RECLAMATION
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**FINAL FULL REPORT**

# Republican River Basin Study

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

**March 2016**

# Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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.

Cover image: Republican River, looking downstream (eastward) from Cambridge State Aid Bridge (Nebraska Highway 47 crossing), just south of Cambridge, Nebraska. Source: *http://commons.wikimedia.org/wiki/File:Republican_River_from_NE47_DS.JPG*

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STUDY PARTNERS

Bureau of Reclamation
*Nebraska-Kansas Area Office, Great Plains Region*

State of Colorado
*Colorado Division of Water Resources*

State of Nebraska
*Nebraska Department of Natural Resources*

State of Kansas
*Kansas Water Office*
*Kansas Department of Agriculture, Division of Water Resources*

# Acronyms and Abbreviations

| | |
|---|---|
| AF | acre-foot or acre-feet |
| BAC | Basin Advisory Committee (Kansas) |
| Basin | Republican River Basin |
| BCA | benefit-cost analysis |
| BCSD | bias corrected and spatially disaggregated |
| BOD | biochemical oxygen demand |
| CDF | cumulative distribution functions |
| CFR | Comprehensive Facility Review |
| cfs | cubic-feet per second |
| CMIP | Coupled Model Intercomparison Project |
| COD | chemical oxygen demand |
| Commission | Colorado Ground Water Commission |
| Compact | Republican River Compact of 1942 |
| CWA | Clean Water Act |
| D&S | Reclamation Directives and Standards |
| EIS | Environmental Impact Statement |
| EOM | end-of-month |
| EPA | Environmental Protection Agency |
| ESA | Endangered Species Act of 1973, as amended |
| ET | evapotranspiration |
| FCID | Frenchman-Cambridge Irrigation District (Nebraska) |
| FSS | 2003 U.S. Supreme Court Final Settlement Stipulation |
| FVID | Frenchman Valley Irrigation District (Nebraska) |
| GCM | General Circulation Model |
| GHG | greenhouse gases |
| GMD 4 | Northwest Kansas Groundwater Management District No. 4 |
| gpm | gallons per minute |
| HGS | HydroGeoSphere (software) |
| ID | irrigation district |
| IDC | interest during construction |
| IMP | Integrated Management Plan |
| IQR | inter quartile range |

| | |
|---|---|
| IWS | imported water supply (RRCA accounting) |
| KAF | thousands of acre-feet |
| KBID | Kansas Bostwick Irrigation District No. 2 |
| KBID-DOWN | KBID below Lovewell Reservoir |
| KBID-UP | KBID above Lovewell Reservoir |
| KDWPT | Kansas Department of Wildlife, Parks and Tourism |
| KNESCA | Kansas Nongame and Endangered Species Conservation Act |
| $km^2$ | square-kilometer |
| MDS | minimum desirable streamflow |
| MOA | Memorandum of Agreement |
| NBID | Bostwick Irrigation District (Nebraska) |
| NCSD | Nebraska Conservation and Survey Division |
| NDNR | Nebraska Department of Natural Resources |
| NED | National Economic Development |
| NeRRMDA | Nebraska Republican River Management Districts Association |
| NIR | net irrigation requirement |
| NFI | net farm income |
| NNESCA | Nebraska Nongame and Endangered Species Conservation Act |
| NRD | Natural Resource Districts (Nebraska) |
| NGPC | Nebraska Game and Parks Commission |
| NWS | National Weather Service |
| OASIS | Operational Analysis and Simulation of Integrated Systems (modeling software) |
| OMR&P | operations, maintenance, replacement and power |
| PDSI | Palmer Drought Severity Index |
| POS | Plan of Study |
| PR&G | Principles, Requirements, and Guidelines for Water, Land and Related Resources Implementation Studies |
| P-SMBP | Pick-Sloan Missouri Basin Program |
| Reclamation | Bureau of Reclamation |
| RRCA | Republican River Compact Administration |
| RRWCD | Republican River Water Conservation District (Colorado) |

| | |
|---|---|
| RTU | remote terminal unit |
| STORRM | STELLA Operations Republican River Model |
| SYMAP | synergraphic mapping system |
| TDS | total dissolved solids |
| The (Basin) States | Colorado, Kansas and Nebraska |
| TMDL | total maximum daily load |
| STELLA | Systems Thinking Environment and Learning Laboratory Approach (model) |
| UNL | University of Nebraska - Lincoln |
| USACE | U.S. Army Corps of Engineers |
| USDA-NASS | U.S. Department of Agriculture – National Agricultural Statistics Service |
| USGS | U.S. Geological Survey |
| VE | value engineering |
| VIC | variable infiltration capacity |
| WEEG | Water and Energy Efficiency Grants |
| WWCRA | West-Wide Climate Risk Assessments |

