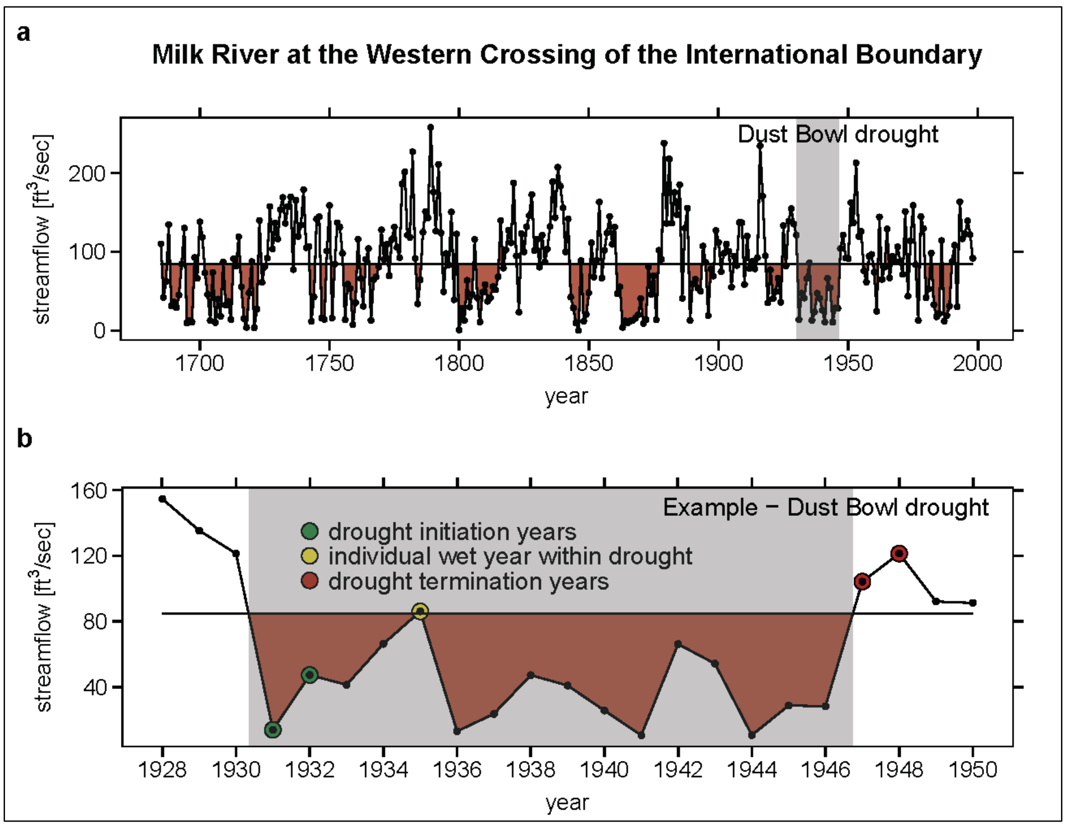


Figure 10.—Graphical representation of a drought as defined in this study. Horizontal black line indicates median flow.

Historical Climate and Water Supply in the Milk and St. Mary River Basins

The Northern Great Plains exhibits a high amount of geographical, ecological, and climatological variability, in part because of the dramatic elevation change across the region (Conant et al. 2018). Elevations in the St. Mary and Milk River basins range between 10,000 ft at the highest elevations of Glacier National Park at the western study area boundary, to about 2,000 ft at the mouth of the Milk River before it enters the Missouri River below Fort Peck Reservoir in MT. The gradient of avg annual precipitation and avg temperature from west to east across the study area generally corresponds with elevation, with greatest levels to the west and lowest levels to the east.

Based on the Daymet historical gridded climate dataset, avg annual historical precipitation ranges from 50 to 60 inches in the headwaters of the St. Mary River basin and 12 to 14 inches near the mouth of the Milk River (figure 11), with an avg of 18 inches across the study area. avg daily temperature varied historically from about 35 to 38 degrees (°) Fahrenheit (F) in the headwaters of the St. Mary River basin to about 44 °F toward the mouth of the Milk River (figure 12), with a study area avg of about 41 °F. Historical avg annual precipitation and temperature (daily avg) reported in this Basins Study Update are roughly comparable to those reported in the 2012 Basins Study, which reported these values over the available periods of record at three weather stations across the study area (table 1.1, Reclamation and MT DNRC 2012).

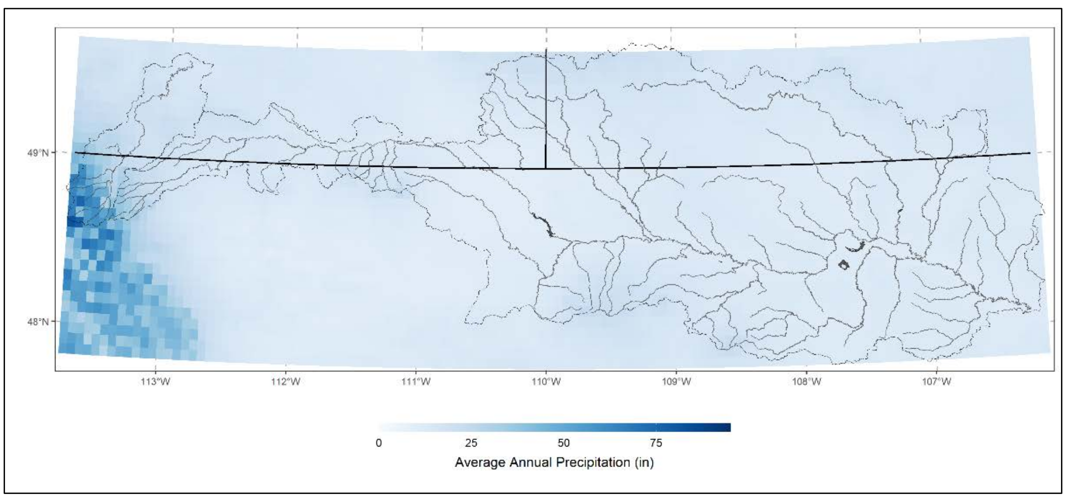


Figure 11.—Historical average annual precipitation (inches).

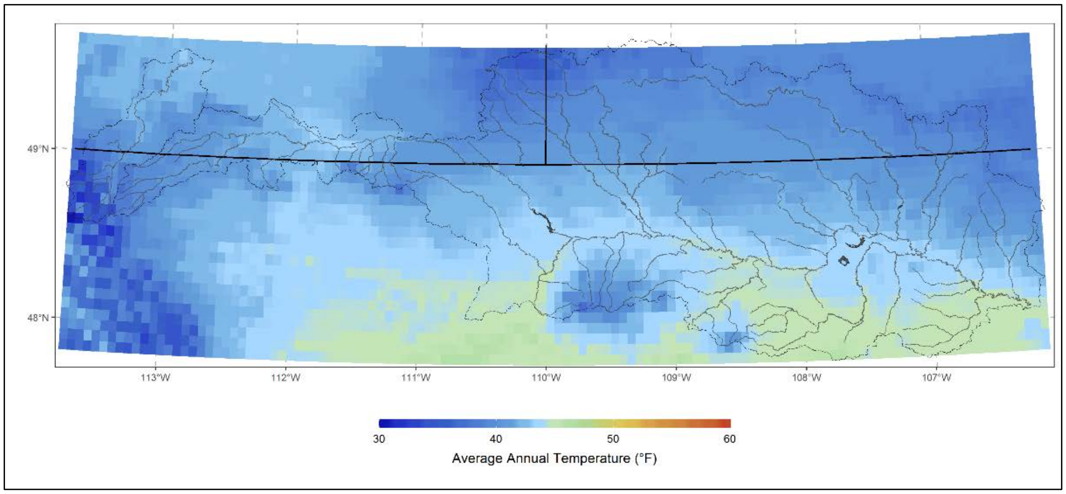


Figure 12.—Historical average annual air temperature (°F).

Because the Northern Great Plains is so far from the coasts and the modulating effect of the oceans, the regional climate system is prone to dramatic climate variability (Conant et al. 2018). Precipitation varies seasonally, with the greatest precipitation falling in May and June (figure 13). Liu et al. (2004) found that from May through August most of the moisture for precipitation in this region comes from the Gulf of Mexico, while from November through March precipitation comes from the Pacific Ocean. On avg over years 1980 to 2015, February received the least precipitation the study area, However, for the St. Mary River basin, the driest month was August. Daily avg temperatures are a greatest in summer months of July and August (figure 13) across the study area.

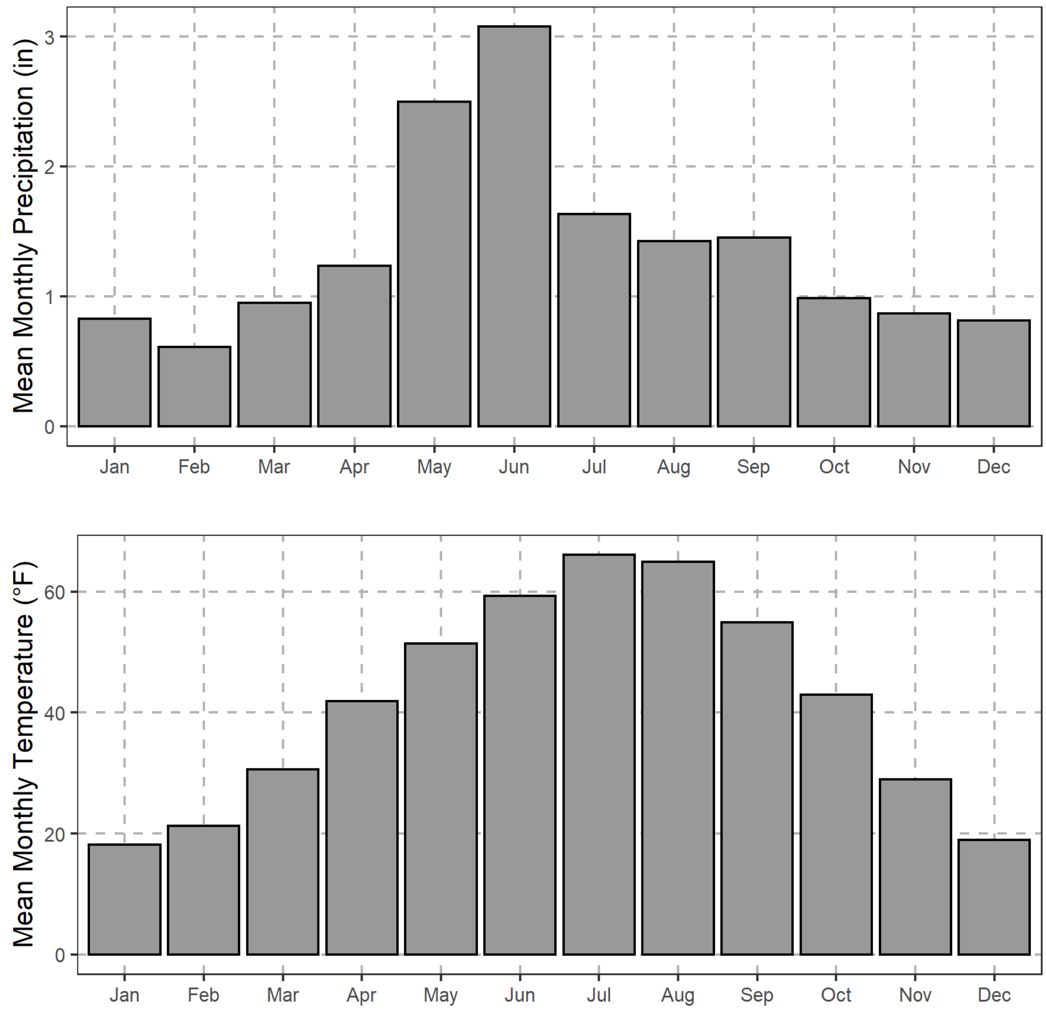


Figure 13.—Historical average monthly precipitation (inches) and temperature (°F) based on Daymet historical climate dataset over calendar years 1980–2015.

Perhaps more relatable metrics of climate include extremes of precipitation and temperature and support understanding of the range of potential changes into the future. Figure 14 illustrates the avg number of days per year historically with precipitation greater than one inch. Values vary from one day or less in the Plains region to up to 11 days in the St. Mary Basin.

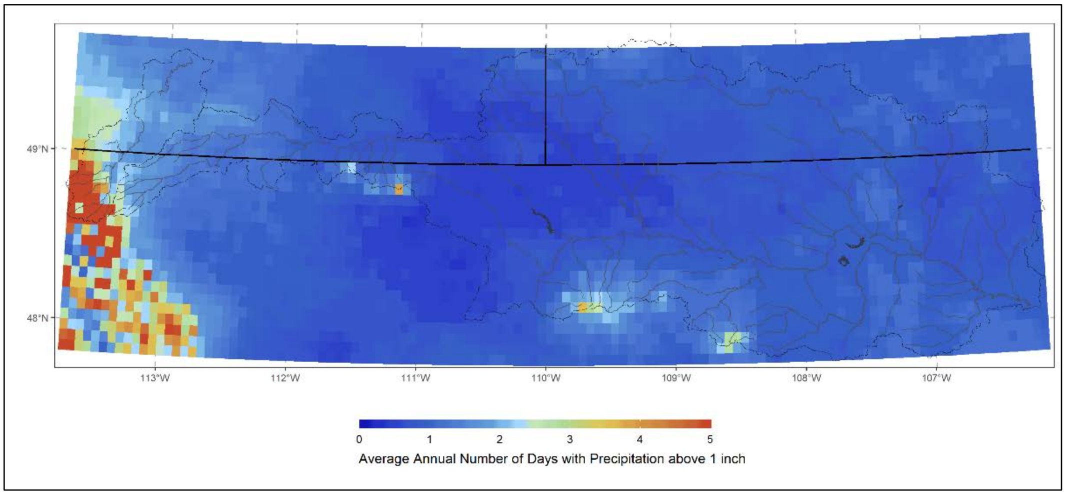


Figure 14.—Historical average number of days with precipitation greater than 1 inch.

Figure 15 summarizes the avg number of days when daily minimum temperature was below freezing (32 °F). Values range from 168 days in the Plains region to over 230 days in the St. Mary Basin.

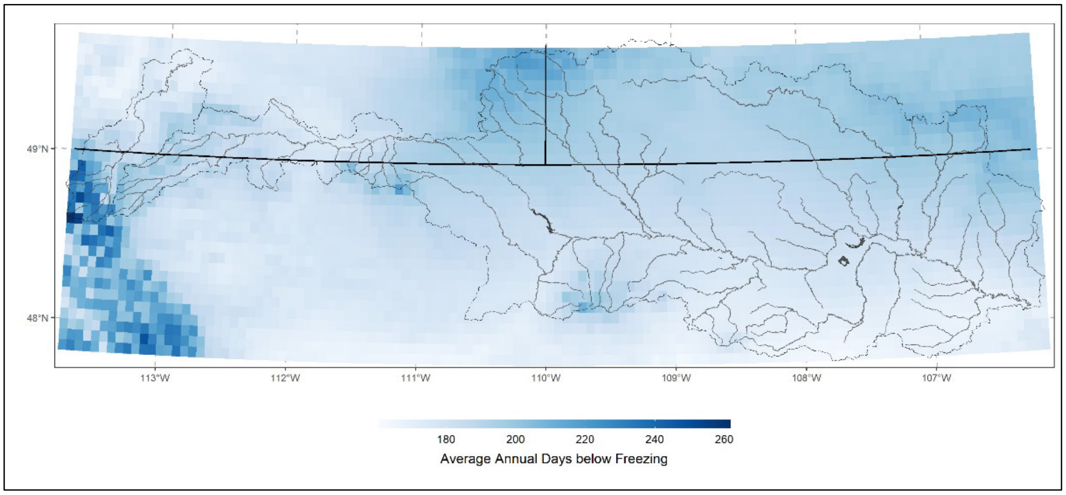


Figure 15.—Historical average number of days below freezing (32 °F).

Figure 16 summarizes the avg number of days when daily maximum temperature was above 95 °F. Values range from zero in the St. Mary Basin to 13 in the Plains Basins (indicating it did occur in a few years). The next section summarizes how these extremes may change into the future.

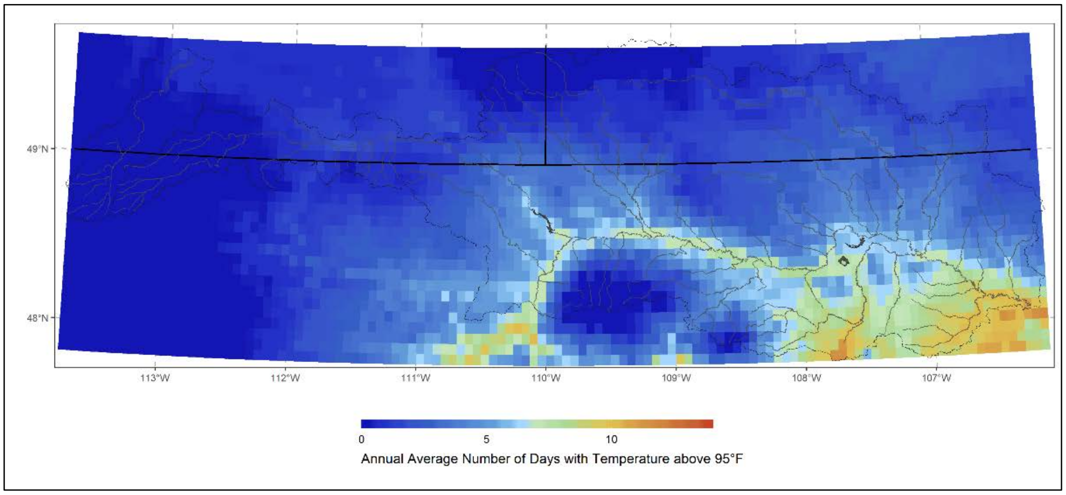


Figure 16.—Historical average number of days above 95 °F.

Review of historical hydroclimate is useful to help understand changes that may have already occurred due to climate change. Trends in avg annual precipitation and avg annual (daily avg) temperature are generally not statistically significant when looking at overall linear trends and a 95 percent confidence level (p-value < 0.05). Annual values are highly variable, particularly as one moves from west to east across the study area. Historical precipitation trends are much more variable from subbasin to subbasin and generally are increasing except for a few subbasins in the Plains region of the study area; however, calculated negative precipitation trends are not statistically significant at a 95 percent confidence level. Historical trends in annual flow volume are also inconclusive and variable by subbasin. Table 4 provides a summary of historical trends in annual precipitation totals, daily avg temperature, peak snow water equivalent (SWE), and total annual flow volume. Statistically significant trends (p-value < 0.05) are highlighted in orange.

Table 4.—Historical trends in annual precipitation, temperature, peak SWE, and annual flow volume (1980–2015)

Calibration basins* (i.e., subbasins)	Annual precipitation (inches/year)	Annual temperature (deg F/year	Peak SWE (inches/year)	Annual flow volume (inches/year)
BCBMO	1.18	0.50	3.99	0.02
BCHMO	-0.23	0.17	0.58	0.75
BGCMO	1.82	-0.54	4.37	1.32
BSCMO	0.12	-0.04	6.47	0.24
BTCIB	0.66	1.68	-0.47	0.02
CLCMO	-0.21	0.21	0.78	0.28
FRRIB	0.14	0.27	-0.46	0.03

Table 4.—Historical trends in annual precipitation, temperature, peak SWE, and annual flow volume (1980–2015)

Calibration basins* (i.e., subbasins)	Annual precipitation (inches/year)	Annual temperature (deg F/year	Peak SWE (inches/year)	Annual flow volume (inches/year)
LBCMO	-0.21	0.12	2.03	0.74
LDCIB	0.71	1.70	0.32	0.00
MRWIB	0.40	0.80	1.05	0.04
NFKMR	0.54	0.82	1.01	0.60
PCCMO	1.80	-0.66	4.24	-0.24
PPCMO	0.42	0.68	0.81	0.03
RKCMO	1.39	-0.52	1.50	0.12
SMRBB	0.33	2.31	0.48	0.03
SWCSB	0.28	2.31	0.41	0.06
WLCMO	1.72	0.33	5.51	0.02
WWCMO	1.39	-0.51	2.98	-0.92

Notes: Historical precipitation and temperature trends were based on Daymet data. Historical peak SWE and annual flow volume trends were based on DCAHM simulations over the historical period, forced by Daymet daily precipitation and temperature.
* green: Plains; light blue: Upper Milk Basin; dark blue: St. Mary Basin

Simulated peak SWE averaged across years in the historical reference simulation period (1980 to 2015) illustrates the relative importance of snowpack as a component of seasonal water supply. Snow sublimation and blowing snow are important considerations in assessment of water supply in the study area, partiucularly in the Plains Basins. Although the hydrologic modeling approach does not explicitely represent these processes, it was developed with the aim of capturing these physical processes collectively.

Peak SWE was selected as the metric to convey historical snow storage and change because snowpack across the study area is highly variable. Use of April 1 snowpack, which is a common metric for evaluating historical and changing snowpack conditions in mountain watersheds where April is representative of peak SWE, may not be as meaningful a metric due to important physical processes in Plains Basins including snow redistribution. In fact, the avg date of peak SWE historically varies from late January (around water year Julian day 119) in the Plains region to early April (around water year Julian day 193) in the St. Mary Basin, as illustrated on figure 17 and summarized in table 5.

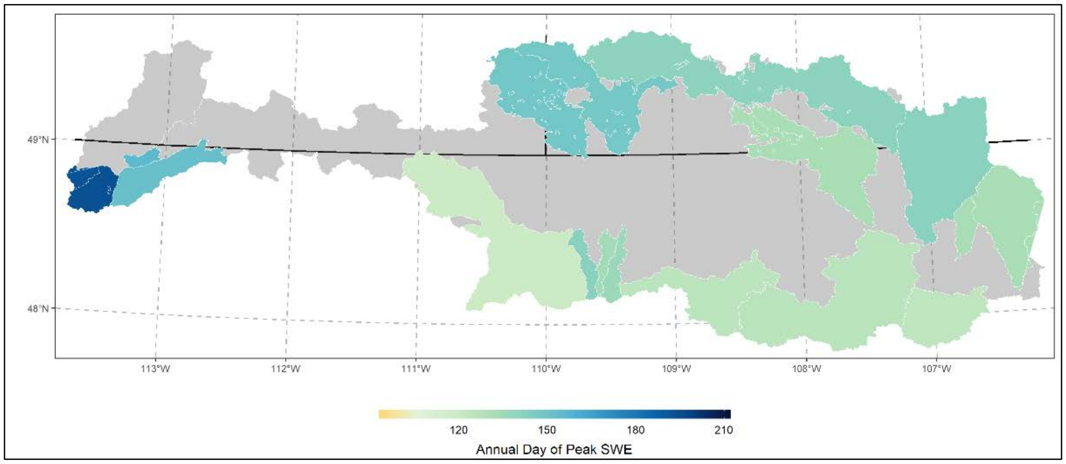


Figure 17.—Historical average date of peak SWE (in Julian days starting October 1).

Table 5.—Historical average date of peak SWE and date of flow centroid by subbasin colors reflect the basin's hydrologic region

Calibration basins* (i.e., subbasins)	Avg Julian day of peak SWE (from October 1)	Avg date of peak SWE	Avg date of flow centroid
BCBMO	126	Feb 02	May 14
BCHMO	142	Feb 18	May 03
BGCMO	132	Feb 09	May 19
BSCMO	120	Jan 27	May 15
BTCIB	148	Feb 24	May 04
CLCMO	137	Feb 13	May 10
FRRIB	141	Feb 17	Apr 30
LBCMO	134	Feb 10	May 14
LDCIB	149	Feb 25	Apr 25
MRWIB	152	Feb 28	May 04
NFKMR	155	Mar 04	May 17
PCCMO	132	Feb 08	Apr 22
PPCMO	126	Feb 02	May 05
RKCMO	141	Feb 18	Apr 29
SMRBB	193	Apr 11	May 20
SWCSB	192	Apr 10	May 14
WLCMO	124	Feb 01	Apr 29
WWCMO	132	Feb 08	Apr 16

* (green: Plains; light blue: Upper Milk Basin; dark blue: St. Mary Basin)

Peak SWE is greatest in the St. Mary Basin with about 25 inches in the SWCSB and 20 inches in the SMRBB (refer to figure 18 and figure 19). Peak SWE is about 4 inches in the Upper Milk Basin and about 1 to 2 inches in the Plains Basins.

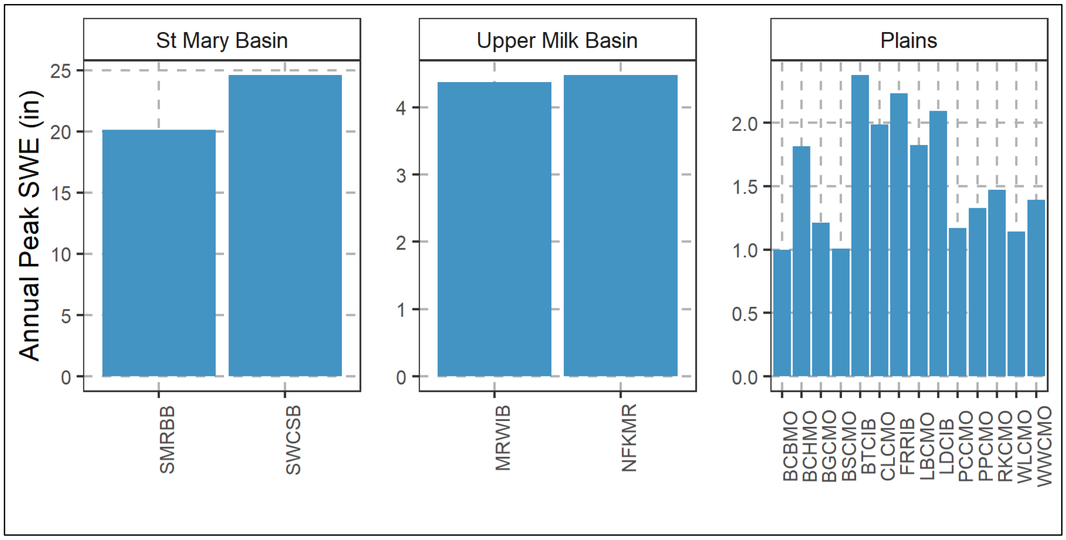


Figure 18.—Average annual peak SWE (in) summarized by hydrologic region within the St. Mary Milk River Basins Study area over 1980-2015 historical period.[1]

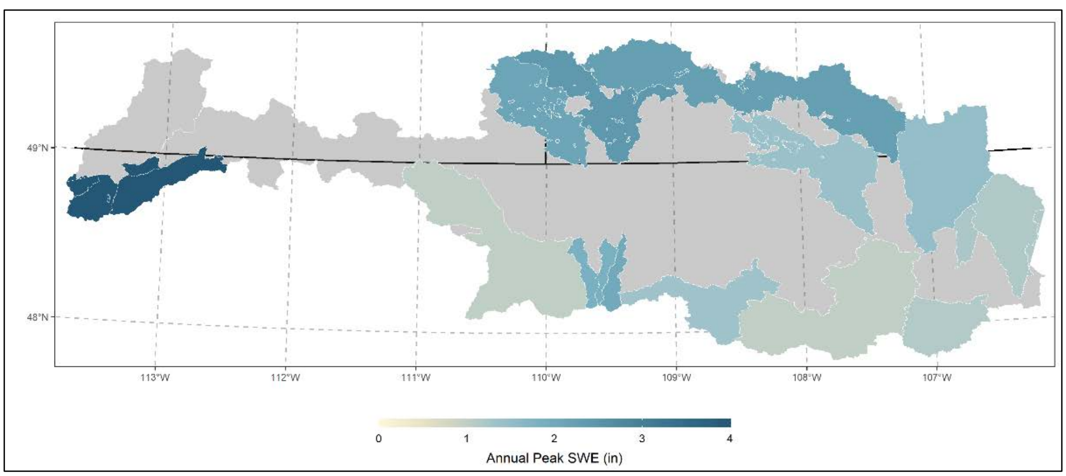


Figure 19.—Average annual peak SWE (in) at calibrated river basins.

[1] It should be noted that historical trends in peak snowpack are not statistically significant (p-value < 0.05) over this period.

We characterize historical streamflow and projected changes in terms of avg annual flow volume, seasonal flow volume, and the avg date (Julian day on a water year basis starting October 1) at which half of the water year annual flow volume has passed. The headwaters of the St. Mary River basin in the U.S. generate high annual flow volume relative to the Milk River basin, as evidenced by figure 20 and by the importance of St. Mary River trans-basin water deliveries to the Milk River basin via the St. Mary canal. The locations reported on in this figure are listed in table 3 and illustrated on figure 6. The SMRBB has an avg annual (natural or unimpaired) flow volume of more than 460 thousand acre-feet (KAF), compared with the MRWIB which has an avg annual (natural or unimpaired) flow volume of 48 KAF. For comparison, the Frenchman River at International Boundary (FRRIB), the portion of the watershed that enters the U.S. from Saskatchewan, Canada, is one of the largest tributaries of the Milk River in the Plains region and has an avg annual flow volume of 60 KAF. The WWCMO and BGCMO, respectively, are smaller Plains creeks that flow into the Milk River (figure 20 and figure 21) contributing around 1.1 to 1.4 KAF of annual flow volume. It should be noted that historical trends in annual flow volume are not statistically significant ($p\text{-value} < 0.05$) over this period.

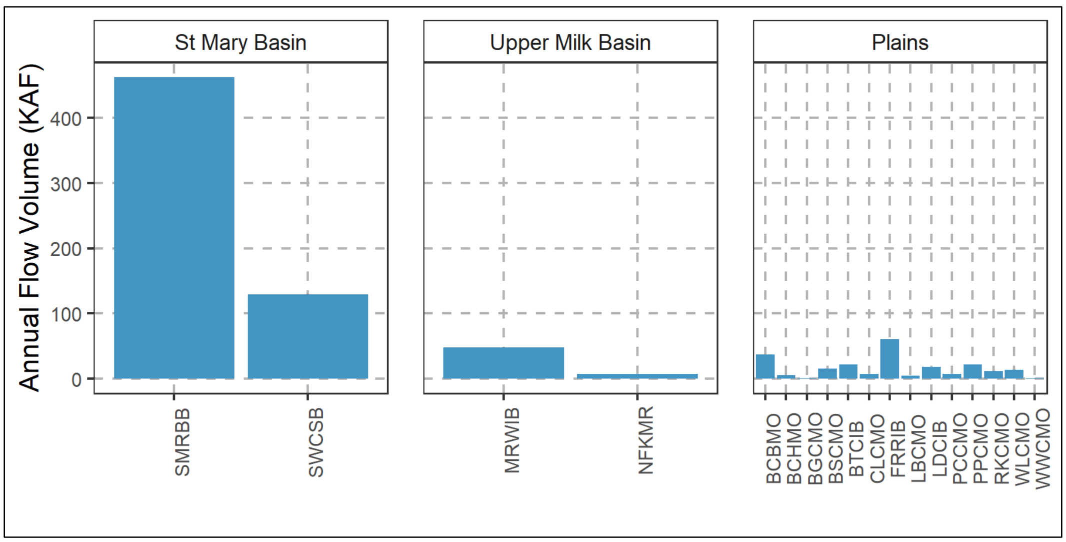


Figure 20.—Average annual flow volume (KAF) summarized by hydrologic region within the St. Mary Milk River Basins Study area over this historical reference period of water years 1981–2015.

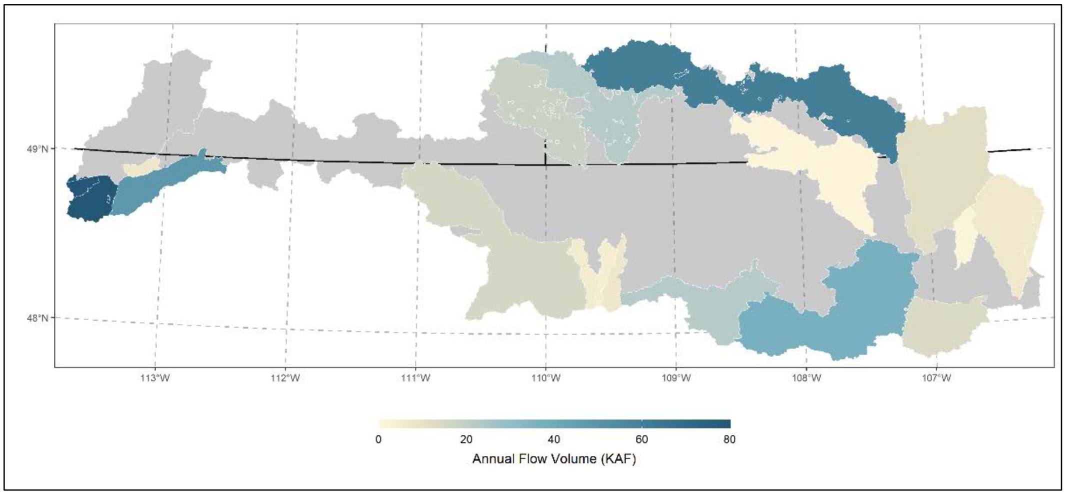


Figure 21.—Average annual flow volume (KAF) at calibrated river basins.

The date of the median flow volume, also termed centroid timing of streamflow, is a valuable measure illustrating the timing of seasonal peak streamflow. Across the study area, the date of the median flow volume is between April 15 (day 198) and May 20 (day 232), with timing being later in the St. Mary Basin and earlier in the Plains Basins (figure 22). The avg date of flow centroid predominantly falls within the defined Season 3 for each of the modeled subbasins.

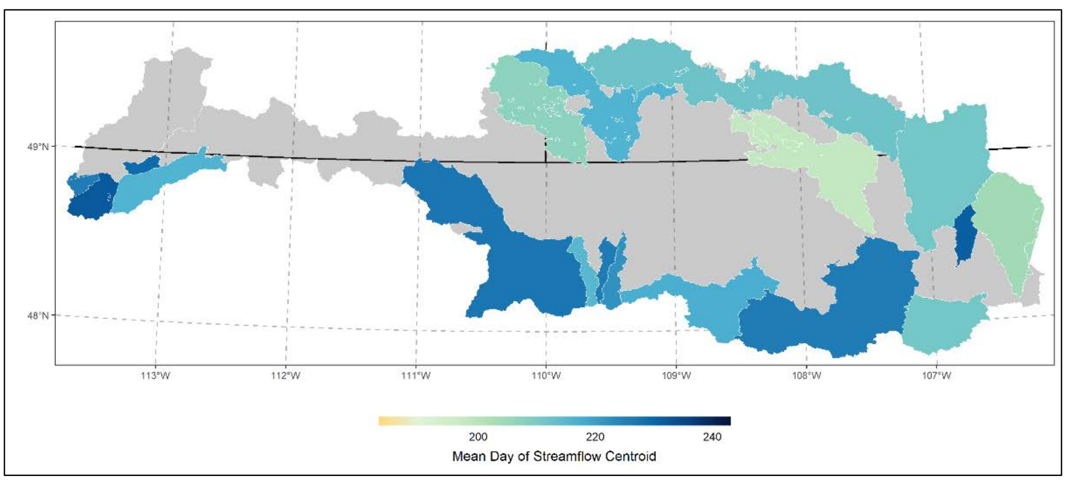


Figure 22.—Historical average date of the flow centroid (in Julian days starting October 1).

Impacts of Climate Change on Climate and Water Supply

The previous section illustrates that the St. Mary River basin generates much more streamflow than the Milk River basin. In some years, the St. Mary River basin supplies up to 95 percent of the streamflow to the Milk River system. Because of the relatively small proportion of total St. Mary and Milk River water supply originating in the Milk River basin, even small changes in annual precipitation due to climate change may have large effects on water management downstream. As presented in the Fourth National Climate Assessment (Conant et al. 2018), future changes in precipitation patterns, warmer temperatures, and the potential for more extreme rainfall events are likely to exacerbate existing water management challenges.

This section discusses the impacts of climate change on hydrology in the study area. The first subsection focuses on precipitation and temperature changes while the following subsection focuses on snowpack and streamflow. Climate scenarios consist of fifteen future climate scenarios that span the projected range of change in annual precipitation and temperature over three future time horizons that include 30-year windows of time centered on each of the 2020s, 2050s, and 2080s decades across the study area. Projected future snowpack and streamflow are based on hydrologic model simulations forced with projected future climate scenarios as input.

Projected Future Climate

Review of climate projections averaged over the St. Mary and Milk River basins suggests a warmer future (no projections suggest cooling may occur) with a range of drier to wetter conditions, compared to the historical time period 1980 to 2015. Figure 23, which illustrates projected changes in annual precipitation and temperature for the 2080s compared with the reference historical period for each of the 64 examined LOCA-downscaled CMIP5 climate projections, shows that annual precipitation is projected to decrease by as much as 10 percent or increase by as much as almost 30 percent, with 77 percent of individual CMIP5 projections showing a projected increase in avg annual precipitation as opposed to a decrease. Figure 23 also shows that avg annual temperature is projected to increase under all projections, with the projected increase ranging from 2 °F to almost 14 °F. The consensus of projections showing projected increases in avg annual temperatures suggests higher confidence in projected temperature than avg annual precipitation, where not all projections are in agreement.

While future climate scenarios generally suggest increases in annual precipitation across the study area, changes also vary spatially (figure 24 and table 6). For example, under the dry scenarios (HD and WD), parts of the study area may experience decreased precipitation on an annual basis. The wetter scenarios suggest that an increase in annual precipitation of 26 percent is possible. The projections of change in annual precipitation are consistent with Reclamation's 2021 SECURE Water Report, which summarizes CMIP5 LOCA-downscaled projections in hydrologic unit code, 8-digit river basins across the 17 western states (Reclamation 2021). However, the 2021 SECURE Report summarizes projected change in precipitation between a 2050s future period and 1970–1999 historical reference period and suggests slightly smaller increases.

The 2012 Basins Study used a similar approach for developing scenarios of projected climate. In this study, two future planning horizons were considered, the 2030s and 2050s. A different historical meteorological dataset was used in the 2012 Basins Study, namely that developed by Maurer et al. (2002). Analysis for the projected change in annual precipitation by the 2050s was to be a 5 percent increase for a CT scenario, while projected change in avg temperature would be a 3.5 °F increase. Projected change in the CT is similar in the 2012 study compared to this current study over roughly the same period; however the projected increase in avg annual temperature is about one degree warmer in this current study than the 2012 Basins Study over roughly the same planning horizon of the 2050s. Differences may originate from the historical observed dataset used, the differences in historical and future time horizons considered, the climate projections used in the analysis, as well as methods for statistical downscaling of those projections.

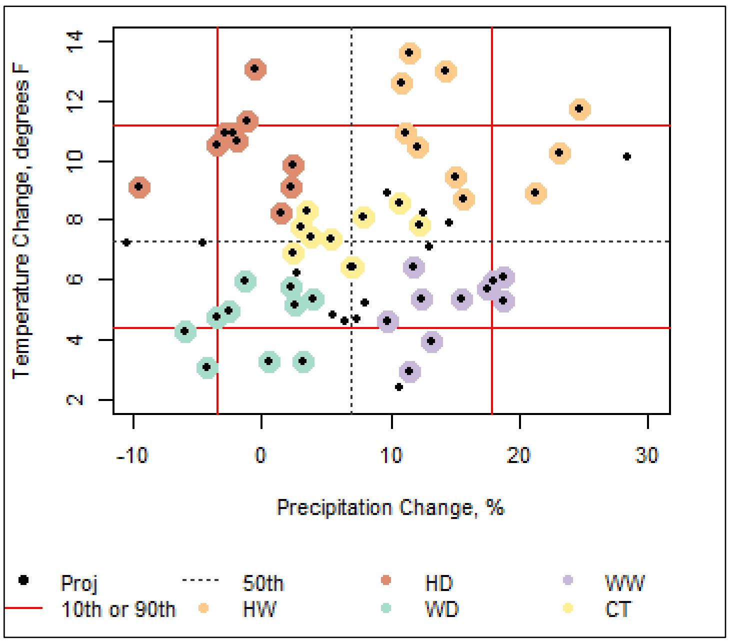


Figure 23.—Change in average annual temperature (°F) versus percent change in average annual precipitation between the 2080s future period and historical reference period of water years 1981–2015.[2]

[2] Projected changes using statistically downscaled CMIP5 GCM simulations are illustrated.

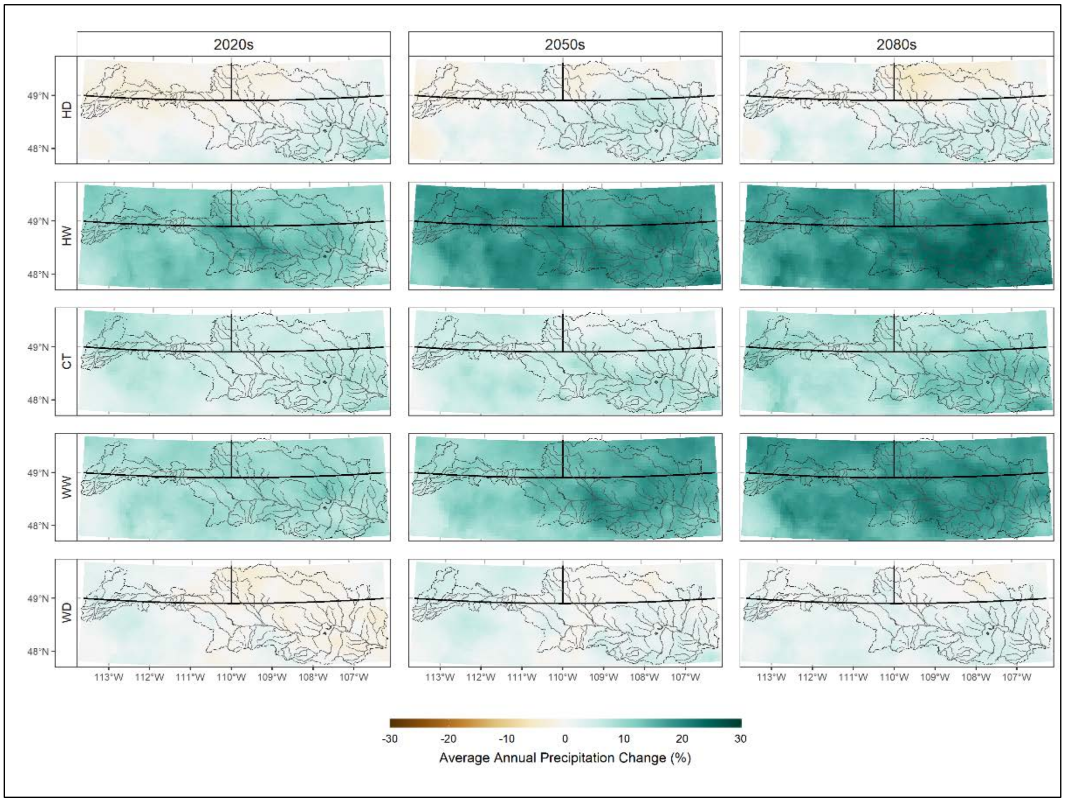


Figure 24.—Projected change in average annual precipitation (percent).

Table 6.—Ranges of projected change in average annual precipitation (percent) across the study area

Scenario	2020s		2050s		2080s	
	Min	Max	Min	Max	Min	Max
HD	-3.6	+10.0	-4.1	+9.9	-5.8	+9.2
HW	+4.5	+19.4	+9.3	+24.8	+10.7	+26.3
CT	+0.7	+10.5	-1.1	+10.9	+3.6	+18.3
WW	+1.4	+14.0	+3.2	+21.5	+6.2	+22.3
WD	-4.0	+5.3	-2.5	+7.4	-3.1	+5.6

Figure 25, which shows the range of projected change in monthly precipitation and temperature across the future climate scenarios and simulation years (water years 1981 to 2015 for all scenarios), suggests that the historically wet months (April and May) are likely to get wetter, while the drier summer months are likely to get drier, indicating increased reliance on stored water supplies to meet consumptive demands during those months.

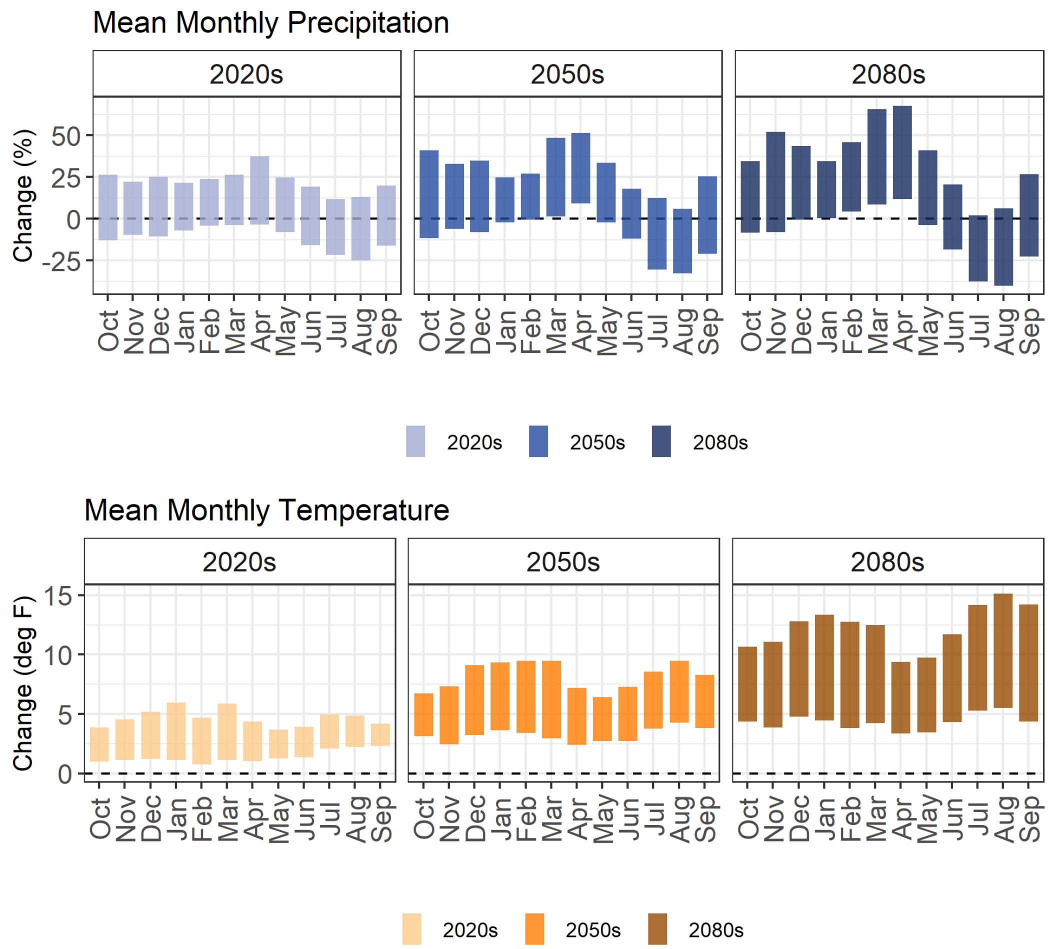


Figure 25.—Range of projected change in average monthly precipitation (percent) and air temperature in °F across the study area.[3]

Further, the Fourth National Climate Assessment also reports that in the region including the St. Mary and Milk River basins, that the number of heavy precipitation events (events with greater than one inch per day of rainfall) is projected to increase (Conant et al. 2018). Changes in extreme events are likely to overwhelm avg changes in both the eastern and western regions of the Northern Great Plains. Major flooding across the basin in 2011 was followed by severe drought in 2012, representing new and unprecedented variability that is likely to become more common in a warmer world.

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[3] The bounds of the range are defined as the 10th and 90th percentiles of change for each month.

The projected change in the number of days with precipitation greater than one inch is illustrated on figure 26. These changes are based on projected future climate scenarios developed for this study using LOCA-downscaled CMIP5 climate projections and these findings are consistent with findings from the Fourth National Climate Assessment. Throughout the study area, projected changes are either close to zero on avg or are greater by about 5 days.

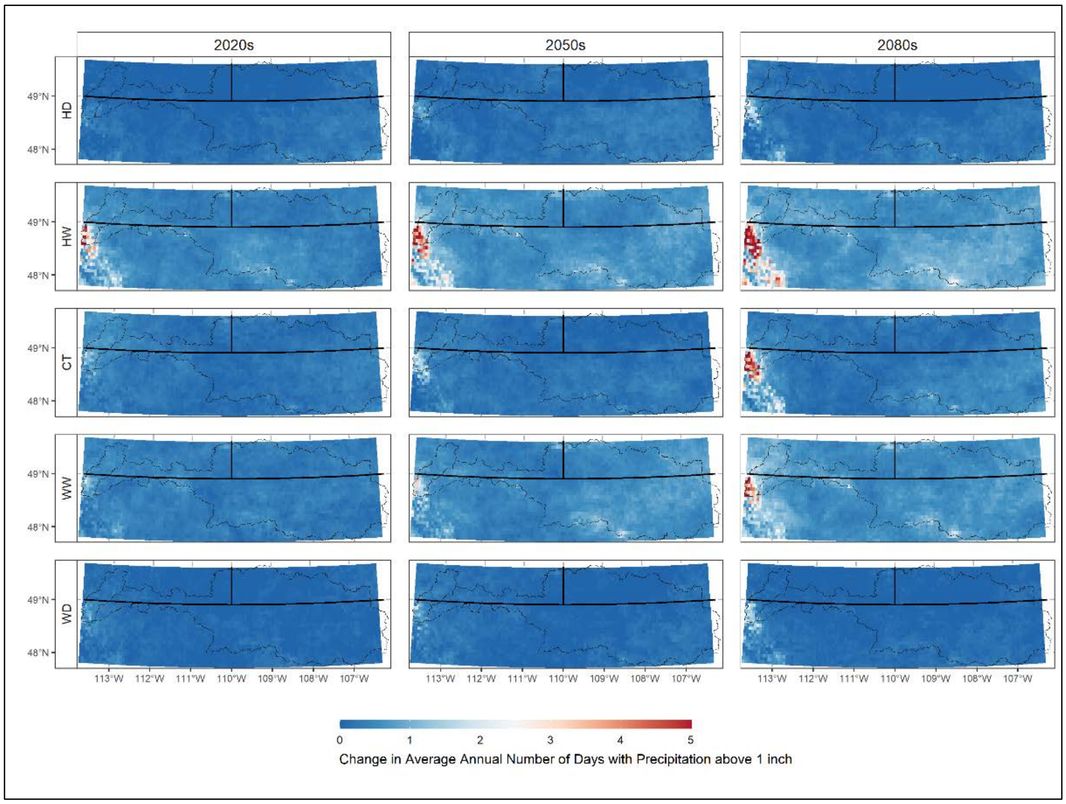

Figure 26.—Projected change in the number of days with precipitation greater than 1 inch.

For the St. Mary and Milk River basins specifically evaluated in this Basins Study Update, daily avg temperatures are expected to continue to increase from 4 to almost 12 °F by the 2080s future period on an annual basis, considering the range of future projections and a historical reference period of 1980 to 2015 (figure 27 and table 7). The projections of change in annual avg temperature are consistent with Reclamation's 2021 SECURE Water Report, which summarizes CMIP5 LOCA-downscaled projections in hydrologic unit code, 8-digit river basins across the 17 western states (Reclamation 2021) and suggests increases of about 6 °F by the 2050s, compared to 1970–1999 climate (similar to projected changes in table 7).

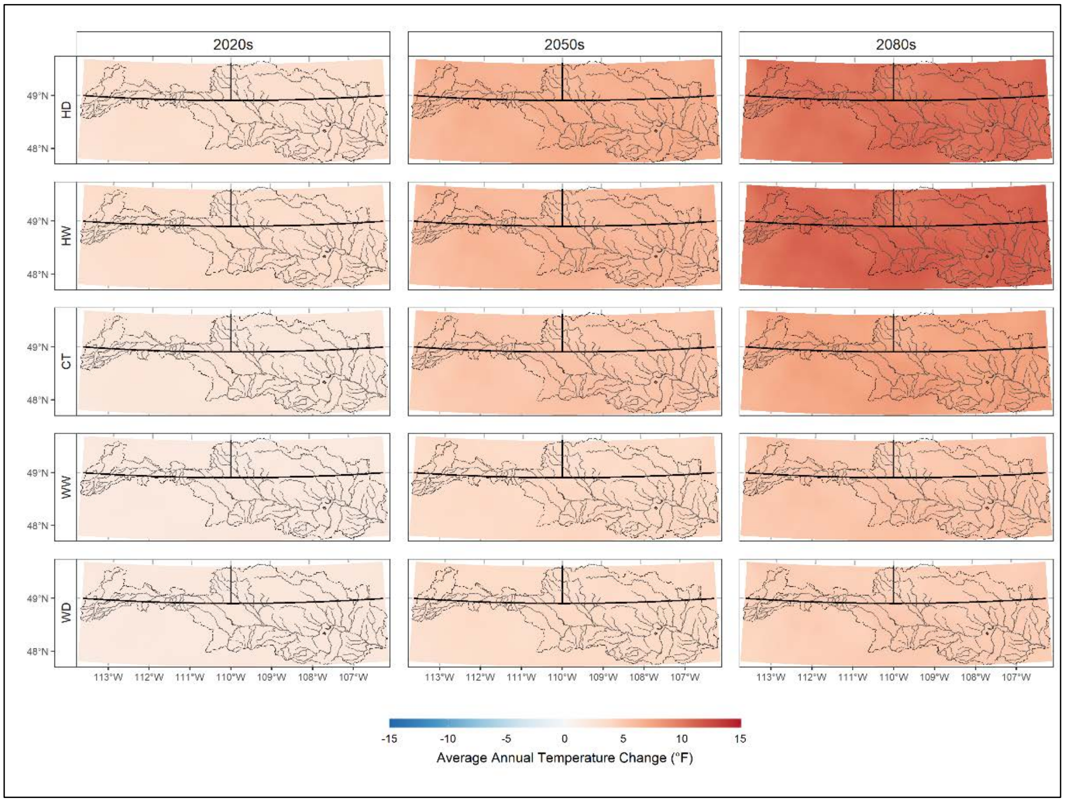

Figure 27.—Projected change in annual average temperature (°F).

Figure 25, which summarizes the range of projected changes in daily avg temperature by month, indicates that temperatures in all months will increase while greater temperature increases are expected in late summer and winter months.

Table 7.—Ranges of projected change in annual average temperature (°F) across the study area

Scenario	2020s		2050s		2080s	
	Min	Max	Min	Max	Min	Max
HD	+2.5	+3.5	+5.5	+7.4	+8.8	+11.2
HW	+2.7	+3.7	+5.2	+6.9	+9.4	+11.8
CT	+1.9	+2.6	+4.3	+5.9	+6.2	+8.4
WW	+1.6	+2.3	+3.0	+4.2	+4.3	+5.9
WD	+1.6	+2.3	+2.8	+3.9	+3.9	+5.2

The Fourth National Climate Assessment chapter on the Northern Great Plains (which utilizes CMIP5 climate projections under the same scenarios of future emissions) indicates that for this region, higher maximum temperatures, longer and more severe heat waves, and higher overnight lows are expected.

The projected change in the avg number of days with minimum temperatures below freezing is illustrated on figure 28. Throughout the study area, the number of days below freezing is projected to decrease, which is consistent with warming temperatures overall. For the hotter scenarios (HD and HW), there are projected to be up to 100 fewer days with minimum temperatures below freezing.

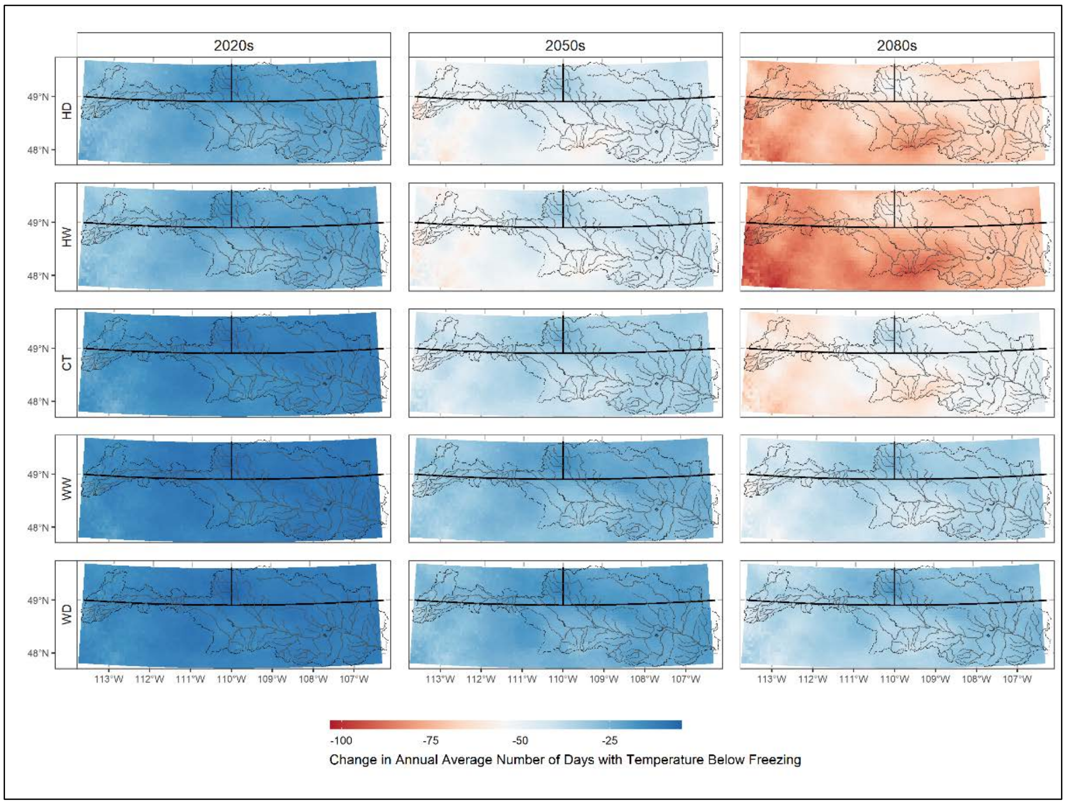

Figure 28.—Projected change in the average number of days below freezing (32 °F).

The projected change in the avg number of days with maximum temperatures above 95 °F is illustrated on figure 29. Throughout the study area, the number of days with daily maximum temperatures above 95 °F is projected to increase, which is consistent with warming temperatures overall. For the hotter scenarios (HD and HW), there are projected to be up to 50 more days with maximum temperatures above 95 °F.

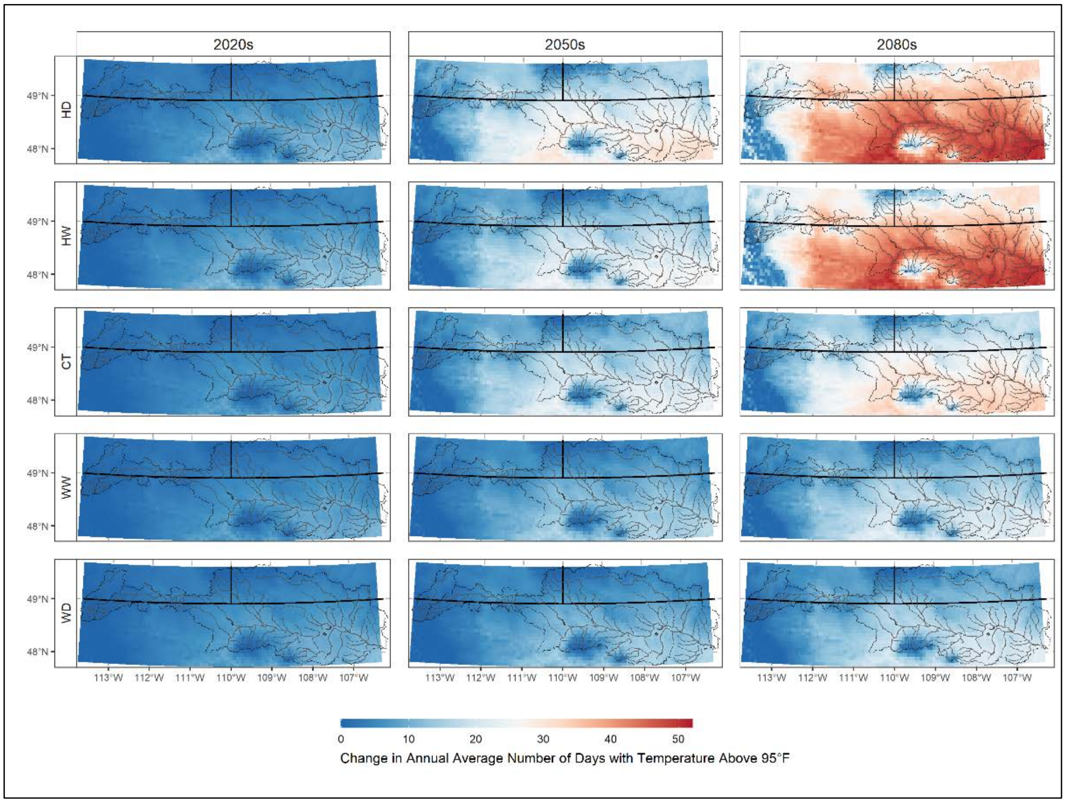

Figure 29.—Projected change in the average number of days above 95 °F.

Projected Future Snowpack and Streamflow

Projected future scenarios of precipitation and temperature were input to the hydrologic modeling framework to simulate projected snowpack and streamflow for subbasins of interest within the study area. Corresponding with projected increases in temperatures across the region and despite projected increases in annual precipitation that are possible, peak snowpack is projected to decrease under all scenarios and futures periods with progressively greater decreases toward the end of the twenty-first century (figure 30). Additionally, the timing of peak SWE is projected to be earlier in the year, as illustrated on figure 31. For the hotter scenarios (HW and HD), the projected change in the date of peak SWE could be as much as 50 days earlier by the 2080s. The CT scenario suggests the change may be around 25 days earlier by the 2080s.

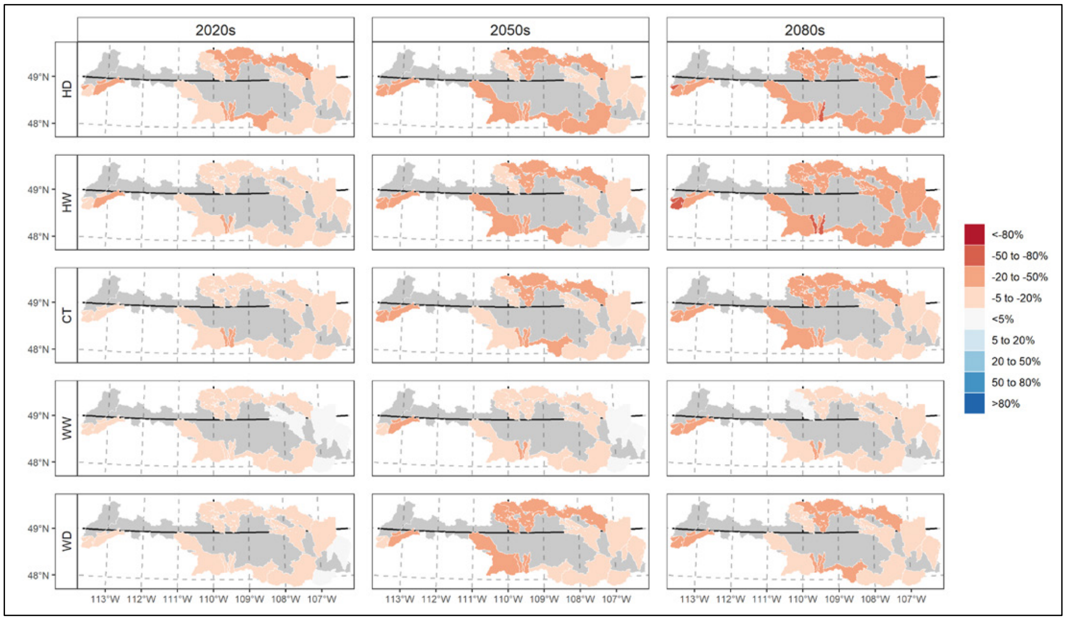

Figure 30.—Projected change in peak SWE (percent).

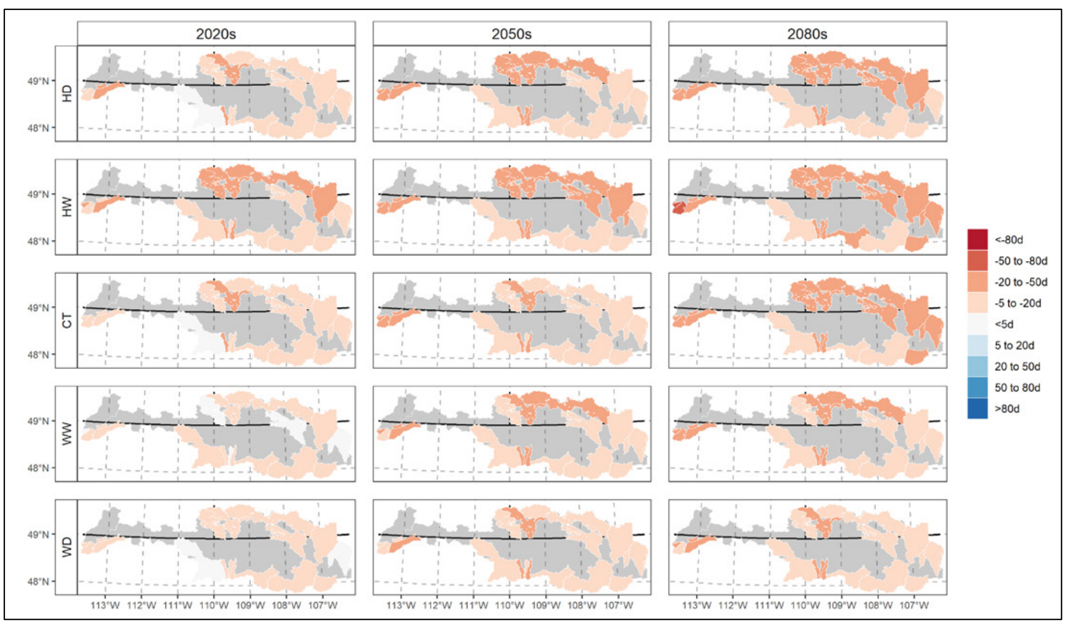

Figure 31.—Projected change in the date of peak SWE. Negative values indicate earlier date of peak SWE.

Projected changes in annual flow volume are much more variable and uncertain due to the combined effects of temperature increases and precipitation change, which itself is highly uncertain (figure 32). For the Plains basins, annual flow volume may decrease by as much as 34 percent or increase by as much as 235 percent in the 2080s, while in the St. Mary Basin, annual flow volume is projected to increase from 2 to 79 percent (figure 32). Projected changes by modeled subbasin are summarized in Appendix B. It should be noted, however that the St. Mary Basin receives an order of magnitude more precipitation on an annual basis than watersheds in the eastern portion of the study area (see figure 11). So small changes in precipitation in the Plains Basins may result in large changes on a percentage basis.

According to the Fourth National Climate Assessment, much of the study area is arid to semiarid, and because temperatures and rates of ET (the evaporation of water from the soil and transpiration from plants) are so high, less than 10 percent of precipitation may reach the Missouri River as runoff. For comparison, other basins in the U.S. yield more than 40 percent runoff (Conant et al. 2018).

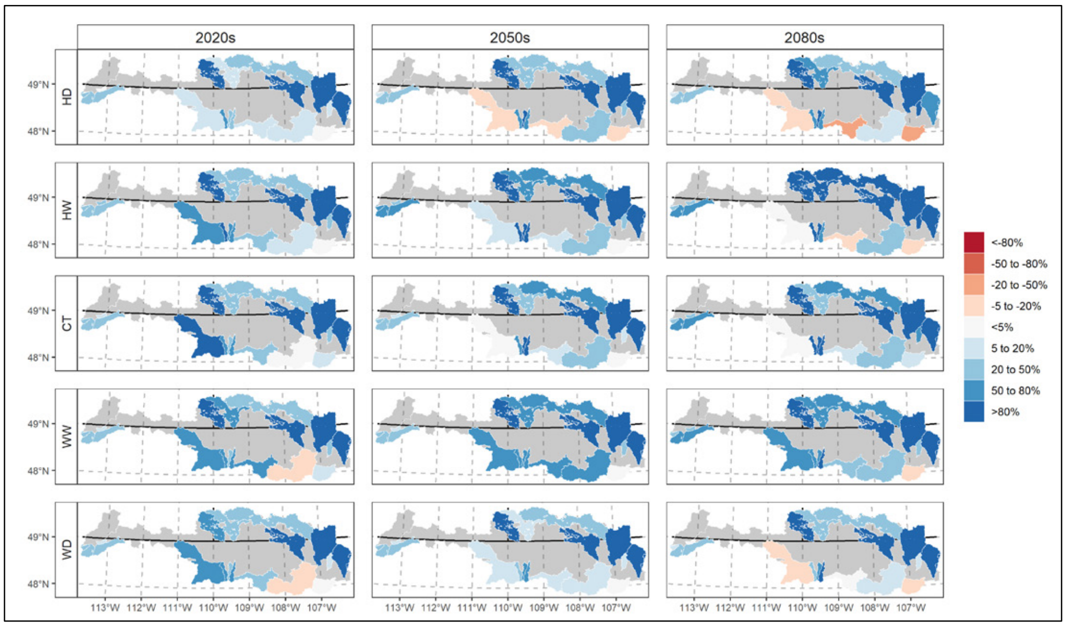

Figure 32.—Projected change in average annual flow volume (percent).

Figure 25 illustrates projected changes in monthly precipitation and temperature averaged across the study area and indicates that summer months are likely to get drier but other months are likely to become wetter. Further, while annual flow volumes are projected to increase, changes in flow volume over the warm season months including April through September are more likely to decrease in parts of the study area, particularly the Plains basins (figure 33). Of the Plains basins, the tributaries to the Milk River coming from the north generally show projected increases in warm season flow volume, while the tributaries of the Milk River originating from the south show predominantly decreases in warm season flow volume. Because the Plains basins have variable behavior, it is important to review how drivers of streamflow, namely precipitation, temperature and elevation, may interplay into the future (figure 34). Upper Milk Basin watersheds suggest increasing or decreasing warm season flow volume depending on the climate scenario, with drier scenarios indicating decreases and wetter scenarios indicating increases. St.

Mary Basin watersheds suggest modest increases in warm season flow volume for drier scenarios and larger increases for wetter scenarios (as much as 60 percent). Ranges of projected change in annual, warm season, and cool season flow volume are summarized by subbasin in “Appendix B. Water Supply Development.”

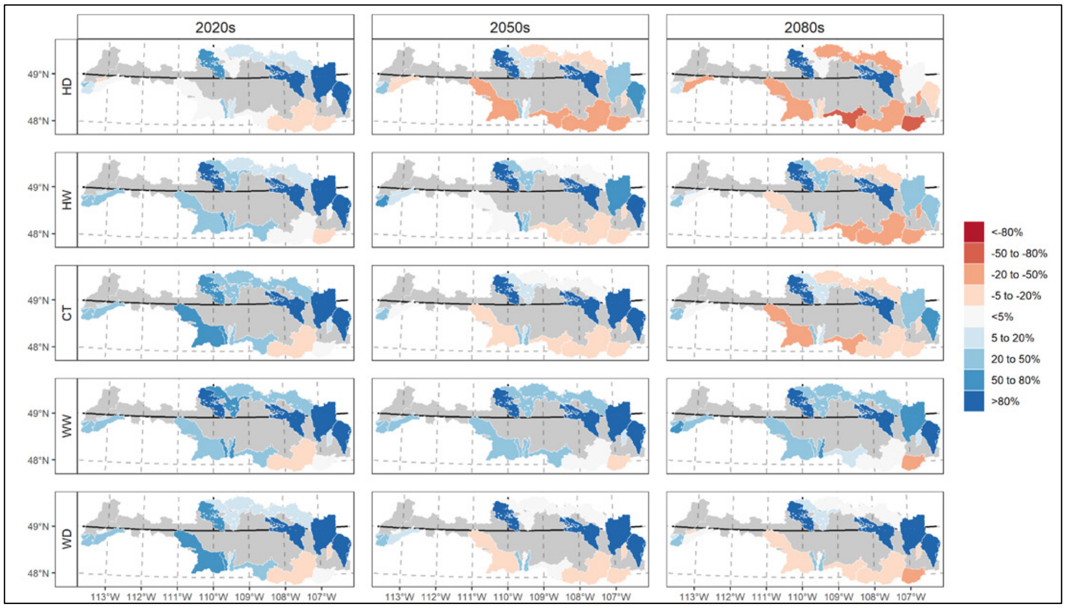

Figure 33.—Projected change in average April–September flow volume (percent).

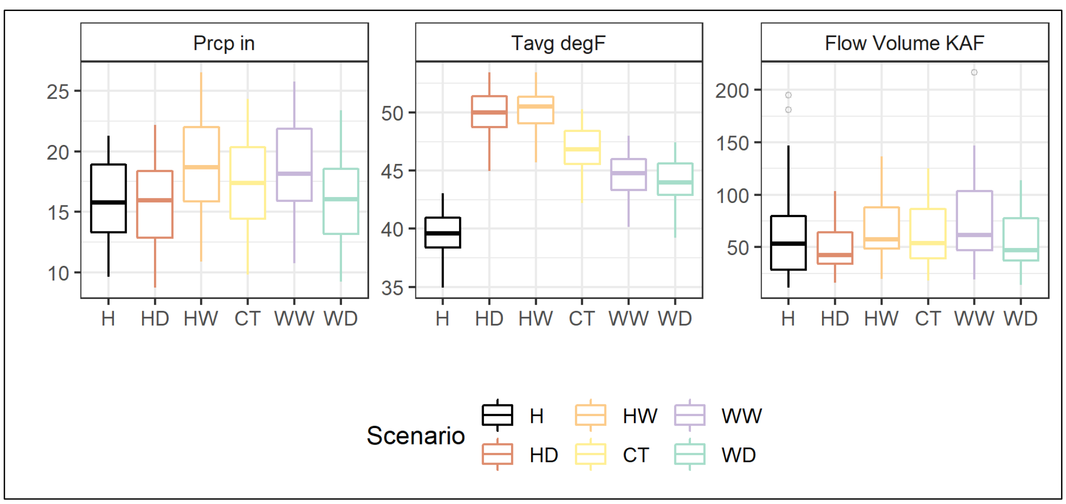

Figure 34.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Frenchman River at International Boundary (USGS ID 06164000).

Projected changes in flow volume over cool season months of the year (October through March), which are expected to become wetter, are correspondingly projected to increase (figure 35). Projected increases on a percent basis are larger in the Plains basins than in the St. Mary Basin or Upper Milk Basin but the ranges are fairly large. For example, in the Swiftcurrent Creek watershed in the St. Mary Basin, cool season flow volume may increase between 30 and 180 percent for the 2080s. In the Frenchman River basin in the plains, the range of projected changes is 107 to 314 percent.

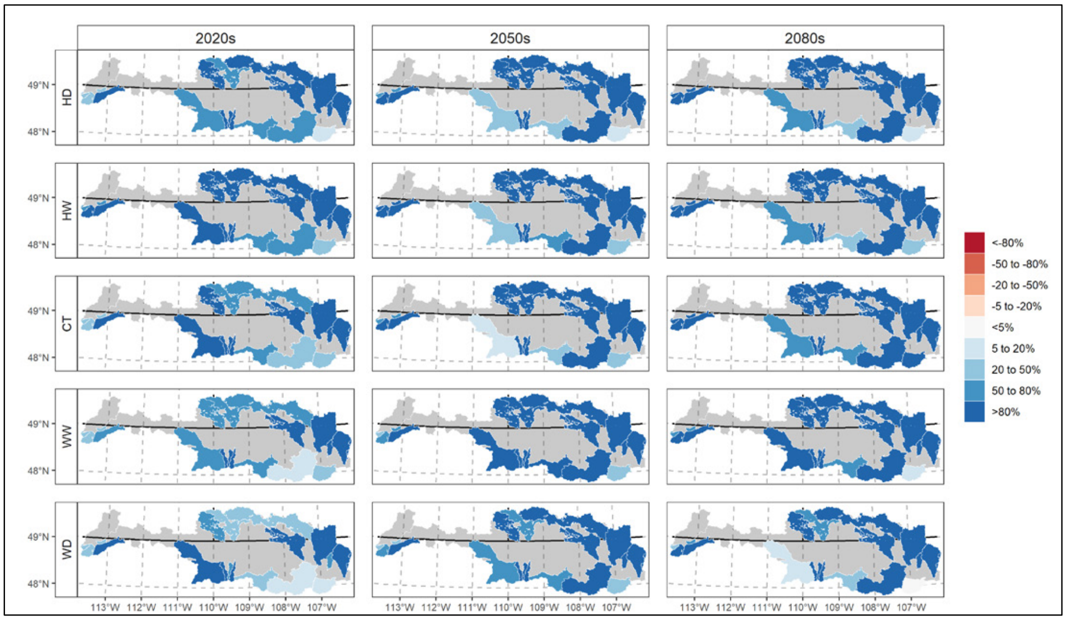

Figure 35.—Projected change in average October–March flow volume (percent).

Projected changes in cool season (October–March) and warm season (April–September) flow volume provides information on the change in seasonality of flow in the study area. The avg date of the flow centroid, which is the date at which half of the flow volume has passed a select location, further illustrates the projected shift in the timing of seasonal runoff in the study area. Figure 36 shows that the flow centroid is projected to shift toward earlier in the year for the vast majority of subbasins in the study area. By the 2080s, the shift could be over one month earlier. The 2012 Basins Study reported changes in runoff timing of 5 to 9 days earlier by the 2050s; results from this Basins Study Update suggest that the range is greater, from 5 to 20 days earlier.

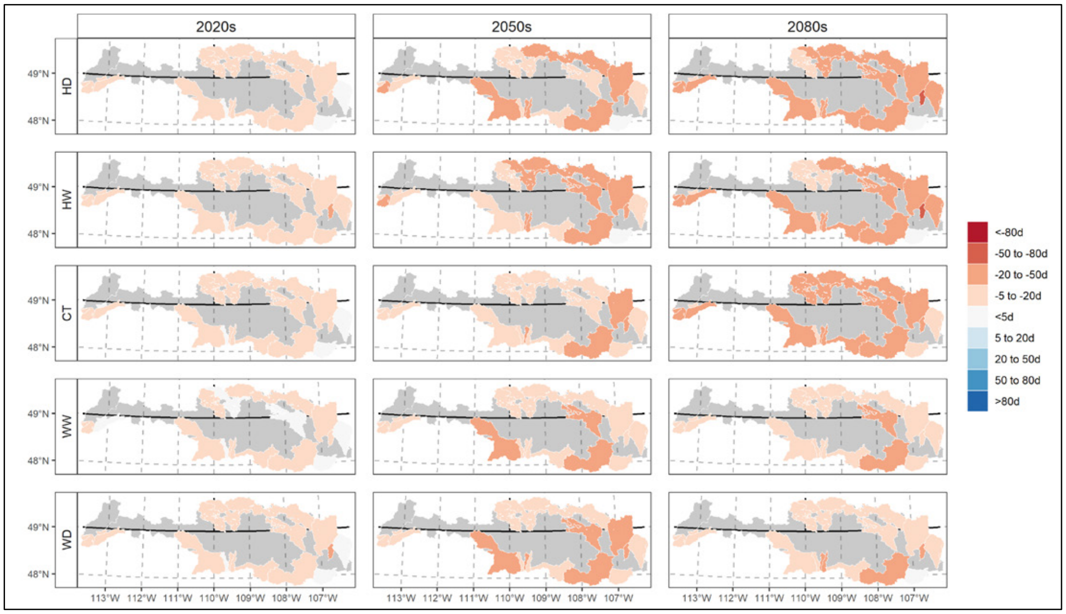

Figure 36.—Projected change in the average date of the flow centroid (number of days), where the centroid of flow is the date at which half of the water year annual flow volume has passed.

Figure 37 illustrates an overall summary of the range of projected change in peak snowpack and annual flow volume across the three hydrologic regions in the study area. It shows increased range of snowpack decrease into the future. By the 2080s, snowpack in the St. Mary Basin may decrease between 24 and 51 percent, while in the Plains basins the range of decrease is 18 to 35 percent.

The right panel of figure 37 summarizes corresponding projected changes in annual flow volume. The scenarios show consensus in an increase in annual flow volume into the future, although the percent of increase is uncertain, as are projected increases in precipitation. Despite the uncertainties associated with precipitation projections and methods for simulating streamflow using these projections, they remain useful in evaluating the vulnerability of the St. Mary and Milk River basins to these stresses. Even as new climate projections become available, certain irreducible uncertainties will continue to exist, as will the need for decision making despite uncertain conditions.

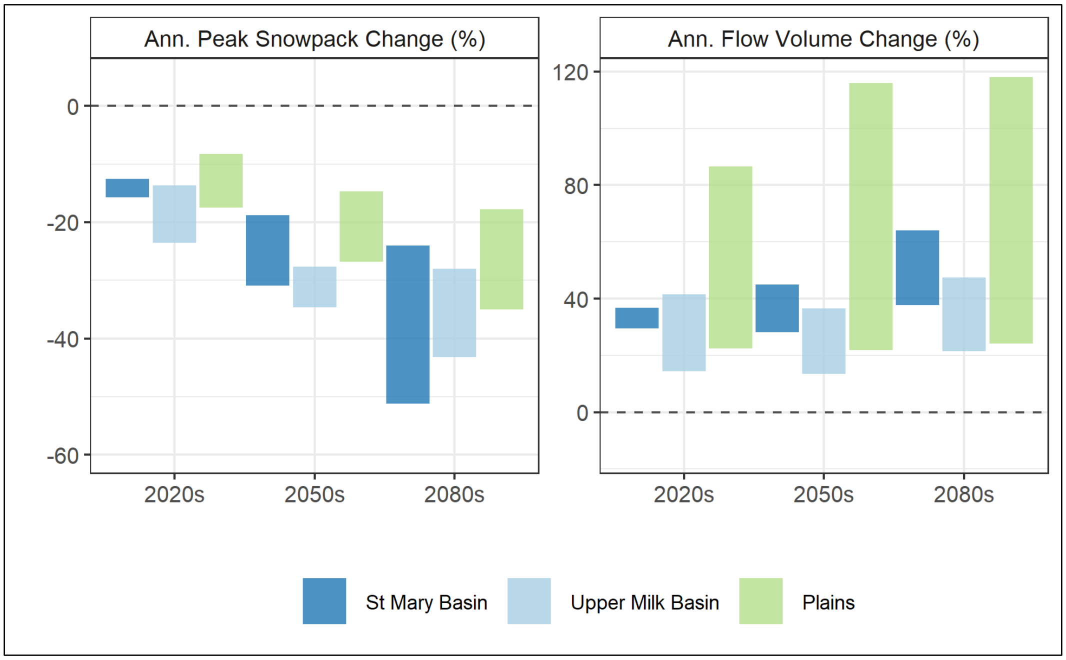

Figure 37.—Projected changes in annual peak SWE and annual flow volume in percent for the 2020s, 2050s, and 2080s compared with a 1981–2015 (water years) reference historical period.

Since hydroclimate in the St. Mary and Milk River basins is variable and projected changes may vary by subbasin, it is informative to view projected changes in precipitation, temperature, and flow volume together to more easily understand how changes in climate may manifest into streamflow changes.

For Swiftcurrent Creek watershed in the St. Mary Basin, the left panel illustrates the distribution of projected changes in annual precipitation for each future climate scenario and for the 2080s future time horizon. Annual precipitation is projected to increase; daily avg temperatures are projected to increase, and thereby annual flow volume is projected to increase. The wetter future scenarios indicate greater increases in flow volume (figure 38).

The avg monthly historical and projected hydrographs for Swiftcurrent Creek watershed are illustrated on figure 39. Additionally, the grey ribbon represents the range of the 25th to 75th percentiles of the projected ensemble of flows which illustrates the associated uncertainty. Seasonal peak flows in Swiftcurrent Creek are projected to shift toward earlier in the year as temperatures rise and snowmelt initiates earlier in the year and winter and spring precipitation increases.

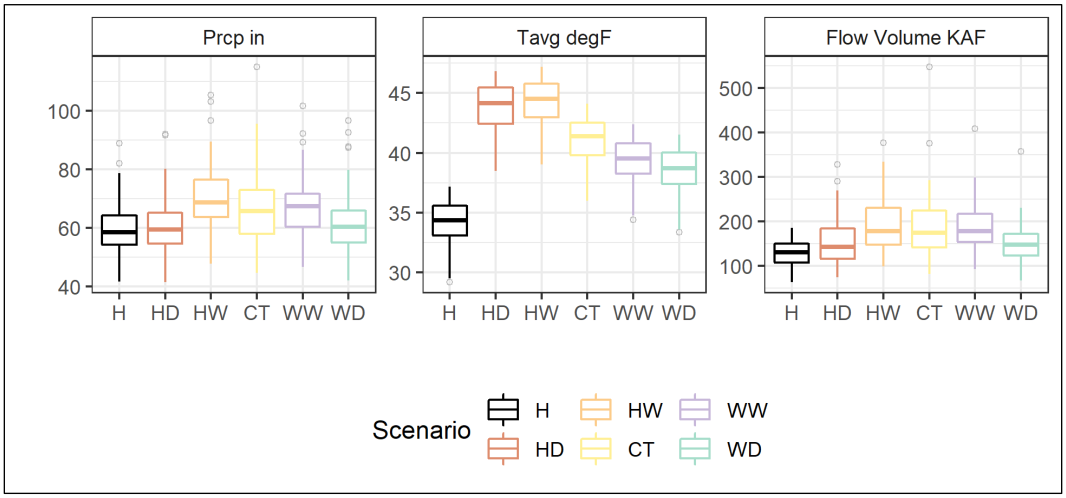

Figure 38.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume for the 2080s at Swiftcurrent Creek at Sherburne (USGS ID 05016000).

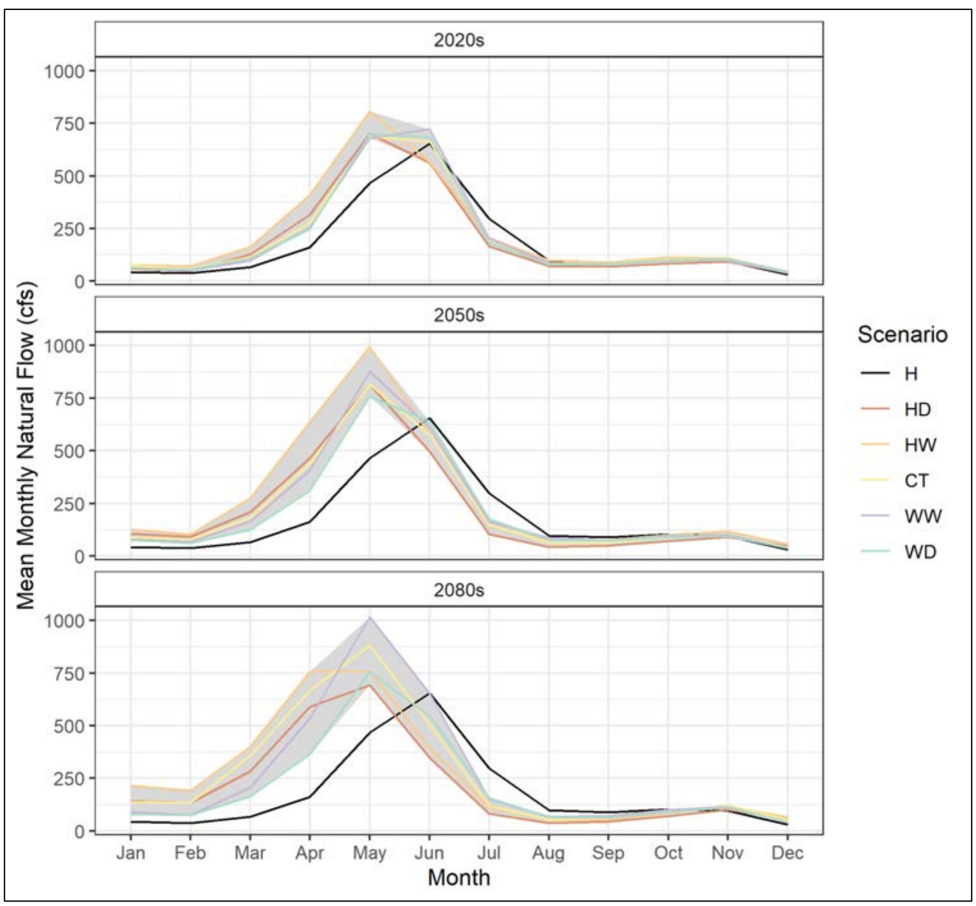

Figure 39.—Historical and projected average monthly streamflow at Swiftcurrent Creek at Sherburne (USGS ID 05016000).

For the Milk River watershed in the Upper Milk Basin upstream of the W MRWIB, annual precipitation is projected to be similar to historical or increase and daily avg temperatures are projected to increase. Annual flow volume is projected to be higher in the wetter scenarios relative to the drier scenarios, and generally corresponds with projected precipitation; however, the wetter scenarios, influenced also by higher temperatures, result in greater ET. The wetter future scenarios indicate greater increases in flow volume (figure 40).

The avg monthly historical and projected hydrographs for MRWIB are illustrated on figure 41. Additionally, the grey ribbon represents the range of the 25th to 75th percentiles of the projected ensemble of flows which illustrates the associated uncertainty. This watershed commonly has two peaks in streamflow, namely around April and June with the June peak being greater. In some years, there is only a late spring/early summer peak. This behavior is evident in both the observed naturalized streamflow dataset used for model calibration as well as the historical simulations. Seasonal peak flows in the MRWIB are projected to shift toward earlier in the year by increasing the first seasonal peak in streamflow and decreasing the second peak.

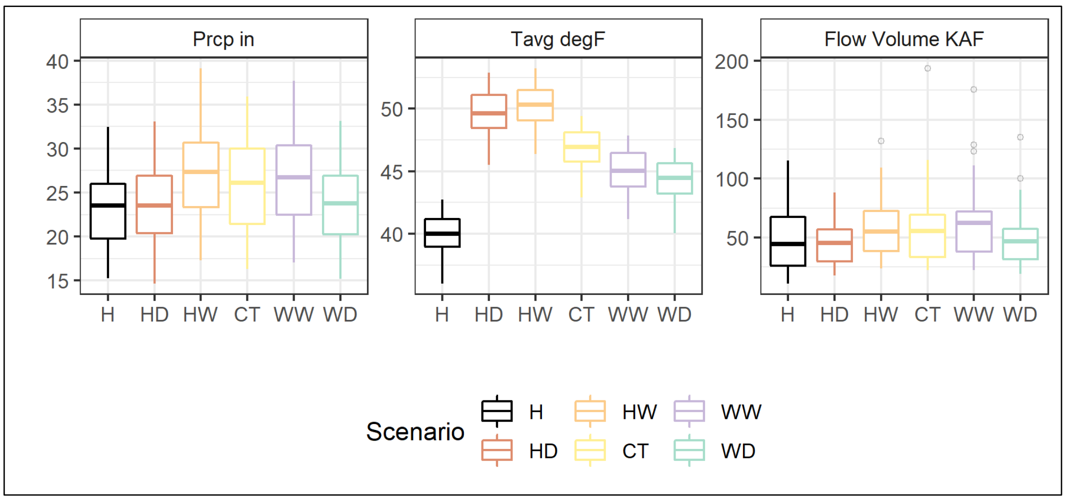

Figure 40.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Milk River at Western Crossing of the International Boundary (USGS ID 06133000).

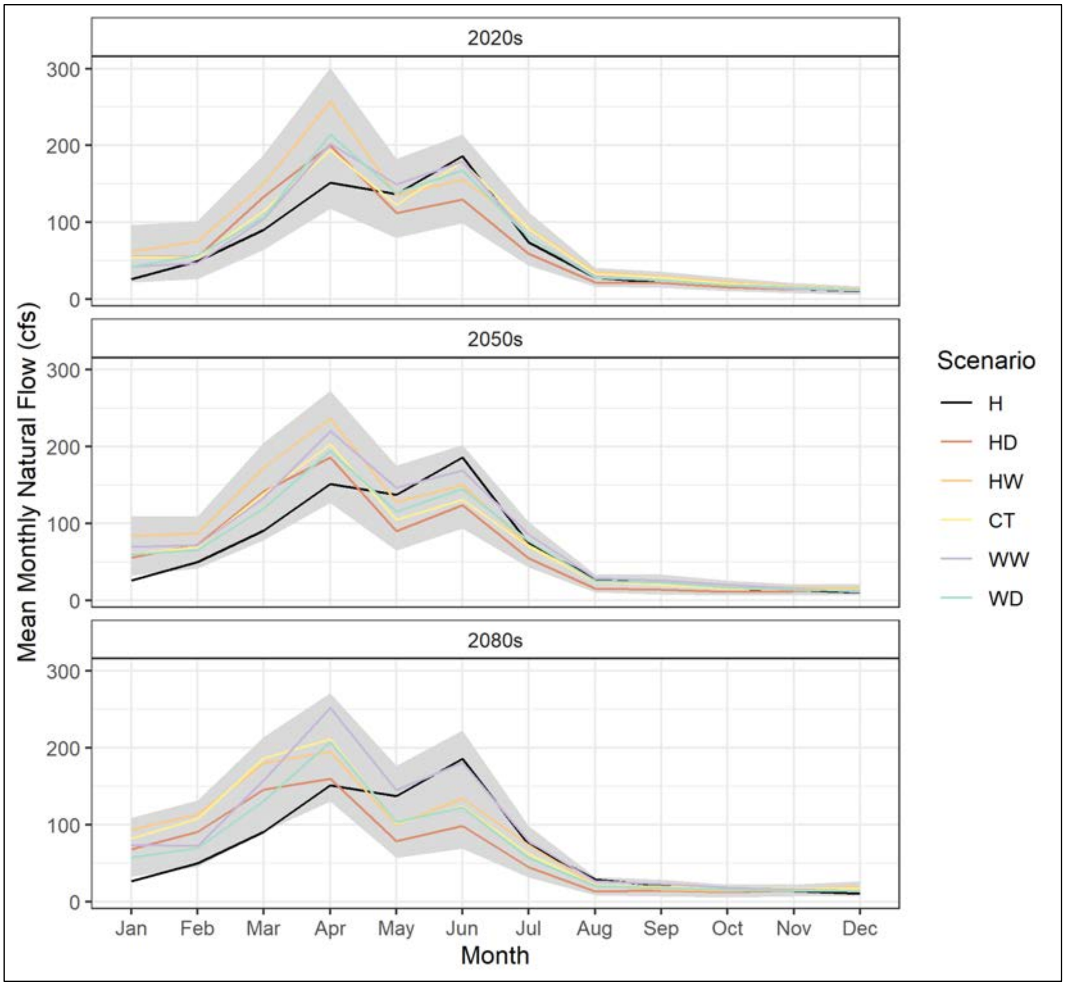

Figure 41.—Historical and projected average monthly streamflow at Milk River at Western Crossing of the International Boundary (USGS ID 06133000).

For FRRIB watershed in the Plains, annual precipitation is projected to be similar as historical or increase; daily avg temperatures are projected to increase, and thereby annual flow volume is projected to increase. The wetter future scenarios indicate greater increases in flow volume (see figure 34).

The avg monthly historical and projected hydrographs for FRRIB are illustrated on figure 42. Additionally, the grey ribbon represents the range of the 25th to 75th percentiles of the projected ensemble of flows which may be considered an illustration of the associated uncertainty. This watershed historically has seasonal peak streamflow around April. Seasonal peak flows in the FRRIB are projected to shift toward earlier in the year and the historical seasonal peak is likely to decrease into the future.

Similar figures illustrating projected change in annual precipitation, temperature, and flow volume in other simulated basins are summarized in appendix B.

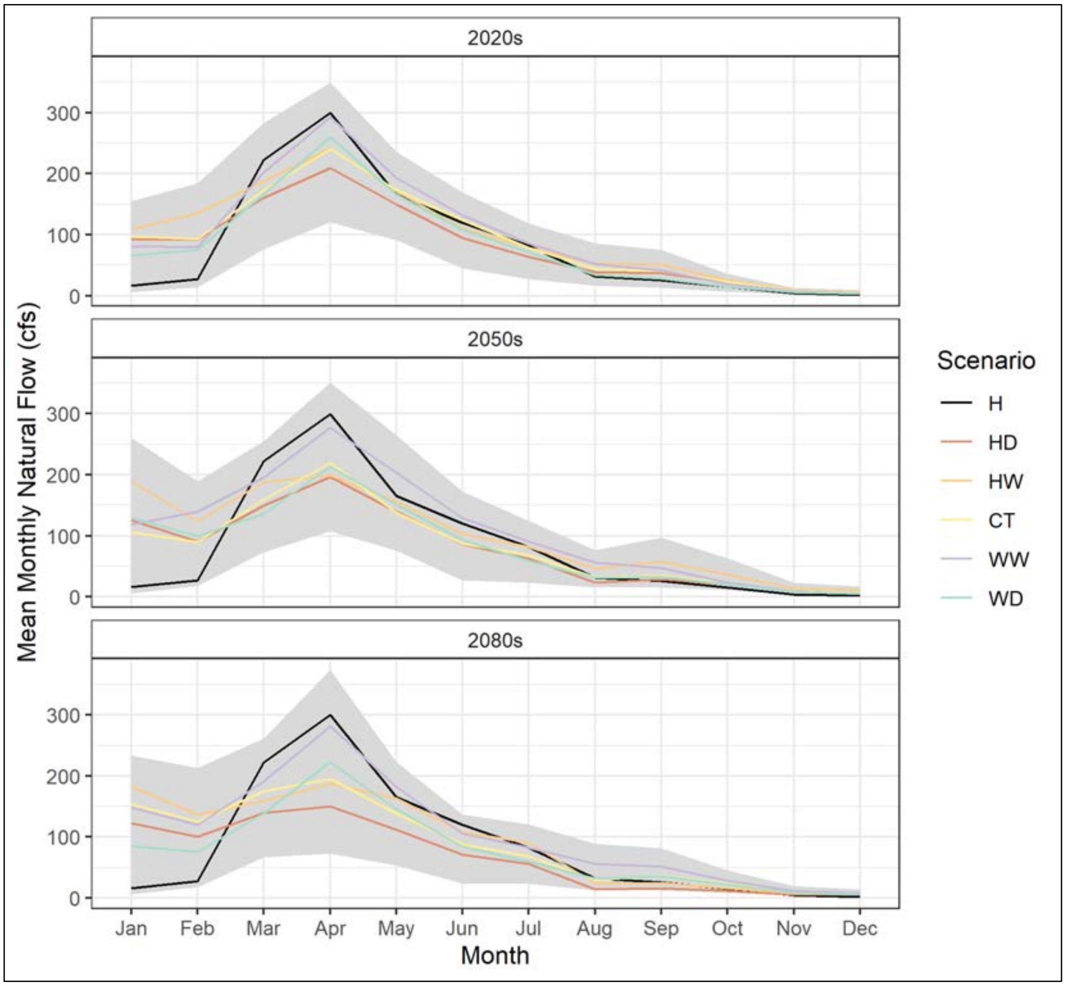

Figure 42.—Historical and projected average monthly streamflow at Frenchman River at International Boundary (USGS ID 06164000).

Paleohydrology and Water Supply

Based on the drought definition described in the "Assessment Approach" section, the three largest droughts defined as the largest avg annual deficit are summarized in table 8. All droughts are defined and quantified by comparing annual avg streamflow in a specific year to the long-term median of annual avg flows. The largest LAD drought is determined as the time period of drought over which the avg of annual streamflow is farthest below the long term median annual flow. One streamflow reconstruction was identified in each of the three distinct hydrologic regions (St. Mary Basin, Upper Milk Basin, and Plains) and these are a listed in table 8. The locations include the St. Mary River near International Boundary (St. Mary Basin), MRWIB (Upper Milk Basin), and LDCIB (Plains). Those droughts with a rank of one are the largest identified droughts in the paleo period, while those with rank 3 are the third largest droughts. The largest droughts in the recent historical period over approximately the last 100 years were also identified are shaded blue. Lastly, major notable droughts of recent memory in the study area are also listed. These notable droughts are not formally defined by the same drought definition; instead, they reflect droughts of interest to the study partners and stakeholder community. Each drought event identified in table 8 was simulated by the river system model to evaluate implications of such droughts reoccurring under current operating policies. These simulations and results are further discussed in "Appendix F. Paleo Event Scenario Development" and "Appendix G. Re-sequenced Paleo Event Scenario Development," and the "Risk Assessment" section.

Table 8.—Summary of paleo drought events

Location	Event	Rank	Year start	Year end	Length
St. Mary River near International Boundary	largest avg annual deficit	1	1719	1725	7
LDCIB	largest avg annual deficit	1	1807	1808	2
MRWIB	largest avg annual deficit	1	1747	1748	2
St. Mary River near International Boundary	largest avg annual deficit	2	1793	1795	3
LDCIB	largest avg annual deficit	2	1801	1804	4
MRWIB	largest avg annual deficit	2	1602	1607	6
MRWIB	largest avg annual deficit	3	1622	1623	2
St. Mary River near International Boundary	largest avg annual deficit	3	1783	1788	6
LDCIB	largest avg annual deficit	3	1651	1652	2
LDCIB	largest instrumental avg annual deficit		1988	1989	2
St. Mary River near International Boundary	largest instrumental avg annual deficit		1901	1904	4
MRWIB	largest instrumental avg annual deficit		1931	1946	16
Study area	historical drought 1 (Hist 1)		1996	2009	14
Study area	historical drought 2 (Hist 2)		1928	1936	9

Groundwater Supply

Interactions between groundwater and surface water were simulated by the St. Mary and Milk Rivers planning model by way of seepage losses and return flows. Historical and projected changes in recharge to groundwater, for example, were not assessed in this Basins Study Update, mainly due to relatively small reliance of water users on groundwater. However, assessment of groundwater and surface water interactions may be evaluated in the future through additional study.

Uncertainties in Analysis

This section briefly summarizes key uncertainties associated with various aspects of the water supply assessment, including the use of projected climate information, paleohydrology information, and a chain of models to evaluate system vulnerabilities under historical and projected future conditions. Generally, uncertainties in the results of this study fall into two categories, those that will always exist, in part due to the inherent randomness of the climate system, and those that may be reduced through improved understanding or data. Chapter 9 of the 2021 West-Wide Climate and Hydrology Assessment (Reclamation 2021) provides a thorough discussion of these types of uncertainties as they relate to climate impacts analysis and modeling. Therefore, these uncertainties are not discussed here in detail.

Projected Climate Information

This Basins Study Update incorporates a variety of methods for identifying potential future hydroclimate conditions. This diversity of approaches (paleohydrology, GCM-based future climate scenarios) collectively provide a more robust analysis – on one hand if there is a consensus on future conditions portrayed by the models, and on another hand by exploring as fully as possible the range of potential future conditions.

Future climate projections and paleohydrology are two complementary types of information that both help to understand and prepare for conditions outside of those seen in the instrumental period. Future projections of streamflow rely on a suite of models—GCMs, downscaling methods, hydrology models, and river routing models—to reveal how increases in GHG concentrations influence hydroclimate processes.

Alternatively, paleohydrology reconstructions use tree rings to better understand the climate of the distant past. These reconstructions rely on statistical models of past annual streamflow. This information allows us to understand recent and distant past drought and pluvial (wet) events that could occur again and may be outside of observed gage records, or even outside the range of what hydroclimate projections may suggest. Both paleohydrology and future projections require unique tools and models, which have associated uncertainties across the analysis steps. Collectively, using multiple approaches broadens the understanding of possible future conditions and allows for a more informed decision-making framework to support robust water resources planning in the West.

Hydrologic Model Framework

Arguably the most common approach for assessing the effects of climate change on surface water hydrology involves using rainfall runoff hydrology models to simulate hydrologic conditions under projected climate conditions. However, these models often do not represent key hydrologic processes related to groundwater and/or large water bodies. The variable infiltration capacity (VIC) model [Liang et al. 1994] was considered for implementation in this study because it is spatially distributed, process-based and uses readily available climate information, namely, daily minimum and maximum air temperature, daily precipitation, and daily windspeed. It has also been enhanced to include representation of lakes (Bowling and Lettenmaier 2010; Mishra, et al. 2010) and frozen soils (Cherkauer and Lettenmaier 1999; Cherkauer et al. 2003), both of which exist in the PPR region. Although this approach appeared promising, the VIC model relies on a static stream network for routing runoff from individual grid cells to the basin outlet. Due to the dynamic contributing area and storage characteristics that is unique to PPR watersheds, and the need for complex hydraulic routings with detailed storage capacity representations in the model, even a process-based model such as VIC in this case was unsuccessful and left us with some choices to consider as a path forward (Broman and McGuire 2020).

The hydrologic model framework developed for the Basins Study Update may have uncertainties associated with its implementation that are not yet fully realized. This modeling approach was developed based on the lumped conceptual model developed by Jakeman and Hornberger (1993) and uses basin averaged precipitation and daily avg temperature as input. Complex hydrologic processes including glacier accumulation and melt, depression storage fill and spill, frozen soils, and dynamic contributing area are represented by a common parameterization. Additional complexities and assumptions are discussed by Gangopadhyay et al (in preparation, MSM paper).

Although this framework was developed over a hydrologically diverse study area of the St. Mary and Milk River basins, the framework has not yet otherwise been tested in other river basins. Also, although frozen soils, depression storage, and groundwater influence are all important processes in this region, the hydrologic modeling framework is not able to distinguish between these different types of water storage, except for quick and slow interflow. Characterization of uncertainties in this approach will continue to be an area of research as it is applied in the St. Mary and Milk River basins and other basins. Appendix B includes discussion of sensitivities in model parameters and related choices that contribute to the discussion of uncertainty in the modeling framework. Again, this will continue to be an area of research moving forward.
It is important to acknowledge the trend toward using multiple hydrologic models rather than a single model or model framework (the standard approach for many prior studies, as well as this one) to evaluate potential future hydroclimate conditions. Ensemble modeling approaches do require substantial computing resources and advanced modeling strategy. For example, decision making under deep uncertainty is an active area of research and practice which incorporates an ensemble modeling approach to quantify a decision space for future planning (Bonjean Stanton and Roelich 2021). This approach was applied in the Colorado Water Supply and Demand Study (Reclamation 2012) and has been since explored in a handful of Reclamation planning efforts.

Expanding awareness of deep uncertainty and increasing knowledge and applications of decision making under deep uncertainty methods will be an important component of Reclamation's future activities related to assessing and adapting to climate change impacts.

Naturalized Flow Datasets

Another source of uncertainty is the naturalized flow data available for comparisons and calibration, as these flow datasets are typically developed based on observed gage records and consumptive use modeling, which may not represent recent irrigation practices. Consumptive use simulations are based off recent irrigation practices and applied to the study period of record. In reality, irrigation practices change over time. Potential variations in irrigation practices over the simulated historical period were not considered in the development of naturalized flow datasets. Therefore, the naturalized flow dataset does not represent the streamflow absent of variable irrigation practices and crop types over time, but instead it represents an estimate of natural streamflow with current irrigation practices removed.

Water Demand Assessment

Water demands in the St. Mary and Milk River basins are dominated by agricultural irrigation. Previous studies have indicated that significant irrigation shortages already occur in the basin. Additional water demands within the St. Mary and Milk River basins include municipal demands for the communities of Havre, Chinook, Harlem, Hill Country, and North Havre Water districts, phreatophyte demands, specifically deep-rooted cotton woods, evaporation from the mainstream Milk River and reservoirs, as well as instream demands for fish, wildlife, and recreation.

The "Water Demand Assessment" section evaluates potential changes in the primary consumptive uses in the study area, specifically, agricultural demands in the form of irrigation water and evaporative demands from reservoirs. The "Water Demand Assessment" section also includes potential changes in phreatophyte demands and evaporation from the mainstream Milk River. Agricultural demands and evaporative losses are influenced by temperature and precipitation. This assessment takes a risk-based scenario planning approach in which demand is assessed in terms of its variability and projected long-term change. The "Water Supply Assessment" section incorporates projected future climate scenarios as well as reconstructed paleohydrology scenarios from up to 419 years ago to help characterize water supply. This is possible through development of statistical relationships between unmanaged streamflow and widths of tree rings. In this "Water Demand Assessment" section, it was not possible to relate historical water demands with tree ring data; therefore, this analysis focuses on quantifying historical demand over a more recent period (water years 1981–2015) as well as using projected future climate scenarios to evaluate potential future demand.

The following subsections detail the assessment approach used to identify and model consumptive uses in the St. Mary and Milk River basins; the set of historical and future water demands for the St. Mary and Milk River basins; and the climate change and paleo event scenarios used in this assessment.

Projected Future Climate Scenarios

To evaluate climate change impacts on water demands, the “Water Demand Assessment” section uses the same projected future climate scenarios as the “Water Supply Assessment” section (i.e., LOCA-downscaled CMIP5 GCM climate projections distilled to 5 scenarios spanning their range of change), each of which are considered equally likely potential climate futures. Development of future agricultural and reservoir evaporation demands scenarios involved using similar future climate scenarios with prior adjustments made to the underlying climate projections to account for biases in projected versus observed weather over irrigated areas (for more information, refer to Reclamation 2015 and appendix C).

Discussions of how the temperature and precipitation projections for the five ensemble-informed hybrid delta scenarios are used to estimate the various future demands are provided in the following sections.

Paleo Event Demand Scenarios

Water demands over the paleo period are unknown, so an approach was developed to select demands for years that correspond with the paleo event streamflow scenarios. Previously in the “Water Supply Assessment” section, we discussed that daily streamflow was developed from the annual streamflow reconstructions over the paleohydrology period by selecting years in the historical reference period with similar annual flow volume (in terms of percentile rank) for each year of the paleohydrology period, and scaling the historical daily timeseries to match the paleo streamflow annual volume for each year. The same historical analog year that was selected to provide the daily pattern of streamflow for a paleo year was selected as the daily demands timeseries for the same paleo year.

Assessment Approach

The “Water Demand Assessment” section incorporates five main types of consumptive demands, including agricultural irrigation demands, reservoir evaporative demands, phreatophyte demands, evaporative demands from the Milk River main channel, and M&I and rural domestic demands. Agricultural, phreatophyte, and evaporative demands were modeled using historical and projected future meteorological data while the M&I and rural domestic demands were developed from previous planning studies. Each type of demand is described in further detail below.