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# Summary

The Republican River Basin is an important region for the states of Nebraska, Colorado and Kansas (the States) that includes highly productive agricultural lands, large reservoirs with recreational and wildlife habitat features, and established communities that rely on the agriculturally-driven economy and the water supplies that sustain it. The water management issues in the Republican River Basin are extremely complex and involve a long history of stakeholder involvement and activities. Declines in groundwater levels and streamflows have and continue to be widespread throughout the Basin, creating intense competition for limited water supplies and litigation. This Study provided an opportunity for the three States to move forward toward overcoming some of these challenges by coordinating with the Bureau of Reclamation (Reclamation) to identify and evaluate alternative management and infrastructure changes that might benefit water users within the Basin, while strengthening the local economy and protecting environmental resources. The inclusion of future climate scenarios provided an indication of the robustness of the system under climate variability, such as how the reservoirs and canals might operate and adapt under severe drought conditions, and how physical and operational changes may impact local economic benefits relative to costs. Because of the legal, physical, and institutional complexity of water operations in the Basin, the sub-basin models developed under this Basin Study may be especially important in helping the States investigate relationships between management decisions and physical responses to the Basin water supply. The achievements made through this Basin Study are owed to the high levels of professionalism and collaboration displayed among Basin Study partners. Coupled with recent and ongoing negotiations and agreements, sustainable, win-win solutions to solving the Basin's complex water supply issues appear promising.

A comprehensive discussion highlighting key components of this Full Report is provided in a stand-alone Executive Summary Report on the Republican River Basin Study (Reclamation 2015). Below is a brief discussion of study findings; details are provided at the end of this report in Section 9.0: Findings and Conclusions.

# I. Findings and Conclusions Summary

- This study was a technical assessment and does not provide recommendations or represent a statement of policy or position of the Bureau of Reclamation, the Department of the Interior, or the funding partners. The study does not propose or address the feasibility of any specific project, program or plan. Nothing in the Study is intended, nor shall the Study be construed, to interpret, diminish, or modify the rights of any participant under applicable law. Nothing in the Study represents a commitment for provision of Federal funds.

- Through extensive collaborative efforts between the States, modeling tools were developed for the Nebraska and Lower Kansas sub-basins that provide a consistent representation of hydrology and water operations in the Basin; this was important in helping the States assess impacts of taking no action and may be especially important in investigating relationships between future management decisions and physical responses to the Basin water supply.

# A. Impacts of Climate Variability and Change under No Action

## 1. Surface and Groundwater Supplies

- Average annual streamflow in the Colorado sub-basin is projected to decrease by 7% under the warmer/drier scenario (“Scenario 1”) but increase by 22% under the less warm/wetter scenario (“Scenario 3”, with little change under the central tendency scenario (“Scenario 2”).

- Average annual streamflow in the Upper Kansas sub-basin is projected to decrease by 10% under Scenario 1 and increase substantially under Scenarios 2 and 3 by 28% and 166%, respectively.

- Average annual streamflow in the Nebraska sub-basin is projected to decrease by 8% under Scenario 1 and increase under Scenarios 2 and 3 by 10% and 59%, respectively.

- Average annual streamflow in the Lower Kansas sub-basin is projected to increase slightly under Scenarios 1 and 2 by about 1% and increase moderately under Scenario 3 by 12%. Increases under Scenario 1 result from a large projected increase in precipitation over the Lower Kansas sub-basin, despite a projected decrease in basin-average precipitation under this scenario.

- Projected changes in precipitation suggest that groundwater recharge is likely to decrease in the Colorado and Upper Kansas sub-basins under Scenarios 1 and 2, with little change under Scenario 3. Precipitation recharge is likely to increase in the Nebraska sub-basin under Scenarios 2 and 3, with little change under Scenario 1. Precipitation recharge is likely to increase in varying degrees over the Lower Kansas sub-basin under all scenarios, as all three scenarios project increased precipitation over the sub-basin. The effects of changes in surface water diversions, and corresponding seepage and deep percolation, on the total amount of recharge in each sub-basin is likely to be much smaller than the effects of changes in precipitation.

## 2. Water Demands

- For Nebraska, average net irrigation requirements (NIR) for canal service areas increases by 6.9% under Scenario 1 due to a combination of temperature-driven increase in evaporative demand and decreased precipitation. Average NIR decreases by 8.8% under Scenario 2 and decreases by 20.9% under Scenario 3. Results suggest that projected increases in precipitation over the majority of the Nebraska sub-basin under Scenarios 2 and 3 more than offset temperature-driven increases in evaporative demand (reference evapotranspiration) under these scenarios.

- For Nebraska, when applying district acreages and applying an area weighted average, the NIR decreases by 21% for Scenario 1 and increases by 15% and 44% for Scenarios 2 and 3, respectively. This result is based on Nebraska's modeling approach which estimates irrigated acreage based on available supply (i.e., more water is available under the cool/wet scenario, so acreage is increased and total demand (acres x NIR) increases). Under Scenario 1, acreage is reduced due to low supply, resulting in a decrease in overall demand.