Agricultural Demands

Agricultural demands may be defined as the demand for irrigation water by crops and associated conveyance and on-farm application losses. Crops may receive water either from precipitation or irrigation. The net irrigation water requirement (NIWR) is the total crop demand minus that amount of the crop demand satisfied by precipitation (i.e., effective precipitation [P_e]). The NIWR is solely the water required to meet crop demand specifically and does not include additional delivery of irrigation water needed to account for conveyance or on-farm losses.

The total diversion volume to meet agricultural demands is a function of NIWR, conveyance and application efficiencies, and incidental losses. Factors affecting conveyance efficiency include canal seepage and evaporation, canal over-topping, spillway flows and wasteway flows. Factors affecting application efficiency include evaporation, surface runoff and deep percolation. Incidental losses consist of canal seepage and deep percolation consumed by vegetation or lost to deep aquifers and evaporation from canals and during irrigation. Water that is diverted but not consumed by the crop or via incidental losses is considered return flow.

The following sections describe each of the components used to determine the total diversion volume. A discussion of NIWR estimates is presented first, followed by a discussion on irrigated acreage and efficiencies, incidental losses, conveyance efficiencies and maximum flow capacities, and return flows.

Net Irrigation Water Requirements (NIWR)

The NIWR estimates have been developed for the Impacts Assessment through use of a Penman-Monteith (PM) based model for computing ET. Historical and future NIWR estimates were developed for this study following the methods established by Reclamation's West-Wide Climate Risk Assessment (WWCRA; Reclamation 2015). The NIWR estimates were calculated using the ET Demands model originally developed collaboratively by Reclamation's Technical Service Center, the University of Idaho, the Nevada Division of Water Resources, and the Desert Research Institute (DRI). The ET Demands model uses the PM alfalfa-reference ET (ET_r) equation and the dual crop coefficient method to estimate crop ET (ET_c). The PM equation in the Food and Agriculture Organization (FAO) Irrigation and Drainage Paper No. 56 (FAO-56) equation for reference ET (Allen et al. 1998) has been adopted by the American Society of Civil Engineers as the standardized equation for reference (ASCE 2005) and is consistent with previous Reclamation work.

The PM-dual crop coefficient approach, as compared to a traditional single crop coefficient approach, accounts for transpiration and evaporation separately to better quantify variations in evaporation from precipitation and irrigation events. The separation of these two process also better captures winter soil moisture conditions which can have significant impacts on early irrigation season NIWR estimates. Additionally, the dual crop coefficient approach provides a more physically based method with continuous accounting of the soil moisture balance (Allen et al. 2005b) and effective precipitation.

Additional information on the development of agricultural demands including the ET Demands model and the datasets used for the model are included in Appendix C.

Irrigated Acreage

Irrigated acreage in the St. Mary and Milk River basins varies from year to year in response to water availability and other factors. A representative year, 2013, was chosen to represent irrigated acreage during a slightly above normal water supply. Irrigated lands between 2005 and 2017 were evaluated from National Agriculture Imagery Program (NAIP) imagery, showing a total of 196,230 acres, with a variable portion of these areas being irrigated in a given year. In 2013, approximately 82 percent of these lands, or 161,800 acres, were identified as being irrigated. Crop acreages aggregated to the 1/16° ET model grid cells used to estimate NIWR are shown on figure 43.

Crop types were evaluated for year 2013 using crop data from the U.S. Department of Agriculture and Agri-Food Canada (Soil Landscapes of Canada Working Group 2010). The predominant crop types include hay, grains, and alfalfa (table 9). Additional information on development of irrigated acreage and crop types for this study, including a more detailed description of resources is included in appendix C (appendix C, table C-3).

Table 9.—Irrigated acres by crop type

Crop type	Acreage
Hay	56,533
Grain	37,840
Alfalfa	56,469
Winter Wheat	7,625
Corn	3,134
Sugarbeets	126
Barley	45
Total	**161,772**

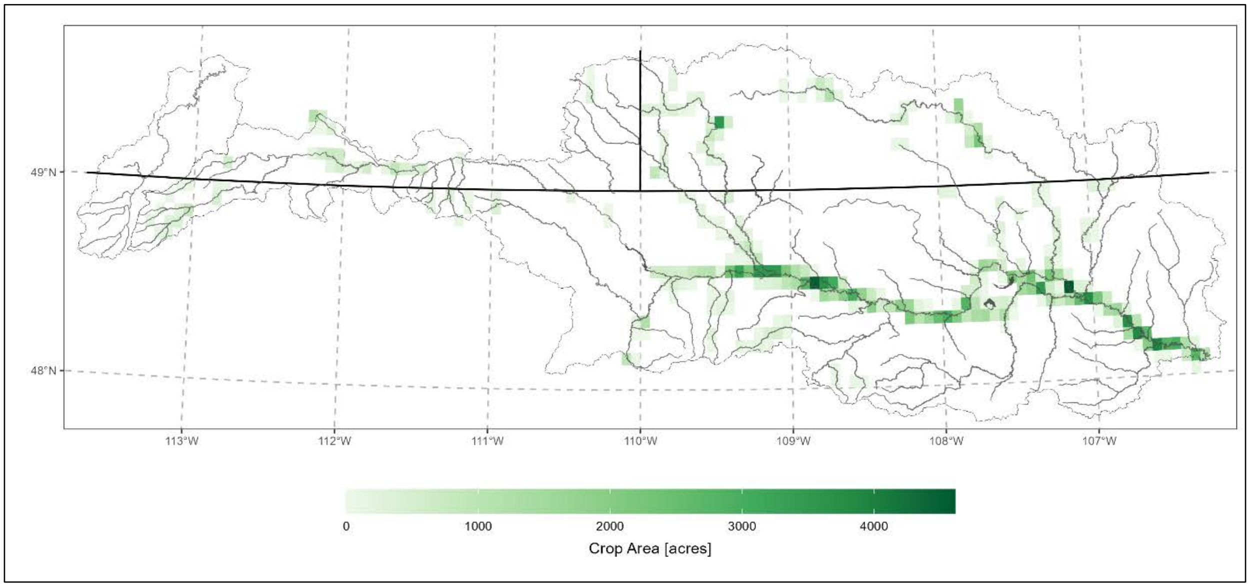

Figure 43.—Crop area by 1/16° evapotranspiration demands grid cell (acres).

Irrigation and Canal Efficiencies

Total irrigation efficiencies, including both on-farm efficiencies and delivery efficiencies, were initially derived from previous modeling efforts in the Milk River basin (Reclamation 2012b). On-farm irrigation efficiencies were originally evaluated using the U.S. Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS) Farming and Irrigation Rating Index program to evaluate seasonal irrigation efficiency as part of the North Central Regional Feasibility Study (Reclamation 2004). Values are based on field observations, interviews with local managers and irrigators, and local knowledge. On-farm irrigation efficiencies vary for different regions and seasons (table 10), ranging from 40 to 56 percent.

Table 10.—On-farm irrigation efficiencies in percent determined using the USDA NRCS Field Irrigation Rating Index program as part of the North Central Regional Feasibility Study

	April	May	June	July	August	September	Seasonal
Chinook division	40	10	42	40	44	48	42
Malta division	37	37	39	37	41	45	39
Glasgow division	46	46	48	46	51	56	48

The previous modeling effort for the 2012 Milk River Basins Study used canal efficiencies estimated based on diversion records, irrigated acres, crop irrigation requirements, and on-farm irrigation efficiencies. These values were reassessed as part of a canal efficiency study conducted as part of the North Central Regional Feasibility Study (Reclamation 2004) to estimate seepage losses from major basin canals. Canal efficiencies from this study are presented in table 11 and ranged from 50 to 65 percent. Canal efficiencies in the St. Mary and Milk Rivers planning model were updated from the calculated values in the 2012 Basins Study to the measured avg efficiencies for each district from the North Central Regional Feasibility canal efficiency study as part of the Impacts and Mitigation of Fort (Ft.) Belknap Indian Community Water Rights Development study (Reclamation 2022).

Table 11.—Canal delivery efficiencies for major canals in the Milk River basin (in percent) evaluated as part of the North Central Regional Feasibility Study

Canal	Efficiency (percent [%])
Fort Belknap ID	65
Paradise Valley ID	65
Harlem ID	65
Fort Belknap Indian Irrigation Project	50
Dodson North	60
Dodson South	50
Nelson South	55
Glasgow ID	65

The combined on-farm and delivery efficiencies within the St. Mary and Milk Rivers planning model derived from these values range from 20 to 40 percent for irrigation district lands, and from 45 to 50 percent for private irrigation lands. These irrigation efficiencies also vary seasonally and can increase during periods with higher water shortages (MT DNRC 2013).

Incidental Losses

Irrecoverable losses, or incidental losses, represent water diverted for irrigation but lost to surface evaporation, use by non-target plants, or seepage to deeper groundwater aquifers (i.e., deep percolation). Irrecoverable loss rates used in the model ranged from about 14 to 17 percent of the water diverted (MT DNRC 2013).

Maximum Flow Capacity

Where possible, when specific canals or irrigation projects were identified and modeled, maximum flow capacities were set according to documentation from the relevant sources. For canals associated with state projects, these capacities typically came from the Manuals for Operation and Maintenance or DNRC staff. Likewise, capacities for canals attached to Federal facilities came from environmental and decision documents associated with the projects and Reclamation personnel.

Return Flows and Percent Surface Return

Water which is diverted but not consumed by crops or via incidental losses was returned to the modeled system at either the same node as the diversion or at a downstream node. Diversions are modeled as a function of the irrigation requirement, incidental losses, and efficiencies, resulting in higher simulated return flows for less efficient systems.

Return flows are split between surface and groundwater using an assumed percent which varies with irrigation system type and between subbasins. These percentages were updated from previous DNRC modeling efforts in the 2012 Basins Study Report (Reclamation 2012b) based on updated data and most recently as part of the Impacts and Mitigation of Ft. Belknap Indian Community Water Rights Development study (Reclamation 2022) to maintain water balance in the system. Sprinkler initial overall return flow percentage was 10 percent with 50 percent return flow for flood irrigation; however, adjustments to the weighted percent surface return flow for a water user were made based on the system distributions associated with the corresponding overall irrigation efficiencies. The remaining portion of the return flow was simulated to follow through a groundwater path, with a 1-year lagging factor (Reclamation 2022).

Evaporative Demands

The estimated evaporation rates for the Reclamation reservoirs in the basin were calculated using the complementary relationship lake evaporation (CRLE) model (Morton et al. 1985). The CRLE is an open water evaporation model that accounts for water temperature, albedo, emissivity, and heat storage effects to estimate monthly evaporation. Reclamation first collaborated with the DRI in the development and application of the model as part of the WWCRA Irrigation Demand and Reservoir Evaporation Projections (Reclamation 2015). In that effort, evaporation was modeled for twelve reservoirs in the Western U.S. The WWCRA Demands Assessment (Reclamation 2015) provides a detailed description of the CRLE model. The CRLE model was also used to simulate monthly evaporation rates for the reservoirs in the Missouri Headwaters region upstream of Fort Peck Reservoir (Reclamation and MT DNRC 2020).

The CRLE model calculates evaporation for historical avg reservoir conditions. Inputs to the CRLE model include precipitation, temperature (T), dewpoint temperature (T_{dew}), and solar radiation. T_{dew} and solar radiation are not direct inputs to the model but were derived from daily minimum and maximum temperature data. For this study, evaporation from reservoirs was modeled using gridded meteorological data bias-corrected to local meteorological stations.

The CRLE model was used to develop evaporation rates for several reservoirs in the St. Mary and Milk River basins. Additional model details and input datasets are discussed in Appendix D.

Phreatophyte Demands

Phreatophyte demands on the Milk River were modeled based on a provided ET rate and acreage of the riparian area. The ET rates are estimated using the ET Demands model discussed in Appendix C. A total of 8,790 acres of phreatophytes were modeled for this study, a summary of phreatophyte acreages in different regions along the Milk River are presented in table 12.

Table 12.—Phreatophyte acreage by region

Object	Acres
Phreatophytes Havre to Fort Belknap	860
Phreatophytes Ft. Belknap to Paradise Valley	396
Phreatophytes PV to Harlem ID	325
Phreatophytes Harlem ID to FT Belknap Reservation	490
Phreatophytes Ft. Belknap to Dodson	1,678
Phreatophytes Dodson to Vandalia	3,120
Phreatophytes Vandalia to Mouth	1,840
Total Phreatophyte acres	8,709

Milk River Evaporation Loss

Additional evaporation losses occur at the surface of the Milk River. Increased surface area of the Milk River due to the addition of water through the St. Mary Canal results in further evaporative losses. Milk River evaporative losses are calculated as the product of the surface area of a given river reach (based on the channel inflow) and an evaporation rate. Evaporative channel losses from the Milk River are calculated using the PM equation for open water in ET Demands Model (appendix C).

Municipal and Industrial (M&I) and Rural Domestic Demands

The communities of Havre, Chinook, Harlem, Hill County, and North Havre Water District have water supply contracts with Reclamation for municipal water. The current annual avg water uses and the total water volume of for each contract is listed in table 13. The communities currently use an avg of about 2,600 AF annually. The combined contracted amount of water is up to 4,600 AF annually, so they are presently using considerably less than the contracted volume. Municipal use represents less than one percent of total Milk River diversions. These demands generally are met.

Table 13.—Historical estimates of municipal and industrial demands

Municipalities	Avg (AF)	Contract volume (AF)
Havre	1,825	2,800
Chinook	360	700
Harlem	130	500
Hill County	250	500
North Havre	35	100
Total	**2,600**	**4,600**

The Rocky Boy’s/North Central MT Rural Water System is currently being constructed. As the water supply for this system is from Tiber Reservoir, it might reduce the contracted volume of municipal water currently used from the Milk River. Havre, Hill County Water District, and North Havre Water District are all within the Milk River Project boundary and have signed Letters of Intent to be served by the rural water system. Water service from the Rocky Boy’s/North Central MT Rural Water System to these communities is planned within the next five years. Once each of these areas receives water, Hill County Water District and North Havre Water District would significantly reduce or possibly eliminate their contracts for water from the Milk River. Havre might keep their water contract and use the treated water to serve areas on the eastern side of the project boundary. Because of these factors, future water uses of these communities are expected to remain within the current contracted volume.

Non-Consumptive Demands

Non-consumptive water demands in the St. Mary and Milk River basins include demands for supporting recreation, water quality, and fish and wildlife. These demands may not be quantified. However, non-consumptive demands that are quantified are further discussed below.

Fish, Wildlife, and Recreation Demands

The Bowdoin National Wildlife Refuge provides food and habitat for migratory birds (including the endangered piping plover and interior least tern), upland birds, and many species of waterfowl. The refuge has a reserved water right from Beaver Creek and a contract with Reclamation for Milk River Project water. Under the contract, up to 3,500 AF of project water annually is diverted to the refuge from the Dodson South Canal. The refuge also receives return flow from the Malta Irrigation District.

Water Quality Demands

The communities of Havre, Chinook, and Harlem have wastewater discharge permits from the MT Department of Environmental Quality. To provide adequate mixing flows for treated wastewater in the Milk River, a minimum release of 25 cfs from Fresno Reservoir is provided under contract by Reclamation during the non-irrigation season. This also allows the communities downstream to have water of suitable quality to divert from the Milk River. This flow rate in the winter typically is exceeded because the outlet works at Fresno Reservoir would be damaged by cavitations at lower flows. Current operation procedures are that the flow from Fresno Reservoir during the non-irrigation season is not to be reduced below approximately 45 cfs. This flow rate will continue to be met into the future. If releases are reduced, water temperatures will increase, and dissolved oxygen will decrease. Minimum releases from Fresno Reservoir are not anticipated to increase in the future.

Historical Water Demands in the Milk and St. Mary River Basins

Consumptive water demands in the Milk River basin are historically dominated by agricultural irrigation, accounting for an annual avg of approximately 508,852 AF, or 89 percent of total demand. Reservoir evaporation requires approximately 8 percent of total demand with M&I demands accounting for less than 1 percent (table 14).

Table 14.—Summary of primary historical consumptive water demands

Basin wide consumptive uses and losses	Estimated avg annual quantity (AF/year)	% of total annual use
Agricultural irrigation	508,852	85.8
M&I and rural domestic	2,600	0.4
Reservoir and lake evaporation	44,376	7.5
Phreatophyte ET	13,845	2.3
Milk River Channel evaporation	23,110	3.9
Total consumptive uses and losses	**555,828**	**100**

The following sections describe each type of consumptive demand in greater detail.

Agricultural Demands

Historical agricultural demands over the irrigation season (defined as April through September) are summarized on figure 44. Demand is presented as an annual weighted avg NIWR based on crop distribution within each 1/16° model grid cell (figure 44). Alfalfa-reference ET and crop ET estimates from the ET Demands model are presented on figure 45 and figure 46, respectively. Patterns of ET_r and ET_c correlate with the NIWR values.

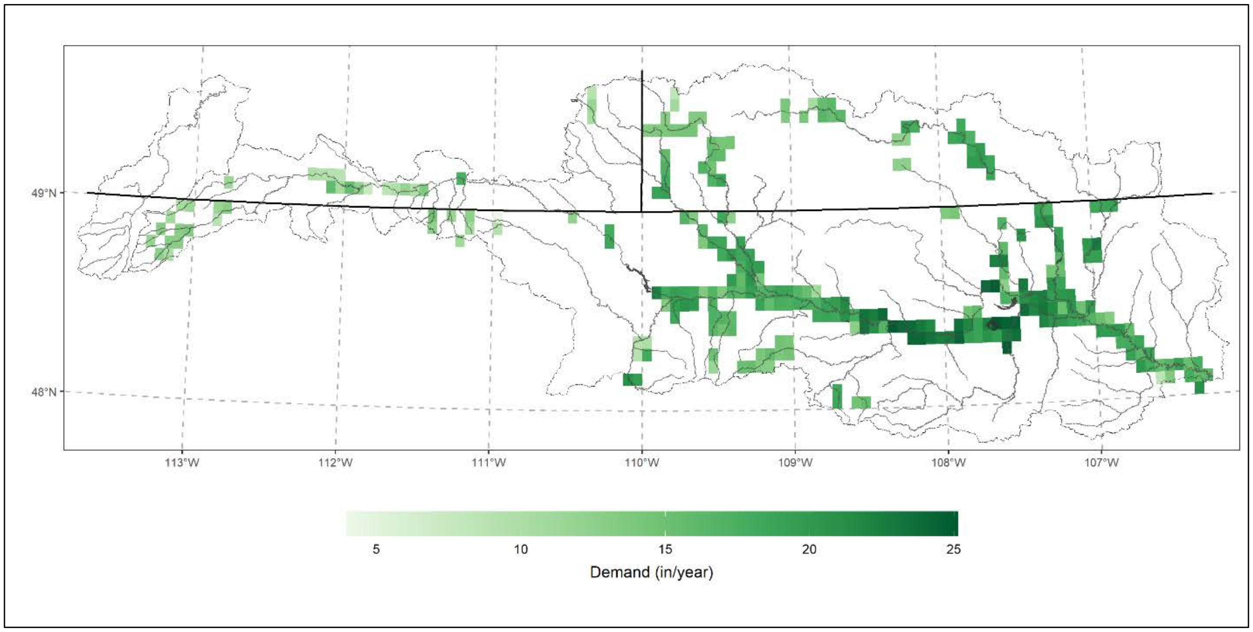

Figure 44.—Historical agricultural demand (NIWR) by 1/16° evapotranspiration demands grid cell (inches per year).

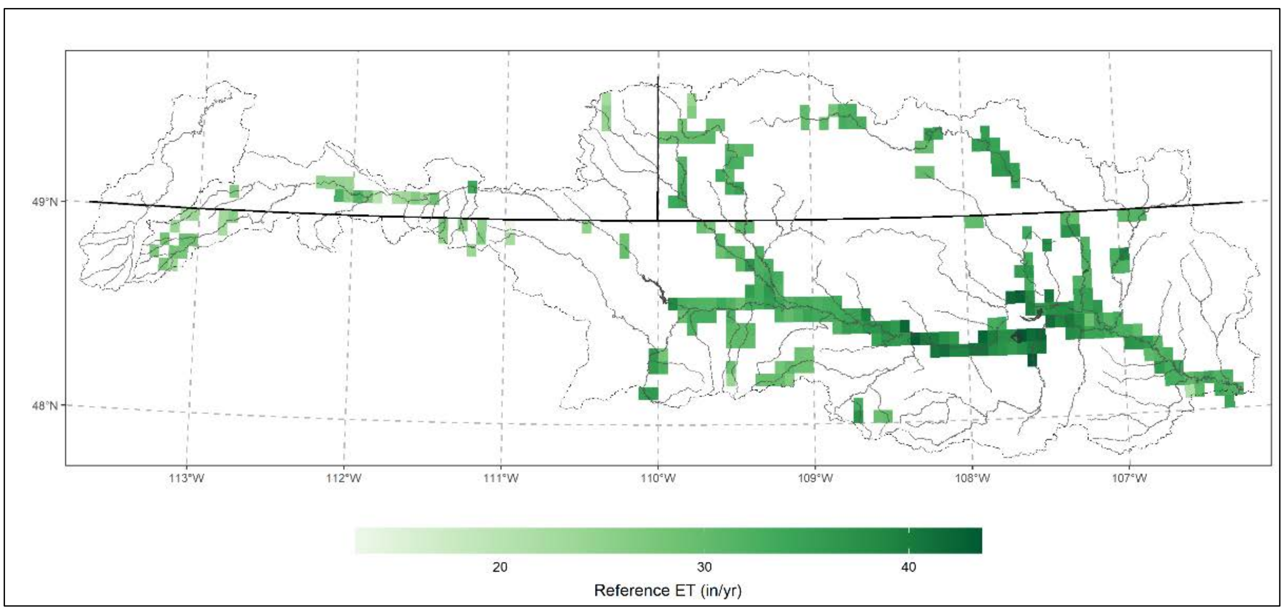

Figure 45.—Historical alfalfa-reference evapotranspiration (ET_r) by 1/16° evapotranspiration demands grid cell (inches per year).

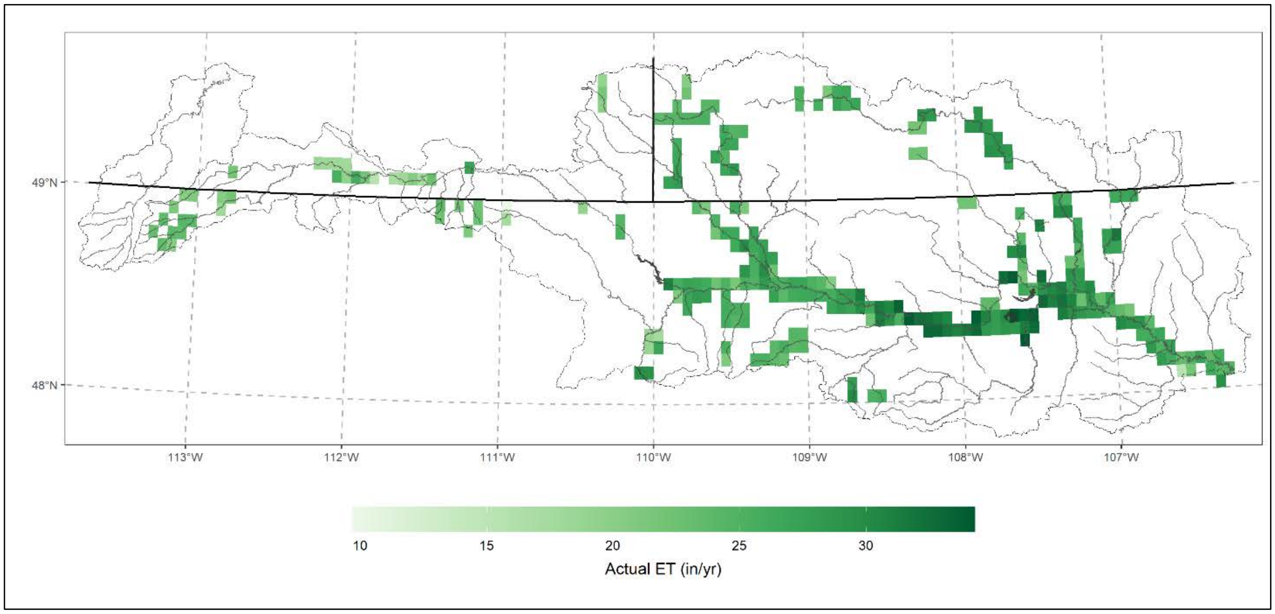

Figure 46.—Historical crop evapotranspiration (ET_C) by 1/16° evapotranspiration demands grid cell (inches per year).

The NIWR annual rates vary between the different regions of the Milk River basin, with the highest values in the Plains region where reference ET is the greatest likely due to higher avg temperatures, and lowest in the upper headwaters where reference ET and temperature are the lowest (figure 47).

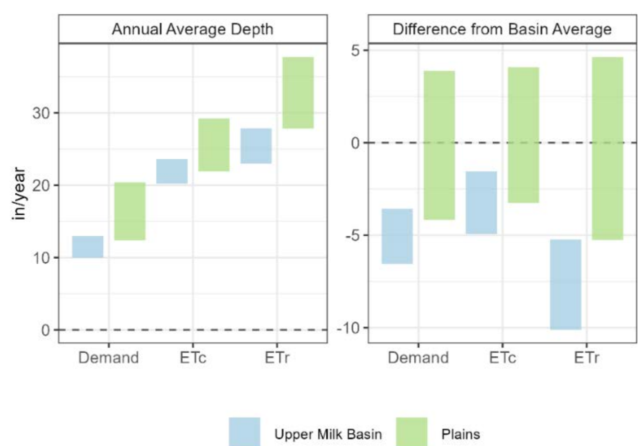

Figure 47.—Historical agricultural demand (Demand), crop evapotranspiration (ETc) and alfalfa reference evapotranspiration (ETr) aggregated by region.[4]

[4] Values are presented as average annual depths and their differences from the total Milk River basin annual averages.

Reservoir Evaporative Demands

Historical reservoir evaporative demand volumes were estimated within the St. Mary and Milk Rivers planning Management model (MT DNRC 2013) by using the evaporation rates from the CRLE model. The planning model calculates daily reservoir evaporation volume as the product of net reservoir evaporation rate (evaporation minus precipitation in inches per day) and reservoir surface area. Reservoir evaporation is dependent on both climate and operations, which determines reservoir surface area.

Historical annual avg net evaporation rates (evaporation minus precipitation) for reservoirs in the study area over the historical reference period (1980–2015) are shown on figure 48. Reservoirs at lower elevation in the downstream area of the basin have the largest historical avg net evaporation rates. The avg monthly evaporation rates for each of the modeled reservoirs are shown on figure 49. Evaporation rates at each reservoir follow a similar temporal pattern with the highest evaporation rates in July and August.

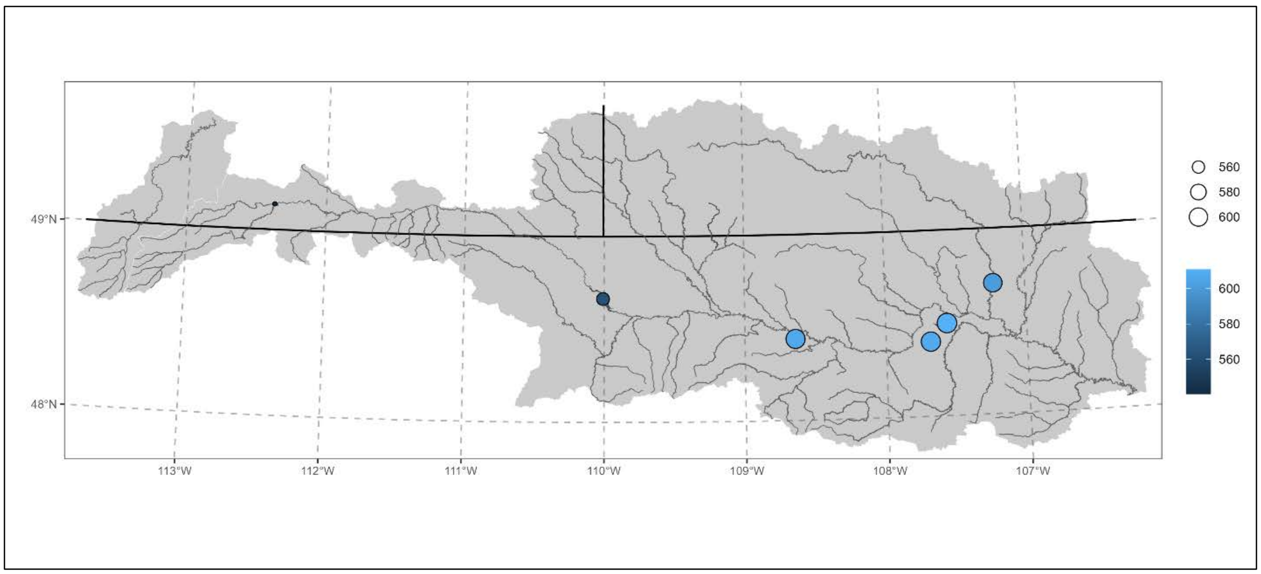

Figure 48.—Historical average annual net reservoir evaporation by water year (inches/year).

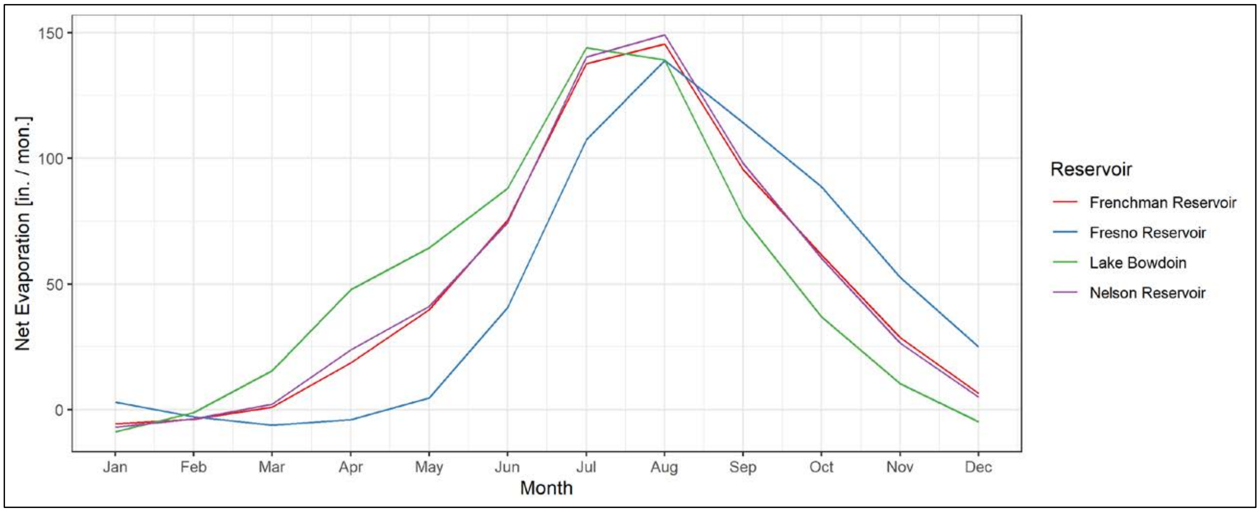

Figure 49.—Average monthly net reservoir evaporation during the historical period.

Phreatophyte Demands

Phreatophyte demands along the Milk River range from 18 to over 20 inches per year, with a total annual avg volume of 14,004 acre-ft per year. These demands were estimated assuming cottonwood trees to be the dominant species and using the ET Demands model. A summary of phreatophyte demands along different stretches of the Milk River is included in table 15.

Table 15.—Annual average phreatophyte evapotranspiration rates along different reaches of the Milk River

Reach	Annual avg ET rate (inches/year)	Annual avg Volume (AF/year)
Havre to Fort Belknap	17.6	1,260
Ft. Belknap to Paradise Valley	17.6	580
PV to Harlem ID	18.0	487
Harlem ID to FT Belknap Reservation	17.5	715
Ft. Belknap to Dodson	19.3	2,699
Dodson to Vandalia	20.6	5,355
Vandalia to Mouth	19.0	2,909
Total annual avg volume		14,000

Milk River and St. Mary Canal Evaporation Loss

Additional evaporation losses occur from the Milk River and the St. Mary Canal. Milk River and St. Mary Canal evaporative losses were calculated as the product of the surface area of a given reach (based on the channel inflow) and an evaporation rate. Evaporative channel losses from the Milk River and St. Mary Canal were calculated using the PM approach for open water in ET Demands Model (Appendix C).

Impacts of Climate Change on Water Demands

Agricultural and evaporative demands are projected to change based on potential future temperature and precipitation projections. A summary of projected annual temperature and precipitation is provided in table 16. All scenarios in all time periods show increases in avg annual temperature up to 10.9 °F. Changes in annual avg total precipitation range from small decreases to large increases in precipitation.

Table 16.—Summary of projected changes in basin averaged climate variables

Variable	Scenario	2020s	2050s	2080s
Avg annual temperature increase (°F)	HD	3.2	6.7	10.4
	HW	3.4	6.2	10.9
	CT	2.3	5.36	7.5
	WW	2.0	3.8	5.2
	WD	2.1	3.6	4.7
Avg annual precipitation (% change)	HD	0.6	1.9	1.0
	HW	11.6	17.6	19.1
	CT	5.3	5.1	9.9
	WW	8.5	13.8	16.8
	WD	-0.4	1.4	1.7

Future Demand Assumptions

The “Water Demands Assessment” section used several key assumptions for future demands. First, agricultural practices and irrigated acreage were assumed to be static throughout time. Historically, flood irrigation has transitioned to sprinkler irrigation, which typically increases consumptive use and reduces return flows, but these transitions were not represented. Second, crop distributions were also assumed to remain constant throughout time. The M&I demands were assumed to remain unchanged in future scenarios.

Agricultural Demands

Agricultural demands are impacted by both changes in temperature and precipitation. Temperature increases in future climate scenarios result in increased rates of alfalfa reference ET and subsequently crop ET and NIWR. Additionally, precipitation increases, which can impact the amount of precipitation available to crops (i.e., effective precipitation), can affect NIWR. Agricultural demand, Alfalfa reference ET, and crop ET are projected to increase across the St. Mary and Milk River basins (figure 50, figure 51, and figure 52, respectively) for all climate scenarios. Increases in NIWR range from 11.6 percent in the 2020s WW scenario to 40.7 percent in the 2080s hot-dry scenario (table 17). Historical and projected NIWR by water user are summarized in appendix C, table C-6.

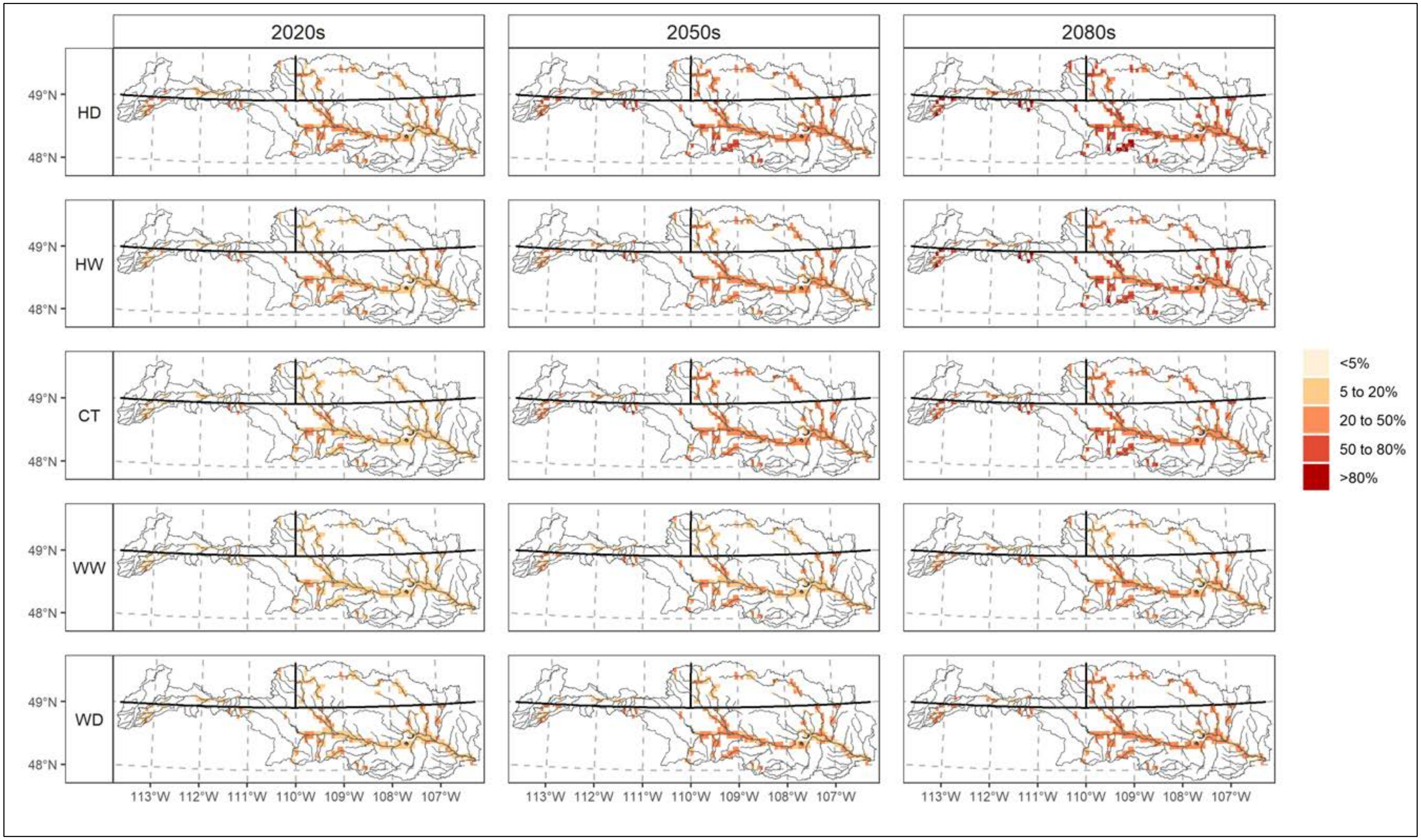

Figure 50.—Projected changes in agricultural demand (NIWR) by 1/16° evapotranspiration demands grid cell, compared with a historical reference of water years 1981–2015.

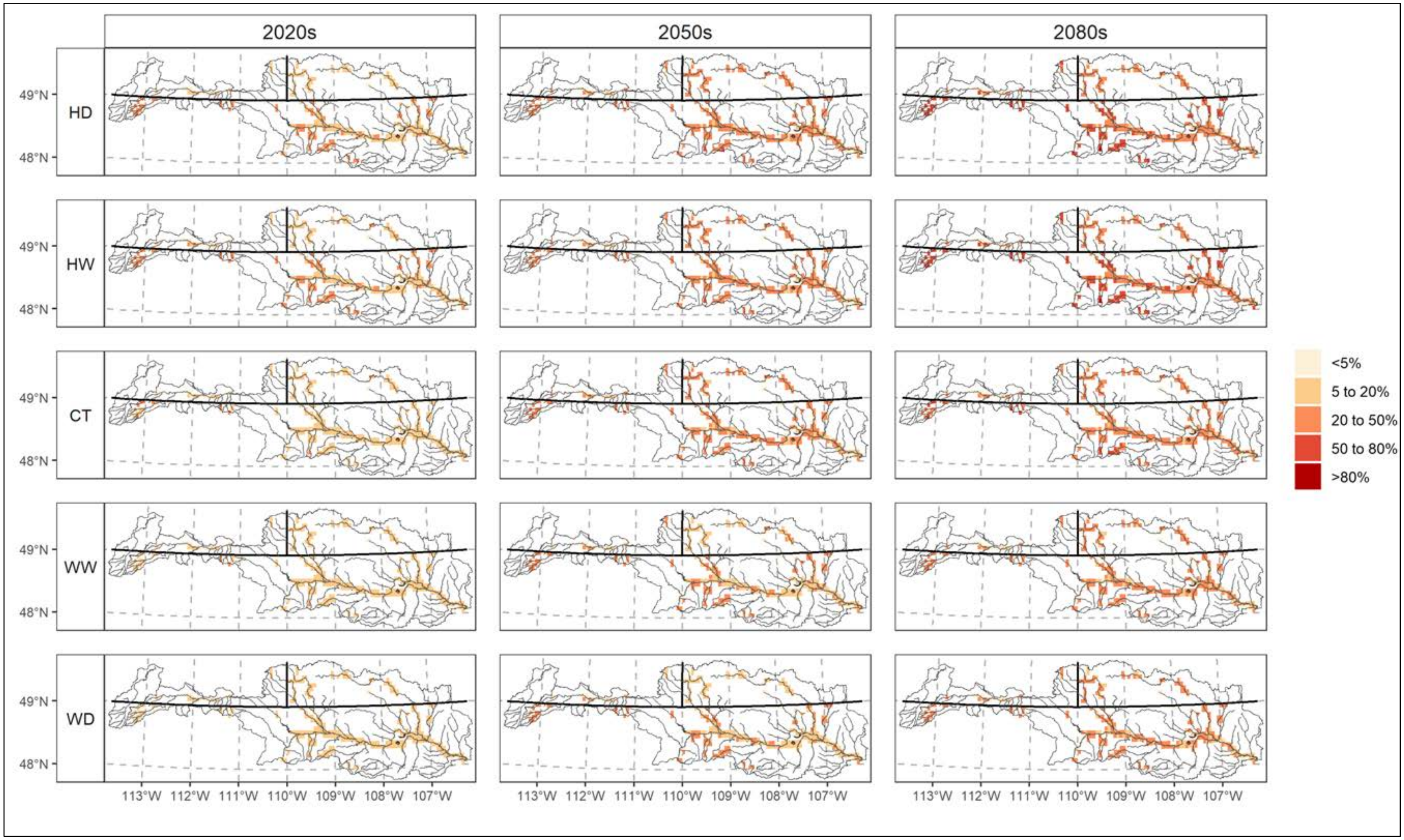

Figure 51.—Projected changes in reference evapotranspiration (ET_r) by 1/16° evapotranspiration demands grid cell, compared with a historical reference of water years 1981–2015.

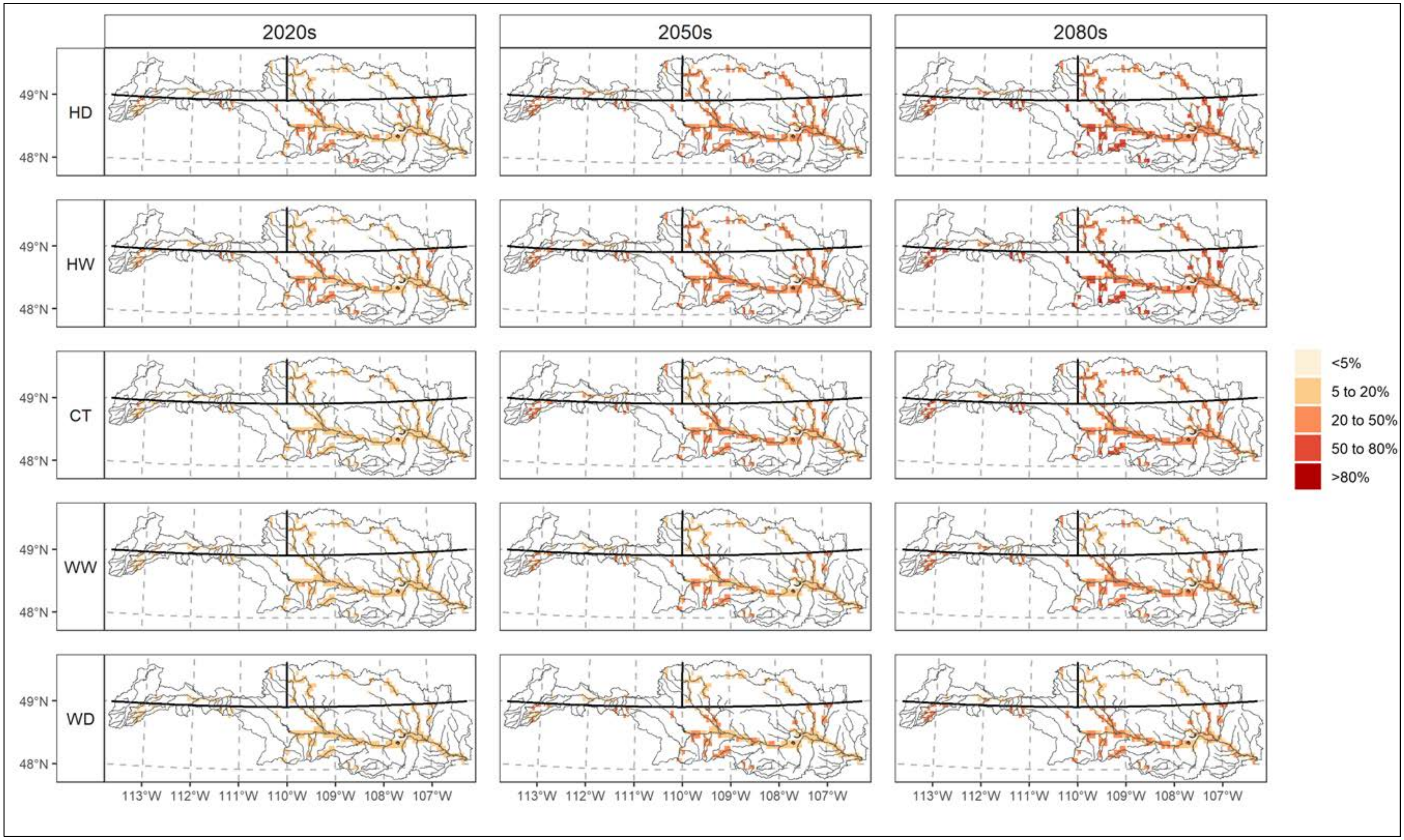

Figure 52.—Projected changes in crop evapotranspiration (ET_C) by 1/16° evapotranspiration demands grid cell, compared with a historical reference of water years 1981–2015.

Table 17.—Summary of percent change in projected basin averaged depletion request from the historical average

Period	HD	HW	CT	WW	WD
2020s	19.3	15.5	14.5	11.6	16.1
2050s	29.6	22.3	23.5	15.5	19.6
2080s	40.7	34.5	29.1	19.7	23.4

Projected changes in NIWR and precipitation over crop areas for the three future time horizons are summarized on figure 53. The largest percent changes in NIWR demands occur in the Upper Milk Basin region at higher elevation than the Plains region. Historical NIWR requirements are lowest in this region during the historical period, however, increasing temperatures resulted in greater percent increases in reference ET in areas where reference ET was historically low. Results indicate important demand changes in regions where demand is historically low.

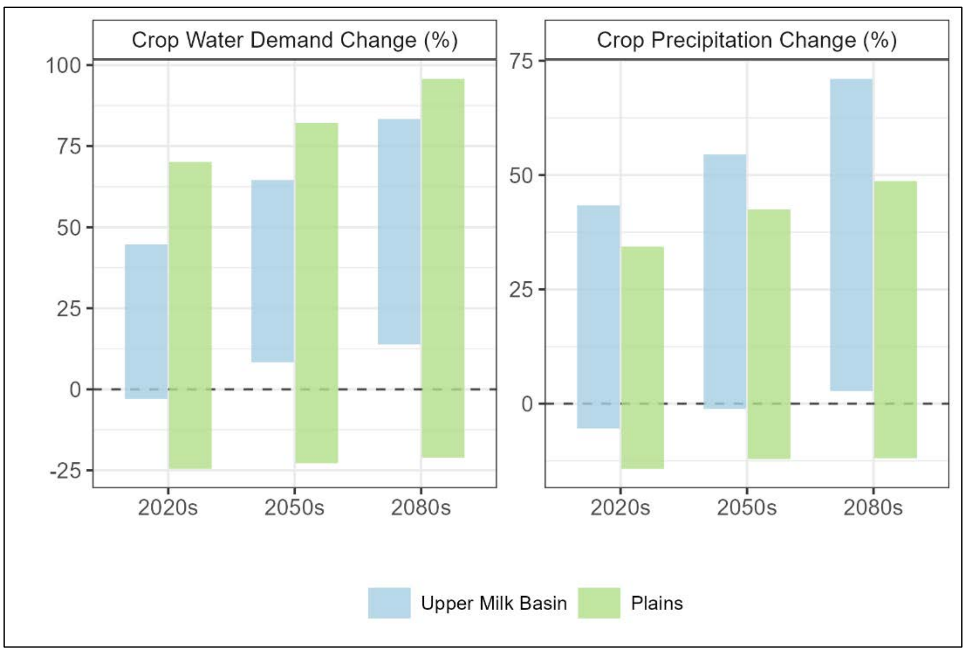

Figure 53.—Percent changes in crop water demand (also termed net irrigation water demand) and crop precipitation by region.

The timing of agricultural demands is also expected to change as a result of changing climate. Warmer temperatures may create conditions for earlier planting and green-up of crops, as well as longer growing seasons overall for perennial crops. Figure 54 and figure 55 illustrate avg monthly NIWR for the Glasgow Irrigation District and irrigation between Beaver Creek and Havre, respectively. In both subbasins, the growing season is projected to lengthen (i.e., more months with above-zero NIWR), and the overall NIWR is expected to increase. Reference ET for both regions increases for all months with the greatest increases in summer (June to August).

Comparison of NIWR monthly patterns shows significant a significant increase in the early season, April and May, due to earlier planting dates. Depending on crop type, this can result in lower NIWR in later summer after harvest.

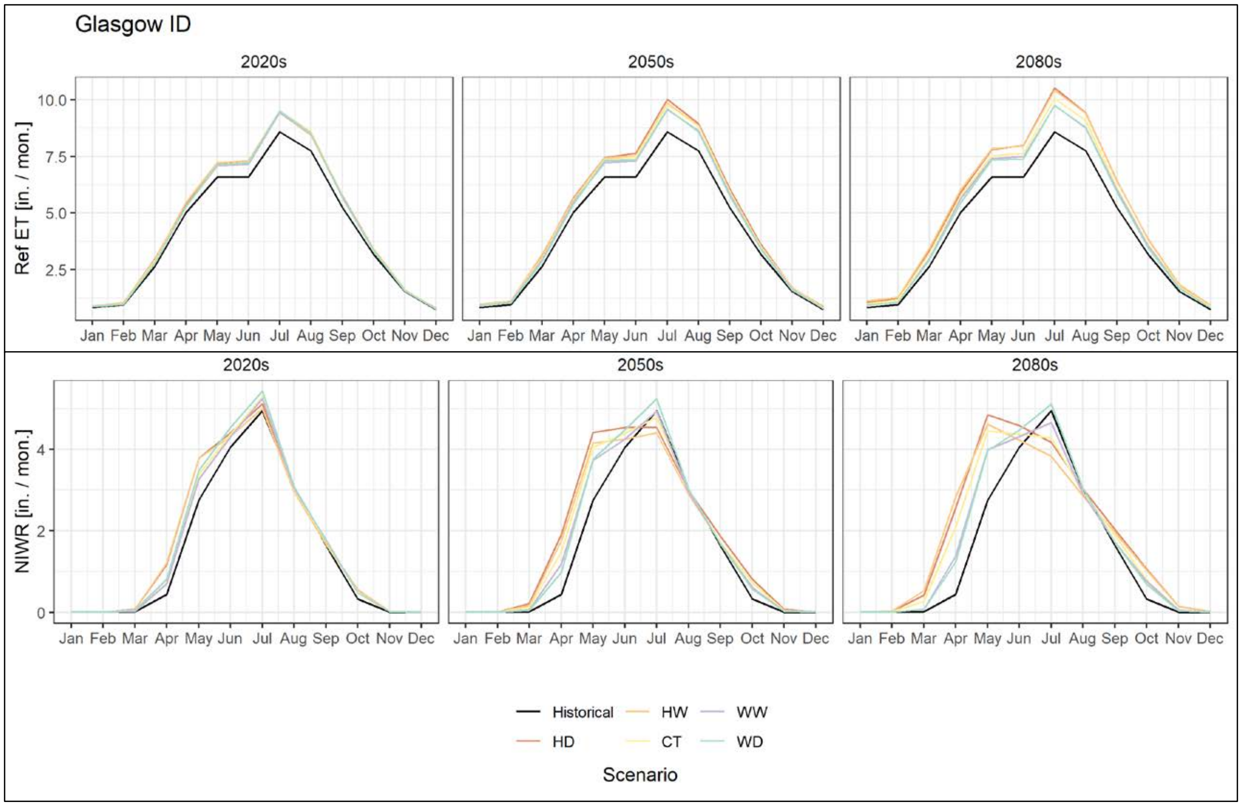

Figure 54.—Historical and projected monthly Reference evapotranspiration and net irrigation water requirement (inches/month) for the Glasgow Irrigation District.

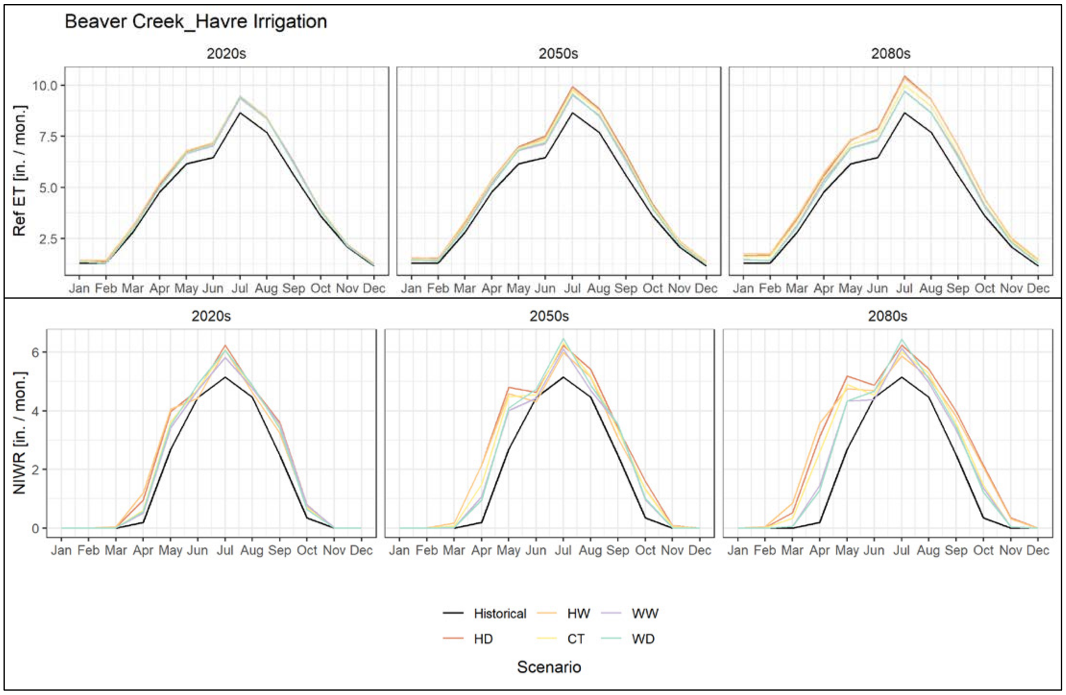

Figure 55.—Historical and projected monthly reference evapotranspiration and net irrigation water requirement (inches/month) for irrigation between Beaver Creek and Havre.

Spatially, we can observe this same phenomenon with large increases in avg monthly NIWR across the region, over 80 percent in some regions, in May (figure 56). However, changes in NIWR are much more variable in August (figure 57), where some regions experience higher NIWR and some regions see lower projected NIWR rates due to an earlier start to the growing season.

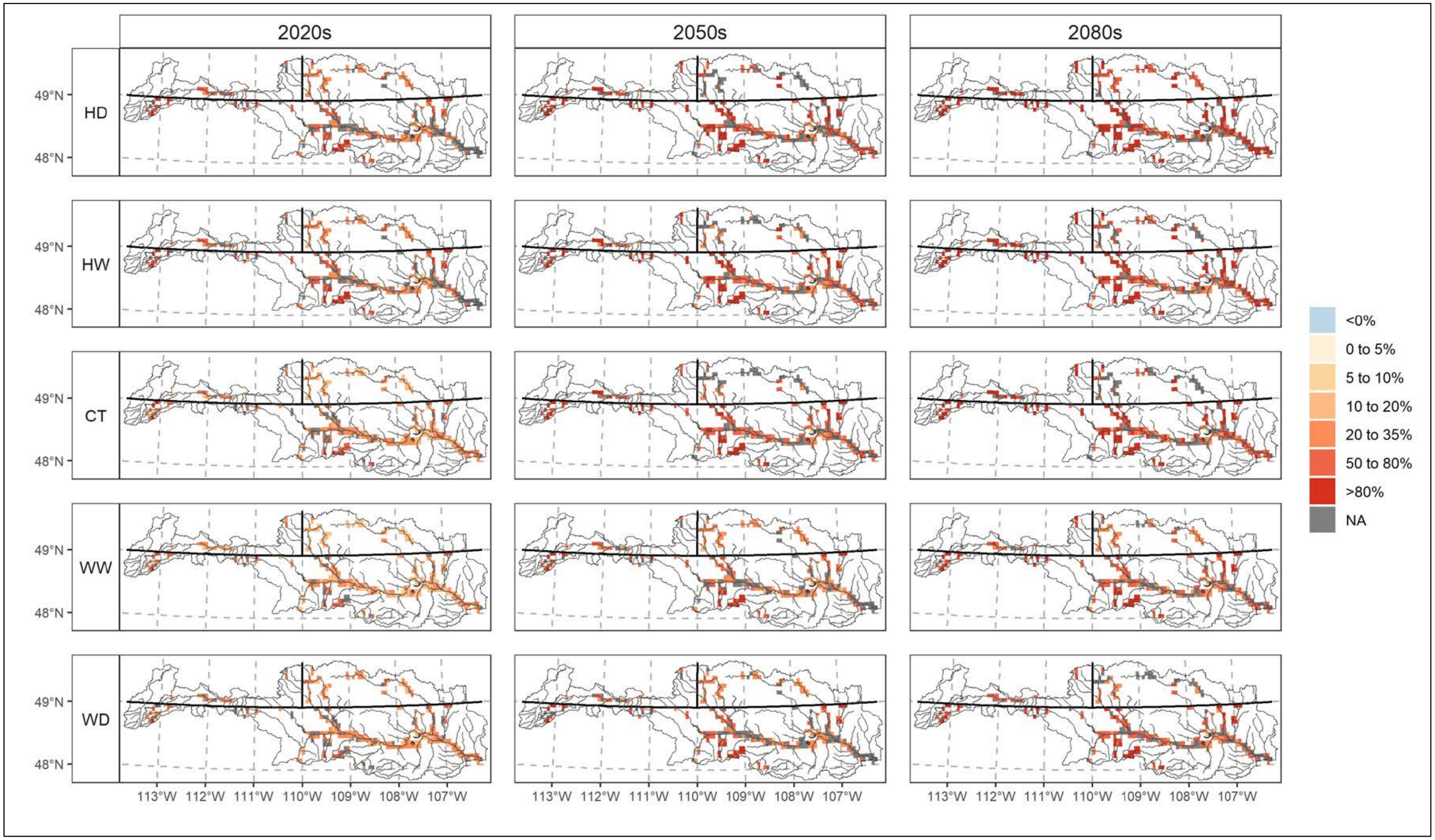

Figure 56.—Projected changes in agricultural demand (NIWR) by 1/16° evapotranspiration demands grid cell, compared with a historical reference for the month of May.[5]

[5] Gray cells indicate areas where historical agricultural demand in May was zero.

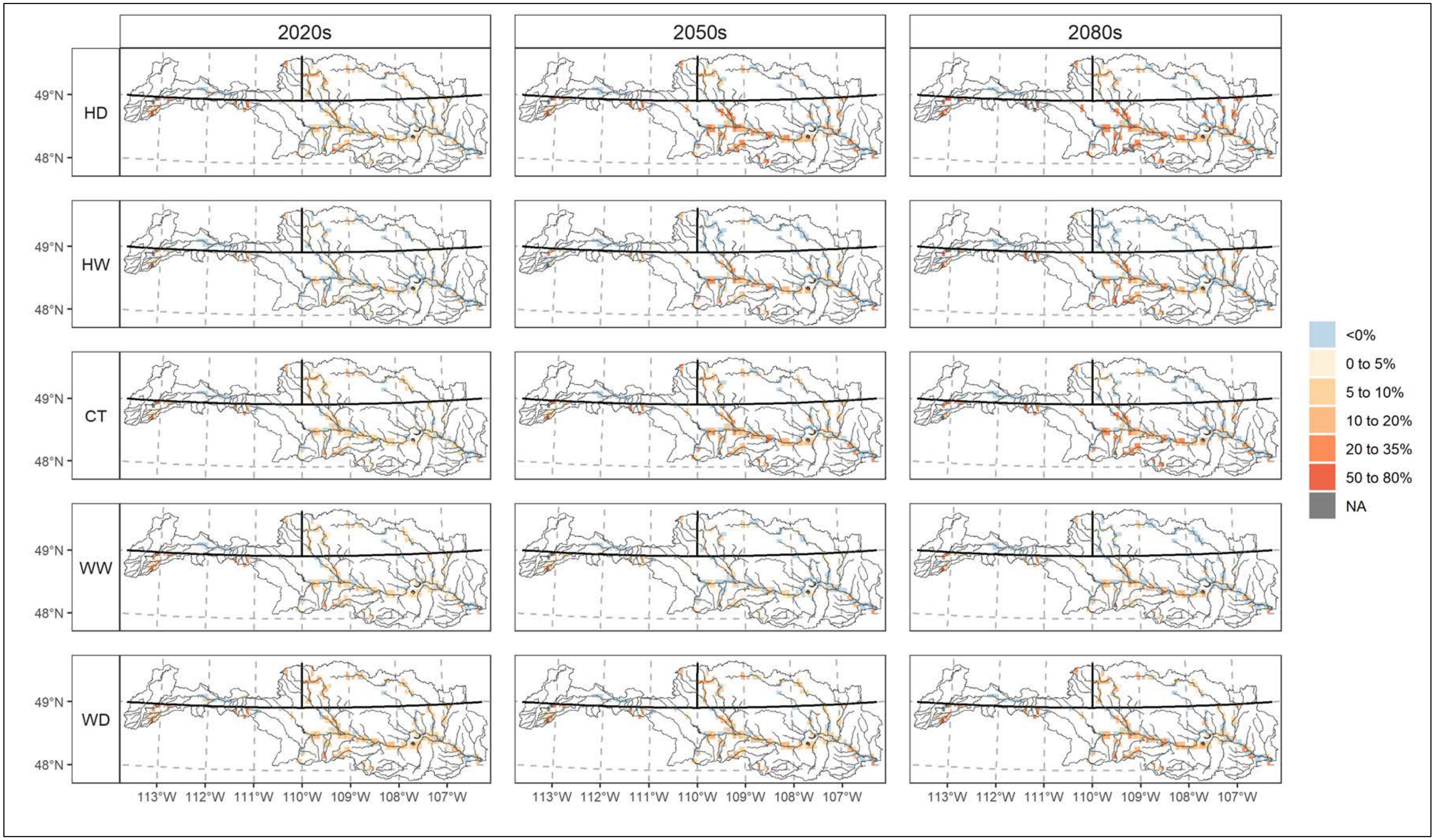

Figure 57.—Projected changes in agricultural demand (NIWR) by 1/16° ET Demands grid cell, compared with a historical reference for the month of August.

Evaporative Demands

Reservoir evaporation increased from historical estimates for all reservoirs within the study area (figure 58; table D-5 “Appendix D. Reservoir Evaporation Estimates Development”). Percent change in reservoir evaporation ranged from 6 to 21 percent. Increases in evaporation are driven by temperature increases in all scenarios. Changes in net evaporation are more variable due differences in precipitation between the future scenarios and ranged from a 10.8 percent decline to a 27.6 percent increase in annual avg rates.

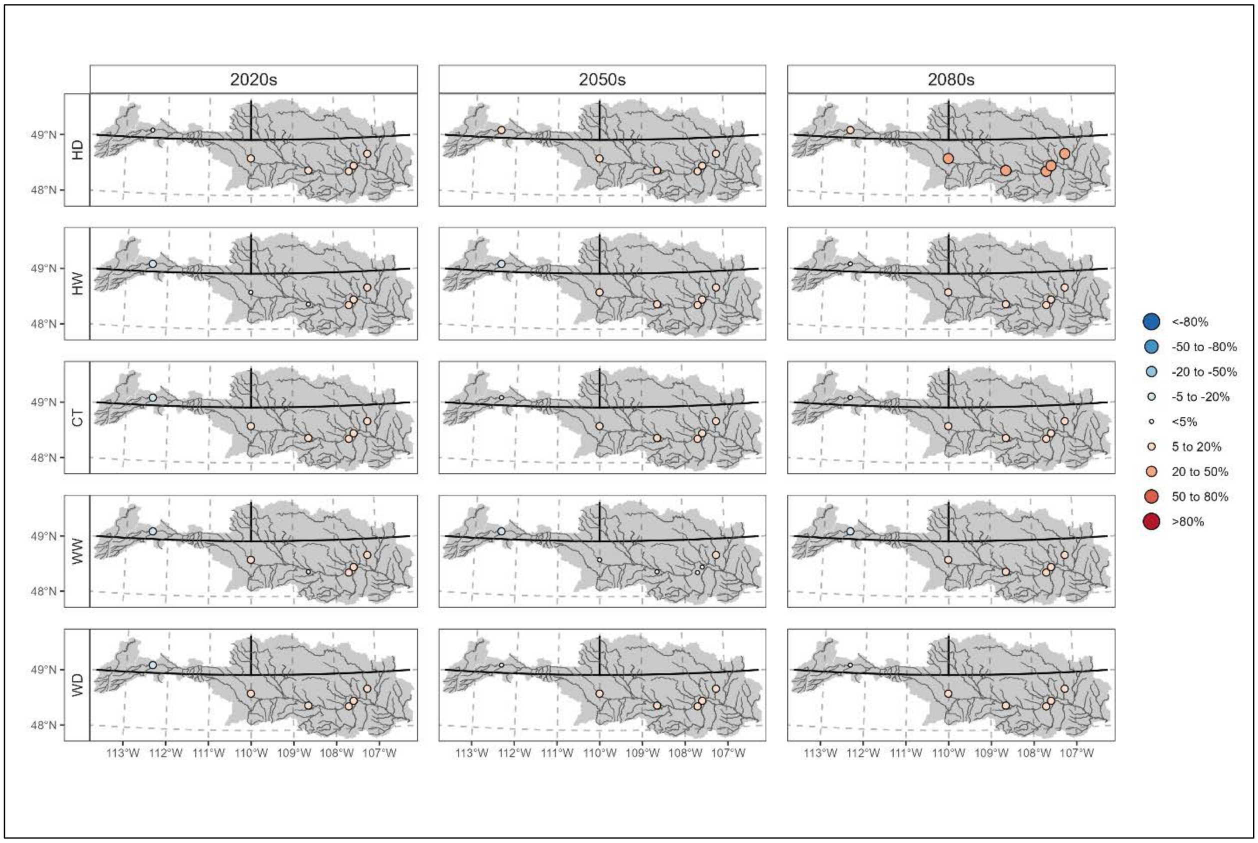

Figure 58.—Projected changes in annual reservoir evaporation presented as percent change from the historical reference of water years 1981–2015.

Increases in reservoir evaporation vary seasonally, with the largest increases for all future simulations during the summer (July to August) months and only slight increases in the winter (figure 59). Peak evaporation timing is generally consistent from the historical to future climate periods for all reservoirs with the largest increases for the hot-dry scenarios and the least increase in the WW scenarios.

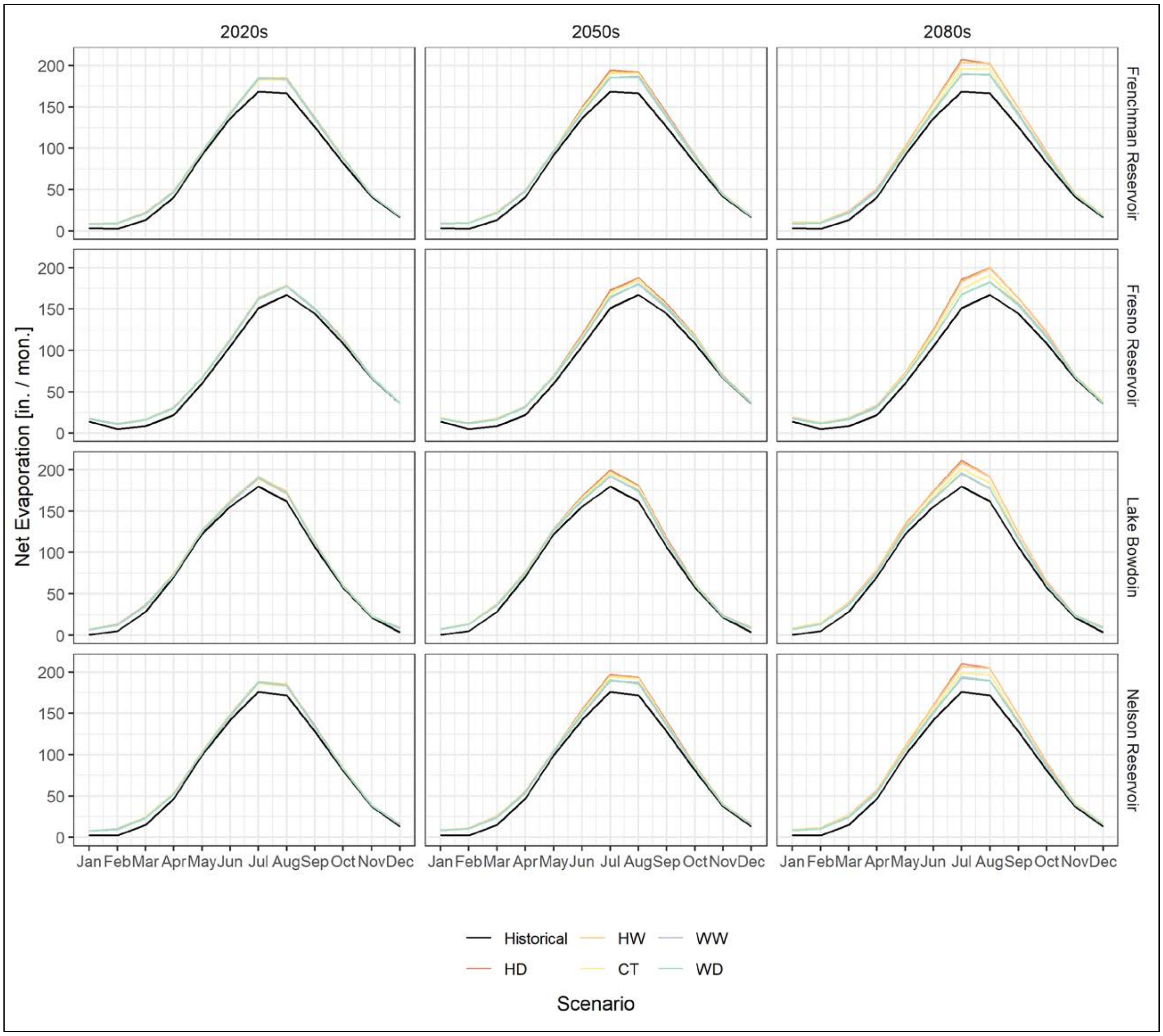

Figure 59.—Average monthly net reservoir evaporation by scenario for Nelson Reservoir, Frenchman Reservoir, Fresno Reservoir, and Lake Bowdoin.

Phreatophyte Demands

Phreatophyte demands increase significantly up to a 58.7 percent increase in the hot dry 2080s scenario (table 18). Current model configuration assumes the acreage of phreatophytes, or cottonwoods remains the same across scenarios, including historical. Changes in phreatophyte demand by reach are included in "Appendix C. Water Demands Development."

Table 18.—Phreatophyte percent change in annual average evapotranspiration rates

Period	HD	HW	CT	WW	WD
2020s	23.8	20.0	17.5	15.8	20.0
2050s	40.3	30.0	31.3	20.6	25.3
2080s	58.7	52.7	40.1	28.1	30.4

Milk River and St. Mary Canal Evaporation Loss

Milk River and St. Mary Canal evaporation losses increase under all future climate scenarios. However, these increases vary greatly between six to almost 30 percent. A summary of changes in Milk River and St. Mary Canal evaporation losses is included in “Appendix C. Water Demands Development,” table C-9.

Uncertainties in Analysis

Agricultural Demands

There are numerous uncertainties and limitations for estimating both timing and volume of agricultural demands. One source of uncertainty are the underlying assumptions in modeling reference ET, crop ET, and NIWR. It is uncertain how farming practices will change over time and in response to climate changes. This study assumes static lands use, where crop types and quantities do not change over time or with climate change. Given the variability in water demand for different crop types, both total acreage and crop choice would have significant impacts on future agricultural demands. This study also assumes additional static farming practices such as irrigation efficiency, though it does estimate changes in planting and harvest dates which ET Demands estimates based on cumulative growing days. Additional uncertainties associated with parameterization of the ET Demands model are further detailed in the WWCRA Demands Report.

Further, the ET Demands model assumes well-watered conditions to meet crop demands. However, previous reports have indicated a local practice in the Milk River basin of deficit irrigation. Deficit irrigation is believed to take place regardless of water availability, possibly due to a history of frequent water shortages. To account for deficit irrigation, management factors were applied in the model to scale diversion volumes (Reclamation 2022). These management factors were calibrated based on historical diversion records. However, there is uncertainty in how much deficit irrigation is currently occurring as well as how this practice may change in response to climate change.

Estimation of soil conditions is an additional source of uncertainty for modeling NIWR. Soil type controls precipitation runoff and soil water holding capacity. Soil type can vary even within a single irrigated parcel; however, this study assumes a single weighted avg soil type for each

1/16° model grid cell, calculated as described in Reclamation (2015). The degree of uncertainty in the weighted avg soil conditions used depends on the variability of soil types within each of the 1/16° model grid cell.

Climate variables used to estimate reference ET provide additional uncertainty in the model. There are numerous sources of uncertainty in these climate variables, including underlying uncertainties in the algorithm that generates the Daymet meteorological dataset (Thorton et al. 2016) and additional uncertainty introduced when the data was interpolated to the 1/16th° grid and corrected for biases. Variables not provided by the Daymet dataset, including total solar radiation, relative humidity, and dewpoint temperature were estimated using empirical approaches.

Historical agricultural weather station data was used to estimate the spatial distribution of historical and projected avg monthly dewpoint depression and windspeed. Given the uncertainties and limited availability in future projections of humidity and windspeed, avg monthly dewpoint depression and windspeed were considered static for future periods. While there is considerable uncertainty in projecting future reference ET, estimation of reference ET for historical periods using the assumptions outlined above was shown to be robust when compared to agricultural weather station estimated reference ET.

Evaporative Demands

Uncertainties in estimated reservoir evaporation are largely centered on CRLE energy balance considerations, specifically heat storage. One important limitation of the CRLE model is its reliance on energy balance without considering the effects of windspeed on evaporation. However, one could argue that using an approach that heavily relies on windspeed and is therefore extremely sensitive to uncertainties in windspeed (i.e., the aerodynamic-mass transfer or combination approach), may actually increase evaporation uncertainty, especially under future climates where projections of near surface local scale windspeed estimates are extremely uncertain. The CRLE model also does not consider the impacts of reservoir inflow and outflow advection effects, which could have significant impacts on the energy balance.

It is significant that reservoir evaporation and net evaporation (i.e., evaporation minus precipitation) demands were estimated in terms of monthly rates based on historical avg reservoir depth and salinity. A more rigorous analysis would be required to model evaporation under predicted future reservoir conditions using dynamic reservoir depth. According to Morton et al. (1985), modeled evaporation by the CRLE model is generally not sensitive to changes in salinity, except for high levels of salinity in the range of 5,000 parts per million. It is also rather insensitive to changes in avg depths of less than five percent.

Municipal and Industrial (M&I) and Rural Domestic Demands

Uncertainties associated with M&I and rural domestic demands are related to the assumption that current use was unlikely to change significantly. Assuming increases in NIWR under future climate scenarios, outdoor use would likely increase. However, these uncertainties are not expected to have a significant impact given the relatively small contribution of M&I and rural domestic users to the total demand.

Risk Assessment

This risk assessment evaluates the implications of historical and future water supply and demand, detailed in the previous sections, on water management in the study area. A river and reservoir system model of the St. Mary and Milk Rivers was developed in RiverWare as part of the 2012 Basins Study (Reclamation 2012; Reclamation 2013) to evaluate water management upstream of the Milk River confluence with the Missouri River. This model was improved for this Basins Study Update (called the St. Mary and Milk Rivers planning model) and configured for simulations of multiple scenarios.

St. Mary and Milk Rivers Planning Model Configuration

Water management under each supply and demand scenario was simulated using the St. Mary and Milk Rivers planning model. The model was developed using the reservoir system modeling software platform RiverWare™. RiverWare is developed by the Center for Advanced Decision Support for Water and Environmental Systems at the University of Colorado at Boulder, with substantial support from Reclamation, the U.S. Army Corps of Engineers, and the Tennessee Valley Authority. RiverWare has been used by several Federal and State agencies across the western U.S. to support water resources planning and management (e.g., implementing the Truckee River Operating Agreement, optimizing daily operations of the Tennessee Valley for variety of uses, water supply planning and hydropower operations of the Columbia River by Bonneville Power Administration). Simulation results provide water managers with a basis for evaluating management risks given selected tolerances or thresholds for failure to meet management objectives.

The St. Mary and Milk Rivers planning model was originally developed for the 2012 Basins Study (Reclamation 2012) and was based on the previous Hydrologic River Operation Study System Basins Study Model. Documentation for the St. Mary and Milk Rivers planning model as well as a few updates following the 2012 Basins Study are detailed in Reclamation (2013). An overview of inflow locations to the model is provided on figure 60. Further updates to the model were completed in 2022, including:

- Addition of mass balance object to ensure mass balance is maintained for each reach and throughout the model.

- Fresno Reservoir minimum release rate was updated from 25 cfs to 45 cfs to account for minimum gate opening.

- Ungaged drainage area ratios were updated to calibrate ungaged inflows.

- Canal efficiencies were updated in accordance with the North-Central MT Regional Feasibility Study (Reclamation 2004).

Additional model improvements were made to better model the Fort Belknap Indian Irrigation Project (FBIIP) and Peoples Creek Irrigation Project (Reclamation 2022).

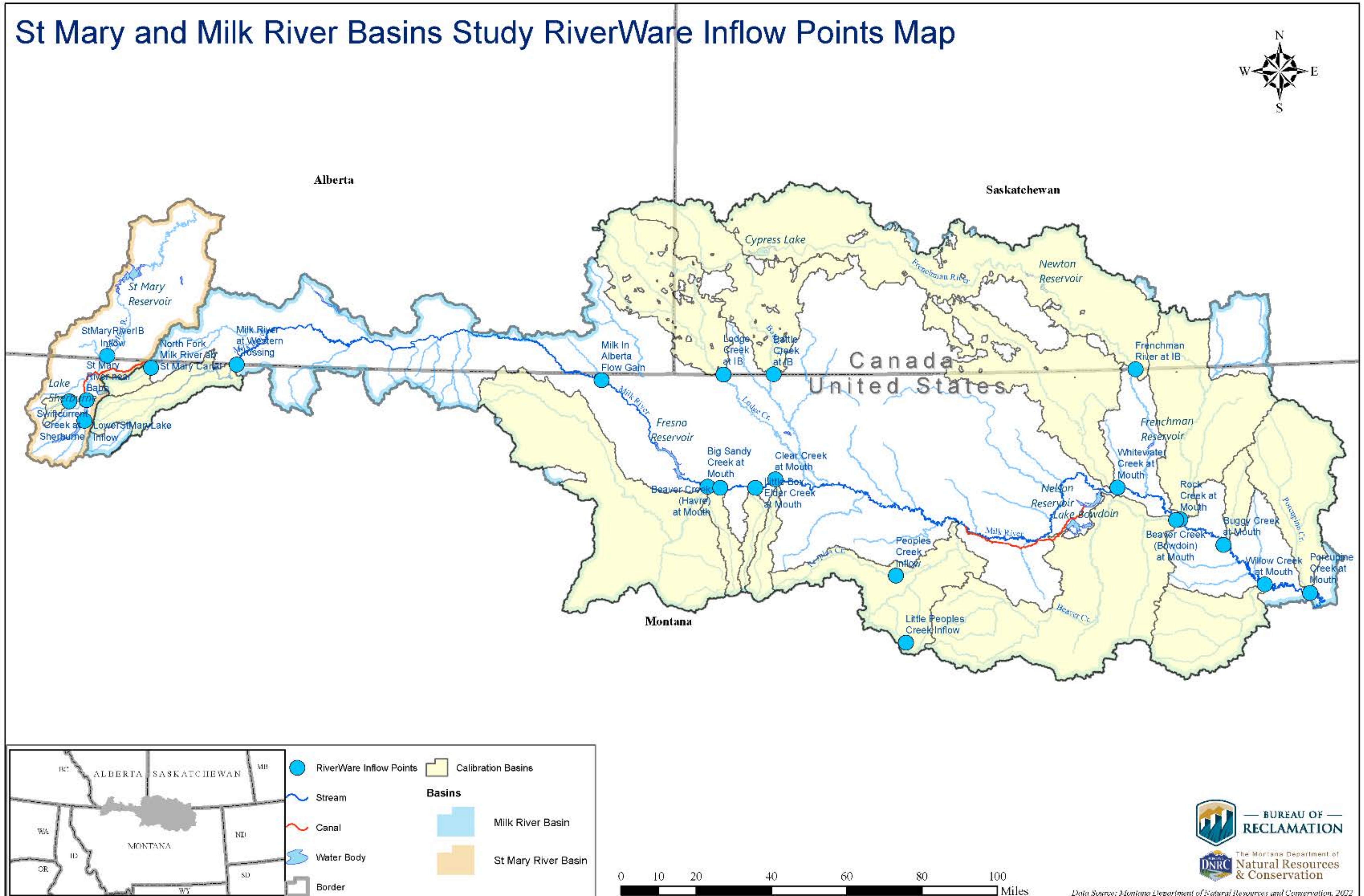

Figure 60.—St. Mary and Milk Rivers planning model inflow locations.

Risk Assessment Measures

The "Risk Assessment" section uses the historical and projected future water supplies and demands discussed in the previous sections along with a suite of measures to evaluate the current and future management risks in the St. Mary and Milk River basins. Additionally, it allows for the evaluation and comparison of adaptation strategies to potentially mitigate any identified imbalances in water supply and demand. The use of quantitative risk assessment measures facilitates a deeper understanding of potential future impacts on specific resources and objectives relevant to water management in the basin. Measures were identified in accordance with the Basins Study Directives and Standards (WTR 13-01 2016). They are based on input from stakeholders and resource managers in the basin and span five resource categories.
Risk assessment measures for each resource category are listed in table 19 and described in the following sections.

Table 19.—Summary of risk assessment measures

Measure category	Measure description	Location of analysis
Hydrologic responses	Change in annual flow volume	Table I-1: Streamflow gage locations
	Change in April-September flow volume	Table I-1: Streamflow gage locations
	Change in October-March flow volume	Table I-1: Streamflow gage locations
	Change in day of centroid of streamflow timing	Table I-1: Streamflow gage locations
	Change in end of month reservoir storage	Table I-2: Reservoir storage locations
	Change in monthly reservoir inflows	Table I-3: Reservoir inflow locations
Water deliveries	Change in end of water year (EOWY) reservoir storage	Table I-2: Reservoir storage locations
	Change in April 1 reservoir Storage	Table I-2: Reservoir storage locations
	Change in monthly depletions, depletion requests, and depletion shortages	Table I-4: Water users
	Change in annual depletions, depletion requests, and depletion shortages	Table I-4: Water users
Flood controls	Change in number of days above flood pool elevation	Table I-2: Reservoir storage locations
	Change in avg daily reservoir pool elevation	Table I-2: Reservoir storage locations
	Change in number of days streamflow exceeding active flood levels	Table I-1: Streamflow gage locations
Recreation	Change in unusable days at boat ramps	Table I-5: Reservoir boat ramp locations
Ecological	Change in daily streamflow	Table I-1: Streamflow gage locations
	Change in 7-day low and high streamflows	Table I-1: Streamflow gage locations

Hydrologic Responses

Hydrologic response measures were identified to quantify changes in the river system as simulated by the St. Mary and Milk Rivers planning model under future scenarios and paleohydrology scenarios relative to the historical reference period scenario. These risk assessment measures include changes in annual and seasonal streamflow, end of month reservoir storage, and the change in day of the flow centroid for streamflow (i.e., the date by which half of the annual flow volume on a water year basis has flowed past a gauge location). Annual flow volume is computed based on water year. Streamflow and reservoir storage locations at which these measures were computed are listed in appendix I in table I-1 (streamflow locations) and table I-2 (reservoir storage locations).

Water Deliveries

Evaluating potential impacts of future water supply and demand conditions on water deliveries provides information on how Reclamation’s ability to deliver water to its customers may change. Risk assessment measures include irrigation water demands, deliveries and shortages, end of September reservoir storage (also called EOWY storage), April 1 reservoir storage (reservoir storage at the beginning of the irrigation season), and April to September (irrigation season) reservoir inflows. Water shortages for irrigation are defined as depletion shortages: the difference between the amount of water that an irrigated crop would deplete, through the process of ET, for optimal growth and production (depletion request, water demand), minus the amount of water the crop is modeled to deplete (actual depletion or deliveries). Because the reservoirs in the St. Mary and Milk River basins provide water supply primarily for irrigation and generally do not store water intended for use over multiple years, April 1 reservoir storage and April to September reservoir inflows are a relevant measure of a reservoir’s ability to meet irrigation demands. Locations at which water demands, deliveries, and shortages are summarized are listed in table I-3 (water users). Reservoirs at which storage is summarized are listed in table I-2.

Flood Control Operations

Lake Sherburne and Fresno Reservoir provide flood control benefits by storing water during the peak runoff period. The flood control performance measure used to evaluate historical and future flood risks is the avg number of days per year where the flood pool is exceeded at each of these reservoirs. Changes in days above flood levels at specified streamflow locations were also evaluated. The associated flood pool elevation thresholds are listed by reservoir in table I-2.

Recreation

Lake Sherburne, Fresno Reservoir, and Nelson Reservoir provide recreation to the region. Both Fresno and Nelson reservoirs provide access via boat ramps, however, for this study only Fresno's ramps were evaluated. The recreation measure evaluated for this study is the avg number of days during months April through October that reservoir pool elevations are below boat ramp access thresholds. The reservoirs and boat ramps evaluated are listed in table I-5.

Ecological Resources

Under Reclamation's Directives and Standards for Basin Studies (WTR 13-01 2016), the ecological resource measure category encompasses: fish and wildlife, listed or candidate species under the ESA, flow and water dependent ecological resiliency, and water quality. Because the scope of this study does not include detailed water quality modeling or quantitative analysis of impacts to fish and wildlife, attention is focused on streamflow-related measures that are known to be related to water quality and/or fish and wildlife habitat conditions. Risk assessment measures include:

- Annual maximum and minimum 7-day streamflow.
- Avg daily streamflow.

Risk assessment measures for annual maximum and minimum 7-day streamflow are calculated as the highest and lowest 7-day avg streamflow in each year, respectively. These measures are two of the Indicators of Hydrologic Alteration (Richter et al. 1996) that are commonly used in developing or evaluating environmental flow recommendations. Locations for the annual maximum and minimum 7-day streamflow and streamflow distributions are listed in table I-1.

Water Management Implications

This section summarizes the historical and projected future risk for the water supply in the St. Mary and Milk River basins using the risk assessment measures identified in the previous section. Results are used to evaluate implications of projected future changes on water management risks throughout the basin, including changing water supply and demand.

Hydrologic Responses

The following section summarizes hydrologic responses in the St. Mary and Milk River basins under paleohydrology and future scenarios relative to the historical reference period scenario.

As discussed in the proceeding "Water Supply Assessment" section, all future scenarios developed through this study suggest that climate will continue to warm. Subsequently, snowpack in the St. Mary and Milk River basins is generally projected to decrease with warming temperatures. Projected changes in avg annual streamflow are dependent on changes in annual temperature and precipitation. Projected changes in precipitation are more variable, and annual avg precipitation may be less than or greater than the historical reference period. Seasonal streamflow volume is also expected to change with climate and be affected by decreasing snowpack.

Projected changes in avg annual streamflow volume, avg seasonal streamflow volumes (for April to September and October through March), and avg annual peak streamflow timing were evaluated at 17 USGS gage locations throughout the study area (Streamflow locations are listed in table I-1).

For the 2020s, annual streamflow volume is generally projected to increase from the historical reference period scenario, except for the HD scenario, which shows mostly declining annual avg streamflows with some small increases in St. Mary River headwaters and at WWCMO (figure 61; refer to figure 6 for location of Whitewater Creek). The largest increases in streamflows from the historical reference period scenario are shown in the HW scenario. For the drier scenarios (WD and HD) the projected change in avg annual streamflow, not including Whitewater Creek, is between a 17 percent decrease and a 53 percent increase. Projected change for the CT scenario indicates a range of 6 percent decrease to a 68 percent increase. For the wetter scenarios (WW and HW) the projected change is between a 14 percent decrease to an increase of over 96 percent, indicating a larger range of variability in flow changes for the wetter scenarios. Evaluation of changes in annual streamflow volume on a percentage basis allows for comparison across sites with a wide range of total annual flow volumes. Tributary sites with a large percentage of change, such as Whitewater Creek, may not have high annual streamflow and therefore may not be big contributors to flow in the Milk River mainstem. Streamflow changes for the 2080s show similar results; however, the HD and HW see additional avg annual streamflow declines at downstream gage locations.

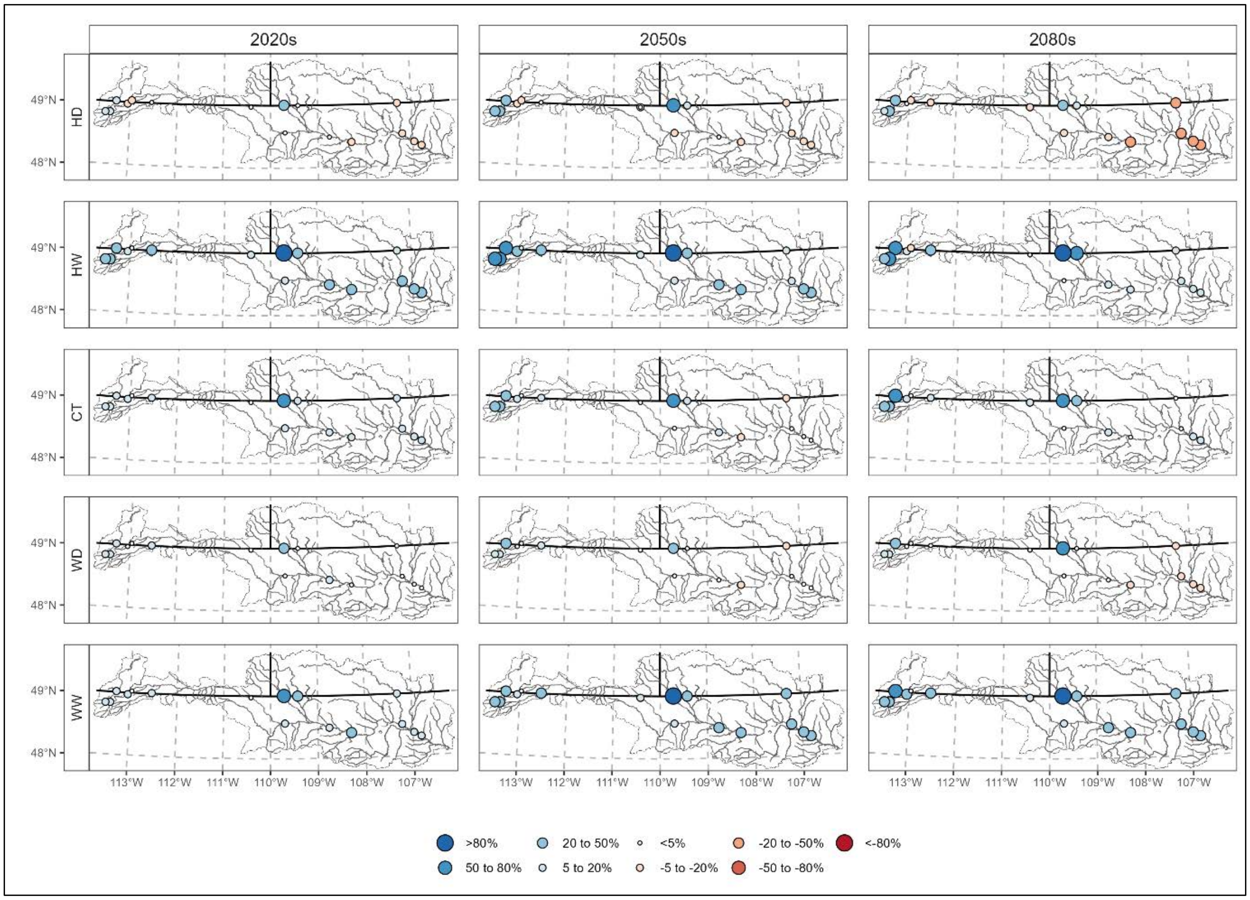

Figure 61.—Projected changes in water year annual flow volume at 17 USGS gage locations for the 2020s, 2050s, and 2080s (percent).

Changes in seasonal streamflow volumes were evaluated over April to September (figure 62) and October to March (figure 63). October–March volume is indicative of the period where historically a large proportion of precipitation in the mountains was stored in snowpack, while April–October volume is indicative of water availability over a typical irrigation season. Future scenarios indicate that the range of projected changes in October–March streamflow volume (figure 63) is likely to be larger than the range of annual streamflow volume changes (see figure 61). Greater projected increases in October–March streamflow volume coincide with a greater portion of precipitation falling as rain versus snow. Some future scenarios, particularly the WD and HD show decreases in flow volume at a few downstream locations during these months, but the reductions are small compared with the projected increases in other scenarios. For April–September (irrigation season) streamflow volume (figure 62) at the upstream locations show small increases compared to the annual and October to March streamflow volume changes; and downstream locations, except for the wetter scenarios, see larger declines in streamflow, indicating less water availability at downstream locations in the irrigation season.

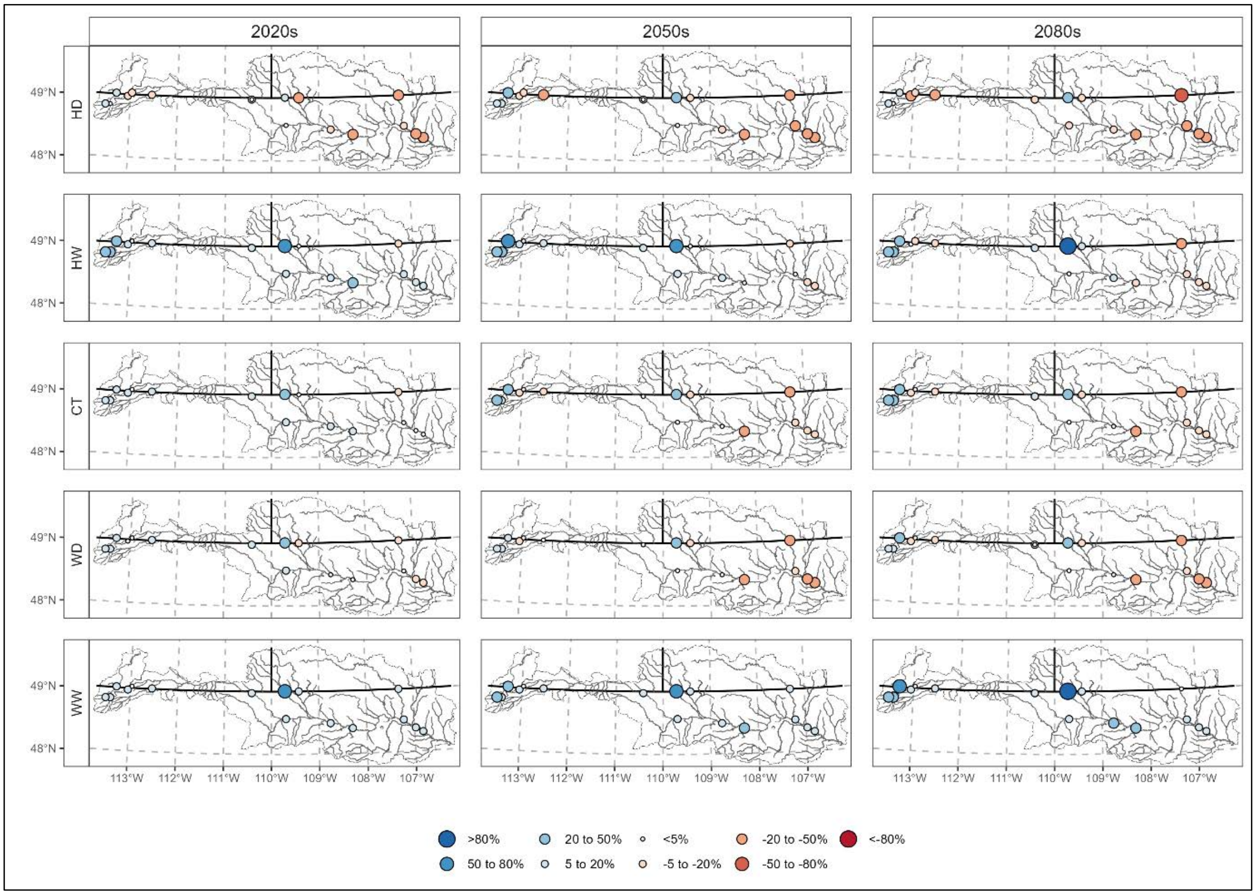

Figure 62.—Projected changes in average April–September flow volume at 17 USGS gage locations and for the 2020s, 2050s, and 2080s (percent).

Decreased snowpack storage in the future with similar or more precipitation suggests that more precipitation will come as rain and will not be stored as snowpack. Changes in seasonal timing of streamflows, quantified as the change in the date of the centroid of flow timing, were also evaluated. In snow dominated basins, this measure is tied to runoff from snowpack and provides information about whether more runoff is likely to occur earlier or later in the water year. A positive shift indicates more runoff occurs later in the year, while a negative shift indicates more runoff occurs earlier in the year. Streamflow locations for which this measure was computed are illustrated on figure 64 and listed in table I-1.

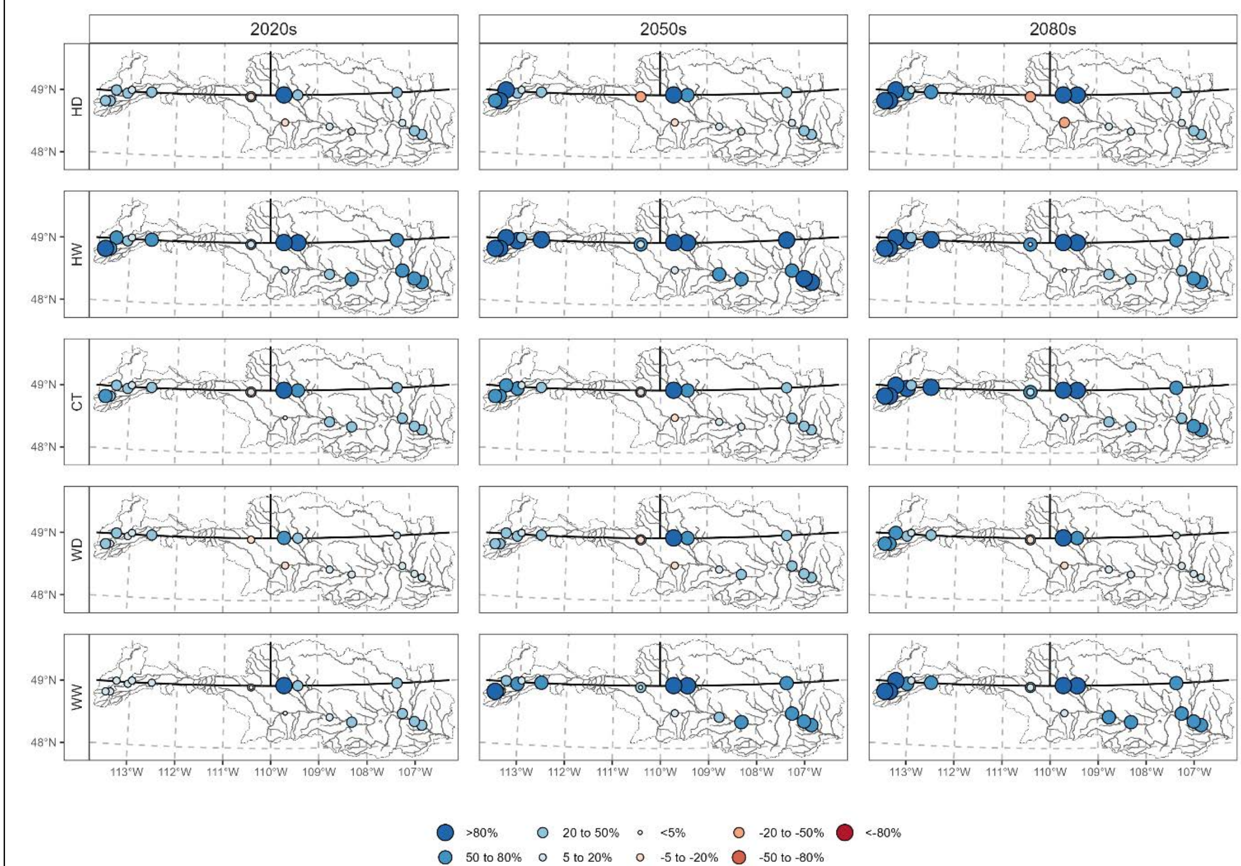

Figure 63.—Projected changes in average October-March flow volume at 17 USGS gage locations and for the 2020s, 2050s, and 2080s (percent).

For all periods, and all scenarios, projected changes for all but a few streamflow locations show a shift towards earlier flows (figure 64). The WW scenario presents the least extreme change in median flow timing, ranging from 16 days earlier to 25 days later. The drier scenarios show shifts in median scenarios from 49 days earlier to 13 days later.

Overall, future scenarios suggest that flow volume from October - March may increase, seasonal flow volumes during the irrigation season April – September may decrease at downstream locations, and the timing of seasonal runoff will shift toward earlier in the year.

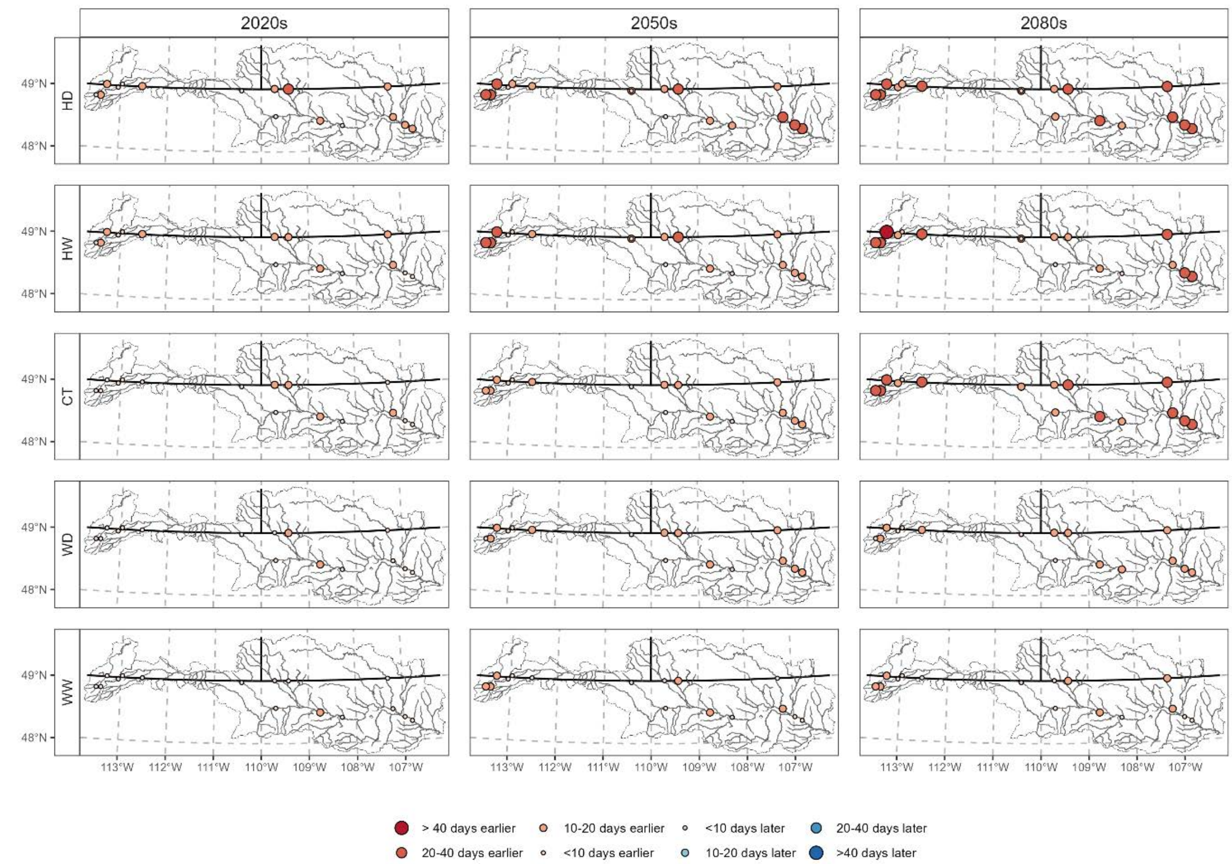

Figure 64.—Projected changes in the date of the centroid of inflow at 17 USGS gage locations for the 2020s, 2050s, and 2080s (in number of days).

Projected changes are also evaluated in the context of paleohydrology scenarios for select streamflow locations. Figure 65 summarizes projected changes in annual and seasonal streamflow volumes at the St. Mary River at International Boundary gage (USGS ID 05020500) according to future scenarios. Similar figures for other locations are included in Appendix J. Figure 65 also includes annual and seasonal streamflow volumes during significant paleo events compared to the historical reference period. For brevity, only five paleohydrology drought event scenarios, which are detailed in table 20, are presented in the following figures. Annual and seasonal averages for the historical reference period and future scenarios are calculated over the full 35-year simulation period, whereas annual and seasonal averages for the paleo events are only calculated over the drought period noted in table 20.

Table 20.—Summary of presented paleohydrology drought events subset

Location	Event	Rank	Drought abbreviation*	Drought year start	Drought year end	Drought length
MRWIB	largest instrumental average annual deficit	NA	LAD Inst	1931	1946	16
	historical drought 1	NA	Hist 1	1996	2009	14
	historical drought 2	NA	Hist 2	1928	1936	9
	largest average annual deficit	1	LAD 1	1747	1748	2
	largest average annual deficit	2	LAD 2	1602	1607	6
	largest average annual deficit	3	LAD 3	1622	1623	2

* Abbreviations in this column stand for the full descriptions in the "Event" column plus any modifiers in the "Rank" column and will be used in various figures in this report.

Future scenarios indicate a greater range of changes in annual streamflow volumes at the St. Mary at International Boundary gage than do the paleohydrology drought events when compared to the historical reference period (figure 65). All future scenarios showed an increase in annual and seasonal streamflow, with the largest increase in the HW scenarios for all future periods. Annual and seasonal streamflow also increased from the 2020s to 2080s for all future scenarios. For the paleohydrology drought event scenarios (LAD drought events), annual and seasonal streamflow changes were smaller and more variable than the more recent historical drought events. The two droughts that showed lower avg annual streamflow volumes in relation to the historical reference period scenario, the LAD based on instrumental data (LAD Inst) and the 3rd ranked LAD event (LAD 3), showed a higher percent difference in streamflow during the April to September season compared to the October to March season. However, seasonal results for paleo events should be evaluated more critically, as the paleo scenarios were developed based on flow distributions from historical analog years selected based on ranked annual values ("Appendix F. Paleo Event Scenario Development").

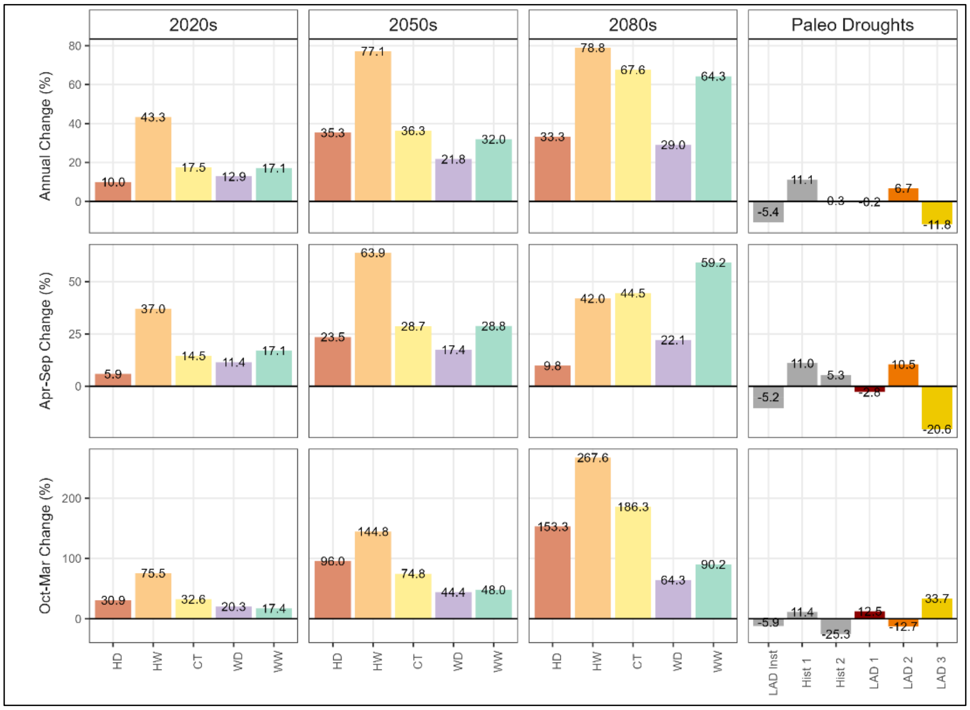

Figure 65.—Projected changes in average annual and seasonal streamflow volume in the St. Mary River at the international boundary gage (USGS ID 05020500) based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

At the Milk River at Eastern Crossing gage (figure 66), future scenarios indicate the greatest magnitude of change from the historical reference period scenario in October to March streamflow volumes, indicating a shift towards more rain events during the winter period and more rapid snowmelt. These increases in October to March streamflow volumes continue to increase across the future periods with the largest increases in the 2080s period. Changes in annual and April to September streamflow volumes, however, decrease across the future period, with declines in April to September streamflow volumes in all but the WW scenario in the 2080s period. Results at the Milk River at Nashua (figure 67) display similar behavior to the Milk River at Eastern Crossing streamflow changes. However, Milk River annual and seasonal streamflow volumes at the Nashua gauge during the presented paleo droughts, with exception of the 'Historical 2' (Hist 2) drought, are significantly lower than the historical and future scenarios, likely due to overall lower water supplies during these drought events.

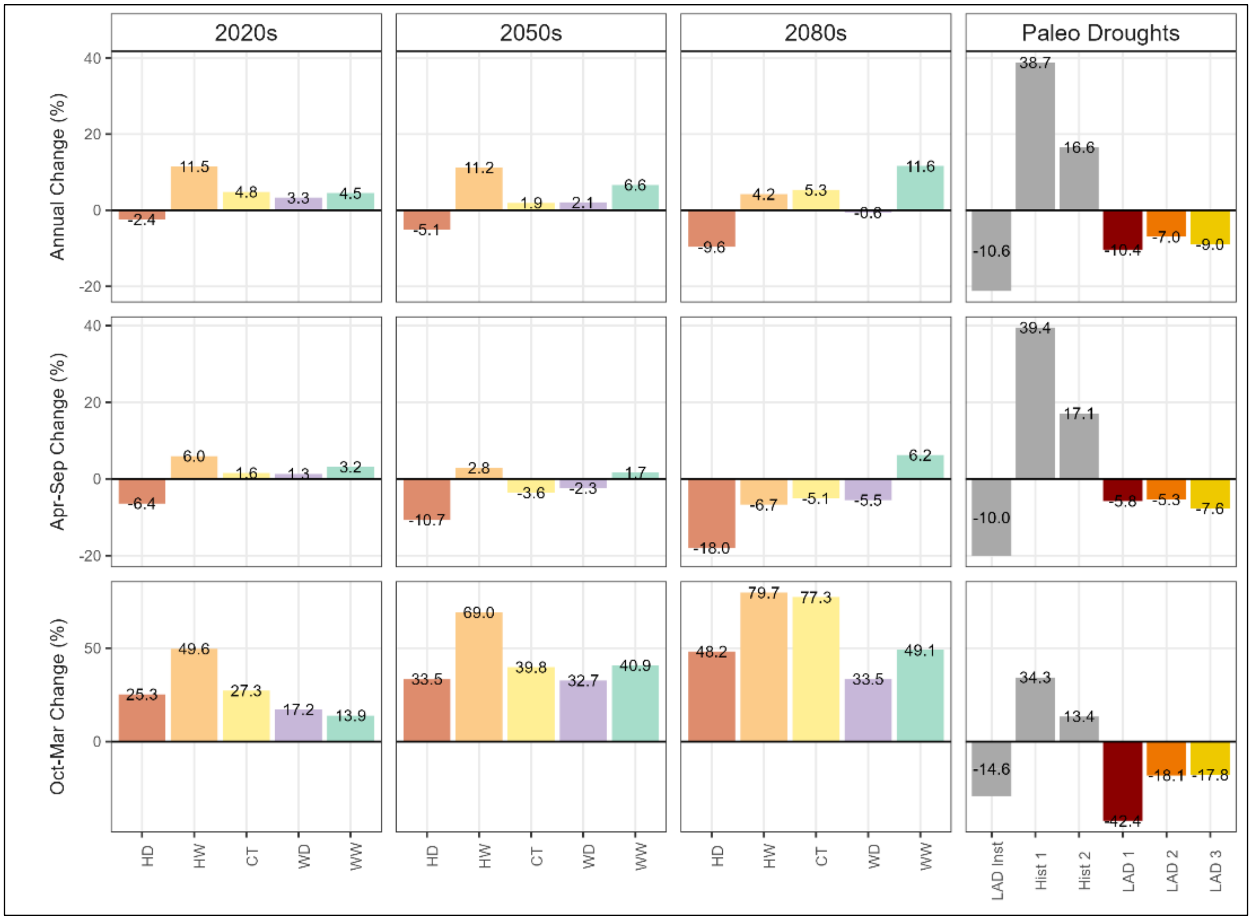

Figure 66.—Projected changes in average annual and seasonal streamflow volume in the Milk River at Eastern Crossing gage (USGS ID 06135000) based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

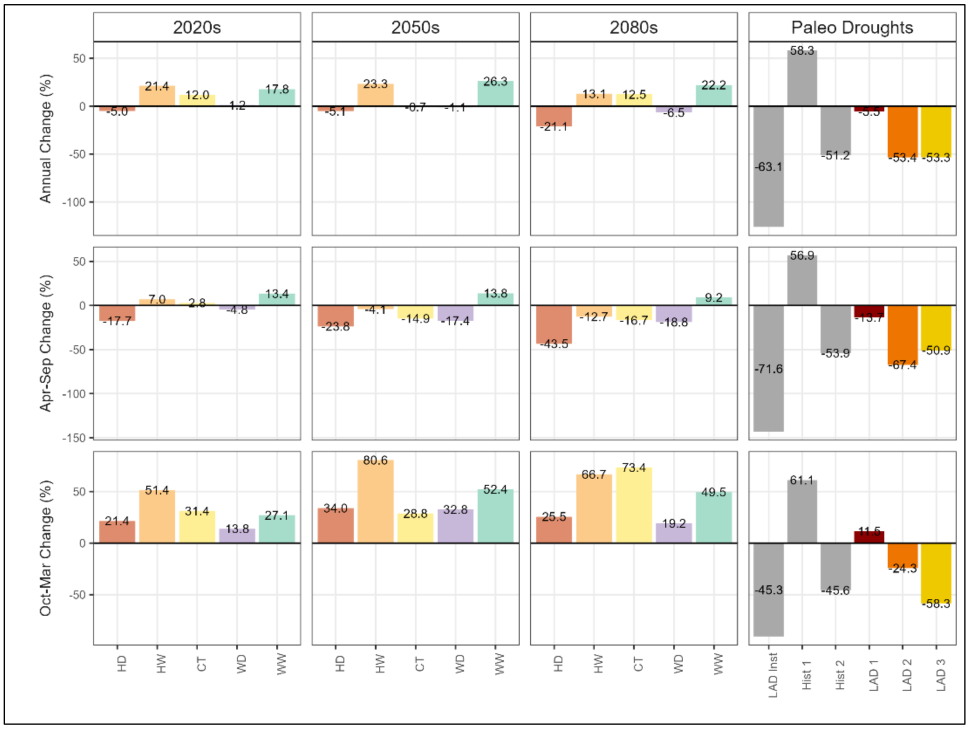

Figure 67.—Projected changes in average annual and seasonal streamflow volume in the Milk River at Nashua based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

Changes in hydrology will affect reservoir storage. This is especially true if operating policies are not adapted for these changes. This risk assessment presents hydrologic responses without changes in operating policies to highlight potentially needs for operating adaptations. Figure 68 illustrates the potential future shifts in timing and volume of reservoir storage and inflow at Lake Sherburne. Similar figures are provided in Appendix J for other reservoirs in the study area. In the top panels, avg monthly storage is presented for each hydroclimate scenario, including the historical reference period scenario (black line), projected future scenarios (colored lines), and paleohydrology drought events (light grey band). Under current operating policies, Lake Sherburne may, on avg, fill earlier in the year and be evacuated earlier under all future scenarios with and without paleohydrology, particularly under the hotter scenarios with earlier snowmelt. Future scenarios suggest that future conditions may be outside the range of the paleohydrology events experienced in the distant past. It should be noted that future scenarios were summarized over the entire future time horizon and not focused on droughts per se, while drought events were evaluated only over the duration of the drought, which provides some reasoning for the statement above. Additionally, the projected range of storage under future scenarios is broader than the historical reference period scenario and paleohydrology events, particularly in the early spring months when management decisions highly influence the ability to meet the needs of water users through the irrigation season. With the exception of the Historical Drought, the presented paleohydrology droughts are defined by the LAD drought on the Milk River which may not indicate declines in flows along the St. Mary River or Swiftcurrent Creek which flows into Lake Sherburne.

Changes in Lake Sherburne end of month storage and avg monthly inflows are presented in the top and middle row of figure 68, respectively. These figures illustrate the earlier timing of peak flows into the reservoir as well as rapid and earlier draining of the reservoir during the irrigation season. Changes in median inflow timing, presented at the bottom of figure 68, further illustrates the shift in inflow timing, with all future scenarios showing earlier median inflow timing which shifts even earlier from the 2020s period to the 2080s period for all future scenarios.

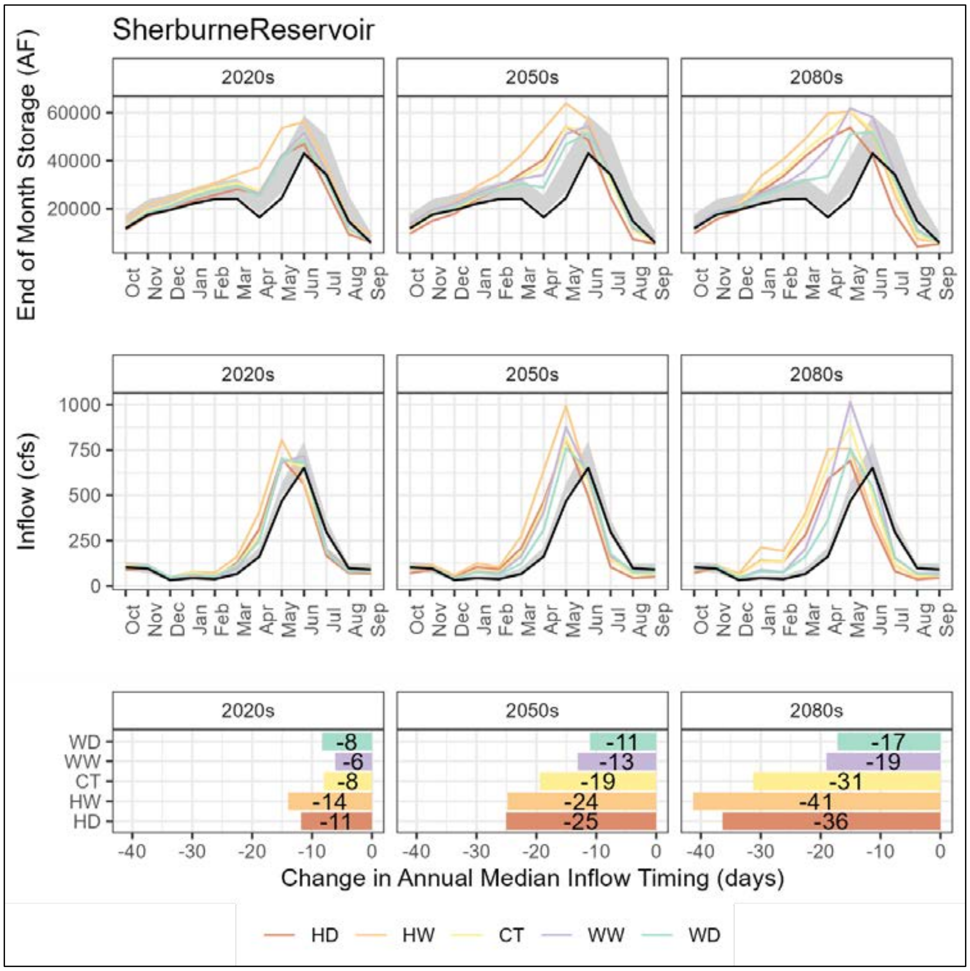

Figure 68.—Summary of average end of month storage (top), average monthly inflow (middle), and change in annual median inflow centroid (days) to Lake Sherburne.[6]

[6] Results are presented for the historical scenario (black line), future scenarios for the 2020s, 2050s, and 2080s (colored lines and bars), and paleohydrology drought events (light grey ribbon).

Water Deliveries

Measures related to water deliveries were defined as avg EOWY storage (September 30) and April 1 reservoir storage (beginning of irrigation season), reservoir inflows from April to September (during irrigation season), as well as monthly and total annual water demands, deliveries, and shortages, defined as the difference between demands and actual water consumption.

The EOWY storage discussion focuses on Lake Sherburne (figure 69) and Fresno Reservoir (figure 70) which respectively represent a reservoir closer to the headwater of the St. Mary River and a downstream reservoir on the Milk River closer to the irrigation demands. Results for additional reservoirs are included in Appendix J. Figure 69 and figure 70 show the difference between future and paleo scenarios compared to the historical reference period scenario: projected future climate scenarios are shown as colored bars in the left panels and paleohydrology drought events in the right panels.

At Lake Sherburne (figure 69), April 1 storage and April to September inflows increase for all future scenarios, indicating an increase in water supply availability from the reservoir. Smaller increases, or a small decrease in the case of the HD scenario, in the EOWY storage indicate higher demands on the reservoir and little carryover from year-to-year. Paleohydrology droughts show variable changes at Lake Sherburne.

Fresno Reservoir results vary significantly from Lake Sherburne. EOWY storage decreases for all scenarios except the HW 2020s and by as much as 46 percent for the 2080s HD scenarios. EOWY storage declines become greater over time as irrigation demands increase in the future scenarios. However, despite lower EOWY reservoir levels, April 1st storage increases under all future scenarios, with exception of the 2080s HD scenario which has the largest decrease in streamflow. However, despite higher storage at the beginning of the irrigation season, for most future scenarios, Fresno Reservoir inflows during the irrigation season (April to September) decline, reducing the total amount of available water for irrigators. Similarly, Fresno EOWY storage, the declines in April to September inflows become greater over time except for the WW scenario. The LAD Inst and LAD 2 paleohydrology droughts show lower April 1st storage and April to September inflows in comparison to the historical reference period scenario, which resulted in lower in EOWY storage at Fresno.

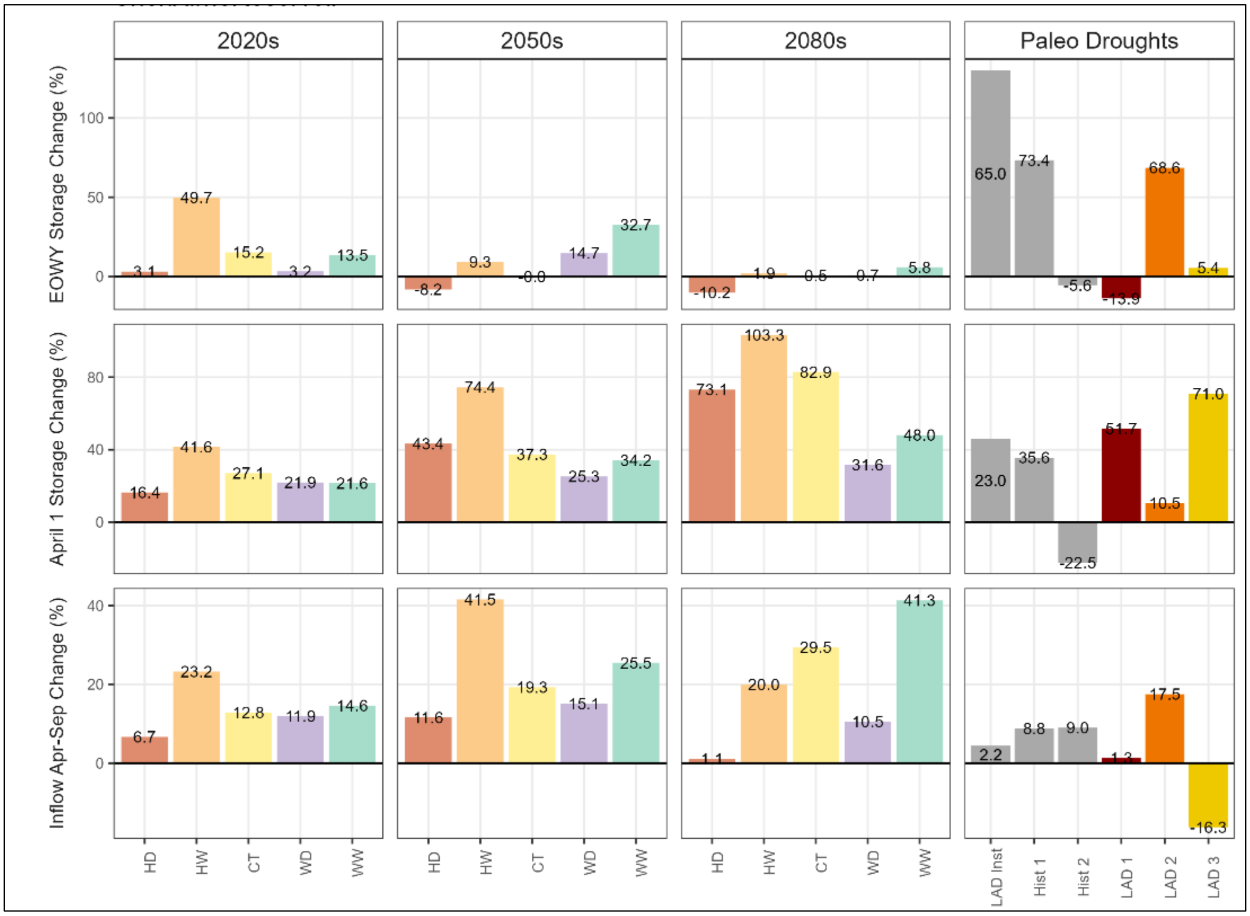

Figure 69.—Projected changes in end of water year (September) storage, April 1 storage, and April to September Inflows at Lake Sherburne based on projected future climate scenarios for three future time horizons and extreme paleo event scenarios.

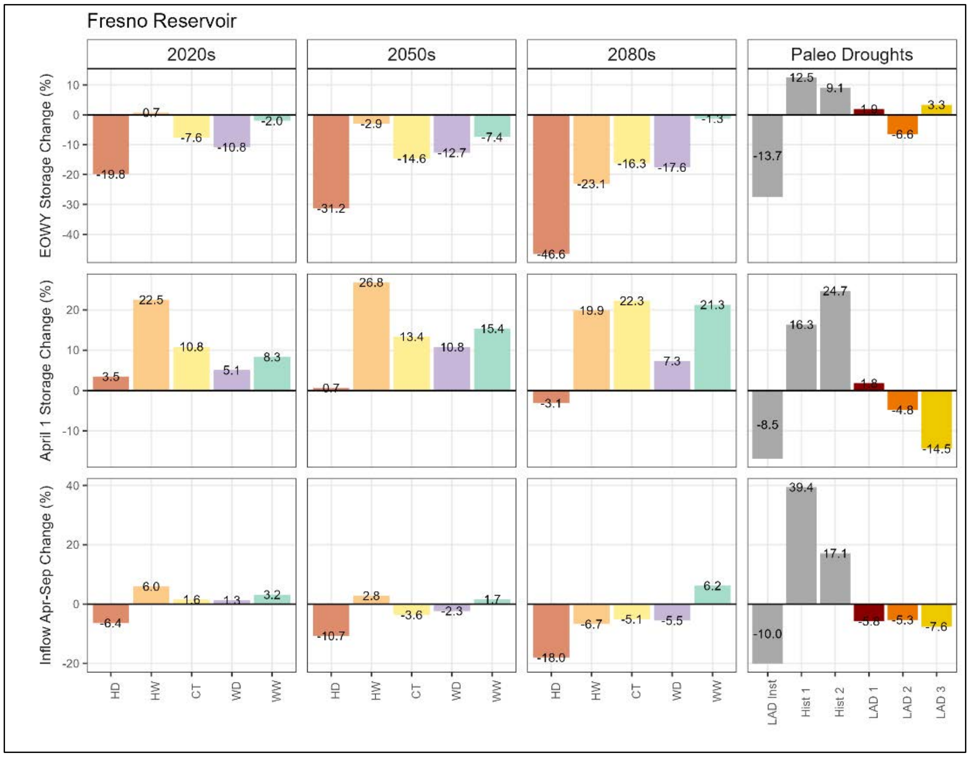

Figure 70.—Projected changes in end of water year (September) storage, April 1 storage, and April to September inflows at Fresno Reservoir based on projected future climate scenarios for three future time horizons and extreme paleo event scenarios.

Figure 71 summarizes flow volume changes across for the St. Mary Canal, which delivers a portion U.S.' share of the St. Mary River to the Milk River for uses downstream. The top row panels show changes in avg annual flow volume for each future period and significant paleohydology droughts, the middle and bottom rows show changes in seasonal flow volumes. All future scenarios, with the exception of the 2020s HW, show declines in avg annual flow volumes and April to September seasonal flow volumes. Declines increase in magnitude from the 2020 to 2080s periods for all scenarios. October to March seasonal flows, opposingly, show increases in flow volume, however, most flow in the St. Mary canal occurs during the April to September period, making changes to October to March less impactful on the annual flow volume. Results for the significant paleohydrology events show variable results as the paleohydrology drought events are defined by Milk River flows. However, during the LAD Inst drought, the October-March flows were 49 percent lower over the course of this drought compared with the avg historical flows.

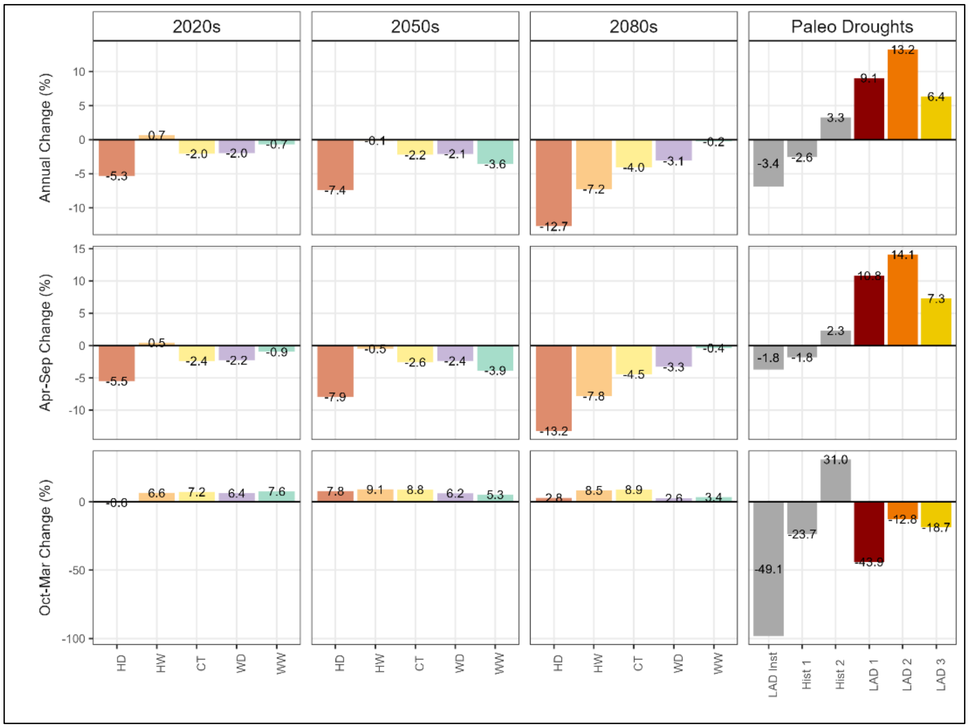

Figure 71.—Projected changes in average annual and seasonal streamflow volume across the St. Mary Canal based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

The avg annual depletions (consumptive use), depletion requests (demand), and depletion shortages (demand shortages) under future scenarios and paleohydrology droughts for Milk River Project users are presented on figure 72. All future scenarios show an increase in annual avg depletion requests, depletions, and depletion shortages for Milk River Project irrigators across all future time periods. Hotter scenarios, HD and HW, had the largest increases in depletion requests due to increased crop demands. The wetter scenarios, HW and WW, showed the largest increases in avg annual depletions; however, the differences between projected future and historical depletion requests are less than the differences in depletions, indicating that the water supply is not able to keep up with increasing demands. Subsequently, the hotter scenarios, HD and HW, show the largest increases in depletion shortages for all future scenarios and increasing across future periods. The LAD Inst and LAD 2 paleohydrology droughts also show greater depletion shortages compared to the historical reference period scenario; however, unlike the future scenarios where increases in depletion shortages were driven by increases in demand, the LAD Inst drought was driven by decreases in depletions indicating a lack of available water supply regardless of increasing irrigation demands.

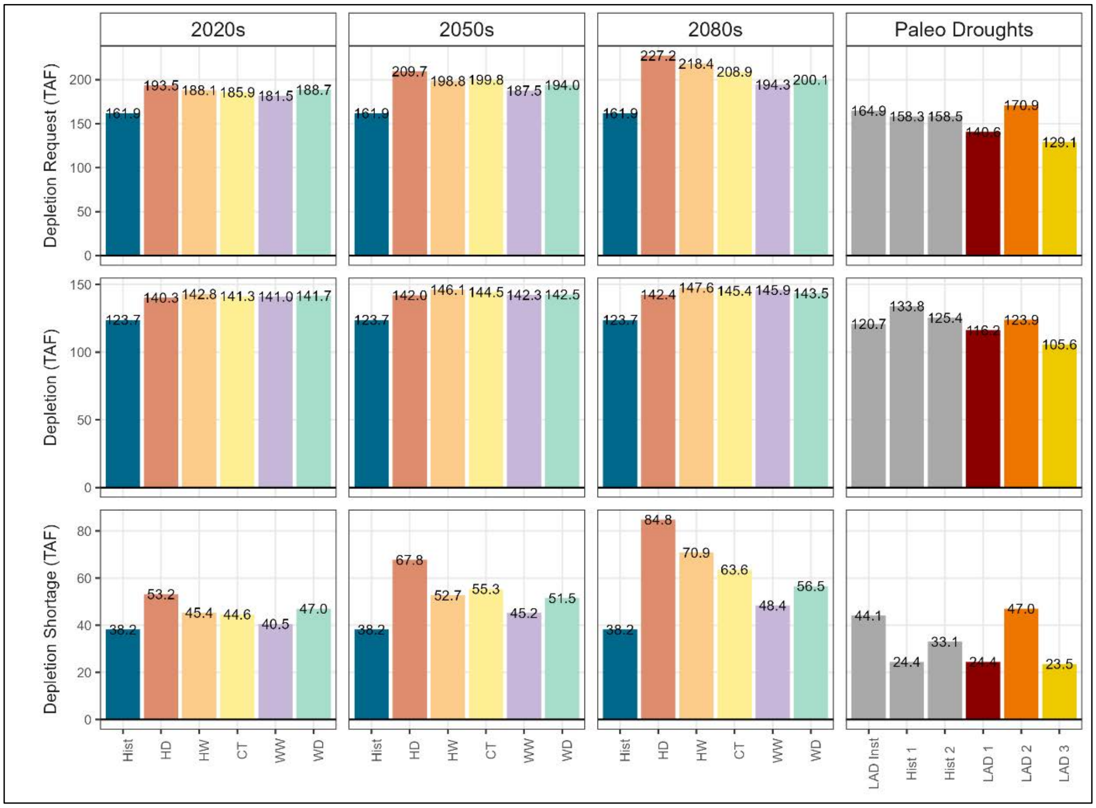

Figure 72.—Historical and projected depletions, depletion requests, and depletion shortages for Milk River Project irrigation water users.

Figure 73 provides avg monthly consumptive use (depletions), user demand (depletion requests), and demand shortages (depletion shortages) under future scenarios for all irrigation water users. Bar plots are color coded by their respective period and the bar plot range shows the span of the different scenarios with the period. Consumptive use increases most significantly in the early irrigation season months, April to June, with variable increases in peak summer months July and August. A similar pattern is observed in User Demands, indicating that climate conditions, specifically higher temperatures, are resulting in increased early season irrigation demands. Consumptive use below the historical level is likely due to depleted water supplies from earlier season increases irrigation demands as well as decreases in irrigation streamflows.

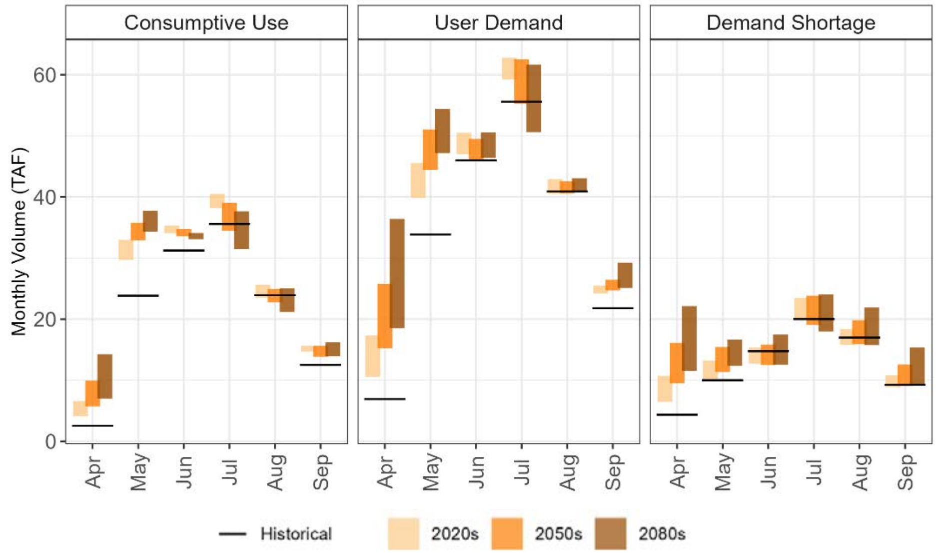

Figure 73.—Total monthly consumptive use (depletions), user demand (depletion requests), and demand shortage (depletion shortages). Results are displayed as ranges of the five future climate scenarios for each of the future periods, 2020s, 2050s, and 2080s.

Flood Control Operations

Two reservoirs in the study provide flood control benefits: Lake Sherburne and Fresno Reservoir. These reservoirs provide flood control benefits by storing water during the peak runoff period. Figure 74 presents projected changes in the avg number of days per year that Lake Sherburne exceeds the top of active conservation elevation which corresponds with the spillway crest elevation. Figure 75 presents the projected avg number of days per year that Fresno Reservoir is above the Top of Active Conservation and within the flood pool, thereby crossing the threshold into the Section 7 flood control operations with U.S. Army Corps of Engineers. Finally, figure 76 presents the projected avg number of days per year that Fresno Reservoir is above the Top of Joint Use elevation which corresponds with the spillway crest elevation.

For the Fresno reservoir, most future scenarios project fewer days where the pool elevation is within the joint use space. Figure 78, which presents avg daily Fresno pool elevations, shows that the Fresno pool elevation often occupies this joint use space during the summer months to provide water for irrigators when space is not needed for flood operations. For most future scenarios, except the WW scenario, the number of days within the joint use space declines from the 2020s through the 2080s. Similarly, most future scenarios project fewer days above the top of joint use elevation.

The number of days per year that Lake Sherburne is above the flood pool elevation increases for all future scenarios and across all periods. This increase is due to peak flow timing in the future scenarios leading to higher pool elevations between April and July (figure 77) increasing the likelihood that snow melt events will raise pool elevation above the top of active conservation elevation.

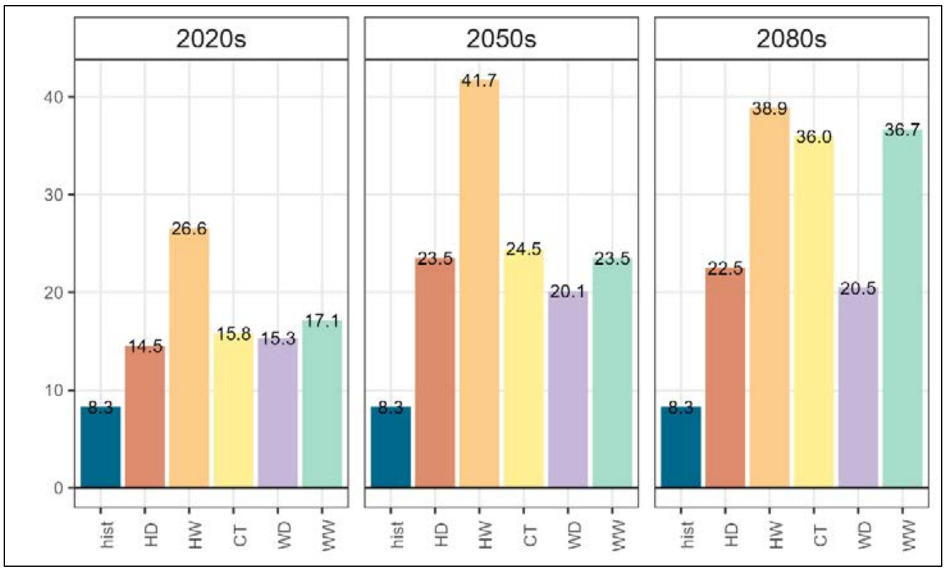

Figure 74.—Average number of days per year above Top of Active Conservation Elevation (4,788 ft) for Lake Sherburne.

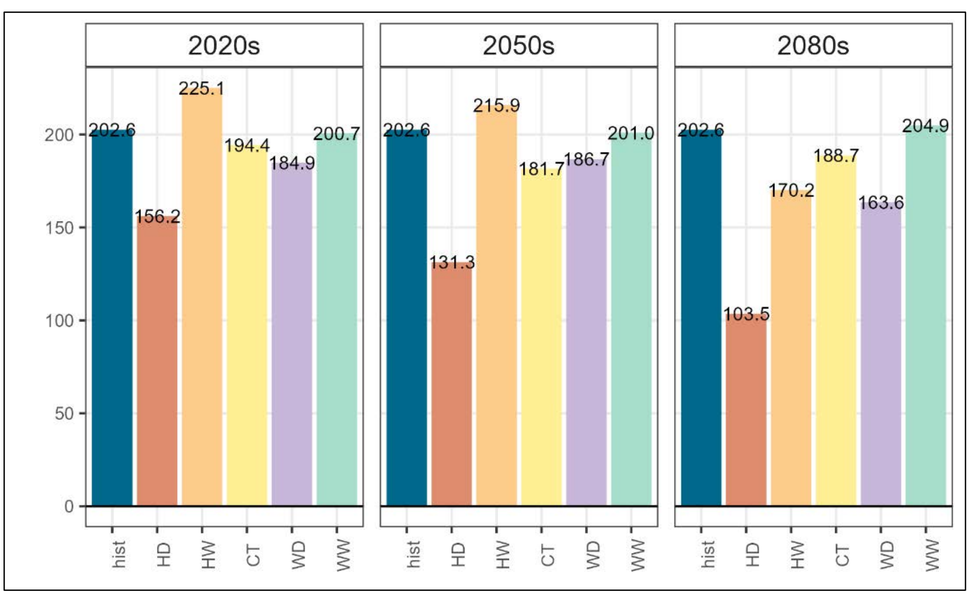

Figure 75.—Average number of days per year above Top of Active Conservation Elevation (2,568 ft) for the Fresno Reservoir.

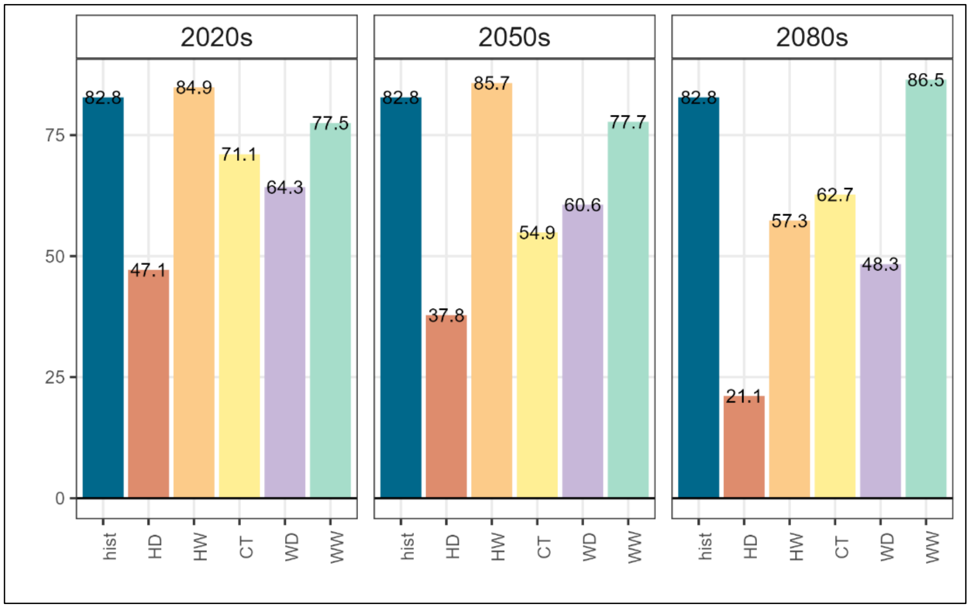

Figure 76.—Average number of days per year above top of joint use elevation (2,575 ft) for the Fresno Reservoir.

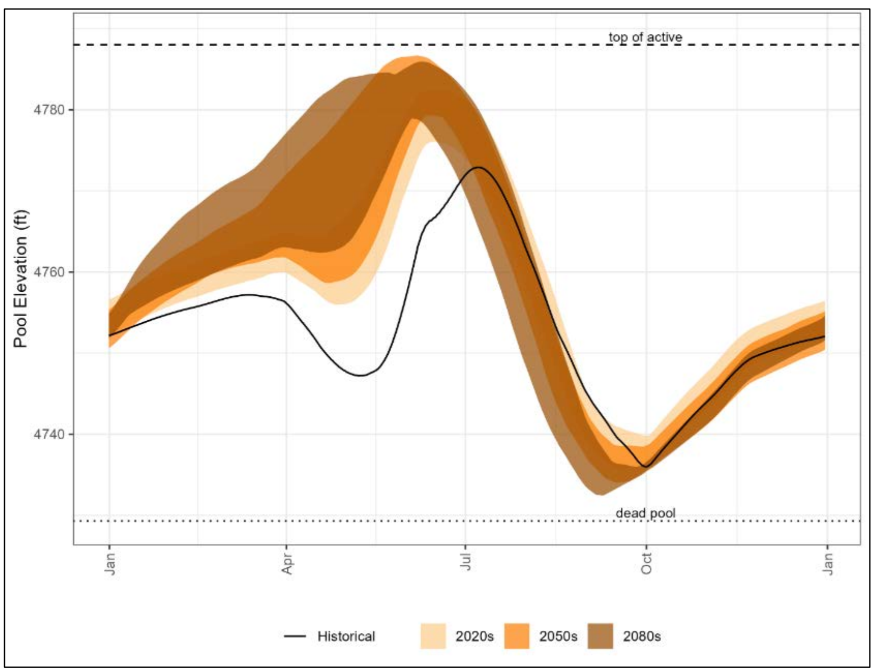

Figure 77.—Lake Sherburne average daily pool elevation. Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

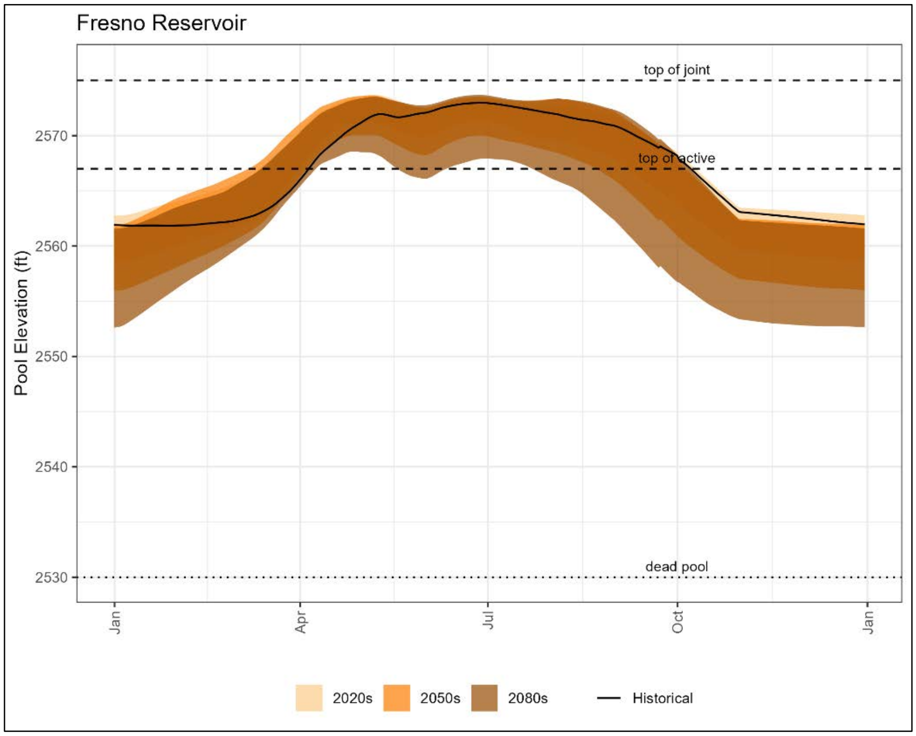

Figure 78.—Fresno Reservoir average daily pool elevation. Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

Changes in the number of days above flood levels at 7 USGS gages along the Frenchman, Milk and St. Mary Rivers are presented in table 21. Only one location showed an increase in flooding potential, the St. Mary at International Boundary gage. At this gage location, future scenarios see an increase in the number of active, flood, moderate, and major flood levels for all scenarios, up to an increase of almost two days per year, on avg, for the HW scenario.

Table 21.—Days above flood levels at USGS gage flow locations and the percent change from the historical reference period*

Gage	Flood level	Historical	HD 2050s		HW 2050s		CT 2050s		WD 2050s		WW 2050s	
		Days	Days	% Change	Days	% Change	Days	% Change	Days	% Change	Days	% Change
FRRIB**	Above active	1.2	0.0	-97.6	0.2	-83.3	0.0	-100.0	0.1	-92.9	1.0	-16.7
	Above flood	0.5	0.0	-100.0	0.0	-100.0	0.0	-100.0	0.0	-100.0	0.1	-82.4
Milk River at Juneberg Bridge	Above active	1.9	0.0	-100.0	0.3	-85.3	0.0	-100.0	0.2	-89.7	0.7	-63.2
	Above flood	0.9	0.0	-100.0	0.1	-93.3	0.0	-100.0	0.0	-100.0	0.1	-83.3
	Above moderate	0.1	0.0	-100.0	0.0	-100.0	0.0	-100.0	0.0	-100.0	0.0	-100.0
	Above major	0.0	0.0	-	0.0	-	0.0	-	0.0	-	0.0	-
Milk River at Tampico	Above active	5.4	1.2	-78.2	2.5	-54.3	0.8	-85.1	0.9	-83.5	3.9	-27.7
	Above flood	4.0	0.3	-92.9	1.0	-75.2	0.0	-100.0	0.2	-94.3	2.2	-46.1
	Above moderate	3.3	0.1	-95.7	0.7	-79.5	0.0	-100.0	0.2	-94.0	1.5	-53.8
	Above major	0.0	0.0	-	0.0	-	0.0	-	0.0	-	0.0	-
Milk River near Dodson	Above active	1.5	0.2	-86.3	0.3	-78.4	0.1	-90.2	0.3	-78.4	0.7	-52.9
	Above flood	0.6	0.0	-100.0	0.2	-61.9	0.0	-100.0	0.2	-66.7	0.3	-52.4
	Above moderate	0.0	0.0	-	0.0	-	0.0	-	0.0	-	0.0	-
	Above major	0.0	0.0	-	0.0	-	0.0	-	0.0	-	0.0	-
Milk River near Harlem	Above active	1.7	0.5	-72.9	0.9	-45.8	0.3	-81.4	0.1	-93.2	0.7	-57.6
	Above flood	1.1	0.3	-75.7	0.4	-64.9	0.3	-75.7	0.0	-100.0	0.4	-64.9
	Above moderate	0.0	0.0	-	0.1	-	0.0	-	0.0	-	0.0	-
	Above major	0.0	0.0	-	0.0	-	0.0	-	0.0	-	0.0	-
St. Mary at International Boundary	Above active	10.0	19.9	99.4	33.3	233.4	21.0	109.7	17.7	77.1	21.0	110.3
	Above flood	0.8	7.5	839.3	12.0	1396.4	7.0	778.6	4.4	450.0	7.7	864.3
	Above moderate	0.0	2.0	-	4.0	-	1.7	-	0.3	-	1.4	-
	Above major	0.0	0.8	-	1.7	-	0.9	-	0.2	-	0.6	-

* Milk River at Eastern Crossing, Milk River at Havre Gage had no days above the active flood level in either the historical or futures scenarios

** Frenchman River at International Boundary

Recreation

The St. Mary and Milk River basins provide access to many water-dependent recreation activities that could be impacted by future changes in hydrology. There are three main reservoirs in the St. Mary and Milk River basins, Lake Sherburne, Fresno Reservoir, and Nelson Reservoir which provide recreation to the region. Lake Sherburne on Swiftcurrent Creek is mostly within Glacier National Park where recreation activities are managed by the National Park Service. Fresno Reservoir, on the Milk River, and it's 65 miles of shoreline provide recreation including fishing and boating. Fresno's facilities, including 2 boat launching ramps are managed by Reclamation. Nelson reservoir also provides opportunities for recreation including two boat launching ramps.

Projected changes in future hydrology are expected to impact the timing and magnitude of streamflow throughout the St. Mary and Milk River basins. Changes in flows and reservoir levels could create unfavorable conditions for in-stream and lake recreation and possibly lead to a shorter recreation season. These changes may impact recreation use and economic value, such as decreased overall visitor numbers due to low reservoir levels preventing boat access.

Consideration of effects on reservoir boating recreation in this study focuses on the accessibility of reservoirs via boat ramps. Figure 79 illustrates projected changes in the number of unusable days at Fresno reservoir, respectively, based on boat ramp elevation and simulated reservoir levels. Unusable days are defined as the avg number of days per year where reservoir elevations are below the elevation of identified boat ramps. With exception of the HD scenario, most future scenarios show a decline in the unusable days at Fresno Reservoir, indicating that reservoir elevations will fall below the boat ramps less often during this period, with exception of the HD scenario in the later 2050s and 2080s period. The wetter scenarios HW and WW have the least number of unusable days.

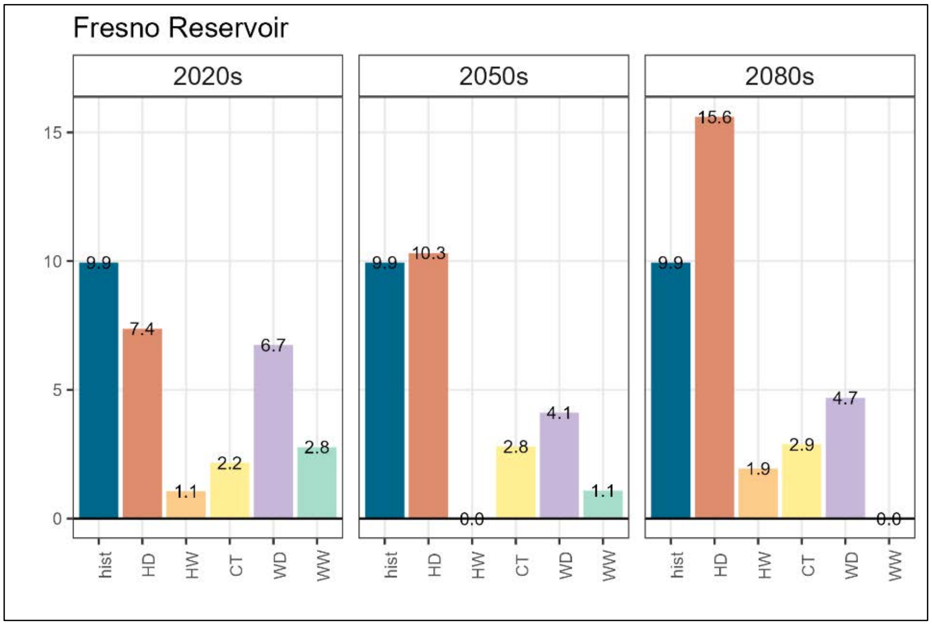

Figure 79.—Average annual number of days below boat ramp elevation at Fresno Reservoir.

Ecological Resources

Measures used here to evaluate the impact of historical and future simulations on ecological resources include changes in avg monthly flows and projected changes in two Indicators of Hydrology Alternation (avg 7-day low flow and avg 7-day high flow) at select locations (Richter et al. 1996). The scope of this study only considered flow related measures. Additional possible impacts on water quality, fish and wildlife habitat, and ESA-listed species are outside the scope of this study.

Figure 80 illustrates projected changes in avg daily Milk River streamflow at Nashua before the Milk River flows into the Missouri River. All future scenarios show increases in late winter, early spring Milk River flows and declines in flows over the irrigation season, with consistently low flows form from August to October. Future scenario flows decline relative to the historical reference period scenario through the 2020s and 2050s, with the lowest flows in the 2080s.

The avg daily flows for the Milk River below Fresno are presented on figure 81. Similar to flows at the Nashua gage, avg annual daily flows increase earlier in the year, with declines in avg daily flows over the summer. The impacts of water management are more obvious at this gage, where winter flows are set to minimum outflows during the winter. Overall, results for both gages show decreases in the summer, with the largest declines in the 2080s period.

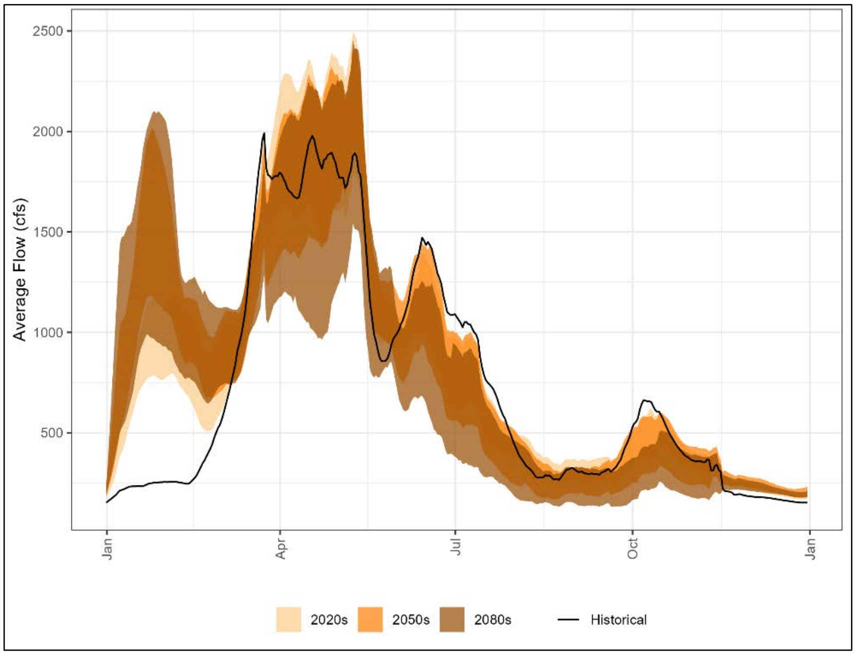

Figure 80.—Average daily Milk River at Nashua flow rates. Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

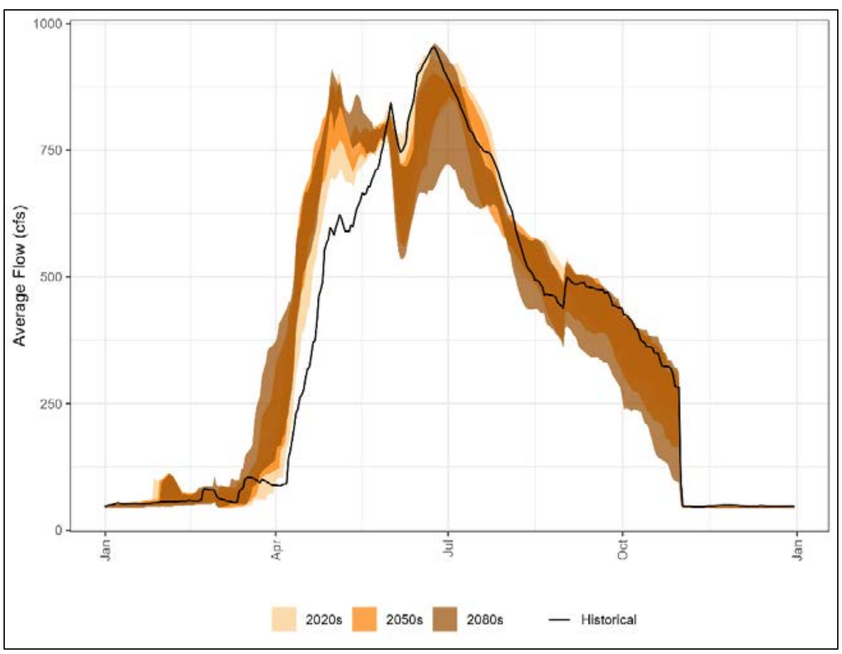

Figure 81.—Average daily Milk River below Fresno Reservoir flow rates.[7]

[7] Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

Potential impacts on ecological resources can also be evaluated by quantifying the avg 7-day low flow and avg 7-day high flow for the future scenarios. Figure 82 illustrates projected changes in these low and high flow values for the Milk River at Nashua just upstream of the confluence with the Missouri River. At Nashua, future scenarios show variable changes in the 7-day high and 7-day low flow values compared with the historical reference period scenario. The drier scenarios, HD and WD, generally show decreases in both high and low flow volumes across all three periods. The wet scenarios, however, show increases in both high and low flows, except for the HW scenario in the latest 2080s period.

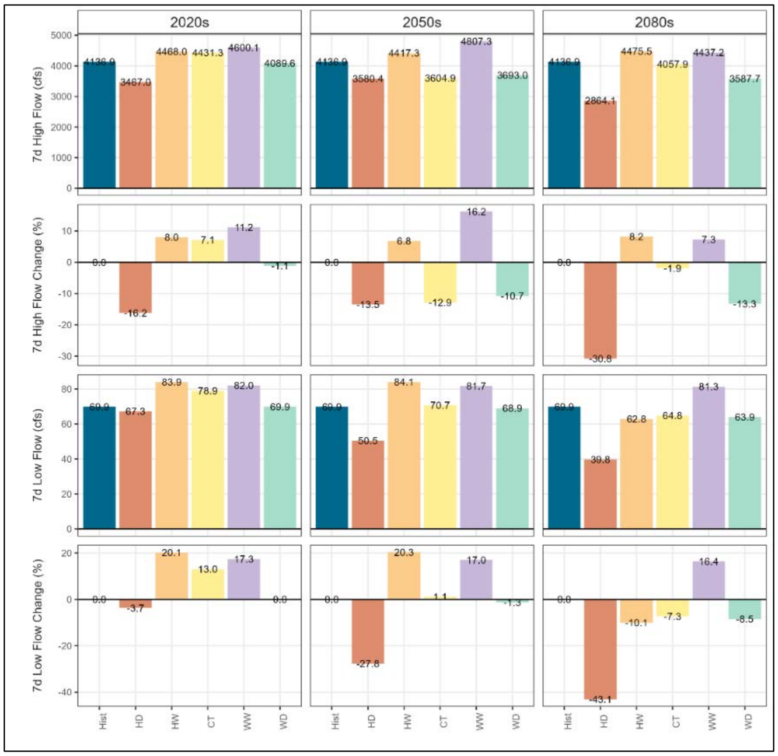

Figure 82.—Projected changes in 7-day minimum and maximum streamflow at Milk River near Nashua for future scenarios.

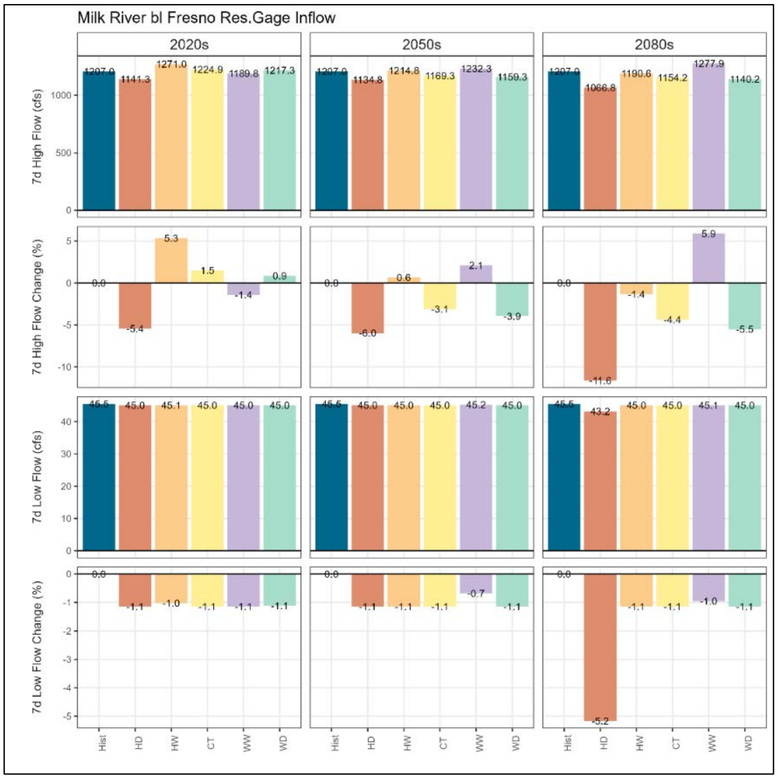

Figure 83.—Projected changes in 7-day minimum and maximum streamflow at Milk River below Fresno Reservoir for future scenarios.

Summary and Key Findings

In the future scenarios, the warming climate increases the amount of precipitation that falls as rain, ultimately reducing the snowpack. Temperature changes also impact snow melt timing and subsequently peak and median streamflow timing, which are anticipated to shift earlier, with winter (October to March) streamflows increasing and irrigation season (April to September) streamflows generally decreasing. This creates a timing mismatch between peak streamflow and peak demand, resulting in an increased reliance on water storage and project infrastructure. Overall, annual total streamflow volumes at most locations in the basins are anticipated to increase for all future scenarios, except for the hottest, driest scenario.

Upstream reservoirs, like Lake Sherburne, are projected to have an increase in total water supply (April 1 storage plus April through September inflows). However, additional water demands during the irrigation season, in addition to higher reservoir evaporation rates, result in minimal changes in EOWY storage and carryover for the next water year. Downstream reservoirs like Fresno, are projected to see increases in April 1 storage (except for the hot dry scenario) due to earlier snowmelt, however, most future scenarios show decreases in April to September inflows, with additional decreases as we move further into the future 2080s scenarios. These changes may increase reliance on project infrastructure to capture and store early season streamflows for the irrigation season.

Future scenarios see an increase in water deliveries (depletions) for all scenarios due to increases in annual streamflows as well as an increase in water demands (depletion requests) due to increased temperatures and ET. Despite increased water supplies and deliveries, demand increases outpace supply changes and total delivery shortages to water users increase in all future scenarios. Additionally, we see a change in irrigation demand timing due to earlier potential planting and green-up dates from rising temperatures and changes to the growing season which increase water demands in the early irrigation season.

Future scenarios also present impacts to flood control operations and recreation. Specifically, inflows to Lake Sherburne lead to an increase in the number of days above top of active conservation at the reservoir for all future scenarios, which increases the likelihood of flooding compared to the historical reference period scenario. Increases in water demand in the future scenarios is expected to impact downstream reservoirs by decreasing reservoir levels and impacting recreational activities, specifically access to the boat ramps, which are expected to be inaccessible more frequently under all future climate scenarios. Flood risk along the St. Mary and Milk Rivers generally decreases in the future scenarios, except for the St. Mary River at International Boundary gage which is projected to see significant increases in flooding potential for all future scenarios.

Risk Assessment with Strategies

The strategies presented in the following sections were developed to address water resource challenges identified in the "Risk Assessment" section, evaluate current issues identified by study partners and through stakeholder outreach, and examine the impact of and potential mitigation methods for increased future water demands. These strategies include changes to current water management practices, changes to existing infrastructure, and development of new infrastructure. Where possible, strategies have been developed to be proactive rather than reactive and to develop a system more resilient to water supply changes. Simulations of the system under existing operations, and with existing infrastructure, provides a baseline (typically termed no-action) to which simulations with strategies can be compared.

Objectives and Constraints

While strategies were primarily developed to address gaps in water supply and demand, some were formulated to address multiple objectives while others were single purpose. Strategies include management changes, different operations for existing infrastructure, and structural changes, such as new storage reservoirs or increasing the capacity of existing reservoirs. Although a strategy's ability to address water supply challenges was addressed, they were not evaluated for economic or financial feasibility.

Approach to Strategy Identification

Reclamation and MT DNRC together identified strategies for addressing present and potential future water supply challenges and investigating the effects of increased water use in the study area and its tributaries. The list of strategies considered in this Basins Study Update encompass strategies evaluated in the 2012 Basins Study that are still relevant today, as well as additional strategies that have been raised by stakeholders through existing planning meetings that took place over the course of the Basins Study Update. In addition, strategies were developed specifically to address new water uses and storage projects as part of the Blackfeet and Fort Belknap compacts and settlements.

Known existing water supply/demand imbalances were evaluated under future water supply and demands scenarios. Future conditions also were evaluated to assess whether there were any new imbalances in supply and demands that needed to be addressed. Reclamation and MT DNRC leveraged existing planning meetings through the Basins Study Update to convey strategy results and receive feedback.

Approach to Strategy Analysis

The following sections describe each of the identified strategies and summarize evaluation of results. The strategies have been separated into three categories “System Wide Water Management Strategies”, “Providing Water for Future Uses”, and “Mitigating Future Water Uses”. The first category, “System Wide Water Management Strategies” includes strategies developed to address water supply reliability concerns and includes improvements to conveyance and on-farm efficiencies, increases to the St. Mary Canal capacity, Fresno reservoir capacity increase, and balancing the U.S./Canadian shares for the St. Mary River on an annual time period. A final strategy was added to this first category to evaluate the impacts of a total failure of the St. Mary Canal on the entire system under current and future water use conditions. The second category of strategies “Providing Water for Future Uses” includes strategies to address future water uses including the 5,000 AF for Blackfeet Compact and a proposed 60 KAF off-stream storage project for the Ft. Belknap Compact. The final category of strategies to “Mitigate Future Water Uses” includes a series of strategies to mitigate these future water uses as well as a final strategy A summary of these strategies is provided in table 22, and a summary of the St. Mary and Milk Rivers planning model implementation of each of these strategies is provided in “Appendix H. St. Mary and Milk Rivers Planning Model Inputs.”

The following sections provide the background for each strategy and present performance and tradeoff results for sets of assessment measures which were determined relevant for each strategy under historical, future, and paleo drought event scenarios.

Table 22.—List of evaluated strategies

Strategy description	Strategy abbreviation
System-wide water management strategies	
Conveyance and On-farm Efficiency Improvements	OnFarmEff
St. Mary Canal Capacity Increase	Canal850
Fresno Reservoir Capacity Increase	Fresno3
Annual Balancing of U.S./Canada Shares	AnnualIJCBalancing
St. Mary Canal Failure	StMaryCanalFailure
Providing water for future uses	
5000 AF for Blackfeet Tribe (Compact)	Blackfeet5KAF
Proposed 60 KAF off-stream storage project in Ft. Belknap Compact	FBIIPRes
Mitigating future water uses	
Max Dodson Canal Capacity Increase	MaxDodson700
Nelson Pumps	Nelson50
Duck Creek Canal	Duck200
Mitigate 35,000 AF for Fort Belknap Water Rights Settlement Implementation	FBIIP35000AF
Combined strategies	
Canal850 + MaxDodson700	Combined1a
Canal850 + MaxDodson700 + FBIIP35000AF	Combined1b
Fresno3 + Canal850	Combined2a
Fresno3 + Canal850 + FBIIP35000AF	Combined2b
OnFarmEff + Fresno3 + Canal850 + Nelson50 + Duck200 + FBIIP35000AF	Combined3

System Wide Water Management Strategies

The strategies discussed in this section were developed to alleviate current and possible future challenges related to water supply availability and to evaluate the impacts and water supply challenges of a catastrophic failure of the St. Mary Canal. There were five strategies identified that have implications for water supply and demand across much of the study area, these strategies include:

- Increasing on-farm efficiencies for all agricultural water users.
- Increasing the St. Mary Canal capacity
- Increase the Fresno Reservoir storage capacity
- Annual Balancing of the U.S. and Canada share of the St. Mary River
- St. Mary Canal failure

Each strategy is further described in the sections that follow. Performance and trade-offs were evaluated based on selected assessment measures determined for each strategy. Each strategy was simulated with historical and projected future flows (e.g., HW). Results were compared to the historical simulation without the implemented strategy (referred to as the historical reference period scenario or historical baseline), to projected future simulations without the implemented strategy, and paleo drought event scenarios without the implemented strategy. The various simulations without strategies are hereafter collectively referred to as baseline scenarios.

Conveyance and On-farm Efficiency Improvements

Improvements to conveyance and on-farm efficiencies were previously evaluated as part of the 2012 Basins Study Technical Report. The previous Basins Study report evaluated a combined conveyance and on-farm efficiency improvement of 17 percent. Additional studies indicate that the overall on-farm efficiency improvement potential is from 42.9 to 62.1 percent, an increase of 19.2 percent (Dalton 2000). For this Basins Study, we evaluated a conservative 5 percent combined conveyance and on-farm efficiency improvement for Milk River Project water users which is consistent with the Regional Feasibility Report for North Central MT (Reclamation 2004).

Performance and Trade-Offs

On-farm and conveyance efficiency improvements have a significant impact on reducing depletion shortages throughout the system. Depletion shortages for the conveyance and on-farm efficiency improvement strategy for the historical reference period scenario (historical baseline) are presented in table 23. The avg annual depletion shortages for all water users decreased by 1.7 percent for the 2050s CT scenario (i.e., central tendency) with strategy, relative to the historical reference period scenario (historical baseline). Similar to the 2012 Basins Study, depletion shortages decreased for all water year types. However, the magnitude of these decreases varied between the previous and current Basin Studies due to the difference in conveyance and on-farm efficiency improvements. In this study, the largest impact of the conveyance and on-farm efficiency scenarios occurs in the driest years, with a decrease in depletion shortages compared to the historical reference period scenario (historical baseline). This 3 KAF differs from the 2012 study, which indicated that the efficiency improvements would be most effective in the wettest years and least effective in the driest years. One reason for this variation between results may be the canal efficiency and mass balance updates which were updated in the St. Mary and Milk Rivers planning model (Reclamation 2022).

Results of the 2012 Basins Study and the current Basins Study strategies also differ regarding Milk River total annual avg flow at the Nashua gage (table 24). The 2012 Basins Study shows declines in avg total annual flow volume for all water year types, with the largest reduction in the driest water years. Current strategy results show slight increases in total annual streamflow, but similarly indicate the lowest flow volumes for the driest years.

Table 23.—On-farm and conveyance efficiency improvements strategy impacts on depletions and depletion shortages for all irrigation users*

	2012 Basins Study (17%)				Current Basins Study (5%)			
	Depletion shortages (annual avg, AF/yr)				Depletion shortage (annual avg, AF/yr)			
	Without alternative	With alternative	Change	% Change	Without alternative	With alternative	Change	% Change
Avg	106,000	86,000	-20,000	-18.9	102,392	100,676	-1,716	-1.7%
Wettest 10 years	77,000	57,000	-20,000	-26.0	66,738	65,590	-1,147	-1.7%
Middle 10 years	97,000	75,000	-22,000	-22.7	105,923	104,554	-1,368	-1.3%
Driest 10 years	140,000	124,000	-16,000	-11.4	132,712	129,969	-2,743	-2.1%
Driest 5 years	173,000	158,000	-15,000	-8.7	160,166	157,124	-3,042	-1.9%

* Results for the 2050's CT futures scenario are compared to results from the 2012 Basins Study CT scenario.

Table 24.—On-farm and conveyance efficiency improvements strategy impacts on average total annual flow volume at the Milk River at Nashua gage*

	2012 Basins Study (17%)				Current Basins Study (5%)			
	Milk River at Nashua (avg total annual volume, AF/yr)				Milk River at Nashua (avg total annual volume, AF/yr)			
	Without alternative	With alternative	Change	% Change	Without alternative	With alternative	Change	% Change
Avg	477,000	459,000	18,000	-3.8	521,550	527,029	5,479	1.1%
Wettest 10 years	643,000	627,000	16,000	-2.5	721,460	729,995	8,535	1.2%
Middle 10 years	473,000	452,000	21,000	-4.4	483,264	488,348	5,084	1.1%
Driest 10 years	195,000	179,000	16,000	-8.2	437,011	439,664	2,653	0.6%
Driest 5 years	131,000	118,000	13,000	-9.9	317,623	320,501	2,878	0.9%

* Results for the 2050's CT futures scenario are compared to results from the 2012 Basins Study CT scenario.

Selected assessment measures for the conveyance and on-farm efficiency strategy are presented on figure 84. Results for each strategy are presented in a similar figure format and are located within each strategy discussion section below. Figures with similar format include: figure 84, figure 87, figure 89, figure 91, figure 96, and figure 99. Results are presented as the percent change in assessment measures under different future and paleoclimate scenarios relative to the baseline simulation—which uses the existing St. Mary and Milk Rivers planning model system configuration, and existing system operating rules. Futures results are shown only for the 2050s period for brevity. These changes are shown on the figures both as colors—increasingly dark red for negative changes, and increasingly dark green for positive changes—and arrows indicating the direction of change—an up arrow (△) for positive change and a down arrow (▽) for negative change. If changes, positive or negative, are less than five percent, they are shown as no change. If changes, positive or negative, exceed the limits of the provided scale they are shaded as plus or minus the scale limits and marked with a dot (•).

The left panel on figure 84 shows performance under future and paleoclimate scenarios without strategies (baseline) compared to the historical reference period scenario without strategies (historical baseline). The HD, HW, CT, WD, and WW future scenarios are shown along with the selected paleo drought events described previously in table 20. This panel suggests how climate alone will impact system performance and identifies vulnerabilities under a range of different scenarios. The middle panel shows the effect of strategies under future and paleoclimate scenarios relative to the historical baseline. This panel helps evaluate how each given strategy impacts the climate vulnerabilities identified in the first panel. The final right panel shows the effects of strategies against their corresponding baseline scenario (e.g., HW scenario with strategy versus HW scenario without strategy). The panel evaluates the relative impact of the strategy under different climate conditions and helps evaluate the relative impact of the strategy in different climate conditions.

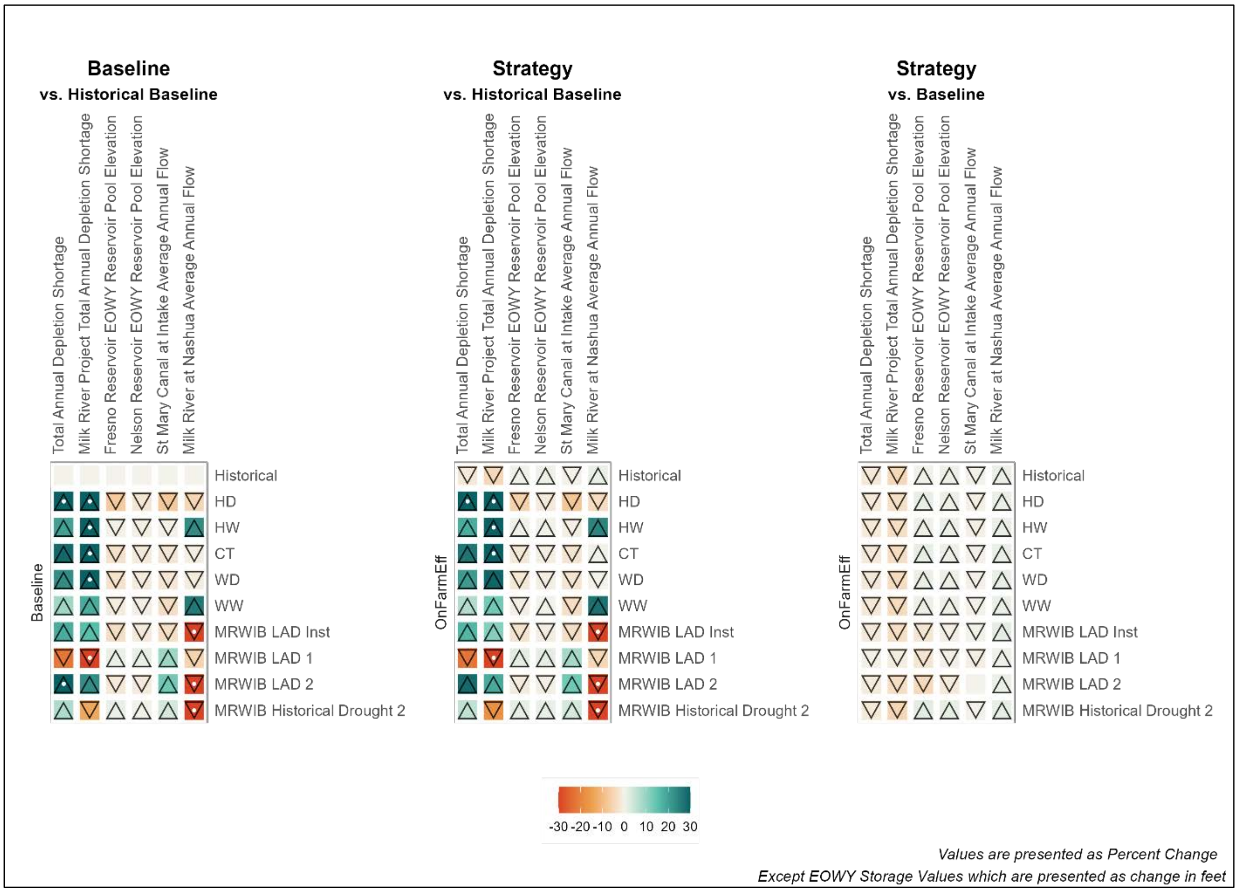

Figure 84.—Comparison chart of selected assessment measures for the conveyance and on-farm efficiency improvements strategy relative to the baseline scenarios.[8]

[8] Results presented include historical, 2050s futures and selected paleo drought event scenarios.

Comparisons of the on-farm efficiency improvements verses the respective baseline scenario (right panel on figure 84) shows that the on-farm and conveyance efficiency improvement strategy has a similar impact on the system for all future climate scenarios and paleo drought events. Specifically, all scenarios show decreases in avg annual total depletion shortages, from their relative baseline simulations, for all water users and for Milk River Project.

The avg monthly Milk River Project water user diversions and diversion shortages are presented on figure 85 and figure 86, respectively. Diversions represent the total volume of water diverted to meet water user depletions and associated conveyance losses through the distribution system. The conveyance and on-farm efficiency strategy evaluated over the historical reference period results in lower diversions for all months relative to the historical baseline, with the greatest decline in diversion shortages from May through August when irrigation demands are at their highest. This corresponds with changes in diversion shortages, which also show the greatest declines from May to August. Results for the future scenarios indicate that the conveyance and on-farm efficiency improvements have even greater impacts on decreasing diversion shortages under future conditions than over the historical reference period.

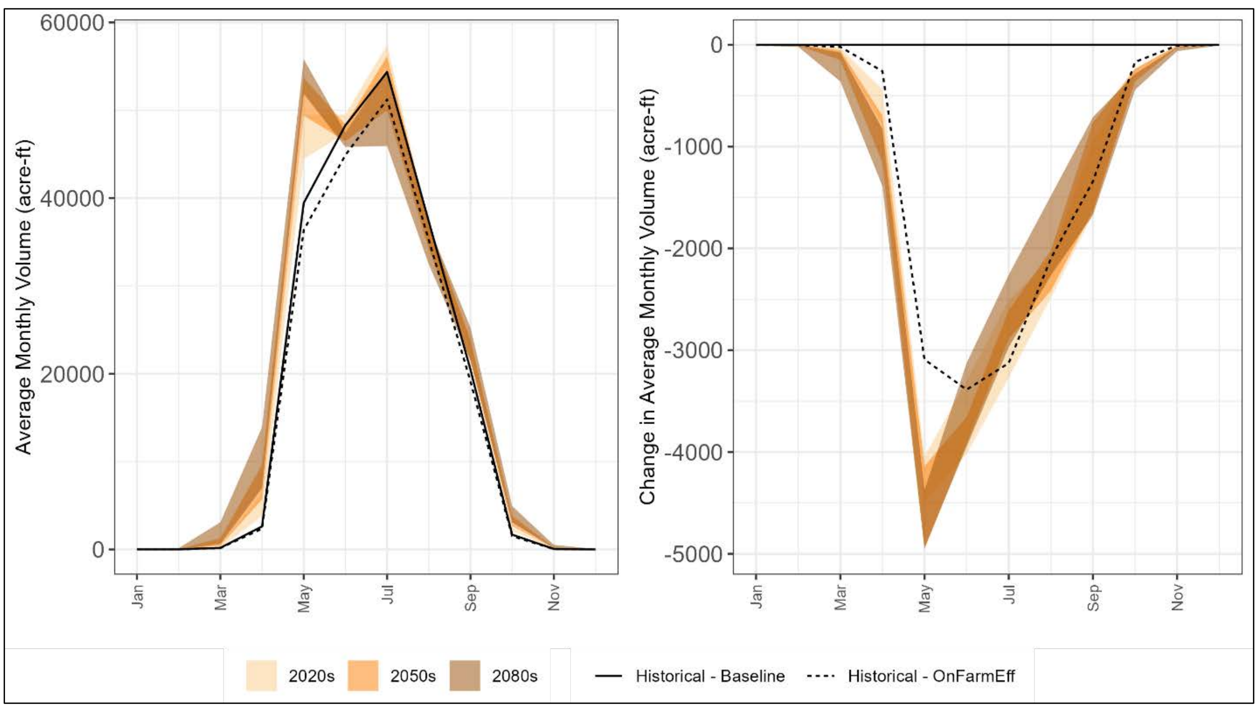

Figure 85.—Milk River Project water users' average monthly diversion volumes for the conveyance and on-farm efficiency improvement strategy (left panel) and the change in those average monthly diversion volumes from the baseline scenarios (right panel).[9]

[9] Future results are presented for the Conveyance and On-Farm Efficiency Improvement strategy as a range of 5 future scenarios (HW, HD, CT, WW, WD) for each future period.

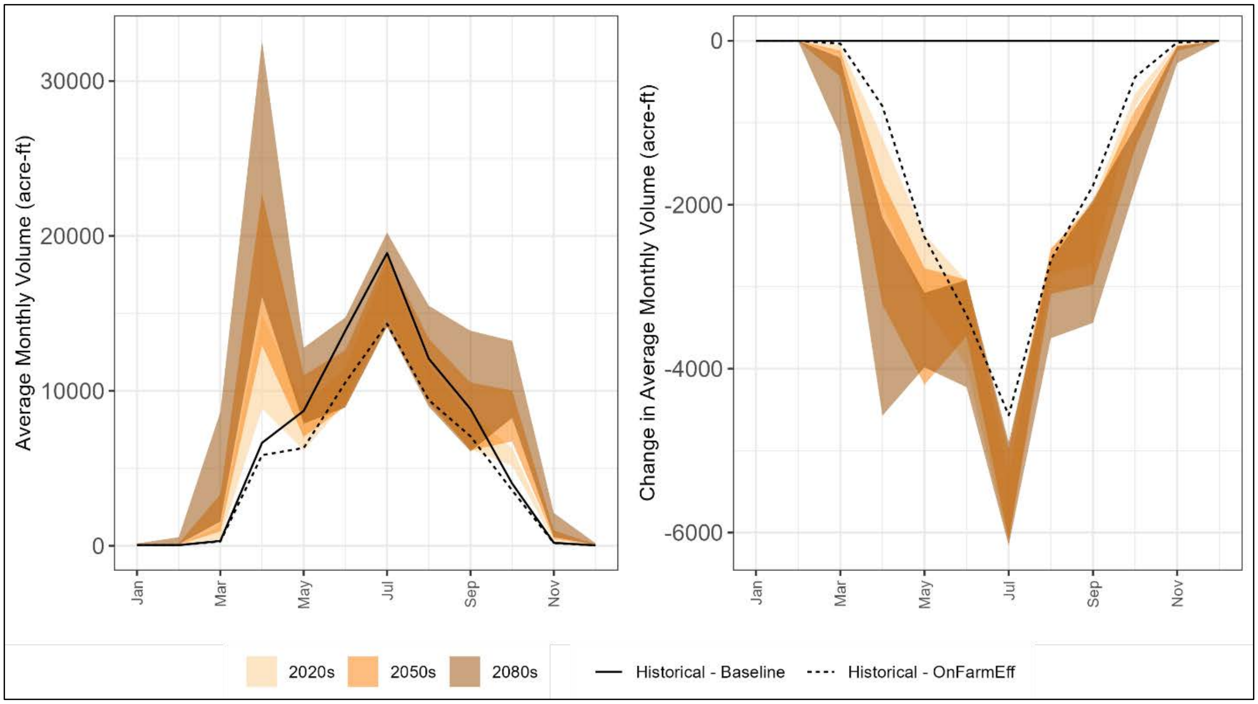

Figure 86.—Milk River Project water users' average monthly diversion shortage volumes for the conveyance and on-farm efficiency improvement strategy (left panel) and the change in those average monthly diversion shortage volumes from the baseline scenarios (right panel).[10]

St. Mary Canal Capacity Increase

The maximum capacity of the 100-year-old St. Mary Canal and diversion dam has degraded from the original water right of 850 cfs to a reduced capacity of 600 cfs (DNRC 2022). Rehabilitation of the St. Mary Canal back to the original water right capacity would allow the U.S. to capture more of its share of the St. Mary River and increase available water supply in the Milk River basin. The baseline St. Mary and Milk Rivers planning model represents the current St. Mary Canal capacity as 600 cfs from May through July and 550 cfs from August through October when growth of aquatic vegetation reduces flows in the canal. This canal capacity increase strategy increases these canal capacities by 250 cfs to 850 cfs and 800 cfs for the May through July and August through October periods, respectively. A similar study strategy was implemented in the 2012 Basins Study which increased the St. Mary Canal capacity from 650 cfs to 850 cfs.

Performance and Trade-Offs

Selected assessment measures for the St. Mary Canal Capacity Increase strategy are presented on figure 87. As anticipated, over the historical reference period, increases in the capacity of the St. Mary Canal results in an increase in avg annual flow volumes across the St. Mary Canal and

[10] Futures results are presented as a range of 5 future scenarios (HW, HD, CT, WW, WD) for each future period compared to their corresponding baseline simulation.

subsequently an increase in avg annual flow volumes in the Milk River at Eastern Crossing downstream from the St. Mary Canal, relative to the historical baseline simulation. This increase in the captured U.S. share of the St. Mary River effectively increases the water supply and decreases the avg annual total depletion shortage for all water users for the historical and future scenarios, as well as during the paleo drought event scenarios, relative to their respective baseline (i.e., no strategy) simulations.

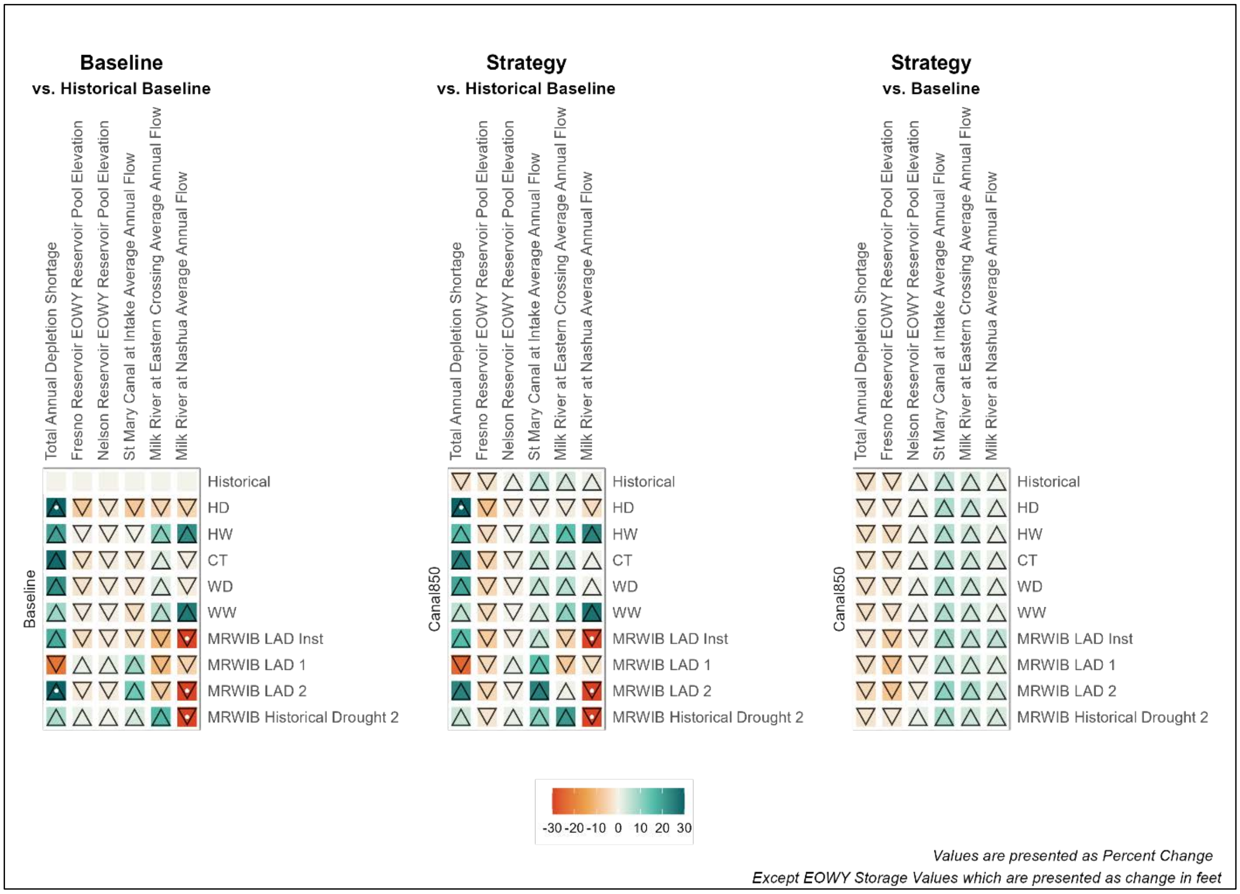

Figure 87.—Comparison chart of selected assessment measures for the St. Mary Canal Capacity Increase strategy relative to the baseline scenarios.[11]

The avg monthly St. Mary Canal Diversion volumes are presented for the historical and future scenarios on figure 88. Relative to the baseline scenarios (i.e., historical and future scenarios without strategies), monthly flows across the St. Mary Canal are higher from March through July and lower from August through September. Future scenarios show a slightly earlier timing in peak and low flows through the St. Mary Canal reflects the future hydrology changes in the St. Mary basin.

[11] Results presented include historical, 2050s futures and selected paleo drought event scenarios.

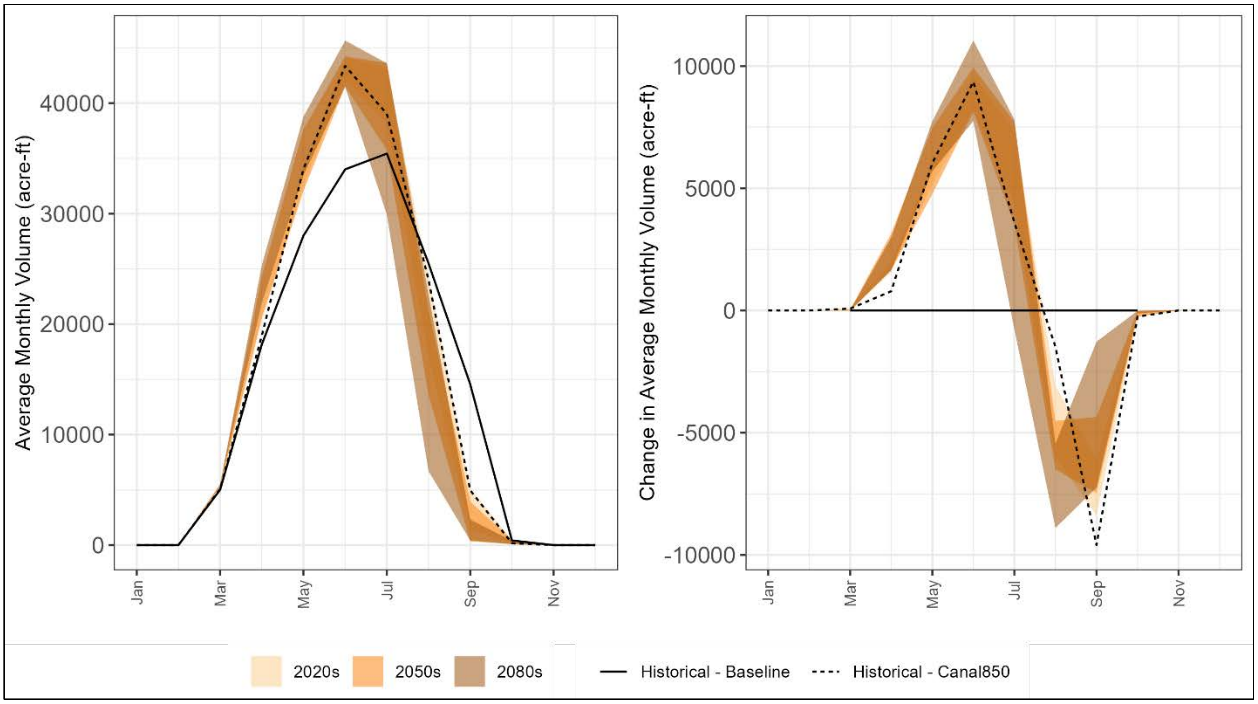

Figure 88.—St. Mary Canal average monthly diversion volumes for the St. Mary Canal Capacity Increase strategy (left panel) and the change in those average monthly diversion volumes from the baseline scenarios (right panel). [12]

Current Basins Study results are compared to a similar strategy evaluated in the 2012 Basins Study for their respective historical scenarios in table 25. Both the 2012 and current Basin Studies show an increase in avg annual total flow volumes across the St. Mary Canal Intake; however, they vary in their results for different water year types. The 2012 Basins Study presents an overall higher increase in the avg annual flow volumes across the St. Mary Canal of 10.1 percent compared to the 6.7 percent for the current study compared to their respective historical baseline. However, the current Basins Study indicates a higher increase in avg annual flow volumes across the St. Mary Canal in the driest 5 water years at an 8 percent increase compared to the 2012 Basins Study which only evaluated a 0.7 percent increase.

Comparative results between the 2012 and current Basins Studies are also presented for the avg annual total depletion shortages for all water users in table 26. Both studies show overall declines in total depletion shortages. However, the 2012 Basins Study shows a higher overall impact of the strategy on water supply, with a 4.7 percent reduction in avg annual total depletion shortages, compared with a 2.5 percent decline in depletion shortages in the current Basins Study. Results for the driest 5 years show a slight increase of 0.6 percent in the 2012 Basins Study and a

[12] Futures results are presented as a range of 5 future scenarios for each future period compared to their corresponding baseline simulation.

decrease of almost 2 percent in the current Basins Study. These differences between the results for the two Basin Studies may be reflective of the updated hydrology and demands datasets, different historical simulation periods, and model improvements.

Table 25.—St. Mary Canal Capacity strategy impacts on diversion through the St. Mary Canal*

	2012 Basins Study				Current Basins Study			
	St. Mary Canal at Intake (avg total annual volume, AF/yr)				St. Mary Canal at Intake (avg total annual volume, AF/yr)			
	Without alternative	With alternative	Change	% Change	Without alternative	With alternative	Change	% Change
Avg	198,000	218,000	20,000	10.1%	157,489	167,965	10,476	6.7%
Wettest 10 years	195,000	237,000	42,000	21.5%	168,421	176,193	7,773	4.6%
Middle 10 years	208,000	231,000	23,000	11.1%	157,351	171,243	13,892	8.8%
Driest 10 years	170,000	172,000	2,000	1.2%	145,806	154,642	8,835	6.1%
Driest 5 years	148,000	149,000	1,000	0.7%	141,886	153,289	11,403	8.0%

* Results for the 2050's CT futures scenario are compared to results from the 2012 Basins Study CT scenario.

Table 26.—St. Mary Canal Capacity strategy impacts on depletions and depletion shortages for all irrigation users*

	2012 Basins Study				Current Basins Study							
	Depletion shortage (avg total annual volume, AF/yr)				Depletion (avg total annual volume, AF/yr)				Depletion Shortage (avg Total Annual Volume, AF/yr)			
	Without alternative	With alternative	Change	% Change	Without alternative	With alternative	Change	% Change	Without alternative	With alternative	Change	% Change
Avg	106,000	101,000	5,000	-4.7%	157,070	159,875	2,804	1.8%	102,392	99,862	-2,531	-2.5%
Wettest 10 years	77,000	71,000	6,000	-7.8%	150,518	152,392	1,875	1.2%	66,738	65,053	-1,685	-2.5%
Middle 10 years	97,000	90,000	7,000	-7.2%	161,182	164,496	3,314	2.1%	105,923	102,905	-3,018	-2.8%
Driest 10 years	140,000	139,000	1,000	0.7%	157,175	159,741	2,566	1.6%	132,712	130,418	-2,294	-1.7%
Driest 5 years	173,000	172,000	1,000	0.6%	147,261	150,471	3,211	2.2%	160,166	157,330	-2,836	-1.8%

* Results for the 2050's CT futures scenario are compared to results from the 2012 Basins Study CT scenario.

Fresno Reservoir Capacity Increase

The capacity of the Fresno Reservoir has declined from its 129,062 acre-ft initial volume to 91,746 acre-ft measured during the most recent 2010 sedimentation survey. This represents a total loss in capacity of at least 37,318 acre-ft. To mitigate this capacity loss, we evaluated the impact of a 3-ft dam raise, presently being evaluated in the current risk assessment. This dam raise strategy would provide an additional 16,638 acre-ft of storage capacity. In the St. Mary and Milk Rivers planning model, raising the Fresno Dam is implemented by placing stoplogs in the uncontrolled spillway, and raising the top of joint use pool (the administrative division of the reservoir between flood control and water supply storage). The characteristics of outlet facilities are maintained. The spring and October storage targets were also increased by 20,000 AF each from 60,000 to 80,000 AF and 42,000 to 62,000 AF, respectively.

Performance and Trade-Offs

Selected assessment measures for the Fresno Reservoir Capacity Increase strategy are presented on figure 89. All 2050s future scenarios show an increase in Fresno Reservoir EOWY pool elevation as well as a small decrease in total annual depletion shortages. Additionally, all scenarios show an increase in the number of days that the Fresno Reservoir pool elevation is above the previous top of joint use elevation (2,575 ft) indicating that the reservoir does use the additional storage space provided by this capacity increase.

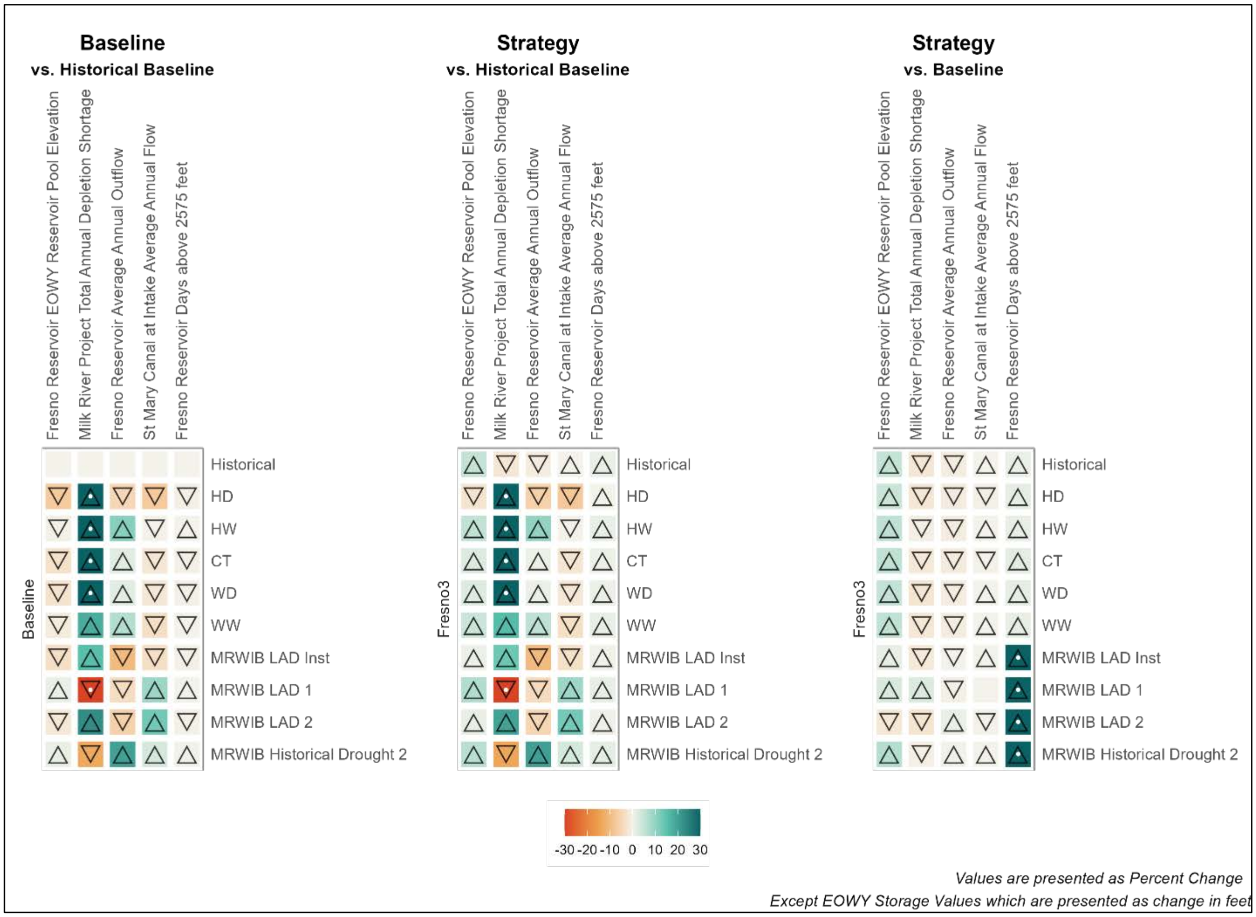

Figure 89.—Comparison chart of selected assessment measures for the Fresno Reservoir capacity increase strategy relative to the baseline scenarios.[13]

Fresno Reservoir monthly avg pool elevations are presented on figure 90. For all months in the historical and future scenarios, the Fresno Reservoir monthly avg pool elevation is above the historical baseline simulation, with the largest increases in pool elevation occurring between October and January and the smallest changes occurring in the irrigation season from April to August.

A few of the selected assessment measures show variable results across the different climate scenarios. Results for the historical strategy scenario show a small increase in the avg annual total flow volume diverted across the St. Mary Canal compared to the historical baseline simulation; however, results are mixed for the 2050s futures and paleo drought event scenarios. Historical and 2050s strategy results all show a small decline in Milk River Project users total annual depletion shortages, with mixed results for the paleo drought event scenarios. However, during the two paleo drought event scenarios which indicate increases in Milk River Project users' total annual depletion shortages relative to the historical baseline, the MRWIB LAD Inst

[13] Results presented include historical, 2050s futures and selected paleo drought event scenarios.

drought and the MRWIB LAD 2 drought, the Fresno Reservoir Capacity Increase strategy shows a decline in shortages relative to their respective baseline scenarios, indicating that the capacity increase may be most beneficial during droughts which have the largest impacts on Milk River Project users.

The methodology for implementing the Fresno Reservoir Capacity Increase strategy as well as the rules for Fresno Reservoir releases have been identified as areas for future model improvements. These future model improvements may provide further insights into the impacts of increasing the reservoir's capacity.

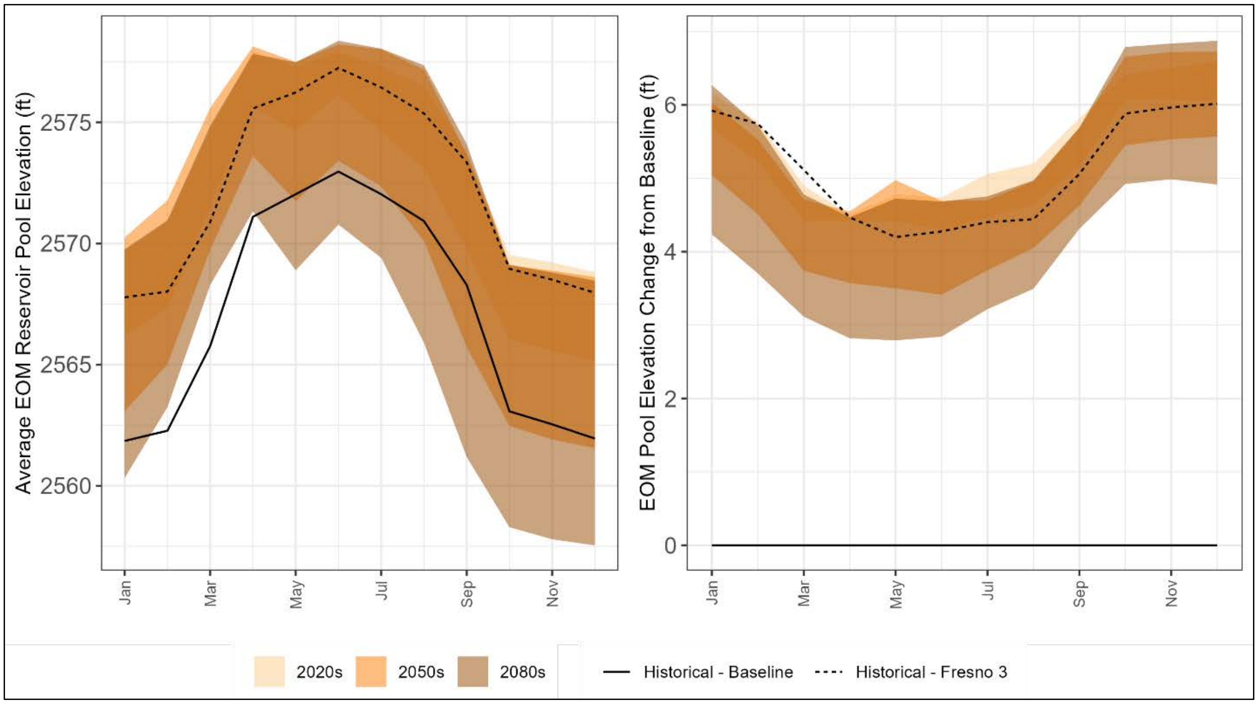

Figure 90.—Fresno Reservoir average end-of-month pool elevation for the Fresno Reservoir Capacity Increase strategy (left panel) and the change in those average end-of-month pool elevation from the baseline scenarios (right panel).[14]

Increasing the capacity of the Fresno Reservoir was also evaluated as part of the 2012 Basins Study, results between the two basins studies are presented in table 27. Both studies show decreases in depletion shortages with implementation of the Fresno Capacity Increase strategy. However, the studies vary in the magnitude of the decrease. This is partially due to differences in the 2012 and current strategies, specifically, the 2012 Basins Study evaluated a 5-ft raise with a 28,000 acre-ft increase in capacity, compared to the current study which evaluated a 3-ft raise and a 16,638 AF capacity increase. Though the 2012 Basins Study showed a greater decrease in

[14] Futures results are presented as a range of 5 future scenarios for each future period compared to their corresponding baseline simulation.

depletion shortages on avg over the whole simulation period, the current Basins Study shows better performance in the driest water years compared to the 2012 Basins Study. Differences between the two studies are likely due to the updated hydrology, changes in streamflow timing, and model improvements including canal efficiencies.

Table 27.—Fresno Reservoir increase strategy impacts on depletion shortages for all irrigation users*

	2012 Basins Study				Current Basins Study			
	Depletion shortage (avg total annual volume, AF/yr)				Depletion shortage (avg total annual volume, AF/yr)			
	Without alternative	With alternative	Change	% Change	Without alternative	With alternative	Change	% Change
Avg	106,000	101,000	-5,000	-4.7%	102,392	101,757	-635	-0.62%
Wettest 10 years	77,000	70,000	-7,000	-9.1%	66,738	66,758	20	0.03%
Middle 10 years	97,000	92,000	-4,000	-4.1%	105,923	105,511	-412	-0.39%
Driest 10 years	140,000	138,000	-2,000	-1.4%	132,712	130,769	-1,943	-1.46%
Driest 5 years	173,000	171,000	-2,000	-1.1%	160,166	156,476	-3,690	-2.30%

* Results for the 2050's CT futures scenario are compared to results from the 2012 Basins Study CT scenario

Annual Balancing of U.S./Canada Shares

This strategy evaluates the impact of changing the IJC account balancing period which controls the division of water between the U.S. and Canada. Currently, international apportionment of the St. Mary River is balanced on a semi-monthly basis. Deficit deliveries to Canada for any day within a 15 or 16-day period can be offset by surpluses within that period. For this strategy, the IJC account balancing periods is adjusted from the current semi-monthly balancing period (used in the baseline simulation) to an annual balancing period. This strategy would allow the U.S. to make daily deficit deliveries to Canada, as long as they are made up at another time of the year by surplus deliveries. The annual balancing scenario would balance annual flows from November 1 through October 31 so that winter surplus deliveries to Canada would accumulate and allow the U.S. to draw on those surpluses as credit to make deficit deliveries during the summer. It is anticipated that this change would divide the shares more equitably and possibly provide additional water supplies to the U.S.

Performance and Trade-offs

A comparison of selected assessment measures for the Annual Balancing of U.S./Canada shares of the St. Mary River strategy is presented on figure 91. As anticipated, annual balancing increases the avg annual total flow volumes across the St. Mary Canal with a higher captured portion of U.S. shares compared to the historical baseline simulation. Results from the historical strategy scenario show an increase in avg annual total flow volumes across the St. Mary Canal diversion of 21 KAF (form 161 KAF to 182 KAF). 2050s future scenarios show a consistent, similar increase of 20 to 21 KAF with this strategy.

Higher flow volumes across the St. Mary Canal result in higher Milk River at Eastern Crossing avg annual total flow volumes and a decrease in avg annual total depletion shortages for Milk River Project users in all scenarios. For the historical reference period, the Annual Balancing of U.S./Canada Shares strategy decreased annual avg total depletion shortages for Milk River Project users by 2,100 AF compared to the historical baseline simulation. Results show variable decreases for the 2050s scenarios from 1,190 to 3,050 AF.

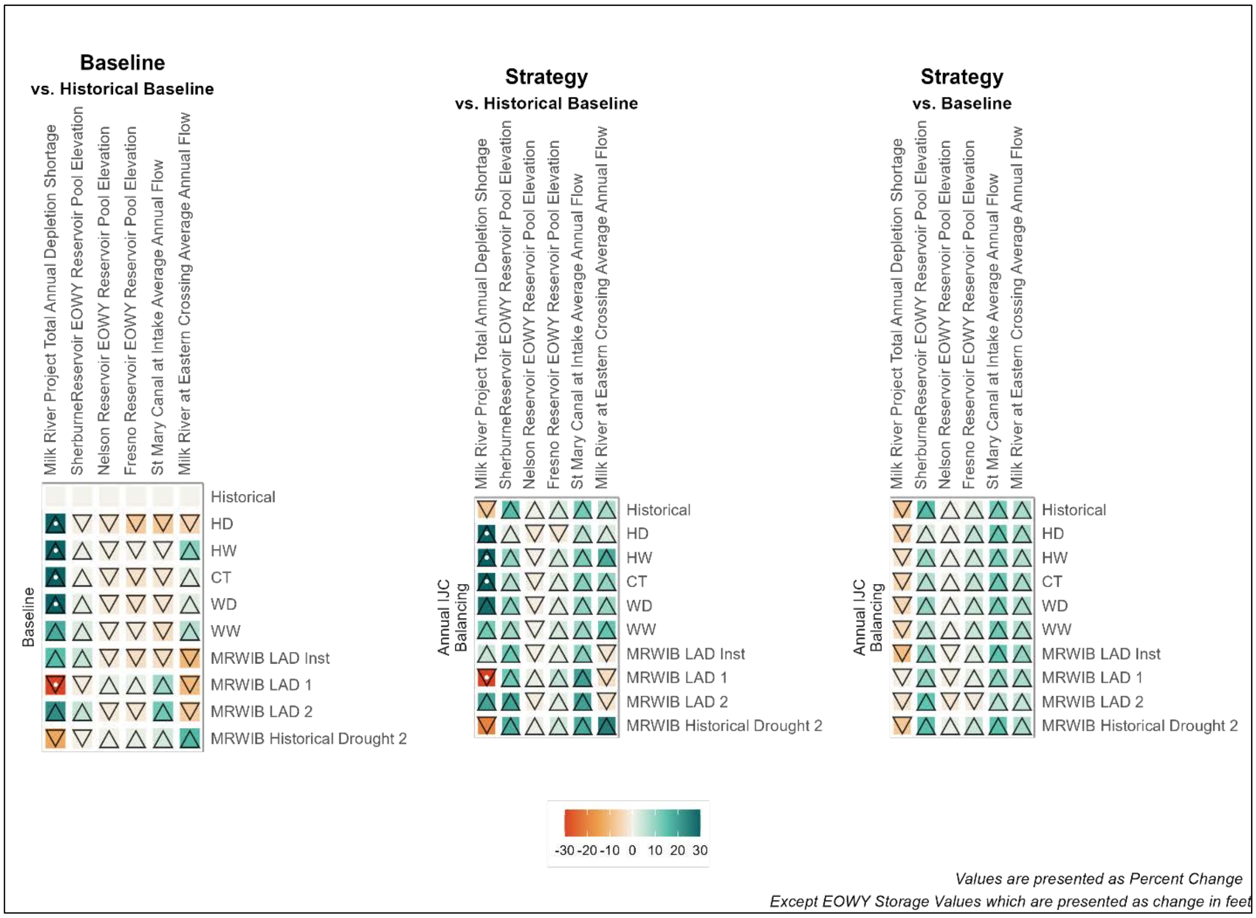

Figure 91.—Comparison chart of selected assessment measures for the annual balancing of U.S./Canada shares strategy relative to the baseline scenarios.[15]

[15] Results presented include historical, 2050s futures and selected paleo drought event scenarios.