- For Kansas, average NIR increases by 41.4% under Scenario 1 due to a combination of temperature-driven increase in evaporative demand and decreased precipitation. Average NIR increases by 9.3% under Scenario 2 and decreases by 22.1% under Scenario 3.

## 3. Water Supply Imbalances

- This study assessed the effects of imbalances as part of the System Reliability Analysis. System reliability for the Nebraska sub-basin evaluated the effects of water supply imbalances based on irrigated acreage, irrigation diversions and deliveries, and the frequency of Compact Call Years[1]. System reliability for the Lower Kansas sub-basin evaluated the effects of water supply imbalances based on irrigation diversions and deliveries to the Kansas-Bostwick Irrigation District (KBID) above and below Lovewell Reservoir.

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[1] Deficits and shortages for Nebraska were calculated by Reclamation staff based on Nebraska's modeling results. The analysis was for hypothetical purposes only and is not representative of Nebraska's modeling approach.

## B. Nebraska Alternatives

- Nebraska formulated action alternatives to ensure compliance with the Republican River Compact and to increase supplies for all users in the Basin. The alternatives evaluated included augmenting the supply of Swanson Lake and building a new dam on Thompson Creek, a tributary of the Republican River.
- Augmentation of Swanson Lake could be done either by pumping water from Frenchman Creek (Alternative "3A") or from the Republican River (Alternative "3B"). Results showed that both options would increase diversions to the Frenchman-Cambridge Irrigation District (FCID), but this may reduce storage in Harlan County Lake (HCL), which is important to the system in determining when a "Compact Call Year" would be triggered[2]. A reduction in HCL storage would increase the number of Compact Call Years and reduce diversions to the Nebraska-Bostwick Irrigation District (NBID) by a proportionate amount.
- The capital costs estimated by Reclamation for Alternative 3B are over two times more than Alternative 3A ($82 million versus $36 million, respectively).
- Results indicate that that the pumping volumes of 3,000 and 5,000 gallons per minute (gpm) proposed under Alternatives 3A and 3B, respectively, could be increased because pump augmentation operations were almost always able to operate at full capacity for those years in which pumping was allowed. Higher pumping levels would also make the impacts from pump augmentation operations more pronounced, perhaps providing more definitive results to help determine which alternative has more merits.
- Results from this Study also indicate that options exist to modify operations of Alternative 3A/3B – for instance to allow for releases at Swanson Lake in exchange for additional storage at HCL. This would require a more complex modeling effort than that which was undertaken for this Study.
- Construction of a new dam on Thompson Creek (Alternative "5A") increases Franklin Canal diversions, which allows HCL to store more

[2] During Compact Call Years, special provisions are triggered regarding supply augmentation pumping, reservoir releases, and canal diversions throughout the Nebraska portion of the Basin to ensure that compact compliance is achieved.

water, thereby increasing NBID diversions. The capital costs estimated by Reclamation for Alternative 5A totals $92 million.

- The net economic benefits of 3A were the highest of Nebraska's three alternatives, followed by 3B and Alternative 5A. All three alternatives yielded negative net benefits.

## C. Kansas Alternatives

- Kansas formulated action alternatives to address water supply shortages to KBID and to maximize beneficial uses. The primary alternative evaluated included raising the dam at Lovewell Reservoir, which would yield a corresponding increase in volume by 16,000 acre-feet (AF), 25,000 AF, or 35,000 AF.

- Results showed that raising Lovewell Reservoir's dam reduces the magnitude and frequency of KBID shortages by only a small amount under the Baseline Climate Scenario. This is largely due to operational assumptions under the No Action Alternative made by Nebraska during Compact Call Years which require measures to be taken to ensure Compact compliance.

- A reduction in the magnitude and frequency of KBID shortages is slightly more pronounced under the warmer/drier climate scenario, with the 25,000 AF option providing a greater shortage reduction than the 16,000 AF option and a similar shortage reduction than the 35,000 AF option - but at a lower capital cost ($59 million for 25,000 AF versus $84 million for 35,000 AF[3], respectively).

- Considering the high cost of reservoir expansion options and the relatively small reductions to KBID shortages, the only expansion alternative that was selected for an economics analysis (i.e., benefit relative to costs) was the 25,000 AF expansion option. The economics analysis suggests that this alternative may yield positive net benefits due to the increase in reservoir elevation and surface acreage associated with raising the dam and the resulting projected increase in recreational visitation to Lovewell Reservoir; water supply benefits were relatively low

[3] The cost estimates for other expansion options is provided in *Republican River Basin Appraisal-Level Engineering and Cost Estimates on Structural Alternatives, Technical Memorandum No. RRB-8130-BSA-2014-1*. Prepared by the Bureau of Reclamation, Technical Service Center, August 2014.