The avg monthly St. Mary Canal diversion for the Annual Balancing of U.S./Canada Shares strategy are presented and compared to baseline scenarios on figure 92. Results show an increase in avg monthly flows mostly over the July to September period, which varies from the pattern of increase in St. Mary Canal diversions shown in the canal capacity increase strategy which displayed the largest increase in April to July. Future scenarios show potential for even higher increases in flow volumes across the St. Mary Canal with the Annual Balancing strategy, indicating this strategy may be more valuable under future conditions.

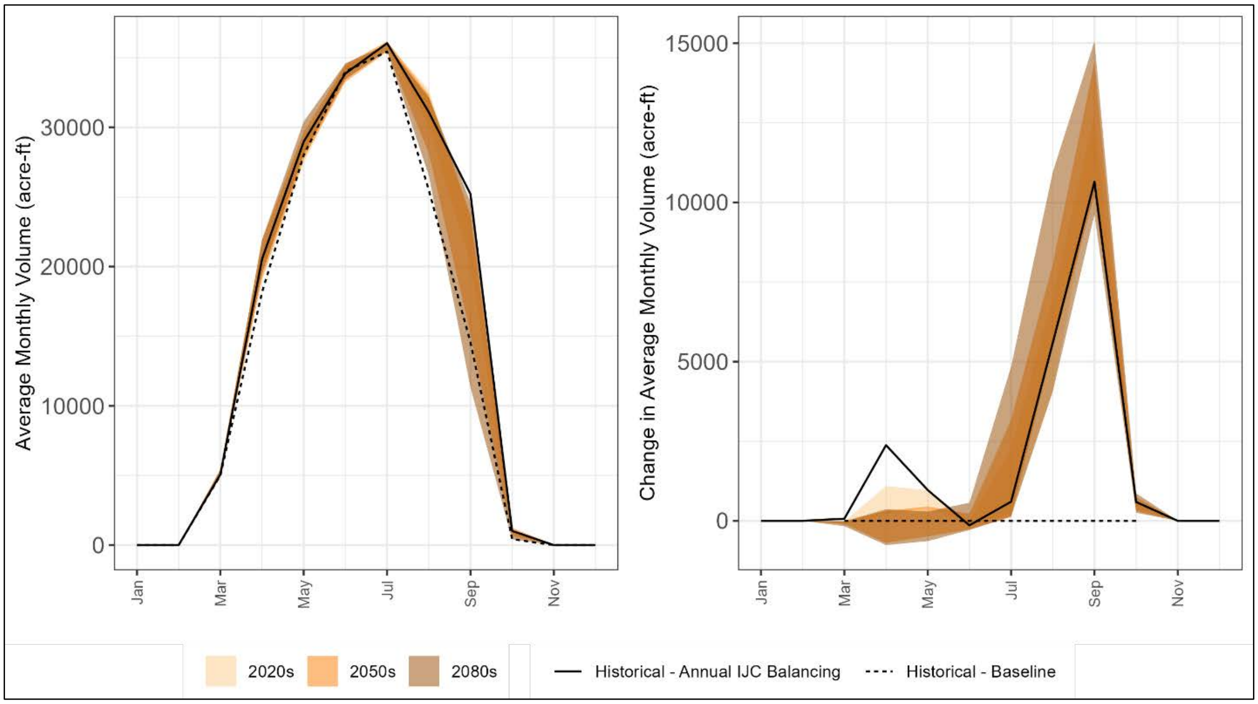

Figure 92.—St. Mary Canal average monthly diversion volumes for the Annual Balancing of U.S./Canada Shares strategy (left panel) and the change in those average monthly diversion volumes from the baseline scenarios (right panel).[16]

St. Mary Canal Failure

Aging and deterioration of the St. Mary Canal have led to concerns about a potential catastrophic failure. This strategy evaluates the impacts of a catastrophic failure of the St. Mary Canal and is implemented in the St. Mary and Milk Rivers planning model by setting the St. Mary Canal capacity to zero.

[16] Futures results are presented as a range of 5 future scenarios for each future period compared to their corresponding baseline simulation with the same forcing scenario.

Performance and Trade-Offs

A comparison of selected assessment measures for the St. Mary Canal Failure strategy is presented on figure 93. The avg annual total depletion shortages increased significantly for all scenarios, with an increase of 25,470 AF (32.0 percent) for the historical scenarios and similar increases for the 2050 scenarios with an increase ranging from 24,340 (28.1 percent) to 35,240 AF (30.2 percent). Milk River Project user annual total depletion shortages are specifically impacted with an increase across all scenarios ranging from 23,970 acre-ft (86.7 percent) for the historical reference period to 33,373 AF (68 percent) for the HD 2050s scenario. The Milk River Project users are also highly impacted by the St. Mary Canal Failure scenario during the paleo drought events where Milk River Project users' total annual depletion shortages were 114 percent higher for the MRWIB Hist 2 (27,290 AF) and 174 percent higher for the MRWIB LAD 1 paleo drought event (46,000 AF). This strategy had the most significant impact on deliveries to water users.

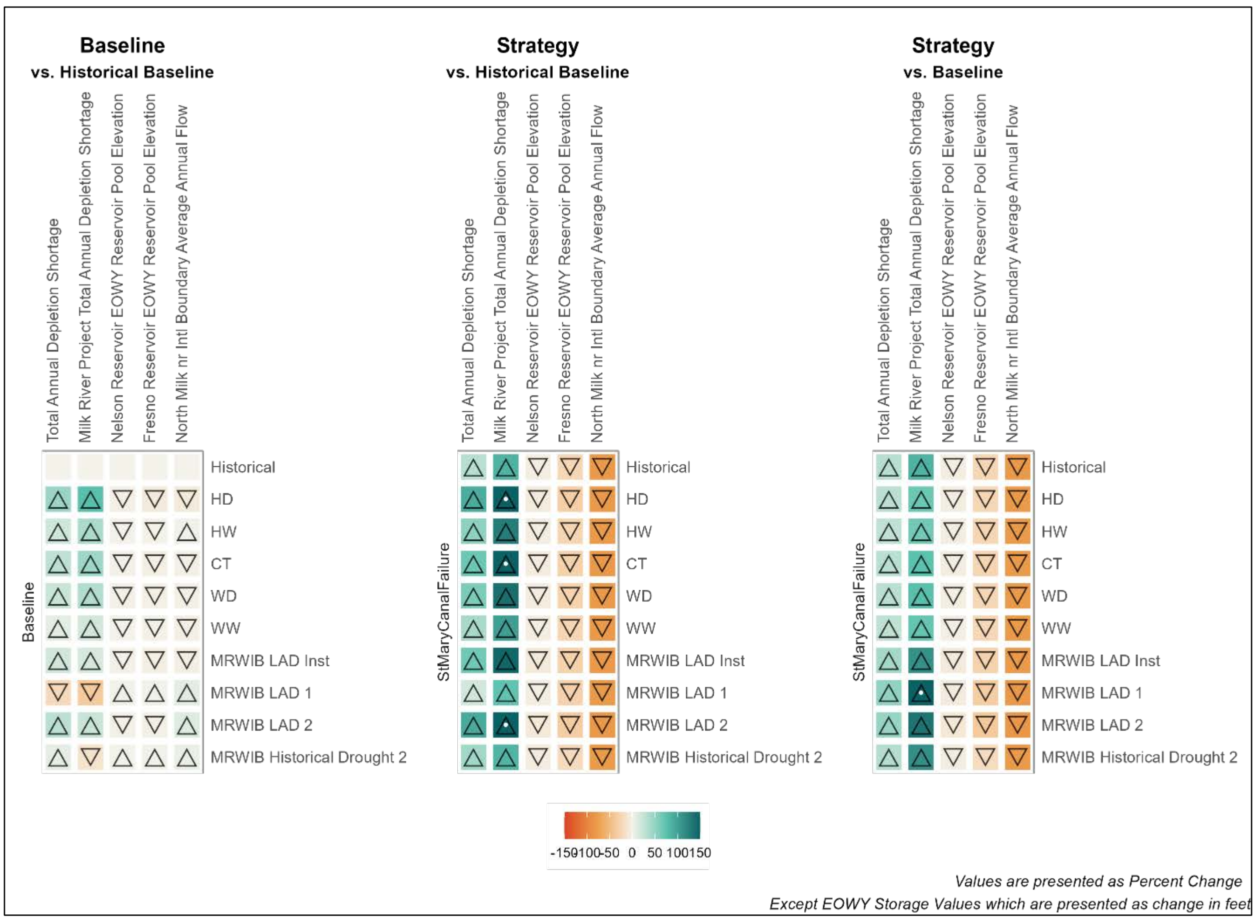

Figure 93.—Comparison chart of selected assessment measures for the St. Mary Canal Failure strategy relative to the baseline scenarios.[17]

[17] Results presented include historical, 2050s futures and selected paleo drought event scenarios.

Impacts of the St. Mary Canal Failure on Fresno storage are presented on figure 94. Monthly avg pool elevations at Fresno decrease significantly for all months of the year, up to a 30-ft decrease in pool elevation during peak summer in August and more than 20 ft at the EOWY for the 2080s future scenarios.

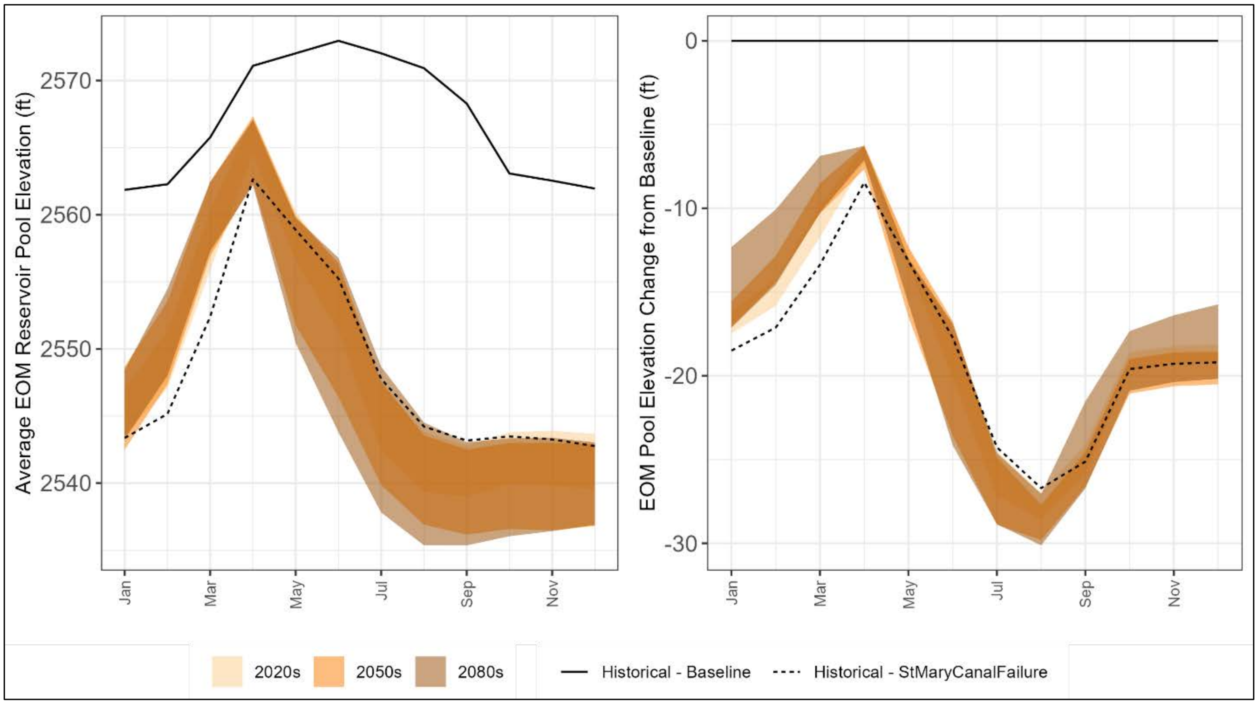

Figure 94.—Fresno Reservoir average end-of-month pool elevation for the St. Mary Canal Failure strategy (left panel) and the change in those average end-of-month pool elevation from the baseline scenarios (right panel).[18]

Providing Water for Future Uses

Increased demand for water in the future is a likely factor for long term planning. We considered two future water uses in the region including water for the Blackfeet Compact and the Fort Belknap Compact. Strategies discussed in this section were developed to evaluate the current and possible future challenges related to implementation of these compacts. We evaluated two strategies that have implications on changes in future water use.
These strategies include:

- 5,000 acre-ft for the Blackfeet Tribe (Compact)
- Proposed 60,000 acre-ft off-stream storage project for the Ft. Belknap Indian Community

[18] Futures results are presented as a range of 5 future scenarios for each future period compared to their corresponding baseline simulation.

5,000 Acre-feet (AF) for Blackfeet Tribe (Compact)

The Blackfeet Compact has been finalized and is in the early stages of implementation. The Blackfeet Water Rights Settlement Compact (§85-20-1501:1511, MCA) provides the Blackfeet Tribe with 50,000 AF of water from the St. Mary River basin, however only 5,000 AF is to be delivered through the St. Mary Canal. This strategy only includes this 5,000 AF, which is first in priority and added as a diversion from the St. Mary Canal. This water cannot be stored and there are currently no identified uses.

Performance and Trade-Offs

The avg monthly diversion volumes for the Blackfeet Tribe Compact Use are presented on figure 95. Blackfeet Compact Use diversion requests are the same for historical and future scenarios in the 5,000 AF for the Blackfeet Tribe strategy. However, actual diversion volumes for the future scenarios are below the historical reference period values in the later summer months due to changes in flow timing on the St. Mary River and Annual IJC U.S./Canadian Balancing applied in this strategy.

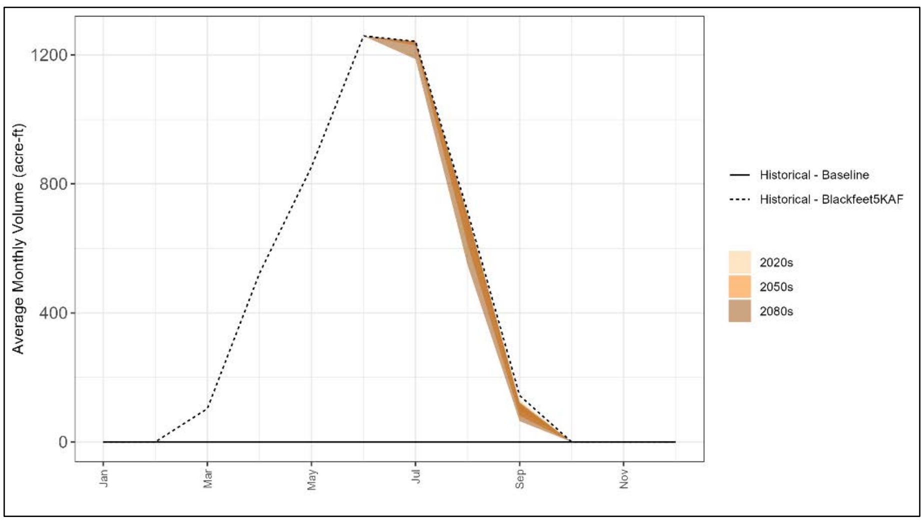

Figure 95.—Blackfeet average monthly diversion volumes for the 5000 acre-feet for the Blackfeet Tribe (Compact) strategy and the change in those average monthly diversion volumes from the baseline scenarios.[19]

Results for selected assessment measures for the 5,000 AF for the Blackfeet Tribe (Compact) strategy relative to the baseline simulations are presented on figure 96. As anticipated, diversions from the St. Mary Canal for the Blackfeet Compact Use strategy resulted in decreased avg annual total flow volumes along the North Milk River near the International Boundary, downstream from the St. Mary Canal inflow into the Milk River relative to the baseline

[19] Futures results are presented as a range of 5 future scenarios for each future period compared to their corresponding baseline simulation.

simulation for all scenarios. For the historical scenario, the avg annual flow volume of the North Milk River near the International Boundary decreased 3.5 percent or 5.8 KAF from the historical baseline simulation, the 2050 future scenarios show a similar decline of 3.6 to 3.7 percent (5.6 to 6.0 KAF) compared to their relative baseline simulation.

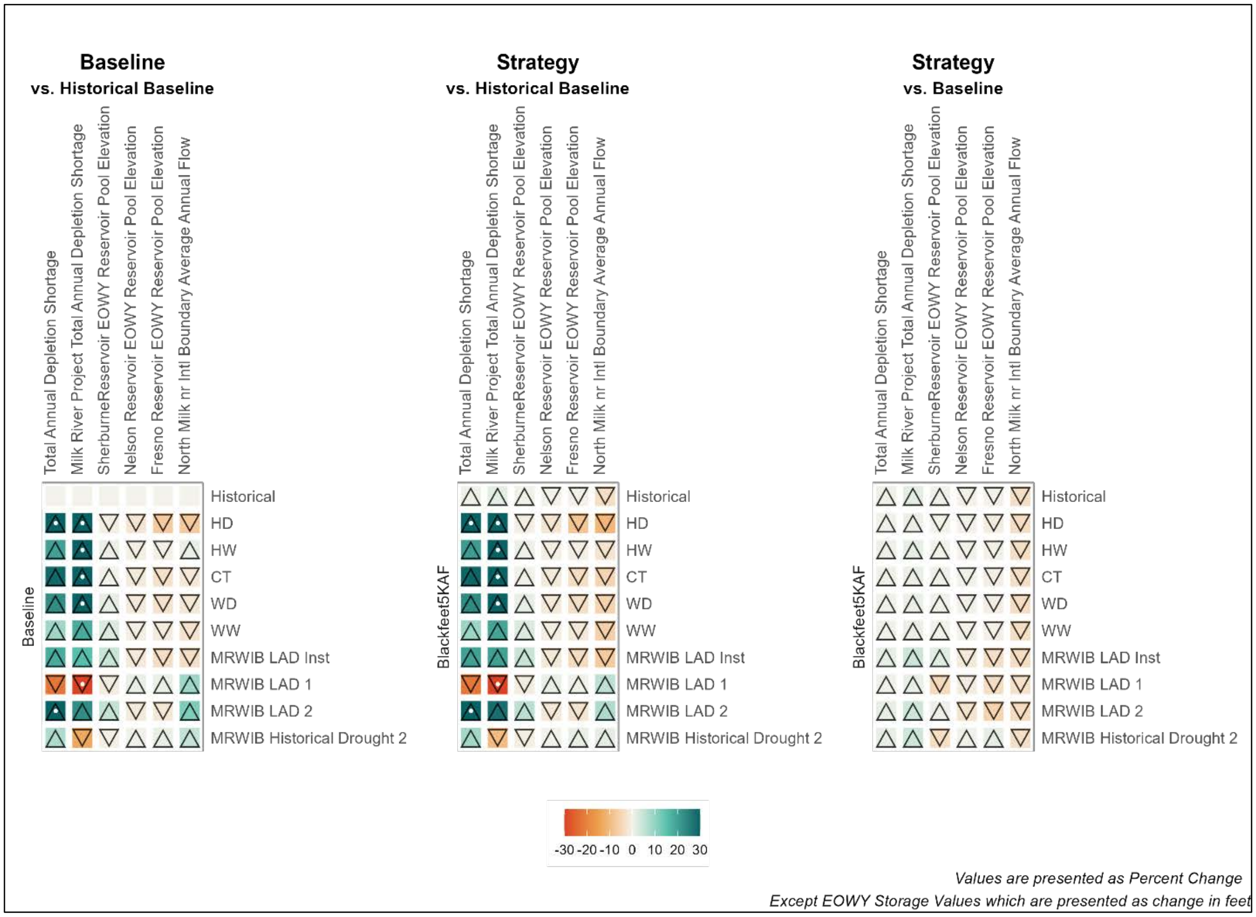

Figure 96.—Comparison chart of selected assessment measures for the 5000 acre-feet for Blackfeet Tribe (Compact) strategy relative to the baseline scenarios.[20]

The avg monthly flow volumes for the North Milk River near International Boundary and their relative change from the baseline scenarios are presented on figure 97. The largest monthly declines, relative to the historical baseline simulation, occur during the peak of the irrigation season for both the historical and future scenarios (refer to left panel).

Declines in the North Milk River near International Boundary flows subsequently reduced the water supply to Milk River Project users and for all scenarios and resulted in increases in total annual depletion shortages for all water users. For the historical scenario, the 5,000 AF for the

[20] Results presented include historical, 2050s futures and selected paleo drought event scenarios.

Blackfeet Tribe strategy increased total annual depletion shortages for Milk River Project users by 483 AF or 1.7 percent relative to the historical baseline simulation (i.e., no strategy). 2050 future scenarios were impacted similarly, with increases in total annual depletion shortages for Milk River Project users ranging from 297 to 485 AF (0.8 to 1.2 percent) from the respective baseline simulations. The largest impact on Milk River Project user was noted in the paleo drought events up to a 4.1 percent increase in annual avg depletion shortages.

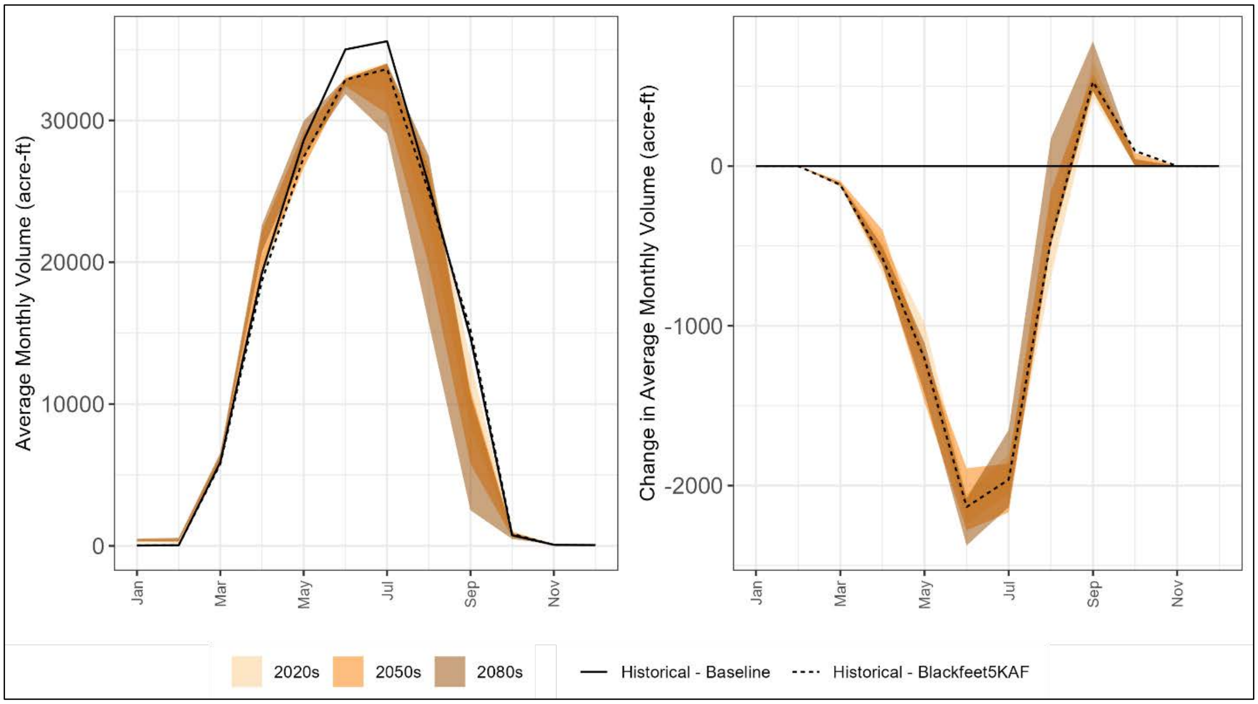

Figure 97.—North Milk River near International Boundary average monthly flow volumes for the 5000 acre-feet for Blackfeet Tribe (Compact) strategy (left panel) and the change in those average monthly flow volumes from the baseline scenarios (right panel).[21]

Proposed 60 KAF Off-stream Storage Project in Fort Belknap Compact

The Fort Belknap Compact, negotiated between the State of MT and the Ft. Belknap Indian Community, was passed by the MT Legislature in 2001. At the time of publication of this report, the Tribes are in negotiations for a settlement with the federal government. The Fort Belknap Indian Reservation Compact provides the Tribes with first priority of the U.S. share of Milk River natural flow. The first 125 cfs of natural flow is for an existing irrigation project with a maximum of 10,425 acres, and the next 520 cfs of natural flow for direct use and/or storage up to 60,000 acre-ft annually from the Milk River. The FBIIP currently receives 1/7 of Fresno

[21] Futures results are presented as a range of 5 future scenarios for each future period compared to their corresponding baseline simulation.

Reservoir storage (which only includes Milk River water and is not currently represented in the model). This strategy helps prepare for the implementation of the Fort Belknap Compact by evaluating the 60 KAF off-stream storage project.

Implementation of this strategy required updating the St. Mary and Milk Rivers planning model to represent the proposed 60 KAF off-stream storage projected, referred to as Peoples Creek Reservoir, and the Peoples Creek Irrigation Project, planned in the FBIC Comprehensive Water Development Plan (NRCE 2019). The proposed reservoir is on Peoples Creek upstream of the Peoples Creek near Hays gage and the confluence with Little Peoples Creek. Implementation of this project also includes the People's Creek Irrigation Project which sits just upstream of the confluence but below the gage. People's Creek Irrigation Project is assumed to include 1,107 irrigated acres. Additionally, part of the plan includes rehabilitation of irrigation on Little Peoples Creek and Beaver Creek of 2,194 and 1,239 acres, respectively. Fort Belknap water users irrigated acreage was also increased from the current actively irrigated 3,404 acres in the baseline model (determined through GIS analysis, discussed in the Water Demand Assessment) to the full historical use of 10,425 acres.

Performance and Trade-Offs

End-of-month pool elevations in the proposed 60 KAF off-stream storage reservoir are presented on figure 98. Historical and futures results show the highest reservoir storage in April prior to the beginning of the irrigation season. The future scenarios show large ranges of potential EOWY pool elevations for the new reservoir, especially for the 2080s period, which are mostly below the historical reference period simulation (historical baseline), indicating less potential storage carryover in the future scenarios.

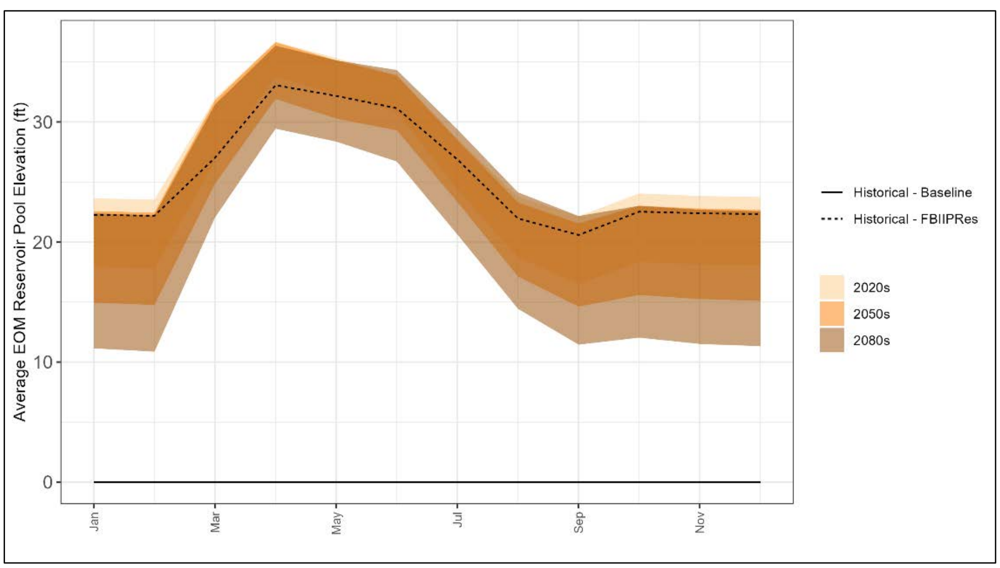

Figure 98.—FBIIP Reservoir projected average end-of-month pool elevation for the proposed 60 KAF off-stream storage project.[22]

[22] Futures results are presented as a range of 5 future scenarios for each future period.

Selected assessment measures for the proposed 60 KAF off-stream storage project are presented on figure 99. All scenarios show increases in avg annual total depletions and decreases in avg annual total depletion shortages, relative to their respective baseline simulations. For the historical scenario, avg annual total depletions increased by more than 30 KAF, a 23.5 percent increase from the baseline simulation. Even larger increases in avg annual total depletions are shown in the future scenarios between 37 to 39 KAF. Paleo drought scenarios also show increases in avg annual total depletions around 22 to 25 percent from the baseline simulation. These increases in avg annual total depletions are accounted for by increases in depletions to FBIC water users, rather than Milk River Project water users. Implementation of the proposed 60 KAF off-stream storage project does result in small increases in Milk River Project user avg annual total depletion shortages for the historical reference period of 1,150 AF (2.1 percent), and for the 2050s future scenarios from 174 (WW) to 1,210 AF (CT) relative to the corresponding baseline simulations. Impacts on Milk River Project users were variable for paleo drought events, ranging from a 3,000 AF increase (MRWIB LAD Inst drought) to 1,570 AF decrease (MRWIB LAD 1) in avg annual total depletion shortages from the baseline simulation.

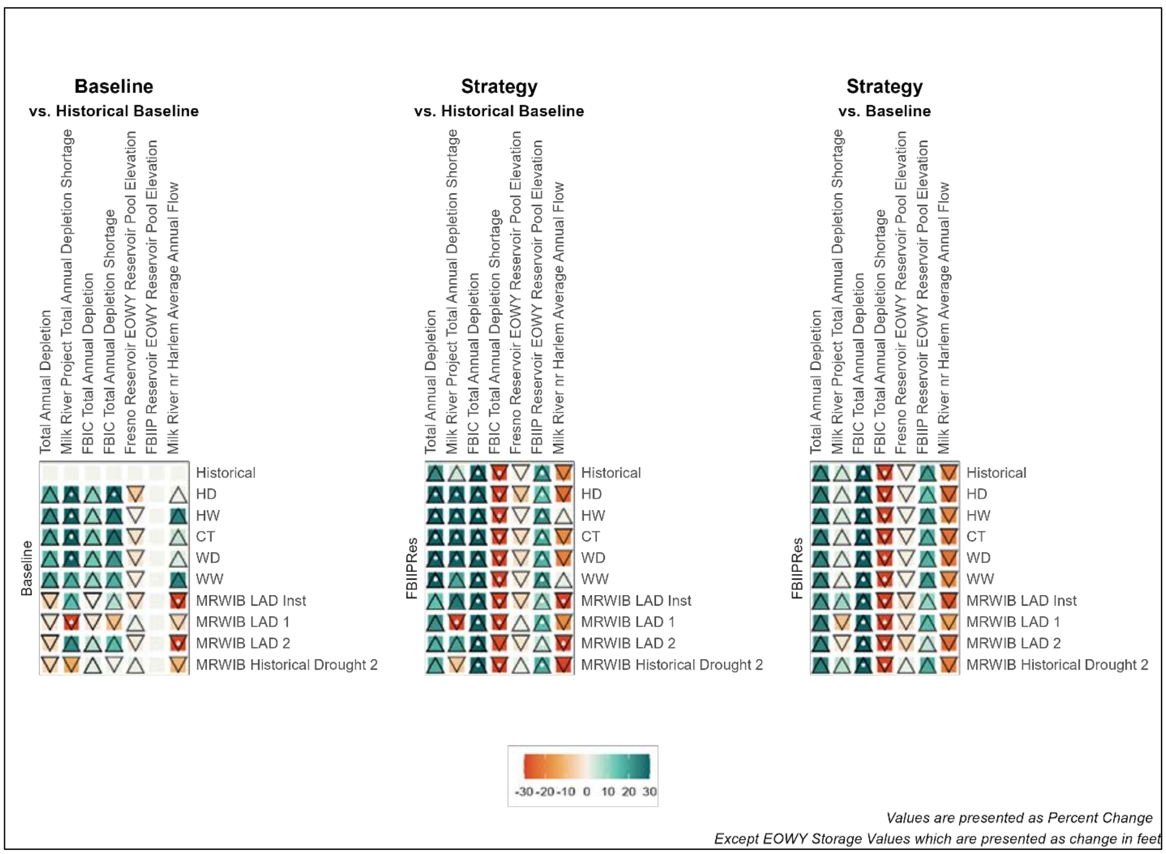

Figure 99.—Comparison chart of selected assessment measures for the proposed 60 KAF off-stream storage project strategy relative to the baseline scenarios.[23]

[23] Results presented include historical, 2050s futures and selected paleo drought event scenarios.

The avg annual total flow volumes at the Milk River near Harlem, downstream from the proposed 60 KAF off-stream storage project, decreased for all scenarios (see figure 99). The avg monthly flow volumes at Milk River near Harlem, are presented on figure 100. Results show an overall decrease in streamflow below the proposed reservoir for historical and future scenarios. The future scenarios all show higher early spring flows with corresponding greater decreases in early spring flows with the proposed reservoir in comparison to the baseline simulation. Additionally, the lower late summer flows in the futures scenarios compared to the historical baseline were further depleted by the implementation of the proposed 60 KAF reservoir.

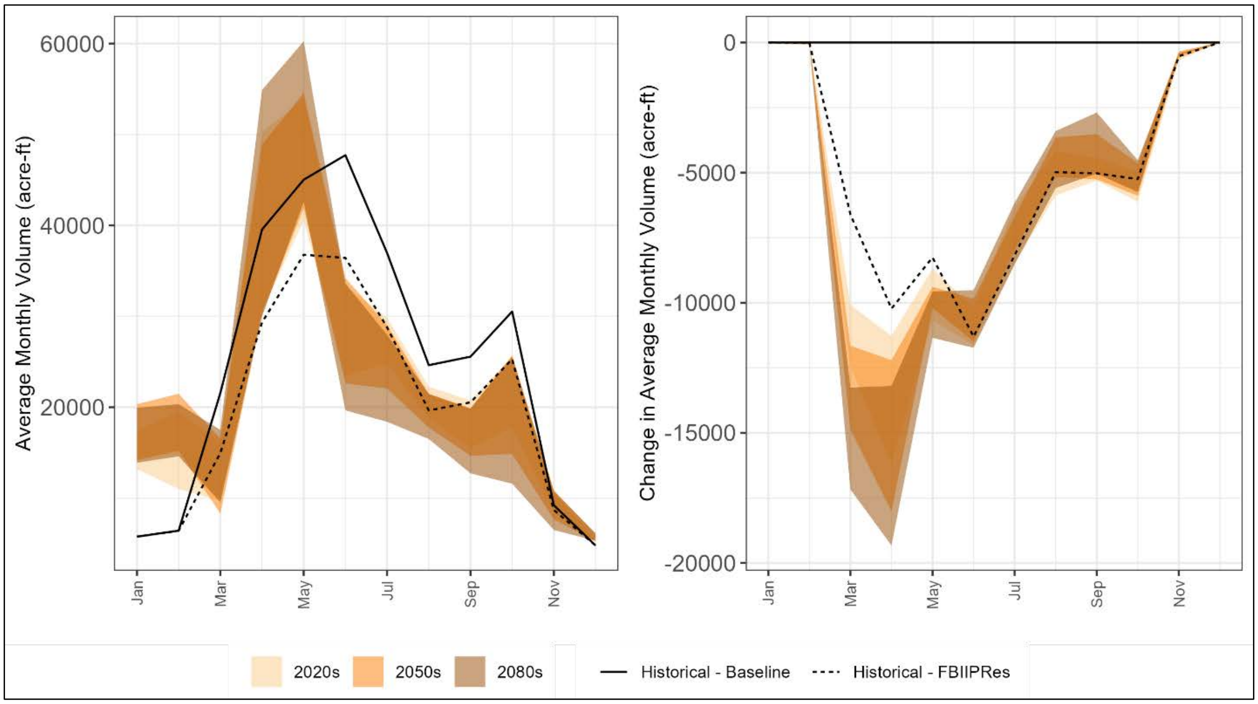

Figure 100.—Milk River near Harlem (downstream from the FBIIP Reservoir) average monthly flow volumes for the 5,000 acre-feet for proposed 60 KAF off-stream storage project strategy (left panel) and the change in those average monthly flow volumes from the baseline scenarios (right panel).[24]

Mitigating Future Water Uses

This section evaluates strategies to mitigate the future water uses presented in the previous section. These mitigation strategies include:

- Development of the Duck Creek Canal to provide water from Ft. Peck Reservoir.
- Implementation and operation of the Nelson Pumps.
- Increasing the capacity of the Dodson South Canal.

[24] Futures results are presented as a range of 5 future scenarios for each future period compared to their corresponding baseline simulation.

These mitigation strategies were evaluated individual and together in a final strategy to address the 35,000 AF for the Fort Belknap Water Rights settlement.

Duck Creek Canal

Duck Creek canal would convey water from the Ft. Peck Reservoir via a new canal to the Milk River above Vandalia dam. In the St. Mary and Milk Rivers planning model, the Duck Creek canal is represented with a capacity of 200 cfs, with no losses along the canal, and with a continuously available water supply. This strategy is implemented in addition to the St. Mary and Milk Rivers planning model changes in the proposed 60 KAF off-stream storage project strategy.

Performance and Trade-Offs

A comparison of selected assessment measures for the Duck Creek Canal strategy relative to the proposed 60 KAF off-stream storage project strategy are presented on figure 101. All scenarios show decreases in avg annual total depletion shortages and increases in avg annual streamflow volumes at Milk River near Vandalia below the outlet of the Duck Creek Canal into the Milk River. A significant volume of inflows from the Duck Creek Canal were immediately taken by irrigators closest to the outlet of the Duck Creek Canal, this is shown by the increase in annual avg diversions to private irrigators from Nelson to Vandalia for all scenarios. The Duck Creek canal also supplied other downstream water users, with reductions in Milk River Project total annual depletion shortages for the 2050s future scenarios relative to the baseline simulations.

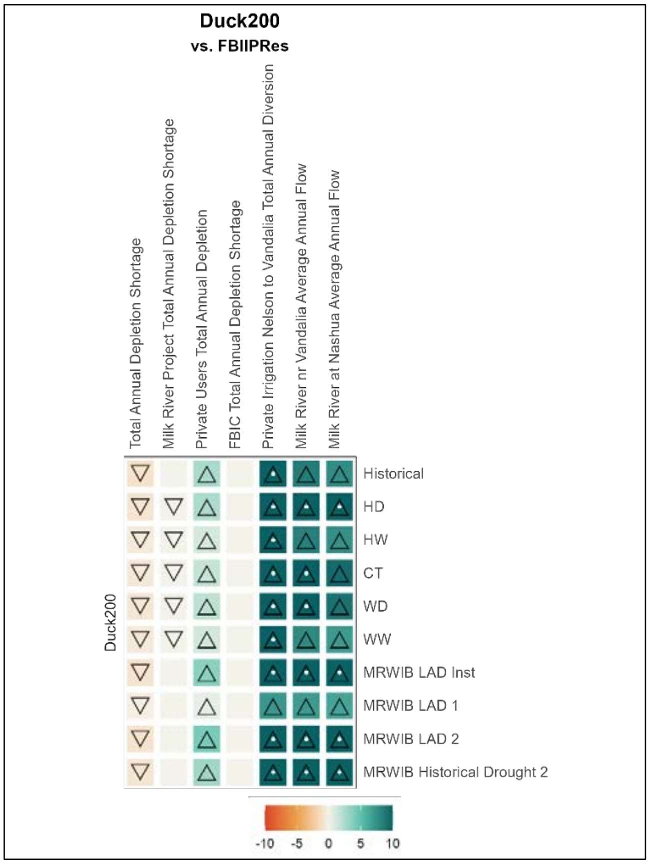

Figure 101.—Comparison chart of selected assessment measures for the Duck Creek canal strategy relative to the proposed 60 KAF off-stream storage project strategy. [25]

A comparison of avg annual total depletion shortages for the Duck Creek Canal strategy compared to the baseline scenarios and the proposed 60 KAF off-stream storage project strategy, which share similar irrigated acreages as the Duck Creek Canal strategy, are provided in table 28. The avg annual total depletion shortages for the Duck Creek Canal strategy decreased for all scenarios, in comparison to both the baseline and proposed 60 KAF off-stream storage project strategy. Impacts of the Duck Creek Canal on Milk River Project users' depletion shortages were minimal relative to the proposed 60 KAF off-stream storage project strategy (table 29) with small 1 to 2 AF changes in some of the 2050s future scenarios.

[25] Results presented include historical, 2050s futures and selected paleo drought event scenarios. Results are compared to the proposed 60 KAF off-stream storage project strategy simulations with the same climate conditions.

Table 28.—Duck Creek Canal strategy average annual total depletion shortages compared to the baseline scenarios and proposed 60 KAF off-stream storage project (FBIIPRes) strategy

Scenario	Baseline avg annual total depletion shortage (AF/yr)	FBIIPRes		Duck200		
		Avg annual total depletion shortage (AF/yr)	Change from baseline	Avg annual total depletion shortage (AF/yr)	Change from baseline	Change from FBIIPRes
Historical	79,507	64,885	-14,622	64,284	-15,223	-601
HD	116,819	98,587	-18,232	97,827	-18,993	-760
HW	95,530	75,326	-20,204	74,984	-20,546	-342
CT	102,395	82,943	-19,452	82,444	-19,951	-499
WD	97,881	79,371	-18,510	78,811	-19,070	-560
WW	86,541	66,566	-19,975	66,213	-20,329	-354
MRWIB LAD Inst	94,141	83,699	-10,442	82,967	-11,174	-732
MRWIB LAD 1	61,727	44,048	-17,679	43,943	-17,785	-105
MRWIB LAD 2	103,537	91,355	-12,182	90,552	-12,985	-803
MRWIB Hist 2	85,335	70,347	-14,988	69,793	-15,542	-554

Table 29.—Duck Creek Canal strategy Milk River Project users' average annual total depletion shortages compared to the baseline scenarios and proposed 60 KAF off-stream storage project (FBIIPRes) strategy

Scenario	Baseline avg annual (AF/yr)	FBIIPRes		Duck200		
		Avg annual (AF/yr)	Change from baseline	Avg annual (AF/yr)	Change from baseline	Change from FBIIPRes
Historical	27,650	28,800	1,149	28,800	1,149	0
HD	49,054	50,269	1,215	50,267	1,213	-2
HW	38,170	39,199	1,029	39,198	1,028	-1
CT	40,069	40,920	851	40,919	850	-1
WD	37,294	38,152	858	38,152	858	0
WW	32,725	32,899	174	32,899	174	0
MRWIB LAD Inst	31,943	34,956	3,013	34,956	3,013	0
MRWIB LAD 1	17,690	16,117	-1,572	16,117	-1,572	0
MRWIB LAD 2	34,027	33,117	-910	33,117	-910	0
MRWIB Hist 2	23,935	25,450	1,515	25,450	1,515	0

Nelson Pumps

The Nelson pumps divert flow from the Milk River to the Nelson Reservoir. In the St. Mary and Milk Rivers planning model, the Nelson pumps divert flow from the Milk River below the return flow point of seepage from the Nelson Reservoir, allowing the Nelson pumps to effectively return Nelson seepage to the Nelson Reservoir. A 50 cfs pump capacity for the Nelson pumps was implemented to model this strategy as well as a 10 cfs minimum bypass based on preliminary design documents (Reclamation 1999). Additional refinement of the water rights to supply the Nelson pumps is needed, however, here we assume that pumping was not limited by water rights. This strategy is implemented in addition to the St. Mary and Milk Rivers planning model changes in the proposed 60 KAF off-stream storage project strategy.

Performance and Trade-Offs

The avg monthly diversion volumes for the Nelson Pumps for historical and futures scenarios are presented on figure 102. The historical scenario shows peak diversions through the Nelson pumps in May; however, the future scenarios show higher diversion volumes in the late winter and early spring months likely due to earlier spring snowmelt and peak flows.

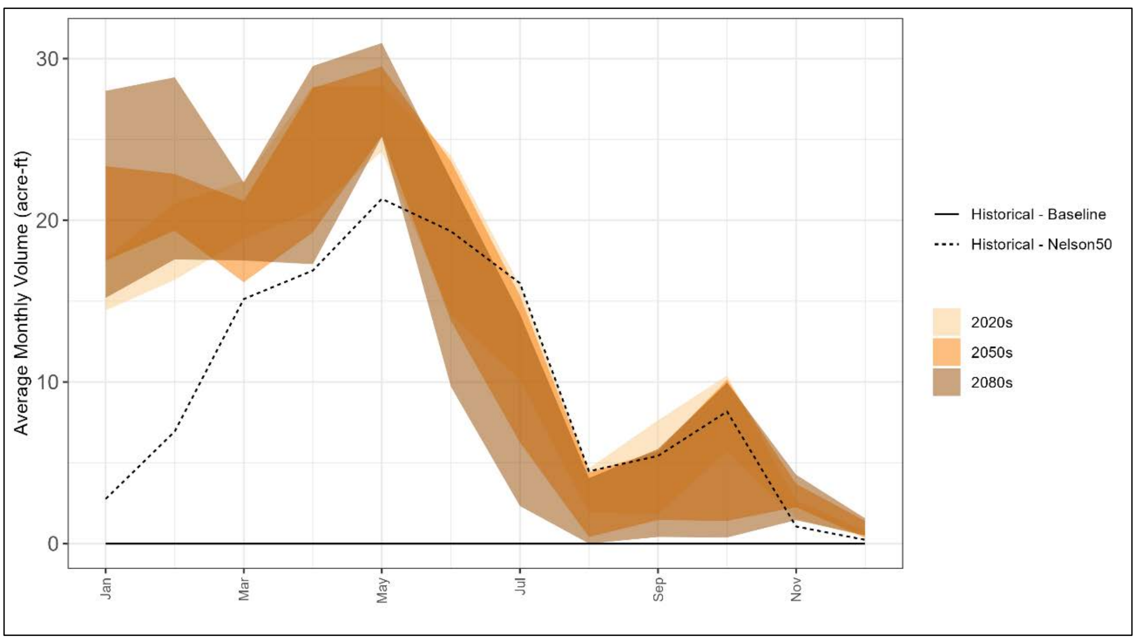

Figure 102.—Nelson Pump average monthly diversion volumes for the Nelson Pump strategy compared to the baseline scenarios.[26]

[26] Futures results for the Nelson Pump strategy are presented as a range of 5 future scenarios for each future period.

A comparison of selected assessment measures for the Nelson Pump strategy relative to the proposed 60 KAF off-stream storage project strategy are shown on figure 103. All scenarios show consistent results in regard to declines in avg annual total depletion shortages, with a 580 AF decline for the historical baseline and a 1,180 to 1,580 AF decline in the 2050s future scenario from the proposed 60 KAF off-stream reservoir strategy. All scenarios also indicate a decline in avg annual Milk River Project users' total depletion shortages of 640 AF in the historical baseline up to 1,530 AF in the 2050s HD scenario. Specifically, operation of the Nelson Pumps increased Lower Malta diversions, which divert water from the Nelson Reservoir to Lower Malta ID via the Lower Nelson Canal. Operation of the Nelson pumps also led to a decline in avg annual Malta South Diversions from the Milk River upstream of the Nelson Pump diversion.

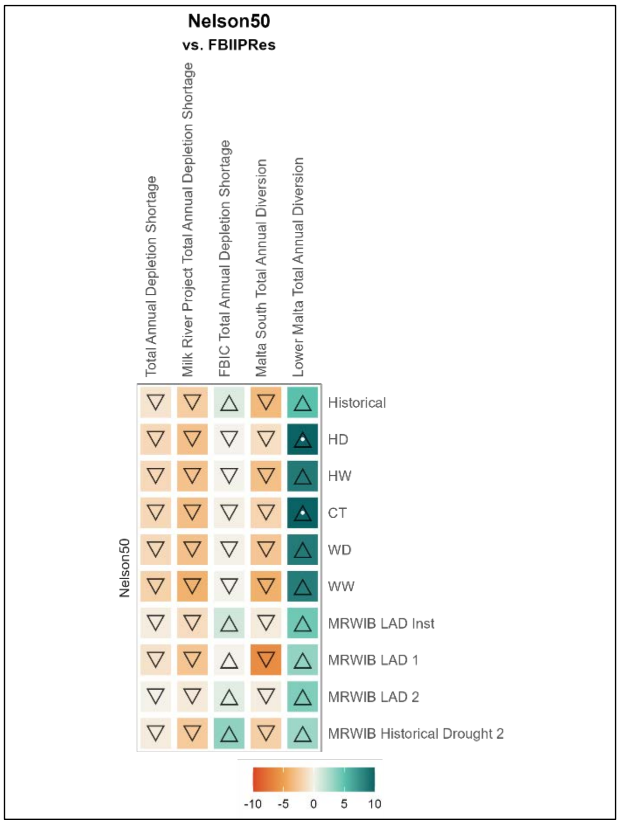

Figure 103.—Comparison chart of selected assessment measures for the nelson pumps strategy relative to the proposed 60 KAF off-stream storage project strategy.[27]

[27] Results presented include Historical, 2050s futures and selected paleo drought event scenarios. Results are compared to the proposed 60 KAF off-stream storage project strategy simulations with the same climate conditions.

The impacts of Nelson pump diversions on avg end-of-month Nelson Reservoir pool elevation are presented on figure 104. Operation of the Nelson Pumps resulted in higher pool elevations in the Nelson Reservoir for the historical and all future scenarios throughout the year, with the highest increases in pool elevation during the summer months for the historical baseline and during the spring for the futures scenarios.

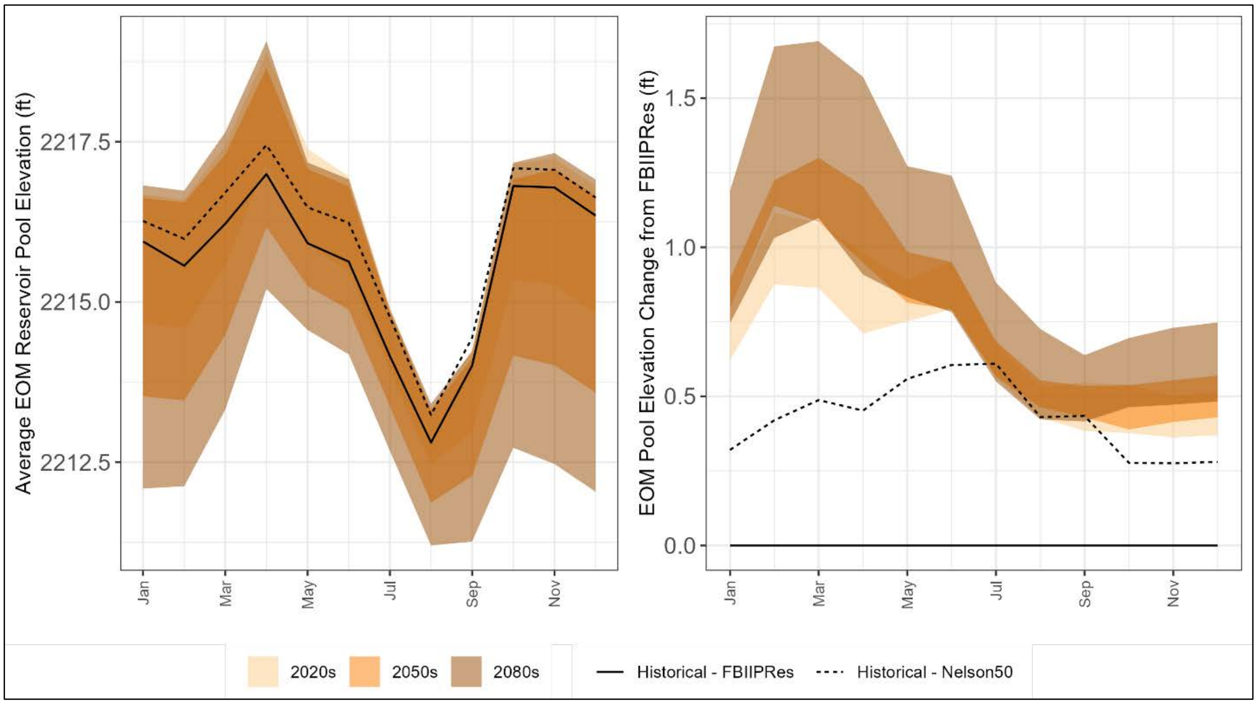

Figure 104.—Nelson Reservoir average end-of-month pool elevation for the Nelson Pumps strategy (left panel) and the change in those average end-of-month pool elevation from the proposed 60 KAF off-stream storage project strategy (right panel).[28]

Dodson South Canal Capacity Increase

The Dodson South Canal diverts water from the South Dodson Canal, which is fed by Malta South Diversions from the Milk River above Dodson, to the Upper Malta ID. Dodson South Canal capacity increases are represented in the St. Mary and Milk Rivers planning model as an increase of the Malta South Canal diversion object in the model. For this strategy, the Malta South Canal diversion capacity is increased from 500 to 700 cfs. Combined diversion limits are maintained in the model as determined by water rights and the sum of Dodson North and South diversions. This strategy is implemented in addition to the model changes in the proposed 60 KAF off-stream storage project strategy.

[28] Futures results are presented as a range of 5 future scenarios for each future period compared to their corresponding proposed 60 KAF off-stream storage project strategy.

Performance and Trade-Offs

The avg monthly Malta South diversion volumes and changes from the proposed 60 KAF off-stream storage project strategies are presented on figure 105. Except for monthly avg Malta South diversion in October and November, monthly diversions increase for all months in the historical and all future scenarios. Malta South diversion volume increases are greatest for the future scenarios in the spring months during snowmelt (April through June).

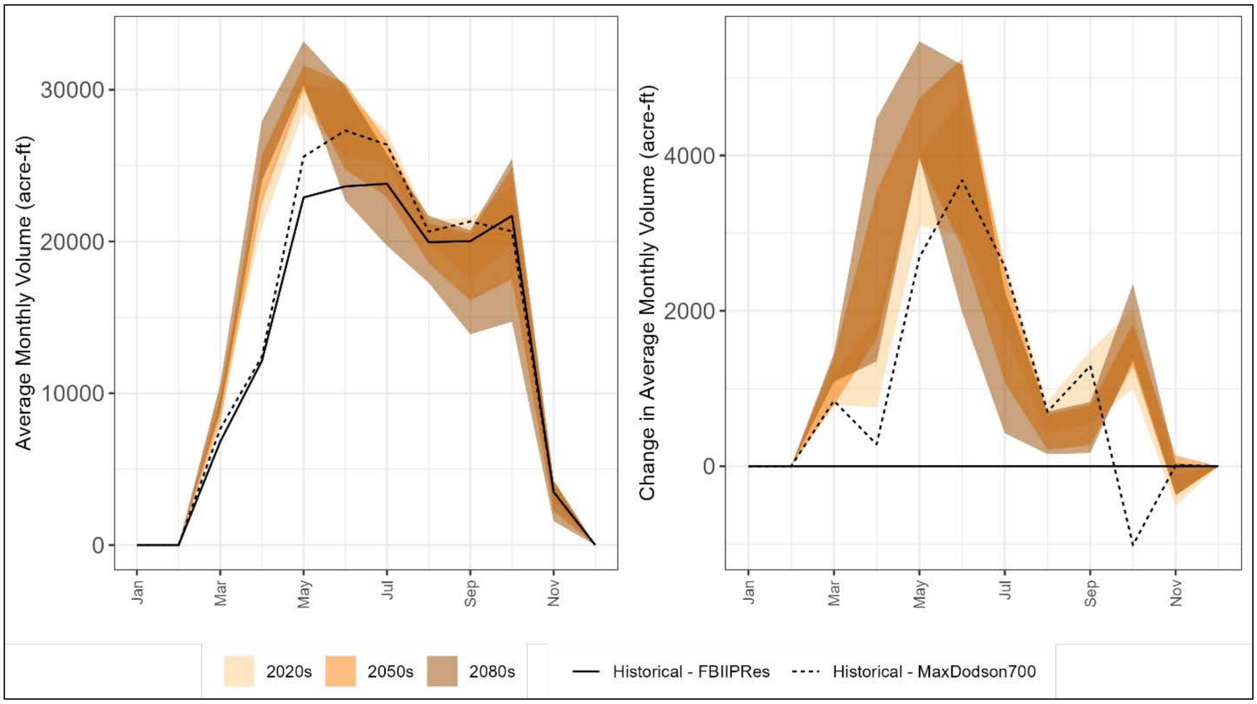

Figure 105.—Malta South average monthly diversion volumes for the Dodson South Canal Capacity Increase strategy (left panel) and the change in those average monthly diversion volumes from the baseline scenarios (right panel).[29]

A comparison of selected assessment measures for the Dodson South Canal Capacity Increase strategy relative to the proposed 60 KAF off-stream storage project strategy is presented on figure 106. All scenarios show an increase in avg annual Malta South Diversion volumes, with the largest percent increases in the 2050s future scenarios ranging from 9.0 to 10.5 percent compared to the historical which noted a 7.2 percent increase from the proposed 60 KAF off-stream storage project. The paleo drought event scenarios saw an increase in Malta South Diversions, but these increases were relatively small compared to the futures, which saw an increase of 3.0 to 5.2 percent from the proposed 60 KAF off-stream storage project strategy.

[29] Futures results are presented as a range of 5 future scenarios for each future period compared to their corresponding baseline simulation.

Increases in Malta South Diversions resulted in decreased downstream flows at the Milk River near Dodson gage for all scenarios up to a 13.7 percent decrease in avg annual total flow volumes during the 1931 to 1946 MRWIB LAD Inst drought.

The avg annual total depletion shortages decreased for all water users and for Milk River project users across all scenarios. Historical scenario annual avg total depletion shortages decreased from the proposed 60 KAF off-stream storage strategy by 1,000 AF (1.5 percent) and 1,050 AF for all water users and for Milk River Project water users, respectively. Future scenarios saw greater decreases, relative to the proposed 60 KAF off-stream storage strategy, in avg annual total depletion shortages ranging from 1,870 to 1,930 AF (2.3 to 2.8 percent) for all water users and 1,810 to 1,900 AF (3.8 to 5.5 percent) for Milk River Project water users. The paleo drought event scenarios also showed declines in avg annual shortages ranging from 300 to 720 AF (0.3 to 1.0 percent) for all water users and 420 to 1,020 AF (1.4 to 4.0 percent) for Milk River Project users. Results indicate that the Malta South Diversion strategy is helpful for mitigating impacts on water users in all scenarios, but most effective for future scenarios.

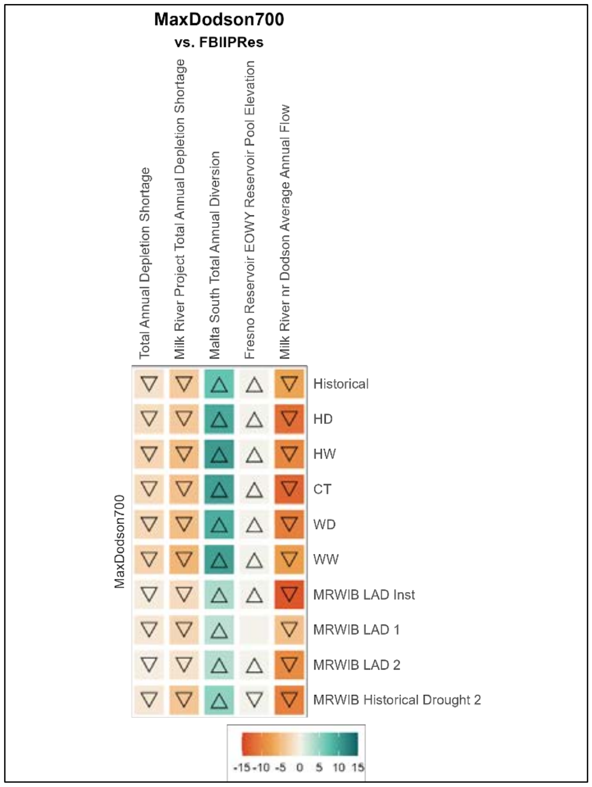

Figure 106.—Comparison chart of selected assessment measures for the Dodson South Canal Capacity Increase strategy relative to the proposed 60 KAF off-stream storage project strategy simulations.[30]

Mitigate 35,000 Acre-feet (AF) for Fort Belknap Water Rights Settlement Implementation

This strategy was initially presented as part of the Fort Belknap Compact. It includes the implementation of the proposed 60 KAF off-stream storage project strategy in combination with several previous mitigation strategies including the system wide water management strategy to raise the Fresno dam and mitigating future water use strategies including the operation of the Nelson Pumps, Duck Creek Canal, and the Dodson South Canal Capacity increase.

Performance and Trade-offs

Results for the Mitigate 35,000 AF for the Forth Belknap Water Rights Settlement strategy are compared to the proposed 60 KAF off-stream storage project with selected assessment measures on figure 107. The avg annual total depletion shortages and Milk River Project user depletion shortages were reduced by implementation of the mitigation measures in all scenarios. The

[30] Results presented include historical, 2050s futures and selected paleo drought event scenarios. Results are compared to the proposed 60 KAF off-stream storage project strategy simulations with the same climate conditions.

impact on FBIC total annual depletion shortages varies, with declines for the historical and 2050s futures scenarios and increases during paleo drought event scenarios. These results would indicate that implementation of mitigation measures helps alleviate increased shortages to Milk River Project users while slightly increasing irrigation shortages to FBIC water users and decreasing EOWY storage in the off-stream reservoir during the paleo drought events.

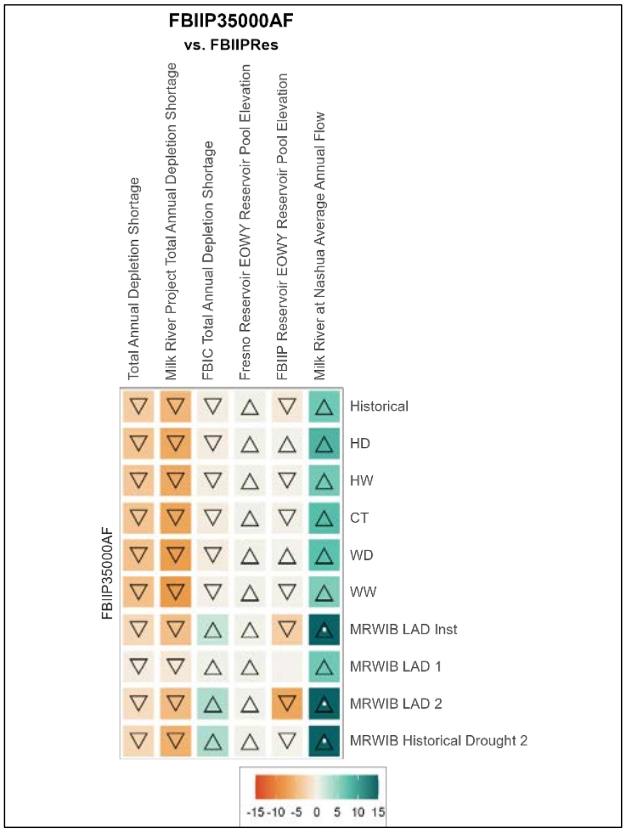

Figure 107.—Comparison chart of selected assessment measures for the Mitigate 35,000 acre-feet for Fort Belknap Water Use strategy relative to the proposed 60 KAF off-stream storage project strategy.[31]

Additional details on changes in depletion shortages for all water users and for Milk River Project water users are provided in table 30 and table 31, respectively. The Mitigate 35,000 AF for Forth Belknap Water Rights Settlement strategy shows significant reductions in avg annual total depletion shortages for all water users in all scenarios, up 23 KAF in the WW 2050 future scenario and over 12 KAF for all paleo drought event scenarios relative to the historical baseline. Implementation of the multiple mitigation strategies with the proposed 60 KAF off-stream

[31] Results presented include historical, 2050s futures and selected paleo drought event scenarios. Results are compared to the proposed 60 KAF off-stream storage project strategy simulations with the same climate conditions.

storage strategy shows declines in annual avg Milk River Project users total depletion shortages for the historical and 2050s future scenarios, however, it's unable to mitigate all impacts on Milk River Project users, specifically during MRWIB LAD Inst drought and the MRWIB Hist 2.

Table 30.—Change in annual average total depletion shortages for all water users*

Scenario	Baseline	Fresno3	FBIIP35000AF	FBIIPRes	Duck 200	Nelson 50	MaxDodson 700	FBIIP35000AF
		Change from baseline			Change from FBIIPRes			
Historical	79,507	-641	-16,843	64,885	-601	-577	-998	-2,220
HD	116,819	-1,058	-22,359	98,587	-760	-1,583	-1,960	-4,127
HW	95,530	-270	-23,172	75,326	-342	-1,184	-1,931	-2,968
CT	102,395	-720	-22,882	82,943	-499	-1,347	-1,896	-3,430
WD	97,881	-967	-22,091	79,371	-560	-1,218	-1,883	-3,581
WW	86,541	-669	-22,998	66,566	-354	-1,334	-1,873	-3,023
MRWIB LAD Inst	94,141	-589	-12,450	83,699	-732	-301	-544	-2,009
MRWIB LAD 1	61,727	501	-17,910	44,048	-105	-451	-426	-231
MRWIB LAD 2	103,537	-907	-13,949	91,355	-803	-64	-301	-1,767
MRWIB Hist 2	85,335	-111	-16,704	70,347	-554	-310	-724	-1,716

* The Fresno dam raise (Fresno 3) is compared to the baseline simulation. All other strategies are compared to the proposed 60 KAF off-stream storage project strategy.

Table 31.—Change in annual average Milk River Project users' total depletion shortage*

Scenario	Baseline	Fresno3	FBIIP35000AF	FBIIPRes	Duck 200	Nelson 50	MaxDodson700	FBIIP 35000 AF
		Change from baseline			Change from FBIIPRes			
Historical	27,650	-581	-412	28,800	0	-642	-1,041	-1,562
HD	49,054	-1,012	-2,085	50,269	-2	-1,527	-1,902	-3,300
HW	38,170	-261	-1,531	39,199	-1	-1,158	-1,883	-2,560
CT	40,069	-675	-1,989	40,920	-1	-1,287	-1,834	-2,840
WD	37,294	-920	-2,077	38,152	0	-1,161	-1,813	-2,934
WW	32,725	-631	-2,461	32,899	0	-1,296	-1,818	-2,636
MRWIB LAD Inst	31,943	-533	1,401	34,956	0	-471	-709	-1,612
MRWIB LAD 1	17,690	476	-1,734	16,117	0	-449	-415	-162
MRWIB LAD 2	34,027	-853	-2,551	33,117	0	-180	-449	-1,640
MRWIB Hist 2	23,935	-131	6	25,450	0	-630	-1,026	-1,509

* The Fresno dam raise (Fresno 3) is compared to the baseline simulation. All other strategies are compared to the proposed 60 KAF off-stream storage project strategy (FBIIPRes).

Combined Strategies

Additional strategies were evaluated to assess the combined impact of the system wide water management, providing water for future use, and mitigating future water use strategies detailed in the previous sections. These combined strategies include:

- Combined Strategy 1a: evaluates the combined impact of canal capacity increases for the Dodson South Canal from 500 to 700 cfs and for the St. Mary Canal from 600/650 cfs to 800/850 cfs.
- Combined Strategy 1b: evaluates the combined impacts of the canal capacity increases in the Combined Strategy 1a along with the proposed 60 KAF off-stream storage project strategy.
- Combined Strategy 2a: evaluates the impact of the Fresno Reservoir Capacity Increase strategy in combination with the St. Mary Canal Capacity increase.
- Combined Strategy 2b: evaluates the Combined Strategy 2a with the addition of the proposed 60 KAF off-stream storage project.

- Combined Strategy 3: evaluated the combination of most of the strategies detailed in the above section, specifically, the Conveyance and On-Farm Efficiency Improvements, the Fresno Reservoir Capacity Increase, the St. Mary Canal Capacity Increase, operation of the Nelson Pumps, Duck Creek Canal, and the proposed 60 KAF off-stream storage project.

Performance and Trade-Offs

A summary comparison of selected assessment measures for the combined strategies compared to the baseline simulation is presented on figure 108. A quick review of the figure shows that all combined strategies reduce annual avg total depletion shortages and annual avg Milk River Project users' total depletion shortages in all scenarios. Combined Strategies 1b and 2b which include the proposed 60 KAF off-stream storage reservoir result in decrease system outflows at the Milk River at Nashua gage; however, the Combined Strategy 3 which includes the conveyance and on-farm efficiency improvements increase annual avg streamflow volumes at the Milk River at Nashua gage.

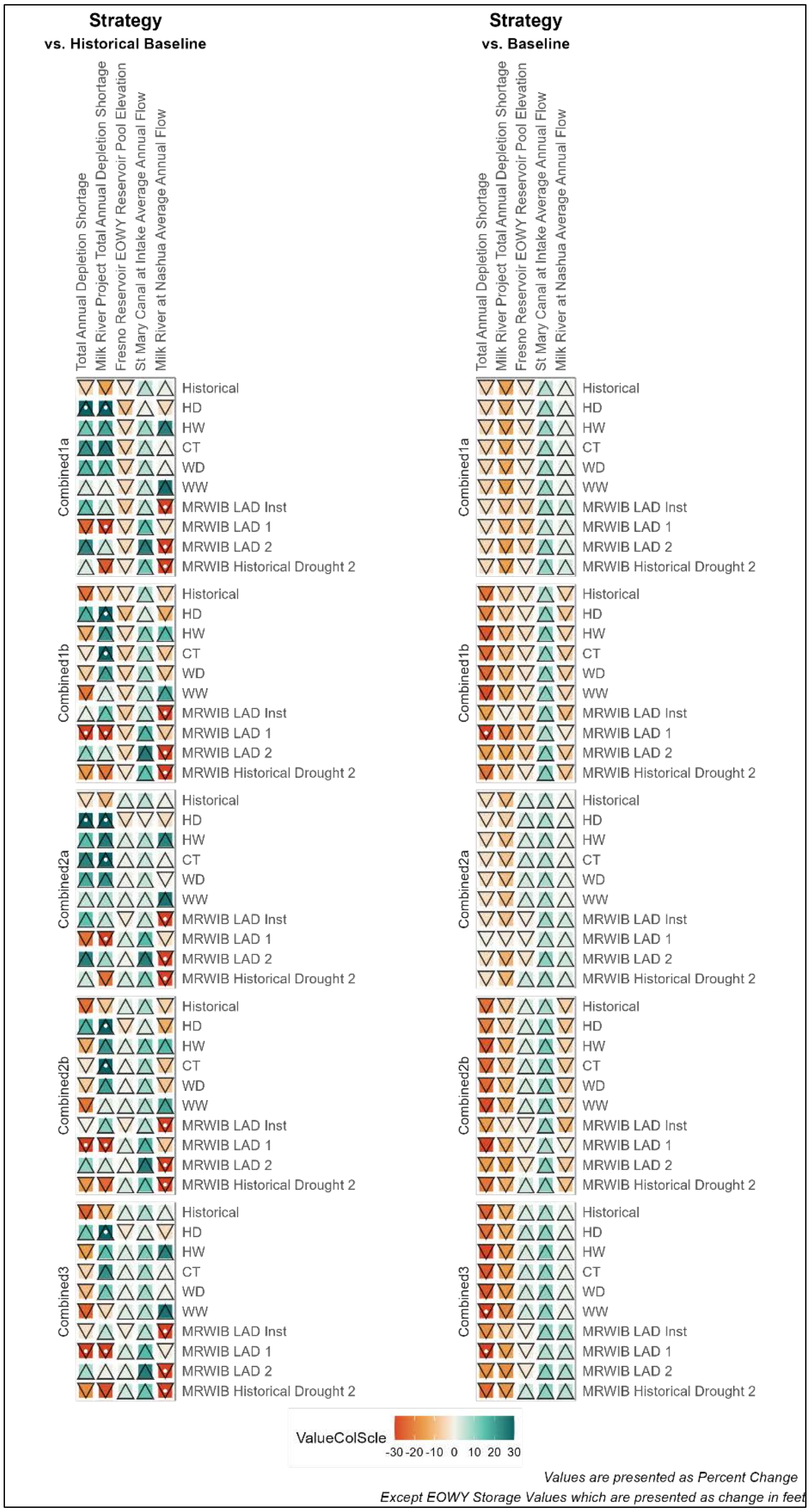

Figure 108.—Comparison chart of selected assessment measures for the Combined strategies relative to the baseline scenarios.[32]

[32] Results presented include historical, 2050s futures and selected paleo drought event scenarios.

Impacts of the Combined Strategies 1a and 1b on depletion shortages were evaluated for all water users and Milk River Project users in table 32 and table 33, respectively. The Combined Strategies 1a and 1b include capacity increases on the St. Mary Canal and Dodson South Canals, combining these strategies is effective both with and without the proposed 60 KAF off-stream storage project strategy for all scenarios. These combined strategies are also more effective than the individual strategies in reducing total annual depletion shortages for Milk River Project users, during the historical, future, and paleo drought event scenarios both with and without the proposed 60 KAF off-stream storage project strategy. The majority of the depletion shortage reductions were to Milk River Project users, accounting for 95 percent of shortage reductions for all water users in the historical baseline scenario relative to the proposed 60 KAF off-stream storage project strategy alone. Similarly, futures scenarios showed 95 to 97 percent of shortage reductions to all water users go to Milk River Project users. This is more extreme for the drought scenarios where reductions in annual avg Milk River Project users' depletion shortages were higher than total depletion shortage declines, indicating that while Milk River Project users saw declines in depletion shortages overall, other user groups saw moderate increases.

Table 32.—Change in annual average total depletion shortage for all water users*

Scenario	Baseline	Canal850	Combined1a	FBIIPRes	MaxDodson700	Combined1b
		Change from Baseline (AF/yr)			Change from FBIIPRes (AF/yr)	
Historical	79,507	-2,526	-4,145	64,885	-998	-3,663
HD	116,819	-2,629	-5,631	98,587	-1,960	-5,195
HW	95,530	-3,079	-5,537	75,326	-1,931	-5,527
CT	102,395	-2,804	-5,336	82,943	-1,896	-5,113
WD	97,881	-2,873	-5,287	79,371	-1,883	-5,196
WW	86,541	-2,563	-5,075	66,566	-1,873	-4,759
MRWIB LAD Inst	94,141	-1,950	-3,087	83,699	-544	-3,305
MRWIB LAD 1	61,727	-1,898	-1,935	44,048	-426	-1,940
MRWIB LAD 2	103,537	-4,464	-5,321	91,355	-301	-3,739
MRWIB Hist 2	85,335	-2,209	-3,842	70,347	-724	-3,861

* Results for the St. Mary Canal Capacity increase and Combined Strategy 1a are compared to the baseline simulation. Results for the Dodson South Canal Capacity increase and Combined Strategy 1b are compared to the proposed 60 KAF off-stream storage project strategy (FBIIPRes).

Table 33.—Change in annual average total depletion shortage for Milk River Project users*

Scenario	Baseline	Canal850 Change from Baseline (AF/yr)	Combined1a Change from Baseline (AF/yr)	FBIIPRes	MaxDodson700 Change from FBIIPRes (AF/yr)	Combined1b Change from FBIIPRes (AF/yr)
Historical	27,650	-2,369	-3,918	28,800	-1,041	-3,478
HD	49,054	-2,516	-5,413	50,269	-1,902	-5,040
HW	38,170	-2,933	-5,319	39,199	-1,883	-5,308
CT	40,069	-2,671	-5,135	40,920	-1,834	-4,902
WD	37,294	-2,734	-5,051	38,152	-1,813	-4,958
WW	32,725	-2,460	-4,890	32,899	-1,818	-4,549
MRWIB LAD Inst	31,943	-1,843	-2,952	34,956	-709	-3,366
MRWIB LAD 1	17,690	-1,882	-1,920	16,117	-415	-1,898
MRWIB LAD 2	34,027	-4,402	-5,202	33,117	-449	-4,313
MRWIB Hist 2	23,935	-2,054	-3,643	25,450	-1,026	-3,888

* Results for the St. Mary Canal Capacity increase and Combined Strategy 1a are compared to the baseline simulation. Results for the Dodson South Canal Capacity increase and Combined Strategy 1b are compared to the proposed 60 KAF off-stream storage project strategy (FBIIPRes).

Impacts of the Combined Strategies 2a and 2b on avg annual depletion shortages were evaluated for all water users and Milk River Project users in table 34 and table 35, respectively. Similar to the Combined Strategies 1a and 1b, these strategies saw reductions in depletion shortages that are mainly accounted for by the reductions in Milk River Project users' depletion shortages, accounting for 91 percent and 95 to 96 percent of all reductions in depletion shortages for the historical and futures scenarios, respectively. Again, this percentage was even higher during paleo drought events up to 112 percent, again indicating that private and FBIC users saw increases in depletion shortages with the addition of these mitigation measures relative to the proposed 60 KAF off-stream storage project.

Table 34.—Change in annual average total depletion shortage for all water users

Scenario	Baseline	Fresno3	Canal850	Combined2a	FBIIPRes	Combined2b
		Change from Baseline (AF/yr)				Change from FBIIPRes (AF/yr)
Historical	79,507	-641	-2,526	-2,861	64,885	-3,759
HD	116,819	-1,058	-2,629	-3,251	98,587	-5,448
HW	95,530	-270	-3,079	-3,590	75,326	-5,820
CT	102,395	-720	-2,804	-3,434	82,943	-5,179
WD	97,881	-967	-2,873	-3,542	79,371	-5,359
WW	86,541	-669	-2,563	-3,139	66,566	-4,868
MRWIB LAD/ Inst	94,141	-589	-1,950	-2,966	83,699	-4,374
MRWIB LAD 1	61,727	501	-1,898	-234	44,048	-645
MRWIB LAD 2	103,537	-907	-4,464	-4,178	91,355	-4,023
MRWIB Hist 2	85,335	-111	-2,209	-2,803	70,347	-4,190

* Results for the St. Mary Canal Capacity increase and Combined Strategy 1a are compared to the baseline simulation. Results for the Dodson South Canal Capacity increase and Combined Strategy 1b are compared to the proposed 60 KAF off-stream storage project strategy (FBIIPRes).

Table 35.—Change in annual average total depletion shortage for Milk River Project water users*

Scenario	Baseline	Fresno 3	Canal850	Combined2a	FBIIPRes	Combined2b
		Change from Baseline (AF/yr)				Change from FBIIPRes (AF/yr)
Historical	27,650	-581	-2,369	-2,686	28,800	-3,423
HD	49,054	-1,012	-2,516	-3,114	50,269	-5,191
HW	38,170	-261	-2,933	-3,428	39,199	-5,555
CT	40,069	-675	-2,671	-3,293	40,920	-4,914
WD	37,294	-920	-2,734	-3,387	38,152	-5,067
WW	32,725	-631	-2,460	-2,998	32,899	-4,603
MRWIB LAD Inst	31,943	-533	-1,843	-2,820	34,956	-4,270
MRWIB LAD 1	17,690	476	-1,882	-243	16,117	-681
MRWIB LAD 2	34,027	-853	-4,402	-4,021	33,117	-4,505
MRWIB Hist 2	23,935	-131	-2,054	-2,675	25,450	-4,481

* Results for the St. Mary Canal Capacity increase and Combined Strategy 1a are compared to the baseline simulation. Results for the Dodson South Canal Capacity increase and Combined Strategy 1b are compared to the proposed 60 KAF off-stream storage project strategy (FBIIPRes).

The final combined strategy provided the most significant reduction in depletion shortages, up to 8,800 AF reduction in annual avg total depletion shortages from the proposed 60 KAF off-stream storage project for the 2050s HD scenario (table 36). From table 36 it’s clear that the canal efficiency improvements in Combined Strategies 1a and 1b were more effective in reducing depletion shortages across all water users without the proposed 60 KAF off-stream storage project for all scenarios. Whereas the combination of Fresno Storage Improvements and the Fresno Capacity Increase in Combined Strategies 2a and 2b were more effective when combined with the proposed 60 KAF off-stream storage project. This conclusion holds true for reduction in annual avg total depletion shortages for Milk River Project users (table 37).

Table 36.—Change in annual average total depletion shortage for all water users

Scenario	Baseline	Combined1a	Combined2a	FBIIPRes	Combined1b	Combined2b	Combined3
		Change from Baseline (AF/yr)			Change from FBIIPRes (AF/yr)		
Historical	79,507	-4,145	-2,861	64,885	-3,663	-3,759	-5,547
HD	116,819	-5,631	-3,251	98,587	-5,195	-5,448	-8,842
HW	95,530	-5,537	-3,590	75,326	-5,527	-5,820	-7,986
CT	102,395	-5,336	-3,434	82,943	-5,113	-5,179	-7,787
WD	97,881	-5,287	-3,542	79,371	-5,196	-5,359	-7,778
WW	86,541	-5,075	-3,139	66,566	-4,759	-4,868	-6,949
MRWIB LAD Inst	94,141	-3,087	-2,966	83,699	-3,305	-4,374	-6,580
MRWIB LAD 1	61,727	-1,935	-234	44,048	-1,940	-645	-1,210
MRWIB LAD 2	103,537	-5,321	-4,178	91,355	-3,739	-4,023	-5,709
MRWIB Hist 2	85,335	-3,842	-2,803	70,347	-3,861	-4,190	-5,709

* Results for the St. Mary Canal Capacity increase and Combined Strategy 1a are compared to the baseline simulation. Results for the Dodson South Canal Capacity increase and Combined Strategy 1b are compared to the proposed 60 KAF off-stream storage project strategy (FBIIPRes).

Table 37.—Change in annual average total depletion shortage for Milk River Project users

Scenario	Baseline	Combined1a	Combined2a	FBIIPRes	Combined1b	Combined2b	Combined3
		Change from baseline (AF/yr)			Change from FBIIPRes (AF/yr)		
Historical	27,650	-3,918	-2,686	28,800	-3,478	-3,423	-4,824
HD	49,054	-5,413	-3,114	50,269	-5,040	-5,191	-7,750
HW	38,170	-5,319	-3,428	39,199	-5,308	-5,555	-7,397
CT	40,069	-5,135	-3,293	40,920	-4,902	-4,914	-7,042
WD	37,294	-5,051	-3,387	38,152	-4,958	-5,067	-6,970
WW	32,725	-4,890	-2,998	32,899	-4,549	-4,603	-6,422
MRWIB LAD Inst	31,943	-2,952	-2,820	34,956	-3,366	-4,270	-5,814
MRWIB LAD 1	17,690	-1,920	-243	16,117	-1,898	-681	-1,040
MRWIB LAD 2	34,027	-5,202	-4,021	33,117	-4,313	-4,505	-5,295
MRWIB Hist 2	23,935	-3,643	-2,675	25,450	-3,888	-4,481	-5,566

* Results for the St. Mary Canal Capacity increase and Combined Strategy 1a are compared to the baseline simulation. Results for the Dodson South Canal Capacity increase and Combined Strategy 1b are compared to the proposed 60 KAF off-stream storage project strategy (FBIIPRes).

Summary and Key Findings

A significant portion of the water supply to the Milk River Project is provided by the St. Mary River through St. Mary Canal. Changes in avg annual St. Mary Canal diversion volumes relative to this historical baseline scenario for the system wide management strategies and selected combined strategies are presented on figure 109. Increasing the capacity of the St. Mary Canal and adjusting the annual balancing period for dividing the U.S. and Canadian shares of the St. Mary Canal significantly increased the avg annual flow volumes through the canal. The Annual Balancing of U.S./Canada share of the St. Mary River strategy had the greatest impact on increasing flow through the St. Mary Canal, with the most significant increases in flows across the canal occurring later in the summer. Increasing the capacity of the St. Mary canal had the largest impact during the driest water years and significantly increased flows from May through July during snowmelt when flows through the canal are most limited by its capacity.

Increasing the capacity of the Fresno reservoir increased the avg storage volume in the reservoir for all scenarios but had a relatively small impact on diversions through the St. Mary canal or water deliveries to users. However, the Combined 2a strategy, which includes the St. Mary Canal Capacity Increase strategy in addition to the Fresno Reservoir Capacity Increase strategy, showed additional increases in avg annual St. Mary Canal diversions relative to the St. Mary Canal Capacity Increase strategy alone, indicating that these two strategies may work well together, especially in the future scenarios.

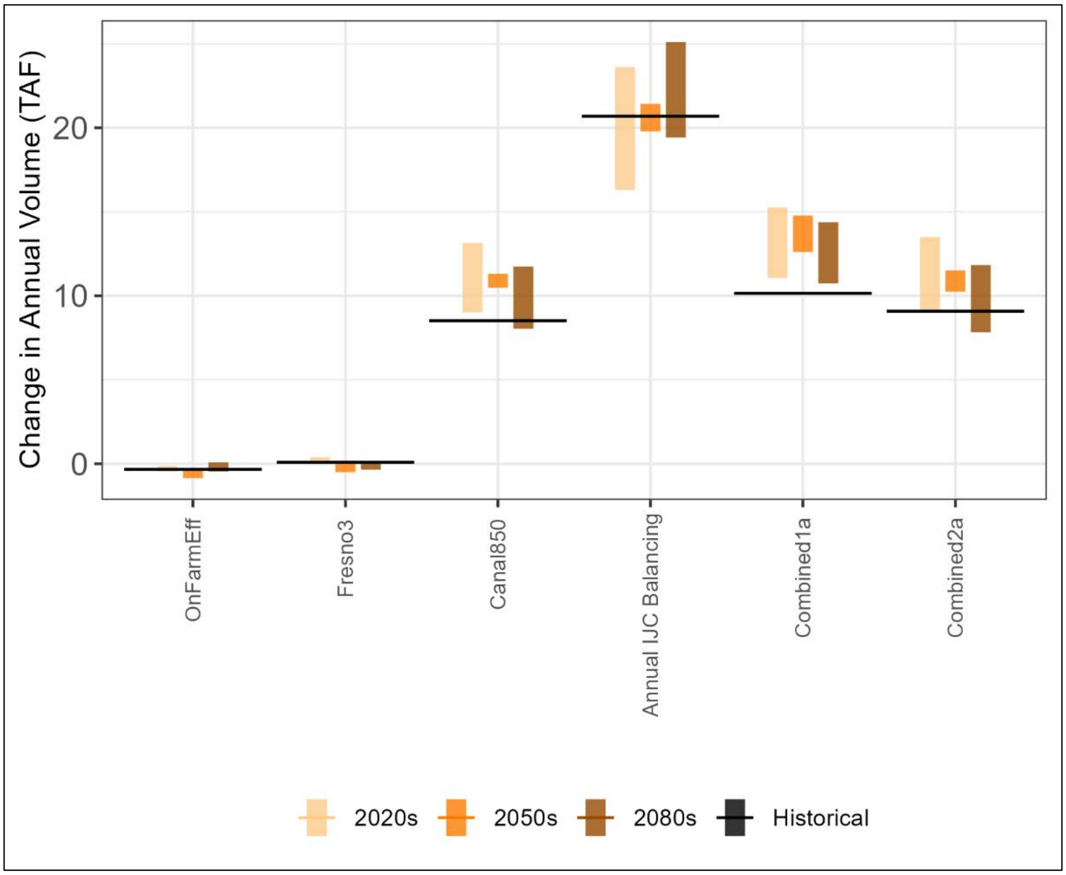

Figure 109.—Change in the average annual diversion volume across the St. Mary Canal from the from the baseline scenarios.[33]

By increasing water supply through the St. Mary Canal, the St. Mary Canal Capacity Increase and Annual Balancing of U.S./Canada Share strategies had the largest impact on increasing deliveries and reducing delivery shortages to all water users (figure 110). Though the Annual

[33] Future results are presented as a range of 5 future scenarios (HD, HW, CT, WD, WW) for each future period relative to their respective baseline scenario.

Balancing of U.S./Canada Share strategy had the largest impact on St. Mary Canal diversions, impacts on reducing water delivery shortages were relatively equal, indicating that the timing of additional water supply delivered through the St. Mary Canal is important.

Delivery shortages were also reduced by improvements to the on-farm and conveyance efficiencies which was successful for all scenarios. These improvements to conveyance and on-farm efficiencies had the largest impacts during the driest water years and during the early irrigation season from May through June, when irrigation demands are anticipated to increase due to a warmer climate.

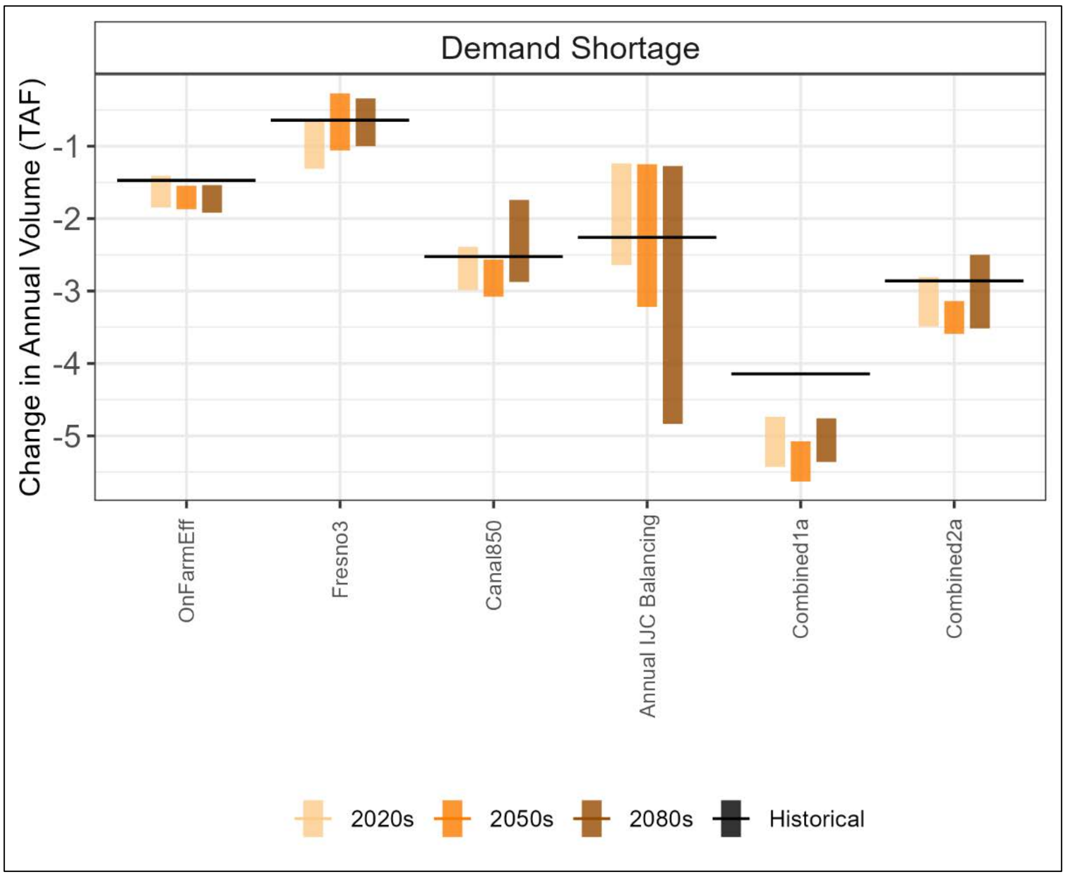

Figure 110.—Change in the average total annual demand shortage for all water users from the baseline scenarios.[34]

Water deliveries were significantly impacted by the evaluated future water uses. Providing 5 KAF for the Blackfeet Tribe (Compact) reduced flows from the St. Mary Canal to the Milk River, reducing the total water delivery to downstream users. Implementation of the proposed

[34] Future results are presented as a range of 5 future scenarios (HD, HW, CT, WD, WW) for each future period relative to their respective baseline scenario.

60 KAF off-stream storage reservoir successfully increased the available storage volume in the system and increased the total volume of water deliveries to all water users in the study area, however not all users saw delivery increases individually and Milk River Project users as a whole saw an overall slight decrease in deliveries and increase in water shortages.

The system wide water management strategies and several of the mitigation strategies, including implementation of the Nelson pumps and increasing the capacity of the Dodson South Canal, provide potential pathways for reducing delivery shortages to all water users, including Milk River Project users, and reduce the impact of future water uses on existing users (figure 111). Results showed, both in the Mitigating 35,000 AF for the Fort Belknap Water Rights Settlement strategy and the combination strategies, that there are multiple combinations of these system wide water management strategies and future water use mitigation strategies which can effectively reduce delivery shortages for existing and new water users more than the individual strategies alone.

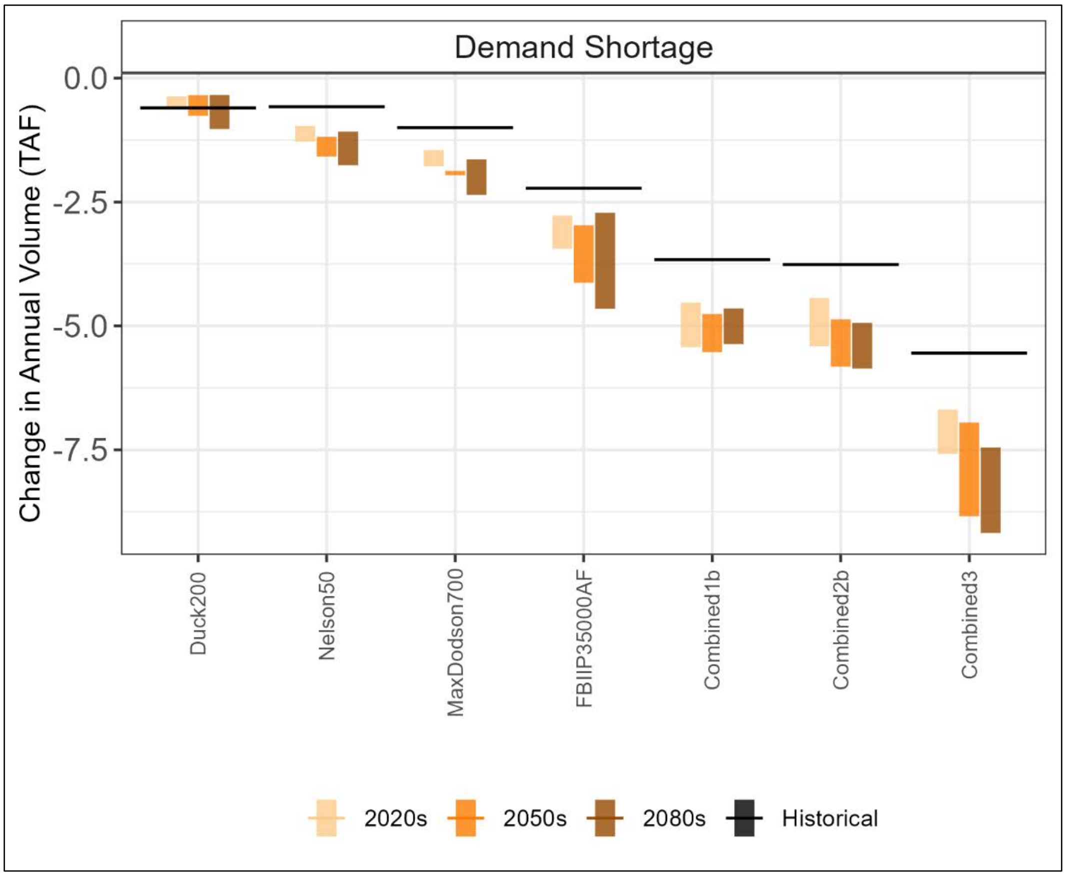

Figure 111.—Change in the average total annual demand shortage for all water users from the Proposed 60KAF Off-stream Storage Project strategy.[35]

[35] Future results are presented as a range of 5 future scenarios (HD, HW, CT, WD, WW) for each future period relative to their respective proposed 60 KAF off-stream storage project scenario.

Next Steps and Future Considerations

The datasets and modeling tools developed in this study are valuable contributions to greater scientific understand of the watersheds and also to ongoing and future studies. For example, the St. Mary and Milk Rivers planning model is being used in the IJC study for exploring opportunities for apportionment of St. Mary and Milk River water between the U.S. and Canada. It is also being used in ongoing water rights negotiations. Even as the St. Mary and Milk Rivers planning model has been expanded for use in these studies (in addition to this current Basins Study Update), the modeling team has identified needed improvements to the planning model to make it more robust as a decision support tool, including:

- Representation of water deliveries sourced from Fresno Reservoir needs to be improved.
- Sweetgrass Hills water user representation needs to be improved.
- The Letter of Intent for accounting for St. Mary and Milk River credits between U.S. and Canada needs to be improved and applied consistently.
- Lower St. Mary Lake

The hydroclimate dataset used as the basis for water supply scenarios in the Basins Study Update may benefit from further evaluation. The hydrologic modeling framework developed for this study has not been fully tested outside these watersheds. Further, at the time of this report, the modeling approach has not yet been published in peer reviewed literature. Further evaluation of the approach and testing may identify improvements for future applications. Still, this framework provided a meaningful dataset for use in evaluating water supply and demand imbalances.

The naturalized flow dataset was published by the MT DNRC. As the dataset is evaluated for use in other studies mentioned above, improvements in the methods may be identified.

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Appendix A

Forcing Comparison and Selection

The tools developed in the Basins Study Update to simulate streamflow, reservoir evaporation, and crop irrigation water requirements, all require meteorological forcings as inputs, which at a minimum consist of minimum and maximum air temperature, precipitation, and windspeed. Additional variables that may complement these inputs include humidity (relative, specific, or vapor pressure) and solar radiation (net shortwave and longwave).

Reclamation long-term planning studies have historically relied on the 1/8° gridded dataset developed by Maurer et al. (2002) or a version of the 1/16° dataset developed by Livneh et al. (2013). These datasets have served as the historical reference for statistical downscaling of climate projections Bias Correction and Spatial Downscaling, Bias Correction using Constructed Analogs, and LOCA (Pierce et al. 2014; Pierce et al. 2015). Both Maurer and Livneh datasets have derived temperature and precipitation information from station observations and windspeed from the National Center for Environmental Prediction-National Center for Atmospheric Research Reanalysis (Kalnay et al. 1996). Adjustments to the temperature and precipitation fields are made using the long-term climate normal from PRISM (also termed the Parameter elevation Regression on Independent Slopes Model; PRISM Climate Group 2020).

This Basins Study Update relies on the Daymet Version 3 (Thornton et al. 2016) dataset for observed historical temperature (daily maximum and minimum) and observed historical daily precipitation, re-gridded from its native resolution of 1 kilometer (km) to 1/16° using bilinear interpolation, and the North American Regional Reanalysis (NARR; Mesinger et al. 2006) for windspeed. The NARR model uses the very high-resolution National Center for Environmental Prediction Eta Model (32 km/45 layer) together with the Regional Data Assimilation System which, significantly, assimilates windspeed along with other variables. The selection of meteorological forcing dataset considered the following elements:

- Spatial resolution of the dataset
- Temporal resolution of the dataset
- Spatial extents of the dataset
- Period of record of the dataset
- Variables available
- Performance in reflecting the 'truth'
- Performance in producing unbiased hydrology, reservoir evaporation estimates, and crop irrigation water requirements, with an emphasis on hydrology
- Connection to downscaled climate projections

A variety of forcing datasets were considered with respect to these elements, and a subset was more thoroughly evaluated that potentially met the study needs (see table A-1). This Basins Study Update required meteorological data at a spatial resolution fine-scale enough to represent changes in temperatures and precipitation driven by elevation differences, and to model irrigation water requirements at the watershed scale (see “Appendix C”). Because the Livneh 1/16° dataset has served as the basis for prior long-term planning efforts, the chosen dataset needed to be at a minimum 1/16° spatial resolution. Analysis performed in the Basins Study Update required a daily temporal resolution or finer. The spatial extent of the study area spans portions of both the U.S. and Canada, as the St. Mary and Milk River basins extend into Alberta and Saskatchewan. For the period of record, there has been interest in modeling well-known historical drought periods, which in MT include the early 2000s, and the dust bowl drought of the 1930s.

While other meteorological forcing datasets were examined for use in this analysis, the Daymet dataset combined with NARR windspeed appeared to best correspond with available station observations that the Missouri Basin River Forecast Center (MBRFC) uses to model the Milk River basin and Reclamation used in the 2012 Basins Study (Reclamation 2012a, 2012b). The time period used as the basis for historical analysis as well as the basis of comparison for projected future simulations is calendar years 1980–2015. Modeling of water management (Risk Assessment section) and evaluation of strategies (Risk Assessment with Strategies) focus on the time period including water years 1981–2015.

Table A-1.—Meteorological forcing datasets considered for the St. Mary and Milk River Basins Study Update

Dataset	Spatial resolution	Temporal resolution	Spatial extents	Period of record	Variables
Livneh (L16)[1] (Livneh et al. 2013)	1/16°	Daily	North America	1915-2015	tmin, tmax, precipitation, windspeed
Daymet[1] (Thornton et al. 2016)	1 km	Daily	North America	1980-Present	tmin, tmax, precipitation, vapor pressure, shortwave radiation, SWE
PNWNAMET (PCIC) [1] (Werner et al. 2019)	1/16°	Daily	Northwest U.S. and Southwest Canada	1945-2012	tmin, tmax, precipitation, windspeed
PRISM[1,2] (PRISM Climate Group 2020)	4 km	Daily	Contintental U.S. (CONUS)	1980-Present	tmin, tmax, precipitation
CanGrid	50 km	Monthly	Canada		
NOAA Analysis of Record[1] (NWS 2021)	1 km	Hourly	U.S. and Mexican and Canadian watershed areas	1979-Present	temperature, precipitation

Table A-1.—Meteorological forcing datasets considered for the St. Mary and Milk River Basins Study Update

Dataset	Spatial resolution	Temporal resolution	Spatial extents	Period of record	Variables
gridMET (Abatzoglou 2013)	4 km	Daily	CONUS	1979-Present	tmin, tmax, precipitation; shortwave radiation, Windspeed, max and min relative humidity, specific humidity

[1] Datasets considered for further analysis
[2] PRISM was included in further analysis given its wide use and familiarity, however its spatial extents prevented if from being considered for this study.

An assessment of the forcing datasets against observations against station observations from the MBRFC was performed to examine performance of each dataset against a measure of 'truth', however there are challenges when comparing gridded datasets to observations.

Average monthly precipitation (inches) for the St. Mary Basin region and Upper Milk Basin are summarized on figure A-1, including datasets that were considered for the Basins Study Update The L16 dataset has a similar timing in avg monthly precipitation (figure A-1) compared with the MBRFC dataset that is considered the reference for comparison. The Daymet dataset has a high bias in high elevation areas compared with the MBRFC data. The biases are most pronounced in January -June and in some parts of the St. Mary Basin also from September – December, which is when precipitation totals tend to be highest. In the Upper Milk Basin, such as Milk River at Eastern Crossing, the datasets show low bias.

Figure A-1.—Comparison of average monthly precipitation (inches) for the St. Mary Basin region and Upper Milk Basin across datasets considered for the Basins Study Update.[1]

[1] Daymet is regridded to 1/16th°; L16 is Livneh et al. 2013; MBRFC is dataset used in 2011 Basins Study.

In the U.S. tributaries to the Milk River in the Plains region (figure A-2) as well as Canadian tributaries of the Milk River in the Plains region (figure A-3), there are seasonality differences in precipitation datasets. For example, in Peoples Creek, both the L16 and Daymet datasets show higher monthly precipitation than the MBRFC dataset in spring months April through June (figure A-2). Similar differences are also evident in Battle Creek and Frenchman River basins (figure A-3). The mainstem Milk River locations evaluated (figure A-4) show closely comparable avg monthly precipitation.

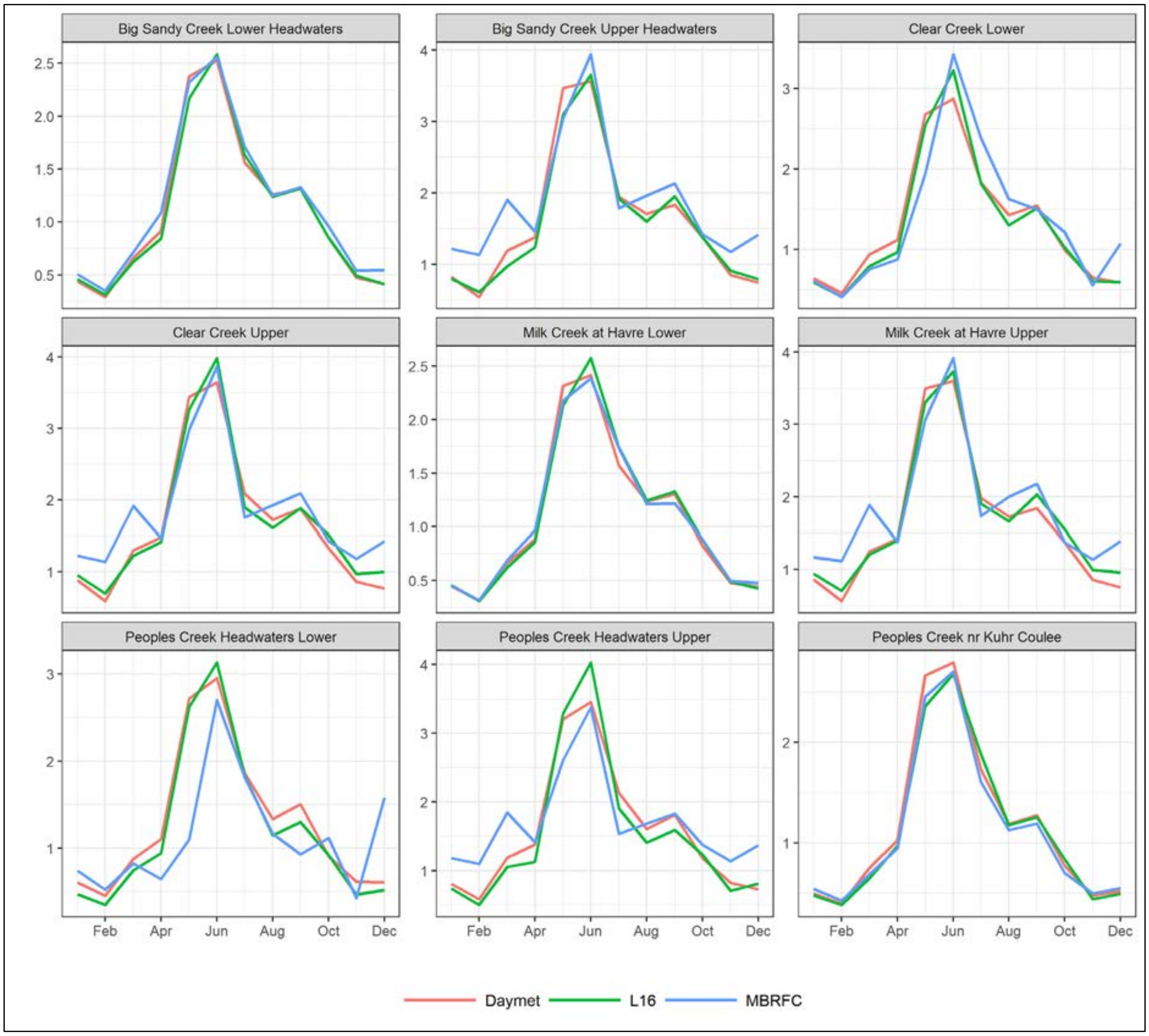

Figure A-2.—Comparison of average monthly precipitation (inches) for the Plains region across datasets considered for the Basins Study Update.[2]

[2] Daymet is regridded to 1/16°; L16 is Livneh et al. 2013; MBRFC is dataset used in 2011 Basins Study.

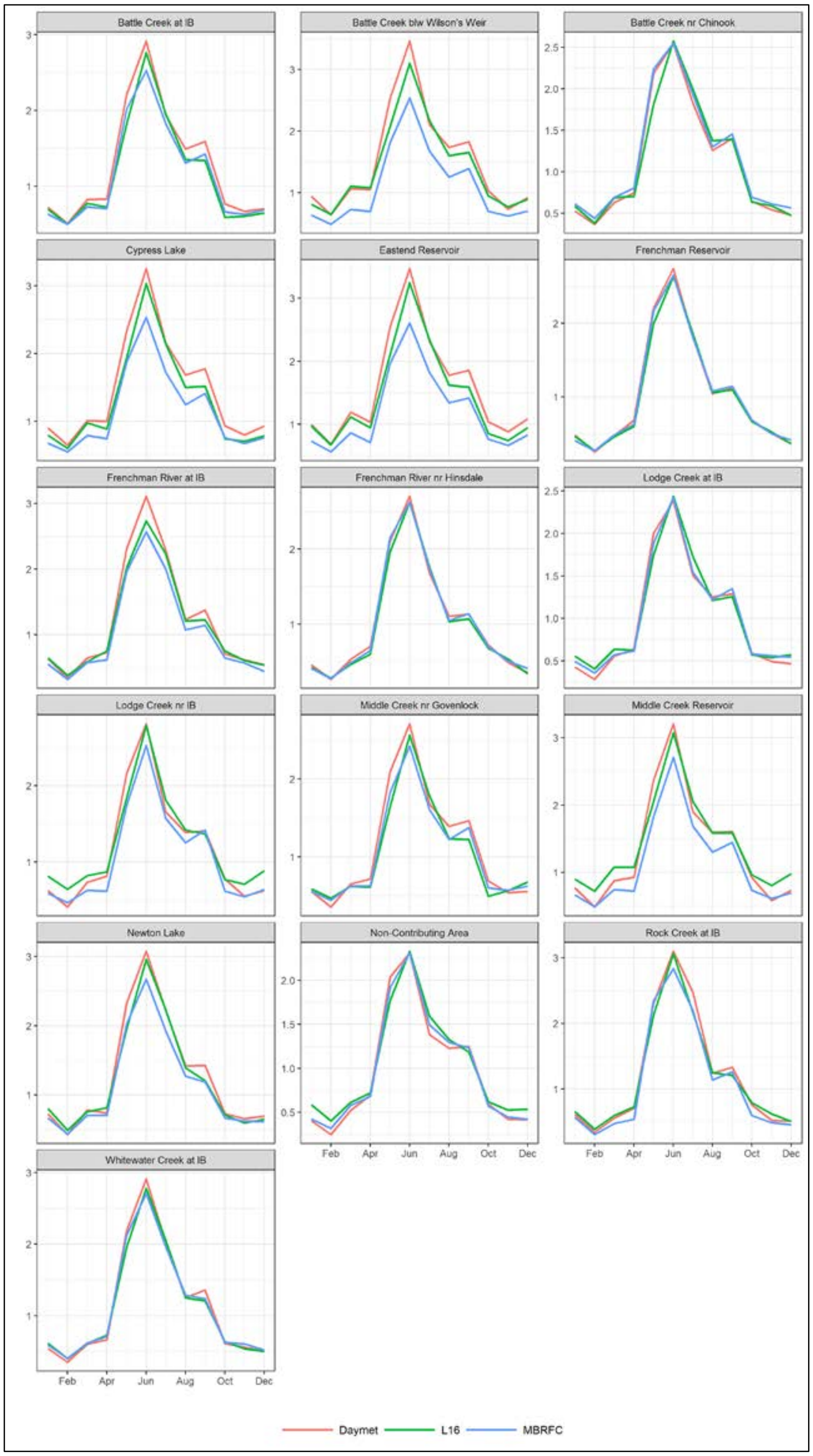

Figure A-3.—Comparison of average monthly precipitation (inches) for the Canadian tributaries region across datasets considered for the Basins Study Update analyses.[3]

[3] Daymet is regridded to 1/16°; L16 is Livneh et al. 2013; MBRFC is dataset used in 2011 Basins Study.

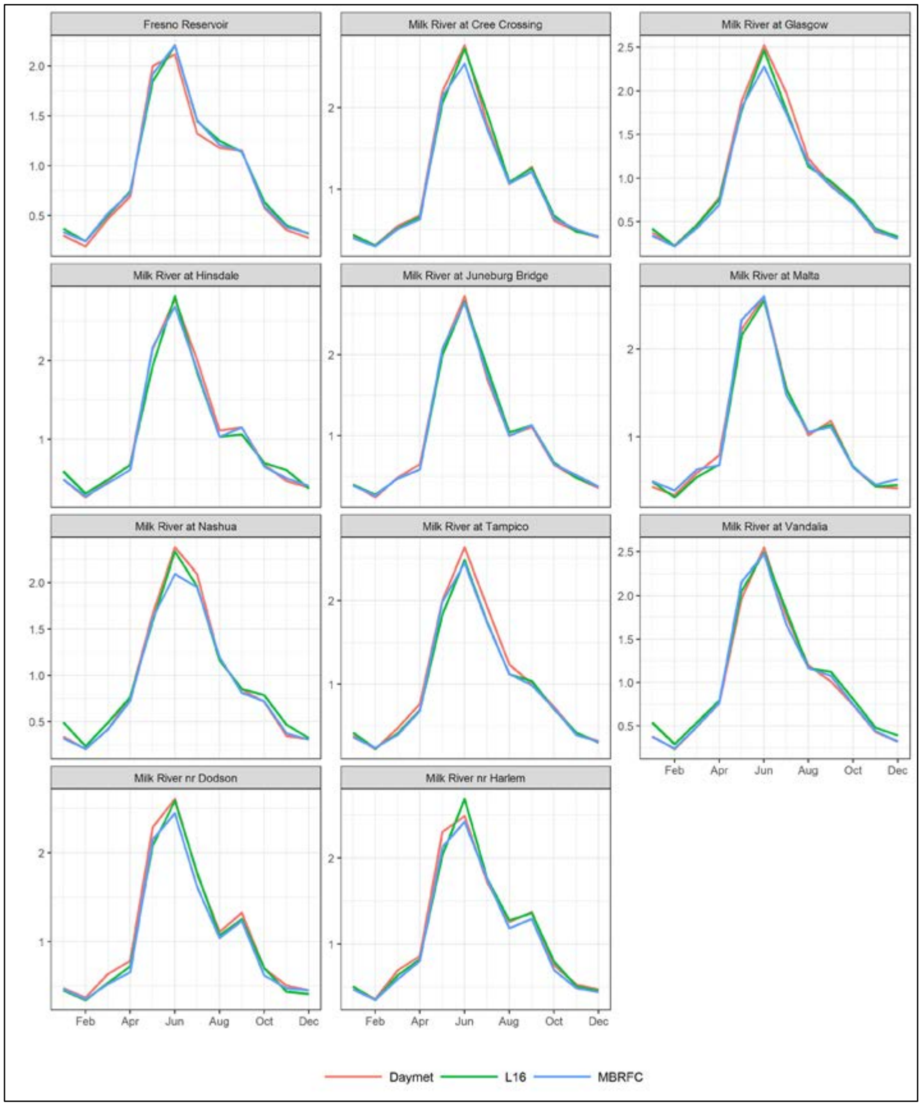

Figure A-4.—Comparison of average monthly precipitation (inches) for the mainstem Milk River portion of the Plains region across datasets considered for the Basins Study Update analyses.[4]

Generally, the avg daily minimum and avg daily maximum temperature are similar across the MBRFC, L16, and Daymet datasets so supporting figures are not provided. However, there are some notable differences by region. In the St. Mary basins, the MBRFC dataset has lower avg daily maximum temperature than the L16 dataset, particularly in winter months, with Daymet falling in between. The MBRFC and Daymet datasets are similar in terms of avg daily minimum temperature, with the L16 dataset being lower, particularly in winter months. In the Canadian tributaries to the Milk River, the MBRFC avg daily maximum temperature is higher in winter months and lower in summer months than the L16 and Daymet datasets. The MBRFC avg daily

[4] Daymet is regridded to 1/16°; L16 is Livneh et al. 2013; MBRFC is dataset used in 2011 Basins Study.

minimum temperature is higher in winter months than the L16 dataset, with Daymet in between. In the Milk River mainstem region, the MBRFC dataset has higher avg daily maximum temperature in winter months and lower in summer months compared with the L16 and Daymet datasets. The MBRFC dataset also has higher avg daily minimum temperatures, particularly in winter months. Finally in the Plains basins, datasets are similar in terms of avg daily maximum temperatures and avg daily minimum temperature, with the MBRFC dataset being slightly higher in winter months in both cases.

This comparison supports the decision to move forward with use of Daymet Version 3 as the meteorological forcings dataset for use in the Basins Study Update. This dataset compares reasonably with the MBRFC dataset, which is based on station observations. The Daymet dataset for precipitation, regridded from its native resolution of 1 km to 1/16° using bilinear interpolation, was used developed along with the NARR (Mesinger et al. 2006) for windspeed, using 10 meters U and V windspeed, regridded from its native resolution of approximately 32 km to 1/16° using bilinear interpolation.

Daymet Version 3 (Thornton et al. 2022) was superseded in 2021 by Version 4 namely to address identified biases in daily precipitation and maximum temperature due to the timing of measurements of these variables (7 am previous day to 7 am reporting day) compared with stream gage records (midnight to midnight on reporting day). Because hydrologic modeling was well underway by this time, Version 4 was not incorporated into the study.

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Appendix B

Water Supply Development

This appendix provides supporting information on development of projected future climate scenarios and development of a DCAHM (Dynamic Contributing Area Hydrologic Modeling) framework for application in the Basins Study Update.

The DCAHM uses Daymet Version 3 (Thornton et al. 2016) for observed historical temperature (daily maximum and minimum) and observed historical daily precipitation, re-gridded from its native resolution of 1 km to 1/16° using bilinear interpolation, and the NARR (Mesinger et al. 2006) for windspeed. While other meteorological forcing datasets were examined for use in this analysis (see appendix A), the Daymet dataset combined with NARR windspeed appeared to best correspond with available station observations used in modeling of the Milk River basin by the Missouri Basin River Forecast Center (Reclamation 2012a, 2012b).

Hydroclimate Scenario Development

As summarized in the Water Supply Assessment section of the Basins Study Update report, CMIP5 general circulation model (GCM) projections were used and statistically downscaled with the Localized Constructed Analogs (LOCA) approach developed by Pierce et al. (2014) and Pierce et al. (2015). In this method, downscaled estimates were developed using a multi-scale spatial matching scheme to pick appropriate analog days from the Livneh et al. (2013) 1/16° spatial scale observed meteorological dataset. A subset of the full ensemble of CMIP5 projections were used in this study, based on projections with two GHG emissions scenarios, namely CMIP5 RCP 4.5, and CMIP5 RCP 8.5. This subset, comprised of 64 individual projections, is the full set of LOCA-downscaled projections available on the Downscaled Climate and Hydrology Projections archive (https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html). More conservative GHG emissions groupings, including CMIP5 RCP 2.6, are broadly outside the projected range of future conditions considered by major climate assessments, including those produced by the Intergovernmental Panel on Climate Change (Sun et al. 2015). Further, the Fourth National Climate Assessment (USGCRP 2018), considers CMIP5 4.5 and CMIP5 8.5 projections only.

Climate scenarios were developed based on climate projections that bracket the range of potential futures, from less to more warming and drier to wetter conditions, for a total of five sub-ensembles of climate scenarios: WW, WD, HW, HD, and CT. Scenarios were developed for each of three future time horizons:

- 2020s (spanning water years 2010–2039)
- 2050s (spanning water years 2040–2069)
- 2080s (spanning water years 2070–2099)

A total of 15 climate scenarios were developed for this study, including three future time horizons (2020s, 2050s, and 2080s) and five sub-ensembles of projected change (HW, HD, CT, WW, and WD).

The process for selecting sub-ensembles from the full ensemble of LOCA-downscaled CMIP5 projections to inform the development of change factors for each is illustrated on figure B-1, figure B-2, and figure B-3. Each data point shown in each of the figures represents the projected change in basin-averaged annual temperature (absolute change, vertical axis) and precipitation (percent change, horizontal axis) between the reference period and future period from a single downscaled projection. For this study, the 10 individual GCM projections that are closest to the intersections of the red lines (indicating 10th and 90th percentiles of change in avg annual precipitation and temperature) and the intersection of the dashed lines (indicating 50th percentile) were selected for development of monthly change factors. For each of the five sub-ensembles, the 10 selected GCM projections are colored similarly on figure B-1, figure B-2, and figure B-3. The process was repeated for each of the three future time periods to develop unique change factors. As such, different sets of GCM projections were selected for each future planning horizon. The choice of this method for establishing factors for change in annual precipitation and temperature incorporates change signals from both multidecadal natural variability and long-term climate change. Using a sub-ensemble of projections instead of a single projection emphasizes consistent changes in precipitation and temperature and mutes the effect of different model representations of natural variability; however, natural variability still inherently exists and needs to be considered in the interpretation of results (Reclamation 2010).

Figure B-3 shows that annual precipitation is projected to decrease by the 2080s as much as 10 percent or increase as much as almost 30 percent, with many more individual CMIP5 projections showing a projected increase in avg annual precipitation than a decrease. Figure B-3 also shows that temperature is projected to increase by the 2080s under all projections, with the projected increase ranging from 2 °F to almost 14 °F.

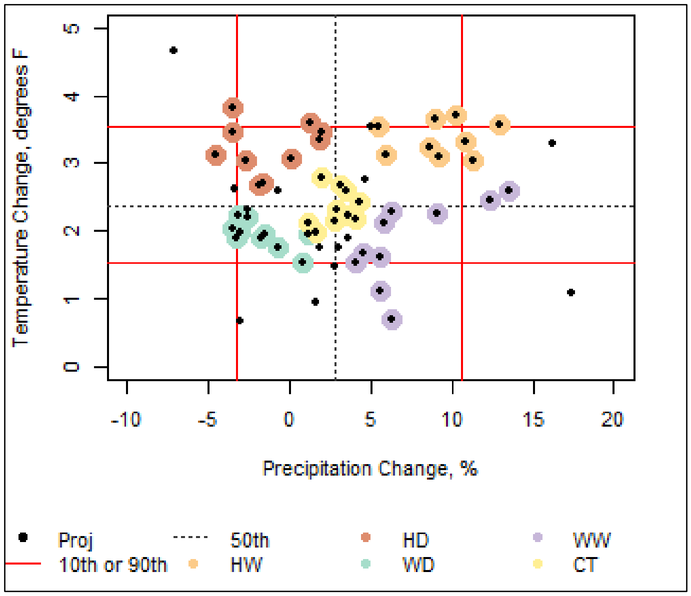


Figure B-1.—Change in average annual temperature (°F) versus percent change in average annual precipitation between the 2020s future period and historical reference period of 1980–2015.[1]

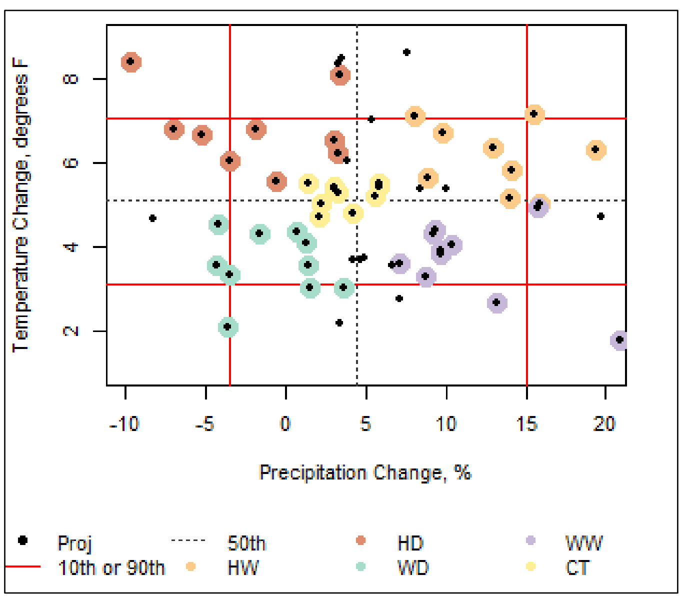


Figure B-2.—Change in average annual temperature (°F) versus percent change in average annual precipitation between the 2050s future period and historical reference period of 1980–2015.[2]

[1] Projected changes using statistically downscaled CMIP5 GCM simulations are illustrated.
[2] Projected changes using statistically downscaled CMIP5 GCM simulations are illustrated.

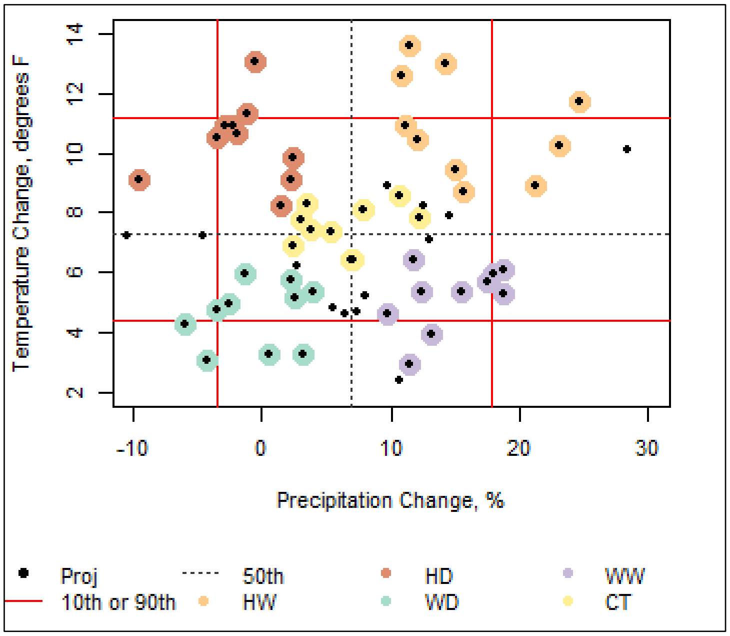


Figure B-3.—Change in average annual temperature (°F) versus percent change in average annual precipitation between the 2080s future period and historical reference period of 1980 - 2015.[3]

The study team used the ensemble-informed hybrid delta approach (Reclamation 2011; Hamlet et al. 2013) to apply climate change factors and to develop climate adjusted weather timeseries. This method pools the selected projections together to form a single cumulative distribution function for each month and variable (i.e., temperature and precipitation), including all values for the 10 selected projections. A cumulative distribution function was also developed for each projection and variable over the reference historical period (1980–2015). Then change factors were determined as the difference in temperature (and percent change in precipitation) between the simulated historical and projected cumulative distribution functions at various percentile levels and applied to the historical observations to generate climate-adjusted weather.

In summary, the datasets listed in table B-1 were used to develop projected future climate scenarios.

[3] Projected changes using statistically downscaled CMIP5 GCM simulations are illustrated.

Table B-1.—Summary of Datasets for ensemble-informed Hybrid Delta climate scenario development

Dataset	Source	CDF Values for Each Month	Comment
Observed Historical	Daymet Version 3 (Thornton et al. 2016)	36 values (one for each year 1980–2015)	reference historical dataset
Simulated Historical	64 LOCA-downscaled GCM projections	56 values (one for each year) from given projection's simulated historical 1950–2005	
Simulated Future	64 LOCA-downscaled GCM projections	30 values (one for each year) from given projection's simulated future 30-year window)	Future time horizons include, 2010–2039, 2040–2069, 2070–2099)

Projected future climate scenarios of precipitation and temperature were used directly as input to a hydrologic model framework, as further described in the next section.

Hydrologic Modeling Framework

The St. Mary and Milk River basins encompass a wide range of complex hydrologic processes. In the St. Mary River basin, high alpine and snow and glacier accumulation and melt are important processes that drive streamflow. As an example, figure B-4 illustrates how glaciers have been receding in the headwaters of the St. Mary River basin.

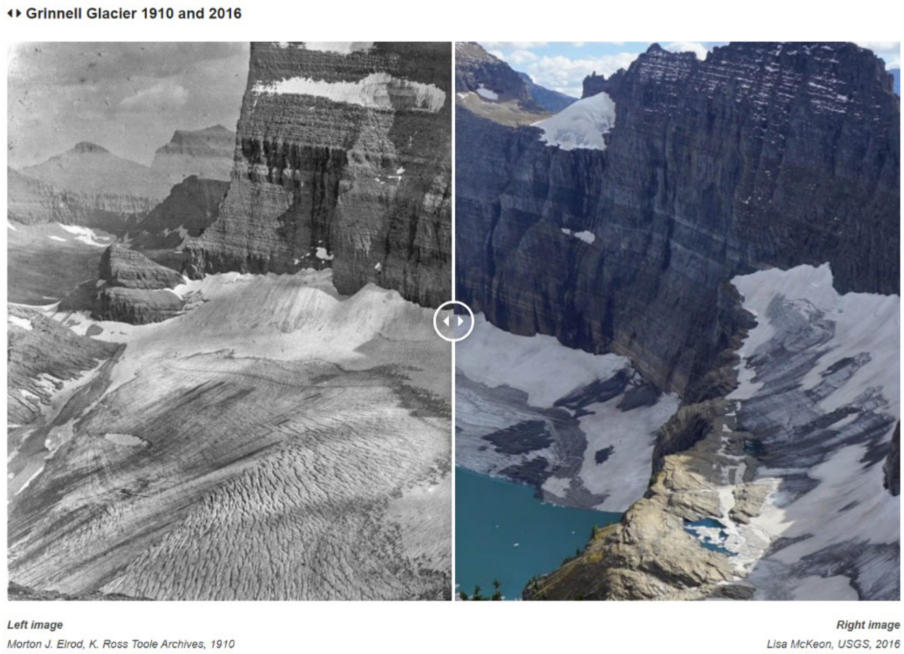


Figure B-4.—Grinnell Glacier photos taken in 1910 (left) and 2016 (right).[4]

Further east in the Milk River basin and at lower elevations, tributaries in the plains consist of networks of shallow depression storage, generally referred to as potholes, that extend over a region commonly referred to as the PPR (figure 5 in the Water Supply Assessment section). A watershed with dynamic depression storage (e.g., shallow lakes or wetlands) and stream connectivity does not have a static stream network. The contributing area of flow for this type of basin exhibits seasonal variability, which is manifested through the dynamic depression storage characteristics of these watersheds. Figure B-5 illustrates the concept of depression storage filling and potentially not contributing to surface runoff until depression storage is filled, similar to a reservoir.

[4] Source: https://www.nps.gov/glac/learn/nature/glacier-repeat-photos.htm.

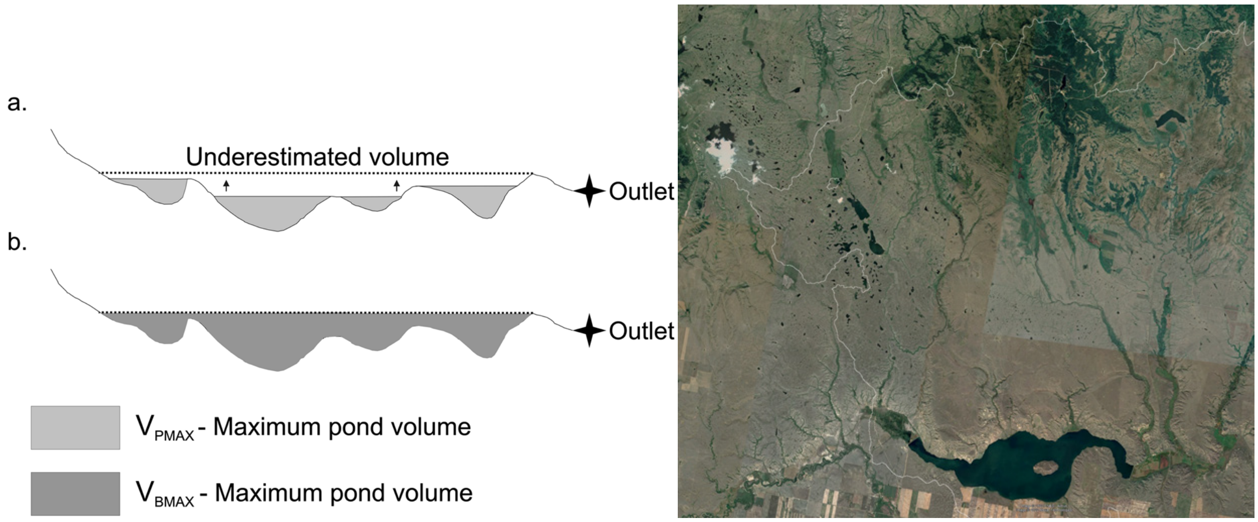


Figure B-5.—(left) Figure 4 from Shaw et al. (2013) that conceptually illustrates filling of depression storage and ability to generate surface runoff. (right) Google maps imagery dated 8/4/2021 to illustrate depression storage in the upper Frenchman River basin, a Canadian tributary of the Milk River.

Hydrology characterized by seasonally varying contributing area, whether it be due to glacier processes, depression storage, or other process, is a challenging problem where a conventional surface water hydrology model with static watershed contributing area fail to produce adequate streamflow simulations. For the Basins Study Update, to accurately simulate streamflow across the full range of timescales (daily to annual), a hydrologic modeling framework was developed that allows for:

- simulating the dynamics of streamflow variability for a storage dominated hydrologic system and,

- scaling this hydrologic response with appropriate contributing area of the watershed which is varying with time through the specified simulation period.

This appendix describes the methodology used to conduct the streamflow simulations - the datasets, model development including calibration, and verification approaches of the proposed methodology. A flowchart depicting the overall surface hydrology modeling methodology is shown on figure B-6. Components of the flowchart are further discussed in subsequent sections.

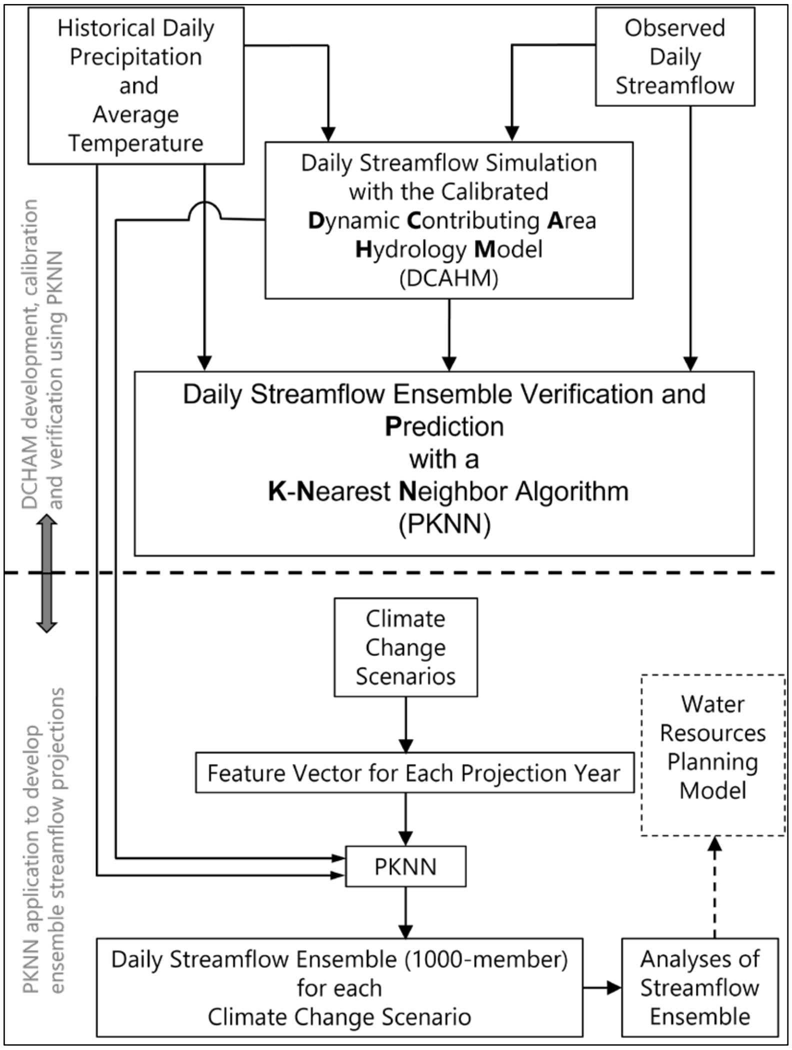


Figure B-6.—Flow chart depicting the overall modeling methodology.

Model Description

The study team explored numerous options for development of surface water hydrology that could be used as the basis for the water supply assessment. In the 2012 Basins Study, hydrologic model simulations were developed using a calibrated version of the National Weather Service River Forecasting Center's SAC-SMA/SNOW-17 model of the St. Mary River and Milk River basins. Streamflow generated by the SAC-SMA/SNOW-17 surface water runoff hydrology model using temperature and precipitation of the base period 1950– 1999 did not always adequately match the historical gauging station-based data in annual and seasonal volume. This required adjustment of the streamflow developed for the five future climate scenarios to correct the bias between the surface water runoff model simulated historical streamflow and the historical streamflow used in the river system model. While there were also limitations identified in using the SAC-SMA/SNOW-17 model, the version that was used in the 2012 Basins Study was not available for use in this Basins Study Update.

The study team investigated use of alternative hydrologic modeling approaches including the USGS Precipitation-Runoff Modeling System (PRMS; Markstrom et al. 2015) and the VIC model (Liang et al. 1994). Following are discussions around these applications and how they were not suitable for the Basins Study Update. Hay et al. (2018) used the PRMS modeling the PPR of North Dakota in the U.S./Upper Pipestem Creek basin (drainage area: 1,126 km^2) to simulate the effects of surface depression storage on watershed response. The study focused on simulating lake elevations to understand habitat consequences, and analyzed streamflow contributions from surface runoff, interflow and groundwater. This study, using the distributed parameter and process based PRMS model in a multi-step calibration sequence, was able to successfully simulate changes in storage behavior of the potholes, specifically site-specific Cottonwood Lake elevations, and thereby streamflow in the Upper Pipestem Creek basin. The normalized root mean square error between monthly observed and simulated runoff ranged from about 5 percent for the calibration period to 19 percent for the evaluation period. Though this study considered the PPR hydrologic processes, it focused on a single basin with a specific objective to simulate lake water levels and was not designed to be applicable for wide-ranging hydrologic simulation across the PPR to support water resources planning studies.

The VIC model was considered for implementation in this study because it is spatially distributed, process-based and uses readily available climate information, namely, daily minimum and maximum air temperature, daily precipitation, and daily windspeed. It has also been enhanced to include representation of lakes (Bowling and Lettenmaier 2010; Mishra et al. 2010) and frozen soils (Cherkauer and Lettenmaier 1999; Cherkauer et al. 2003), both of which exist in the PPR region. Although this approach appeared promising, the VIC model relies on a static stream network for routing runoff from individual grid cells to the basin outlet. Due to the dynamic contributing area and storage characteristics that are unique to PPR watersheds, and the need for complex hydraulic routings with detailed storage capacity representations in the model, even a process-based model such as VIC in this case was unsuccessful.

Considering challenges encountered with other tested hydrologic models for this study, the study team developed a new approach with initial focus on simulating hydrologic processes in the complex watershed of the Frenchman River. It couples a temperature index snowmelt model (Dingman 1994) with a daily timestep rain-runoff model (Jakeman and Hornberger 1993) that incorporates unit hydrograph convolution of runoff to streamflow based on Ye et al. (1997).

The snow melt/accumulation module of this approach is based on the modified degree-day method to convert measured precipitation to equivalent precipitation, which was used as an input to the Jakeman and Hornberger (1993) model. The first computation is the estimation of the amount of precipitation that is rain and snow based on equation (1) from McCabe and Markstrom (2007).

$$P_{snow} = P * \left[\frac{T_{rain} - T}{T_{rain} - T_{snow}}\right]¶$$

Where P is daily precipitation and T is daily avg temperature. When T is below a specified threshold (T_{snow}), all precipitation is considered to be snow. If temperature is greater than an additional threshold (T_{rain}), then all precipitation is considered to be rain. Within the range defined by T_{snow} and T_{rain}, the amount of precipitation that is snow decreases linearly from 100 percent to 0 percent of total precipitation.

A Temperature Index model or Degree-Day Melt model described by Dingman (1994) was employed to estimate daily snowmelt as a linear function of daily avg temperature.

$$Q = M_f * (T_a - T_{crt}) + b$$

Where Q is the depth of melt, T_a is the avg daily temperature, T_{crt} is the temperature threshold for snowmelt (determined through calibration), M_f is the melt factor, and b is the depth of melt when $T_a = T_{crt}$.

An important component of this model is the melt factor, which is determined in this application via calibration (described in the next section). The melt factor may vary with latitude, elevation, slope, aspect, forest cover and time of year. Dingman (1994) and others have proposed formulas for empirically estimating this factor. However, in absence of this data, calibration is a practical approach.

The quantified rainfall and snowmelt become the total liquid precipitation that is input to the rainfall-runoff model. The rainfall-runoff scheme implemented in this overall modeling approach is the IHACRES (ID of unit hydrograph and component flows from rainfall, ET, and streamflow) model. The model was developed at the Centre for Resource and Environmental Studies at the Australian National University and the Institute of Hydrology, United Kingdom, by Jakeman and Hornberger (1993). It has been applied worldwide to catchments of different size and under various climatic conditions.

The Jakeman and Hornberger (1993) model is a dynamic lumped parameter model consisting of two modules: a non-linear loss module which transforms input liquid precipitation into excess or effective precipitation, and a linear module that represents the relationship between effective rainfall and total streamflow, including quick and slow response, with streamflow represented as a convolution of the total unit hydrograph with effective rainfall (Ye et al. 1997). Figure B-7 shows the overall model approach schematic.

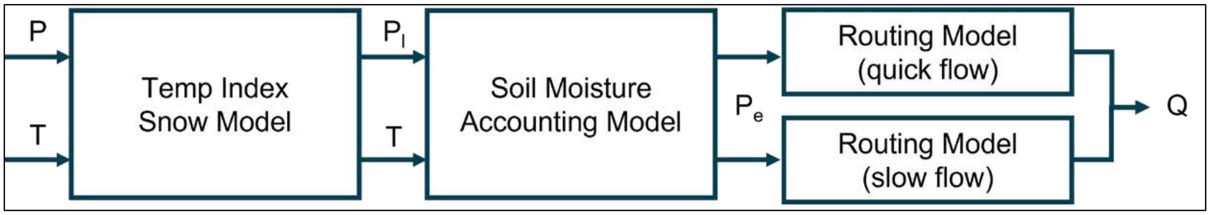


Figure B-7.—Jakeman and Hornberger (1993) model schematic, with the extensions to ephemeral catchments of Ye et al. 1997.

The modeling approach applied here consists of several parameters that were estimated based on existing references and sensitivity analyses, and were made static throughout all model simulations, including model calibration. These parameters are listed in table B-2. Static model parameters were determined independently for each of three study area calibration regions, illustrated on figure B-8. These regions include the St. Mary Basin, the Upper Milk Basin (essentially basins upstream of Milk River at Western Crossing), and the Plains Basins (Milk River and tributaries contributing downstream from the Upper Milk Basin). These regions were determined to be hydrologically similar in terms of these parameters, and correspond to the three regions identified in the paleohydrology analysis (refer to figure F-1 in "Appendix F. Paleo Event Scenario Development"). Model simulations for this Basins Study Update focused on subbasins where routed unimpaired streamflow is a required input to the river management model. Other regions within the study area were not simulated (illustrated as gray areas on figure B-8). The subbasin boundaries illustrated on figure B-8 are based on delineations using methods described by Reclamation (2011), which rely on a 15-arcsecond DEM and the USGS HydroSHEDS archive (Lehner et al. 2008). These delineations quantify non-contributing areas that are identified in the underlying data products.

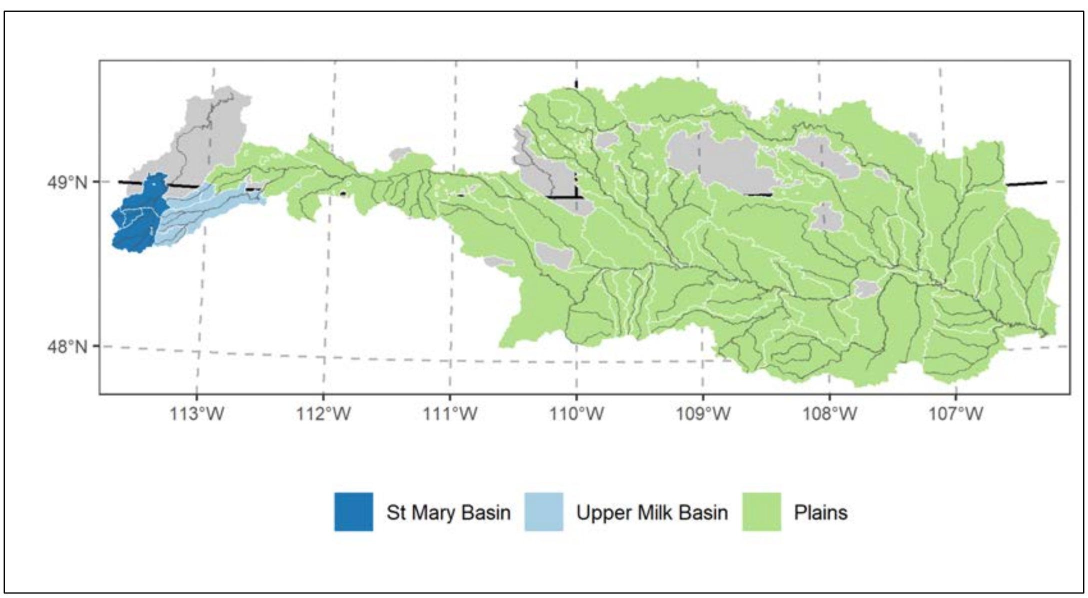


Figure B-8.—IHACRES hydrologic model calibration regions.

It is widely acknowledged that the overall contributing area of a river basin (i.e., that contributing area that may contribute to runoff under extremely wet conditions) may not equal the effective drainage area (Pomeroy et al. 2005). Pomeroy et al. (2007) further acknowledges that blowing snow transport and frozen soils are important and complex processes in cold land hydrology, including the southern portion of Saskatchewan that encompasses part of the Milk River basin. The DCAHM allows for simulating the dynamics of streamflow variability due to complex processes affecting the contributing area and allows for scaling hydrologic response with appropriate contributing area of the watershed for different periods of time.

Table B-2.—Static model parameters for combined modeling approach

Model Param.	Module	Description	St. Mary Basin	Upper Milk Basin	Plains Basins	Param. Range	Dim.
Tsnow	Snow model	Temperature below which all precipitation is considered snow	-7	-5	-3.0	-10 – 10	°C
Train	Snow model	Temperature above which all precipitation is considered rain	7	5	0.0	-5 – 10	°C
t_w	Soil Moisture Accounting Model	Catchment drying time constant	32	80	30.0	0 – 100[1]	days
f	Soil Moisture Accounting Model	Temperature modulation factor	0.5	0.5	0.5	0 – 8[1]	1/°C
C	Soil Moisture Accounting Model	Volume forcing constant; normalizing parameter	0.001	0.001	0.001		1/mm
t_q	Linear unit hydrograph routing module	Decay response time for quick flow	0.1	0.1	0.10	0 – 5[2] 0.5-10[5]	Days
t_s	Linear unit hydrograph routing module	Decay response time for slow flow	10.0	10.0	10.0	5 – 100[2] 10 – 350[1]	Days
Vs	Linear unit hydrograph routing module	Slow flow index (comparable to baseflow index)	0.98	0.98	0.99	0 – 1[6]	unitless

[5] https://wiki.ewater.org.au/display/SD41/IHACRES-CMD+-+SRG#:~:text=IHACRES%20has%20been%20used%20to,et%20al.%2C%201997)
[6] Andrews, F., (2011). Hydromad Tutorial. 21p.

We introduce a seasonally varying contributing area fraction to satisfy the representation of a time-varying storage discharge relationship. Conceptually, this parameter allows for calculating runoff volume per unit time as the product of runoff depth times contributing area, where contributing area may be less (or more) than the total drainage area. The factor may vary from zero to a number greater than one, depending on the season. For example, a contributing area fraction greater than one conceptually represents runoff volume that may be comprised of surface runoff, discharge from depression storage, as well as groundwater discharge. In another example, a contributing area fraction less than one conceptually represents runoff volume that may be collecting in depression storage or groundwater storage and may not be discharging to a stream network.

Five seasons are defined for a watershed non-parametrically, based on the probability density function of daily naturalized streamflow that includes all years (January through December). Probability density functions of local peaks in streamflow are derived from local polynomial change point analysis. Peaks in the probability density function (example for Frenchman River shown on figure B-9) indicate peaks in streamflow, likely due to unique runoff generating mechanisms. For example, season 2 peak streamflow may generally correspond with runoff driven by snowmelt and melting of frozen soils. Season 3 peak streamflow may generally correspond with rainfall events associated with weather patterns coming from the Gulf of Mexico that drive runoff (Liu et al. 2004), and these peak flow events tend to generate less streamflow volume that those in season 2. Different runoff mechanisms thereby require different hydrologic model parameterization.

Based on the local polynomial change point analysis, the seasons with similar peak flow timing are identified visually as the periods between the blue vertical lines. The beginning date for each defined season and calibration basin is summarized in table B-3. Although we define distinct periods as seasons, they do not align explicitly with the traditional four seasons. As part of the DCAHM calibration process, we determine a scaling coefficient for each season within each year of calibration that is multiplied by the total drainage area to represent a time-varying storage discharge relationship.

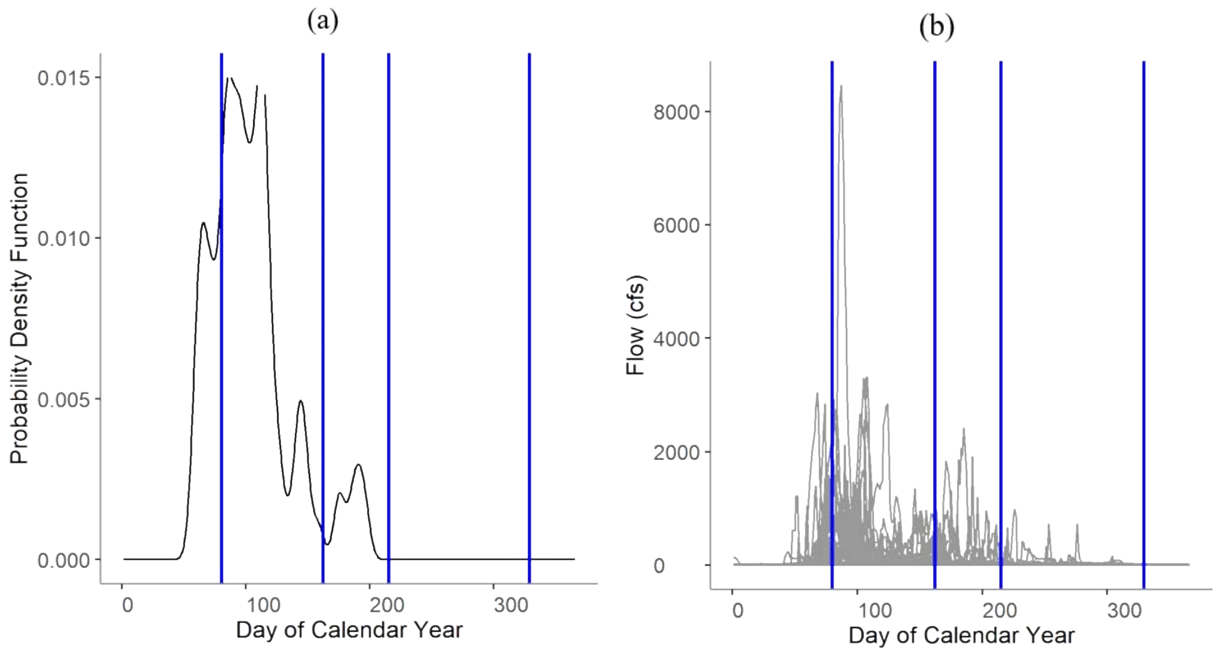


Figure B-9.—Probability density function of streamflow for Frenchman River at International Boundary (a) and corresponding daily naturalized streamflows for each year (b).

Table B-3.—Dates indicating the beginning of a season, which are indicative of different contributing area fractions

Calibration Basin	Season Dates					
	S1	S2	S3	S4	S5	Date of Flow Centroid
BCBMO	1-Jan	1-Feb	24-Apr	9-Aug	13-Oct	22-Apr
BCHMO	1-Jan	8-Feb	18-May	16-Aug	19-Nov	4-May
BGCMO	1-Jan	13-Feb	6-May	12-Jul	14-Oct	20-May
BSCMO	1-Jan	20-Jan	28-Apr	15-Aug	--	25-Apr
BTCIB	1-Jan	7-Feb	21-May	26-Jun	27-Jul	3-May
CLCMO	1-Jan	19-Feb	19-Apr	10-Jul	7-Sep	14-May
FRRIB	1-Jan	13-Feb	13-May	14-Jun	27-Jul	14-May
LBCMO	1-Jan	23-Jan	14-Apr	9-Sep	29-Oct	17-May
LDCIB	1-Jan	3-Feb	20-May	13-Aug	18-Oct	19-May
MRWIB	1-Jan	4-Feb	5-May	16-Aug	--	15-May
NFKMR	1-Jan	1-Mar	5-May	7-Jul	1-Nov	4-May
PCCMO	1-Jan	3-Feb	13-May	28-Jun	27-Jul	14-May
PPCMO	1-Jan	21-Feb	11-Apr	28-Jul	27-Oct	30-Apr
RKCMO	1-Jan	4-Feb	9-May	20-Jun	10-Aug	29-Apr
SMRBB	1-Jan	21-Mar	11-Jun	3-Aug	25-Nov	20-May

Table B-3.—Dates indicating the beginning of a season, which are indicative of different contributing area fractions

Calibration Basin	Season Dates					
	S1	S2	S3	S4	S5	Date of Flow Centroid
SWCSB	1-Jan	19-Mar	10-Jun	29-Jul	23-Nov	10-May
WLCMO	1-Jan	6-Feb	30-Apr	13-Aug	23-Nov	29-Apr
WWCMO	1-Jan	7-Feb	13-Apr	5-Jun	9-Jul	5-May

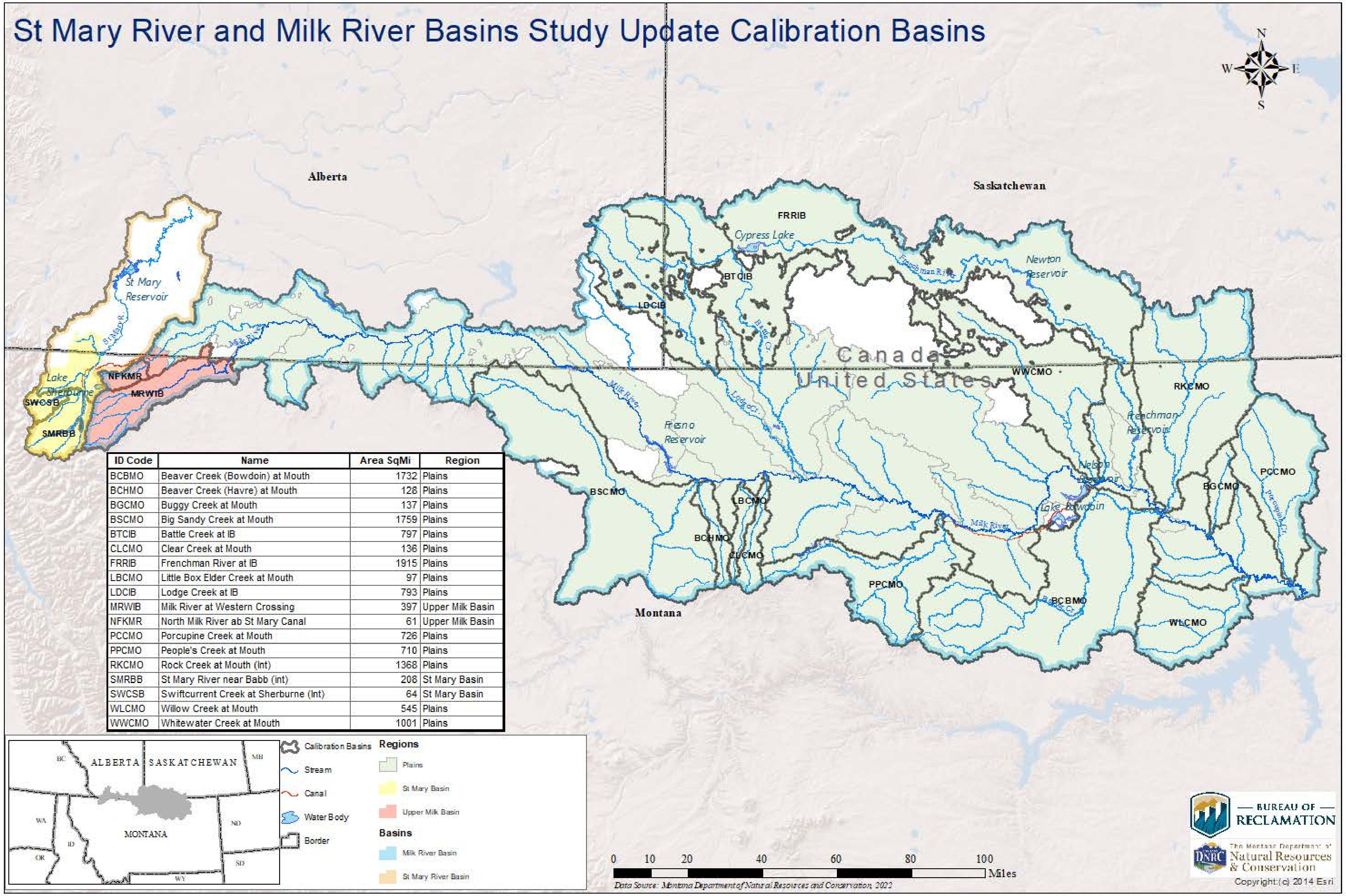
Model Calibration

A calibration and validation workflow was developed and applied over a historical period of record 1980-2015 (calendar years). As part of the calibration process, simulated streamflow was compared with naturalized streamflow by way of identified metrics. A daily naturalized streamflow dataset was developed by MT DNRC using twice-monthly natural flow records from the IJC, as well as through observed gage records and consumptive use estimates (Blythe et al. 2023). Calibration points are summarized in table B-4 and illustrated on figure B-10.

The calibration approach for the conceptual hydrologic model was focused on comparison of monthly streamflow. The avg monthly streamflow statistics were computed from daily simulated streamflow and compared with the same statistics computed from daily naturalized streamflow.

Table B-4.—Conceptual hydrologic model calibration points

Calibration Basins	Description	USGS ID (if applicable)	Location
BCBMO	Beaver Creek (Bowdoin) at Mouth	06167500	Plains
BCHMO	Beaver Creek (Havre) at Mouth	06140000	Plains
BGCMO	Buggy Creek at Mouth	06172200	Plains
BSCMO	Big Sandy Creek at Mouth	06139500	Plains
BTCIB	Battle Creek Inflow	06149500	Plains
CLCMO	Clear Creek at Mouth	06142400	Plains
FRRIB	Frenchman River Inflow	06164000	Plains
LBCMO	Little Box Elder Creek at Mouth	06141600	Plains
LDCIB	Lodge Creek	06145500	Plains
MRWIB	Milk River at Western Crossing	06133000	Upper Milk Basin
NFKMR	Upper North Fork Milk River Inflow	06133500	Upper Milk Basin
PCCMO	Porcupine Creek at Mouth	06175000	Plains
PPCMO	People's Creek at Mouth	06154550	Plains
RKCMO	Rock Creek at Mouth	06171000	Plains
SMRBB	St. Mary River near Babb	05017500	St. Mary Basin
SWCSB	Swiftcurrent Creek at Sherburne, MT	05016000	St. Mary Basin
WLCMO	Willow Creek at Mouth	06174000	Plains
WWCMO	Whitewater Creek at Mouth	NA	Plains



ID Code	Name	Area SqMi	Region
BCBMO	Beaver Creek (Bowdoin) at Mouth	1732	Plains
BCHMO	Beaver Creek (Havre) at Mouth	128	Plains
BGCMO	Buggy Creek at Mouth	137	Plains
BSCMO	Big Sandy Creek at Mouth	1759	Plains
BTCIB	Battle Creek at IB	797	Plains
CLCMO	Clear Creek at Mouth	136	Plains
FRRIB	Frenchman River at IB	1915	Plains
LBCMO	Little Box Elder Creek at Mouth	97	Plains
LDCIB	Lodge Creek at IB	793	Plains
MRWIB	Milk River at Western Crossing	397	Upper Milk Basin
NFKMR	North Milk River ab St Mary Canal	61	Upper Milk Basin
PCCMO	Porcupine Creek at Mouth	726	Plains
PPCMO	People's Creek at Mouth	710	Plains
RKCMO	Rock Creek at Mouth (Int)	1368	Plains
SMRBB	St Mary River near Babb (int)	208	St Mary Basin
SWCSB	Swiftcurrent Creek at Sherburne (Int)	64	St Mary Basin
WLCMO	Willow Creek at Mouth	545	Plains
WWCMO	Whitewater Creek at Mouth	1001	Plains

Figure B-10.—Map of conceptual hydrologic model calibration basins.

Several hydrologic model parameters were optimized based on a shuffle complex evolution optimization approach (Duan et al. 1992). These calibration parameters are summarized in table B-5 along with descriptions and parameter ranges not to be exceeded in calibration. Model calibration was performed for each year independently. The objective function for calibration included minimizing differences in these metrics: monthly Nash Suttcliffe Efficiency (NSE; Nash and Suttcliffe 1970), daily NSE, and monthly correlation. The choice of metrics was based on the desire to improve flow volume and timing.

Table B-5.—Calibration model parameters for combined modeling approach

Model Parameter - optimized	Module	Description	Parameter Range	Dimensions
M_r	Snow model	Melt-rate factor	0.5 – 10	Mm/°C/day
Tcrt	Snow model	Temperature threshold for snowmelt	0.0 – 5	°C
S_0	Soil Moisture Accounting Model	Initial storage factor	0.0 – 10	Unitless
A1	Streamflow generation module	Contributing area fraction to streamflow during season 1	0.01 – 20	Unitless
A2	Streamflow generation module	Contributing area fraction to streamflow during season 2	0.01 – 20	Unitless
A3	Streamflow generation module	Contributing area fraction to streamflow during season 3	0.0001 – 1	Unitless
A4	Streamflow generation module	Contributing area fraction to streamflow during season 4	0.0001 – 1	Unitless
A5	Streamflow generation module	Contributing area fraction to streamflow during season 5	0.0001 – 1	Unitless

The ranges for calibration parameters listed in table B-5 were determined from a variety of methods. The range of the snow melt-rate factor, M_f, was determined from Dingman (1994). The range of the temperature threshold for snowmelt, T_{crt}, was determined from McCabe and

Markstrom (2007). The range of the initial storage factor, S_0, was determined through sensitivity analysis. We used different ranges (e.g., 0–10, 0–100, 0–1000) and found that the highest annual NSE and correlation coefficients were computed using range of S_0 as 0–10. Ranges for the empirical coefficient for each of 5 seasons (A1 through A5) were determined also through sensitivity analysis as well as consideration of the intent of this coefficient. For season 1 and season 2 (refer to table B-3 for the start dates of each season by calibration basin), a sensitivity analysis was performed with two trial calibrations. The first trial calibration used a range of coefficients for these seasons (A1, A2) from 0–1. Results from these calibrations suggested that area contributing to streamflow may be greater than 1 during these periods. That is, calibrations were unsatisfactory for many years using a range limited to 0-1. Further, a second trial calibration used a range of coefficients for these seasons (A1, A2) from 0 to 50. One result of this trial was that calibrations were prohibitively long in terms of run time. Another result of this trial is that optimal coefficients only exceeded 20 in season 1 for one calibration year (FRRIB, was the test case). Therefore, ranges for coefficients A1 and A2 were limited to 0–20. This range in A1 and A2 also accounts for possible future change where snowmelt may occur earlier in the year than it has historically. Coefficients A3, A4, and A5 were limited to 0–1 following reasoning that streamflow during these seasons is generally a small fraction of annual streamflow and area contributing to streamflow is generally smaller than the overall drainage area in these periods. Sensitivity analysis of coefficients during A4 and A5 also indicated these values are less than one.

Model calibration results for each calibration basin are summarized in table B-6. Metrics reported in this table encompass a broader range of metrics than were used in the calibration objective function, namely by also including KGE. However, those metrics that were used in calibration are highlighted in gray.

Moriasi et al. (2007) evaluated a variety of hydrologic models in their ability to reproduce observed natural streamflow. They arrived at a series of criteria for determining satisfactory model performance. These criteria include monthly NSE greater than 0.5, monthly PBIAS less than 25 percent (high or low) and RSR less than or equal to 0.7. RSR is the route mean squared error divided by the standard deviation. These criteria were applied to calibrated model simulations for each year individually since each simulation year was calibrated individually for each basin. Figure B-11 illustrates those years with satisfactory simulations for each basin (blue) and those years that did not meet the criteria (yellow). Satisfactory years are notable in the hydrologic modeling framework because only these years inform future streamflow scenario development (described later).

Table B-6.—Calibration results for the conceptual hydrologic model framework*

Calibration Basin	Optimal Run Statistics 1980-2015							
	Monthly NSE	Seasonal NSE	Monthly correlation	Daily correlation	Monthly KGE	Seasonal KGE	Monthly Pbias	Seasonal Pbias
FRRIB	0.922	0.897	0.961	0.673	0.894	0.904	8.800	5.000
BTCIB	0.849	0.958	0.922	0.734	0.909	0.968	0.400	2.000
LDCIB	0.746	0.959	0.865	0.650	0.776	0.822	12.600	17.200
MRWIB	0.863	0.912	0.933	0.725	0.875	0.849	-10.200	-14.500
NFKMR	0.705	0.738	0.880	0.734	0.644	0.614	-31.000	-30.200
SWCSB	0.962	0.962	0.985	0.875	0.906	0.894	-9.300	-10.300
PPCMO	0.755	0.877	0.895	0.785	0.646	0.839	-12.100	-10.400
CLCMO	0.774	0.783	0.918	0.775	0.604	0.678	-20.200	0.774
BSCMO	0.875	0.955	0.936	0.744	0.893	0.954	0.200	1.900
BHCMO	0.640	0.761	0.808	0.545	0.624	0.721	-21.900	-20.700
LBCMO	0.739	0.771	0.910	0.615	0.557	0.643	-21.600	-17.700
BCBMO	0.843	0.931	0.926	0.744	0.791	0.911	3.700	4.200
WWCMO	0.761	0.766	0.877	0.682	0.653	0.668	31.000	30.000
RKCMO	0.840	0.899	0.918	0.665	0.852	0.855	10.200	10.600
BGCMO	0.645	0.906	0.869	0.547	0.504	0.735	-12.500	-11.200
PCCMO	0.599	0.873	0.799	0.407	0.553	0.804	-1.500	4.600
WLCMO	0.801	0.910	0.900	0.689	0.766	0.896	-7.300	-5.400

* Grey shaded columns illustrate those calibration metrics that were used in the shuffle complex evolution optimization approach. Statistics were calculated over all calibration years.

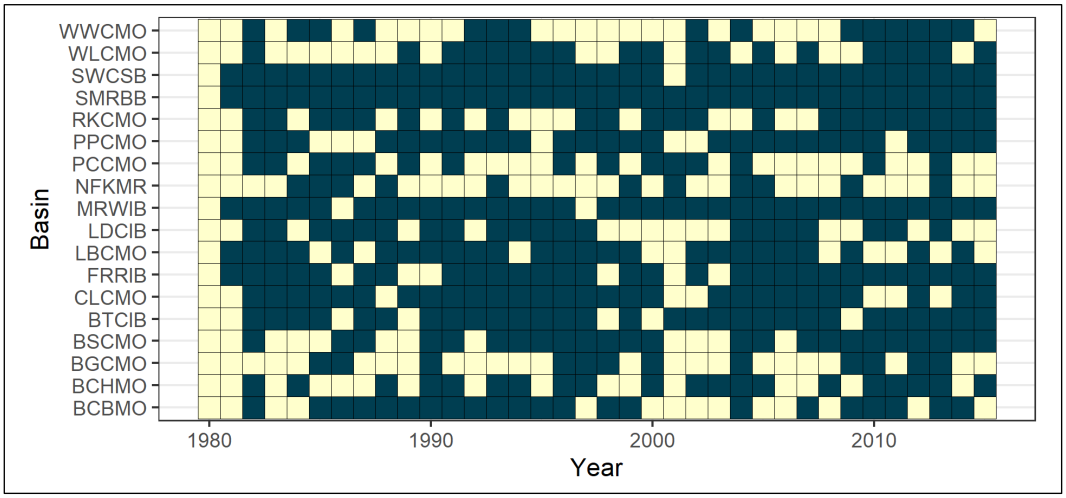


Figure B-11.—Illustration of hydrologic model simulation years deemed satisfactory (blue) based on Moriasi et al. (2007) criteria.[7]

Historical Model Verification

A traditional approach of splitting the hydrologic modeling period into a calibration period and validation period was not feasible in this study due to the time varying nature of the model parameters and independent calibration for each year of model simulation. The model verification approach taken in this Basins Study Update was to develop daily streamflow ensemble verification and prediction method, following approaches by Nowak et al. (2010) and Prairie et al. (2008) and following the workflow diagram on figure B-6. In this approach, a PCA was used to identify historical analog years similar to each calibration/simulation year from 1980–2015. The PCA analysis was performed based on feature vectors that include aggregations of precipitation and temperature that drive streamflow for each year. These are:

- October–December daily avg temperature
- October–December total precipitation
- December daily avg temperature
- December total precipitation
- November–December daily avg temperature
- November–December total precipitation
- March–May daily avg temperature
- March–May total precipitation
- December–February daily avg temperature
- December–February total precipitation

[7] Black boxes indicate years have satisfactory simulations and may be used as nearest neighbors in the PKNN approach for developing future streamflow simulations. Yellow boxes indicate years did not meet the criteria and parameters for these years were not selected for future streamflow simulations.

Because model calibrations were performed over calendar years January through December, variables in the feature vector also adhered to the calendar year convention. Antecedent conditions that may be important for informing the water budget early in the calendar year (including snowpack, frozen soil, glaciers, etc.) were considered in the S0 (initial storage) term of the model and are not explicitly represented. This is in part due to the lack of observed naturalized flow data during winter months that can be used for model calibration.

We call this approach to calibration and verification a predictive K-nearest neighbor approach, or PKNN, and we applied this method for all modeled basins based on the success of model verification in the Frenchman River basin (FRRIB). Only years that met satisfactory calibration criteria by Moriasi et al. (2007) were included in the PCA analysis and thereby available for selection as analog years to supply model parameters. Six nearest neighbor years (square root of 36 simulation years is the rule of thumb) were selected for each simulation year. Optimal model parameters for each of the near neighbor years associated with a simulation year were used in combination with meteorology from the simulation year to generate six nearest neighbor streamflow traces. These nearest neighbor streamflow traces were randomly resampled with greater weight given to the first nearest neighbor compared with the sixth nearest neighbor. One thousand resampled traces were generated from the six nearest neighbor traces. In this approach, we test the assumption that years with similar meteorological conditions will have similar optimal hydrologic model parameters.

Table B-7 summarizes comparison statistics for the avg timeseries of the verification (PKNN) ensemble, simulated streamflow using the calibrated model (hereafter called OPAR), and avg monthly observed naturalized streamflow (OBSV) for Frenchman River at International Boundary. Statistics were calculated across all years collectively, as well as for dry years only, wet years only, and avg years only. The avg, wet, and dry years were determined by ranking avg annual observed naturalized streamflow at this location (only for those years considered satisfactory in model calibration) and calculating terciles. Those years in the lowest tercile were considered dry, and so forth. Using these criteria, there are 8 dry years, 10 avg years, and 11 wet years from 1980–2015. There are 29 years considered in total from the full 36-year period of record. Statistics in the table show high correlation, high NSE, and relatively low RSR when considering all years. It also shows that this approach does not perform as well for dry years.

Figure B-12 illustrates how the DCAHM model SWE compares with Daymet-derived SWE for avg, dry, and wet years in the FRRIB basin, using the same approach described above. Generally, DAYMET-derived SWE melts more gradually than simulated SWE using the DCAHM over the same period (1980–2015). Daymet-derived SWE is itself a model, so additional comparisons including observations of SWE would be beneficial in future analysis.

Table B-7.—Summary of statistics for simulated streamflow at Frenchman River at International Boundary

Comparison case	Percent bias	Correlation	NSE	RSR
All years				
PKNN-OBSV	-10.70	0.87	0.74	0.49
OPAR-OBSV	8.00	0.98	0.95	0.21
PKNN-OPAR	-17.30	0.95	0.86	0.36
Dry years only				
PKNN-OBSV	91.90	0.97	-0.19	1.04
OPAR-OBSV	13.30	0.99	0.96	0.18
PKNN-OPAR	69.30	0.98	-0.07	0.99
Wet years only				
PKNN-OBSV	-44.40	0.81	0.47	0.70
OPAR-OBSV	8.60	0.97	0.94	0.23
PKNN-OPAR	-48.80	0.92	0.53	0.65
Avg years only				
PKNN-OBSV	18.60	0.90	0.74	0.49
OPAR-OBSV	4.40	0.98	0.95	0.21
PKNN-OPAR	13.60	0.97	0.89	0.32

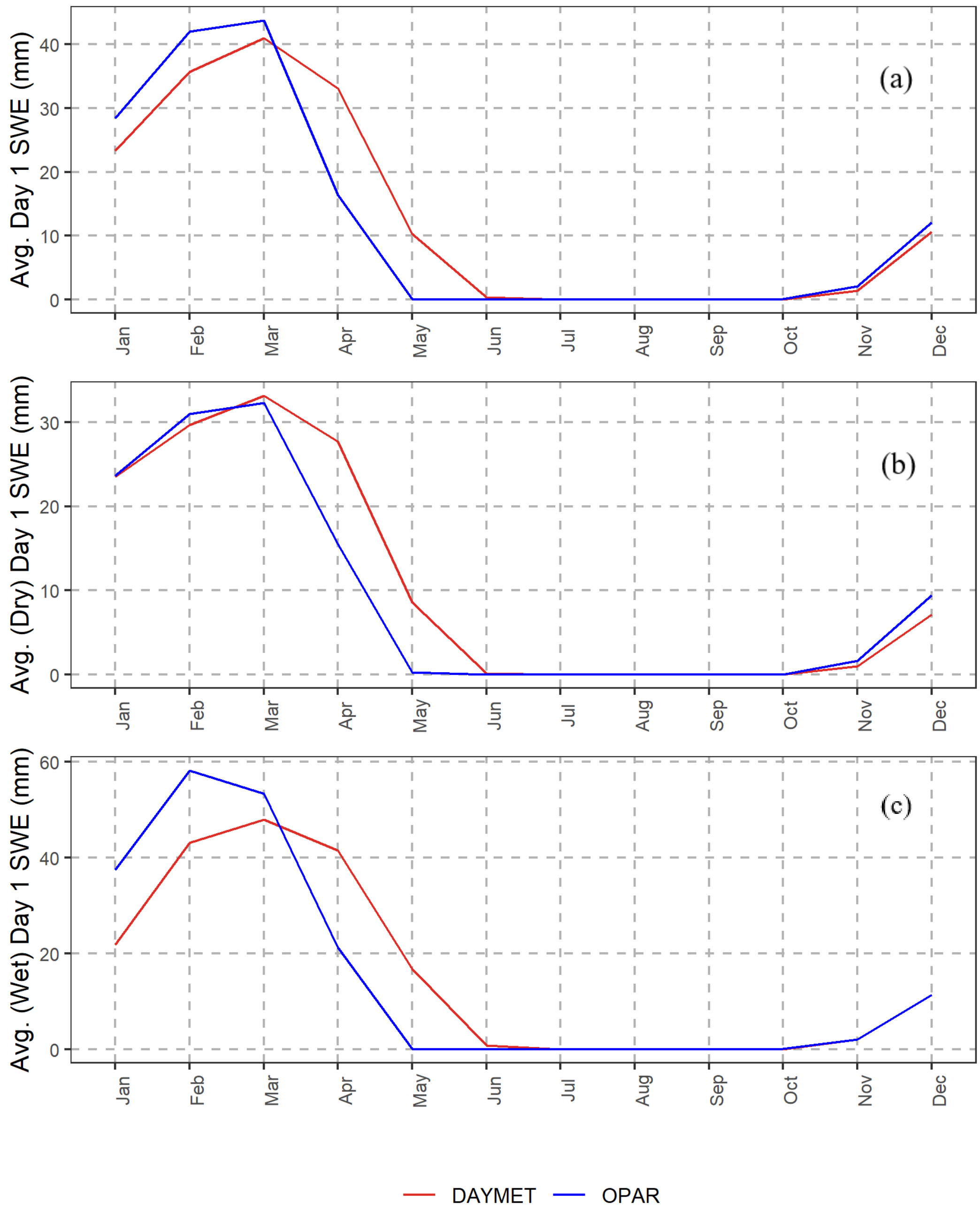


Figure B-12.—Average SWE on first day of the month for all years (a), dry years only (b), and wet years only (c).

Figure B-13 illustrates a comparison of avg monthly flows resulting from the PKNN approach for model verification, simulated streamflow using the calibrated model, and avg monthly observed naturalized streamflow for FRRIB.

Results from historical model verification indicate that model parameters are generally consistent depending on driving precipitation and temperature. The PKNN median monthly streamflow deviates most from the observed naturalized streamflow (OBSV) and calibrated simulation (OPAR) during the month of March, when snowpack is historically at its peak (see figure B-12). This result may correspond with the available nearest neighbor years used for verification, or other reasons not yet explored. Results from this verification also indicate that the approach is applicable for developing future streamflow simulations. This procedure and results are discussed in the next section.

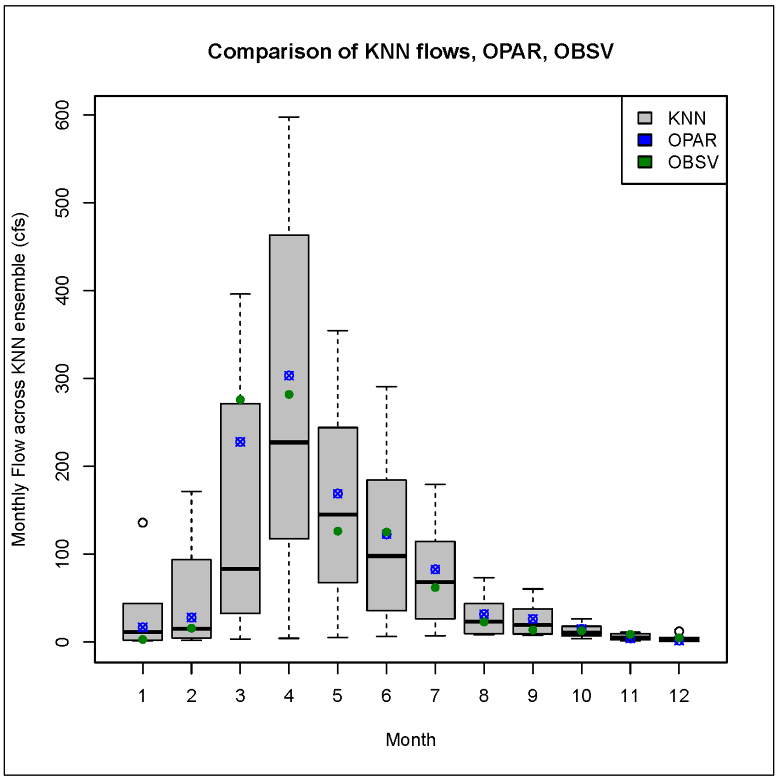


Figure B-13.—Monthly streamflow summarized at Frenchman River at International Boundary, including average monthly observed natural streamflow (green), average monthly streamflow from calibrated simulation (blue), and average monthly streamflow for each of 1000 resampled traces using the PKNN approach (grey boxplots).

Future Simulations

Following a similar approach described for historical hydrologic model verification, illustrated on figure B-6, feature vectors, using the same variables listed previously, were developed for each projected future climate scenario (15 scenarios) and a PCA analysis was performed for to identify six nearest neighbor years to each projected future year in each climate scenario. Again, this approach was performed for each simulation basin. Also similar to the historical model verification, only historical years that met satisfactory calibration criteria by Moriasi et al. (2007) were included in the PCA analysis and thereby available for selection as analog years.

Optimal historical model parameters for each of the nearest neighbor years associated with a future simulation year were used in combination with meteorology from the future simulation year to generate six nearest neighbor daily streamflow traces. These nearest neighbor streamflow traces were then randomly resampled with greater weight given to the first nearest neighbor compared with the sixth nearest neighbor. One thousand resampled traces were generated from the six nearest neighbor traces. The avg streamflow timeseries from the 1,000 resampled traces was determined to be the future scenario daily streamflow. The end result is a single future timeseries of daily streamflow for each future scenario.

Additional Basin Results

Summaries of percent change in annual flow volume, April – September flow volume, and October – March flow volume are presented in table B-8, table B-9, and table B-10, respectively.

Table B-8.—Projected percent change in annual flow volume by subbasin

ID	Name	2020s		2050s		2080s	
		Min	Max	Min	Max	Min	Max
BCBMO	Beaver Creek (Bowdoin) at Mouth	-7	16	14	55	7	45
BCHMO	Beaver Creek (Havre) at Mouth	58	95	49	85	47	116
BGCMO	Buggy Creek at Mouth	5	24	10	45	10	169
BSCMO	Big Sandy Creek at Mouth	16	84	-9	64	-15	53
BTCIB	Battle Creek Inflow	16	54	19	57	24	84
CLCMO	Clear Creek at Mouth	32	69	61	109	51	125
FRRIB	Frenchman River Inflow	22	45	31	66	20	82
LBCMO	Little Box Elder Creek at Mouth	25	71	54	119	74	134
LDCIB	Lodge Creek	65	109	89	170	118	226
MRWIB	Milk River at Western Crossing	23	48	28	58	25	61
NFKMR	Upper North Fork Milk River Inflow	-2	21	-1	31	2	30
PCCMO	Porcupine Creek at Mouth	83	151	116	189	61	181
PPCMO	People's Creek at Mouth	19	55	-8	55	-22	26
RKCMO	Rock Creek at Mouth	301	373	100	357	112	235
SMRBB	St. Mary River near Babb	21	44	31	76	37	79
SWCSB	Swiftcurrent Creek at Sherburne, MT	27	37	19	51	16	47
WLCMO	Willow Creek at Mouth	-3	9	-15	1	-34	19
WWCMO	Whitewater Creek at Mouth	138	260	234	454	246	2206

Table B-9.—Projected percent change in April - September flow volume by subbasin

ID	Name	2020s		2050s		2080s	
		Min	Max	Min	Max	Min	max
BCBMO	Beaver Creek (Bowdoin) at Mouth	-15	-2	-24	-5	-43	-5
BCHMO	Beaver Creek (Havre) at Mouth	37	74	27	55	19	57
BGCMO	Buggy Creek at Mouth	-10	11	-17	12	-45	13
BSCMO	Big Sandy Creek at Mouth	3	69	-24	41	-37	33
BTCIB	Battle Creek Inflow	4	51	5	31	5	34
CLCMO	Clear Creek at Mouth	11	52	6	42	-5	61
FRRIB	Frenchman River Inflow	5	35	-5	35	-32	30
LBCMO	Little Box Elder Creek at Mouth	5	34	3	33	-13	26
LDCIB	Lodge Creek	65	98	82	153	120	214
MRWIB	Milk River at Western Crossing	-1	34	-10	24	-23	29
NFKMR	Upper North Fork Milk River Inflow	-11	12	-13	14	-15	20
PCCMO	Porcupine Creek at Mouth	80	126	60	149	-12	120
PPCMO	People's Creek at Mouth	-1	45	-29	38	-51	9
RKCMO	Rock Creek at Mouth	299	364	35	325	0	98
SMRBB	St. Mary River near Babb	16	36	26	58	14	60
SWCSB	Swiftcurrent Creek at Sherburne, MT	21	38	10	39	-1	39
WLCMO	Willow Creek at Mouth	-14	3	-26	-13	-54	-11
WWCMO	Whitewater Creek at Mouth	102	156	125	197	139	265

Table B-10.—Projected percent change in October - March runoff volume by subbasin

ID	Name	2020s		2050s		2080s	
		Min	Max	Min	Max	Min	max
BCBMO	Beaver Creek (Bowdoin) at Mouth	16	76	106	222	102	202
BCHMO	Beaver Creek (Havre) at Mouth	120	165	120	184	106	313
BGCMO	Buggy Creek at Mouth	78	137	139	295	126	1079
BSCMO	Big Sandy Creek at Mouth	57	127	17	132	12	114
BTCIB	Battle Creek Inflow	31	106	68	183	70	252
CLCMO	Clear Creek at Mouth	93	145	149	305	218	313
FRRIB	Frenchman River Inflow	38	114	99	219	107	314
LBCMO	Little Box Elder Creek at Mouth	73	193	206	436	247	546
LDCIB	Lodge Creek	63	156	106	214	112	257
MRWIB	Milk River at Western Crossing	62	109	95	179	115	224
NFKMR	Upper North Fork Milk River Inflow	20	60	49	105	51	121
PCCMO	Porcupine Creek at Mouth	90	250	199	426	154	445
PPCMO	People's Creek at Mouth	47	76	36	92	37	74
RKCMO	Rock Creek at Mouth	245	490	221	540	167	783
SMRBB	St. Mary River near Babb	30	88	64	178	81	310
SWCSB	Swiftcurrent Creek at Sherburne, MT	31	53	43	105	48	183
WLCMO	Willow Creek at Mouth	9	37	8	32	2	82
WWCMO	Whitewater Creek at Mouth	178	392	372	836	383	4674

Summaries of projected precipitation, temperature, flow volume, and avg monthly simulated streamflow, similar to those presented in the Water Supply Assessment for St. Mary River at International Boundary, Milk River at Western Crossing, and Frenchman River at International Boundary, are presented here for all other simulation basins (refer to figure B-14, figure B-16, figure B-18, figure B-20, figure B-22, figure B-24, figure B-26, figure B-28, figure B-30, figure B-32, figure B-34, figure B-36, figure B-38, figure B-40, figure B-42, figure B-44, figure B-46, and figure B-48). In the hydrograph figures, the grey shaded area represents the range between the minimum of the 25th percentile of simulated projected streamflow and the maximum of the 75th percentile of the resampled ensemble (refer to figure B-15, figure B-17, figure B-19, figure B-21, figure B-23, figure B-25, figure B-27, figure B-29, figure B-31, figure B-33, figure B-35, figure B-37, figure B-39, figure B-41, figure B-43, figure B-45, figure B-47, and figure B-49).

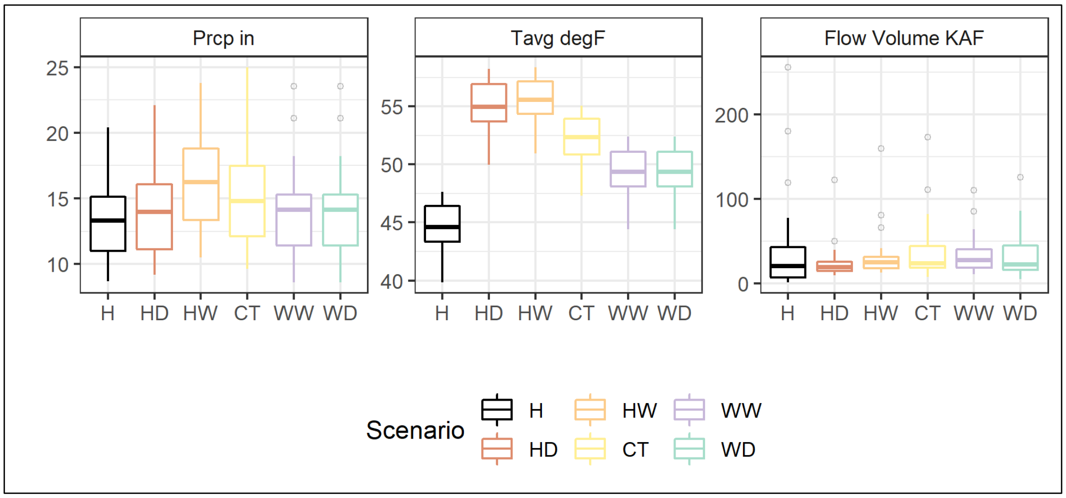


Figure B-14.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Beaver Creek (Bowdoin) at Mouth (USGS ID 06167500).

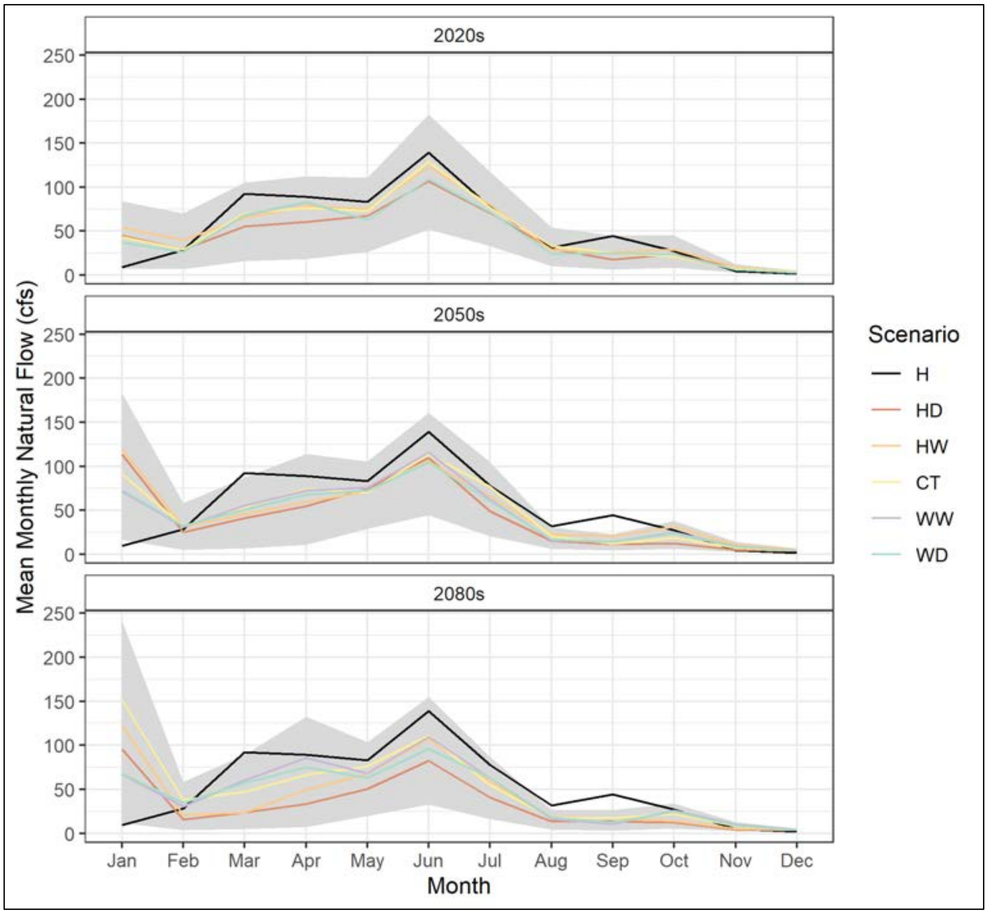


Figure B-15.—Historical and projected average monthly streamflow at Beaver Creek (Bowdoin) at Mouth (USGS ID 06167500)

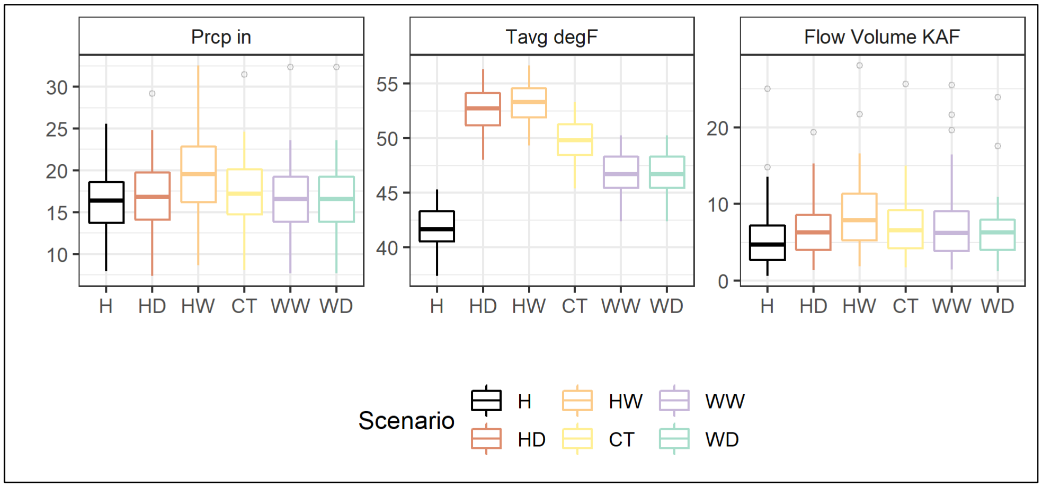


Figure B-16.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Beaver Creek (Havre) at Mouth (USGS ID 06140000).

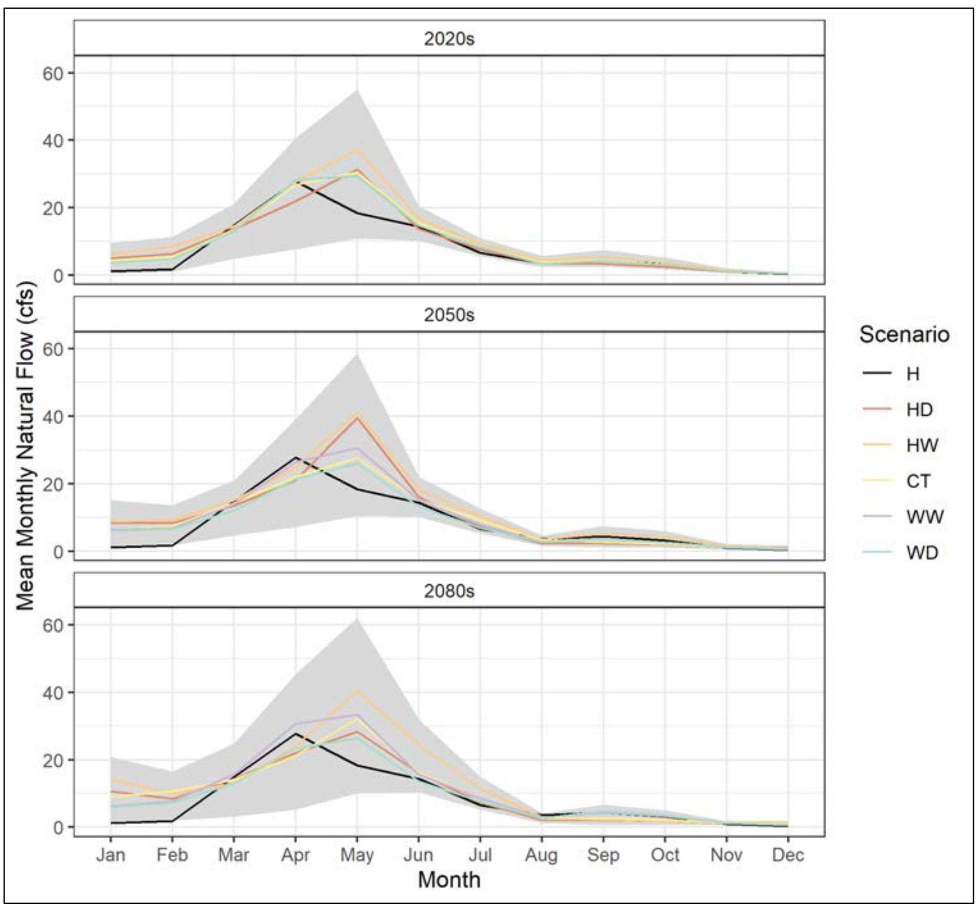


Figure B-17.—Historical and projected average monthly streamflow at Beaver Creek (Havre) at Mouth (USGS ID 06140000).

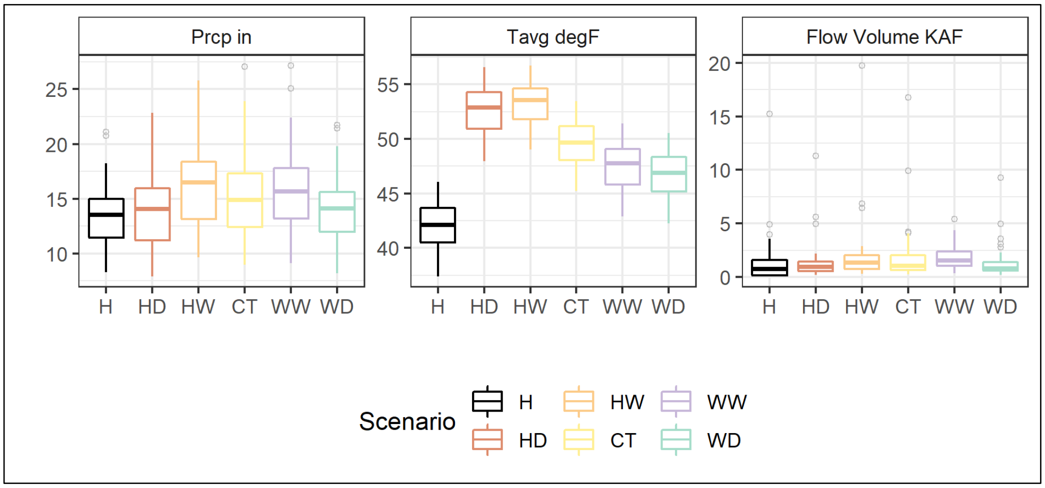


Figure B-18.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Buggy Creek at Mouth (USGS ID 06172200).

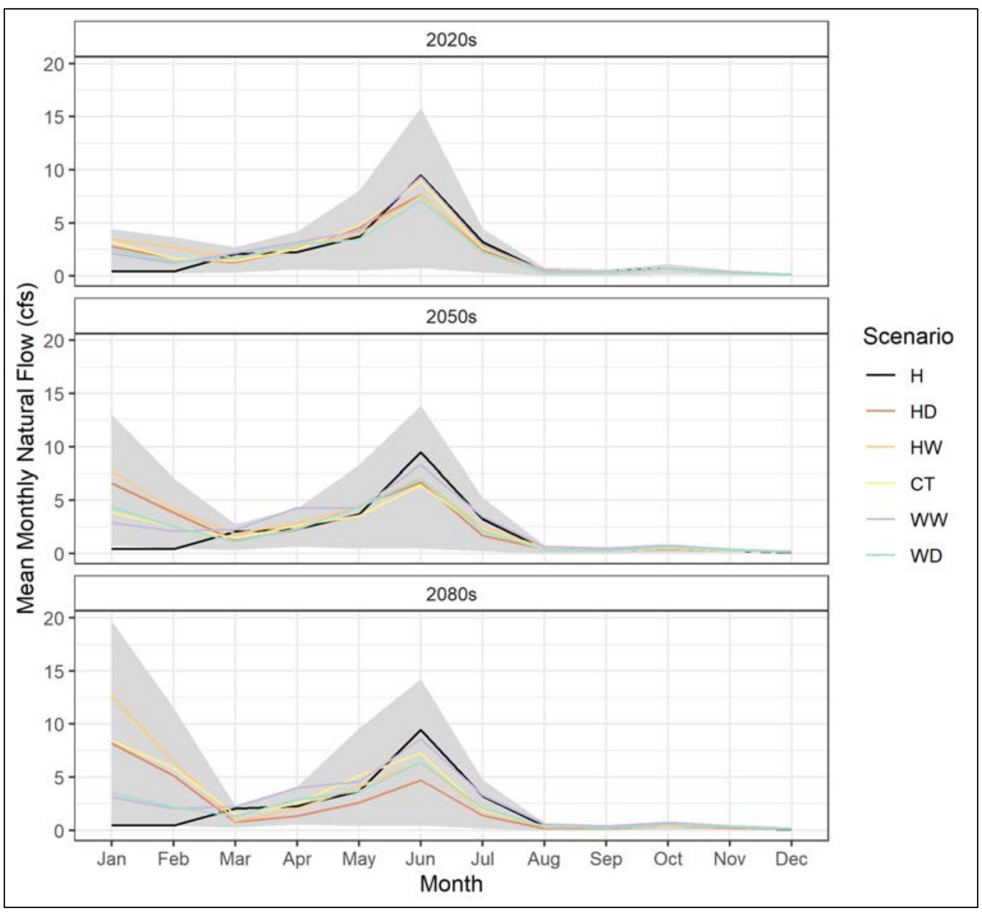


Figure B-19.—Historical and projected average monthly streamflow at Buggy Creek at Mouth (USGS ID 06172200).

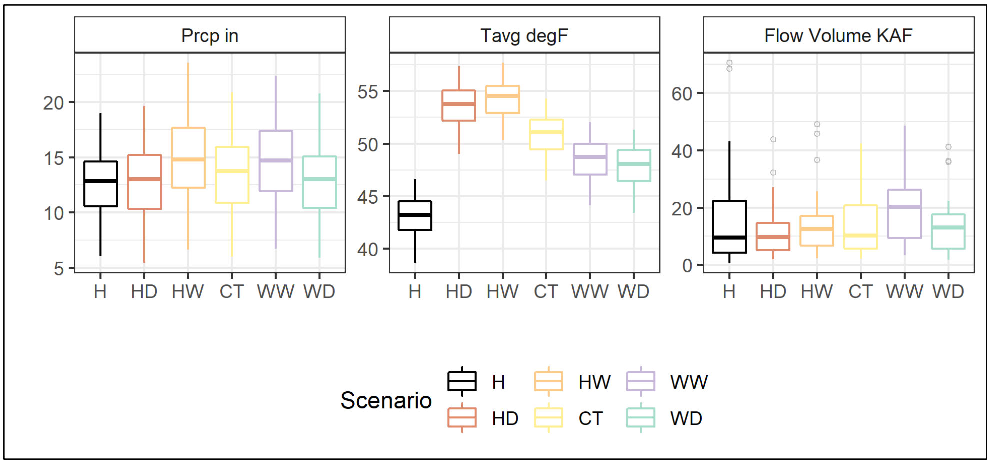


Figure B-20.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Big Sandy Creek at Mouth (USGS ID 06139500).

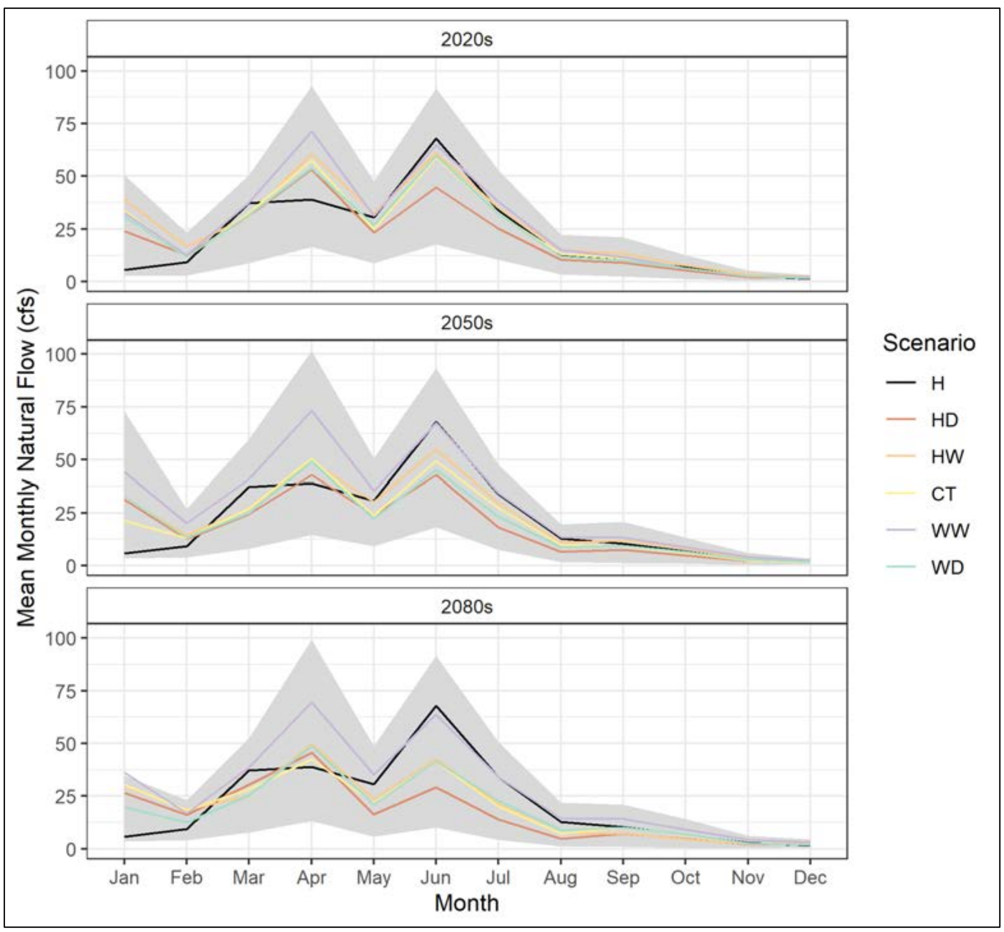


Figure B-21.—Historical and projected average monthly streamflow at Big Sandy Creek at Mouth (USGS ID 06139500).

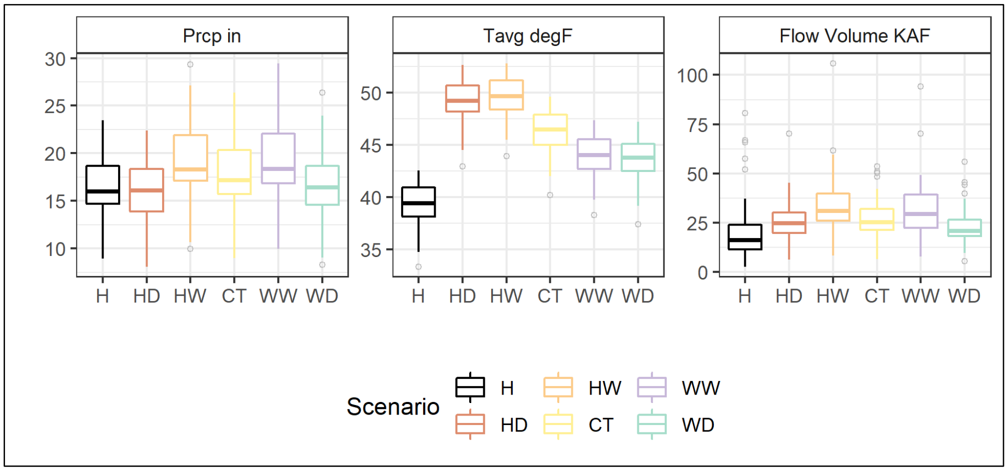


Figure B-22.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Battle Creek Inflow (USGS ID 06149500).

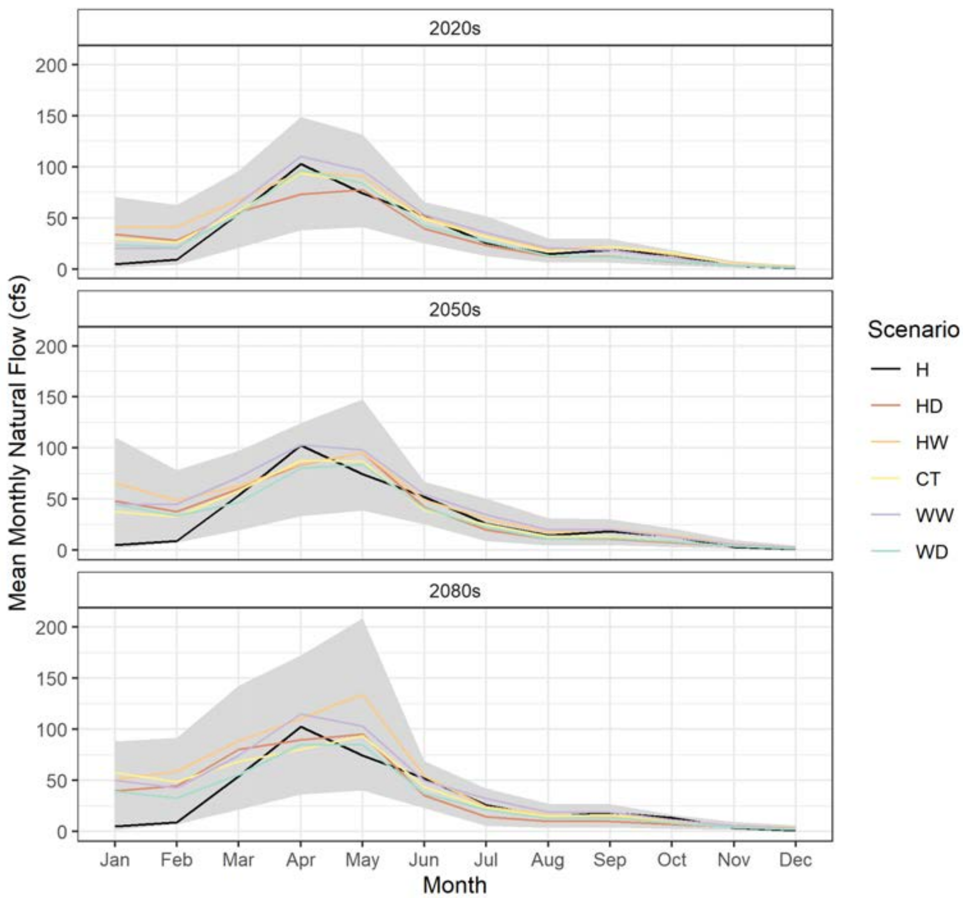


Figure B-23.—Historical and projected average monthly streamflow at Battle Creek Inflow (USGS ID 06149500).

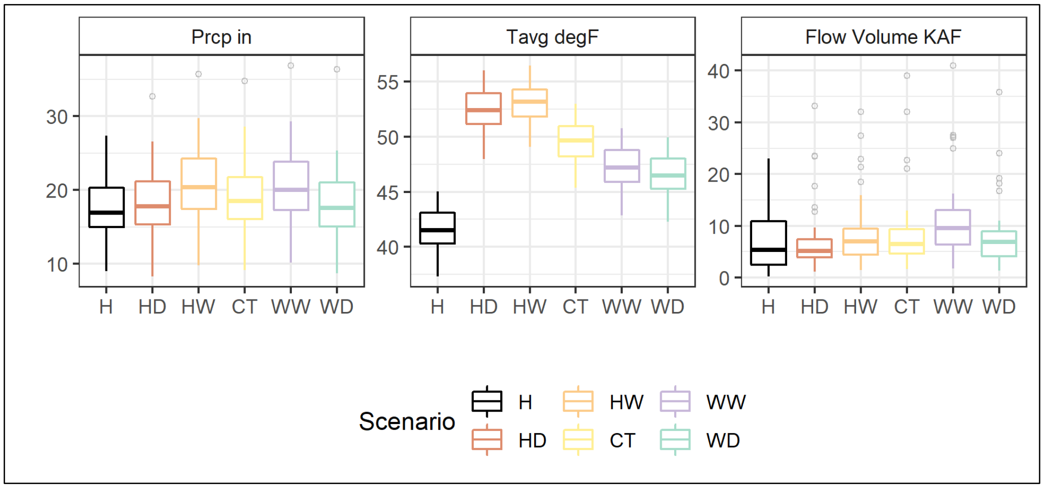


Figure B-24.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Clear Creek at Mouth (USGS ID 06142400).

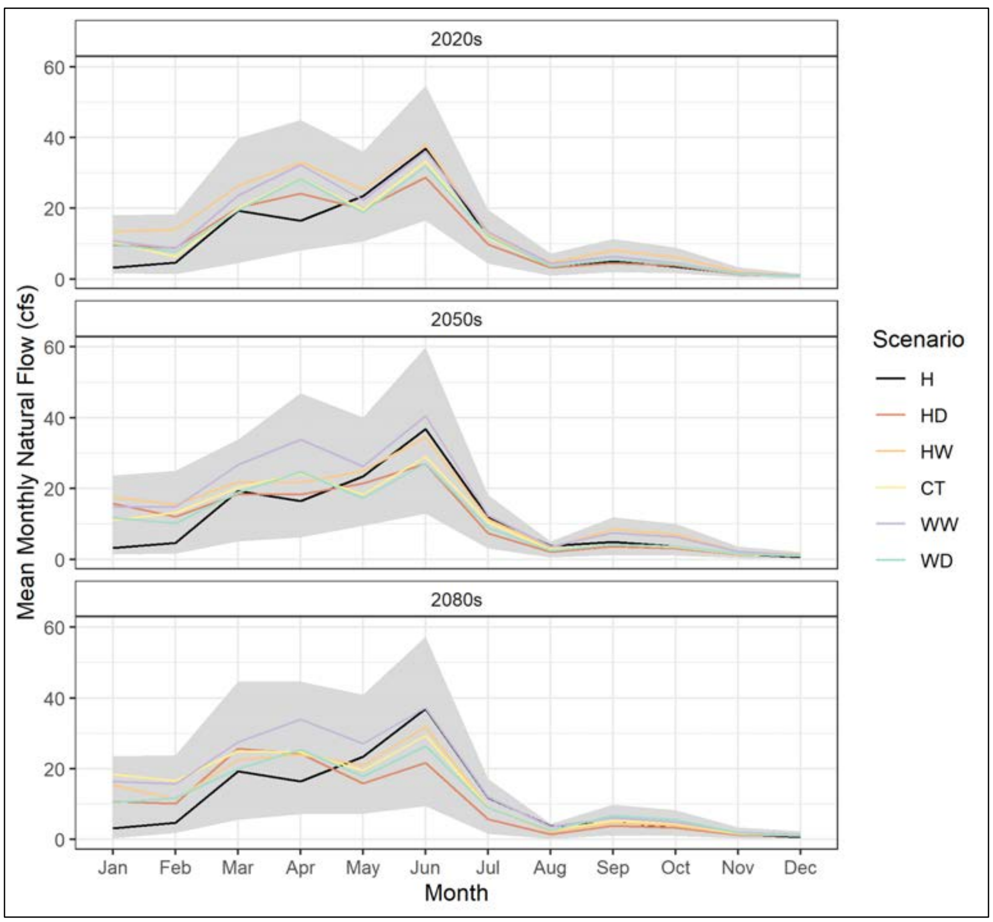


Figure B-25.—Historical and projected average monthly streamflow at Clear Creek at Mouth (USGS ID 06142400).

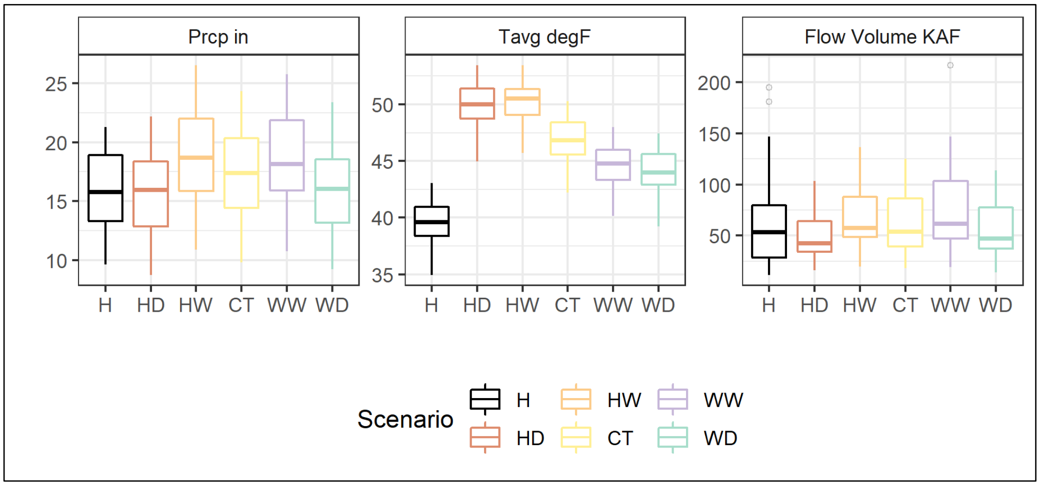


Figure B-26.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Frenchman River Inflow (USGS ID 06164000).

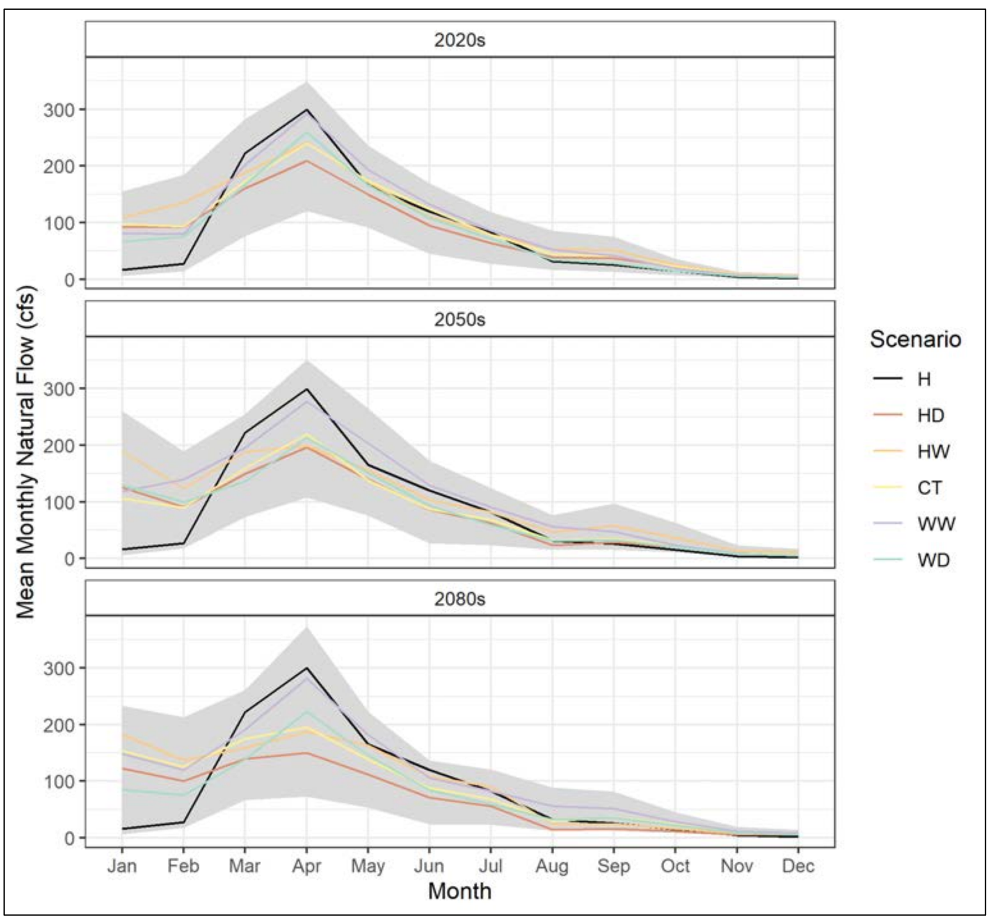


Figure B-27.—Historical and projected average monthly streamflow at Frenchman River Inflow (USGS ID 06164000).

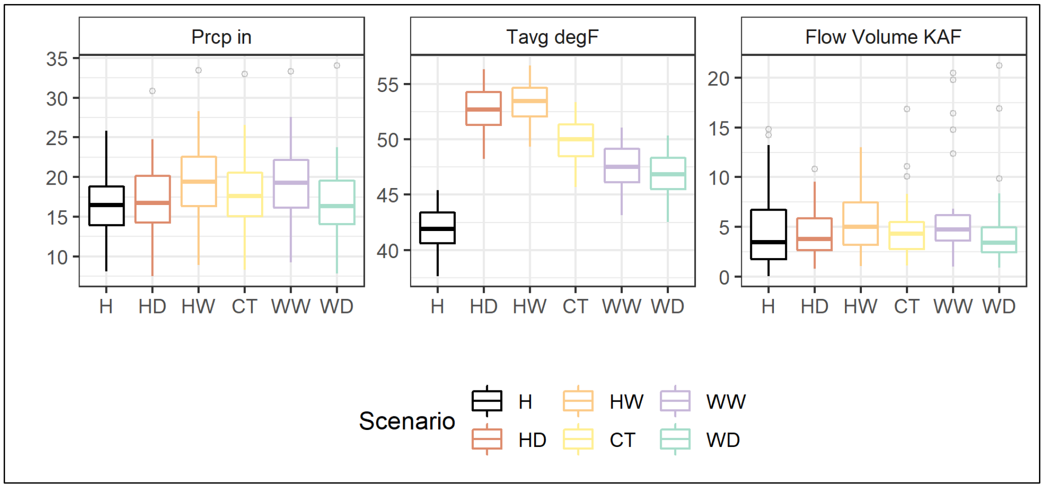


Figure B-28.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Little Box Elder Creek at Mouth (USGS ID 06141600).