# I. Introduction

## A. Authority

This Basin Study was conducted under the authority of the 2009 SECURE Water Act (P.L. 111-11) which directed the U.S. Department of the Interior to develop a sustainable water management policy that considers the risks and associated impacts of climate change to water supplies, as well as adaptation strategies to mitigate and minimize those impacts. The Secretary of the Interior established the WaterSMART (Sustain and Manage America's Resources for Tomorrow) program, an umbrella program with many components designed to implement various directives set forth in P.L. 111-11. The Basin Study Program is one of those components, which allows Reclamation to partner with Tribal, State, regional, and local water managers in collaborative efforts to address basin-wide issues associated with water scarcity.

Using Section 9503(b)(3) of P.L. 111-11 as a guide, Reclamation finalized Directives and Standards (D&S) that outline specific requirements for Basin Studies (*http://www.usbr.gov/recman/temporary_releases/wtrtrmr-65.pdf*). According to the D&S, the following elements must be included in Basin Studies: (1) Projections of future water supply and demand, considering specific impacts resulting from climate change; (2) Analyses of how existing water and power infrastructure and operations will perform given current imbalances between water supply and demand and in the face of changing water realities due to climate change; (3) Development of appropriate adaptation and mitigation strategies to meet current and future water demands; and (4) A trade-off analysis of the strategies identified in terms of their ability to meet study objectives.

Federal funding is provided on a competitive, 50/50 cost-share basis with willing non-Federal entities that must submit an application through an open solicitation process. In Fiscal Year 2012, the States of Colorado, Kansas, and Nebraska applied for and received $413,000 in funding for the Republican River Basin Study. These funds were matched with non-Federal funds totaling about $435,000 at the time, representing a 49 to 51% Federal to non-Federal cost share[4].

Reclamation and the States signed a Memorandum of Agreement to begin the Study in November 2012. Signatories of this document included the Director of the Colorado Division of Water Resources, the Secretary of the Kansas Department of Agriculture, the Chief Engineer of the Kansas Division of Water Resources, the Director of the Kansas Water Office, the Director of the Nebraska Department of Natural Resources, and the Area Manager of the Bureau of Reclamation's Nebraska-Kansas Area Office.

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[4] The non-Federal contribution has substantially exceeded this amount. A final accounting of Federal and non-Federal costs will be done at the conclusion of this study.

Accompanying the signed MOA was a Plan of Study (POS) describing (among other things) the purpose and scope of the Basin Study, as well as roles/responsibilities of study partners, schedule, etc. The original schedule contemplated a study completion date within 24 months, or by November 2014. Modeling complications delayed the effort, so the Study completion date was extended 12 months to November 2015. Details regarding the Study's purpose and objectives can be found in *Section 2.0: Purpose and Objectives*.

## B. Location and Description of the Study Area

The Republican River Basin (Figure 1) encompasses all lands draining to the Republican River above the U.S. Geological Survey (USGS) gauging station at Clay Center, KS, including portions of eastern Colorado, southern Nebraska, and northern Kansas. The Basin covers approximately 16 million acres, the majority of which overlie the Ogallala Aquifer, the largest groundwater system in North America that spans eight western states.

The Republican River originates in the high plains of northeastern Colorado, western Kansas, and southern Nebraska. Tributaries originating in northeastern Colorado and western Nebraska flow to the southeast to join the northern side of the mainstem Republican River, while tributaries originating in northwestern Kansas flow in a northeastern direction to join the south side of the mainstem. Approximately 31% of the Basin lies within Colorado, 30% within Kansas, and 39% in Nebraska.

Milford Lake was excluded from the Study area because it is owned and operated by the U.S. Army Corps of Engineers (USACE) and because, with the exception of flood management, its operations do not affect surface water supply, demands, or operations in the Study area, which are the focus of the Study. Irrigation is by far the dominant water demand within the Basin. The Study area contains over 2.7 million acres of irrigated agriculture served by a combination of surface water and groundwater supplies. Of this total farmland, 1.6 million acres are in Nebraska (approximately 90,000 acres in Reclamation projects), 435,000 acres are in Kansas (approximately 50,000 acres in Reclamation projects), and 550,000 acres are in Colorado. In addition to irrigated agriculture, water uses within the Basin include municipal and domestic uses, industry, recreation, and wildlife.

Surface water within the Study area is managed primarily for agricultural uses and flood control. The study area includes seven Reclamation storage reservoirs and one USACE reservoir that provide water for irrigated agriculture, as well as six Reclamation diversion dams that divert water for irrigation purposes. Surface water diversions serve irrigated agriculture in the alluvial valleys that border the Republican River and its primary tributaries throughout the Study area.