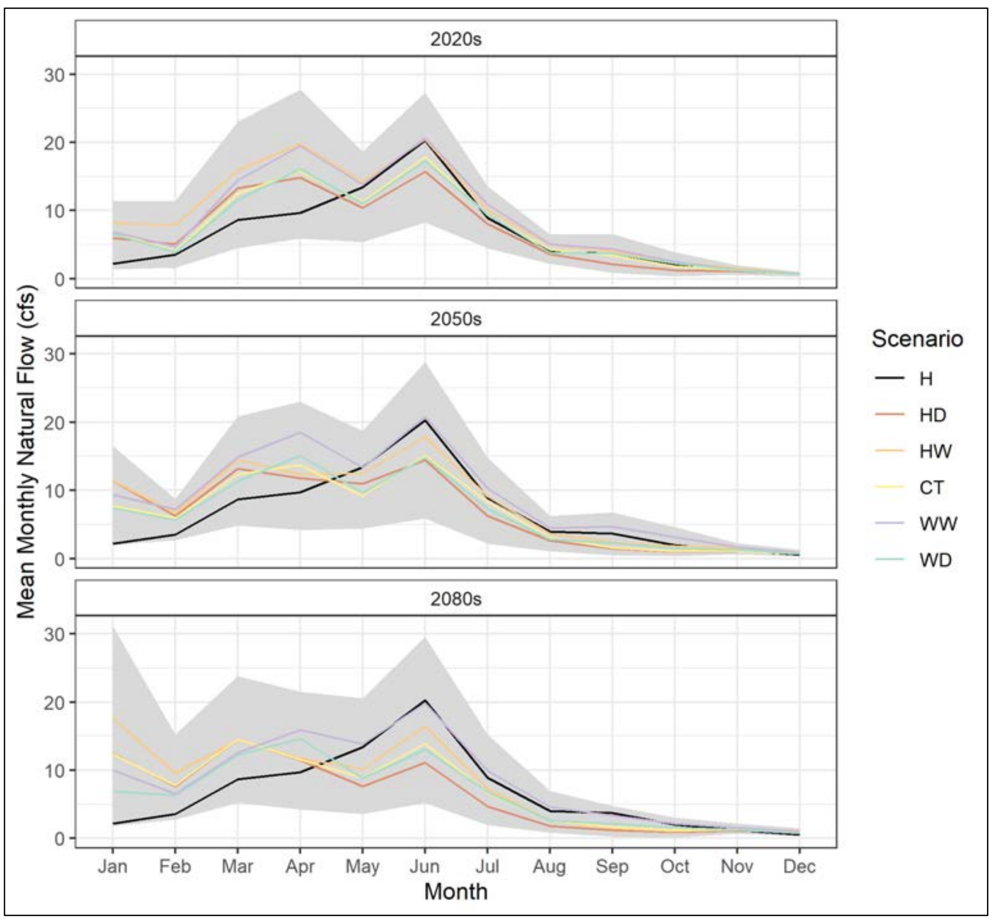


Figure B-29.—Historical and projected average monthly streamflow at Little Box Elder Creek at Mouth (USGS ID 06141600).

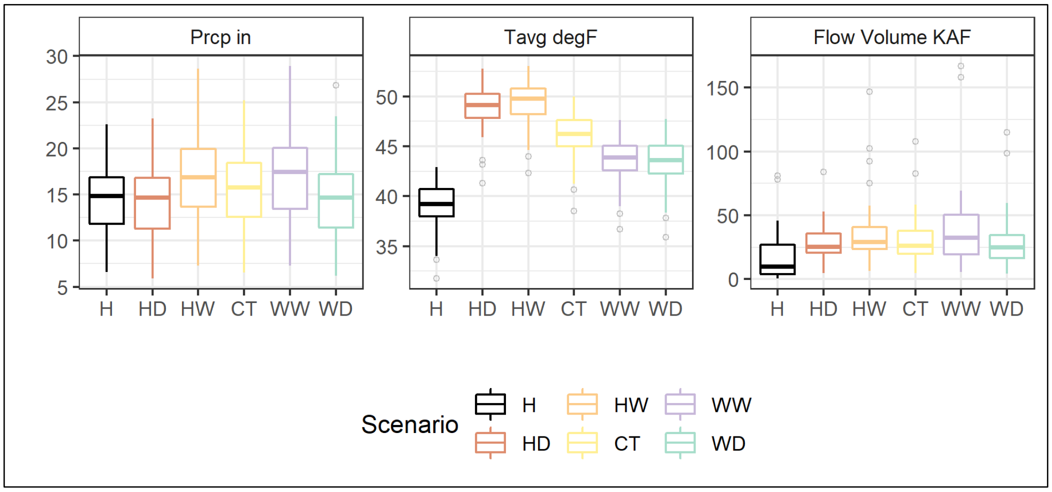


Figure B-30.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Lodge Creek at International Boundary (USGS ID 06145500).

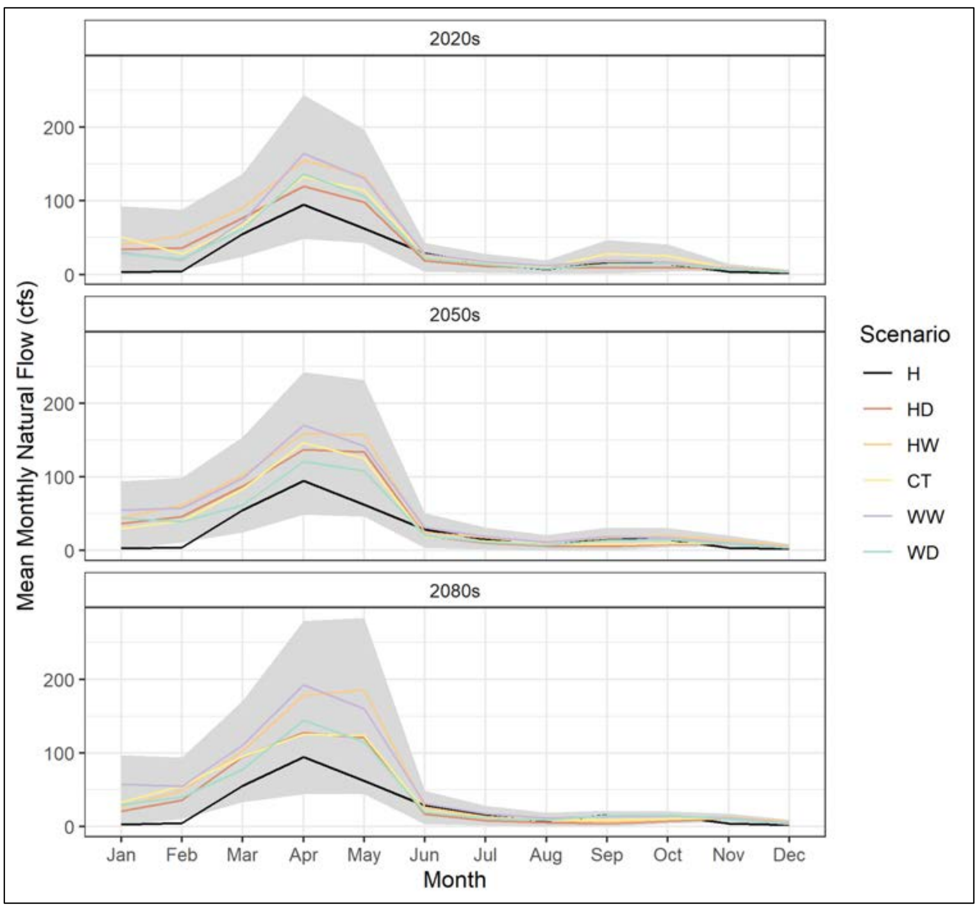


Figure B-31.—Historical and projected average monthly streamflow at Lodge Creek at International Boundary (USGS ID 06145500).

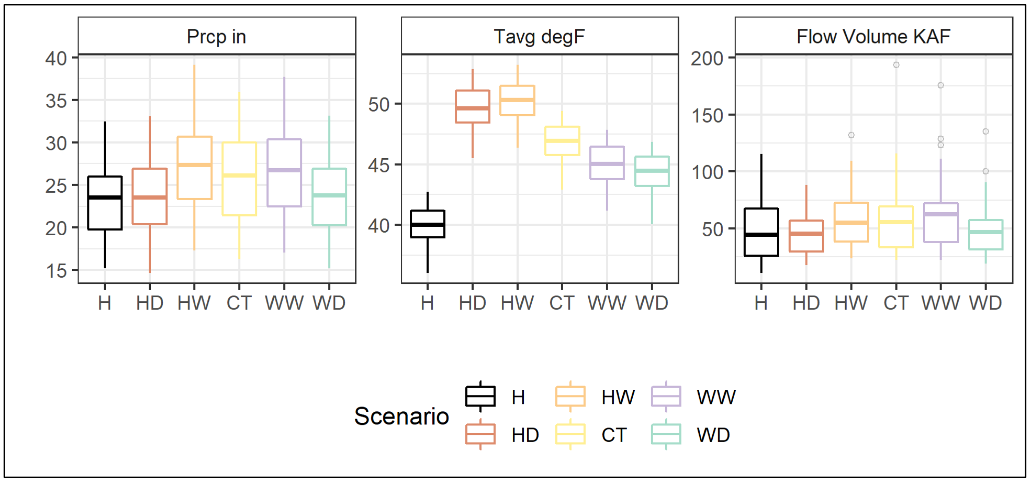


Figure B-32.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Milk River at Western Crossing (USGS ID 06133000).

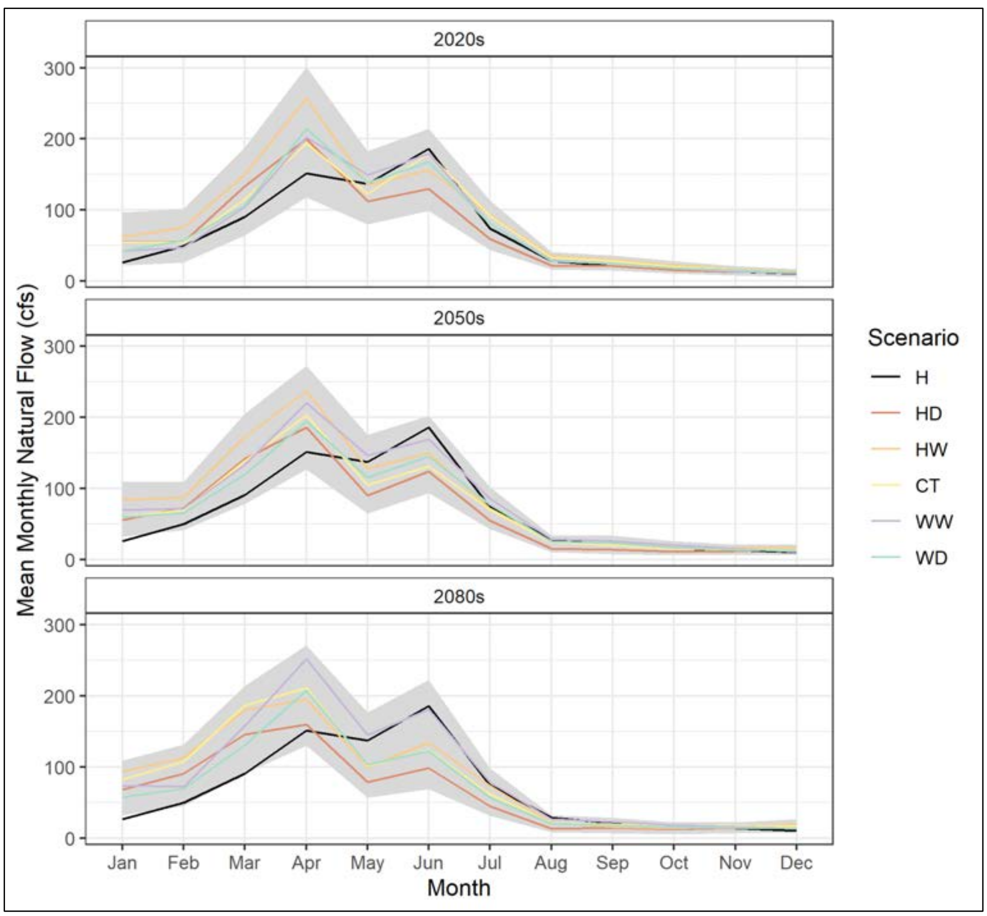


Figure B-33.—Historical and projected average monthly streamflow at Milk River at Western Crossing (USGS ID 06133000).

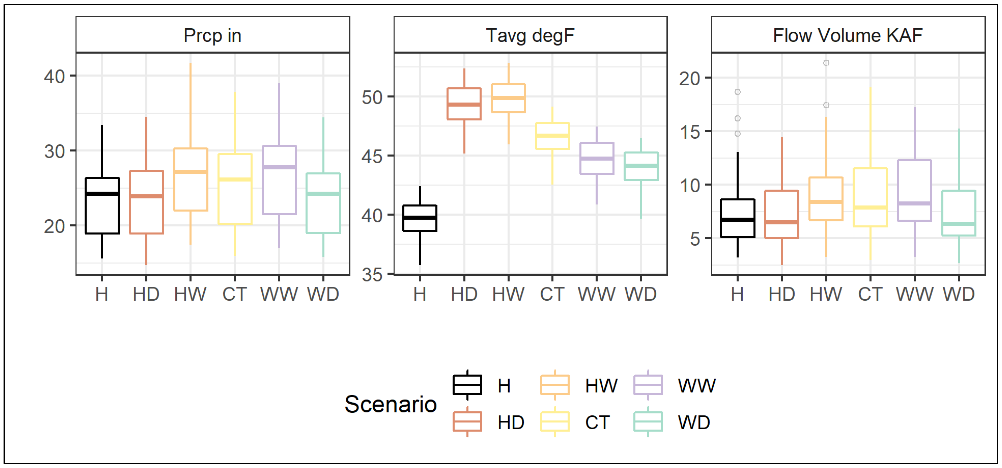


Figure B-34.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Upper North Fork Milk River Inflow (USGS ID 06133500).

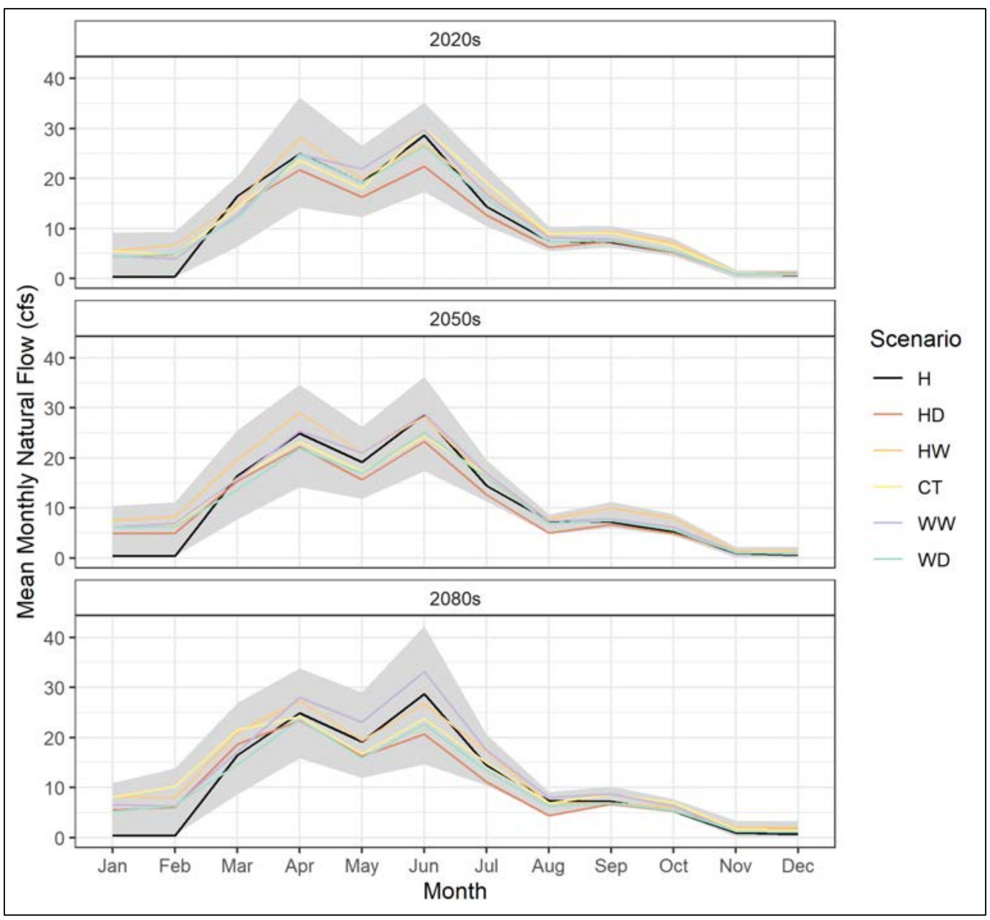


Figure B-35.—Historical and projected average monthly streamflow at Upper North Fork Milk River Inflow (USGS ID 06133500).

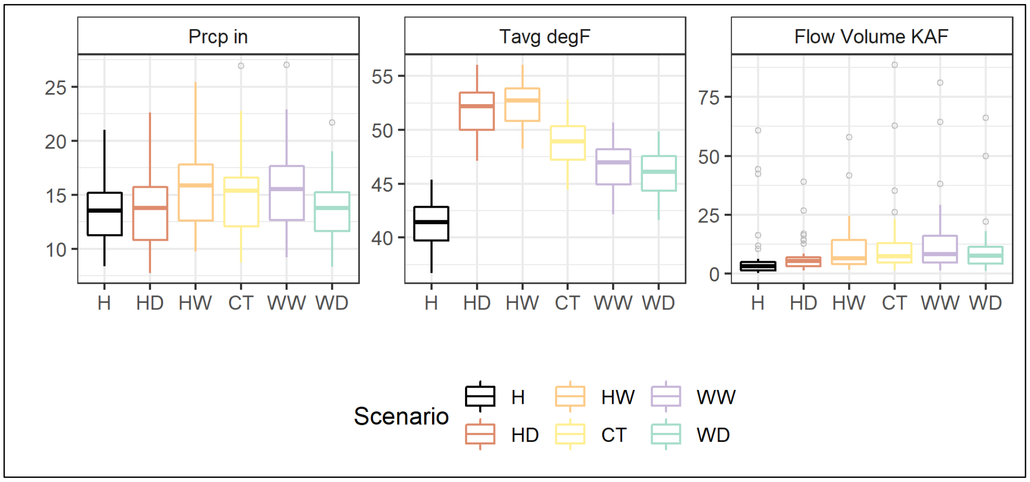


Figure B-36.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Porcupine Creek at Mouth (USGS ID 06175000).

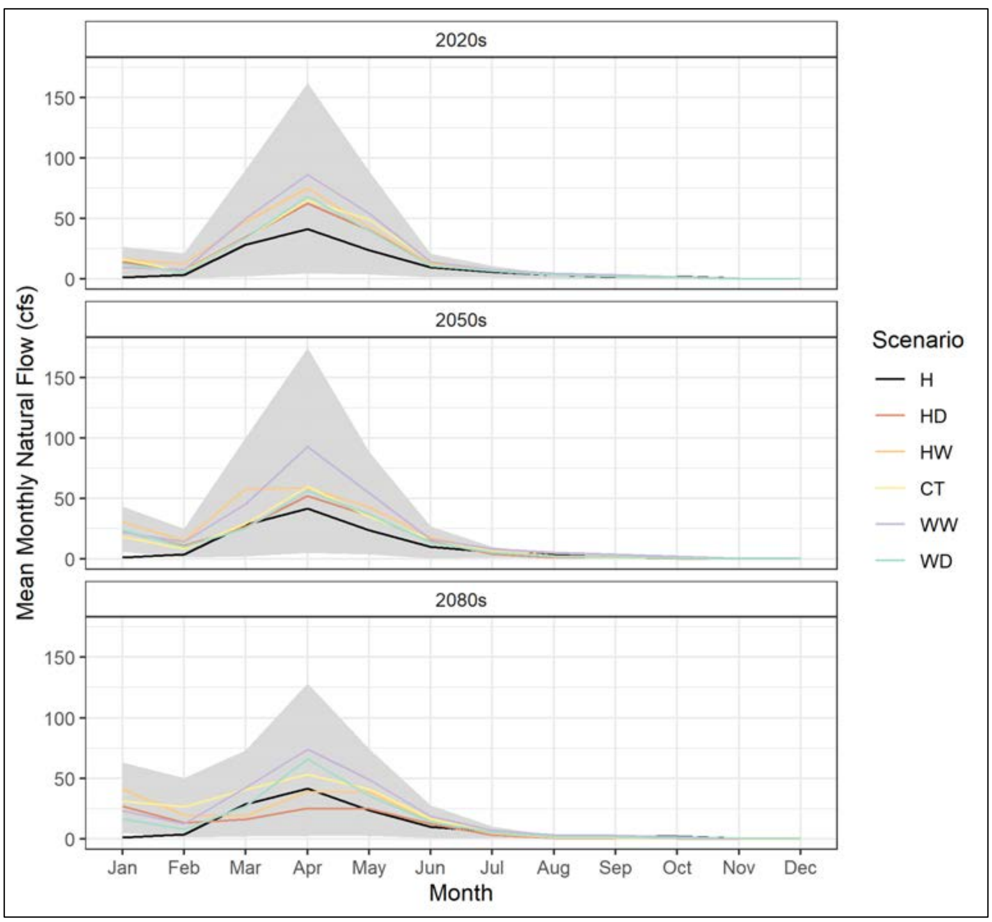


Figure B-37.—Historical and projected average monthly streamflow at Porcupine Creek at Mouth (USGS ID 06175000).

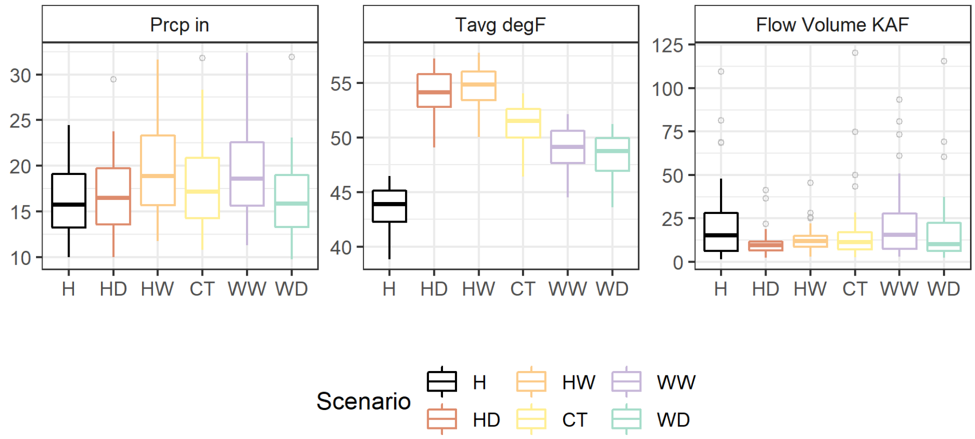


Figure B-38.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at People's Creek at Mouth (USGS ID 06154550).

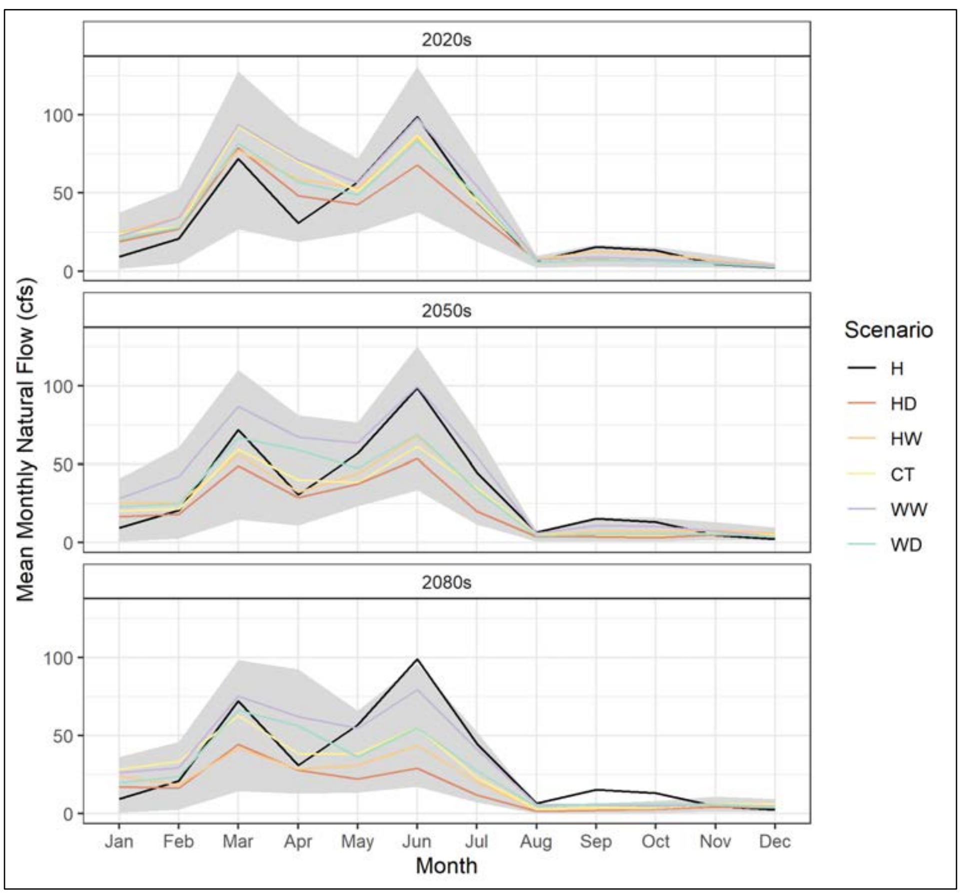


Figure B-39.—Historical and projected average monthly streamflow at People's Creek at Mouth (USGS ID 06154550).

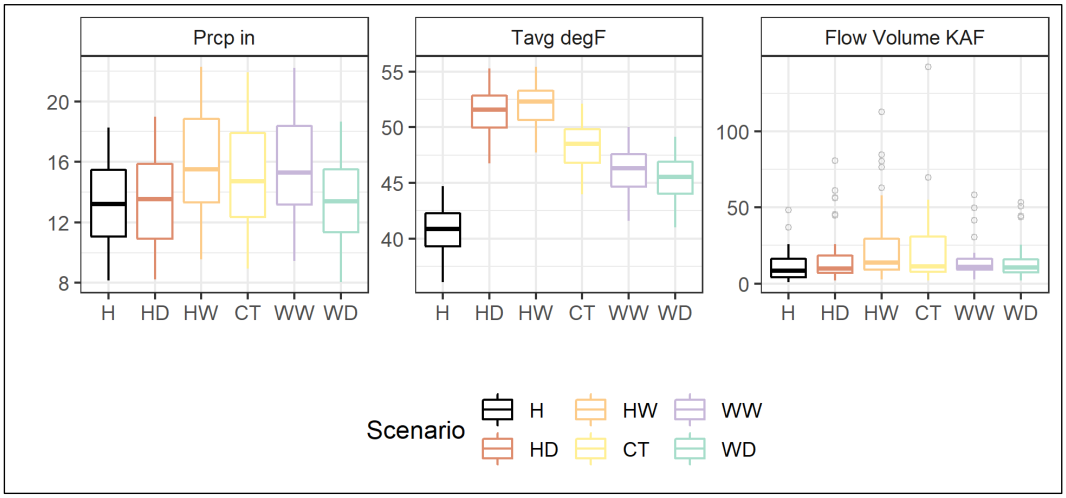


Figure B-40.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Rock Creek at Mouth (USGS ID 06171000).

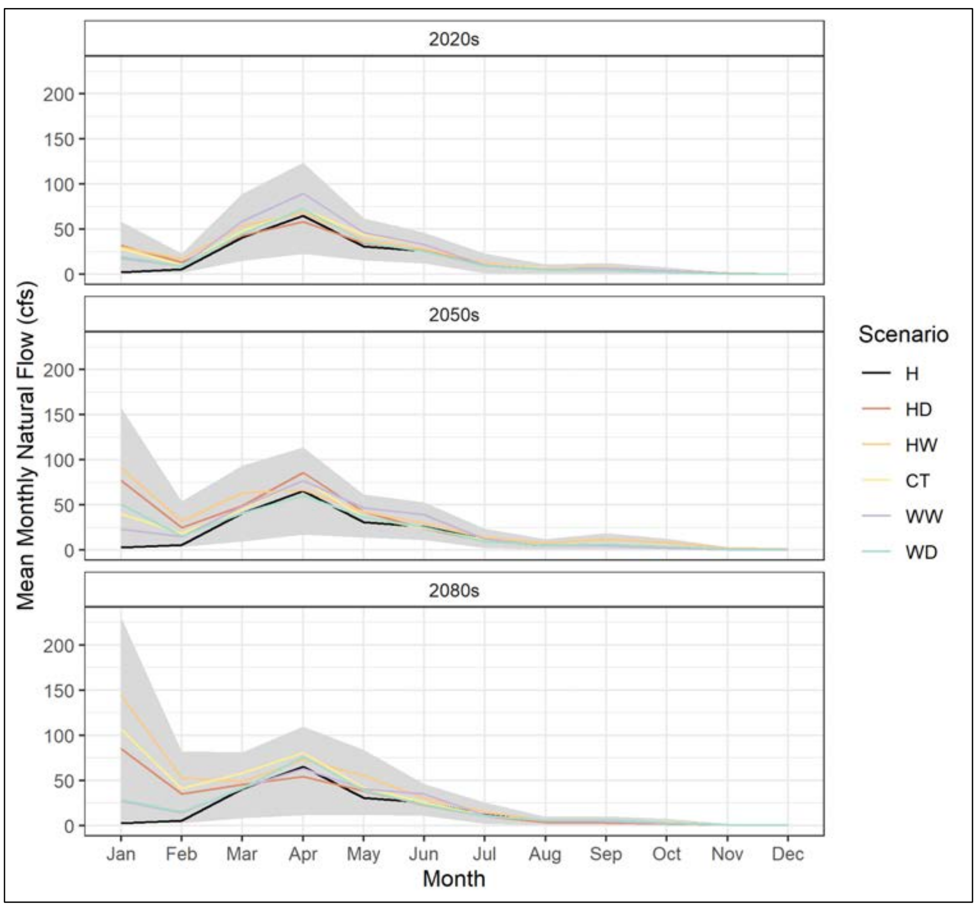


Figure B-41.—Historical and projected average monthly streamflow at Rock Creek at Mouth (USGS ID 06171000).

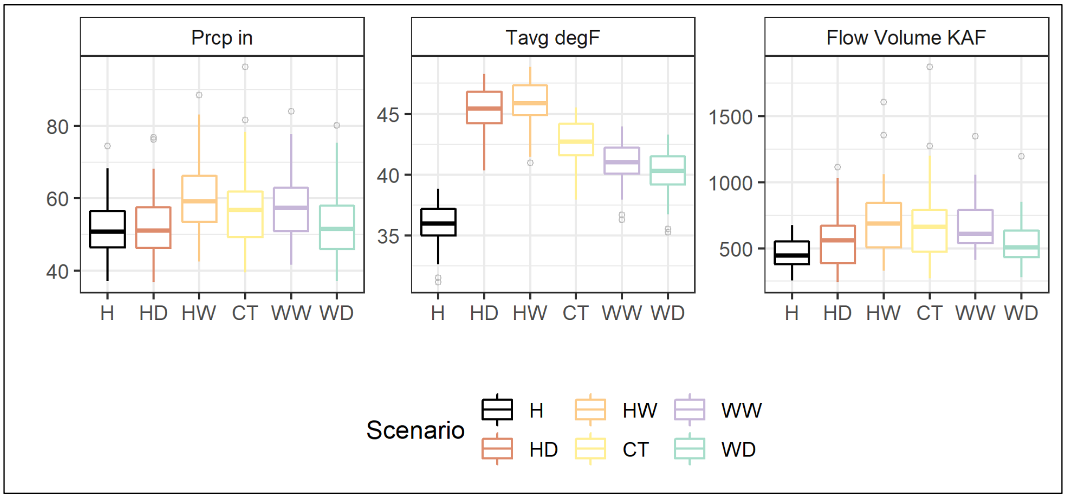


Figure B-42.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at St. Mary River near Babb (USGS ID 05017500).

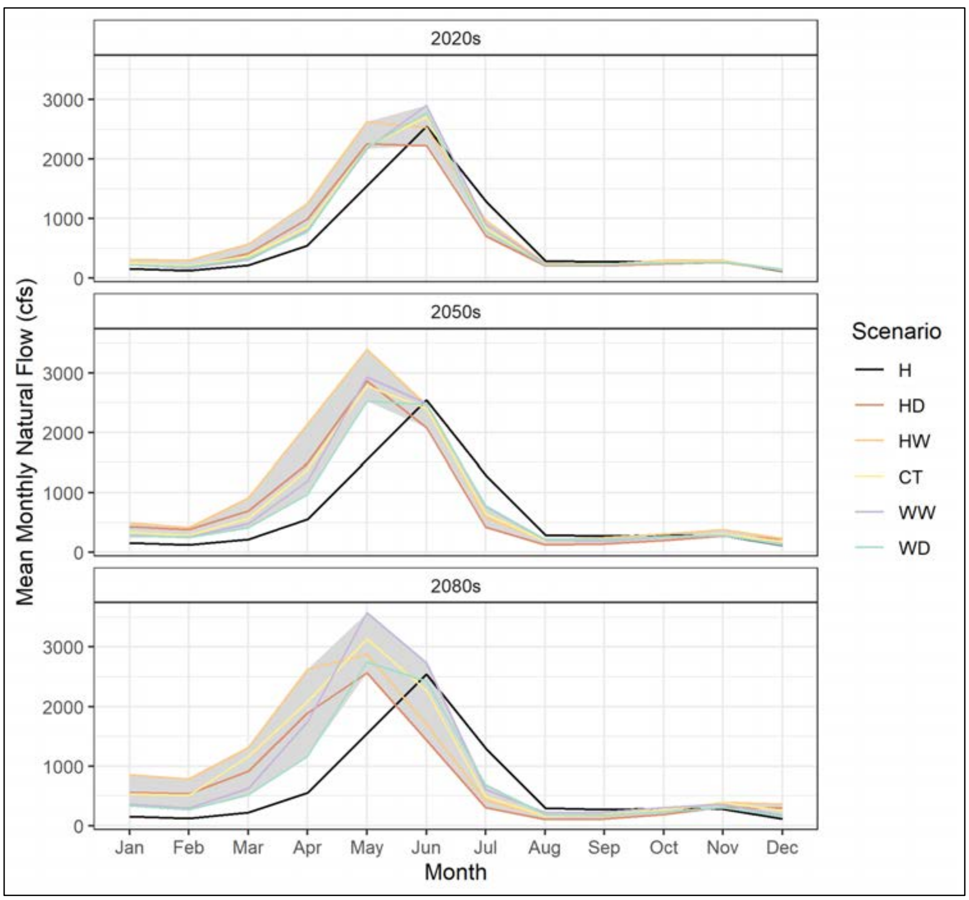


Figure B-43.—Historical and projected average monthly streamflow at St. Mary River near Babb (USGS ID 05017500).

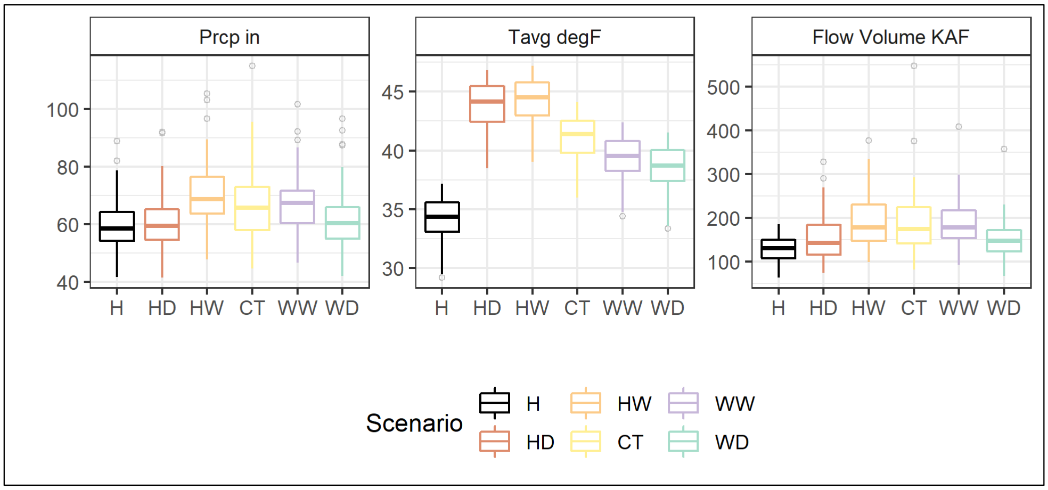


Figure B-44.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Swiftcurrent Creek at Sherburne ,MT (USGS ID 05016000).

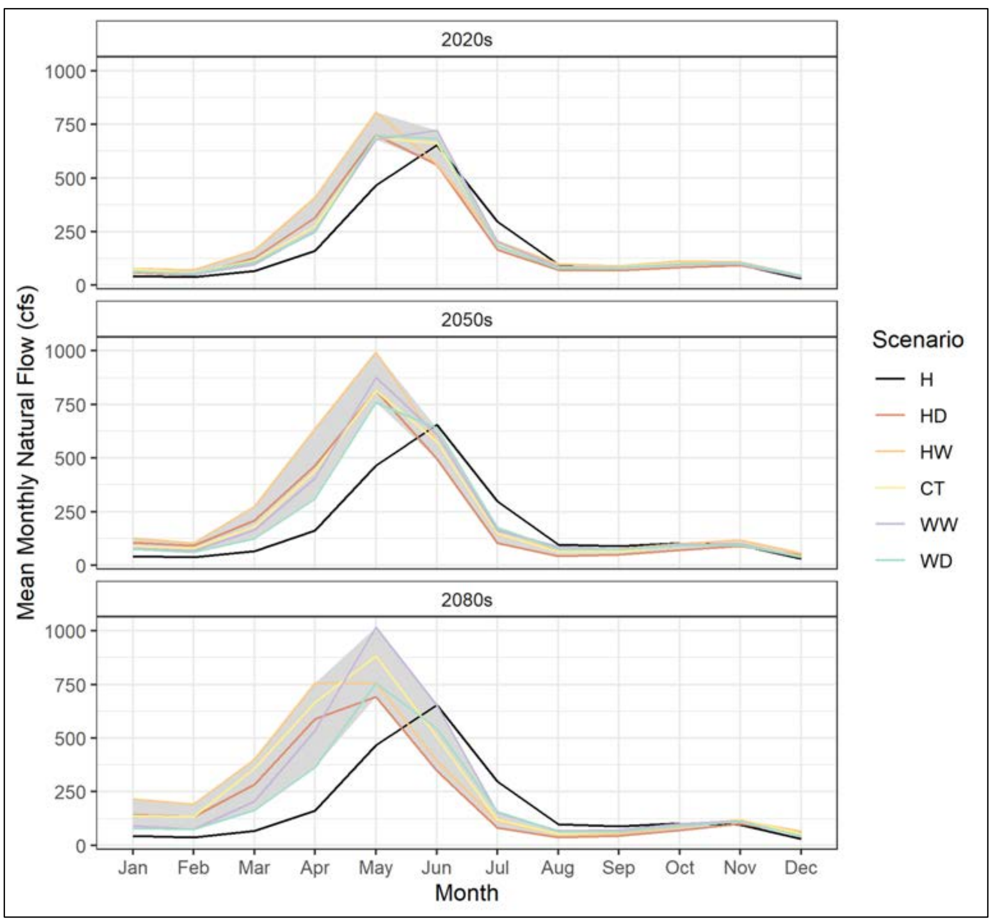


Figure B-45.—Historical and projected average monthly streamflow at Swiftcurrent Creek at Sherburne, MT (USGS ID 05016000).

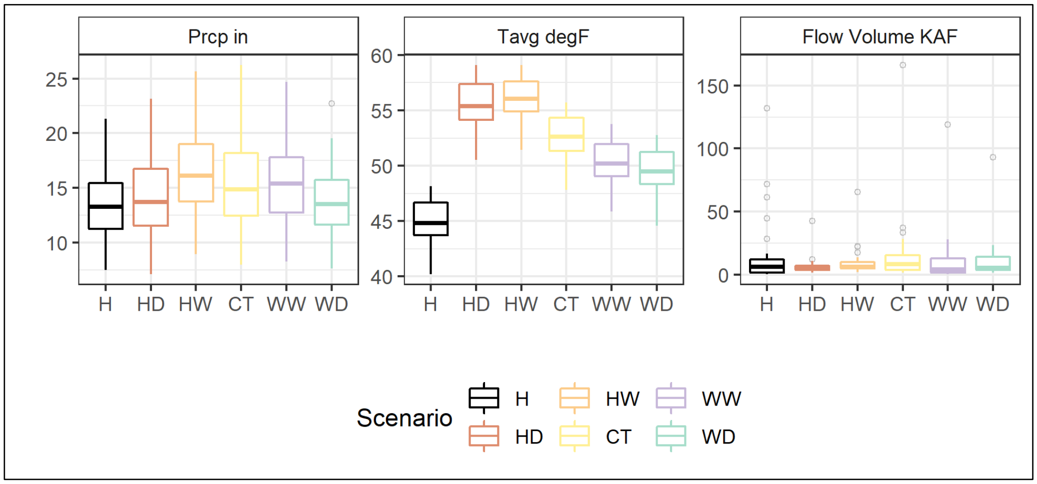


Figure B-46.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Willow Creek at Mouth (USGS ID 06174000).

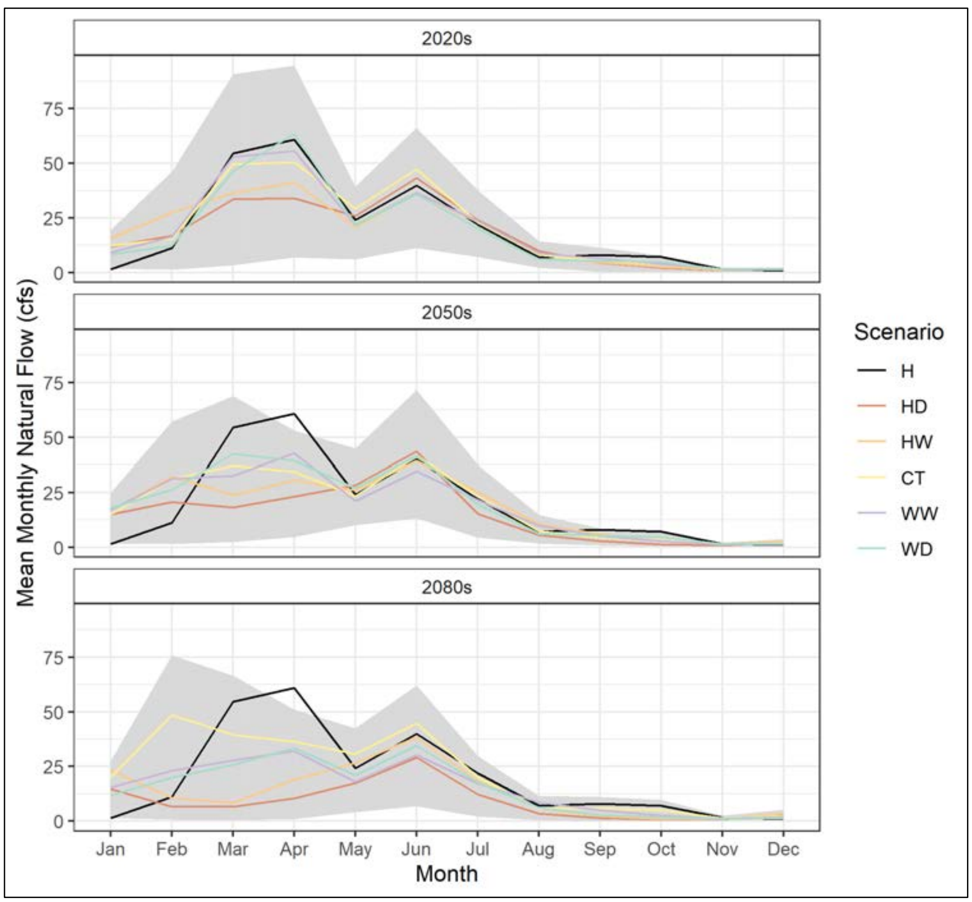


Figure B-47.—Historical and projected average monthly streamflow at Willow Creek at Mouth (USGS ID 06174000).

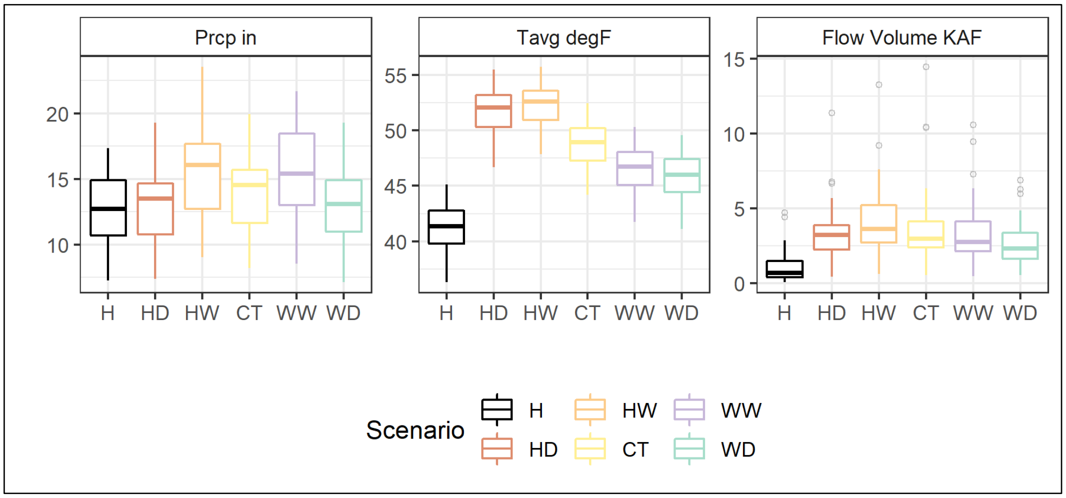


Figure B-48.—Historical and projected annual precipitation, annual average daily temperature, and corresponding annual flow volume at Whitewater Creek at Mouth (no USGS gage).

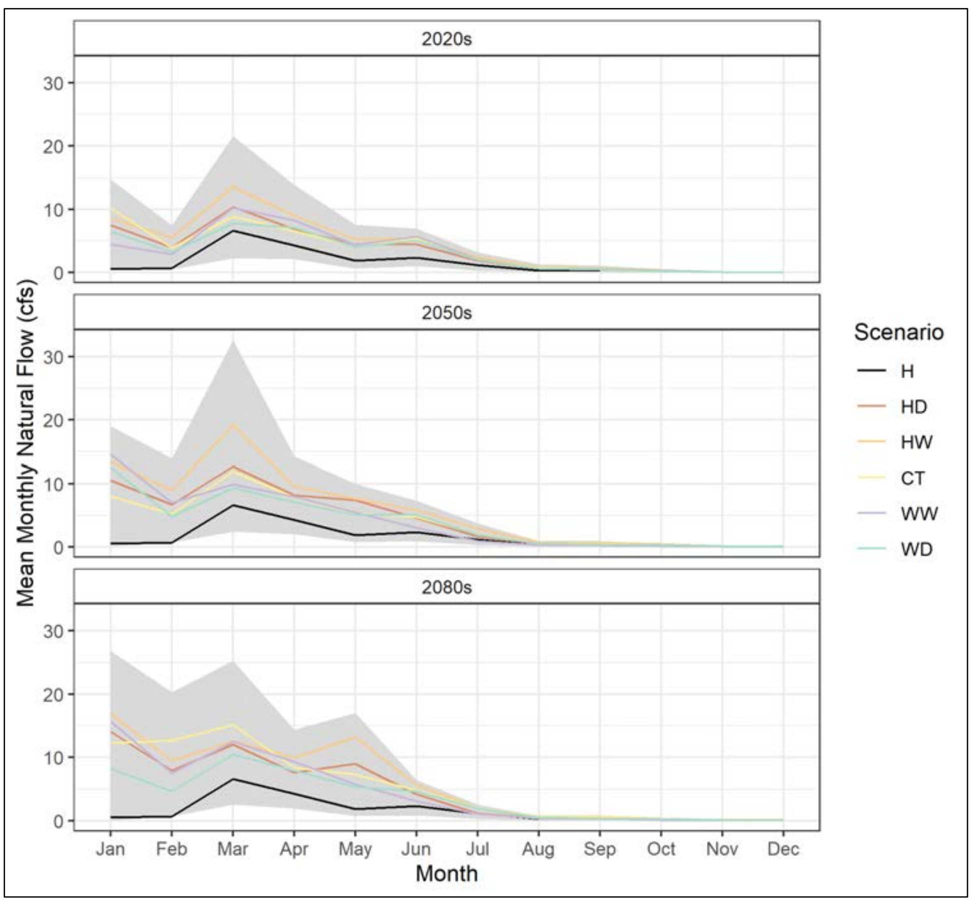


Figure B-49.—Historical and projected average monthly streamflow at Whitewater Creek at Mouth (no USGS gage).

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Appendix C

Water Demands Development

Irrigation demands were simulated for agricultural areas along the St. Mary River, the Milk River, and their tributaries using the ET Demands Model (*https://github.com/usbr/et-demands*; Allen et al. 1998, Allen et al. 2005, Huntington and Allen, 2010, Reclamation, 2015), an ET and irrigation water requirement model. The ET Demands model was originally developed by the University of Idaho, Nevada Division of Water Resources, and the DRI. Recent modifications to the model were made through a collaborative effort by Reclamation, DRI, and the University of Idaho (Reclamation 2015) for Reclamation's WWCRA program.

The following sections provide an overview of the methods used by the ET Demands model, model inputs, including meteorological forcing data, irrigated area and crop mix, and soil data, followed by an overview of model calibration and summary result tables.

Methods

The ET Demands model is based on the PM reference ET equation and the dual crop coefficient method (Allen et al. 1998). The American Society of Civil Engineers has adopted the FAO-56 PM equation as the standardized equation for calculating reference ET (ET_o) (ASCE 2005). The alfalfa reference crop (ET_r) version of the PM equation was used to be consistent with previous Reclamation work.

The PM dual crop coefficient method was used, rather than a single crop coefficient approach, because it accounts for transpiration from vegetation and evaporation from the soil separately. This approach better quantifies evaporation from variable precipitation and simulated irrigation events and allows for accounting of winter soil moisture conditions, which can be a significant factor when estimating early irrigation season NIWR. The dual crop coefficient method provides a robust means for estimating NIWR based on continuous accounting of soil moisture balance and daily estimation of effective precipitation.

Inputs to the ET Demands model include daily meteorological information, soil conditions, and crop types. For this study, ET Demands was run on a 1/16° grid, with all model inputs provided for each grid cell. Each of these model inputs are discussed in sections below.

The ET Demands model first calculates daily reference ET for alfalfa (ET_r) for each 1/16° grid cell as a function of daily climate variables. Daily crop ET (ET_c) is then calculated as a function of the two primary crop coefficients and a crop stress coefficient. ET_c for all crop types within a given grid cell was estimated using Equation 1:

$$ET_c = (K_s K_{cb} + K_e) ET_r \qquad (1)$$

where ET_r is the ASCE-PM alfalfa reference ET, K_{cb} is the basal crop coefficient, K_e is the soil water evaporation coefficient, and K_s is the stress coefficient. K_{cb} and K_e are dimensionless and range from 0 to 1.4. K_e is a function of the soil water balance in the upper 0.1 meter of the soil column, since this zone is assumed to be the only layer supplying water for direct evaporation from the soil surface. K_s is dimensionless and ranges from 0 to 1, where 1 equates to no water stress. A daily soil water balance for the simulated effective root zone is required and computed in ET Demands to calculate K_s. K_s is generally one but can be less than one in the winter if precipitation is low and winter surface cover is specified to be anything other than bare soil, such as mulch or grass.

Daily values of K_{cb} for a given crop vary seasonally and annually to simulate plant phenology as impacted by solar radiation, temperature, precipitation, and agricultural practice. Planting of annuals and emergence of perennials and seasonal changes in vegetation cover and maturation are simulated in the ET Demands model as a function of air temperature. Date of planting of annuals and date of emergence of perennials are estimated based on 30-day avg air temperature (T_{30}) and then K_{cb} is expressed in terms of cumulative growing degree days. After planting of annuals or the emergence of perennials, the value of K_{cb} gradually increases with increasing temperatures until the crop reaches full cover. Once this happens, and throughout the middle stage of the growing season, the K_{cb} value is generally constant or is reduced due to simulated cuttings and harvest. From the middle stage to the end of the growing season, the K_{cb} value reduces to simulate senescence. GDD is calculated in the ET Demands model by three different methods as described in Reclamation (2015). The GDD equations' constants were calibrated based on historical data (green-up or planting, timing of full cover, harvest, and termination dates). A summary of calibration locations for this model is provided in a following section. Simulating year-to-year variations in the timing of green-up or planting, timing of effective full cover, harvest, and termination, is necessary for integrating the effects of temperature on growing season length and crop growth and development, especially under changing climate scenarios.

The NIWR rate or depth is calculated in the ET Demands model by factoring in effective precipitation (P_e) using equation 2:

$$NIWR = ET_c - P_e \qquad (2)$$

P_e is calculated as a function of daily precipitation (from the climate data set), antecedent soil moisture, and precipitation runoff. Soil moisture is a function of the moisture holding capacity of the weighted avg soil type input to the model for each grid cell. Precipitation runoff is calculated based on daily precipitation using the NRCS curve number method (USDA-SCS 1972).

Previous studies have indicated that irrigators often do not apply the full crop irrigation requirement due to a history of frequent water shortages (Reclamation 2004). To account for this deficit irrigation practice, NIWR is scaled by a management factor ranging from 60 percent to 90 percent. Management factors were calibrated within the St. Mary and Milk Rivers planning model using an initial 70 percent estimate and adjusted based on comparisons with diversion records (Reclamation 2022).

Simulation of irrigation events by the ET Demands model occurs when the crop root zone moisture content drops to the crop specific maximum allowable depletion threshold. Irrigation events are specified to fill the root zone by the difference between field capacity[1] and the cumulative soil moisture depletion depth amount.

The NIWR and ET_c rates for each crop within a given grid cell are multiplied by the ratio of the acres of the crop to total irrigated acres within the grid cell and all crop values are summed to calculate weighted avg grid cell NIWR and ET_c rates, as shown in Equation 3.

$$water\ user\ rate\ =\ \sum_{i=1}^{i=n} crop\ ratio\ i * crop\ rate\ i \qquad (3)$$

The product of the weighted avg NIWR and the total irrigated acreage within a given grid cell yields the NIWR volume for each grid cell in AF. Crop types and corresponding percentages of total crop acreage by water user are provided in table C-5.

Model Inputs

The ET Demands model for the Milk River basin is run on a 1/16° grid. Required model input data for each grid cell includes a timeseries of meteorological forcing data, avg soil properties, crop mix and associated acreages for each crop, and calibrated crop coefficient curves. The ET zones for the Milk River basin are defined by the 1/16° grid used by the meteorological forcing datasets developed by Livneh et al. (2013). This relatively fine-scale grid, roughly 6 km by 6 km, provides a more detailed representation of irrigation demands.

Meteorological Forcing Data

Daily meteorological forcing data is required to estimate daily alfalfa reference ET for each 1/16° grid cell. The ET_r for both the historical and projected future climate scenarios was calculated as a function of maximum and minimum daily air temperature (T_{max} and T_{min}), vapor pressure, solar radiation, and wind speed per the methods recommended by ASCE (2005). Estimation of crop ET uses the calculated daily ET_r and daily avg dewpoint temperature in addition to the meteorological variables used to estimate ET_r.

Meteorological data for the historical reference simulation period (water years 1981–2015) including daily minimum and maximum temperature, vapor pressure, shortwave radiation, and precipitation are provided by the Daymet forcing dataset ("Appendix A. Forcing Comparison and Selection"). Additional variables including relative humidity, total radiation, and dewpoint temperature are empirically estimated as described in Reclamation (2015). Windspeed was provided by NARR model (Mesinger et al. 2006). The data was remapped and bilinearly interpolated from its original 1/8° resolution to the ET zone 1/16° grid cell resolution.

[1] Field capacity is the amount of water that a well-drained soil should hold against gravitational forces, or the amount of water remaining when downward drainage has markedly decreased (Allen et al., 1998).

Meteorological forcing data for each of the future climate scenarios was developed by perturbing the historical meteorological dataset based on the projected changes in simulated monthly climate factors. Development of the meteorological forcing dataset for the future scenarios, which included daily minimum and maximum temperature, precipitation is discussed in the Water Supply Assessment section of this report. Dewpoint temperature was estimated from the daily minimum temperature and the avg monthly dewpoint depression, Ko, estimated from the historical dataset. Vapor pressure, saturation vapor pressure, and total radiation were empirically estimated using these perturbed meteorological variables as described in Reclamation (2015).

Bias Correction

Irrigation practice can lower minimum and maximum air temperatures in arid or semi-arid climates. To ensure that meteorological inputs to the ET Demands model are representative of irrigated conditions, meteorological observations in irrigated areas are used to bias-correct gridded meteorological data. A previous study developing consumptive use requirements for crops in Idaho (Allen and Brockway 1983), adjusted minimum and maximum temperature from meteorological weather stations determined to be representative of irrigation practices based on information about the land surrounding each station. A similar approach was used to filter a set of meteorological weather stations located within the St. Mary and Milk River basins and identify those nominally representative of irrigation practices. To ensure meteorological weather stations did not violate this requirement, stations were selected based on their proximity to irrigated lands.

AgriMet stations run by Reclamation's Missouri Basin and Arkansas-Rio Grande-Texas and Gulf Regions office (formerly Great Plains Region Office; Reclamation) were included as these sites were located to measure weather conditions representative of irrigated conditions. A set of stations from the National Weather Service observation network, the National Weather Service Cooperative Observer Program (COOP), the Alberta Climate Information Service (ACIS), and local mesonet networks were screened using a two-step process to identify additional stations. First, stations were screened using the Cropland Data Layer (CDL) dataset (Boryan et al. 2011) in the U.S. and the Annual Crop Inventory (ACI) dataset (Fisette et al. 2013) in Canada. Two buffer distances, 100 meters (approximately 328 ft) to represent the land immediately around the station, and 1,600 meters (approximately 1 mile) to represent the land in the area around the station, were used with the CDL or ACI to identify stations with likely irrigated agriculture in the vicinity. CDL and ACI classifications were simplified into non-agricultural lands, crop lands, and grassland/pasture lands. Stations with a combined 50 percent crop land and grassland/pastureland within 50 meters (approximately 164 ft) and 75 percent crop land and grassland/pastureland within 1,600 meters in any year included in the analysis were retained. The set of remaining stations were then overlaid on a satellite image with the 50 meters and 1,600 meters buffers and manually inspected to identify the final set of stations. Figure C-1 shows an example of these satellite images with the site on the right selected for the final set. The station on the left (Automatic Weather Reporting System [COOP ID CWOE]; latitude 49.11667, longitude -110.467) had a high percentage of grassland/pastureland, but the satellite image shows no evidence of irrigation. The station on the right (Big Flat Near Turner Weather Station, Montana [AgriMet ID BFTM]; latitude 48.8356, longitude -108.5636) had a high percentage of crop land and the satellite image shows clear evidence of center pivot irrigation. The final set of stations retained are detailed in table C-1.

Figure C-1.—Satellite images from the meteorological station screening process.

The X indicates the location of the station, with the inner circle showing 50 meters around the station, and the outer circle showing 1,600 meters around the station. The left station (CWOE; Onefour Automatic Weather Reporting System; https://w1.weather.gov/data/obhistory/CWOE.html) was rejected, and the Agrimet site, BFTM, Big Flat Near Turner Weather Station, Montana retained.

Table C-1.—Meteorological observations stations used to bias correct gridded meteorological data

Station	Network	Station Management Office	Station Abbreviation	Station Name	Latitude	Longitude	Elevation	State	Lat_L16	Lon_L16
AgriMetGLGM	AgriMet	USBR Great Plains Regional Office	GLGM	Glasgow, MT	48.1432	-106.609	635	MT	48.15625	-106.594
AgriMetMATM	AgriMet	USBR Great Plains Regional Office	MATM	Malta, MT	48.374	-107.777	692	MT	48.34375	-107.781
AgriMetHRLM	AgriMet	USBR Great Plains Regional Office	HRLM	Harlem, MT	48.5436	-108.835	719	MT	48.53125	-108.844
ACISMASN	ACIS	Alberta Ministry of Agriculture and Forestry	MASN	Masinasin AGDM	49.126	-111.655	960	AB	49.15625	-111.656
AgriMetBFTM	AgriMet	USBR Great Plains Regional Office	BFTM	Big Flat - Turner, MT	48.8357	-108.564	946	MT	48.84375	-108.594
ACISMNYB	ACIS	Alberta Ministry of Agriculture and Forestry	MNYB	Manyberries AGDM	49.3638	-110.678	927	AB	49.34375	-110.656
ACISBLDT	ACIS	Alberta Ministry of Agriculture and Forestry	BLDT	Blood Tribe Ag. Project IMCIN	49.5592	-113.064	998.99	AB	49.53125	-113.094

Table C-1.—Meteorological observations stations used to bias correct gridded meteorological data

Station	Network	Station Management Office	Station Abbreviation	Station Name	Latitude	Longitude	Elevation	State	Lat_L16	Lon_L16
AgriMetBFAM	AgriMet	USBR Great Plains Regional Office	BFAM	Blackfeet-Seville Colony, MT	48.6754	-112.589	1190	MT	48.65625	-112.594
ACISDBNT	ACIS	Alberta Ministry of Agriculture and Forestry	DBNT	Del Bonita AGCM	49.05	-112.81	1310	AB	49.03125	-112.781

Irrigated Areas and Corp Mix

The total land areas receiving irrigation water vary from year to year in response to water availability and other factors. Rather than creating an artificial composite of lands receiving irrigation water on avg, a base year was selected to represent a slightly above normal water supply. The year 2013 was chosen to represent the irrigated acres dataset due to a slightly above median water supply based on Milk River gage station records and reservoir content. This year also falls in the later portion of the period of record used for the Basins Study Update's modeling efforts.

Irrigated lands and crop types for the Basins Study Update were mapped using ArcMap version 10.8.1. The total irrigated lands for the Milk River basin were estimated to be about 196,230 acres (including Milk River Project, private, and tribal irrigation). This was determined by comparing NAIP imagery from 2005 to 2017. In 2013, 161,800 acres were identified as receiving irrigation water, or 82 percent of the total acres identified as irrigated lands that receive irrigation water from the Milk River and its tributaries. In any given year, some percentage of the 196,230 acres identified receive irrigation water depending on water supply.

Crop types for the irrigated lands were identified using 2013 crop data from the USDA and Agriculture and Agri-Food Canada (Soil Landscapes of Canada Working Group 2010). Resources used to determine irrigated lands used a variety of resources listed in table C-2. Fallowed, but historically irrigated fields were also delineated, however these acreages were not used in the ET Demands model runs. Crop types identified in the irrigated acreages geodatabase and their associated ET Demands model crop type are shown in table C-3. The irrigated lands were delineated based on water users in the St. Mary and Milk Rivers planning model and 1/16th° grid cell used by the ET Demands model. A breakdown of the crop types and acreages for each water user are presented in table C-4 and crop distributions by % for each water user are presented in table C-5.

Table C-2.—Resources Used to Identify Irrigated Lands in the Milk River Basin

GIS Coverage	Description	Use	Source
2012 Basins Study Irrigation GIS Layer	Acres mapped to support the 2012 Basins Study	Used as the starting point for mapping irrigated lands for the Study Update	MT DNRC
NAIP Color Imagery	Natural Color Imagery, 1 Meter Pixel Resolution for years 2005-2017. Multiple years were used to determine fields that are irrigated but may not receive water every year.	Identify irrigated fields and field boundaries	USDA
NAIP CIR Imagery	Color Infrared Imagery 1 Meter Pixel Resolution for years 2005-2017. Multiple years	Assists in determining if field	USDA

Table C-2.—Resources Used to Identify Irrigated Lands in the Milk River Basin

GIS Coverage	Description	Use	Source
	were used to determine fields that are irrigated but may not receive water every year.	received irrigation water	
MT Water Resources Survey	Glacier, Toole, Liberty, Hill, Blaine, Phillips, and Valley Counties.	Used as a cross check to determine if lands are irrigated.	MT DNRC
MT Water Rights Query System	Provides Water Rights Information on Lands	Used to help validate or verify if field of interest has a water right and is irrigated	MT DNRC
Final Land Unit Classification	Classifies Agricultural Lands into Six Uses: Fallow, Hay, Grazing, Irrigated, Continuously Cropped, and Forest. Irrigated is Further Broken Down into Flood, Pivot and Sprinkler.	Used as a cross check to determine if lands are irrigated and water application method.	MT Department of Revenue
DNRCWater Rights Query System	Searchable database of MT water rights	Used to help differentiate between Milk River Project acres and private acres on the Milk River main stem.	MT DNRC
Canada ACI	30 Meter Resolution of Field Crop Data in Alberta and Saskatchewan for 2013.	Provide field crop data for Canadian irrigated lands in the Milk River basin.	Agriculture and Agri-Food Canada
MT CDL	30 Meter Resolution of Field Crop Data in MT for 2013.	Provide field crop data for MT irrigated lands in the Milk River basin.	USDA
MT Cadastral Mapping Project	Provides General Property Information	Used as a cross check against water rights	MT State Library

Table C-3.—Irrigated Acreages geodatabase crop types

Crop Type	CDL Crop Code	ET Demands Crop	ET Demands Crop Code
Alfalfa	36	Alfalfa – Beef Style	3
Hay	37[a]	Grass Hay	4
Grain	25 [b]	Spring Grain – irrigated	11
Winter Wheat	24	Winter Grain – irrigated	13
Corn	1	Field Corn	7
Barley	21	Spring Grain – irrigated	11
Sugarbeets	41	Sugar beets	31
Canola	31	Canola	40
Spring Wheat	23	Spring Grain – irrigated	11
Potatoes	43	Potatoes	30
Lentils	52	Snap and Dry Beans – fresh	5
Fallow	NA	NA	NA

[a] CDL crop – Other Hay/Non-Alfalfa
[b] CDL crop – Other Small Grains

Table C-4.—Summary of crop types and associated acreage by St. Mary and Milk Rivers planning model water user

Water User	Crop							Total
	Hay	Grain	Alfalfa	Winter Wheat	Corn	Sugarbeets	Barley	
Battle Creek to International Boundary (IB) Irrigation	6,322	1,294	-	-	-	-	-	7,616
Battle Creek to Milk River Irrigation	-	876	1,009	589	-	-	-	2,474
Beaver Creek Havre Irrigation	-	84	541	-	-	-	-	625
Big Sandy Creek Irrigation	310	752	852	608	454	-	-	2,976
Buggy Creek Irrigation	85	-	-	-	-	-	-	85
Canadian Irrigation	1,519	4,349	-	-	129	126	-	6,123
Clear Creek Irrigation	66	228	480	-	0	0	-	774
Fort Belknap Canal Irrigation Districts: Alfalfa Valley ID	270	535	2,202	338	102	-	-	3,447
Fort Belknap Canal Irrigation Districts: Fort Belknap ID	1,855	953	2,561	631	6	-	45	6,051
Fort Belknap Canal Irrigation Districts: Zurich ID	513	1,737	4,182	229	75	-	-	6,736
Fort Belknap Reservation Irrigation Project: Milk River Unit	850	323	1,097	551	-	-	-	2,821
Fort Belknap Reservation Irrigation Project: White Bear Unit	235	186	-	138	-	-	-	559
Frenchman River to IB Irrigation	9,444	1,501	-	-	-	-	-	10,945
Glasgow ID	3,203	5,487	5,510	466	1,094	-	-	15,760
Harlem Irrigation District: East Portion	1,340	335	967	-	-	-	-	2,642
Harlem Irrigation District: West Portion	1,343	1,921	2,796	187	-	-	-	6,247
Irrigation above Frenchman Reservoir	76	91	741	-	-	-	-	908
Irrigation below Frenchman Dam: Lower	727	121	436	-	-	-	-	1,284
Irrigation below Frenchman Dam: Upper	288	629	675	-	-	-	-	1,592
Little Boxelder Creek Irrigation	18	123	170	-	-	-	-	311
Lodge Creek to IB Irrigation	2,167	130	-	-	-	-	-	2,297
Lodge Creek to Milk River Irrigation	394	377	644	63	-	-	-	1,478
Lower Malta ID: Beaver Creek	9,307	922	1,919	180	48	-	-	12,376
Lower Malta ID: Milk Returns	878	906	887	-	110	-	-	2,781
ND Irrigation Above Beaver Creek	761	1,108	2,933	73	61	-	-	4,936
ND Irrigation Dodson to Nelson	601	180	133	334	-	-	-	1,248
ND Irrigation FT Belknap to Dodson	190	732	1,589	-	-	-	-	2,511
ND Irrigation Havre to FT Belknap	209	469	544	322	-	-	-	1,544

Table C-4.—Summary of crop types and associated acreage by St. Mary and Milk Rivers planning model water user

Water User	Crop							Total
	Hay	Grain	Alfalfa	Winter Wheat	Corn	Sugarbeets	Barley	
ND Irrigation Nelson to Vandalia	13	534	467	-	-	-	-	1,014
ND Irrigation Paradise Valley Reach	61	404	625	-	-	-	-	1,090
ND Irrigation PV to Harlem ID	45	46	355	-	172	-	-	618
ND Irrigation Vandalia to Mouth	439	-	16	-	-	-	-	455
North Malta ID	2,762	336	3,834	239	-	-	-	7,171
Paradise Valley Irrigation District: East Portion	747	497	1,273	72	25	-	-	2,614
Paradise Valley Irrigation District: West Portion	542	874	2,595	132	86	-	-	4,229
Peoples Creek Irrigation	249	219	1,702	-	-	-	-	2,170
Private Irrigation Dodson to Nelson	282	-	201	3	-	-	-	486
Private Irrigation Harlem to Dodson	28	14	73	379	-	-	-	494
Private Irrigation Havre to FT Belknap	19	124	150	-	-	-	-	293
Private Irrigation Nelson to Vandalia	412	43	666	398	108	-	-	1,627
Private Irrigation Paradise Valley Reach	-	5	37	-	-	-	-	42
Private Irrigation PV to Harlem	-	-	81	-	-	-	-	81
Private Irrigation Vandalia to Mouth	676	3,423	2,207	-	51	-	-	6,357
Rock Creek Irrigation	800	1,328	1,814	382	252	-	-	4,576
Sweetgrass Hills Irrigation	123	155	548	-	-	-	-	826
Upper Malta ID: Beaver Returns	1,249	167	755	257	-	-	-	2,428
Upper Malta ID: Bowdoin Returns	463	432	1,596	17	162	-	-	2,670
Upper Malta ID: Lower	308	184	83	426	82	-	-	1,083
Upper Malta ID: Upper	2,511	1,190	3,506	611	117	-	-	7,935
U.S. Irrigation on North Milk	-	-	98	-	-	-	-	98
U.S. Irrigation on South Milk	1,449	427	844	-	-	-	-	2,720
Whitewater River Irrigation	384	1,089	75	-	-	-	-	1,548
Total	56,533	37,840	56,469	7,625	3,134	126	45	**161,772**

Table C-5.—Summary of crop distribution (% by type) within St. Mary and Milk Rivers planning model water users

Water User	Crop Distributions (%)						
	Hay	Grain	Alfalfa	Winter Wheat	Corn	Sugarbeets	Barley
Battle Creek to IB Irrigation	83.01	16.99	-	-	-	-	-
Battle Creek to Milk River Irrigation	-	35.41	40.78	23.81	-	-	-
Beaver Creek Havre Irrigation	-	13.44	86.56	-	-	-	-
Big Sandy Creek Irrigation	10.42	25.27	28.63	20.43	15.26	-	-
Buggy Creek Irrigation	100.00	-	-	-	0.00	-	-
Canadian Irrigation	24.81	71.03	-	-	2.11	2.06	-
Clear Creek Irrigation	8.53	29.46	62.02	-	-	-	-
Fort Belknap Canal Irrigation Districts: Alfalfa Valley ID	7.83	15.52	63.88	9.81	2.96	-	-
Fort Belknap Canal Irrigation Districts: Fort Belknap ID	30.66	15.75	42.32	10.43	0.10	-	0.74
Fort Belknap Canal Irrigation Districts: Zurich ID	7.62	25.79	62.08	3.40	1.11	-	-
Fort Belknap Reservation Irrigation Project: Milk River Unit	30.13	11.45	38.89	19.53	-	-	-
Fort Belknap Reservation Irrigation Project: White Bear Unit	42.04	33.27	-	24.69	-	-	-
Frenchman River to IB Irrigation	86.29	13.71	-	-	-	-	-
Glasgow ID	20.32	34.82	34.96	2.96	6.94	-	-
Harlem Irrigation District: East Portion	50.72	12.68	36.60	-	-	-	-
Harlem Irrigation District: West Portion	21.50	30.75	44.76	2.99	-	-	-
Irrigation above Frenchman Reservoir	8.37	10.02	81.61	-	-	-	-
Irrigation below Frenchman Dam: Lower	56.62	9.42	33.96	-	-	-	-
Irrigation below Frenchman Dam: Upper	18.09	39.51	42.40	-	-	-	-
Little Boxelder Creek Irrigation	5.79	39.55	54.66	-	-	-	-
Lodge Creek to IB Irrigation	94.34	5.66	-	-	-	-	-
Lodge Creek to Milk River Irrigation	26.66	25.51	43.57	4.26	-	-	-
Lower Malta ID: Beaver Creek	75.20	7.45	15.51	1.45	0.39	-	-
Lower Malta ID: Milk Returns	31.57	32.58	31.90	-	3.96	-	-
ND Irrigation Above Beaver Creek	15.42	22.45	59.42	1.48	1.24	-	-
ND Irrigation Dodson to Nelson	48.16	14.42	10.66	26.76	-	-	-
ND Irrigation FT Belknap to Dodson	7.57	29.15	63.28	-	-	-	-
ND Irrigation Havre to FT Belknap	13.54	30.38	35.23	20.85	-	-	-

Table C-5.—Summary of crop distribution (% by type) within St. Mary and Milk Rivers planning model water users

Water User	Crop Distributions (%)						
	Hay	Grain	Alfalfa	Winter Wheat	Corn	Sugarbeets	Barley
ND Irrigation Nelson to Vandalia	1.28	52.66	46.06	-	-	-	-
ND Irrigation Paradise Valley Reach	5.60	37.06	57.34	-	-	-	-
ND Irrigation PV to Harlem ID	7.28	7.44	57.44	-	27.83	-	-
ND Irrigation Vandalia to Mouth	96.48	-	3.52	-	-	-	-
North Malta ID	38.52	4.69	53.47	3.33	-	-	-
Paradise Valley Irrigation District: East Portion	28.58	19.01	48.70	2.75	0.96	-	-
Paradise Valley Irrigation District: West Portion	12.82	20.67	61.36	3.12	2.03	-	-
Peoples Creek Irrigation	11.47	10.09	78.43	-	-	-	-
Private Irrigation Dodson to Nelson	58.02	-	41.36	0.62	-	-	-
Private Irrigation Harlem to Dodson	5.67	2.83	14.78	76.72	-	-	-
Private Irrigation Havre to FT Belknap	6.48	42.32	51.19	-	-	-	-
Private Irrigation Nelson to Vandalia	25.32	2.64	40.93	24.46	6.64	-	-
Private Irrigation Paradise Valley Reach	-	11.90	88.10	-	-	-	-
Private Irrigation PV to Harlem	-	-	100.00	-	-	-	-
Private Irrigation Vandalia to Mouth	10.63	53.85	34.72	-	0.80	-	-
Rock Creek Irrigation	17.48	29.02	39.64	8.35	5.51	-	-
Sweetgrass Hills Irrigation	14.89	18.77	66.34	-	-	-	-
Upper Malta ID: Beaver Returns	51.44	6.88	31.10	10.58	-	-	-
Upper Malta ID: Bowdoin Returns	17.34	16.18	59.78	0.64	6.07	-	-
Upper Malta ID: Lower	28.44	16.99	7.66	39.34	7.57	-	-
Upper Malta ID: Upper	31.64	15.00	44.18	7.70	1.47	-	-
U.S. Irrigation on North Milk	-	-	100.00	-	-	-	-
U.S. Irrigation on South Milk	53.27	15.70	31.03	-	-	-	-
Whitewater River Irrigation	24.81	70.35	4.84	-	-	-	-

Soil Data

Weighted avg soil conditions (including allowable water content and percent clay, silt, and sand) for the irrigated lands in each 1/16th° grid cell was required input to the ET Demands model. The soils information for the U.S. is based on data from the NRCS State Soil Geographic database (USDA-SCS 1991). Soil data for Canada were obtained from the Soil Landscapes of Canada dataset version 3.2 produced by the Agriculture and Agri-Food Canada. The soil parameters affect the estimation of irrigation scheduling, evaporation losses from soil, deep percolation from root zones, antecedent soil moisture condition, and runoff from precipitation.

Soil data is provided as GIS polygon data that delineates soil regions. Each soil region can contain multiple soil types, and each soil type contains soil properties for multiple soil layers. For each soil type with defined soils properties, layers up to 190cm were retained. The avg soil type, sand and clay percentages were calculated using each layer's sand and clay percentages, weighting them by the layer thickness, and summing over all layers. Available water capacity (AWC) was calculated using the approach described in Cordeiro et al. (2018) which uses provided water moisture content at -33 (KP33) and -1500 (KP1500) kilo-pascals (kPa) to represent soil moisture at field capacity and permanent wilting point, respectively (Givi et al. 2004). Missing values for water moisture content at -33kPa were replaced with water moisture content at -10kPa. The AWC for each layer was calculated as field capacity – permanent wilting point (KP33 – KP1500). The AWC for the avg soil type was calculated as a weighted avg based on layer thickness. Soil properties for each region were estimated as a weight value based on the percentage of each soil type within the region for all soil types with soil properties. If a soil type did not have soil properties, such as bedrock or marsh, were ignored. Given that agricultural activity is unlikely to occur over bedrock or marsh, ignoring these soil types is a reasonable assumption.

Calibration

Calibration of crop coefficients for the ET Demands model was conducted following the methods established by Reclamation (2015). Crop coefficients were calibrated for 10 of the 1/16° grid cells figure C-2 which are spatially distributed throughout the study area. Calibration of the crop parameters used initial typical start and end dates provided by the MT DNRC. Calibration of crop parameters included growing season start and end date, effective full cover timing, harvest and termination dates and killing frost and were based on cumulative growing degree days, 30-day avg air temperature (T_{30}) and day of the year. Calibrated crop parameters were spatially interpreted over all grid cells in the modeling domain using an inverse distance weighting method.

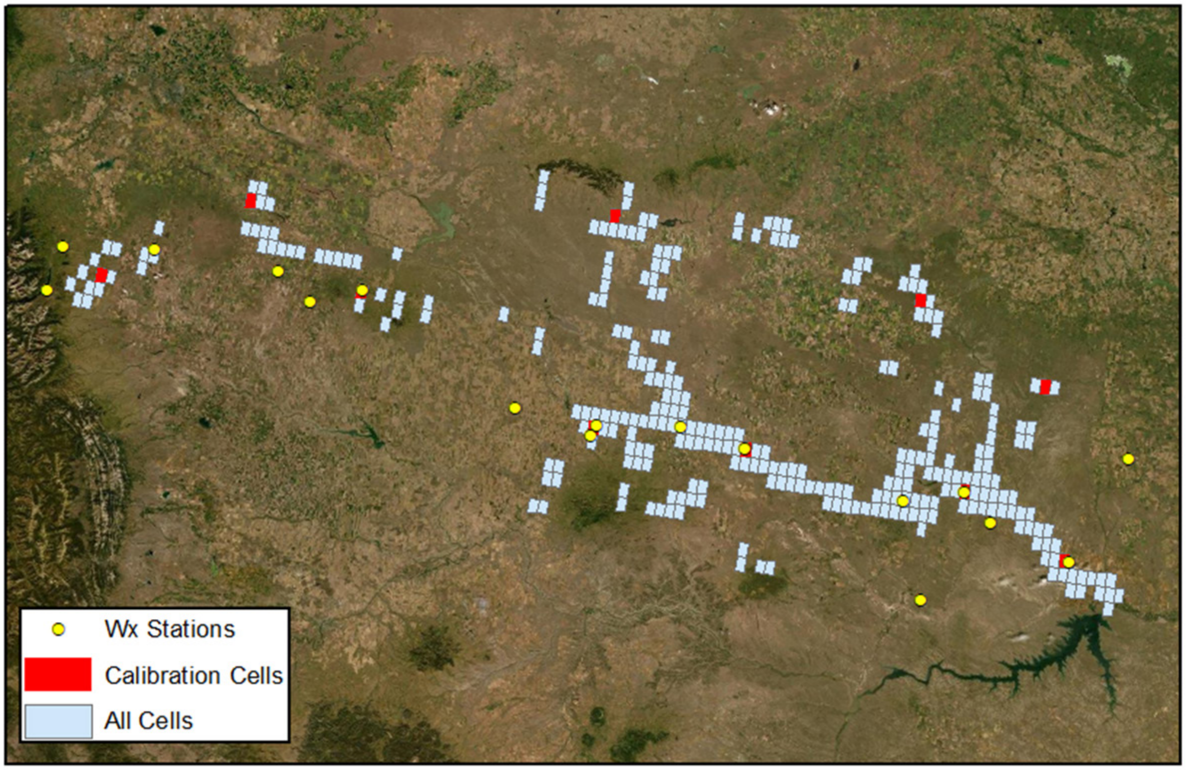

Figure C-2.—Crop parameter calibrated grid cells and meteorologic stations (source: Desert R esearch Institute).

Summary of Demands

Historical and projected annual NIWR by water user (table C-6), historical and projected annual reference ET by water user (table C-7), historical and projected annual crop ET (table C-8), historical and projected annual average channel evaporation (table C-9), historical and projected annual average evapotranspiration of phreatophytes by region (table C-10) are summarized below.

Demands Summary Tables

Table C-6.—Comparison of projected annual net irrigation water requirement (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water User	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Battle Creek to IB Irrigation	14.5	17.1	16.3	16.2	15.8	16.6	18.6	16.9	17.6	16.2	16.9	20.6	18.9	18.2	16.6	17.5
Battle Creek to Milk River Irrigation	14.6	17.5	16.5	16.8	16.2	16.9	18.5	17.4	17.8	16.6	17.5	19.8	18.6	18.3	17.1	18.1
Beaver Creek Havre Irrigation	19.8	25.1	24.4	24.0	23.6	24.0	28.5	26.8	26.7	24.8	25.7	31.8	31.1	28.7	26.0	26.6
Big Sandy Creek Irrigation	13.7	16.2	15.3	15.5	15.0	15.6	17.1	16.1	16.5	15.6	16.2	18.1	17.2	16.9	16.0	16.5
Buggy Creek Irrigation	21.4	24.9	24.4	23.9	23.4	24.5	26.8	25.4	25.7	24.2	24.9	28.7	27.7	26.6	24.9	25.6
Canadian Irrigation	10.4	11.7	10.8	11.0	10.8	11.3	11.7	10.7	11.3	10.9	11.1	12.0	11.1	11.4	10.5	11.3
Clear Creek Irrigation	15.1	18.4	17.5	17.5	17.0	17.5	21.1	19.3	19.5	17.9	18.6	23.3	22.1	21.1	18.7	19.5
Fort Belknap Canal Irrigation Districts Alfalfa Valley ID	17.7	22.1	21.1	21.2	20.3	21.1	24.1	22.8	22.8	21.1	22.2	26.6	25.6	24.2	22.1	23.1
Fort Belknap Canal Irrigation Districts Fort Belknap ID	20.1	24.0	22.8	23.3	22.4	23.3	25.6	24.3	24.5	22.8	24.1	27.7	26.5	25.6	23.6	24.9
Fort Belknap Canal Irrigation Districts Zurich ID	17.9	22.1	21.4	21.2	20.5	21.3	24.3	23.0	23.1	21.4	22.2	26.9	25.9	24.5	22.4	23.1
Fort Belknap Reservation	18.8	22.5	21.8	21.7	20.9	21.8	24.6	23.4	23.5	21.9	22.6	26.6	25.3	24.6	22.9	23.4

Table C-6.—Comparison of projected annual net irrigation water requirement (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water User	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Irrigation Project Milk River Unit																
Fort Belknap Reservation Irrigation Project White Bear Unit	17.8	19.9	19.2	19.6	18.9	19.7	20.4	19.6	19.9	18.9	19.8	20.9	19.7	20.1	19.5	20.2
Frenchman River to IB Irrigation	18.0	21.1	20.3	20.3	19.7	20.7	23.0	21.4	21.9	20.2	21.3	25.0	23.7	22.7	20.8	21.9
Glasgow ID	17.2	19.8	19.6	19.1	18.9	19.7	21.4	20.2	20.4	19.5	19.9	22.9	22.1	21.2	19.9	20.4
Harlem Irrigation District East Portion	20.9	25.1	24.4	24.0	23.3	24.3	27.6	26.3	26.3	24.4	25.2	30.3	29.2	27.7	25.7	26.1
Harlem Irrigation District West Portion	18.0	21.7	20.9	20.8	20.2	21.0	23.8	22.4	22.6	21.0	21.8	25.9	24.7	23.8	21.9	22.6
Irrigation above Frenchman Reservoir	19.1	23.7	23.2	22.5	21.9	23.0	27.3	25.4	25.6	23.5	24.1	30.8	30.0	27.3	24.8	25.2
Irrigation below Frenchman Dam Lower	20.4	24.4	24.0	23.2	22.9	24.0	26.7	25.3	25.4	23.8	24.5	29.1	27.9	26.4	24.7	25.4
Irrigation below Frenchman Dam Upper	18.3	21.5	20.9	20.5	20.3	21.2	22.9	21.7	22.1	20.7	21.6	24.9	23.9	22.7	21.2	22.2
Little Boxelder Creek Irrigation	15.6	19.0	18.1	18.0	17.5	18.1	21.0	19.6	19.8	18.4	19.4	22.8	21.8	20.9	19.1	20.0
Lodge Creek to IB Irrigation	16.2	19.0	17.9	18.1	17.7	18.4	20.9	19.3	19.7	18.2	19.0	22.8	21.6	20.7	18.7	19.7
Lodge Creek to Milk River Irrigation	17.8	21.5	20.6	20.6	20.0	20.7	23.4	22.1	22.2	20.8	21.6	25.5	24.4	23.4	21.5	22.4

Table C-6.—Comparison of projected annual net irrigation water requirement (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water User	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Lower Malta ID Beaver Creek	21.9	25.7	25.3	24.7	24.2	25.3	27.7	26.4	26.5	25.0	25.8	29.6	28.5	27.4	25.8	26.4
Lower Malta ID Milk Returns	18.8	21.9	21.4	21.0	20.8	21.6	23.4	22.2	22.4	21.3	21.8	25.1	24.1	23.1	21.8	22.4
ND Irrigation Above Beaver Creek	19.8	23.7	23.3	22.7	22.4	23.2	26.0	24.5	24.7	23.2	23.8	28.4	27.5	25.7	24.1	24.6
ND Irrigation Dodson to Nelson	19.2	22.3	21.6	21.4	20.8	21.8	23.5	22.3	22.7	21.4	22.1	24.6	23.5	23.2	21.9	22.6
ND Irrigation FT Belknap to Dodson	20.5	24.7	24.0	23.8	23.2	23.9	27.2	25.8	25.7	23.9	24.7	30.0	28.9	27.2	25.2	25.7
ND Irrigation Havre to FT Belknap	15.4	18.3	17.4	17.7	17.2	17.8	19.5	18.5	18.8	17.5	18.6	20.7	19.8	19.4	18.1	18.9
ND Irrigation Nelson to Vandalia	17.0	19.8	19.3	19.0	18.9	19.7	21.2	19.8	20.3	19.2	19.6	22.7	21.8	20.9	19.6	20.2
ND Irrigation PV to Harlem ID	15.9	19.7	19.0	18.9	18.2	18.9	21.6	20.5	20.5	18.9	19.9	23.9	23.1	21.8	19.8	20.6
ND Irrigation Paradise Valley Reach	17.3	21.1	20.1	20.4	19.6	20.3	22.7	21.4	21.6	20.1	21.3	25.0	24.0	22.8	20.8	21.9
ND Irrigation Vandalia to Mouth	21.4	24.8	24.3	23.8	23.4	24.3	26.7	25.4	25.6	24.1	25.0	28.8	28.0	26.4	24.9	25.4
North Malta ID	23.7	28.6	27.9	27.5	26.8	27.7	31.4	29.8	29.9	27.8	28.7	34.4	33.3	31.3	29.2	29.7
Paradise Valley Irrigation District East Portion	18.4	22.4	21.7	21.5	20.8	21.6	24.7	23.5	23.4	21.7	22.5	27.2	26.0	24.8	22.7	23.5
Paradise Valley Irrigation District West Portion	17.9	22.1	21.3	21.2	20.5	21.3	24.2	23.0	23.0	21.3	22.3	26.8	25.8	24.4	22.3	23.2

Table C-6.—Comparison of projected annual net irrigation water requirement (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water User	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Peoples Creek Irrigation	16.0	20.1	19.3	18.8	18.1	18.8	23.7	21.5	21.8	19.6	20.3	26.4	25.1	23.6	20.9	21.7
Private Irrigation Dodson to Nelson	24.1	28.9	28.3	27.6	27.2	28.0	31.6	30.0	30.0	28.4	29.0	34.4	33.5	31.5	29.4	29.8
Private Irrigation Harlem to Dodson	12.5	14.4	13.7	14.2	13.4	14.4	14.5	14.1	14.8	13.6	14.5	14.1	12.3	14.1	14.4	14.9
Private Irrigation Havre to FT Belknap	16.8	20.3	19.5	19.5	19.1	19.6	22.0	20.8	21.0	19.6	20.5	24.0	23.1	22.0	20.2	21.1
Private Irrigation Nelson to Vandalia	16.8	20.1	19.7	19.1	18.9	19.7	21.9	20.7	21.0	19.6	20.0	23.8	22.7	21.8	20.4	20.8
Private Irrigation PV to Harlem	20.3	26.1	25.5	24.9	24.2	24.9	29.5	28.0	27.9	25.5	26.6	33.4	32.8	30.0	27.0	27.9
Private Irrigation Paradise Valley Reach	19.3	24.5	23.5	23.6	22.5	23.5	27.3	25.9	25.7	23.6	24.9	30.6	29.8	27.5	24.8	25.9
Private Irrigation Vandalia to Mouth	17.2	19.6	19.3	18.9	18.7	19.5	20.8	19.6	19.9	19.2	19.5	22.1	21.4	20.6	19.5	20.0
Rock Creek Irrigation	16.6	19.5	19.1	18.7	18.5	19.3	21.2	19.9	20.3	19.0	19.5	23.0	22.1	21.1	19.7	20.2
Sweetgrass Hills Irrigation	11.8	15.5	14.4	14.2	13.8	14.3	18.0	16.3	16.6	14.9	15.4	20.3	19.4	18.1	15.6	16.2
U.S. Irrigation on North Milk	10.9	14.4	13.5	13.0	12.8	12.8	18.0	15.5	15.6	14.3	14.1	21.0	19.4	17.6	15.3	15.5
U.S. Irrigation on South Milk	12.2	14.7	13.8	13.5	13.4	13.5	16.6	14.9	15.3	14.2	14.3	18.3	17.0	16.2	14.6	15.2
Upper Malta ID Beaver Returns	22.5	26.5	26.0	25.5	25.1	26.0	28.6	27.3	27.5	26.0	26.7	30.8	29.7	28.6	26.8	27.3
Upper Malta ID Bowdoin Return	21.5	26.0	25.4	24.9	24.6	25.3	28.4	27.0	27.0	25.4	26.2	31.1	30.1	28.4	26.4	26.9

Table C-6.—Comparison of projected annual net irrigation water requirement (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water User	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Upper Malta ID Lower	15.6	17.8	17.1	17.2	16.8	17.5	18.4	17.5	17.9	17.0	17.7	18.8	17.5	17.9	17.3	18.0
Upper Malta ID Upper	22.2	26.3	25.6	25.3	24.7	25.6	28.4	27.1	27.2	25.5	26.4	30.8	29.7	28.3	26.5	27.1
Whitewater River Irrigation	16.7	18.2	17.5	17.8	17.3	18.3	18.3	17.2	18.0	17.2	18.1	18.8	17.7	18.0	17.1	18.2

Table C-7.—Comparison of projected annual reference ET (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water Users	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Battle Creek to IB Irrigation	43.3	47.2	47.3	46.7	46.4	46.6	49.9	49.3	48.9	47.5	47.5	53.0	52.9	50.4	48.7	48.3
Battle Creek to Milk River Irrigation	50.2	54.8	55.1	54.2	54.0	54.1	57.8	57.3	56.7	55.3	55.2	61.3	61.0	58.5	56.7	56.2
Beaver Creek Havre Irrigation	51.6	56.3	56.6	55.7	55.4	55.5	59.5	59.0	58.2	56.9	56.8	63.1	62.8	60.3	58.3	57.8
Big Sandy Creek Irrigation	51.4	56.1	56.3	55.4	55.2	55.2	59.4	58.9	58.1	56.8	56.5	63.2	62.8	60.2	58.2	57.6
Buggy Creek Irrigation	48.5	53.2	53.3	52.4	52.2	52.4	56.0	55.4	54.7	53.6	53.4	59.2	59.0	56.5	54.9	54.3
Canadian Irrigation	44.9	49.0	49.1	48.3	48.0	48.1	51.9	51.5	50.8	49.5	49.3	55.3	54.9	52.6	50.8	50.3
Clear Creek Irrigation	48.0	52.6	52.9	52.0	51.7	51.8	55.8	55.3	54.6	53.2	53.0	59.4	59.1	56.5	54.6	54.1
Fort Belknap Canal Irrigation Districts: Alfalfa Valley ID	50.6	55.3	55.5	54.6	54.4	54.5	58.2	57.8	57.1	55.8	55.7	61.7	61.4	58.9	57.2	56.6
Fort Belknap Canal Irrigation Districts: Fort Belknap ID	58.1	63.4	63.7	62.7	62.5	62.6	66.8	66.3	65.5	64.0	63.9	70.8	70.5	67.7	65.6	65.0
Fort Belknap Canal Irrigation Districts: Zurich ID	50.9	55.6	55.8	54.9	54.7	54.8	58.6	58.1	57.4	56.1	56.0	62.2	61.9	59.3	57.5	57.0
Fort Belknap Reservation Irrigation Project: Milk River Unit	53.6	58.5	58.7	57.8	57.5	57.6	61.8	61.2	60.5	59.1	58.9	65.6	65.3	62.5	60.6	60.0
Fort Belknap Reservation Irrigation Project: White Bear Unit	56.5	61.6	61.9	60.8	60.6	60.7	65.0	64.4	63.7	62.2	62.1	69.0	68.6	65.8	63.8	63.2
Frenchman River to IB Irrigation	48.8	53.4	53.5	52.7	52.5	52.6	56.5	55.8	55.3	53.8	53.8	60.0	59.8	57.0	55.2	54.7

Table C-7.—Comparison of projected annual reference ET (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water Users	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Glasgow ID	49.6	54.4	54.5	53.6	53.4	53.6	57.2	56.6	55.9	54.8	54.6	60.5	60.3	57.7	56.1	55.5
Harlem Irrigation District: East Portion	52.7	57.5	57.8	56.8	56.6	56.7	60.7	60.2	59.4	58.1	57.9	64.5	64.2	61.5	59.6	59.0
Harlem Irrigation District: West Portion	51.0	55.7	55.9	55.0	54.8	54.9	58.8	58.3	57.6	56.3	56.1	62.4	62.1	59.5	57.7	57.1
Irrigation above Frenchman Reservoir	51.0	55.9	56.0	55.0	54.8	55.0	59.0	58.4	57.8	56.4	56.2	62.8	62.5	59.7	57.9	57.2
Irrigation below Frenchman Dam: Lower	49.8	54.7	54.8	53.9	53.7	53.9	57.5	57.0	56.3	55.1	55.0	60.9	60.6	58.1	56.5	55.9
Irrigation below Frenchman Dam: Upper	50.7	55.6	55.8	54.8	54.7	54.9	58.6	58.0	57.3	56.1	56.0	62.1	61.8	59.2	57.5	56.9
Little Boxelder Creek Irrigation	48.2	52.8	53.0	52.1	51.9	52.0	55.8	55.3	54.6	53.3	53.2	59.1	58.9	56.5	54.7	54.1
Lodge Creek to IB Irrigation	43.3	47.1	47.3	46.6	46.4	46.4	50.0	49.4	48.9	47.6	47.6	53.1	53.0	50.5	48.8	48.4
Lodge Creek to Milk River Irrigation	49.5	54.1	54.3	53.5	53.3	53.4	57.0	56.5	55.9	54.6	54.5	60.5	60.2	57.7	56.0	55.5
Lower Malta ID: Beaver Creek	52.0	57.0	57.1	56.2	56.0	56.2	59.8	59.3	58.6	57.4	57.2	63.4	63.1	60.5	58.8	58.2
Lower Malta ID: Milk Returns	50.8	55.8	55.9	55.0	54.8	55.0	58.7	58.1	57.4	56.2	56.0	62.2	61.9	59.3	57.6	57.0
ND Irrigation Above Beaver Creek	51.4	56.3	56.5	55.5	55.3	55.5	59.2	58.7	58.0	56.8	56.6	62.7	62.4	59.8	58.1	57.5
ND Irrigation Dodson to Nelson	55.6	60.9	61.1	60.1	59.9	60.0	64.1	63.6	62.8	61.5	61.3	68.0	67.7	64.8	63.0	62.3
ND Irrigation FT Belknap to Dodson	55.4	60.5	60.7	59.7	59.5	59.6	63.9	63.3	62.5	61.1	60.9	67.8	67.5	64.6	62.6	62.0

Table C-7.—Comparison of projected annual reference ET (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water Users	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
ND Irrigation Havre to FT Belknap	49.4	54.0	54.2	53.3	53.1	53.2	57.0	56.4	55.8	54.5	54.4	60.3	60.1	57.7	55.9	55.3
ND Irrigation Nelson to Vandalia	49.6	54.4	54.6	53.6	53.5	53.7	57.4	56.7	56.1	54.9	54.7	60.7	60.5	57.9	56.2	55.6
ND Irrigation PV to Harlem ID	50.7	55.4	55.7	54.8	54.5	54.6	58.4	57.9	57.2	55.9	55.8	61.9	61.6	59.1	57.4	56.8
ND Irrigation Paradise Valley Reach	49.8	54.4	54.7	53.8	53.6	53.7	57.3	56.8	56.2	54.9	54.8	60.7	60.4	58.0	56.3	55.7
ND Irrigation Vandalia to Mouth	48.6	53.4	53.5	52.6	52.4	52.6	56.2	55.6	55.0	53.8	53.6	59.5	59.3	56.8	55.1	54.5
North Malta ID	56.6	61.9	62.1	61.1	60.9	61.1	65.2	64.6	63.9	62.5	62.4	69.1	68.7	65.9	64.0	63.4
Paradise Valley Irrigation District: East Portion	49.9	54.6	54.8	53.9	53.7	53.8	57.5	57.0	56.4	55.1	55.0	61.0	60.8	58.2	56.5	55.9
Paradise Valley Irrigation District: West Portion	50.0	54.6	54.9	54.0	53.8	53.8	57.6	57.1	56.4	55.1	55.0	61.1	60.8	58.3	56.6	56.0
Peoples Creek Irrigation	48.4	53.1	53.3	52.4	52.1	52.2	56.4	55.8	55.1	53.7	53.5	60.0	59.7	57.1	55.1	54.6
Private Irrigation Dodson to Nelson	55.0	60.3	60.5	59.5	59.3	59.5	63.4	62.9	62.1	60.8	60.7	67.2	66.8	64.1	62.3	61.7
Private Irrigation Harlem to Dodson	54.9	59.9	60.1	59.1	58.9	59.0	63.3	62.7	61.9	60.5	60.3	67.2	66.9	64.0	62.0	61.4
Private Irrigation Havre to FT Belknap	48.9	53.5	53.7	52.8	52.6	52.6	56.5	56.0	55.3	54.0	53.9	60.0	59.7	57.3	55.4	54.9
Private Irrigation Nelson to Vandalia	49.5	54.3	54.5	53.5	53.4	53.6	57.3	56.6	56.0	54.8	54.6	60.6	60.4	57.8	56.1	55.5
Private Irrigation PV to Harlem	50.8	55.5	55.7	54.8	54.6	54.7	58.5	58.0	57.3	56.0	55.9	62.0	61.7	59.2	57.4	56.9

Table C-7.—Comparison of projected annual reference ET (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water Users	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Private Irrigation Paradise Valley Reach	50.1	54.8	55.0	54.1	53.9	54.0	57.6	57.2	56.5	55.2	55.1	61.1	60.8	58.4	56.7	56.1
Private Irrigation Vandalia to Mouth	50.6	55.4	55.5	54.6	54.4	54.6	58.3	57.7	57.0	55.9	55.7	61.7	61.4	58.9	57.2	56.5
Rock Creek Irrigation	49.8	54.6	54.7	53.8	53.6	53.8	57.6	57.0	56.3	55.1	54.9	61.0	60.8	58.2	56.4	55.8
Sweetgrass Hills Irrigation	43.6	47.7	47.7	47.0	46.7	46.8	50.4	50.0	49.3	48.1	47.9	53.8	53.3	51.1	49.4	48.8
U.S. Irrigation on North Milk	41.4	45.2	45.2	44.5	44.2	44.3	47.9	47.4	46.8	45.6	45.4	51.1	50.8	48.4	47.0	46.3
U.S. Irrigation on South Milk	42.6	46.5	46.5	45.8	45.6	45.6	49.2	48.8	48.1	47.0	46.7	52.5	52.2	49.7	48.3	47.7
Upper Malta ID: Beaver Returns	55.6	60.9	61.1	60.1	59.9	60.1	64.0	63.5	62.8	61.5	61.3	67.8	67.5	64.7	62.9	62.4
Upper Malta ID: Bowdoin Returns	55.6	60.9	61.1	60.2	60.0	60.1	64.1	63.6	62.9	61.6	61.4	67.9	67.5	64.8	63.0	62.4
Upper Malta ID: Lower	56.3	61.6	61.9	60.9	60.7	60.8	64.8	64.3	63.6	62.3	62.1	68.7	68.3	65.6	63.8	63.2
Upper Malta ID: Upper	57.0	62.3	62.5	61.5	61.3	61.5	65.6	65.0	64.3	62.9	62.8	69.5	69.1	66.3	64.5	63.9
Whitewater River Irrigation	52.3	57.3	57.5	56.5	56.3	56.5	60.5	59.9	59.2	57.8	57.7	64.2	64.0	61.1	59.3	58.6

Table C-8.—Comparison of projected annual crop ET (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water users	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Battle Creek to IB Irrigation	27.7	30.6	31.1	30.3	30.4	30.1	32.0	32.4	31.5	31.2	30.7	33.7	34.6	32.7	31.9	31.1
Battle Creek to Milk River Irrigation	26.4	29.5	30.0	29.1	29.2	28.8	30.7	31.2	30.5	30.3	29.5	31.8	32.5	31.3	30.9	30.1
Beaver Creek Havre Irrigation	31.0	36.5	37.1	35.7	35.7	35.1	39.9	39.7	38.6	37.6	36.9	43.4	44.4	40.7	39.0	38.0
Big Sandy Creek Irrigation	25.7	28.3	28.8	28.1	28.2	27.7	29.4	30.1	29.3	29.0	28.4	30.5	31.3	30.0	29.7	29.0
Buggy Creek Irrigation	32.6	36.5	36.8	35.8	35.6	35.7	38.6	38.6	37.7	36.8	36.3	40.5	41.1	39.1	37.8	37.0
Canadian Irrigation	22.9	24.2	24.7	24.2	24.3	24.2	24.4	25.2	24.5	24.5	24.2	24.7	25.5	24.9	24.7	24.4
Clear Creek Irrigation	29.0	32.9	33.4	32.1	32.2	31.7	35.7	35.7	34.6	33.9	33.0	38.0	39.0	36.5	35.1	34.1
Fort Belknap Canal Irrigation Districts: Alfalfa Valley ID	29.3	33.8	34.4	33.1	33.0	32.8	36.1	36.3	35.3	34.7	33.9	38.5	39.4	36.9	35.7	34.8
Fort Belknap Canal Irrigation Districts: Fort Belknap ID	33.5	37.7	38.3	37.1	37.1	36.9	39.6	40.0	39.0	38.6	37.7	41.6	42.5	40.5	39.5	38.5
Fort Belknap Canal Irrigation Districts: Zurich ID	29.6	34.0	34.6	33.4	33.3	33.0	36.4	36.6	35.5	34.8	34.2	38.9	39.9	37.3	36.0	35.1
Fort Belknap Reservation Irrigation Project: Milk River Unit	30.6	34.6	35.1	34.0	33.8	33.7	36.8	37.1	36.1	35.4	34.7	38.8	39.5	37.6	36.6	35.5
Fort Belknap Reservation Irrigation	29.1	31.5	31.9	31.4	31.3	31.1	32.3	32.8	32.2	32.0	31.5	32.8	33.3	32.7	32.6	31.8

Table C-8.—Comparison of projected annual crop ET (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water users	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Project: White Bear Unit																
Frenchman River to IB Irrigation	30.2	33.7	34.0	33.1	33.1	33.0	35.4	35.6	34.7	34.1	33.7	37.3	38.1	36.0	34.9	34.2
Glasgow ID	28.6	31.6	31.8	31.2	31.2	30.9	33.0	33.2	32.5	32.2	31.5	34.5	35.4	33.6	32.7	32.1
Harlem Irrigation District: East Portion	32.4	36.9	37.4	36.2	36.0	35.8	39.6	39.7	38.6	37.6	37.0	42.3	43.2	40.5	39.0	38.0
Harlem Irrigation District: West Portion	29.7	33.6	34.1	33.0	32.9	32.7	35.7	36.0	34.9	34.3	33.7	37.9	38.8	36.5	35.4	34.5
Irrigation above Frenchman Reservoir	30.3	35.3	35.8	34.5	34.4	34.2	38.9	38.7	37.6	36.4	35.6	42.4	43.3	39.8	38.1	36.8
Irrigation below Frenchman Dam: Lower	31.9	36.1	36.6	35.4	35.4	35.4	38.5	38.6	37.7	36.8	36.3	40.9	41.7	39.3	38.0	37.1
Irrigation below Frenchman Dam: Upper	30.0	33.5	33.9	33.0	33.1	32.8	35.1	35.4	34.6	34.2	33.5	36.9	37.9	35.8	35.0	34.1
Little Boxelder Creek Irrigation	28.3	32.0	32.5	31.3	31.4	30.9	34.1	34.3	33.4	32.9	32.2	36.0	36.9	34.8	33.8	32.9
Lodge Creek to IB Irrigation	27.6	30.5	30.8	30.1	30.3	29.9	32.4	32.6	31.7	31.2	30.7	34.4	35.1	33.0	32.0	31.3
Lodge Creek to Milk River Irrigation	29.4	33.2	33.8	32.6	32.7	32.4	35.2	35.5	34.6	34.1	33.3	37.2	38.2	36.0	35.0	34.2
Lower Malta ID: Beaver Creek	33.0	37.3	37.6	36.6	36.4	36.5	39.3	39.4	38.5	37.8	37.2	41.4	42.1	39.9	38.8	38.0
Lower Malta ID: Milk Returns	30.0	33.5	33.8	33.1	32.9	32.8	35.1	35.2	34.5	34.1	33.4	36.8	37.6	35.7	34.8	34.1

Table C-8.—Comparison of projected annual crop ET (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water users	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
ND Irrigation Above Beaver Creek	31.0	35.3	35.7	34.7	34.5	34.4	37.6	37.6	36.8	36.1	35.3	40.1	41.0	38.4	37.2	36.2
ND Irrigation Dodson to Nelson	30.6	34.0	34.3	33.5	33.4	33.2	35.3	35.8	34.9	34.6	33.8	36.5	37.3	35.9	35.3	34.5
ND Irrigation FT Belknap to Dodson	32.1	36.5	37.0	35.9	35.8	35.5	39.2	39.3	38.2	37.3	36.6	42.0	42.9	40.1	38.6	37.6
ND Irrigation Havre to FT Belknap	26.8	30.0	30.5	29.6	29.6	29.3	31.3	31.7	31.0	30.7	30.0	32.5	33.2	31.8	31.4	30.6
ND Irrigation Nelson to Vandalia	28.4	31.5	31.9	31.2	31.2	31.1	32.9	33.1	32.5	32.2	31.5	34.5	35.4	33.6	32.8	32.1
ND Irrigation PV to Harlem ID	27.4	31.3	32.0	30.7	30.8	30.5	33.5	33.8	32.8	32.2	31.5	35.8	36.9	34.4	33.2	32.3
ND Irrigation Paradise Valley Reach	29.0	33.0	33.5	32.5	32.4	32.2	34.9	35.2	34.3	33.9	33.1	37.0	38.1	35.7	34.7	33.8
ND Irrigation Vandalia to Mouth	32.5	36.6	36.9	35.8	35.7	35.7	38.8	38.8	37.9	37.0	36.5	40.7	41.4	39.3	38.1	37.2
North Malta ID	35.2	40.4	40.8	39.6	39.4	39.3	43.3	43.3	42.3	41.2	40.6	46.4	47.3	44.2	42.6	41.6
Paradise Valley Irrigation District: East Portion	30.0	34.2	34.8	33.6	33.5	33.4	36.7	36.9	35.8	35.0	34.4	39.2	40.1	37.6	36.3	35.3
Paradise Valley Irrigation District: West Portion	29.7	34.1	34.7	33.4	33.4	33.1	36.5	36.7	35.7	34.9	34.3	39.0	40.0	37.4	36.1	35.2
Peoples Creek Irrigation	30.4	35.1	35.7	34.2	34.1	33.7	39.0	38.8	37.6	36.3	35.6	42.1	43.0	39.9	38.0	36.9
Private Irrigation Dodson to Nelson	35.2	40.4	40.7	39.5	39.3	39.2	43.2	43.1	42.1	41.1	40.5	46.1	47.0	44.0	42.4	41.4

Table C-8.—Comparison of projected annual crop ET (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water users	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Private Irrigation Harlem to Dodson	24.0	26.4	26.9	26.4	26.3	26.0	26.7	27.5	27.3	27.0	26.5	26.1	26.0	26.9	27.7	26.8
Private Irrigation Havre to FT Belknap	27.7	31.4	31.9	30.8	31.0	30.6	33.2	33.5	32.5	32.1	31.5	35.1	36.0	33.8	33.0	32.2
Private Irrigation Nelson to Vandalia	28.1	31.9	32.2	31.3	31.2	31.1	33.7	33.9	33.1	32.5	31.8	35.5	36.1	34.4	33.5	32.6
Private Irrigation PV to Harlem	31.9	37.9	38.6	36.9	36.8	36.5	41.5	41.6	40.3	38.9	38.2	45.5	46.7	42.8	40.7	39.6
Private Irrigation Paradise Valley Reach	30.9	36.3	37.0	35.5	35.4	35.2	39.4	39.5	38.3	37.4	36.6	42.6	43.8	40.5	38.7	37.7
Private Irrigation Vandalia to Mouth	28.6	31.3	31.6	31.1	31.1	30.8	32.5	32.8	32.1	31.9	31.2	33.8	34.8	33.1	32.3	31.7
Rock Creek Irrigation	28.1	31.4	31.8	31.0	30.9	30.8	33.1	33.3	32.6	32.1	31.4	34.8	35.7	33.8	33.0	32.1
Sweetgrass Hills Irrigation	26.8	30.5	30.9	30.0	30.0	29.6	33.2	33.6	32.5	31.3	30.8	35.7	36.7	34.1	32.7	31.8
U.S. Irrigation on North Milk	27.6	31.5	32.1	31.2	31.0	30.7	35.2	35.3	33.9	32.6	31.9	38.5	39.4	36.4	34.5	33.1
U.S. Irrigation on South Milk	27.5	30.6	31.1	30.2	30.1	29.9	32.8	33.2	32.1	31.2	30.7	34.8	35.6	33.7	32.5	31.5
Upper Malta ID: Beaver Returns	33.7	38.2	38.4	37.5	37.4	37.3	40.3	40.5	39.6	38.8	38.2	42.5	43.3	41.0	39.9	39.0
Upper Malta ID: Bowdoin Returns	33.1	38.1	38.3	37.3	37.2	37.0	40.4	40.6	39.6	38.8	38.1	43.2	44.1	41.3	40.0	39.0
Upper Malta ID : Lower	27.5	30.1	30.4	29.9	29.8	29.5	30.6	31.3	30.8	30.6	29.9	31.1	31.7	31.0	31.1	30.3
Upper Malta ID : Upper	33.6	38.1	38.5	37.5	37.3	37.1	40.4	40.5	39.6	38.8	38.2	42.7	43.6	41.1	39.9	39.0

Table C-8.—Comparison of projected annual crop ET (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981–2015)

Water users	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Whitewater River Irrigation	28.4	30.3	30.6	30.3	30.4	30.0	30.5	31.1	30.5	30.8	30.0	30.9	31.9	31.0	30.9	30.3

Table C-9.—Historical and projected annual average channel evaporation (in/year)

Reach	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Milk River to Dodson Dam	35.1	39.2	37.8	38.2	37.4	38.8	41.7	39.5	40.2	37.8	39.6	45.0	42.8	41.5	39.0	40.5
Milk River to Fort Belknap	31.8	35.6	33.9	34.7	33.8	35.2	38.0	35.6	36.5	34.1	36.1	41.1	38.7	37.8	35.3	36.8
Milk River to Harlem ID	32.0	35.9	34.0	35.1	34.1	35.3	38.1	35.8	36.7	34.0	36.4	41.2	38.9	37.7	35.2	37.1
Milk River to Mouth	32.1	35.6	35.4	34.8	34.4	35.7	38.3	36.3	36.9	35.1	36.2	41.2	39.5	38.0	36.2	37.0
Milk River to Nelson Reservoir	37.0	41.2	40.2	40.1	39.5	41.0	43.8	41.6	42.4	39.9	41.7	47.1	44.9	43.6	41.1	42.5
Milk River to Paradise Valley Diversion	31.4	35.4	33.7	34.5	33.6	34.7	37.7	35.4	36.3	33.8	35.9	40.5	38.5	37.5	34.8	36.5
Milk River to Vandalia Dam	33.0	36.8	36.2	35.7	35.5	36.8	39.4	37.3	38.0	35.8	37.3	42.3	40.3	38.9	36.8	38.1
Milk River to Ft. Belknap Reservation	31.3	35.2	33.5	34.3	33.4	34.6	37.4	35.1	36.0	33.6	35.6	40.6	38.1	37.2	34.7	36.3

Table C-10.—Phreatophytes annual average evapotranspiration for each region (inches/year)

Reach	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Phreatophytes Havre to Fort Belknap	17.6	22.2	21.1	21.1	20.6	21.2	25.2	23.3	23.5	21.5	22.6	28.6	27.7	25.4	22.9	23.4
Phreatophytes Ft. Belknap to Paradise Valley	17.6	22.2	21.1	21.1	20.6	21.2	25.2	23.3	23.5	21.5	22.6	28.6	27.7	25.4	22.9	23.4
Phreatophytes PV to Harlem ID	18.0	22.6	21.4	21.6	20.9	21.6	25.5	23.6	23.8	21.5	22.9	29.0	28.0	25.5	23.1	23.8
Phreatophytes Harlem ID to FT Belknap Reservation	17.5	22.0	21.0	20.9	20.4	21.0	25.0	23.0	23.3	21.2	22.3	28.6	27.5	25.1	22.5	23.3
Phreatophytes Ft. Belknap to Dodson	19.3	24.1	23.1	22.8	22.4	23.2	27.2	25.2	25.4	23.3	24.2	31.1	29.8	27.3	24.8	25.3
Phreatophytes Dodson to Vandalia	20.6	25.3	24.6	24.0	23.7	24.7	28.6	26.6	26.9	24.7	25.6	32.2	30.9	28.5	26.2	26.7
Phreatophytes Vandalia to Mouth	19.0	23.2	23.0	22.1	21.9	22.7	26.4	24.4	24.6	23.0	23.5	29.7	28.7	26.2	24.2	24.4

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Appendix D

Reservoir Evaporation Estimates Development

Estimated evaporation rates for the reservoirs in the St. Mary and Milk River basins (listed in table D-1) were calculated using the CRLE model (Morton 1985). The CRLE is an open water evaporation model based on the combined energy and aerodynamic equations with a simple heat storage accounting procedure. Model inputs include solar radiation, air temperature, and dewpoint temperature. The CRLE model estimates and accounts for water temperature, albedo, emissivity, and heat storage effects to estimate monthly evaporation. This approach overcomes the limitations of more data-intensive mass transfer combination approaches, which makes it a better method for regional and longer time period applications with limited weather data.

The CRLE model is well tested and has been used extensively for operations modeling of open-water evaporation including numerous Basin Studies (Reclamation 2015; 2021). Reclamation collaborated with the DRI in the development and application of the CRLE model as part of Reclamation's WWCRA program. As part of the WWCRA, the CRLE model was used to evaluate evaporation for major reservoirs throughout the Reclamation regions across the western U.S. The WWCRA Water Demands Report (Reclamation 2015) provides a more detailed description of the CRLE model and its application.

Table D-1.—Reservoirs where evaporation estimates were developed in the study area

Reservoir	Owner	Met station ID	Met station name
Lake Sherburne	Reclamation	MT0392	BABB 6 NE, MT
Fresno Reservoir	Reclamation	MT3110	FT ASSINNIBOINE
Nelson Reservoir	Reclamation	MT5338	MALTA 7 E
Lake Bowdoin	U.S. Fish and Wildlife Service	MT7265	SACO 1 NNW
Frenchman Reservoir	MT DNRC	MT7265	SACO 1 NNW
Alberta Forks Reservoir (proposed)	-	MT2301	DEL BONITA
FBIIPReservoir (proposed)	-	MT3929	HARLEM

The CRLE was run on a monthly timestep and requires monthly meteorological inputs including avg dew point temperature (T_{dew}), avg air T, and solar radiation. Total precipitation is used to calculate net evaporation from the model outputs but is not used in CRLE calculations. Meteorologic data for each reservoir was extracted from the daily Daymet meteorological dataset ("Appendix B Water Supply Development") for the corresponding grid cell at each reservoir location. The Daymet gridded historical air temperature and precipitation data were bias corrected using observed data from local National Weather Service COOP weather stations using approaches described in Wood et al. (2002) and Wood et al. (2004). Representative met stations were identified for each reservoir based on their relative location and elevation (figure D-1), as well as the completeness of the recorded data over the 1980-2015 reference period. Additionally, the seasonal climatology for avg monthly minimum and maximum temperature from the met station observations was evaluated against the Daymet meteorological data for the corresponding grid cell containing the reservoir.

Additional required CRLE meteorological inputs for solar radiation and T_{dew} were also provided by the Daymet dataset for each reservoir. For the projected scenarios, daily T_{dew} was estimated using daily minimum temperature and avg monthly Ko (i.e., Tmin–Tdew) values computed from the historical bias corrected Daymet data (table D-2).

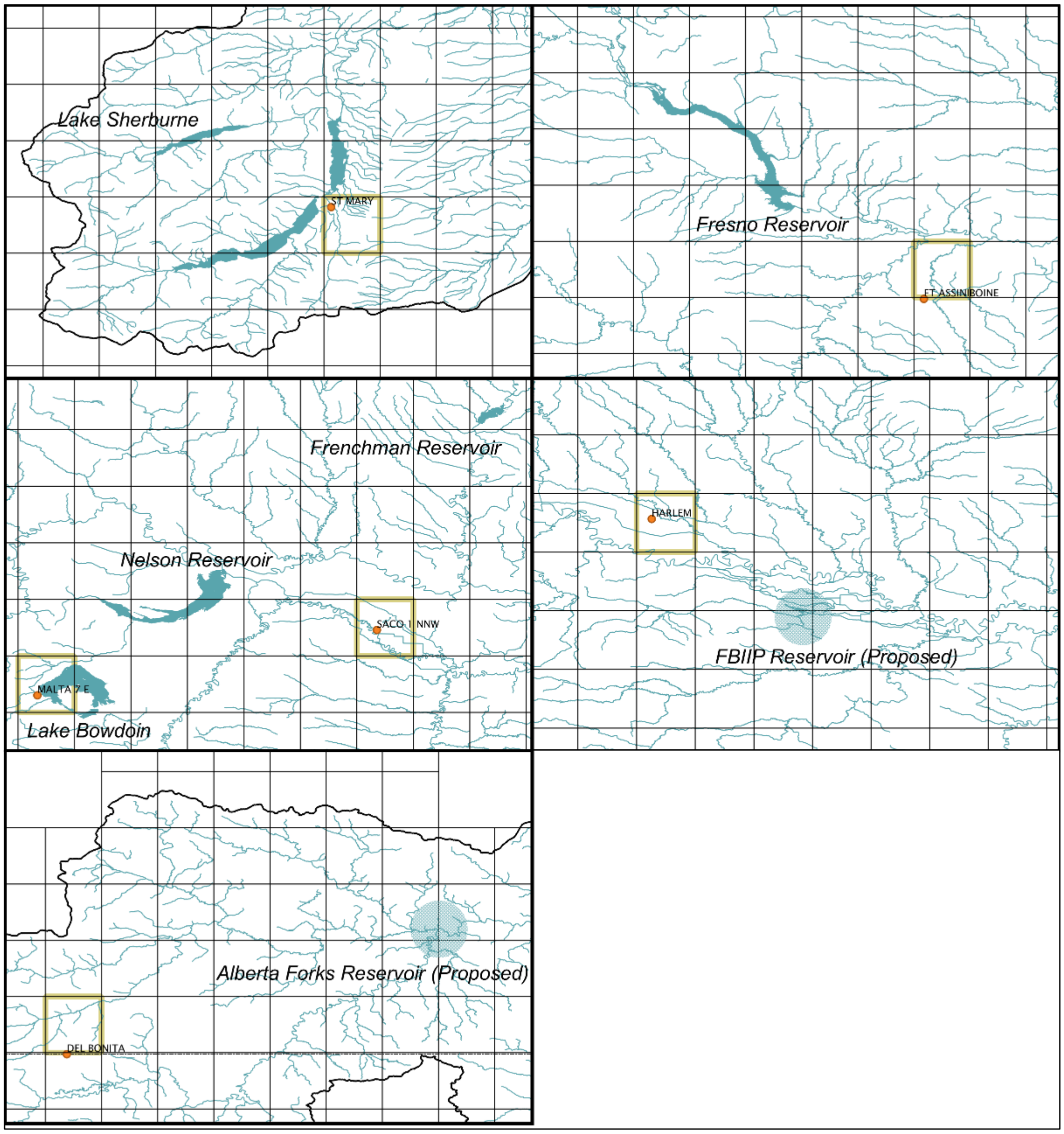

Figure D-1.—Met station and Daymet data used to develop meteorological inputs for complementary relationship lake evaporation for each reservoir.[1]

[1] Lines show 1/16° grid and highlighted box shows the grid cell from which meteorological forcings were extracted for each reservoir.

Table D-2.—Dewpoint depression for complementary relationship lake evaporation estimates

Reservoir name	WRCC station ID	Dewpoint depression Ko											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fresno Reservoir	MT3110	0.32	2.78	7.59	10.75	8.69	4.92	3.69	2.83	2.73	1.25	0.20	0.04
Nelson Reservoir Lake Bowdoin	MT5338	0.48	3.31	8.52	11.58	9.41	5.37	3.60	2.94	2.88	1.45	0.27	0.00
Frenchman Reservoir	MT7265	0.40	3.29	8.84	11.94	9.90	5.59	3.59	2.87	3.00	1.52	0.23	0.00
Alberta Forks Reservoir (Proposed)	MT2301	0.21	2.41	6.14	8.19	6.87	3.63	2.92	2.57	2.00	0.96	0.22	0.02
FBIIP Reservoir (Proposed)	MT3929	0.50	3.22	7.99	11.13	9.31	5.38	3.42	2.62	2.69	1.41	0.26	0.02

In addition to meteorological inputs, CRLE also requires reservoir properties including reservoir latitude, avg elevation, avg total dissolved solids (TDS), and avg depth (table D-4). Data sources for these properties are summarized in table D-3. The values used in CRLE modeling from these sources are summarized in table D-4. A version of the model supporting variable depths has been developed by Reclamation's Technical Service Center, however, a static depth was used for this study. Reservoir elevations for existing reservoirs were determined based on the NHDPlus Waterbodies spatial layer (Moore et al. 2019). Proposed reservoirs, including the Alberta Forks Reservoir and FBIIP Reservoir elevations were determined based on the Google Map elevation at the approximate centroid of the proposed reservoir. Water surface elevation time series were used to compute avg depths; table D-3 lists the sources of lake depth and water quality data and periods of record for each reservoir. Table D-5 and table D-6 summarize projected average total reservoir evaporation depths and net evaporation depths, respectively, for each climate change scenario and future time horizon considered in the Basins Study Update.

Table D-3.—Summary of data sources for static inputs to complementary relationship lake evaporation model

Reservoir	Reservoir elevation (ft)	Water surface elevation data source	Water quality data source
Lake Sherburne	4788	USBR Hydromet	TDS data from U.S. EPA Storage and Retrieval Data from Redrock, Fishercap, and Lake Josephine (upstream of Sherburne)
Fresno Reservoir	2570	USBR Hydromet	TDS data from U.S. EPA Storage and Retrieval Data from Milk River at Eastern Crossing
Nelson Reservoir	2222	USBR Hydromet	Monthly water quality parameters, measured from July 2003 thru Dec 2008, along with measurements taken during the 2011 flood.
Lake Bowdoin	2208	MT DNRC	Water quality parameter data collected in the middle of Lake Bowdoin during the 2005 season, July 2003 thru Dec 2008 and the 2011 flood.
Frenchman Reservoir	2260	MT DNRC	Secchi depth/TDS data from Frenchman Reservoir at international boundary
Alberta Forks Res (Proposed)	3628	Assumed 16.4 ft (5 meters) depth	Secchi depth/TDS data from Milk River at Hwy 880 (downstream from the Town of Milk River)
FBIIP Reservoir (Proposed)	2362	Assumed 16.4ft (5 meters) depth	SC/TDS data from Milk River near Harlem (immediately downstream from A Canal diversions)

Table D-4.—Bias correction Cooperative Observer Program stations, salinity, and average depth for complementary relationship lake evaporation estimates of reservoir evaporation

Reservoir	Lat	Lon	Selected WRCC* met station	WRCC numeric ID	NCDC** station ID	Daymet grid cell	Salinity (TDS in milligrams per liter)	Average depth (ft)
Fresno Reservoir	48.67	-110.01	FT ASSINNIBOINE	243110	20012777	48.46875_-109.78125	145.67	32.2
Nelson Reservoir	48.50	-107.56	MALTA 7 E	245338	20012755	48.40625_-107.71875	386.26	15.1
Lake Bowdoin	48.40	-107.68	MALTA 7 E	245338	20012765	48.40625_-107.71875	13083.64	8.2
Frenchman Reservoir	48.70	-107.23	SACO 1 NNW	247265	20012765	48.46875_-107.34375	617.59	17.1
Alberta Forks Res (Proposed)	49.14	-112.37	DEL BONITA	242301	20012878	48.96875_-112.78125	337.9	16.4
FBIIP Reservoir (Proposed)	48.44	-108.64	HARLEM	243929	20012880	48.53125_-108.78125	424.65	16.4

* Western Regional Climate Center
** National Climate Data Center

Table D-5.—Comparison of projected annual reservoir evaporation (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981-2015)

Reservoir	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Fresno Reservoir	34.9	38.0	38.1	37.8	37.8	37.8	39.6	39.3	39.1	38.3	38.3	41.6	41.5	40.0	39.1	38.8
Nelson Reservoir	36.0	39.1	39.2	38.8	38.8	38.8	40.7	40.4	40.2	39.4	39.4	42.7	42.6	41.0	40.2	39.9
Lake Bowdoin	35.9	38.8	38.9	38.5	38.5	38.5	40.4	40.1	39.8	39.2	39.1	42.3	42.3	40.7	39.8	39.6
Frenchman Reservoir	35.0	38.6	38.7	38.3	38.3	38.3	40.1	39.8	39.5	38.9	38.8	42.1	42.0	40.4	39.6	39.3
Alberta Forks Reservoir (Proposed)	34.0	36.5	36.4	36.2	36.1	36.1	37.8	37.5	37.3	36.7	36.6	39.5	39.5	38.0	37.3	37.1
FBIIP Reservoir (Proposed)	35.2	39.1	39.2	38.8	38.8	38.8	40.7	40.3	40.1	39.4	39.4	42.7	42.6	41.0	40.2	39.9

Table D-6.—Comparison of projected annual reservoir net evaporation (inches) for the five quadrant climate scenarios, compared with the historical reference (water years 1981-2015)

Name	Historical	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD	HD	HW	CT	WW	WD
		2020s					2050s					2080s				
Fresno Reservoir	22.1	24.8	22.7	24.3	23.4	24.8	26.2	23.6	25.3	23.2	25.4	28.2	25.4	25.8	23.8	25.4
Nelson Reservoir	24.0	26.4	25.4	25.9	25.7	26.8	28.2	26.1	27.1	25.2	27.1	30.1	27.6	27.5	25.7	27.4
Lake Bowdoin	23.9	26.1	25.2	25.6	25.3	26.5	27.8	25.8	26.8	24.9	26.8	29.7	27.2	27.2	25.4	27.0
Frenchman Reservoir	23.7	26.2	25.5	25.5	25.3	26.3	27.7	25.9	26.7	25.1	26.6	29.3	27.4	26.9	25.4	26.9
Alberta Forks Reservoir (Proposed)	21.3	21.5	19.0	19.4	19.5	20.2	22.7	19.2	21.0	19.5	20.6	24.1	21.3	21.1	19.2	21.5
FBIIP Reservoir (Proposed)	23.9	26.4	24.6	25.8	25.1	26.4	27.8	25.5	26.7	24.8	26.7	30.0	27.1	27.2	25.4	27.2

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Appendix E

Naturalized Flow Development

Naturalized flows were developed using a range of approaches. The first approach was developed by MT DNRC and was used to develop inflows for St. Mary and Milk Rivers planning model to support the 2012 Basins Study (Reclamation 2012a, 2012b), and these same approaches have been used to extend the naturalized flow records through 2015 or 2017 based on location. Another approach used to develop naturalized streamflows is based on USGS gaged streamflows. These locations are primarily tributary inflows to the Milk River. For these locations, estimated consumptive use, using the same methods described in the Water Demands Assessment section of the report, was added to the depleted gage records to arrive at naturalized streamflows. Table E-1 lists the sites with naturalized flows developed using these various approaches. A detailed description of the development of these naturalized flows can be found in Blythe et al. (2023).

Table E-1.—Summary of naturalized streamflow locations

Naturalized flow locations	Description	USGS ID (if applicable)	Location	Source of naturalized flow data
BCBMO	Beaver Creek (Bowdoin) at Mouth	06167500	Plains	USGS gage flows (natural)
BCHMO	Beaver Creek (Havre) at Mouth	06140000	Plains	calcd based on gage and estimated depletions
BGCMO	Buggy Creek at Mouth	06172200	Plains	calcd based on gage and estimated depletions
BSCMO	Big Sandy Creek at Mouth	06139500	Plains	calcd based on gage and estimated depletions
BTCIB	Battle Creek Inflow	06149500	Plains	MTDNRC (based on IJC naturalized flows)
CLCMO	Clear Creek at Mouth	06142400	Plains	calcd based on gage and estimated depletions
FRRIB	Frenchman River Inflow	06164000	Plains	MTDNRC (based on IJC naturalized flows)
LBCMO	Little Box Elder Creek at Mouth	06141600	Plains	calcd based on gage and estimated depletions
LDCIB	Lodge Creek	06145500	Plains	MTDNRC (based on IJC naturalized flows)
MRWIB	Milk River at Western Crossing	06133000	Lower Headwaters	MTDNRC (based on gage records and estimated depletions)
NFKMR	Upper North Fork Milk River Inflow	06133500	Lower Headwaters	MTDNRC (based on gage records and estimated depletions)
PCCMO	Porcupine Creek at Mouth	06175000	Plains	calcd based on gage and estimated depletions
PPCMO	People's Creek at Mouth	06154550	Plains	calcd based on gage and estimated depletions
RKCMO	Rock Creek at Mouth	06171000	Plains	calcd based on gage and estimated depletions
SMRBB	St. Mary River near Babb, MT	05017500	Upper Headwaters	MTDNRC (based on USGS and Reclamation data)
SWCSB	Swiftcurrent Creek at Sherburne, MT	05016000	Upper Headwaters	MTDNRC (based on USGS and Reclamation data)
WLCMO	Willow Creek near Glasgow, MT	06174000	Plains	USGS gage flows (natural)
WWCMO	Whitewater Creek at International Boundary	NA	Plains	calculated based on gage and estimated depletions

Appendix F

Paleo Event Scenario Development

Tree-ring-based reconstructions of past streamflow that pre-date gage-based records have been utilized in several Basin Studies, including the Colorado River Basin Water Supply and Demand Study (Reclamation 2012c) and the Missouri Headwaters Basin Study (Reclamation and MT DNRC 2021). These long streamflow records help to expand the timeframe over which water managers and decision makers can evaluate water supplies, short- and long-term variability, and potential changes in hydrology associated with changing climate conditions. Streamflow reconstructions also provide a robust long-term perspective from which to evaluate projected changes to future water supplies under various projected future climate scenarios.

In this Basins Study Update, tree rings were again utilized as proxy records for streamflow in an approach (paleohydrology) that takes advantage of the shared sensitivity of both annual streamflow and annual tree growth to yearly fluctuations in regional precipitation and temperature. With the oldest tree-ring records in the general region of the study area dating back to as early as 200 B.C.E., very long estimates of streamflow are possible for some rivers and gage locations that are particularly favorable for reconstruction. The northern Rockies region contains a broad network of tree-ring records that represent a variety of tree growth sensitivities to climate including high elevation trees that reflect high snow years as reduced width of annual growth rings and lower elevations trees that grow wider rings during years with more winter and spring precipitation (figure F-1). While reduced growth of rings of high elevation trees may seem counterintuitive in years with high snowpack, it is important to note that weather conditions leading to more snow also limit radiative energy to these trees (Coulthard et al. 2021). Greater snow cover also depresses spring air temperatures, delaying the onset of annual ring growth (Sergio et al. 2007). As a result, paleohydrologic records for the St. Mary and Milk rivers can be expected to reflect streamflow variability resulting from a diversity of hydrologically important climate factors.

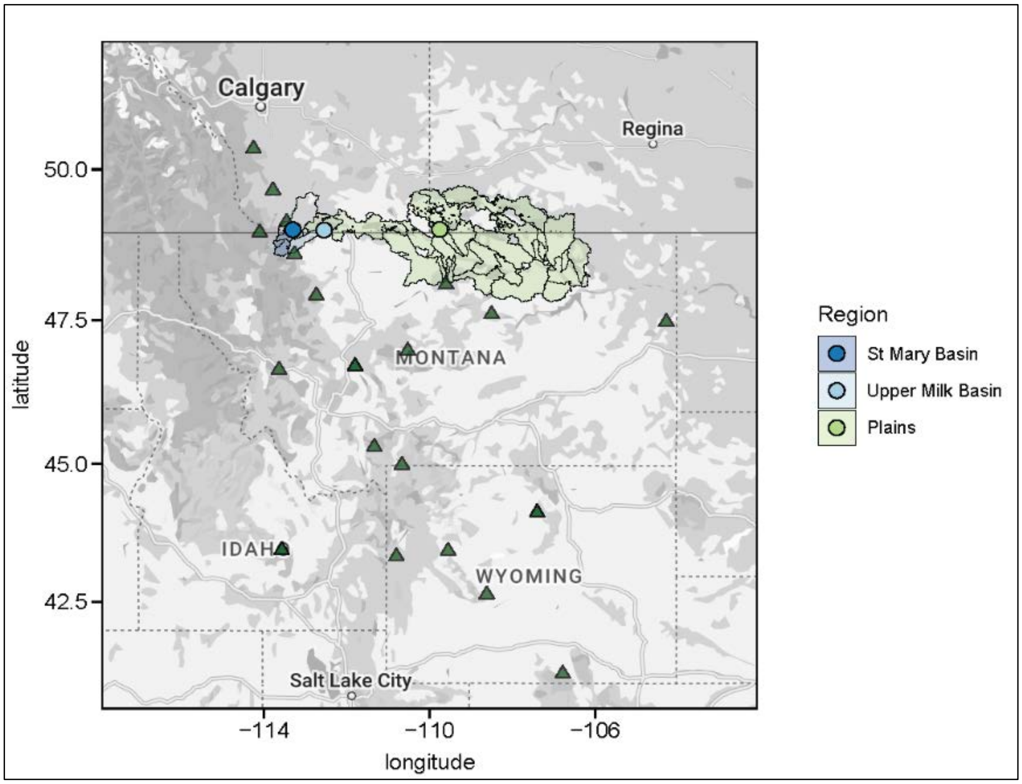

Figure F-1.—Map of the study area showing the eight gage locations (points) with streamflow reconstructed, the HUC 8 watersheds within the St. Mary and Milk basins, and the tree-ring network used to reconstruct water-year streamflow (green triangles).

For this Basins Study Update, scientists at USGS developed reconstructions of water-year (October 1–September 30) streamflow for eight gaging locations across the study area (see figure F-1; Martin and Pederson 2022). Three of the reconstructed gage records are in the St. Mary River basin and five in the Milk River basin. In general, the methodology used to develop the streamflow reconstructions for this Basins Study Update was the same as that used for the Missouri Headwaters Basin Study, the details of which are described in Martin et al. (2019). For gaging locations in the St. Mary and upper portion of the Milk River basins these records have the potential to extend estimates of water-year streamflow close to 1000 years, though it should be noted that error in the records increases with time due to the decreasing number trees within a chronology and the overall number of sites represented in the tree-ring network. For gaging locations in the lower Milk River basin, the reconstructions extend back to the 16th and 18th centuries C.E. To simplify the integration of streamflow reconstructions into Reclamation's modeling exercises, this network of records was reduced to three key gaging locations within the most hydrologically distinct regions of the study area. This simplified network of locations is represented by the St. Mary River at the International Boundary gage (USGS ID 05020500), the Milk River at Western Crossing (USGS ID 06133000), and Lodge Creek at International Boundary (USGS ID 06145500). These locations correspondingly reflect streamflow contributions in the mountain headwaters of St. Mary River basin, the foothills contributions to the mainstem Milk River, and the contributions of the Canadian prairie basins to the lower Milk River.

Figure F-2, figure F-3, and figure F-4 show the reconstructed streamflow time series for the simplified gage network. In each figure, the top panel shows the reconstructed flows over the calibration period for each site and the bottom panel shows the full reconstruction with the naturalized flow record overlaid. Along with reconstruction statistics provided in table F-1, the figures give a sense of how well tree-rings capture the interannual to decadal variability in the naturalized streamflow records -a 20-year spline shown on figure F-2, figure F-3, and figure F-4. The observed naturalized flows shown along with the reconstructions are the same datasets used for the historical record and hydrologic model calibration, validation, and bias-correction. The difference in timescales shown from site to site reflects the increasing length of the reconstructions moving east to west, and higher into the headwaters of the study area.

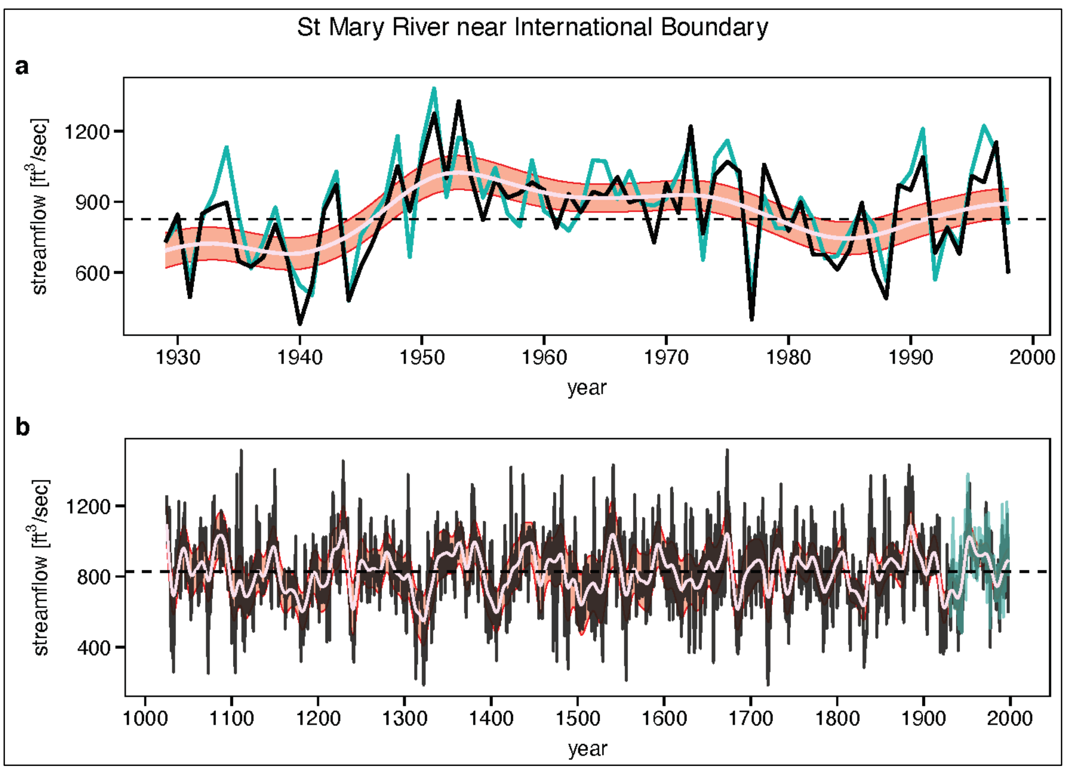

Figure F-2.—Streamflow reconstruction for the St. Mary River at the International Boundary showing a. the observed naturalized flow record and reconstructed records over their common period and, b. the full reconstruction.

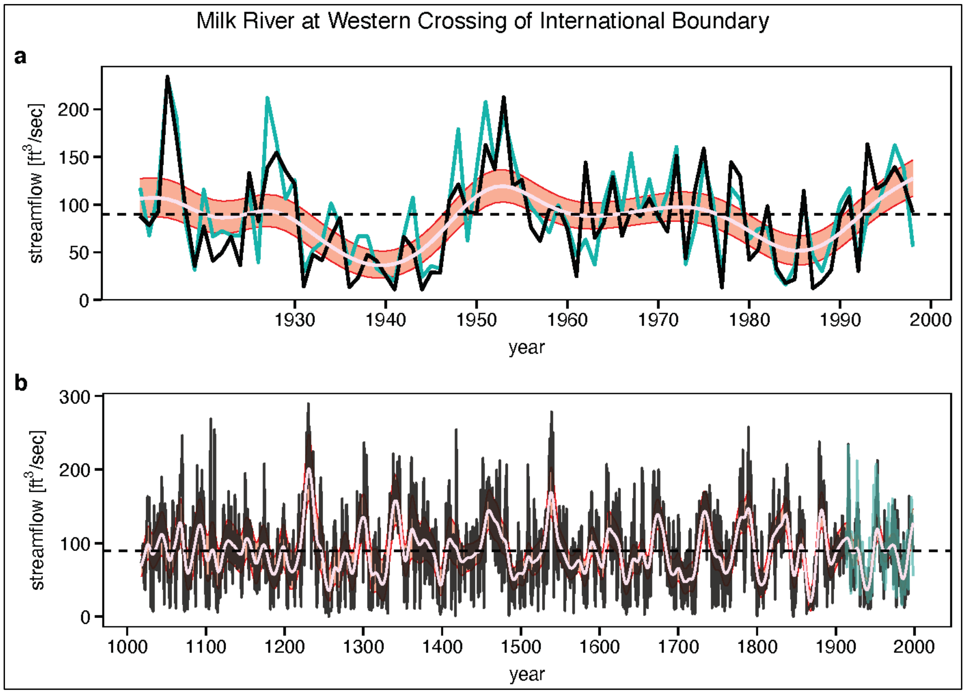

Figure F-3.—Streamflow reconstruction for the Milk River at the Western Crossing showing: a. the observed and reconstructed records over the common period and, b. the full reconstruction.

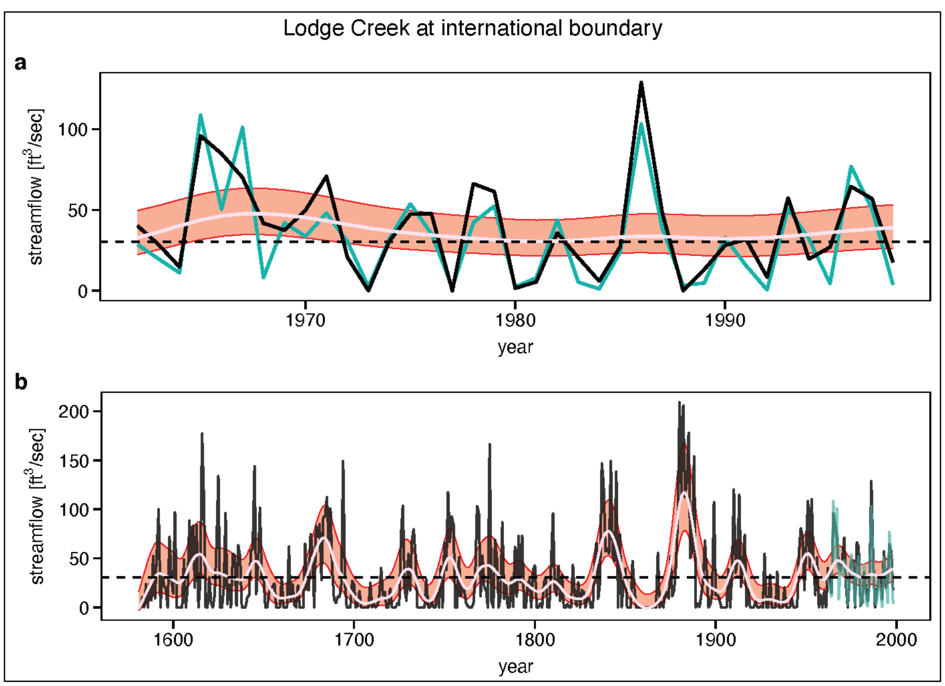

Figure F-4.—Streamflow reconstruction for Lodge Creek at the International Boundary showing: a. the observed and reconstructed records over the common period and, b. the full reconstruction.

Table F-1.—Streamflow reconstruction calibration and cross-validation statistics

Gage	VRSQ[1]	CRSQ[2]	RE[3]	CE[4]	Start Year	Region
Milk River at Western Crossing	0.62	0.68	0.32	0.28	1018	Upper Milk Basin
St. Mary River near International Boundary	0.64	0.71	0.13	0.11	1026	St. Mary Basin
Lodge Creek at international boundary	0.54	0.68	-	-	1581	Plains

1. VRSQ – verification R^2
2. CRSQ – calibration R2
3. RE – reduction of error statistic
4. CE – coefficient of efficiency

A primary feature of interest in the paleohydrologic records examined here was the occurrence of drought events in the past that exceed those during the instrumental era. This is because evidence of drought conditions that exceed those previously experienced by water managers in the basin suggests the potential for low water supply stresses on infrastructure and operating protocols that are outside the envelope of experience for both water managers and end users. In comparing droughts of the past to those evident in the naturalized flow records, we first defined a drought event as:

> "An event beginning with (and including) two or more consecutive years of streamflow below the median flow level that is ended only by (and excluding) two or more consecutive years of streamflow above the median flow level and may include one or more individual wet years within the drought only when bounded on both sides by dry years."

This definition, depicted in figure F-5 using the Dustbowl drought on the Milk River as an example, is the same used for Reclamation's 2021West-Wide Climate and Hydrology Assessment and very similar to that used in the recent Missouri Basin Impacts Assessment (Reclamation 2019) and Missouri Headwaters Basins Study (Reclamation and MT DNRC 2021).

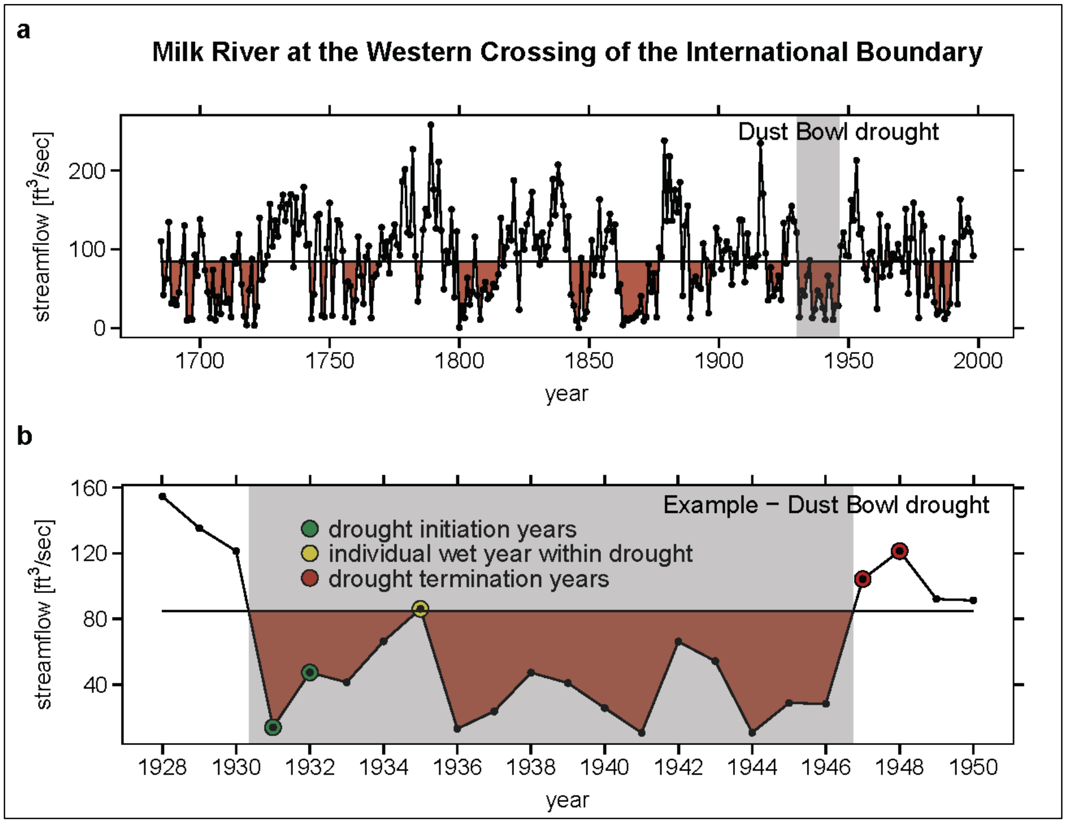

Figure F-5.—Graphical representation of a drought as defined in this study.

To provide a temporally consistent assessment of past droughts across the basin, we examined the long-term history of drought on the St. Mary and Milk Rivers from water years 1581 through 1998, the period common to all three streamflow reconstructions in the simplified gage network. However, for incorporation into the St. Mary and Milk Rivers planning model scenarios, statistical characteristics and annual flow estimates from the full reconstructions were utilized.

Droughts are commonly compared based on their duration and severity, with severity quantified as either the avg or cumulative streamflow deficit over the period of the drought. Here all three metrics of drought are presented simultaneously to understand how recent droughts compare to those of the more distant past in multiple ways. Figure F-6, figure F-7, and figure F-8 depict the largest drought of the 20th century at each gaging location (blue fill) relative to the 3 largest droughts in the prior centuries (red, orange and yellow fill) in terms of cumulative deficits.

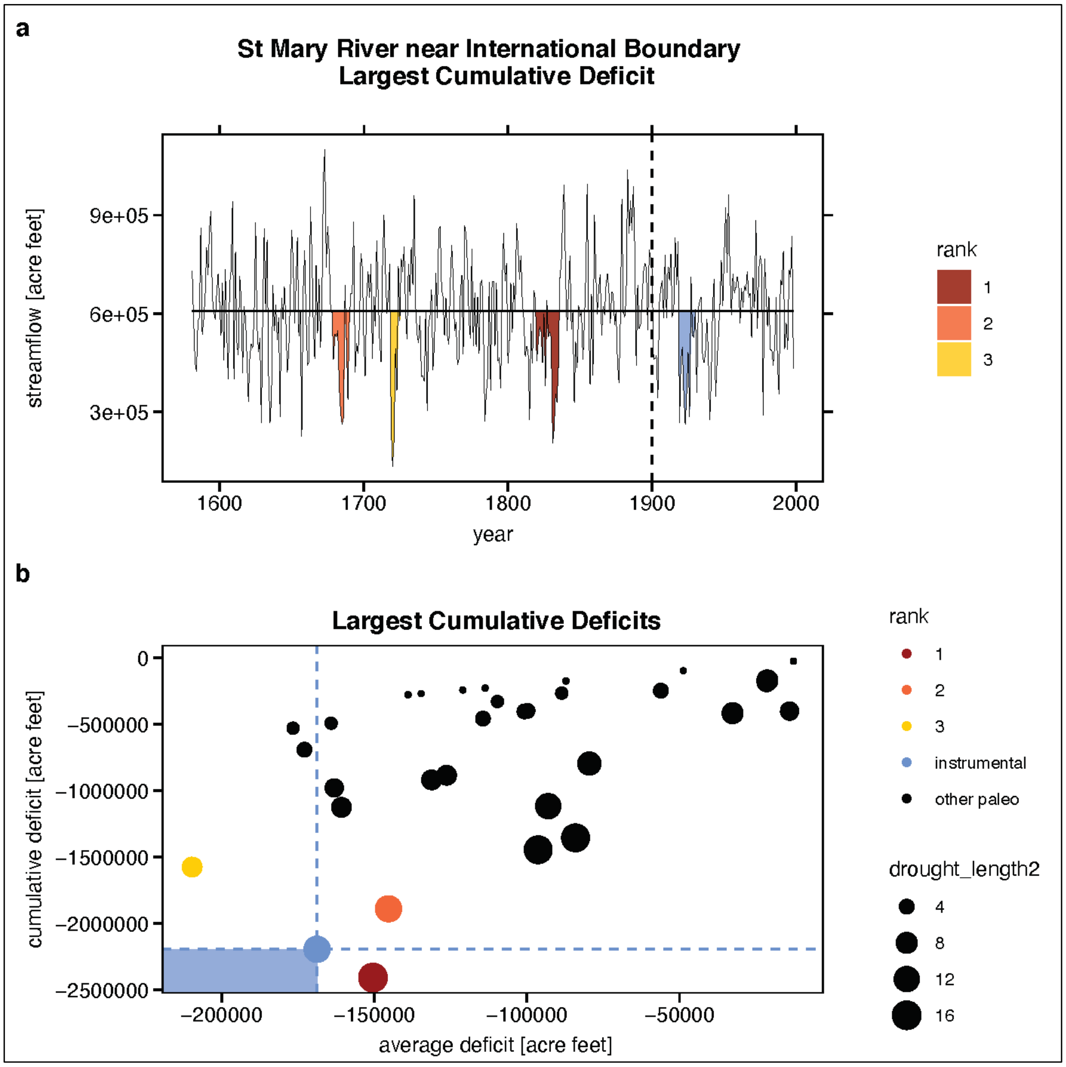

Figure F-6.—Comparison of the largest paleo and 20th century droughts on the St. Mary River ranked on cumulative deficits over time (top) and relative to average annual deficits and event lengths (bottom).

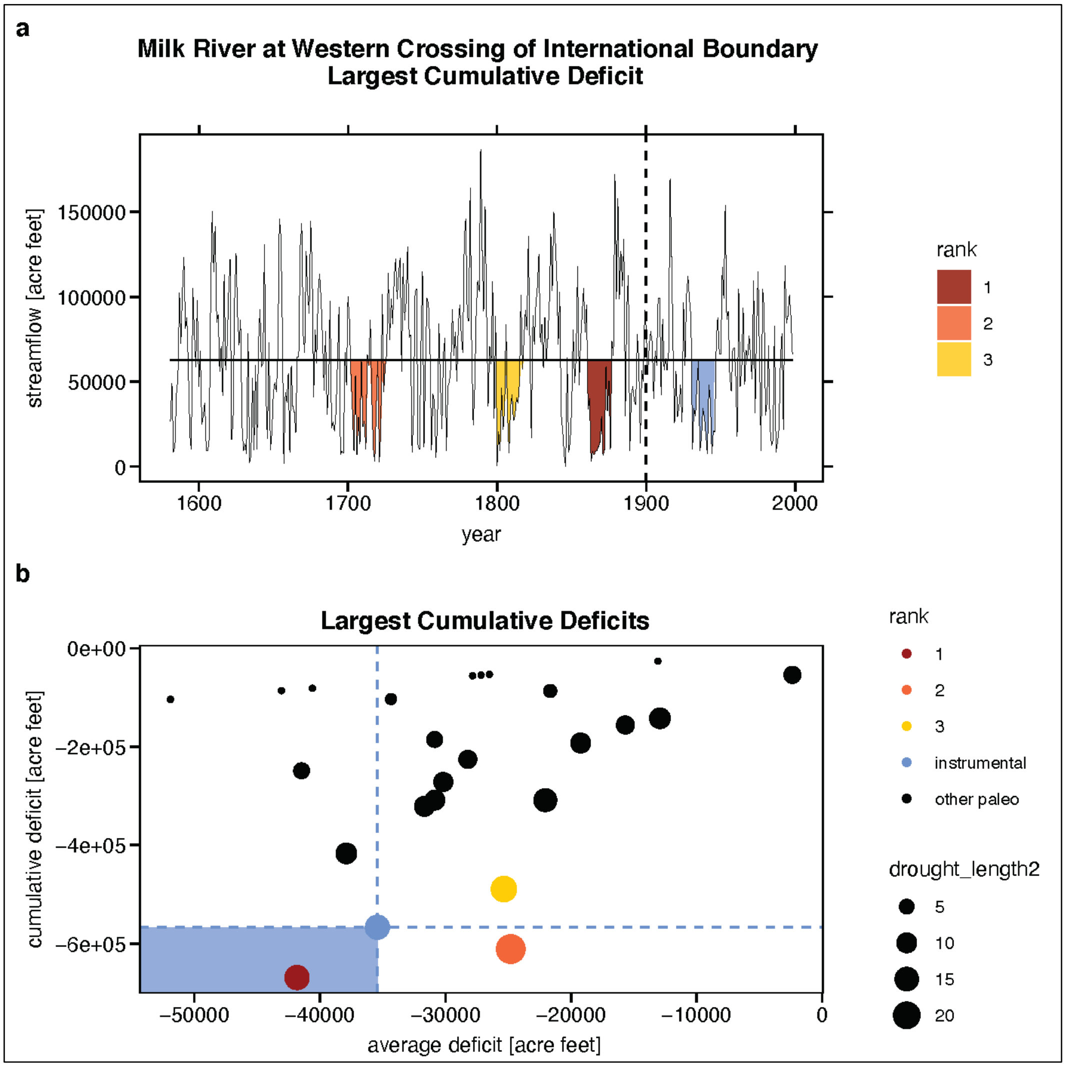

Figure F-7.—Comparison of the largest paleo and 20th century droughts on the Milk River ranked on cumulative deficits over time (top) and relative to average annual deficits and event lengths (bottom).

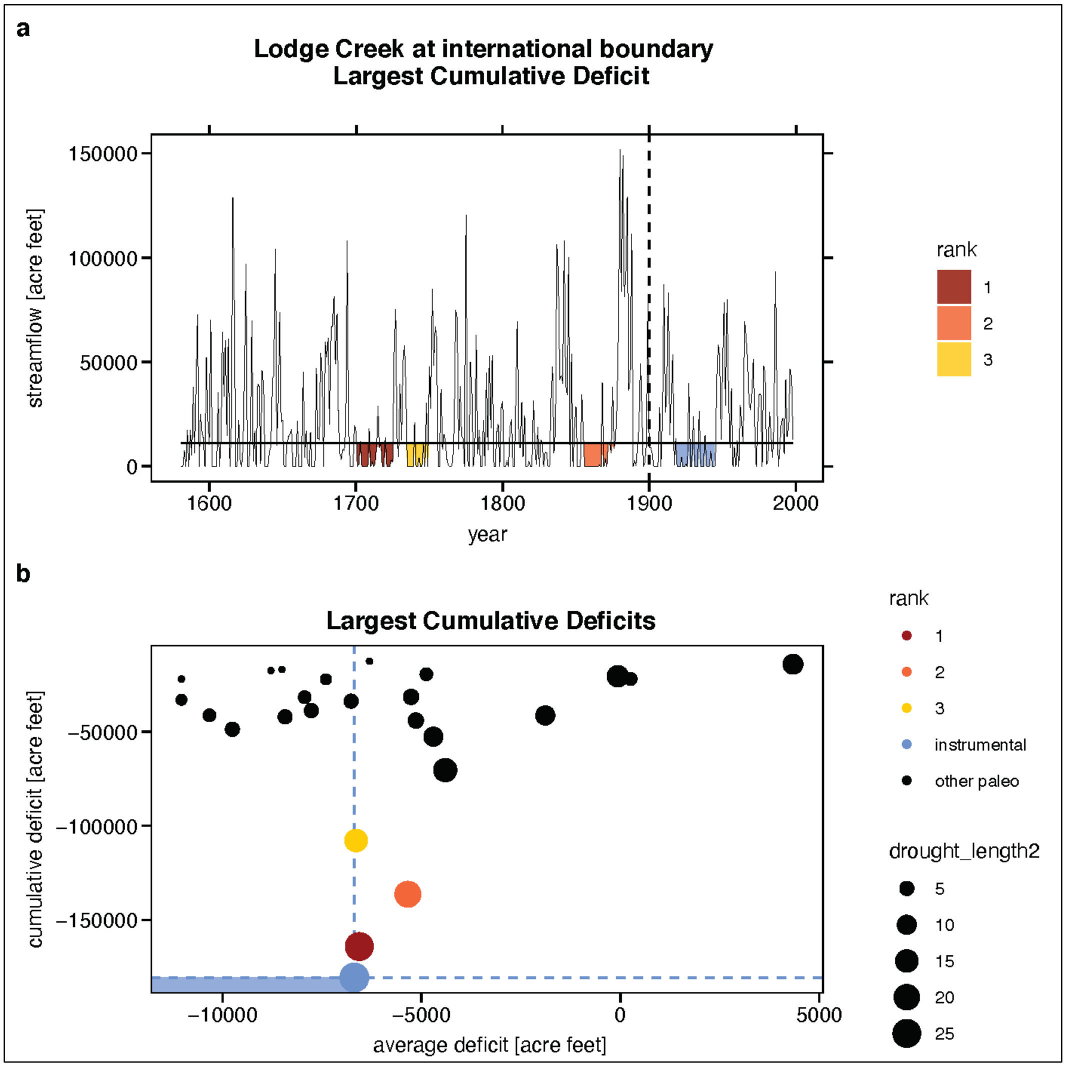

Figure F-8.—Comparison of the largest paleo and 20th century droughts on Lodge Creek ranked on cumulative deficits over time (top) and relative to average annual deficits and event lengths (bottom).

In all cases, the largest drought observed during the 20th century is the Dustbowl drought centered on the 1930s while the timing of the most severe earlier droughts is more variable across the study area. It is apparent from the top panels on figure F-6, figure F-7, and figure F-8 that droughts of greater length and reaching lower annual flow levels than droughts of the 20th century have in some cases occurred prior to 1900. However, the bottom figure panels allow comparison of these events in greater detail by plotting each event in the space of the event cumulative deficit vs the event avg deficit. In this way, it is evident that several droughts of the more distant past exceed those of the 20th century in terms of cumulative or avg deficits, however, only once during the late 1800's on the Milk River at the Western Crossing, did an earlier drought exceed the Dustbowl era drought in terms of both metrics (blue shaded quadrant, see figure F-7, lower panel). At both Lodge Creek and on the St. Mary, the Dustbowl drought was the most severe drought since the late 1500s when assessed in terms of both cumulative and avg deficits. In fact, at Lodge Creek, the Dustbowl drought also exceeded all others in terms of duration, whereas further west in the basin, one to several earlier droughts were longer than the dustbowl drought.

Taken together, it is evident that the Dustbowl drought of the 1930s was probably the most severe and long-duration drought in the region since the late 1500s. In fact, where a longer estimate of drought variability is available from year 1026 on in the St. Mary and upper Milk only a single additional drought event in the early 1300s exceeds the Dustbowl era droughts in terms of combined cumulative and avg severity. As such, the water resource challenges experienced by St. Mary and Milk River water users during the Dustbowl drought likely represent some of the most challenging water supply conditions to be expected from natural climate variability -- based on the tree-ring records of streamflow in the region.

It is also evident from figure F-6, figure F-7, and figure F-8 that as droughts become longer in duration, cumulative deficits consistently increase but over longer duration events avg deficits tend to converge on a relatively narrow range of annual flow deficits. For the St. Mary, Milk, and Lodge Creek drought records, the avg annual flow deficits across the four largest droughts on record are: 168,522; 31,848; and 6,311 AF; respectively. At all three gaging locations, avg annual flow deficits for all 4 major droughts fall within 1.5 standard deviations of their averages. This observation, based on long-term estimates, suggests that in times of extended drought, while individual years may be unusually dry or even wet, water users can expect a relatively similar level of annual water deficits to those described above on an overall event-averaged basis. On the other hand, the largest avg annual deficits evident in the long-term records are generally associated with shorter duration droughts. For water users most directly affected by severe shortages within a single year, rather than the cumulative shortages of a many consecutive drought years, shorter duration drought events may frequently prove more problematic.

The managed river system of the St. Mary and Milk Rivers are most impacted by single annual drought events due to the limited carryover storage of water from one year to the next. Therefore, periods with the largest avg annual deficit were simulated by the river system model to evaluate implications of such droughts reoccurring under current operating policies. These simulations and results are discussed in the Risk Assessment section of the full report.

The LAD drought events are a listed in table F-2. Those droughts with a rank of one are the largest identified droughts in the paleo period, while those with rank 3 are the third largest droughts. The largest droughts in the recent historical period over approximately the last 100 years were also identified are shaded blue. Lastly, major notable droughts of recent memory in the study area are also listed. These notable droughts are not formally defined by the same drought definition; instead, they reflect droughts of interest to the study partners and stakeholder community.

Table F-2.—Summary of paleo drought events

Location	Event	Rank	Year start	Year end	Length
St. Mary River near International Boundary	largest avg annual deficit	1	1719	1725	7
Lodge Creek at International Boundary	largest avg annual deficit	1	1807	1808	2
Milk River at Western Crossing	largest avg annual deficit	1	1747	1748	2
St. Mary River near International Boundary	largest avg annual deficit	2	1793	1795	3
Lodge Creek at International Boundary	largest avg annual deficit	2	1801	1804	4
Milk River at Western Crossing	largest avg annual deficit	2	1602	1607	6
Milk River at Western Crossing	largest avg annual deficit	3	1622	1623	2
St. Mary River near International Boundary	largest avg annual deficit	3	1783	1788	6
Lodge Creek at International Boundary	largest avg annual deficit	3	1651	1652	2
Lodge Creek at International Boundary	largest instrumental avg annual deficit		1988	1989	2
St. Mary River near International Boundary	largest instrumental avg annual deficit		1901	1904	4
Milk River at Western Crossing	largest instrumental avg annual deficit		1931	1946	16
Study Area	historical drought 1		1996	2009	14
Study Area	historical drought 2		1928	1936	9

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Appendix G

Re-sequenced Paleo Event Scenario Development

As part of the Basins Study Update, the study team developed additional paleo scenarios that rely on statistics of water year annual streamflow reconstructions described in "Appendix F Paleo Event Scenario Development." More specifically, these scenarios termed re-sequenced paleo-informed are based on computed probabilities of transitioning from a wet to dry state or dry to wet state. The purpose of these scenarios is to investigate whether more substantial droughts are possible based on the statistics of the paleo record. The approach for developing re-sequenced paleo-informed streamflow scenarios follows the algorithm described in Prairie et al. (2008). The Prairie et al. (2008) algorithm is a conditional Markov Chain (MC; Haan 2002) simulation framework that uses time varying transition probabilities and nonparametric K-nearest neighbor (K-NN) resampling to develop inflow sequences. In summary, this framework consists of three steps:

- developing time varying transition probabilities (with smoothing) to model hydrologic states (say, *S*; e.g., wet or dry) from the paleo-reconstructed streamflow;

- generating a hydrologic state to initialize along with the selection of the transient transition probabilities for use in MC simulation; and (3) MC simulation to generate flows conditionally using K-NN resampling.

Figure G-1 presents the steps of the algorithm. See Prairie et al. (2008) for the complete description of this resampling framework referred to as the nonparametric paleo-conditioning (NPC). Here, the steps of the algorithm are illustrated for the St. Mary River and Milk River basins using the water year annual reconstructed streamflow (see below) historical natural streamflow (period of record, 1980–2015; 36 years), and simulated future streamflow for the St. Mary River at the International Boundary gage (USGS ID 05020500), the Milk River at Western Crossing (USGS ID 06133000), and Lodge Creek at the International Boundary (USGS ID 06145500).

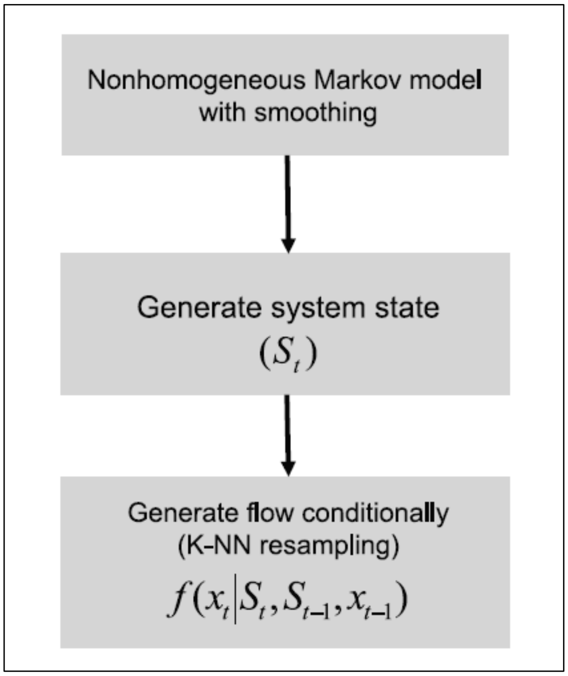

Figure G-1.—Nonparametric paleo-conditioning modeling framework; (Source: Prairie et al. 2008).[1]

To calculate the transient transition probabilities using the paleo reconstructed streamflow, the first operation is to convert the paleohydrology magnitudes into state (wet or dry) information. Streamflow is first normalized using the long-term median. For this work, the common period, years 1581–1999 were used for the St. Mary River at the International Boundary, the Milk River at Western Crossing, and Lodge Creek at International Boundary. Standardized streamflow values greater than zero ($Q > 0$) were assigned to state wet (represented by 1), and standardized values less than and equal to zero ($Q \leq 0$) were assigned to state dry (represented by 0). This transforms the original streamflow time-series into a time-series consisting of either 0 or 1, (i.e., a binary time-series). This two-state (either dry [0] or wet [1]) hydrologic system results in four state transitions – (i) dry to dry (DD); (ii) dry to wet (DW); (iii) wet to dry (WD); and (iv) wet to wet (WW). Figure G-2, figure G-3, and figure G-4 show the transient transition probabilities derived from the streamflow data for each location.

Derivation of the transient transition probabilities was done using the concept of a moving window, where the width of this window was optimally estimated through least squares cross-validation procedure (Scott 2015). The estimation of the transition probability at any given time centered on the optimal window is a weighted avg of the state transitions within this optimal window width. Prairie et al. (2008) used the discrete quadratic kernel function developed by Rajagopalan and Lall (1995) as the weighting function. The optimal window width here was

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[1] Where, S_t *is system state* (dry [0] or wet [1]) at time (t); S_{t-1} *is* system state at time *t-1*; x_t *is inflow* magnitude at time t; x_{t-1} is inflow magnitude at time *t-1*.

estimated for each transition state (i.e., DD, DW, WD, WW) for the Milk River at Western Crossing, St. Mary River near International Boundary, and Lodge Creek at International Boundary using the least squares cross-validation criterion (table G-1).

Table G-1.—Optimal window length (years) based on least squares cross-validation score; years used in resampling, 1981-2016

Basin name	Basin ID	State Transition (D - dry; W - wet)			
		DD	DW	WD	WW
Milk River at Western Crossing	MRWIB	29	16	13	65
St. Mary River near International Boundary	SMRIB	33	59	17	31
Lodge Creek at International Boundary	LDCIB	47	64	52	13

Thus, the transient transition probabilities shown on figure G-2, figure G-3, and figure G-4 broadly represent dry or wet transitions over the periods 1646 to 1934 (289 years), 1640–1940 (301 years), and 1645–1935 (291 years), respectively.

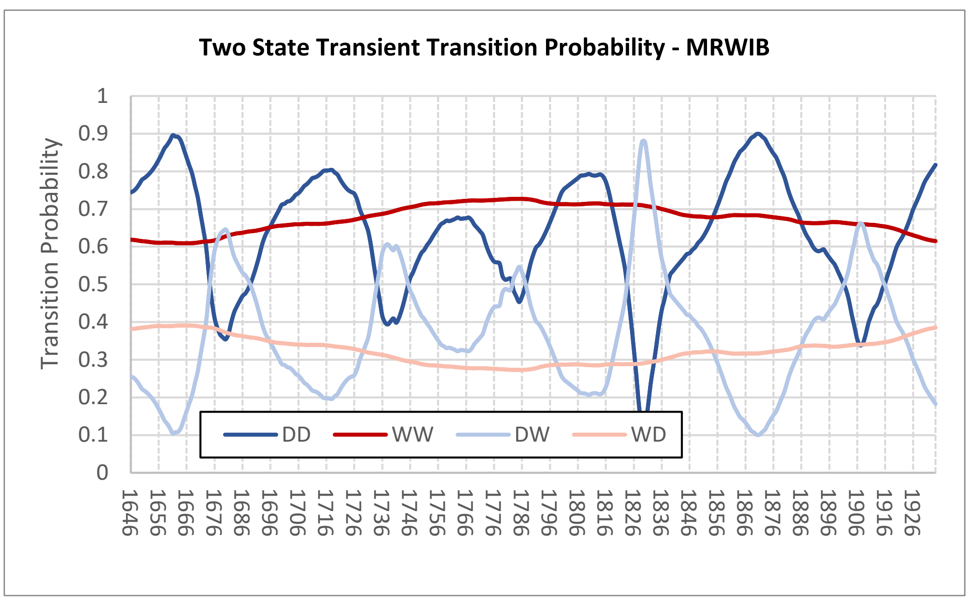

Figure G-2.—Two state transient transition probability with four transitions—DD; DW; WD; and WW, derived from Milk River at Western Crossing (USGS ID 06133000) streamflow.

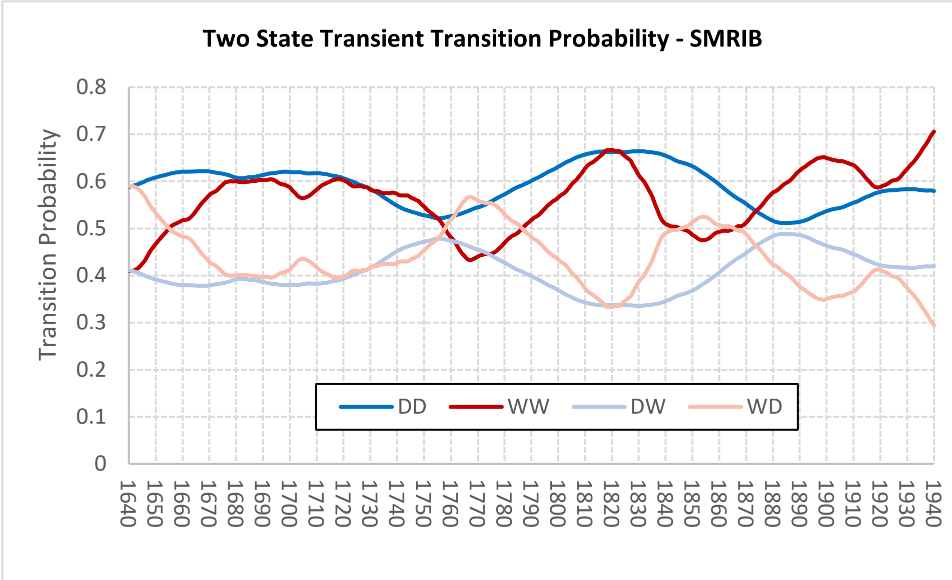

Figure G-3.—Two state transient transition probability with four transitions—DD; DW; WD; and WW, derived from St. Mary River near International Boundary (USGS ID 05020500) streamflow.

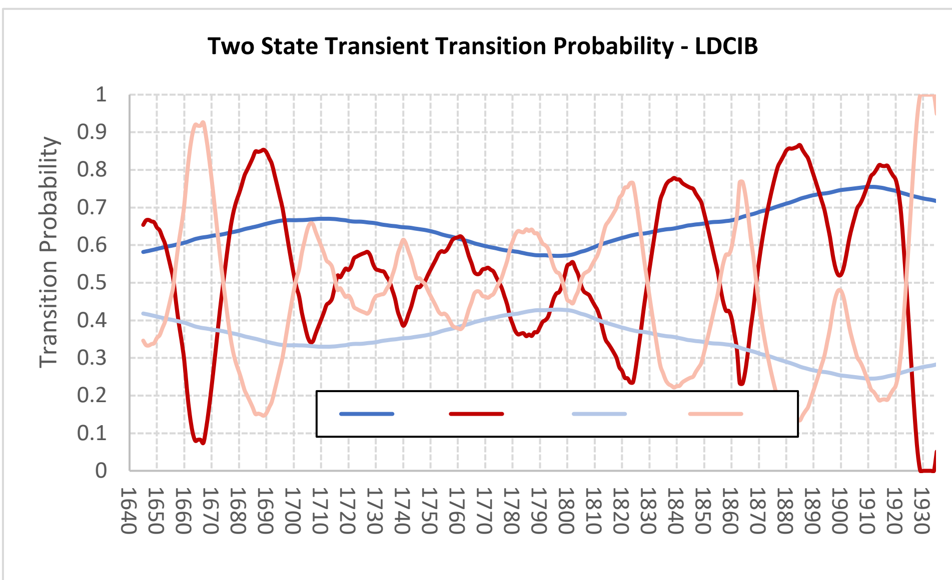

Figure G-4.—Two state transient transition probability with four transitions—DD; DW; WD; and WW, derived from Lodge Creek at International Boundary (USGS ID 06144500) streamflow.

To start the simulation, a simulation horizon of *T* years first needs to be selected. In this case, *T*=36 years was used. This length of years corresponds to the length of the historical period used: 1980 -2015; 36 years. This 36-year time window is then randomly selected starting at any point within the annual paleo reconstructed flow records over which the transition probabilities were developed. Starting with a randomly selected dry or wet year, the transition probabilities over this 36-year window can be used to develop subsequent states of the hydrologic system. Note that, until now, all calculations involved information derived only from the naturalized streamflow time-series data.

In the next part of the calculation, the respective historical natural streamflows at St. Mary River at the International Boundary, the Milk River at Western Crossing, and Lodge Creek at the International Boundary were used. The median streamflows over the historical reference period (1981–2015) for St. Mary River at the International Boundary, the Milk River at Western Crossing, and Lodge Creek at the International Boundary were 817 cfs, 66 cfs, and 13 cfs, respectively. For a given location, a historical year was assigned to be either dry (state represented by 0) if the magnitude of streamflow for the year was less than the median streamflow value, or wet (state represented by 1) if the magnitude of streamflow for the year was equal to or greater than the median streamflow value. This step then results in a binary time-series depicting streamflow at these three locations. Recall, a two-state (dry or wet) hydrologic system results in four state-transitions: DD; DW; WD, and WW. Thus, each year in the historical period can be assigned to one of the four state transition categories (bins labeled say, DD; DW; WD; and WW). As an example, for St. Mary River at the international boundary, the streamflow in year 1991 was 1,214 cfs. This streamflow magnitude is greater than the median inflow value of 817 cfs, and hence 1991 was a wet year. In the following year, 1992, the inflow was 570 cfs, which is less than the median inflow, hence 1992 was a dry year. Thus 1992 was assigned to category WD.

Informed by the states generated from the transient transition probabilities in conjunction with the flow magnitudes, the feature vector [S_t, S_{t-1}, x_{t-1}] was determined. Where S_t is system state (dry [0] or wet [1]) at time (t); S_{t-1} is system state at time ($t-1$); and x_{t-1} is inflow magnitude at time ($t-1$). Again, the state vector [S_t, S_{t-1}] contained in the feature vector is derived using the transition probabilities. Next, a K-NN resampling was done to obtain the set of K neighbors (years) from the historical years that matched the feature vector. The neighbor selection in the NPC methodology is unique because the feature vector combines discrete state and continuous variables (streamflow magnitude) which in general is numerically a large value. This disparity in streamflow magnitude needs to be considered in the neighbor selection process; otherwise, the state information will not influence the neighbor choice (Prairie et al. 2008). The K neighbors are weighted using an exponential decay type weighting function where the most similar neighbor has the highest weight, and subsequent neighbors have progressively lower weights. A neighbor (year) is then randomly selected from the set of K neighbors. The year following this selected year corresponds to the final year selection (year t). The streamflow corresponding to this final year selection is the magnitude x_t.

This process was repeated 1,000 times, (i.e., 1,000 randomly selected starting points were used to traverse the transient transition probabilities). These transition probabilities in conjunction with the streamflow data were used in the K-NN resampling process described above to select the sequence of years and subsequently their corresponding inflows. Each generated streamflow sequence was 35 years long, resulting in an ensemble of 1,000 realizations each 35 years long.

This procedure was first performed using the historical natural streamflow and then repeated for each of the five projected future climate scenarios, WW, WD, HW, HD, and CT, in each of the three future periods: 2020s, 2050s, and 2080s. This resulted in 15 ensembles each with 1,000 realizations of 35-year lengths. To provide a smaller subset of realizations, one scenario in the 95th percentile for cumulative deficit and one realization within the 95th percentile avg annual deficit for each of the three paleo locations were selected for each of the future periods within each of the five climate scenarios, resulting in a total of 96 realizations.

Paleo Resequenced Demand Scenarios

Water demands over the paleo period are unknown, so an approach was developed to select demands for years that correspond with paleo-resequenced future streamflow scenarios. To determine paleo-resequenced future scenarios, years for the corresponding future scenario were reshuffled based on the transition probabilities derived from the paleo-reconstructed streamflow record. Since the projected future climate scenarios are perturbations of the historical reference simulation period (albeit climate-adjusted timeseries associated with historical dates), water demands from the same re-sequenced years may be used to correspond with the re-sequenced streamflows.

Paleo-resequenced future scenarios (demand and streamflow) were evaluated through the St. Mary and Milk Rivers planning model but it was determined that the range of droughts characterized in this dataset were within the range of paleo drought events identified in the paleo record alone. Therefore, results from these simulations are not summarized here.

References

Prairie, J., K. Nowak, B. Rajagopalan, U. Lall, and T. Fulp. (2008). A stochastic nonparametric approach for streamflow generation combining observational and paleoreconstructed data. Water Resources Research, 44(6), 1 - 11. https://doi.org/10.1029/2007WR006684.

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Appendix H

St. Mary and Milk Rivers Planning Model Inputs

The St. Mary and Milk Rivers planning model requires numerous inputs. The natural streamflow inputs (simulated in this study using the DCAHM modeling framework described in the Water Supply Assessment section) are summarized in table H-1. Some inflow points directly result from the DCAHM framework simulations (indicated as Calibration Locations), while other locations were derived from calibration locations via mass balance (Non-calibration Locations). Further, table H-2 summarizes mass balance computations used to arrive at inflows for the "non-calibration" locations. Table H-3 shows changes required to the St. Mary and Milk River's planning model to represent each modelled adaptation strategy.

Table H-1.—Summary of all St. Mary and Milk Rivers planning model inflow locations

St. Mary and Milk Rivers planning model inflow locations	Description	USGS ID (if applicable)	Calibration locations	Non-calibration locations
BCBMO	Beaver_Creek_Bowdoin_Inflow.Inflow	06167500		
BCHMO	Beaver_Creek_Havre_Inflow.Inflow	06140000		
BGCMO	Buggy_Creek_Inflow.Inflow	06172200		
BSCMO	Big_Sandy_Creek_Inflow.Inflow	06139500		
BTCIB	Battle_Creek_Inflow.Inflow	06149500		
CLCMO	Clear_Creek_Inflow.Inflow	06142400		
FRRIB	Frenchman_River_Inflow.Inflow	06164000		
LBCMO	Little_Boxelder_Creek_Inflow.Inflow	06141600		
LDCIB	Lodge_Creek.Inflow	06145500		
LPCKI	Little_Peoples_Creek_Inflow.Inflow			
LSMRI	LowerStMaryLake_Inflow.Inflow			
MREBG	Milk_River_in_Alberta_Flow_Gain.Inflow			
MRWIB	South_Milk_River_Inflow.Inflow	06133000		
NFKMR	Upper_North_Milk_River_Inflow.Inflow	06133500		
PCCMO	Porcupine_Creek_Inflow.Inflow	06175000		
PPCKI	Peoples_Creek_Inflow.Inflow			
RKCMO	Rock_Creek_Inflow.Inflow	06171000		
SMRBG	StMaryRiverIB_Inflow.Inflow			
SWCSB	SherburneReservoir_Inflow.Inflow	05016000		
WLCMO	Willow_Creek_Inflow.Inflow	06174000		
WWCMO	Whitewater_River_Inflow.Inflow	NA		

Table H-2.—Non-calibration locations to be used to compute St. Mary and Milk Rivers planning model inflow inputs

Non-calibration basins	St. Mary and Milk Rivers planning model description	USGS ID (if applicable)	Method for calculation
MREIB	Milk River at Eastern Crossing	06135000	Computed using local polynomial regression between (MRWIB+NFKMR) and MREIB naturalized flow datasets over common time period (1959–1986). Regression equation applied to simulated streamflow at MRWIB+NFKMR (both basins were calibrated) to predict streamflow at MREIB; same equation used to predict historical and future scenario streamflow at MREIB – assuming relationship between (MRWIB+NFKMR) and MREIB is stationary
SMRIB	St Mary River at International Boundary	05020500	Simulated using season definitions and parameters for SWCSB
LSMRI	LowerStMaryLake Inflow	NA	Computed as SMRBB-SWCSB; any negative values were set to zero
SMRBG	StMaryRiverIB Inflow	05020500	Calibrated SMRBB and computed SMRIB by regression; calculated SMRBG as SMRIB-SMRBB; any negative values were set to zero
MREBG	Milk In Alberta Flow Gain	06135000	Using predicted MREIB (see above), computed as MREIB-(MRWIB+NFKMR)
PPCKI	Peoples Creek Inflow	06154550	calculated as PPCMO*0.80
LPCKI	Little Peoples Creek Inflow	06154550	calculated as PPCMO*0.20

Table H-3.—Summary of St. Mary and Milk Rivers planning model changes for each strategy*

	Annual Accounting	On Farm Efficiency	Fresno Dam Raise						Duck Creek Canal	Nelson Pumps		Dodson Canal		People's Creek Reservoir	FBIIP Reservoir	Irrigated Acreage					Blackfeet Diversion	St. Mary Canal
Strategy abbreviation	Annual Accounting.Balancing Switch	Avg Irrigation District Efficiencies.Irrigation Efficiency Improvement	Fresno Data.Dam Raise Switch	Fresno Data.Fresno Raise	Fresno Data.Fresno Spring Target	Fresno Data.October Target	Fresno Data.Top of Joint Use	Fresno Reservoir.Unreg Flow 2 Failure Elevation	Duck Creek Canal Data.Canal Switch	Nelson Pump Diversion.Nelson Pump Switch	Nelson Pump Diversion.Max Diversion	Dodson Nelson Data.Malta South Canal Max	Malta South Diversion.Max Diversion	Run Controls.Peoples Creek Reservoir Switch	FBIIP Accounting.FBIIP Reservoir ON OFF Switch	Run Controls.AnnualAreas.Fort Belknap Reservation Irrigation Project_Milk River Unit (Timeseries)	Run Controls.AnnualAreas.Fort Belknap Reservation Irrigation Project_White Bear Unit (Timeseries)	Run Controls.AnnualAreas.Peoples Creek Irrigation Project (Timeseries)	Run Controls.AnnualAreas.Little Peoples Creek Irrigation (Timeseries)	Run Controls.AnnualAreas.FBIC Beaver Cr Irrigation (Timeseries)	SaintMaryRiver.Blackfeet Diversion Switch	StMaryRiverComp.St. Mary Canal Monthly Max Capacities (Periodic)
Baseline	26	0	0	0	60000	42000	2575	2575	0	0	6	500	500	0	0	2845	559	0	0	0	0	600/550
OnFarmEff	26	0.05	0	0	60000	42000	2575	2575	0	0	6	500	500	0	0	2845	559	0	0	0	0	600/550
Canal850	26	0	0	0	60000	42000	2575	2575	0	0	6	500	500	0	0	2845	559	0	0	0	0	850/800
Fresno3	26	0	1	3	80000	62000	2578	2578	0	0	6	500	500	0	0	2845	559	0	0	0	0	600/550
Annual IJC Balancing	1	0	0	0	60000	42000	2575	2575	0	0	6	500	500	0	0	2845	559	0	0	0	0	600/550
St. Mary Canal failure	26	0	0	0	60000	42000	2575	2575	0	0	6	500	500	0	0	2845	559	0	0	0	0	0
Blackfeet5KAF	26	0	0	0	60000	42000	2575	2575	0	0	6	500	500	0	0	2845	559	0	0	0	1	600/550
FBIIPRes	26	0	0	0	60000	42000	2575	2575	0	0	6	500	500	1	1	5000	5425	1107	2194	1239	0	600/550
MaxDodson700	26	0	0	0	60000	42000	2575	2575	0	0	6	700	700	1	1	5000	5425	1107	2194	1239	0	600/550
Nelson50	26	0	0	0	60000	42000	2575	2575	0	1	50	500	500	1	1	5000	5425	1107	2194	1239	0	600/550
Duck200	26	0	0	0	60000	42000	2575	2575	1	0	6	500	500	1	1	5000	5425	1107	2194	1239	0	600/550
FBIIP35000AF	26	0	1	3	80000	62000	2578	2578	1	1	50	700	700	1	1	5000	5425	1107	2194	1239	0	600/550
Combined1a	26	0	0	0	60000	42000	2575	2575	0	0	6	700	700	0	0	2845	559	0	0	0	0	850/800
Combined1b	26	0	0	0	60000	42000	2575	2575	0	0	6	700	700	1	1	5000	5425	1107	2194	1239	0	850/800
Combined2a	26	0	1	3	80000	62000	2578	2578	0	0	6	500	500	0	0	2845	559	0	0	0	0	850/800
Combined2b	26	0	1	3	80000	62000	2578	2578	0	0	6	500	500	1	1	5000	5425	1107	2194	1239	0	850/800
Combined3	26	0.05	1	3	80000	62000	2578	2578	1	1	50	700	700	1	1	5000	5425	1107	2194	1239	0	850/800

* Highlighted cells indicate changes from the Baseline model

Appendix I

Risk Assessment Locations and Measures

Table I-1.—Locations where streamflow metrics were computed

Location	USGS Gage No.	Latitude	Longitude
Swiftcurrent Creek at Sherburne	05016000	48.82991	-113.521
St Mary River near Babb	05017500	48.83304	-113.421
St Mary at Intl Boundary	05020500	49.01141	-113.3
Milk River at Western Crossing	06133000	49.00752	-112.545
NF Milk above St Mary Canal	06133500	48.97078	-113.056
North Milk near Intl Boundary	06134000	49.02634	-112.97
Milk River below Fresno Reservoir	06136700	48.97482	-110.422
Milk River at Havre	06140500	48.56369	-109.696
Lodge Creek at Intl Boundary	06145500	49.00567	-109.718
Battle Creek at Intl Boundary	06149500	49.00155	-109.422
Milk River near Harlem	06154100	48.48964	-108.759
Milk River near Dodson	06155030	48.40278	-108.294
Frenchman River at Intl Boundary	06164000	49.00002	-107.303
Milk River at Juneberg Bridge	06164510	48.5092	-107.219
Milk River near Vandalia	06172000	48.37304	-106.973
Milk River at Tampico	06172310	48.30791	-106.822
Milk River at Eastern Crossing	06135000	48.97482	-110.422

Table I-2.—Reservoir storage locations

Location	Basin	Top of active elevation (ft)	Top of joint use elevation (ft)	Max water surface elevation (ft)
Nelson Reservoir	Milk River	2221.6	NA	2223
Fresno Reservoir	Milk River	2567	2575	2591
Lake Sherburne	St. Mary River	4788	NA	4810

Table I-3.—Reservoir Inflow Locations

Location	Basin	Latitude	Longitude
Nelson Reservoir	Milk River	48.49886	-107.565
Fresno Reservoir	Milk	48.66503	-110.007
Lake Sherburne	St. Mary River	48.8155	-113.577

Table I-4.—Irrigation water users

Water User	Water User Group
Battle Creek to IB Irrigation	Canadian
Battle Creek to Milk River Irrigation	Private
Beaver Creek: Bowdoin Irrigation	Private
Beaver Creek: Havre Irrigation	Private
Big Sandy Creek Irrigation	Private
Buggy Creek Irrigation	Private
Canadian Irrigation	Canadian
Clear Creek Irrigation	Private
FBIC Beaver Cr Irrigation	FBIC
FBIIP New Acreage	FBIC
Fort Belknap Canal Irrigation Districts: Alfalfa Valley ID	Project
Fort Belknap Canal Irrigation Districts: Fort Belknap ID	Project
Fort Belknap Canal Irrigation Districts: Zurich ID	Project
Fort Belknap Reservation Irrigation Project: Milk River Unit	FBIC
Fort Belknap Reservation Irrigation Project: White Bear Unit	FBIC
Frenchman River to IB Irrigation	Canadian
Glasgow ID	Project
Harlem Irrigation District: East Portion	Project
Harlem Irrigation District: West Portion	Project
Irrigation above Frenchman Reservoir	Private
Irrigation below Frenchman Dam: Lower	Private
Irrigation below Frenchman Dam: Upper	Private
Little Boxelder Creek Irrigation	Private
Little Peoples Creek Irrigation	FBIC
Lodge Creek to IB Irrigation	Canadian
Lodge Creek to Milk River Irrigation	Private
Lower Malta ID: Beaver Creek	Project
Lower Malta ID: Milk Returns	Project
ND Irrigation Above Beaver Creek	Project
ND irrigation Dodson to Nelson	Project
ND Irrigation FT Belknap to Dodson	Project
ND Irrigation Havre to FT Belknap	Project
ND irrigation Nelson to Vandalia	Project
ND Irrigation Paradise Valley Reach	Project
ND Irrigation PV to Harlem ID	Project

Table I-4.—Irrigation water users

Water User	Water User Group
ND irrigation Vandalia to Mouth	Project
North Malta ID	Project
Paradise Valley Irrigation District: East Portion	Project
Paradise Valley Irrigation District: West Portion	Project
Peoples Creek Irrigation Project	FBIC
Peoples Creek Irrigation	Private
Porcupine Creek Irrigation	Private
Private irrigation Dodson to Nelson	Private
Private Irrigation Harlem to Dodson	Private
Private Irrigation Havre to FT Belknap	Private
Private Irrigation Nelson to Vandalia	Private
Private Irrigation Paradise Valley Reach	Private
Private Irrigation PV to Harlem	Private
Private irrigation Vandalia to Mouth	Private
Rock Creek Irrigation	Private
Sweetgrass Hills Irrigation	Private
Upper Malta ID: Beaver Returns	Project
Upper Malta ID: Bowdoin Returns	Project
Upper Malta ID: Lower	Project
Upper Malta ID: Upper	Project
U.S. Irrigation on North Milk	Private
U.S. Irrigation on South Milk	Private
Whitewater River Irrigation	Private
Willow Creek Irrigation	Private

Table I-5.—Reservoir locations with boat ramps (ft above mean sea level)

Location	Elevation threshold
Fresno Reservoir, lowest elevation boat ramp	2541.8

Appendix J

Additional Risk Assessment Measure Figures

Hydrologic Responses

Projected Changes in Average Annual and Seasonal Streamflow Volumes

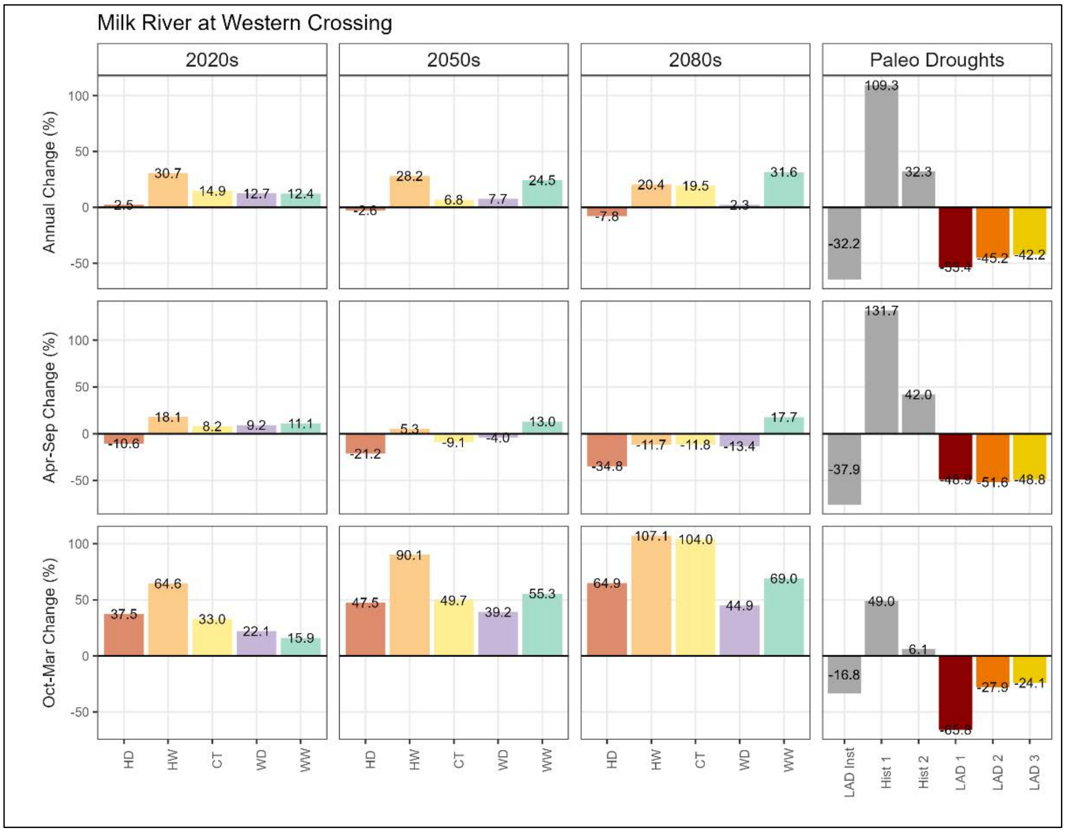

Figure J-1.—Projected changes in average annual and seasonal streamflow volume for the Milk River at Western Crossing gage (USGS ID 06133000) based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

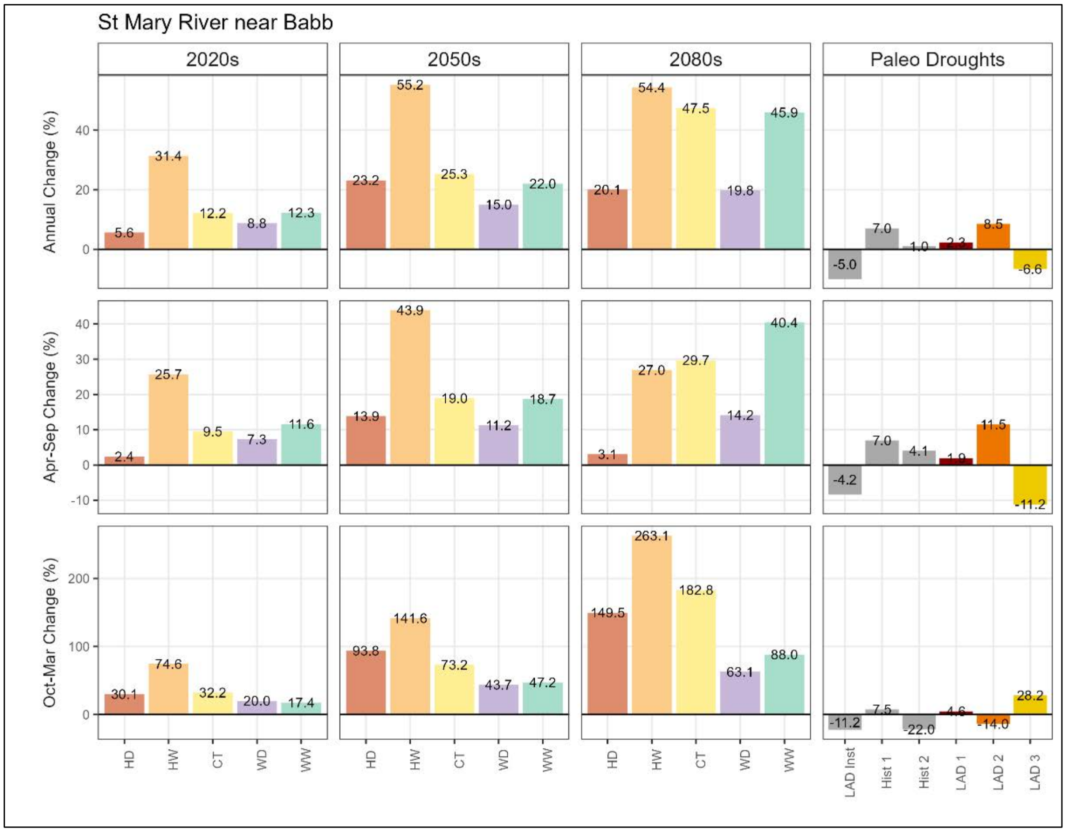

Figure J-2.—Projected changes in average annual and seasonal streamflow volume for the St Mary River near Babb gage (USGS ID 05017500) prior to the St. Mary Canal Intake based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

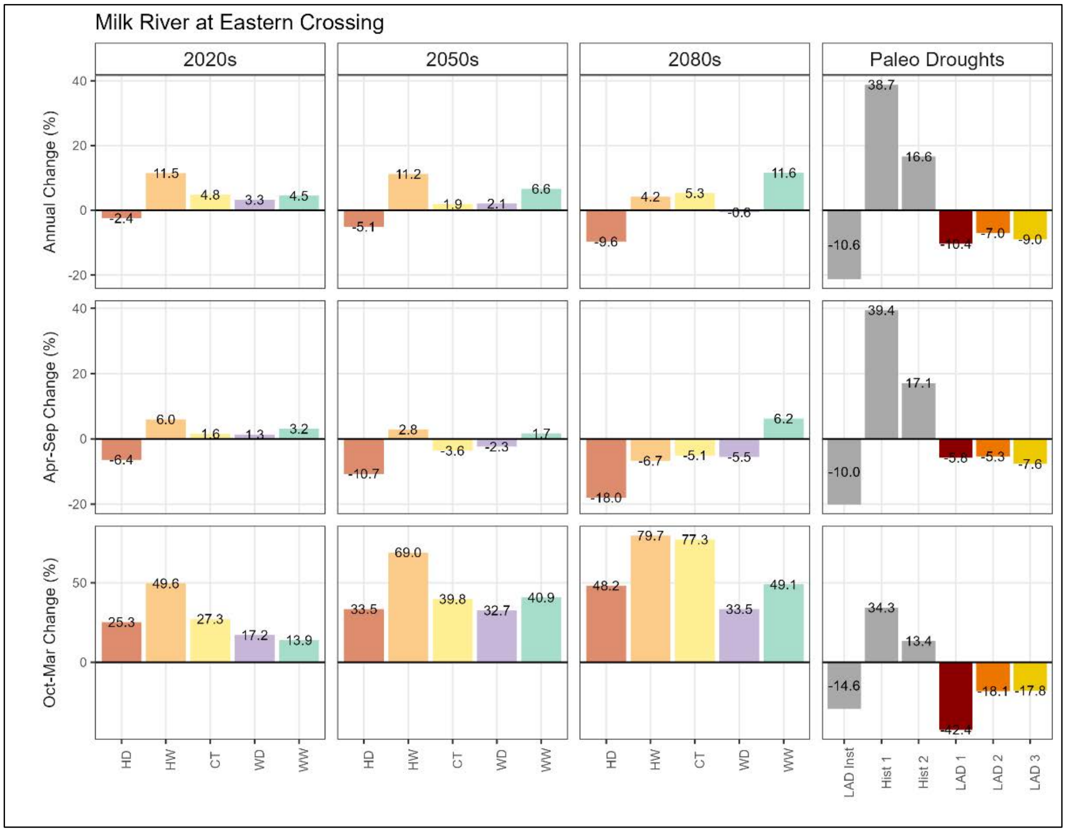

Figure J-3.—Projected changes in average annual and seasonal streamflow volume for the Milk River at Eastern Crossing gage (USGS ID 06135000) based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

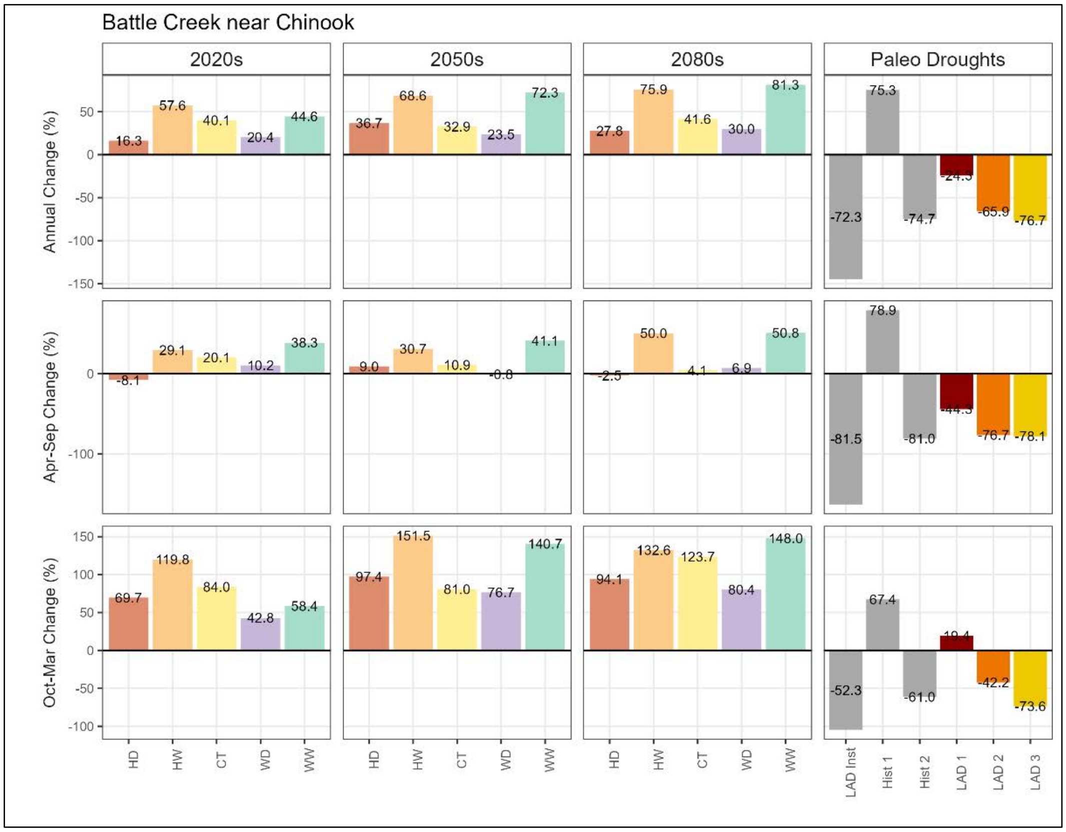

Figure J-4.—Projected changes in average annual and seasonal streamflow volume for Battle Creek near Chinook based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

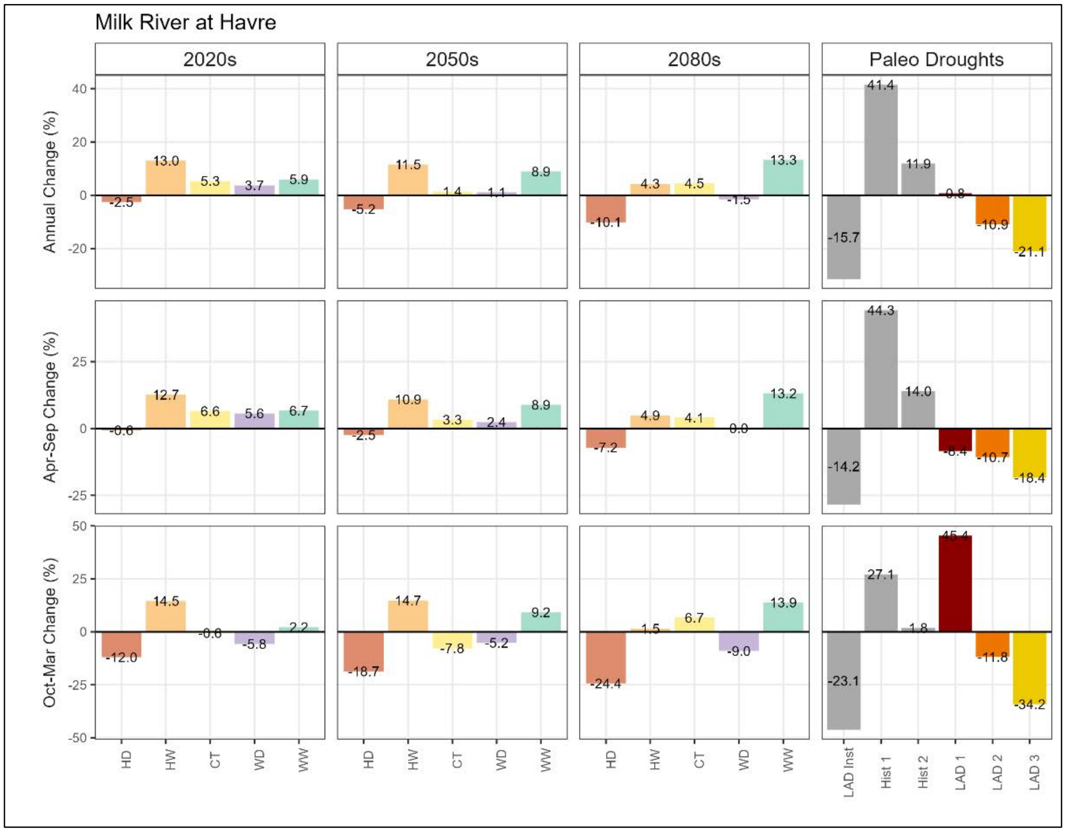

Figure J-5.—Projected changes in average annual and seasonal streamflow volume for Milk River at Havre gage (USGS ID 06140500) based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

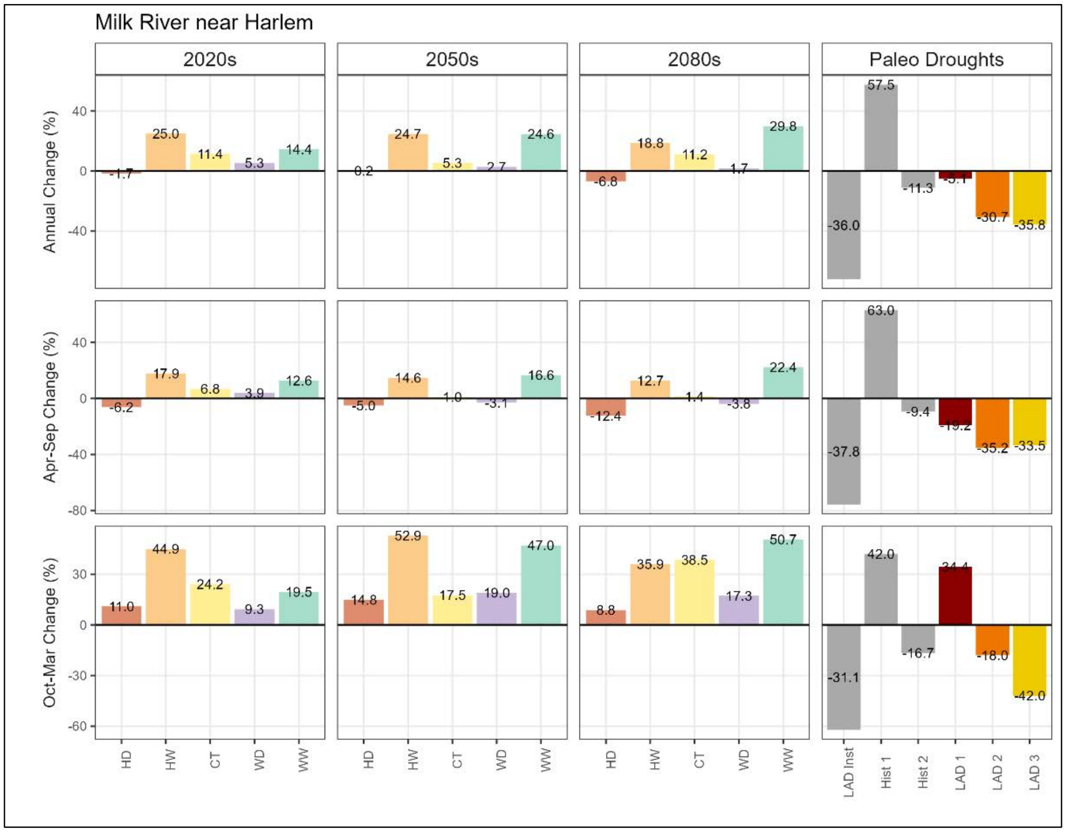

Figure J-6.—Projected changes in average annual and seasonal streamflow volume for Milk River near Harlem gage (USGS ID 06154100) based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

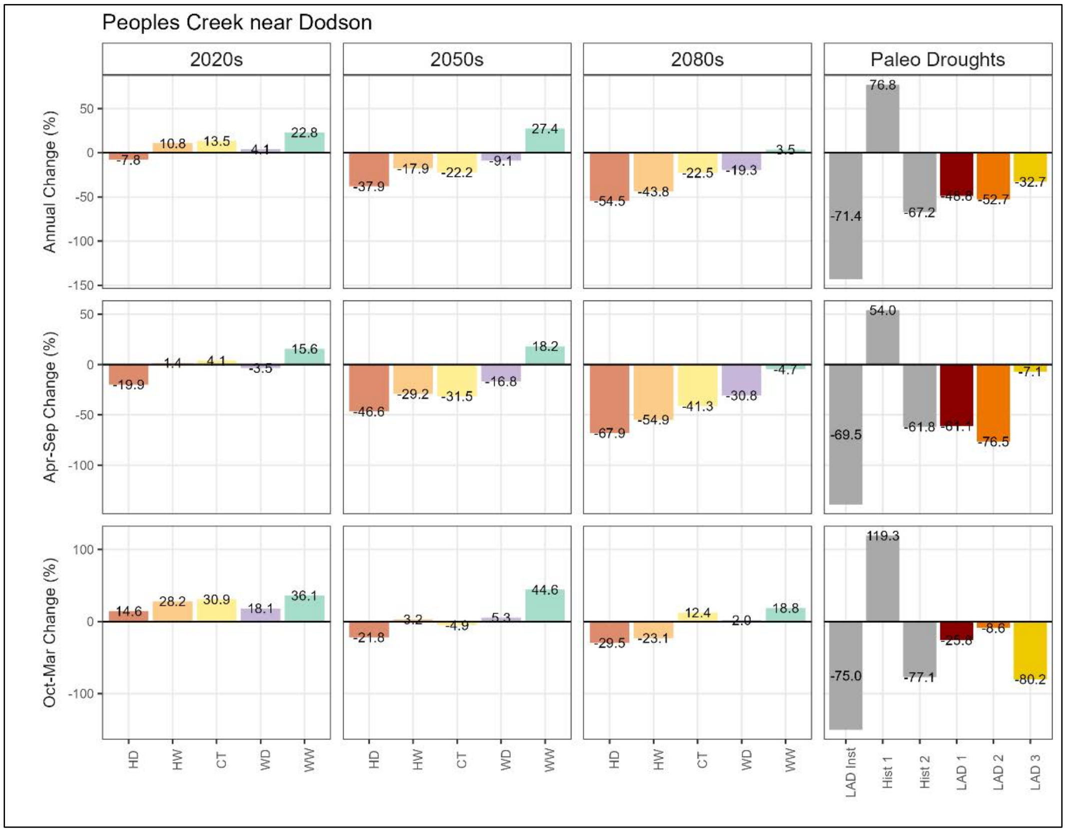

Figure J-7.—Projected changes in average annual and seasonal streamflow volume for People's Creek near Dodson based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

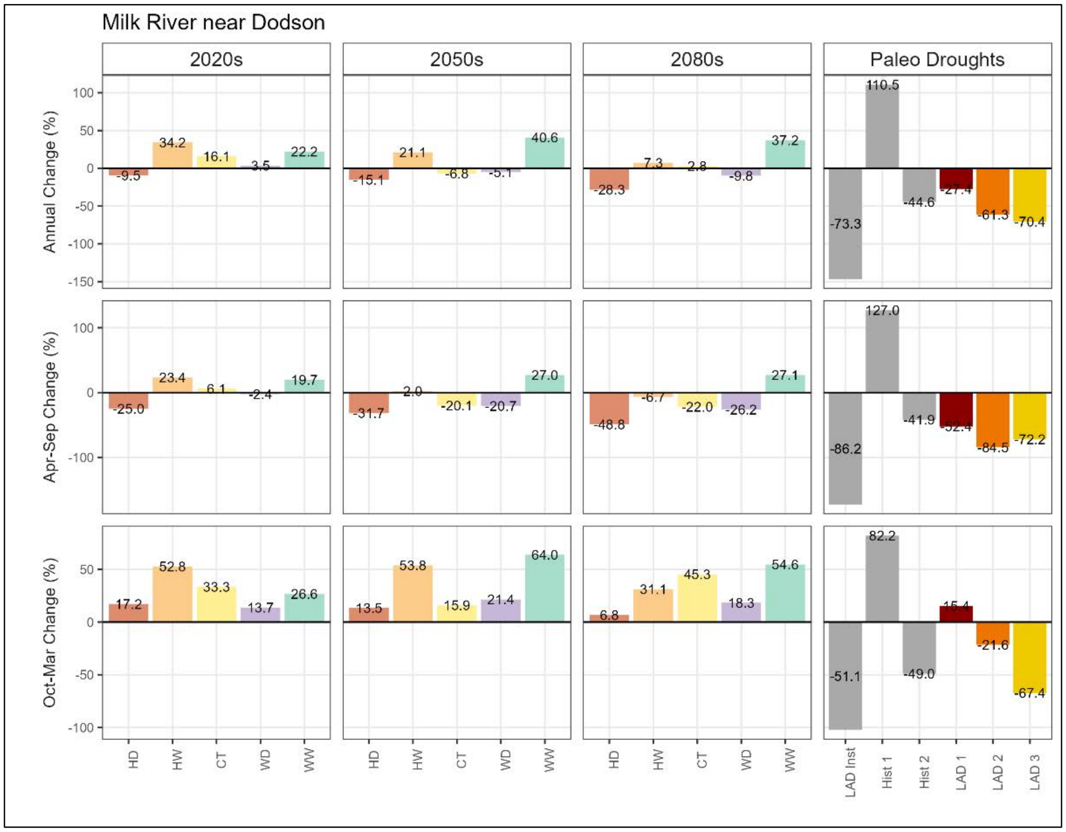

Figure J-8.—Projected changes in average annual and seasonal streamflow volume for Milk River near Dodson gage (USGS ID 06155030) based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

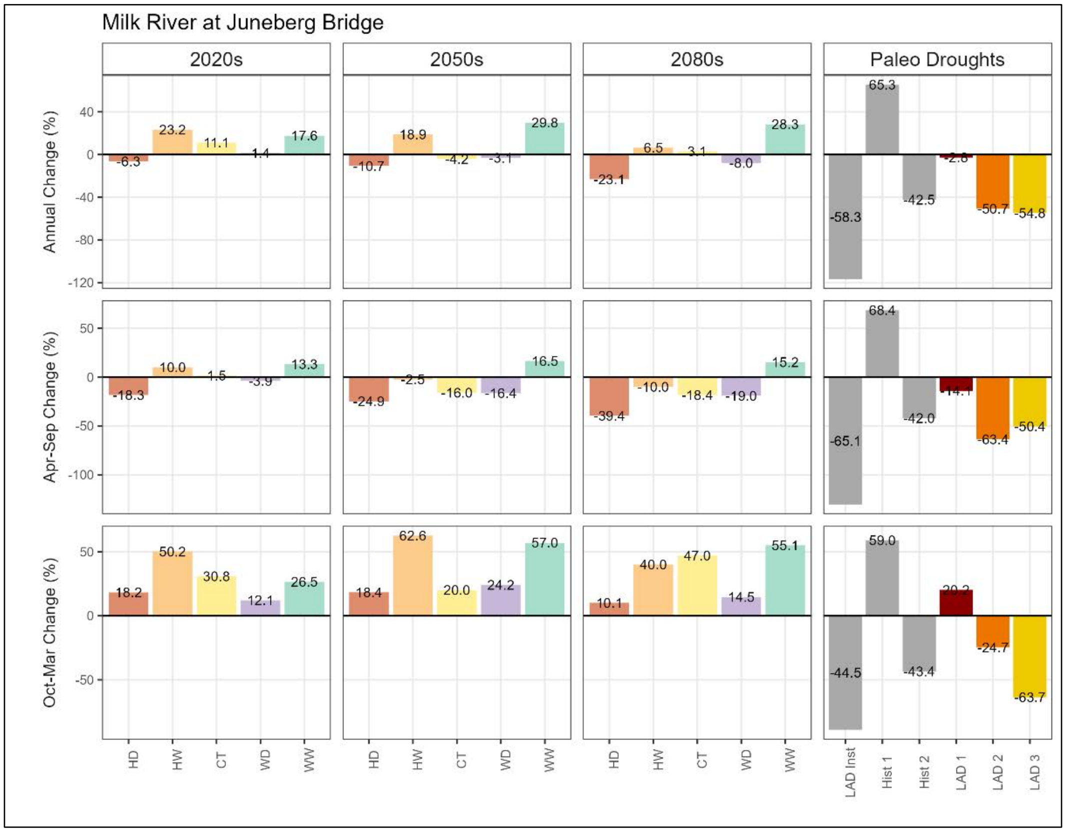

Figure J-9.—Projected changes in average annual and seasonal streamflow volume for Milk River at Juneberg Bridge gage (USGS ID 06164510) based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

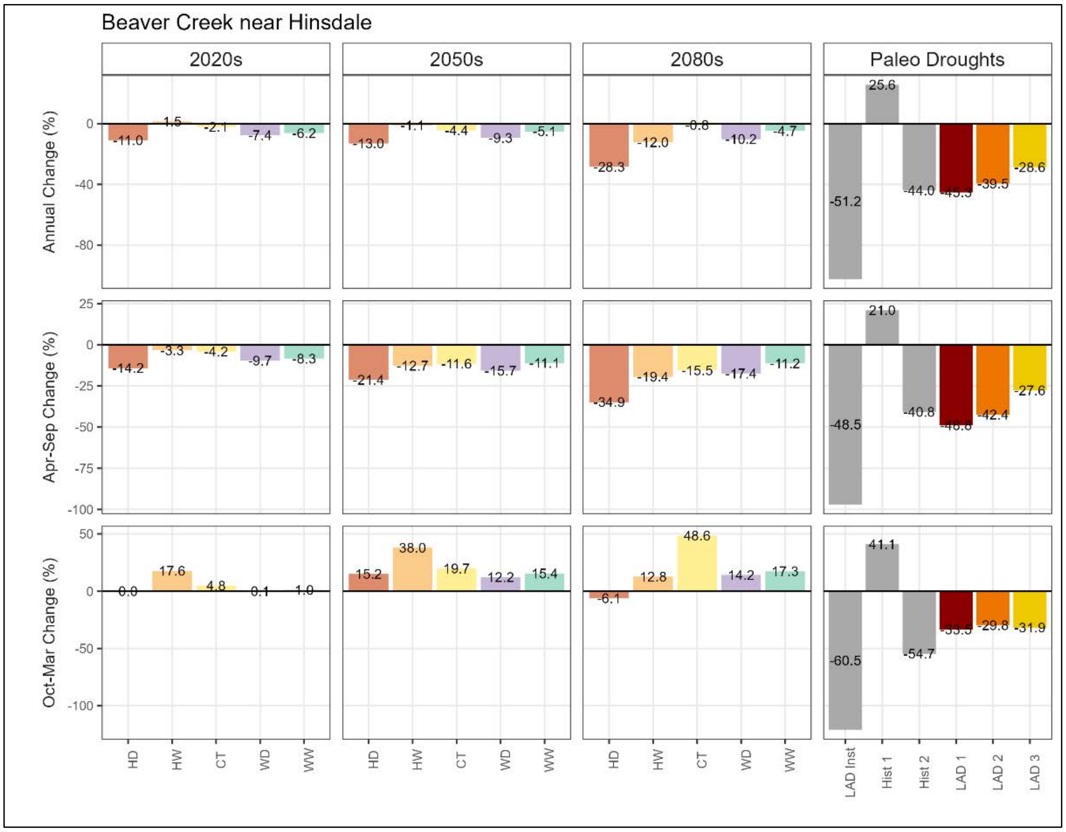

Figure J-10.—Projected changes in average annual and seasonal streamflow volume for Beaver Creek near Hinsdale based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

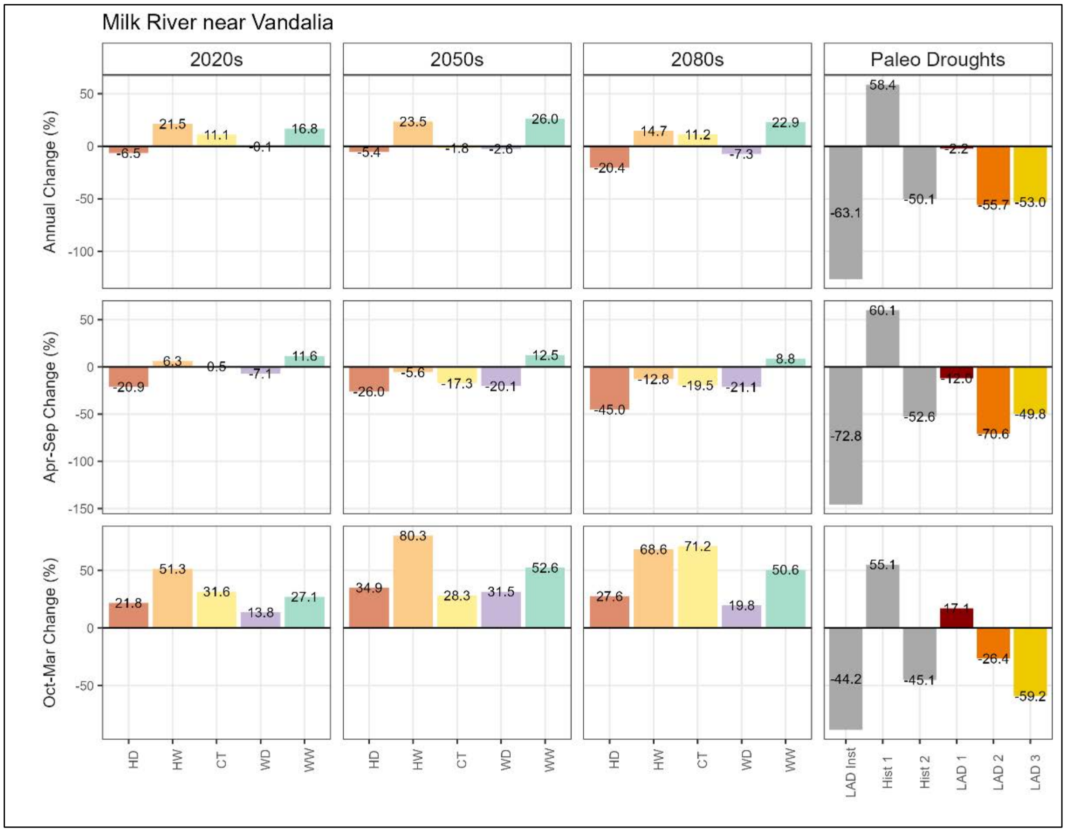

Figure J-11.—Projected changes in average annual and seasonal streamflow volume for Milk River near Vandalia gage (USGS ID 06172000) based on future scenarios for the 2020s, 2050s, and 2080s and extreme paleo event scenarios.