Groundwater within the Basin is managed for agricultural, municipal, and industrial uses. As shown in Figure 1, the majority of the upper Republican River Basin upstream of the Nebraska-Kansas state line near Hardy, NE, is underlain by the Ogallala Aquifer, which is part of the larger High Plains Aquifer. The Basin also encompasses a number of alluvial aquifers along the Republican River and major tributaries. The Ogallala Aquifer and alluvial aquifer systems are the primary water supply for most irrigation, municipal, and industrial water users in the Basin.

Previous studies indicate a strong hydraulic connection between the Republican River and its tributaries and the underlying groundwater aquifers throughout much of the Basin (e.g., Szilagyi 1999, Wen and Chen 2006, Scanlon et al. 2012). Groundwater pumping within the Basin results in capture (depletion) of the Basin's surface water supplies. Conversely, surface water operations affect the timing, distribution, and volume of groundwater recharge that occurs as seepage from surface water channels, including the natural stream channels and unlined irrigation canals and laterals, and as deep percolation of applied irrigation water.

Surface water and groundwater resources within the Basin are managed by each of the Basin States: water management, use, and administration are subject to the laws and regulations of each respective state. In addition, the Republican River is subject to the Republican River Compact, an interstate compact that allocates the "virgin water supply"[5] of the Basin among the States. Following litigation in the U.S. Supreme Court, the States entered into a Final Settlement Stipulation, approved by the U.S. Supreme Court in 2003. Under the Final Settlement Stipulation, most stream flow depletions caused by surface water and groundwater diversions for beneficial consumptive use are included in the determination and allocation of the virgin water supply of the Basin. As a result, interaction between groundwater and surface water is a key component of water management within the Basin. Details on the Compact are provided in *Section 1.5: Existing Water Supply Challenges*.

Modeling and analysis in support of the Basin Study were carried out at the sub-basin scale, with each State leading the development of modeling tools and related datasets for its respective portion of the Basin. This sub-basin modeling approach was selected by the Basin Study partners to facilitate the use of best-available data, tools, and expertise in modeling and evaluating current and future water supplies, demands, and operations, as well as in developing and evaluating management alternatives to improve water operations throughout the Basin. For the purpose of this Study, the Study area was divided into four sub-basins. The spatial extent of the four sub-basins is illustrated in Figure 2. The Colorado and Nebraska sub-basins encompass all portions of the Basin within each respective state; the Upper Kansas and Lower Kansas sub-basins encompass the portions of

[5] Per the Republican River Compact, the term "virgin water supply" is defined here as "the water supply within the Republican River Basin undepleted by the activities of man."

the Basin within Kansas that are upstream and downstream of Harlan County Lake, respectively. For modeling purposes, the hydrologic and water operations models developed for the Lower Kansas sub-basin encompass the portion of the Basin from Harlan County Lake in Nebraska to Milford Lake in Kansas, including the portion of the Basin within Nebraska between Harlan County Lake and the Nebraska-Kansas state line. The portion of the Basin from Harlan County Lake to the Nebraska-Kansas state line is included in the modeling tools developed for both Nebraska and Lower Kansas sub-basins; this area is referred to as the 'sub-basin overlap region.'

This Basin Study provides an assessment of current and future surface water supply, demands, or operations in the Study area as well as potential adaptation strategies to address current and future imbalances between supplies and demands. As described in *Sections 6.3* and *6.4: Adaptation Strategies Considered but Eliminated* of this report, the Study partners chose to focus on meeting the water supply needs of three irrigation districts within the Basin: Frenchman-Cambridge Irrigation District (FCID), Bostwick Irrigation District of Nebraska (NBID), and Kansas Bostwick Irrigation District No. 2 (KBID). In order to evaluate water supplies and operations for these districts, new modeling tools and related datasets were developed for the Nebraska and Lower-Kansas sub-basins. As described in *Section 5.2*, these new modeling tools simulate the hydrology and water operations of these sub-basins and provide the basis for detailed analysis of current and future water supplies and demands for the three irrigation districts considered, as well as analysis of system reliability under various alternatives and under a range of projected future climate scenarios. No new modeling tools were developed for the Colorado or Upper Kansas sub-basins.