Reservoir End of Month Storage, Average Monthly Reservoir Inflow, and Median Reservoir Inflow Centroid

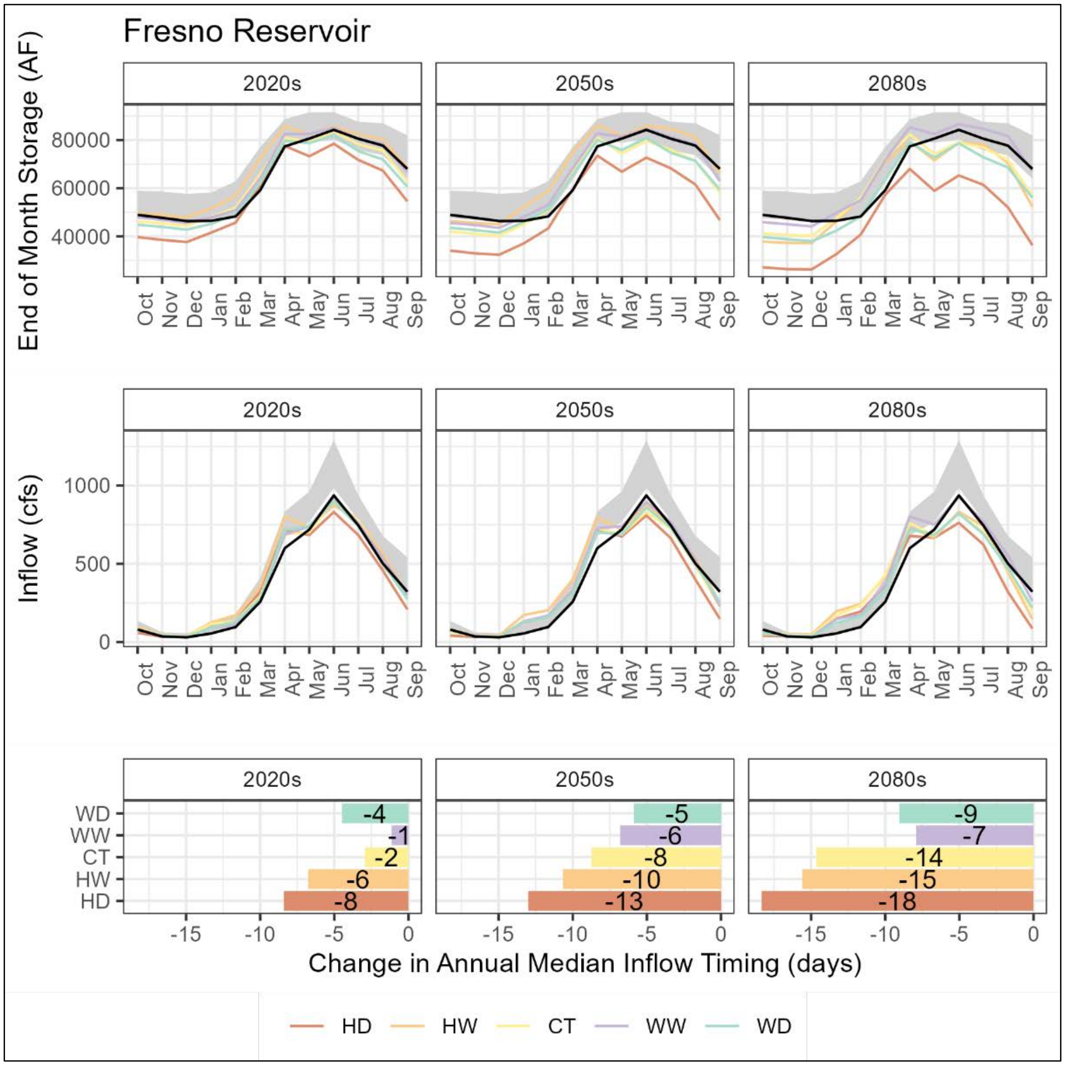

Figure J-12.—Summary of average end of month storage (top), average monthly inflow (middle), and change in annual median inflow centroid (days) to Fresno Reservoir based on future scenarios for the 2020s, 2050s, and 2080s (colored lines and bars), and future scenarios combined with paleohydrology (light grey ribbon).

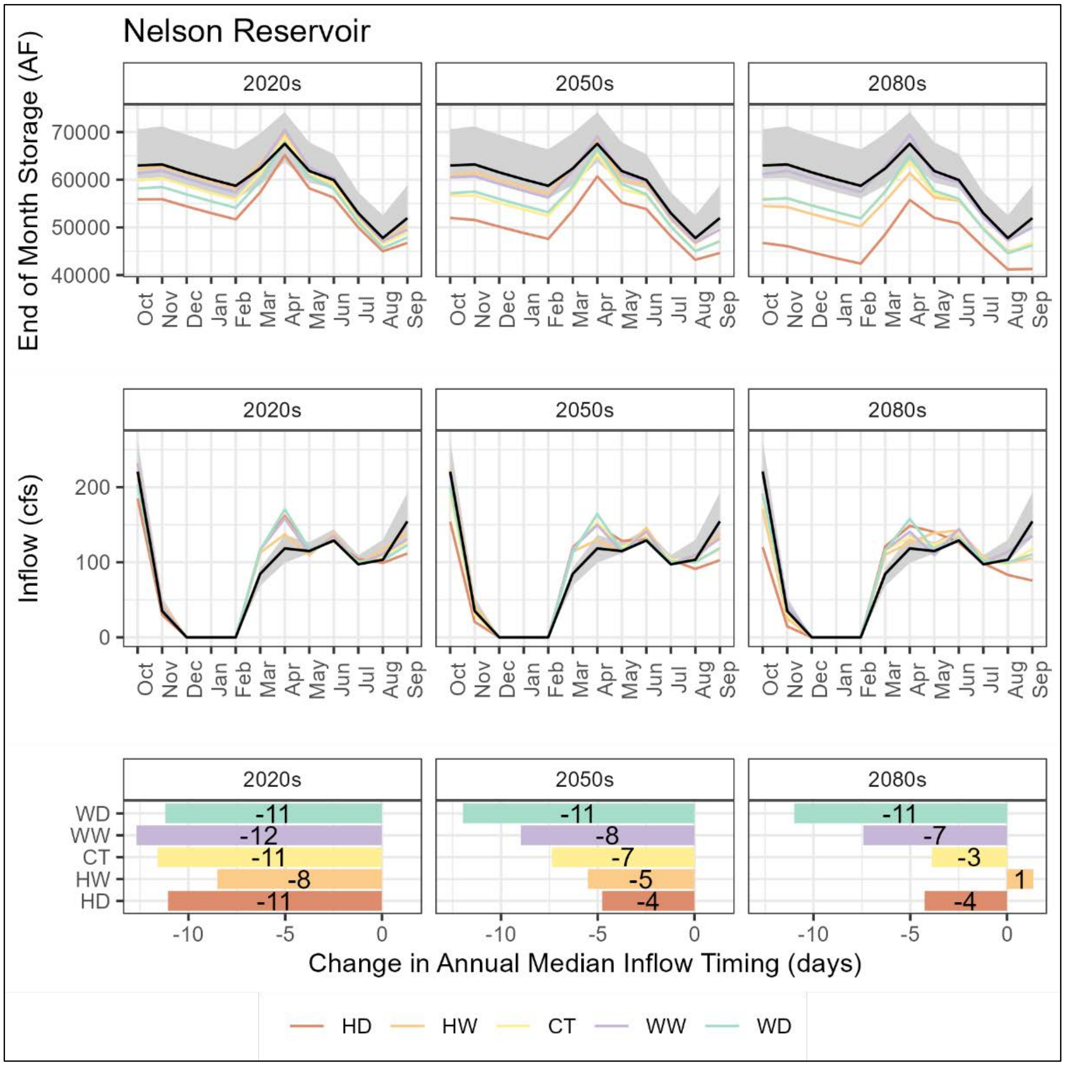

Figure J-13.—Summary of average end of month storage (top), average monthly inflow (middle), and change in annual median inflow centroid (days) to Nelson Reservoir based on future scenarios for the 2020s, 2050s, and 2080s (colored lines and bars), and future scenarios combined with paleohydrology (light grey ribbon).

Water Deliveries

Reservoir End of Water Year Storage, April 1 Storage, and April to September Inflows

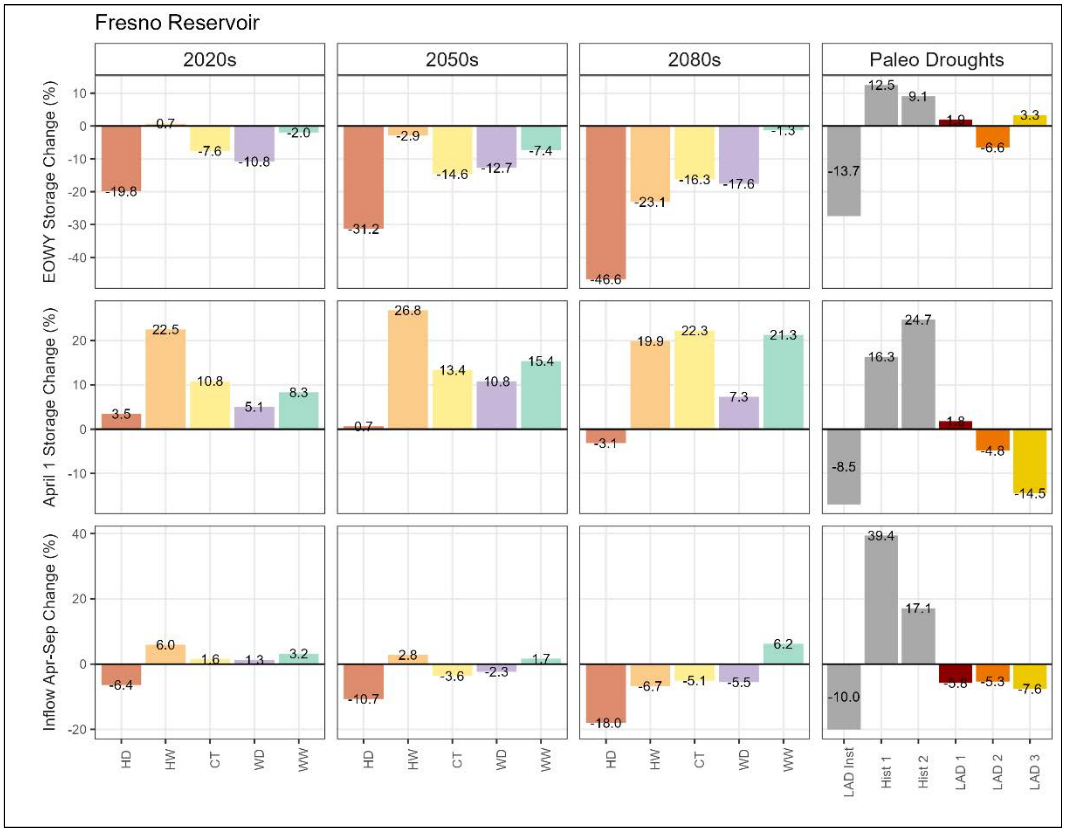

Figure J-14.—Projected changes in end of water year (September) storage, April 1 storage, and April to September Inflows at Fresno Reservoir based on projected future climate scenarios for three future time horizons and extreme paleo event scenarios.

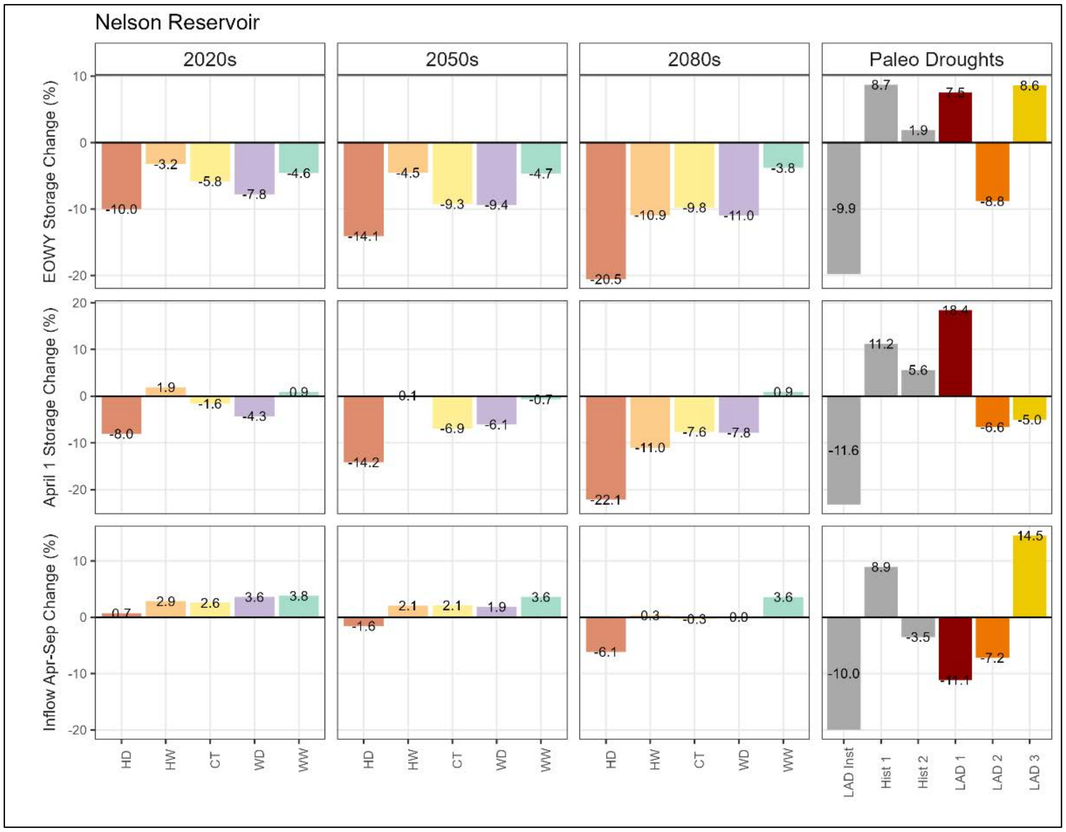

Figure J-15.—Projected changes in end of water year (September) storage, April 1 storage, and April to September Inflows at Nelson Reservoir based on projected future climate scenarios for three future time horizons and extreme paleo event scenarios.

Depletion Requests, Depletions, and Depletion Shortages

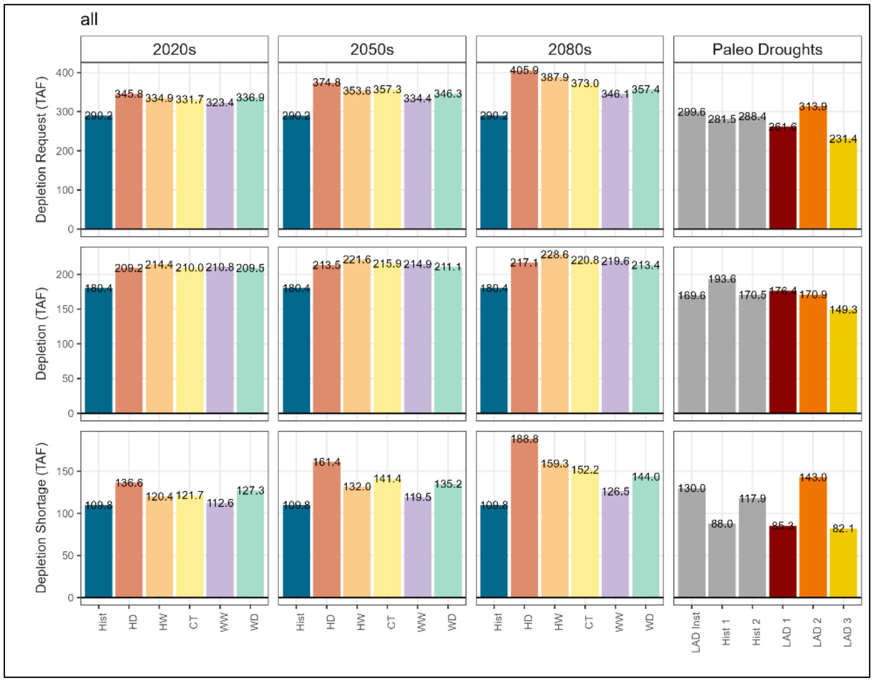

Figure J-16.—Historical and projected depletions, depletion requests, and depletion shortages for all irrigation water users.

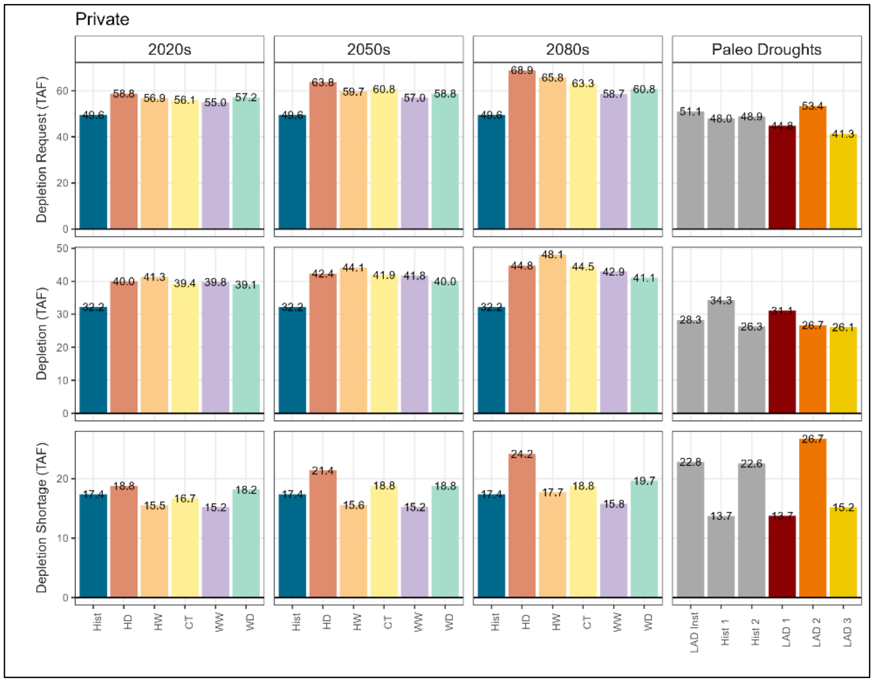

Figure J-17.—Historical and projected depletions, depletion requests, and depletion shortages for private irrigation water users.

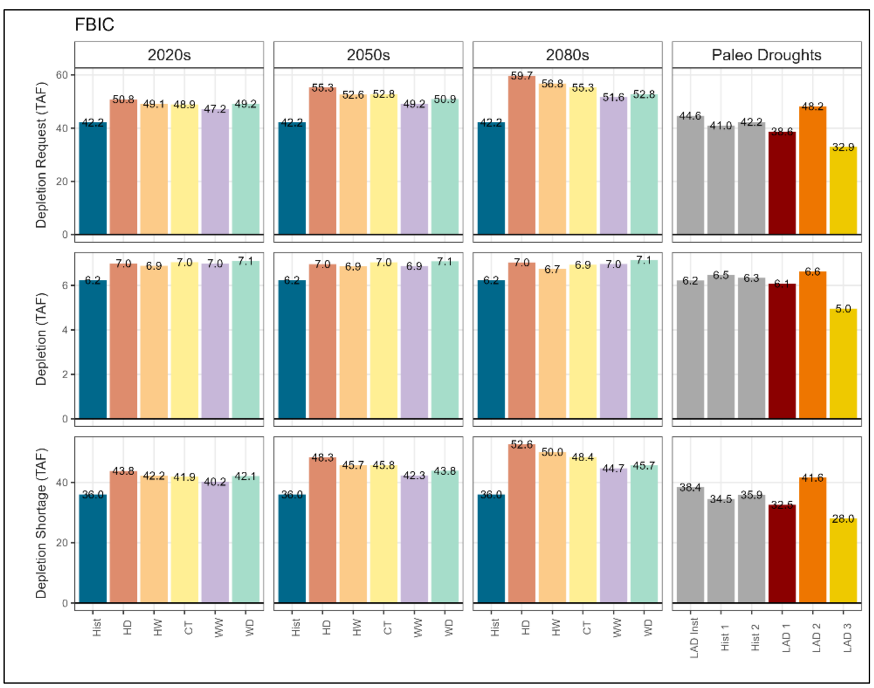

Figure J-18.—Historical and projected depletions, depletion requests, and depletion shortages for FBIC irrigation water users.

Flood Control Operations

Average Daily Reservoir Pool

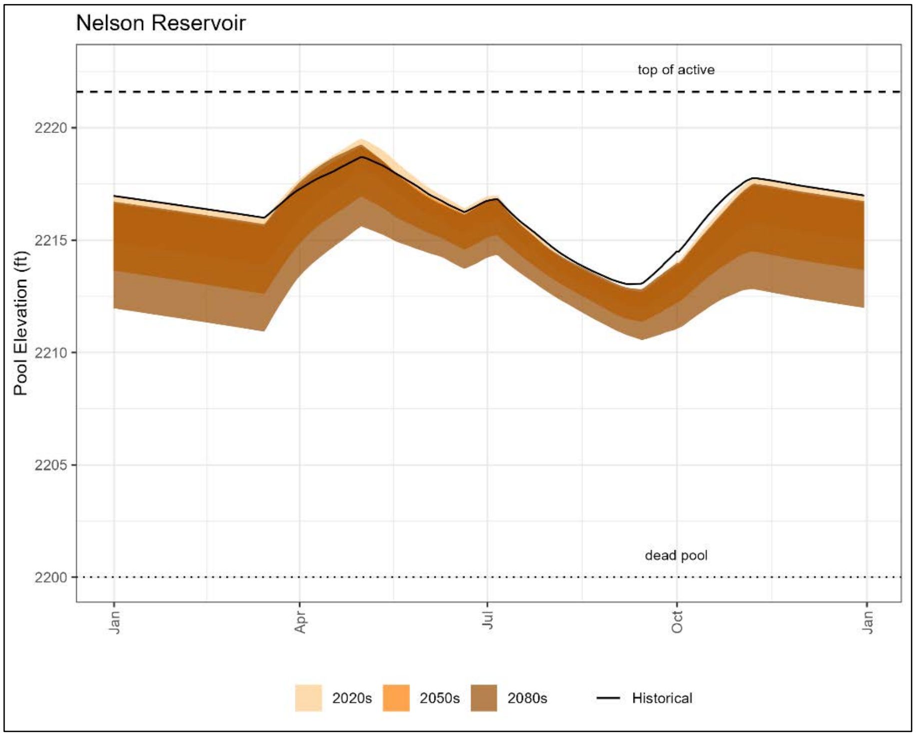

Figure J-19.—Nelson Reservoir average daily pool elevation.

Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

Ecological Resources

Daily Average Flow Rates

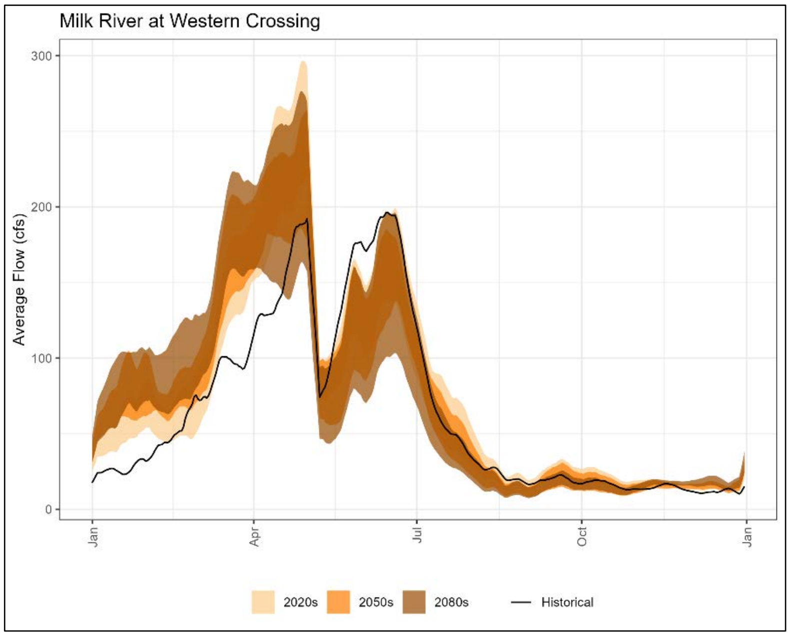

Figure J-20.—Average daily Milk River at Western Crossing (USGS ID 06133000) flow rates.[1]

[1] Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

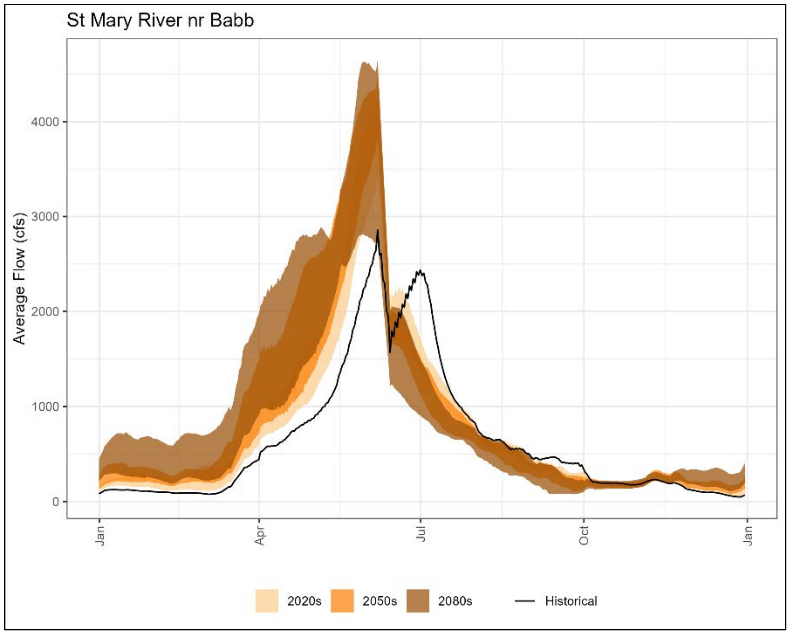

Figure J-21.—Average daily St. Mary River near Babb (USGS ID 05017500) flow rates.[2]

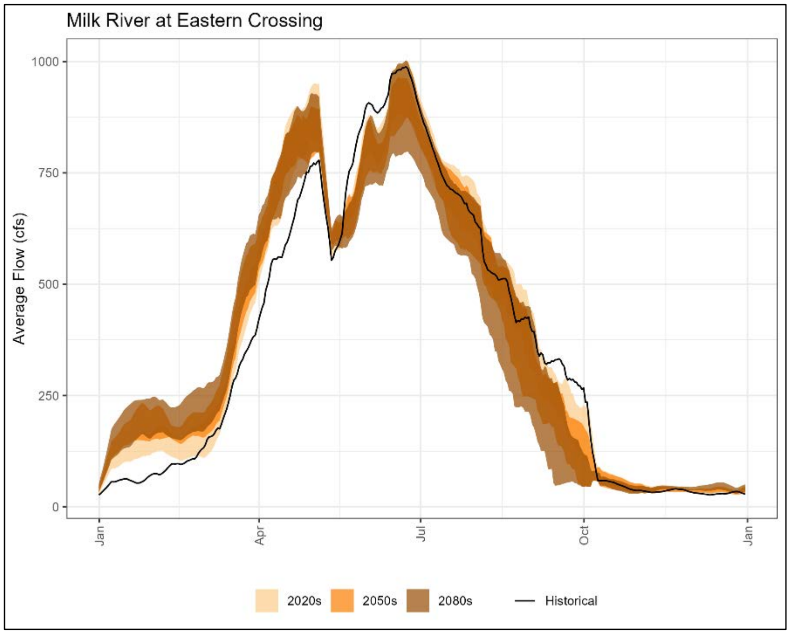

Figure J-22.—Average daily Milk River at Eastern Crossing (USGS ID 06135000) flow rates.[3]

[2] Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

[3] Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

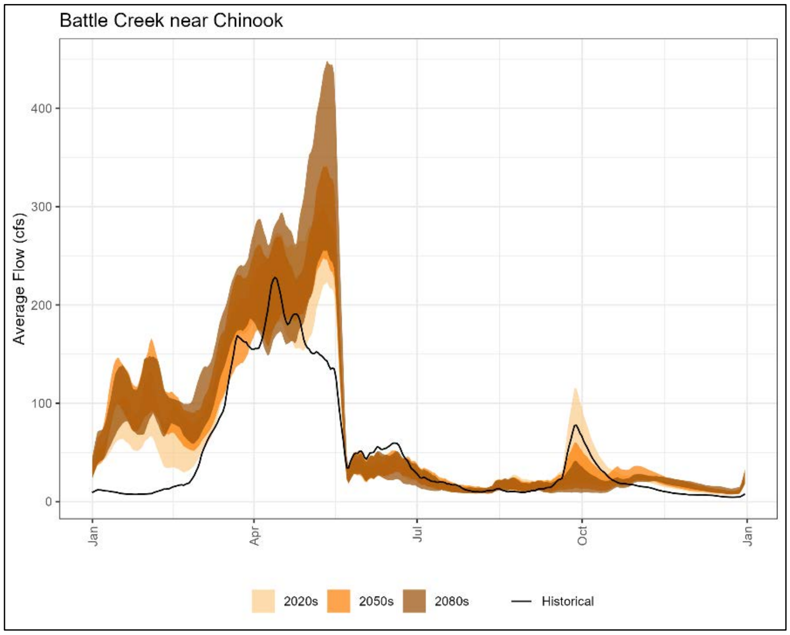

Figure J-23.—Average daily Battle Creek near Chinook flow rates.[4]

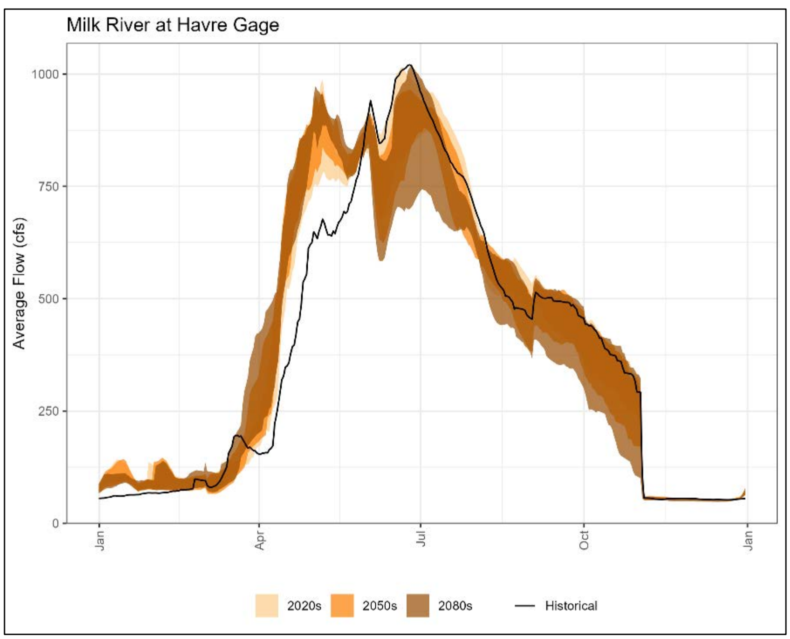

Figure J-24.—Average daily Milk River at Havre (USGS ID 06140500) flow rates.[5]

[4] Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

[5] Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

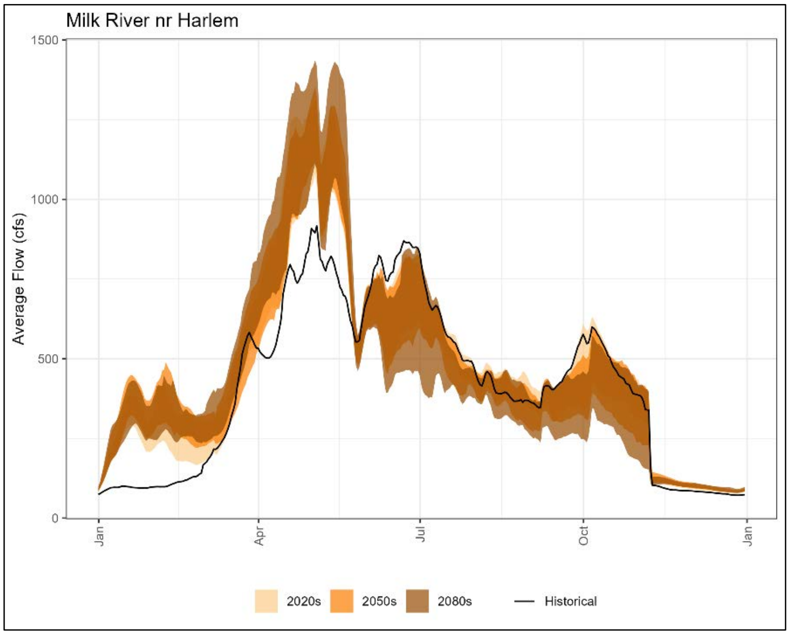

Figure J-25.—Average daily Milk River near Harlem (USGS ID 06154100) flow rates.[6]

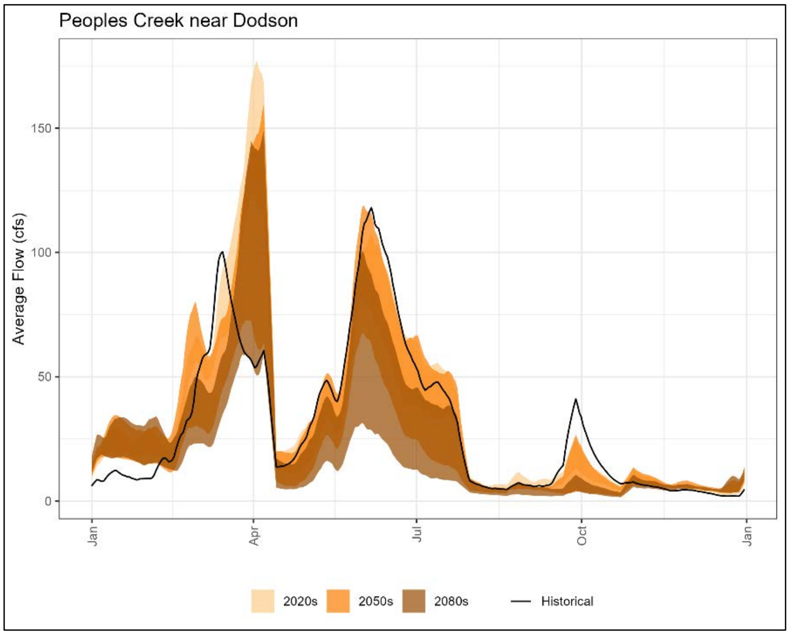

Figure J-26.—Average daily Peoples Creek near Dodson flow rates.[7]

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[6] Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

[7] Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

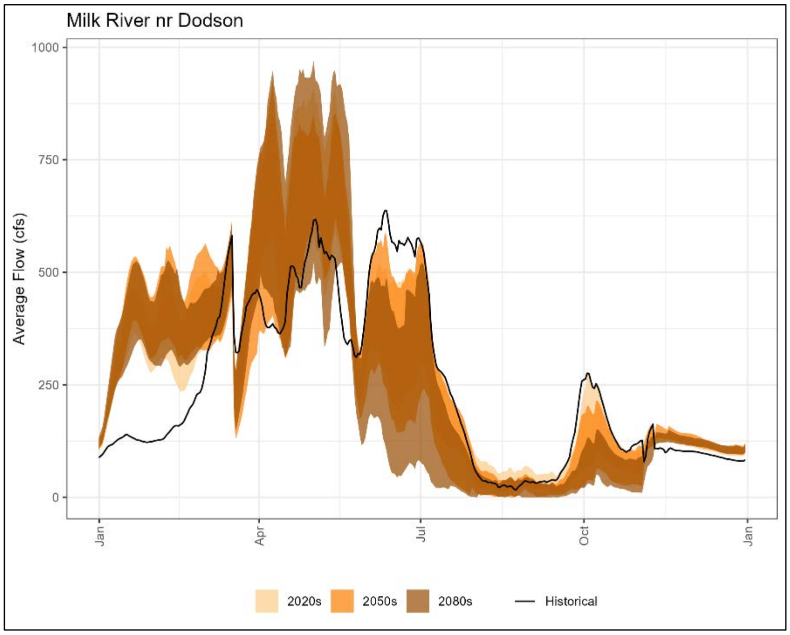

Figure J-27.—Average daily Milk River near Dodson (USGS ID 06155030) flow rates.[8]

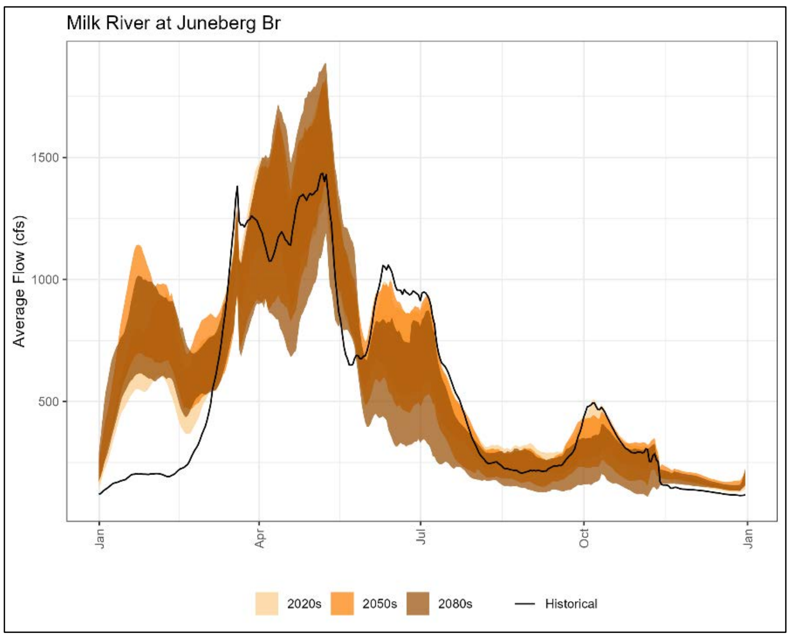

Figure J-28.—Average daily Milk River at Juneberg Bridge (USGS ID 06164510) flow rates.[9]

[8] Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

[9] Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

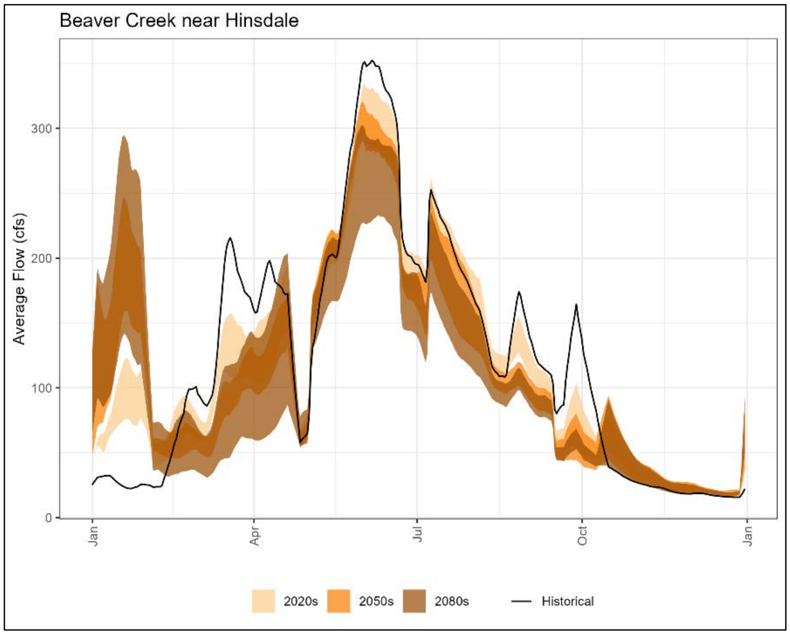

Figure J-29.—Average daily Beaver Creek near Hinsdale flow rates.[10]

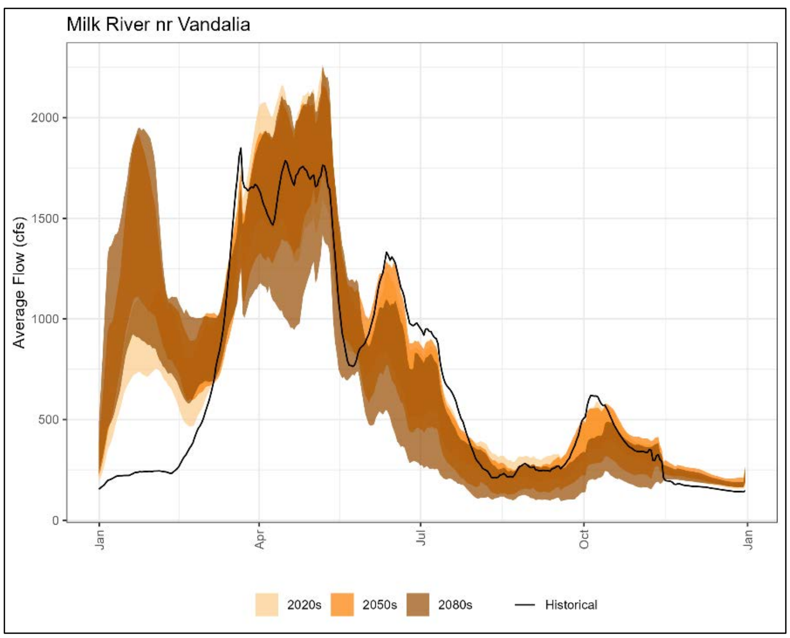

Figure J-30.—Average daily Milk near Vandalia (USGS ID 06172000) flow rates.[11]

[10] Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.
[11] Results are displayed as ranges of the five future climate scenarios within each of the future periods, 2020s, 2050s, and 2080s.

7-Day Minimum and Maximum Streamflow

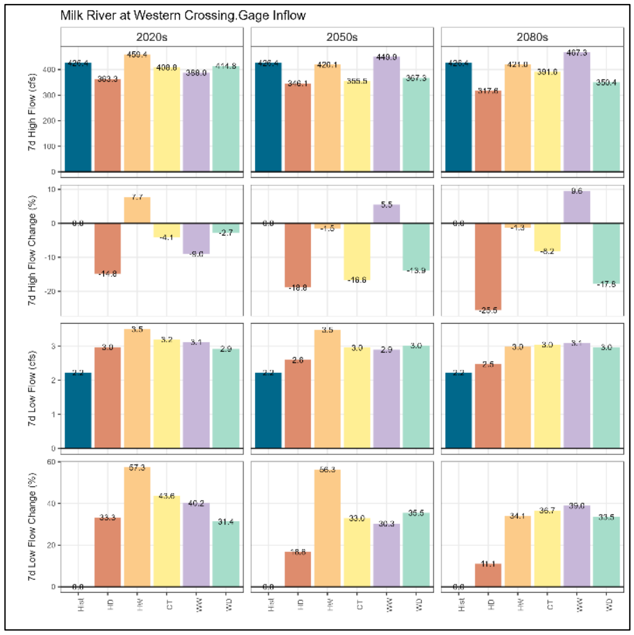

Figure J-31.—Projected changes in 7-day minimum and maximum streamflow at Milk River at Western Crossing (USGS ID 06133000) for future scenarios.

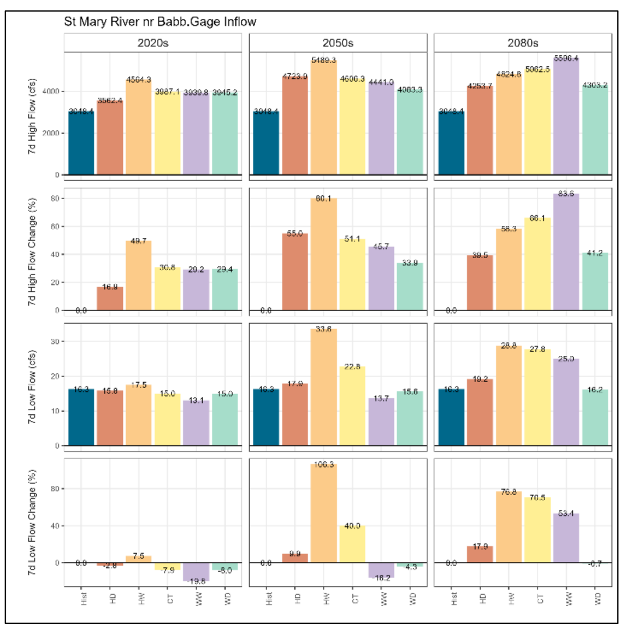

Figure J-32.—Projected changes in 7-day minimum and maximum streamflow at St. Mary River near Babb (USGS ID 05017500) for future scenarios.

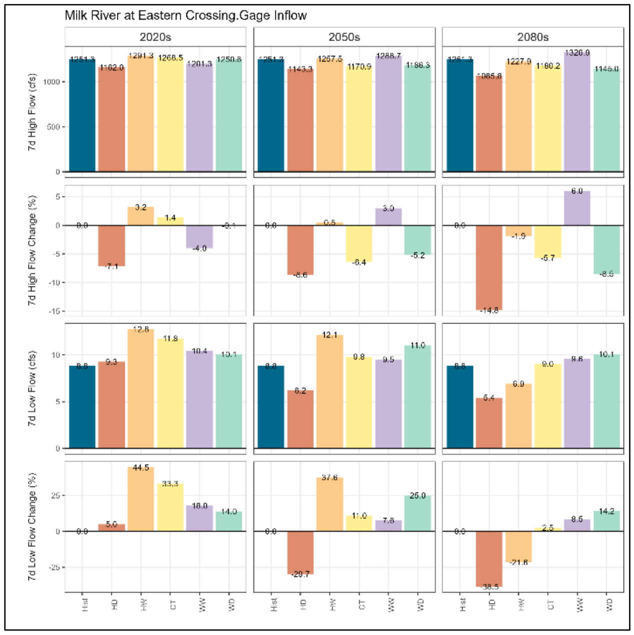

Figure J-33.—Projected changes in 7-day minimum and maximum streamflow at Milk River at Eastern Crossing (USGS ID 06135000) for future scenarios.

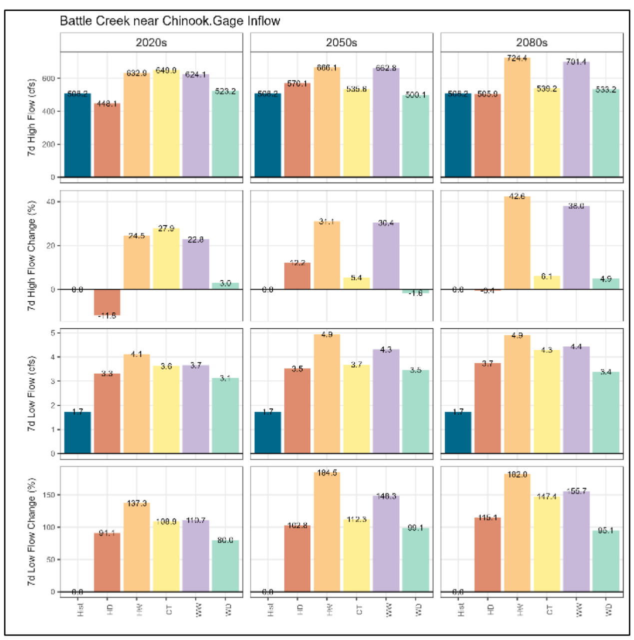

Figure J-34.—Projected changes in 7-day minimum and maximum streamflow at Battle Creek near Chinook for future scenarios.

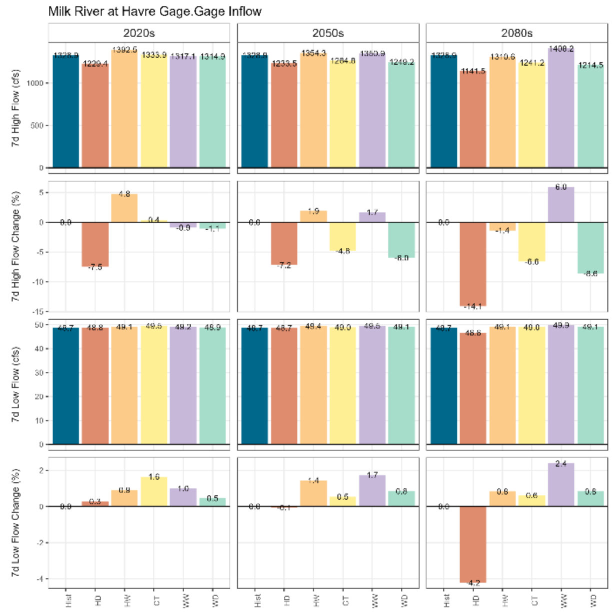

Figure J-35.—Projected changes in 7-day minimum and maximum streamflow at Milk River at Havre (USGS ID 06140500) for future scenarios.

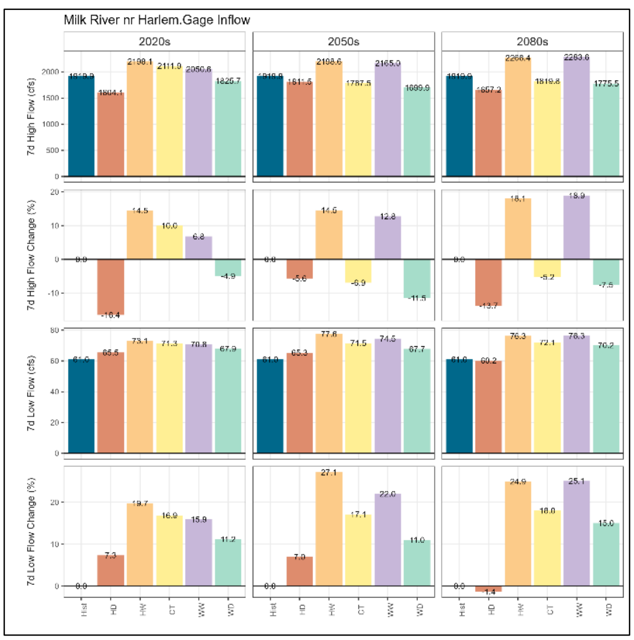

Figure J-36.—Projected changes in 7-day minimum and maximum streamflow Milk River near Harlem (USGS ID 06154100) for future scenarios.

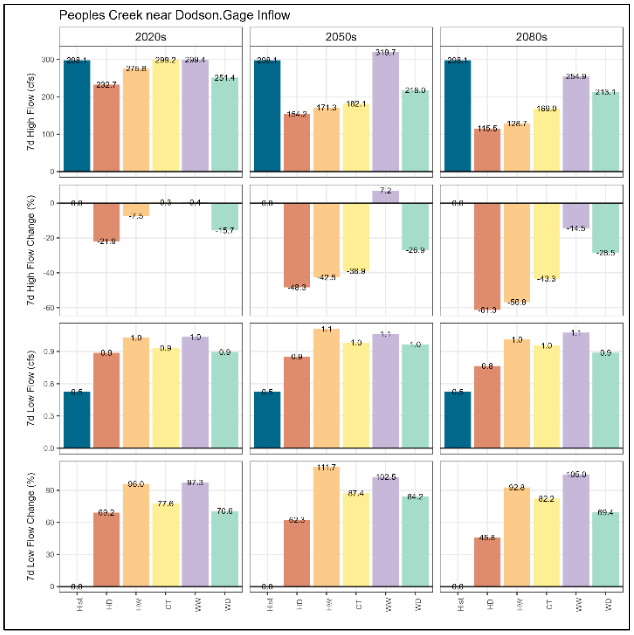

Figure J-37.—Projected changes in 7-day minimum and maximum streamflow at Peoples Creek near Dodson for future scenarios.

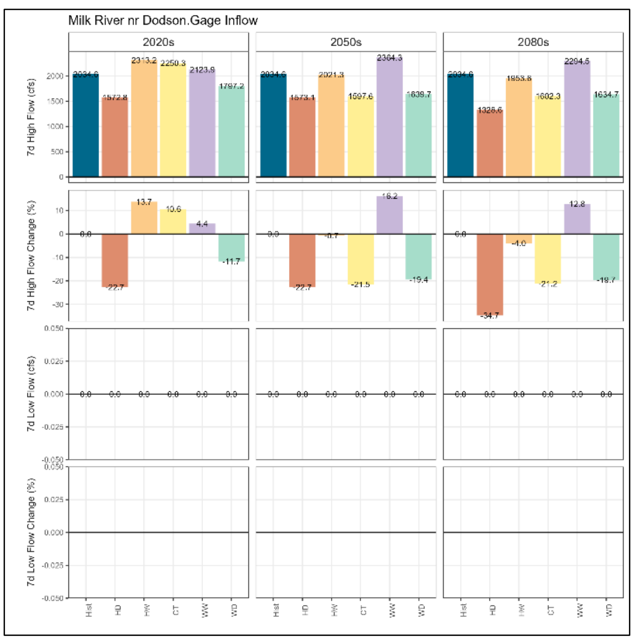

Figure J-38.—Projected changes in 7-day minimum and maximum streamflow at Milk River near Dodson (USGS ID 06155030) for future scenarios.

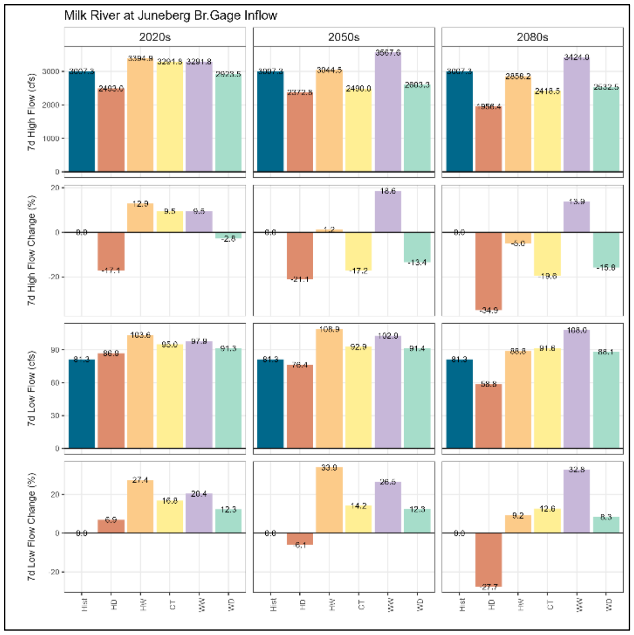

Figure J-39.—Projected changes in 7-day minimum and maximum streamflow at Milk River at Juneberg Bridge (USGS ID 06164510) for future scenarios.

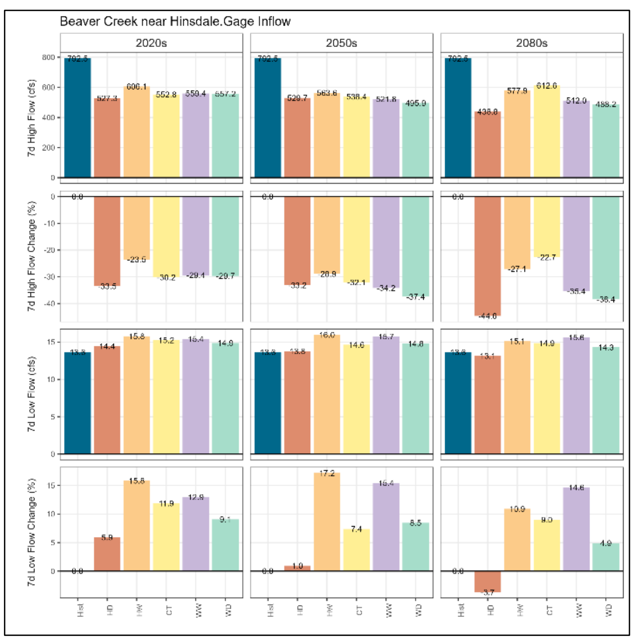

Figure J-40.—Projected changes in 7-day minimum and maximum streamflow at Beaver Creek near Hinsdale for future scenarios.

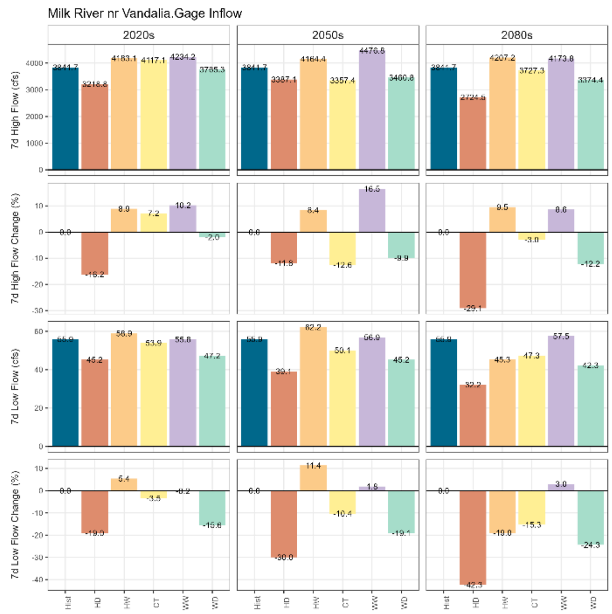

Figure J-41.—Projected changes in 7-day minimum and maximum streamflow at Milk River near Vandalia (USGS ID 06172000) for future scenarios.

Appendix K

Peer Review Summary

Peer Review Summary

The St. Mary and Milk River Basins Study Update (Basins Study Update) was led by the Bureau of Reclamation (Reclamation) Montana Area Office and the Montana Department of Natural Resources and Conservation (DNRC), with support from Reclamation's Missouri Basin – Arkansas – Rio Grande – Texas – Gulf Regional Office, Reclamation's Technical Service Center, and the United States (U.S.) Geological Survey Northern Rocky Mountain Science Center (hereafter referred to as the study team). This Basins Study Update underwent peer review that was designed to ensure that assumptions, findings, and conclusions of the Basins Study Update were clearly stated and supported; oversights, omissions, and inconsistencies were identified; and limitations and uncertainties were disclosed. This peer review summary describes the approach for the peer review process for the Basins Study Update.

The final report underwent a three-step review process, which is detailed in Table K-1. Reclamation performed the technical sufficiency review. The study team first reviewed the draft Basins Study report sections throughout the study process as they were completed. Upon incorporation of those comments, the study team identified qualified reviewers for the technical sufficiency review who were not associated directly or indirectly with the study, but whose scientific and technical background and expertise are relevant to the study component subject matter. Finally, the final report underwent a programmatic review that was conducted by Reclamation's Water Resources and Planning Office.

Table K-1.—Summary of review components

Type of review	Description
Study Team Review	Review performed by study team members at Reclamation, Montana DNRC, and USGS
Technical Sufficiency Review	Review performed by Reclamation Technical Service Center employees that were not involved in the Basin Study Update
Programmatic Review	Review performed by Reclamation's Water Resources and Planning Office

Review comments were compiled and are provided in tables below. Table K-2 summarizes comments made on the St. Mary and Milk River Basins Study Update Summary Report. Tables K-3 summarizes comments made on the St. Mary and Milk Rivers Basin Study Final Report. Brief descriptions of how comments were addressed are provided.

Table K-2.—Review comments for St. Mary and Milk River basins Study Update summary report

Page	Paragraph/section	Comment text	Reviewer	Response to comment
1	Introduction	Weird wording, suggest removing 'single and combinations of'	Manning, Andrew (Drew)	Modified language
2	Study Area	Would it be better to move up the figure to the next page? Currently have to scroll down 3 pages until you can refer to it.	Micek, Stephanie R	Accepted
2	Study Area	Agree. Figure should be before the pictures below to lessen confusion	Kimbrel, Sean W	Accepted
2	Study Area	Is it important to make distinction on who owns and operates Sherburne vs Lower St. Mary Lakes?	Micek, Stephanie R	added clarifying language
2	Study Area	Would be good to identify since this is transbasin	Kimbrel, Sean W	added clarifying language
3	Study Area	Do we need to identify that this is a Reclamation facility?	Micek, Stephanie R	added clarifying language
5	Study Area	Is there a chance to make this map larger/clearer - very hard to read text	Micek, Stephanie R	accepted. Original figure size is 11x17 - will incorporate as original size.
6	Study Area	Hard to read text boxes	Micek, Stephanie R	accepted. Original figure size is 11x17 - will incorporate as original size.
8	Existing Challenges	A sediment survey was completed in 2010 and could have more accurate storage loss numbers	Micek, Stephanie R	Thanks for this reference. We updated the reference and verified that the %loss of storage is still 29%.
8	Existing Challenges	First time using this acronym, suggest writing out kilo acre feet	Manning, Andrew (Drew)	Accepted and wrote out first instance
11	Collaboration and Outreach	Do we want to adjust the language on this to reflect that it's up to 50% cost share?	Manning, Andrew (Drew)	Accepted and added clarifying language

Page	Paragraph/section	Comment text	Reviewer	Response to comment
11	Collaboration and Outreach	Agree with comment "up to" - non-federal funding can be more than 50%	Micek, Stephanie R	Accepted and added clarifying language
15	Water Supply Scenarios	Sentence seems a bit unclear? No storage available in low laying areas to help capture the runoff???	Micek, Stephanie R	Suggested alternative language
19	Water Supply Assessment	Projected*	Manning, Andrew (Drew)	Accepted. Thank you.
22	Risk Assessment	reword	Manning, Andrew (Drew)	Accepted. Suggested alternative language
22	Risk Assessment	? Mentions less, how much more??	Micek, Stephanie R	Suggested alternative language
22	Risk Assessment	Reference figure 10?	Micek, Stephanie R	Suggested alternative language
22	Risk Assessment	Minor note: lots of variance between one space after a sentence vs two spaces	Manning, Andrew (Drew)	Accepted. Thank you.
24	Strategies	Check figure # reference	Micek, Stephanie R	Accepted. Thank you.
24	Strategies	Suggest removing for redundancy	Manning, Andrew (Drew)	Accepted. Thank you.
24	Strategies	Maintain tense. A fourth mitigation strategy evaluates the impacts… Also, this doesn't sound like a mitigation strategy, unless it also evaluates ways to negate the impacts of the failure… but even that sounds more like adaptation (to the failure) rather than mitigation.	Manning, Andrew (Drew)	We moved this strategy under the Basin Wide Strategies umbrella and added explanation as to why this is an important strategy despite it not being an "adaptation strategy"
27	System Wide Water Management Strategies	Increasing*	Manning, Andrew (Drew)	Accepted. Thank you.
27	Providing Water for Future Uses	KAF abbreviation already introduced on page 14	Manning, Andrew (Drew)	Accepted. Thank you.

Page	Paragraph/section	Comment text	Reviewer	Response to comment
27	Mitigating Future Water Uses	Wording's a bit odd here. Suggest changing to 'an additional strategy was presented as part of the Fort Belknap Compact to mitigate...'	Manning, Andrew (Drew)	Suggested alternative language
27	Mitigating Future Water Uses	Change to implementing to maintain the tense	Manning, Andrew (Drew)	Accepted. Thank you.
28	Mitigating Future Water Uses	Confused how this counts as a strategy if it only evaluates effects of a failure and does not offer any suggested course of action	Manning, Andrew (Drew)	We moved this strategy under the Basin Wide Strategies umbrella and added explanation as to why this is an important strategy despite it not being an "adaptation strategy"
28	Mitigating Future Water Uses	Sounds more like an input scenario to compute strategies rather than being a strategy itself	Manning, Andrew (Drew)	We moved this strategy under the Basin Wide Strategies umbrella and added explanation as to why this is an important strategy despite it not being an "adaptation strategy"
28	Tradeoff Analysis	Check Table 3 References	Micek, Stephanie R	Accepted. Thank you.
28	Tradeoff Analysis	Having*	Manning, Andrew (Drew)	Accepted. Thank you.
29	Tradeoff Analysis	This is 1**, but corresponding footnote is 1*	Manning, Andrew (Drew)	Accepted. Thank you.
29	St. Mary Canal Diversion	Page break	Manning, Andrew (Drew)	tech writer will finalize layout
30	St. Mary Canal Diversion	Is there a explanation for differences?	Micek, Stephanie R	Accepted. Suggested language
30	Water Deliveries	Fresno	Manning, Andrew (Drew)	Accepted. Thank you.
31	Water Delivery Shortages	Future*	Manning, Andrew (Drew)	Accepted. Thank you.

Page	Paragraph/section	Comment text	Reviewer	Response to comment
33	Next Steps and Future Considerations	Understanding*	Manning, Andrew (Drew)	Accepted. Thank you.
33	Next Steps and Future Considerations	towards	Manning, Andrew (Drew)	changed to "to"
33	Next Steps and Future Considerations	Period after St	Manning, Andrew (Drew)	Accepted. Thank you.
33	Next Steps and Future Considerations	Change to Basins Study Update. Capitalized in all other mentions	Manning, Andrew (Drew)	Accepted. Thank you.

Table K-3.—Review comments for St. Mary and Milk River basins Study Update final report – Introductory sections

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
28	Study Area		Fonts need to be the same throughout the document.	Erger, Patrick J	Tech writer
28	Study Area		Worth noting this structure is scheduled for replacement. Design is complete and funding secured. Someone from MTAO may want to provide additional info.	Dailey, Michael	Accepted
29	Study Area		Is Lower St Mary Lake a storage facility? Lake Bowdoin is not really a storage reservoir. Is there a reason these are categorized as storage reservoirs?	Dailey, Michael	took term storage out of title
31	Study Area		Should we say, "In a dry years,..."	Erger, Patrick J	Accepted
32	Challenges	Aging Infrastructure	I think there is only one reclamation 2004 reference; check for other 2004a references too.	Bearup, Lindsay A	Accepted
32	Challenges	Sedimentation	This strays away from the heading of Sedimentation. I believe this is covered in other parts of the report. Consider deleting.	Dailey, Michael	Accepted
32	Challenges	Sedimentation	Agree	Erger, Patrick J	Accepted
32	Challenges	Water Shortages	Just to build on this, how does this align with the projected shortages from the 2012 BS? This would also be of interest for stakeholder outreach purposes.	Dailey, Michael	Accepted
32	Challenges	Water Shortages	This is the third time this has been mentioned. Some consolidation is need to minimize repeats.	Dailey, Michael	Removed this sentence here and reviewed the rest of report to remove redundancy.

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
33	Challenges	Water Shortages	600 cfs?	Dailey, Michael	Updated to 600cfs
33	Challenges	Water Shortages	correct	Jordan, Clayton R	Accepted
33	Challenges	Water Shortages	The IJC 1921 Order also limits the US ability to use its share.	Dailey, Michael	Added this sentence here
33	Challenges	Water Rights Adjudication	FYI, the citation for the 2018 Procedures Manual is correct, but I believe the Canadian agency has since changed names.	Dailey, Michael	Accepted
33	Challenges	Water Rights Adjudication	This doesn't really fit in with adjudication. Recommend consolidating international apportionment into one section.	Dailey, Michael	Accepted
33	Challenges	Water Rights Adjudication	Check doc for consistency (mainstem, main stem, main-stem).	Dailey, Michael	Tech writer
34	Challenges	Water Rights Adjudication	Clayton/Lindy do we want to add something here about the adjudication process be completed by the DNRA and MT Water Courts?	Erger, Patrick J	Accepted
34	Challenges	Water Rights Adjudication	I don't think we need to be more specific. I believe the general statement is sufficient.	Jordan, Clayton R	Accepted
34	Challenges	Environmental Challenges	Should this be from a fisheries standpoint since we are talking about environmental challenges?	Dailey, Michael	Accepted
37	Interrelated Activities	Blackfeet Tribe Water Rights Settlement	Should we be using trademarks when referring to RiverWare?	Dailey, Michael	I don't think so

Table K-4.—Review comments for St. Mary and Milk River basins Study Update final report – Water supply assessment

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
40	Water Supply Assessment	Descriptions of Surface and Groundwater Supplies	Much of this is discussed in the previous sections. Can all of the international apportionment stuff be consolidated into one section? See previous comment.	Dailey, Michael	Accepted
36	Water Supply Assessment		GENERAL COMMENTS: A tech writer should do a more thorough check of abbreviations, figure & table numbering, references, abbreviations and general formatting (e.g. paragraph spacing, list formats, page breaks) It would be helpful to have a table of the datasets for each use. It was hard to follow which historical datasets were used (naturalized flows, daymet run through the modeling framework, gage observations, etc.) I flagged a few areas that I felt were redundant or could be rearranged. I suggest a read through of the whole report upon completion to make sure it flows ok. I like the use of the three representative sites, and think that link could be made stronger throughout.	Bearup, Lindsay A	We will continue to improve the document with this comment in mind
39	Water Supply Assessment	Hydrologic Modeling Framework	Perhaps include a photo to show what they look like. Something like this: https://www.fws.gov/media/189191 (fws, should be useable)	Bearup, Lindsay A	Accepted
39	Water Supply Assessment	Hydrologic Modeling Framework	Does this comparison also use the hydro model forced with daymet for the historical reference? If so may want to state that explicitly	Bearup, Lindsay A	Added language
40	Water Supply Assessment	Hydrologic Modeling Framework	Consider moving this figure up closer to number figures in the order they are used (also useful here)	Bearup, Lindsay A	Accepted

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
41	Water Supply Assessment	Hydrologic Modeling Framework	What about the gray areas?	Bearup, Lindsay A	Accepted. Added language.
41	Water Supply Assessment	Water Supply Assessment Hydrologic Modeling Framework	They still change across periods, correct? "Static" makes it sound like they don't change in time. I suggest removing it and just leaving "consistent hydrologic model parameters…"	Bearup, Lindsay A	Accepted
41	Water Supply Assessment	Hydrologic Modeling Framework	Is this published and available yet?	Dailey, Michael	No
43	Water Supply Assessment	Hydrologic Modeling Framework	I sent Marketa an updated version of this map that eliminates duplicate labels, simplifies the legend and consistency in appearance with the other study area maps.	Dailey, Michael	Accepted
41	Water Supply Assessment	Projected Future Climate Scenarios	Previous sentence says CMIP 5 for the update. Confirm CMIP3 is used somewhere and if not also remove from abbreviations page.	Bearup, Lindsay A	Accepted
42	Water Supply Assessment	Projected Future Climate Scenarios	This reads like you used all 64 projections in the scenarios for this study (in previous paragraph subset refers to those selected for each climate scenario). Also it isn't clear that LOCA only has RCP 4.5 and 8.5 available. I recommend reworking this paragraph and the previous 2: First discuss LOCA a bit more (e.g. it is a statistical method, what RCPs are available). Can then put justification of using 4.5 and 8.5 (slow would be helpful to describe what an RCP is). Then talk about scenarios for this study.	Bearup, Lindsay A	Accepted
42	Water Supply Assessment	Projected Future Climate Scenarios	It is probably worth a couple more sentences here on strengths/weaknesses of this approach. E.g. preserves historical sequencing.	Bearup, Lindsay A	Accepted

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
44	Water Supply Assessment	Projected Future Hydrology Scenarios	Fix Water Resources Planning Model & larger PKNN boxes so text doesn't wrap/fits in box Also you don't reference DCAHM in the text. If this is what you are calling the hydro modeling framework, call it out and define in the text too.	Bearup, Lindsay A	Accepted
48	Water Supply Assessment	Paleohydrologic Analysis and Scenarios	Hard to see (dots especially). Enlarge if possible.	Bearup, Lindsay A	Accepted
48	Water Supply Assessment	Paleohydrologic Analysis and Scenarios	Show on the map I suggest stars with corresponding colors if you want to avoid labeling	Bearup, Lindsay A	Accepted
50	Water Supply Assessment	Paleohydrologic Analysis and Scenarios	Figure 10 on page 42 not displaying correctly on my computer	Martin, Justin T	Accepted
69	Water Supply Assessment	Projected Future Snowpack and Streamflow	For this series of plots, consider moving the legend to the bottom like in Figure 22 to make the content larger. Also for final version, crop white space from outer figure margins.	Lindsay Bearup	We did not have time to modify
69	Water Supply Assessment	Projected Future Snowpack and Streamflow	I would prefer the legend on the side as it looks more like a scale. However, the maps appear almost like watermarks so its hard to correlate the scale colors to the maps.	Dailey, Michael	We did not have time to modify
50	Water Supply Assessment	Historical Climate and Water Supply in the Milk and St Mary River Basins	I find these more relatable than average annual temperature and may interest readers in understanding these metrics under the projected futures	Bearup, Lindsay A	Accepted
52	Water Supply Assessment	Historical Climate and Water Supply in the Milk and St Mary River Basins	From daymet too?	Bearup, Lindsay A	Accepted

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
52	Water Supply Assessment	Historical Climate and Water Supply in the Milk and St Mary River Basins	Have you looked at timing of peak SWE?	Bearup, Lindsay A	Accepted
53	Water Supply Assessment	Historical Climate and Water Supply in the Milk and St Mary River Basins	Seasonality of flow would also be useful as background and to support the modeling approach and parameter "seasons"	Bearup, Lindsay A	Accepted
54	Water Supply Assessment	Historical Climate and Water Supply in the Milk and St Mary River Basins	Provide map (add to above figure?) or table of basin names/abbreviations or reference appendix, also labels in this figure are offset from tick mark	Bearup, Lindsay A	Accepted
55	Water Supply Assessment	Historical Climate and Water Supply in the Milk and St Mary River Basins	This might be a good opportunity to address my previous comment and provide basin names, abbreviations, and historical trends. I suggest moving this paragraph before the flow volume and SWE paragraphs when you are already talking about P & T (and then the table is available for reference for Figure 18). Flows nicely into the next paragraph that way too.	Bearup, Lindsay A	Accepted
56	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	Since you talk about it here, I would include it here, but probably just the 2080s one and then the rest can be in the Appendix. Also note the figure number (61) is incorrect. Have the tech writers do a thorough check for figure refs and abbreviations on the final version.	Bearup, Lindsay A	Accepted
56	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	Can you include the % here to be more precise? Ie with xx% of projections showing a projected increase…	Bearup, Lindsay A	Accepted

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
56	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	I suggest breaking this whole section into two subsections: 1) changes in climate and 2) changes in flow volume. This paragraph seems out of place here in the middle of a section. Move above previous paragraph and include what datasets were used for the historical comparisons for both climate (P&T, daymet?) and flow (daymet run through hydro framework??)	Bearup, Lindsay A	Accepted
57	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	This seems like good justification for updating the basin study as well. Might be worth adding to the intro section. I only reviewed the intro briefly but the need for the update did not stick with me. Consider a consolidated paragraph/section on the "why".	Bearup, Lindsay A	Accepted
57	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	If you have time, I think "heavy" precip events would be interesting to add. It helps to explain increases in aggregated precipitation in a helpful way (eg managing larger storms is something very different than managing the same volume spread out over a month). And you can add it above in the historical context too as you noted.	Bearup, Lindsay A	Accepted
59	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	How do the updated P&T changes compare to the 2012 Basin Study? Is there any value in also presenting a quick comparison?	Bearup, Lindsay A	Accepted; added brief comparison from 2012 study

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
60	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	Any attempt to validate snow outputs from hydro modeling framework against daymet etc? Note to self: Check appendix	Bearup, Lindsay A	Accepted. Included Daymet SWE comparison. We may incorporate a comparison with obs SWE if possible as part of the paper (to come) in which case we will report here.
60	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	It would also be interesting to consider changes in timing of peak SWE and melt. Also to confirm these periods are still appropriately represented in the calibration seasons.	Bearup, Lindsay A	Accepted
64	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	For this series of plots, consider moving the legend to the bottom like in Figure 22 to make the content larger. Also for final version, crop white space from outer figure margins.	Bearup, Lindsay A	Will do in next round of revisions after Team review
65	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	Not explicitly accounted for, but	Bearup, Lindsay A	Not changed
65	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	Is this the correct figure reference?	Bearup, Lindsay A	Updated
70	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	finish sentence or delete.	Bearup, Lindsay A	Accepted and modified language

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
70	Water Supply Assessment	Impacts of Climate Change on Climate and Water Supply	How well is that captured in the modeling framework historically?	Bearup, Lindsay A	Accepted. Actually in some years, the seasonal flow has two peaks and in other years only one peak. This is evident in the naturalized flow dataset as well as the historical simulations.
75	Water Supply Assessment	Paleohydrology and Water Supply	Are these defined using the same definition for drought?	Bearup, Lindsay A	No. I added explanation that these are defined by the partners.
75	Water Supply Assessment	St Mary River near International Boundary	I suggest starting with Rank 1 droughts at the top of the table instead of Rank 3.	Bearup, Lindsay A	Accepted
76	Water Supply Assessment	Groundwater Supply	This section seems to be more focused on inputs to the riverware model and not an assessment of groundwater supply. Suggest removing / relocating any unique content to the risk assessment section.	Bearup, Lindsay A	Accepted
76	Water Supply Assessment	Historical and projected changes in recharge to groundwater	Were changes in return flows assessed?	Bearup, Lindsay A	Not here; we can do this in the risk assessment if the teams finds value
77	Water Supply Assessment	Groundwater Supply	This seems out of place	Bearup, Lindsay A	Accepted and moved this text to risk assessment section for later review and potential inclusion

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
78	Water Supply Assessment	Potential future hydroclimate conditions.	Make a climate section	Bearup, Lindsay A	Accepted
78	Water Supply Assessment	Uncertainties in Analysis	Broman and McGuire 2020. This is not in the references. Is it actually a Reclamation report?	Bearup, Lindsay A	Accepted. Added reference.
78	Water Supply Assessment	Uncertainties in Analysis	“has its own uncertainties “ Can you be more specific?	Bearup, Lindsay A	Accepted. Added some language.

Table K-5.—Review comments for St. Mary and Milk River basins Study Update final report – Water demand assessment

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
89	Water Demand Assessment	Irrigation and Canal Efficiencies	Do you think we can round these to the nearness whole number?	Erger, Patrick J	Accepted
91	Water Demand Assessment	Evaporative Demands	Do we reference DRI?	Erger, Patrick J	Accepted
7	Water Demand Assessment	Phreatophyte Demands	Do we really want to project to the 1 decimal place in report?	Erger, Patrick J	Accepted and changed
7	Water Demand Assessment	Phreatophyte Demands	Just say 14,000 AF	Erger, Patrick J	Accepted
1	Water Demand Assessment	Agricultural Demands	Should label consistently with similar graphs. Upper Headwaters as St Mary Basin and Lower Headwaters as Upper Milk Basin.	Dailey, Michael	Accepted
1	Water Demand Assessment	Agricultural Demands	Climate change projections show more precipitation while this figure suggest that it is less. Assume that the graphic is for the irrigation season, which if this is the case, needs to be called out. There is no reference to the figure in the text which needs more explanation.	Dailey, Michael	Accepted
1	Water Demand Assessment	Agricultural Demands	Shouldn't this be 'net irrigation water requirement' to match the acronym?	Dailey, Michael	Accepted

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
4	Water Demand Assessment	Phreatophyte Demands	Please fix.	Erger, Patrick J	Accepted
5	Water Demand Assessment	Agricultural Demands	1/16th degree - is this correct way to display in report?	Erger, Patrick J	Updated
81	Water Demand Assessment	Assessment Approach Agricultural Demands	Suggest more detail is needed. Were the "initially derived" values adjusted? It should be discussed these rates are averages representing mostly flood irrigation, but surely there's some sprinklers out there. And 20% is a very low rate! Typical rates for flood irrigation are 40-60%. I would like to review Reclamation 2011b but I don't see it in the references.	Spears, John (Mark) M	Clarification was added to the text, the 'minimum efficiency' used for RiverWare is a combination of the on-farm efficiencies and canal efficiencies. On-farm efficiencies in previous study ranged from 37-56%, with canal efficiencies ranging from 50 -65%. Canal efficiencies and irrigation efficiencies are separated for larger water users and combined for smaller water users in the RiverWare Model. The text has been updated to better communicate these values. And to include additional details on the original data for the canal efficiencies and on-farm efficiencies. Reference 2011b was a typo, should be 2012b which is the Technical report from the 2012 Study
81	Water Demand Assessment	Irrigation and Canal Efficienciesy	Regardless of what's in Reclamation 2004, we should not show efficiency values to a tenth of a degree! Suggest rounding all values.	John s, Spears (Mark)	Accepted

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
81	Water Demand Assessment	Irrigation and Canal Efficiencies	Suggest this also needs more detail and renaming to Conveyance Efficiency. Canal seepage is only part of the picture and spillway/wasteway losses should be addressed. And more discussion on the recent updating would be good and what are the seepage rates used?	Spears, John (Mark) M	The text was updated to clarify the canal efficiencies. These efficiencies are overall canal efficiencies and not just seepage. Will confirm with Jordan Lanini but I don't believe we have separated spillway/wasteway losses in the MSM model.
87	Water Demand Assessment	Historical Water Demands in the Milk and St Mary River Basins	Is NIWR calc'd using weighted average crop pattern, and if so, this should be mentioned.	Spears, John (Mark) M	The text was updated to clarify that NIWR is weighted based on the crop pattern/distribution.
89	Water Demand Assessment	Reservoir Evaporative Demands	ETc from ET Demands is not actual ET and the figure should be revised accordingly. Also suggest sticking with ETr and not introducing ETpot. ETr and ETc from ET Demands are both potential values assuming optimum growing conditions.	Spears, John (Mark) M	The figure was updated to use ETc and ETr as suggested for clarity.
103	Water Demand Assessment	Uncertainties in Analysis	The fact that actual ET is typically something less than ET Demands estimates should be discussed again here.	Spears, John (Mark) M	Uncertainty in agricultural demands was updated to discuss the fact that ET Demands estimates actual ET with the assumption of well-watered conditions.
104	Water Demand Assessment	Uncertainties in Analysis	Suggest mentioning that no inflow/outflow advection effects is a CRLE weakness.	Spears, John (Mark) M	Updated uncertainty section

Table K-6.—Review Comments for St Mary and Milk River Basins Study Update Final Report – Risk Assessment

Page	Section	Paragraph	Comment Text	Reviewer	Response to Comment
43	7	St Mary and Milk Rivers RiverWare Planning Model Configuration	Should this reference be moved up earlier in report?	Erger, Patrick J	Accepted. Updated.
44	9	Risk Assessment Measures	I count five.	Dailey, Michael	Accepted
45	10	Recreation	Nelson also has boat ramps. We could say only Fresno was evaluated.	Jordan, Clayton R	Accepted. Updated to clarify that both Nelson and Fresno have boat ramps but only Fresno is evaluated.
47	12	Hydrologic Responses	Can the resolution of this graphic be improved? This is a general comment applies to all poor resolution graphics.	Dailey, Michael	Accepted. Updated
48	12	Hydrologic Responses	This is a confusing sentence. I edited it as I understand it. If I got it wrong, it needs to be reworded for clarity.	Dailey, Michael	Accepted, MD's rewording is correct, updated a little more for brevity/clarity

Page	Section	Paragraph	Comment Text	Reviewer	Response to Comment
49	12	Hydrologic Responses	Should this be October or is this different to align with the rain/snow statement?	Bearup, Lindsay A	Accepted, this was a typo and should be October, Corrected
50	12	Hydrologic Responses	Same question.	Dailey, Michael	MD's comment goes with LB's above and was accepted/corrected
52	16	Hydrologic Responses	Maybe my brain is vapor locked, but I do not understand this sentence. Is the greater magnitude positive or negative? Is the periods of extreme drought referring to historical, paleo, future scenario or resequenced future scenario droughts?	Dailey, Michael	Accepted, this sentence was updated for clarity
53	16	Hydrologic Responses	I don't understand what is being conveyed here in this sentence.	Erger, Patrick J	PE's comment goes with MD's above and was accepted/corrected
55	18	Hydrologic Responses	This should also be included in the legend or caption of the figure	Bearup, Lindsay A	Accepted, Updated Figure 68 caption to include historical black line clarification
56	18	Hydrologic Responses	I am surprised at the paleo droughts have higher reservoir levels/inflows than the historical period. Why is that?	Bearup, Lindsay A	Accepted, this question was addressed in a following paragraph. The explanation was

Page	Section	Paragraph	Comment Text	Reviewer	Response to Comment
					moved up to address the question earlier.
59	20	Water Deliveries	This seems to answer my comment above. Likely worth mentioning up there.	Bearup, Lindsay A	Accepted, this question was addressed in LB's last comment, and these lines were moved up earlier in the document to clarify
60	21	Water Deliveries	Should this be 49% to be consistent with Fig. 71?	Bearup, Lindsay A	Accepted, text was updated to 49%
63	24	Flood Control Operations	These appear to be number of days/year not the change in the number of days. If it is change, what is the historical a change from?	Bearup, Lindsay A	Accepted and corrected, it should be the average days per year, not the change. The text as well as the figure captions were updated to clarify it's the number of days not the change.
64	24	Flood Control Operations	Agree, needs to square with referenced graphic captions as well.	Dailey, Michael	MD's comment goes with LB's above and was accepted/corrected

Page	Section	Paragraph	Comment Text	Reviewer	Response to Comment
67	27	Flood Control Operations	Why**?	Erger, Patrick J	Accepted, '**' was removed and is not needed.
71	31	Ecological Resources	I haven't read the next section yet, but I think a summary of the risks identified across the different areas would help wrap up the risk assessment section	Bearup, Lindsay A	Accepted. Added a Summary and Key Findings Section

Table K-7.—Review comments for St. Mary and Milk River basins Study Update final report – Risk assessment with strategies

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
74	34	Approach to Strategy Analysis	Does this have an abbreviation? Should this be a separate section?	Bearup, Lindsay A	Accepted, the St. Mary Canal Failure strategy was added to the strategy table with it's abbreviateion. It's be moved to the 'System Wide Water Management Strategies' category.
75	34	Approach to Strategy Analysis	Are these numbers used elsewhere in the report? If not, I suggest replacing with the strategy name abbreviations (OnFarmEff etc.) to make this table cleaner and easier to use.	Bearup, Lindsay A	Accepted, these numbers were not used elsewhere. The table was updated to remove these numbers and add a separate column with the abbreviation
76	34	Approach to Strategy Analysis	Can these be moved to the abbreviation column then a description of the combo added in this column (could be a list of other abbreviations if that is what these are, e.g. Canal850 + Fresno3)	Bearup, Lindsay A	Accepted, the table was updated with LB's suggestion
77	35	Approach to Strategy Analysis	This table is a great summary of scenario implementation and I found myself referencing it a lot. Could it be color coded to help visualize the changes and scenario combinations? Something like this but prettier: /	Bearup, Lindsay A	Accepted, Table was updated with colors, will ask tech writing team to make it a little more aesthetic
78	35	Approach to Strategy Analysis	I missed where this was described. If it was in a previous section, can it be referenced or summarized somewhere in this section?	Bearup, Lindsay A	Accepted. Table was moved to appendix, historical acreage description was added to the Offstream Storage Project where it's applicable.

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
79	35	Approach to Strategy Analysis	Should this be .05 for this study (.17 for the 2012 study)? If the table is correct please clarify the background section below.	Bearup, Lindsay A	Accepated. Correct the efficiency scenario was change from 0.17 to 0.05, this was a typo and is corrected
80	36	Backgroun d	Add citation.	Bearup, Lindsay A	Accepted. Reference added.
81	36	Performanc e and Trade-Offs	Make sure this is defined somewhere	Bearup, Lindsay A	Accepted. Abbrevation changed from TAF to KAF which is previoiusly defined and in the abbreviatons page.
82	36	Performanc e and Trade-Offs	Would "improved" or "updated" be a better word choice? It is not clear to me what was increased.	Bearup, Lindsay A	Accepted. Changed to updated.
84	38	Performanc e and Trade-Offs	If you want to keep this generic, I suggest listing a range of figures. Otherwise make it clear that it is about this one scenario so that the reader can stop thinking about the others.	Bearup, Lindsay A	Accepted. Update the figure description to be more generic and reference the following figures which use the same presentation format.
85	38	Performanc e and Trade-Offs	Are these 508 compliant for red/green contrast?	Bearup, Lindsay A	I checked in a red-green blindness viewer and it's still possible to differentiate, plus the arrows make it readable if the colors don't work, tech writers said colors are okay.

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
86	39	Performance and Trade-Offs	It might be helpful to describe this diversion to help distinguish it from depletion shortages discussed elsewhere	Bearup, Lindsay A	Accepted. Updated text to explain the difference between depletions and diversion.
87	39	Performance and Trade-Offs	In the text describing this figure, it says this should be monthly diversions (not shortages). Please clarify	Bearup, Lindsay A	Accepted. This figure is Diversions not Diversion shortages and the caption was updated.
88	39	Performance and Trade-Offs	I suggest specifying 5 climate scenarios	Bearup, Lindsay A	Accepted, figure text was revised to specify the 5 future climate scenarios.
89	39	Performance and Trade-Offs	Is this for the right figure only? Otherwise I am not clear what the plots are showing. I suggest noting that they are 5 future scenarios with the strategy included, if that is true.	Bearup, Lindsay A	Accepted. Figure capation was updated to clarify the right vs. left panel and that the future scenarios are shown for the onfareff strategy only.
92	43	Performance and Trade-Offs	Did these two number get transposed? How can wettest 10 be less than middle 10?	Dailey, Michael	Confirmed that these are the correct numbers from the 2012 Report. Possible it had to do with less water needed downstream of the Canal? But would need to reevaluate the 2012 Report to confirm
93	43	Background	According to the table, the spring and October targets were also increased by 20,000 each. Should the be described here?	Bearup, Lindsay A	Accepted. Text was updated to include the changes in the spring and October targest.

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
94	45	Performance and Trade-Offs	By whom?	Bearup, Lindsay A	Accepted, updated "as part of ongoing studies and modeling efforts in the region" Checked in With Jordan Lanini it was evaluated as part of the FBIC Studies, but not necessarily talking about this yet, so left if vague
95	45	Background	Briefly describe what happens in account balancing. How is this implemented in the Riverware model? What does the switch do?	Bearup, Lindsay A	Accepted. Text was updated to expand on the different balancing period
96	47	Performance and Trade-offs	This is clear in the right figure but not the left. Is that because the future scenarios are normalized to their own baselines?	Bearup, Lindsay A	Yes, average annual diversions across the St. Mary Canal decrease in the baseline runs with future forcing, so their starting from a lower annual average diversion volume. Figure caption was revised to make it clear that the right figure is change from their respective Baseline run with the same future scenario forcing.
97	47	Background	Is there a reference for more info?	Bearup, Lindsay A	Accepted. added the citation for the Compact
98	50	Background	Can you describe how this evaluated in the model to compliment the table? It looks like it may be combined with some other irrigation changes so that should also be noted.	Bearup, Lindsay A	Accepted and Updated, there are changes to the irrigated acreages, discussion of this changes was added to the strategy background.

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
100	56	Background	Is this represented in the RiverWare Summary Table 23?	Bearup, Lindsay A	No, Summary Table 23 includes the slots that were changed to implement the model, however, there's a signficant number of slots that are essentially activated when you turn on the Nelson pump. So this isn't a model change per say, the 10cfs minimum is in the Baseline model, but the Nelson pumps are not 'active'. I think the table would get to cluttered if we also add each slot setting involved in each 'activated' part of the model, but most will be inclucded in the old RiverWare model documentation, and the new ones will be clarified in the coming updated RiverWare model documentation.
101	59	Performance and Trade-Offs	Fix all % to percent	Erger, Patrick J	Question for Tech Writer... for APA looks like we should generally use % after a number e.g. 5% and 'percent' after a written out number, e.g. five percent. But we should use numbers e.g. 5 instead of five unless it's the start of a sentence....
102	60	Performance and Trade-offs	Check throughout for consistent capitalization of scenario names	Bearup, Lindsay A	Accepted. Updated.
103	60	Performance and Trade-offs	Why would the shortages be larger under drought relative to the storage project alone? I assume they are compared using the same climate scenario?	Bearup, Lindsay A	Text was updated to clarify. Implementation of the Mitigation Scenarios is helping to alleviate shortages on the Milk River Project users, but not necessarily benefiting the FBIC users in the most extreme droughts

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
104	67	Performance and Trade-Offs	This sentence and the proceeding sentence are not clear to me. I revised the proceeding (confirm correct meaning) but am not sure if here you mean to say that there is a 95-97% reduction or that 95-97% of reductions are for Milk River Users.	Bearup, Lindsay A	Accepted. Paragraph was revised for Clarity that 95 to 97 % of shortage reduction went to Milk River Users.
105	70	Next Steps and Future Considerations	Prior to this section, I think the Rick Assessment with strategies section would benefit from a summary section and potentially a summary figure that shows the benefit of the different strategies relative to each other.	Bearup, Lindsay A	Accepted. Added Summary and Key Findings Section

Table K-8.—Review comments for St. Mary and Milk River basins Study Update final report – Appendix B. Water Supply Development

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
151	Appendix B. Water Supply Development	Hydroclimate Scenario Development	This is the simulated historical data for the 10 selected projects, yes? Something like the following screenshot from Rec. 2010 but with language consistent with the HDe conceptual figure might useful /	Bearup, Lindsay A	Accepted
151	Appendix B. Water Supply Development	Hydroclimate Scenario Development	Is it difference for precip too or percent change?	Bearup, Lindsay A	Accepted
	Appendix B. Water Supply Development	Hydroclimate Scenario Development	Also, make sure I captured your process correctly in the above edits – specifically the “monthly values” part.	Bearup, Lindsay A	Accepted. Made some updates
151	Appendix B. Water Supply Development	Hydroclimate Scenario Development	Consider including the HDe conceptual model again here if you want the appendix to stand alone.	Bearup, Lindsay A	Accepted.
159	Appendix B. Water Supply Development	Hydrologic Modeling Framework. Tp is the snowpack temperature	Should this be Tcrit? Or should Tcrit be this? Make consistent with parameter calibration parameter table and discussion below.	Bearup, Lindsay A	Accepted. Thanks for this catch!

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
159	Appendix B. Water Supply Development	Hydrologic Modeling Framework. b is the depth of melt when Ta=Tp	Did you actually include this parameter? I often see the temp index model without it so if not just remove.	Bearup, Lindsay A	Accepted. Thanks for this catch!
160	Appendix B. Water Supply Development	Hydrologic Modeling Framework	What was used in the gray areas?	Bearup, Lindsay A	Not simulated. Added language to describe reasoning.
161	Appendix B. Water Supply Development	Hydrologic Modeling Framework. Probability density functions of flow	Or is this really probability density functions of the DOY of local peaks in flow?	Bearup, Lindsay A	Accepted. Yes I think so.
161	Appendix B. Water Supply Development	Hydrologic Modeling Framework. with monsoonal rainfall	I am not familiar with monsoon impacts in this region (was a bit surprised to see it mentioned this far north). Either way, I would think Season 4 would align better with NAM monsoon timing (typically about ~Jun-Sep in the southwest anyway.) Perhaps Season 3 is more driven by Pacific events? But May-June still seems like something snow or rain on snow driven to me (particularly in more headwaters basins than the FRRIB location – but dates are not that different across basins)	Bearup, Lindsay A	Accepted
	Appendix B. Water Supply Development	Hydrologic Modeling Framework	To really understand these different peaks, tt might be useful to see this figure along side a hydrograph for the FRRIB (I keep trying to interpret the PDF as one!) with some subsets of example events that fall in each season (since	Bearup, Lindsay A	We added this to the upcoming paper we will be submitting

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
			the pdf gives no indictor of peak magnitude). Perhaps in the paper if time is limiting here. Since these breaks aren't changing for future analyses, I think it is worth a look (or worth some description if already evaluated) to make sure the future conditions are still fitting within these seasons appropriately. This would also possibly support an analysis of changes in snowmelt timing recommended in other comments. Or if it is not worth it because Season 2 and 3 parameters are so similar – just provide the parameter tables in the appendix and note it in the discussion.		
	Appendix B. Water Supply Development	Hydrologic Modeling Framework	Also - the break from season 2-3 seems more pronounced in the pdf curve than in the rug. Might just be overlapping values in the rug or pdf parameters are impacting the pdf low point. Worth a look to make sure parameters aren't impacting dates	Bearup, Lindsay A	Accepted
161	Appendix B. Water Supply Development	Hydrologic Modeling Framework	I don't think the local polynomial change point analysis directly tells us about peak flow characteristics (other than peak flow timing). Consider a different word here.	Bearup, Lindsay A	Accepted
167	Appendix B. Water Supply Development	Hydrologic Modeling Framework daily NSE,	Should this be seasonal NSE (per table 23)?	Bearup, Lindsay A	No. May seem counterintuitive, I understand.

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
168	Appendix B. Water Supply Development	Hydrologic Modeling Framework	Should this be seasons A2 and A3 set to 0-20 with A1,4,5 not contributing to flow? Seems like streamflow during Jan/Feb (season 1) is very small	Bearup, Lindsay A	Accepted
168	Appendix B. Water Supply Development	Hydrologic Modeling Framework	Add that A1 is included to account for future change and that A3-5 were tested in a sensitivity	Bearup, Lindsay A	Accepted
171	Appendix B. Water Supply Development	Hydrologic Modeling Framework October – December daily average temperature	How were these features selected? These are all winter/spring metrics – anything for season 3-5 peaks? As a basin, it seems most of the precip is in May/June but July/Aug still contributes. I also expect spring/summer precip may have more relative importance for some less-snow dominated basins. Also is there an antecedent condition (previous WY) that would be important for the storage relationship? Were any features tested and removed for having low importance?	Bearup, Lindsay A	Accepted. Added some language to communicate justification.
172	Appendix B. Water Supply Development	Hydrologic Modeling Framework Frenchman River at International Boundary	This verification step was done only in the Frenchman, correct? May be worth a line reiterating that near the start of the hist. model verification subsection.	Bearup, Lindsay A	Accepted
172	Appendix B. Water Supply Development	Hydrologic Modeling Framework Frenchman River at International Boundary.	Any comments on March performance since the PKNN ensemble jumps out as being quite different from the observed and simulated monthly flows?	Bearup, Lindsay A	Accepted

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
173	Appendix B. Water Supply Development	Hydrologic Modeling Framework KNN	PKNN vs KNN – are these being used interchangeably in this section? If so, I suggest using one only and if not, check usage and clarify	Bearup, Lindsay A	Accepted. Use PKNN for consistency.
175	Appendix B. Water Supply Development	Hydrologic Modeling Framework feature vectors	Same features as above? See comment there on feature selection.	Bearup, Lindsay A	Accepted.
175	Appendix B. Water Supply Development	Hydrologic Modeling Framework	Was the “closeness” of the nearest neighbors evaluated to make sure each year had a suitable set of neighbors (even if they were nearest they may not be near!)?	Bearup, Lindsay A	Will address this comment as we draft the paper and will add language then
175	Appendix B. Water Supply Development	Hydrologic Modeling Framework	How was this done? Year by year? So is there no correlation from one year to the next?	Bearup, Lindsay A	Right, no correlation from one year to the next, except since the initial storage term, S0, is a calibration parameter we hope that the selected year as an appropriate initial storage term to account for antecedent conditions.

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
177	Appendix B. Water Supply Development	Hydrologic Modeling Framework Projected percent change in annual flow volume by sub-basin.	Color coding this table would be a nice (optional!) addition	Bearup, Lindsay A	What shall we color? Basins by the three regions? Negative versus positive change?
181	Appendix B. Water Supply Development	Hydrologic Modeling Framework In the hydrograph figures	Again – are these historical actual gage data or are they simulated historical timeseries? Helpful to understand possible differences between the lines and would actually be great to see both obs and calibrated model results.	Bearup, Lindsay A	Added language to clarify
181	Appendix B. Water Supply Development	Hydrologic Modeling Framework the grey shaded area represents the range of flows between the 25th and 75th percentiles of the resampled ensemble.	For which scenario? All scenarios?	Bearup, Lindsay A	Yes. Modified language to help clarify.

Table K-9.—Review comments for St. Mary and Milk River basins Study Update final report – Appendix C. Water Demand Development

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
	Appendix C. Demands Development		[In response to copied pasted text from JL's FBIC report] Suggest weaving this info into the management factor discussion.	Spears, John (Mark) M	Update the text to expand upon the purpose of management factors.
	Appendix C. Demands Development. Table 38		Some of the heading abbreviations need defining.	Spears, John (Mark) M	Updated

Table K-10.—Review comments for St. Mary and Milk River basins Study Update final report – Appendix F. Paleo Reconstruction Development

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
241	Appendix F. Paleo Reconstruction Development	high elevation trees that reflect high snow years as reduced width of annual growth rings	Since this is slightly counterintuitive, it might be worth mentioning growth is energy limited and/or a reference (such as https://iopscience.iop.org/article/10.1088/1748-9326/abd5de)	Bearup, Lindsay A	Will let USGS team address
243	Appendix F. Paleo Reconstruction Development	20-year spline shown in Figure 71, Figure 72, and Figure 73	Is this in the naturalized streamflow records, if so recommend moving text in ()'s to the end of this sentence	Bearup, Lindsay A	Accepted
243	Appendix F. Paleo Reconstruction Development	/	Needs a legend – same for 72 and 73	Bearup, Lindsay A	Will let USGS team address
243	Appendix F. Paleo Reconstruction Development	observed	Is this that naturalized streamflow record?	Bearup, Lindsay A	
247	Appendix F. Paleo Reconstruction Development		The color coding in these figures matches the table in the main text well and I recommend that they be presented together.	Bearup, Lindsay A	Will let USGS team address

Page	Section	Paragraph	Comment text	Reviewer	Response to comment
247	Appendix F. Paleo Reconstruction Development		Also in graph a, the y-axis is not clear. Should be cumulative streamflow deficit	Bearup, Lindsay A	Will let USGS team address
250	Appendix F. Paleo Event Scenario Development	For the Riverware Scenarios, the event with the largest instrumental average annual deficit,	Finish thought and include reference it Table 47	Bearup, Lindsay A	Accepted
256	Appendix F. Paleo Event Scenario Development	streamflow	Naturalized streamflow timeseries?	Bearup, Lindsay A	Will let USGS team address
256	Appendix F. Paleo Event Scenario Development	For a given location, a historical year was assigned to be either dry (state represented by 0), if the magnitude of streamflow for the year was less than the median streamflow value or wet (state represented by 1),	This is different from the wet/dry definitions above. Was it actually different or is this a typo? If so, why?	Bearup, Lindsay A	Will let USGS team address