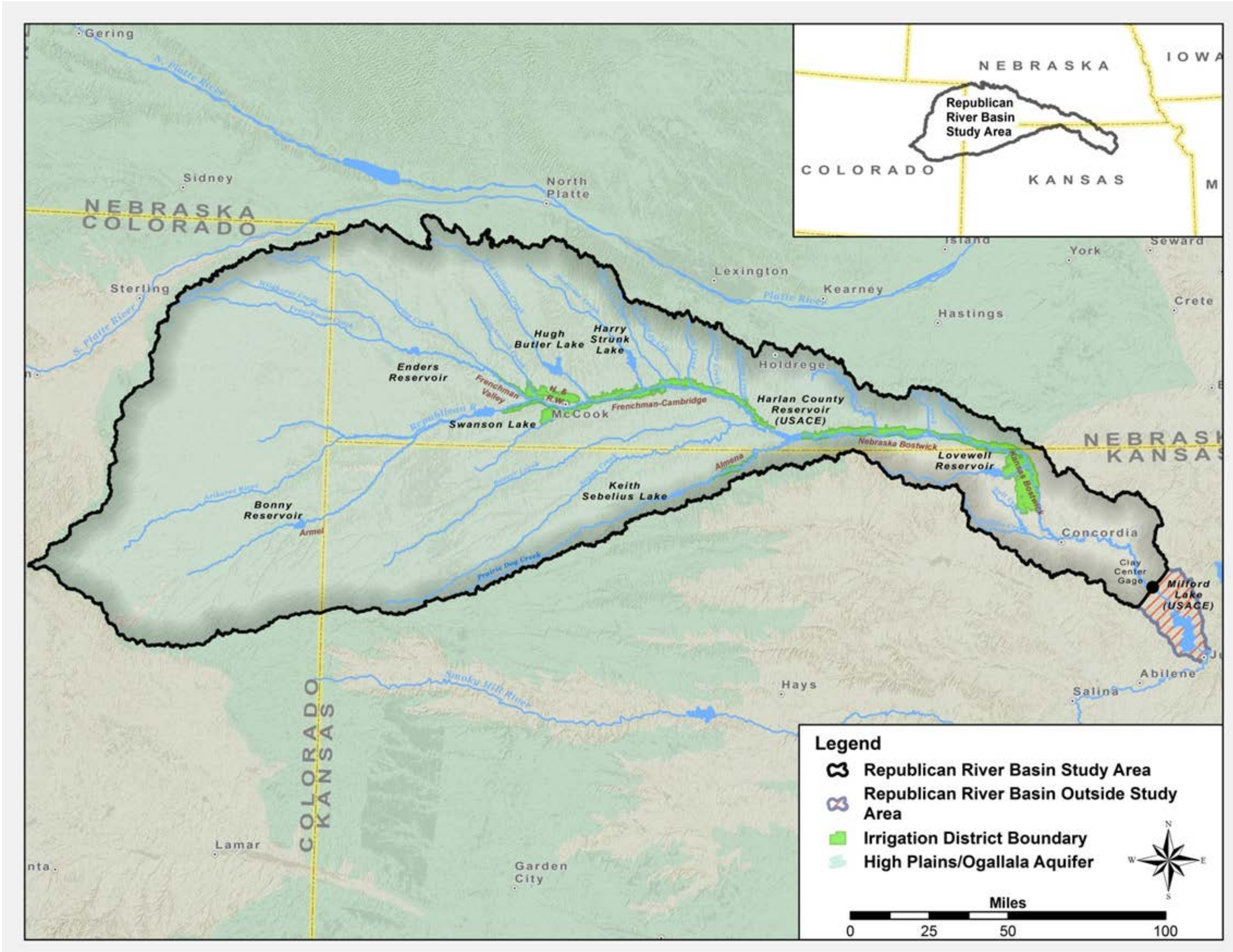



**Figure 1. — Map of Republican River Basin and Study Area**

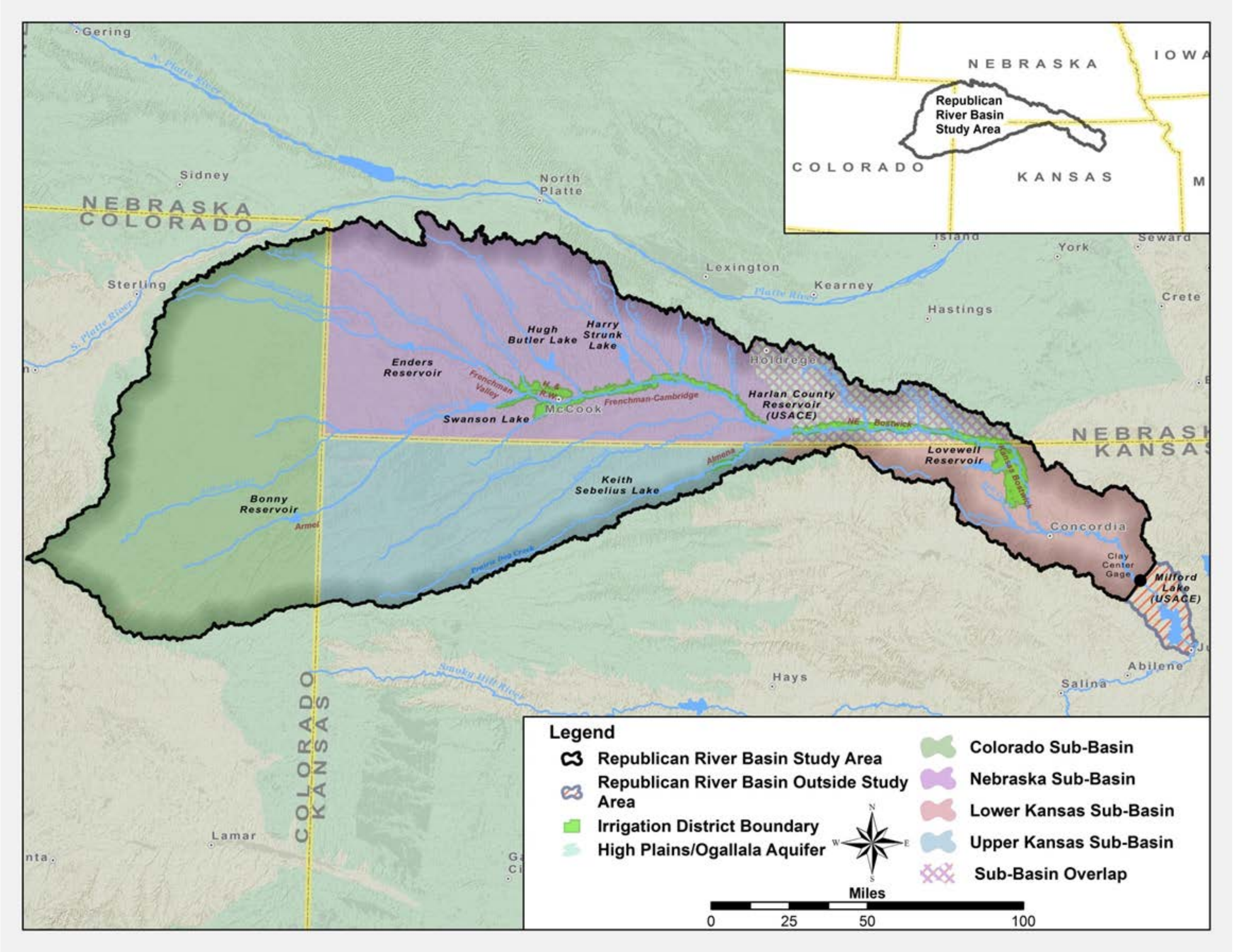



**Figure 2. — Republican River Sub-Basins**

# C. Summary of Federal Features in the Study Area

The Federal features in the Republican River Basin were constructed in the 1940s and 1950s as part of Reclamation's Pick-Sloan Missouri Basin Program (P-SMBP). The features in the Study area include a system of seven Bureau of Reclamation reservoirs, one USACE reservoir, and six irrigation districts. The Reclamation reservoirs include Bonny Reservoir, Swanson Lake, Enders Reservoir, Hugh Butler Lake, Harry Strunk Lake, Keith Sebelius Lake, and Lovewell Reservoir; the USACE reservoir is Harlan County Lake.

The reservoirs in the Study area serve approximately 140,000 irrigated acres within six irrigation districts (IDs). These IDs are divided among four irrigation divisions and multiple units as presented in Table 1.

**Table 1. — Summary of irrigation divisions, units, and districts within the Republican River Basin Study Area**

| State | Irrigation Division | Irrigation Unit | Irrigation District | Reservoir |
|---|---|---|---|---|
| Colorado | Upper Republican | Armel | Hale Ditch* | Bonny |
| Nebraska | Frenchman-Cambridge | Frenchman | Frenchman-Valley | Enders |
| | | | Hitchcock & Red Willow | |
| | | Meeker-Driftwood | Frenchman-Cambridge | Swanson |
| | | Red Willow | | Hugh Butler |
| | | Cambridge | | Harry Strunk |
| | Bostwick Division | Franklin | Bostwick | Harlan County |
| | | Superior-Courtland | Bostwick | |
| Kansas | Bostwick Division | Courtland | Kansas - Bostwick ID No. 2 | Harlan County |
| | | | | Lovewell |
| | Kanaska | Almena | Almena | Keith Sebelius |
| * Hale Ditch is a private canal system. | | | | |

Study partners have undergone an extensive process, both before and during this Basin Study, of considering and eliminating alternatives from consideration to meet their respective planning objectives. For reasons described in *Sections 6.3* (Nebraska) and *6.4* (Kansas) under the "*Adaptation Strategies Considered but Eliminated*" sections of this report, the list of alternative strategies was narrowed for this Study to focus directly on those options that address the water supply needs of the FCID, NBID, and KBID, while also improving recreation benefits and assisting in compliance with the Republican River Compact (discussed further below). The prominent features associated with these alternatives are described below and in *Section 6.5: Description of Adaptation Strategies*.

The FCID provides service to 45,669 acres in Nebraska. Storage water is provided from Reclamation's Swanson Lake (impounded by Trenton Dam). These features are part of the Meeker-Driftwood Unit of the Frenchman-Cambridge Division, part of the P-SMBP authorized by the 1944 Flood Control Act. The dam and its associated facilities were constructed between 1949 and 1953. Generally, storage in Swanson Lake provides the primary irrigation supply to acreage along two canals within the FCID. Irrigation releases from Swanson Lake are made directly into the Meeker-Driftwood Canal, which serves 16,855 acres. The Meeker-Driftwood canal system includes approximately 63 miles of continuous canal with an initial capacity of 284 cubic feet per second (cfs). Irrigation releases for the Bartley Unit are made to the Republican River and diverted at the Bartley Diversion Dam into Bartley Canal, located approximately 32 miles downstream on the Republican River near Indianola, Nebraska. The 19.5 mile-long Bartley Canal system, with a maximum design capacity of 130 cfs, serves 6,353 acres. Beginning in the 1970s, FCID converted all open-ditch laterals to buried pipe. The primary crop grown within the irrigation district is corn, although sorghum, soy beans and alfalfa are also produced.

NBID and KBID comprise the Bostwick Division and provide service to 22,935 acres in Nebraska and 42,500 acres in Kansas. Storage water derives from the USACE's Harlan County Lake and Reclamation's Lovewell Reservoir. The water supply for Harlan County Lake comes from the Republican River and Lovewell's water supply comes from diversions from the Republican River at the Superior-Courtland Diversion Dam with some inflow from White Rock Creek. Irrigation water for the Bostwick Division is diverted directly from Harlan County Lake and Lovewell Reservoir, and from the Republican River at the Superior-Courtland Diversion Dam; a small amount is pumped from the Republican below Harlan County Dam.

# D. Background and History

## 1. Early Canals and Surface Water Irrigation

Settlers had little contact with the Republican River Basin prior to the passage of the Homestead Act in 1862. The period of westward expansion, combined with construction of railroads throughout the West and peaceful relations with American Indians, brought rapid settlement to the valleys along the principal streams and rivers. In the early 1870s, pioneers came to the region to develop the first permanent, non-American Indian settlement at Red Cloud in the eastern

portion of the Basin in Nebraska. Population in the Basin also increased from 1878 to 1882 when the railroad was built along the river.
Residents realized early that the Republican River was not an ideal irrigation stream as the total supply of water would not support extensive irrigation. High flows in the spring or after heavy rain events were usually followed by drier periods over the summer months when crop needs are at their highest. Unpredictable droughts and years of low precipitation also disrupted the steady stream of river water for irrigation.

These issues and increasing competition for water caused the State of Nebraska to pass a major water rights law in 1895. The Prior Appropriation Doctrine reserved water for the oldest water right holder first; then, if any was left, the junior water right holders could take their share (in chronological order). The law also stated that water right holders who were first in time to acquire the right for a given amount of water were first in right to have access to the water.

In 1902, the Reclamation Act authorized the construction of large dams, reservoirs, and irrigation projects using Federal money, and a short time later, the Bureau of Reclamation was developed. Expansion continued during the Great Depression drought years, but one major event prompted a rapid expansion of surface water development in the Basin: the flood of May 1935.

## 2. The 1930s Drought and Flood

Drought in the early 1930s was followed by a devastating flood in May 1935. Rapid rainfall throughout the Basin and near the headwaters area resulted in a flood that devastated areas along the entire length of the river valley, killing 110 people and causing an estimated $8.7 million (equivalent to more than $100 million today) in damage in Nebraska alone. This disaster led the Basin's residents to take the first of a long series of steps to develop, control, and improve the land and water resources in the Basin. Landowners, businessmen, and other concerned citizens requested assistance from the Federal government. In response to these appeals, the Departments of the Interior and Agriculture and the War Department conducted comprehensive studies and surveys of the area. The Bureau of Reclamation started its water resource development work in the Basin in 1939, and on December 31, 1942, the Federal government and Colorado, Kansas, and Nebraska agreed to an interstate compact to allocate water flowing in the Republican River. The Republican River Compact, approved by Congress and signed into law by the President on May 26, 1943, allocates 49% of the river's flows to Nebraska, 40% to Kansas, and 11% to Colorado. However, since its signing, disputes between the States over water use continue despite the Compact's terms. (Details on these disputes can be found in *Section 1.5: Existing Water Supply Challenges and Activities*.)

### 3. Development and Irrigation in the 1940s

As a result of the floods and drought in the 1930s, Congress authorized the Missouri River Basin Project (now the Pick-Sloan Missouri Basin Program [P-SMBP]). Its dams include Harlan County, Milford, Bonny, Enders, Medicine Creek, and Lovewell. The first construction project, called the Bostwick Division, was authorized by Congress in 1944 and work began in 1948. By 1957, the Nebraska part of the Division was essentially complete, and the structures in Kansas were nearing completion. Reservoirs that were developed as part of these projects still provide sources of water for many uses today (i.e., irrigation, recreation, and wildlife habitat). All these water projects continue to be essential to the economies of communities within the Republican River Basin.

The predominant source of groundwater supply within the Republican River Basin is the High Plains/Ogallala Aquifer. Groundwater development in the Basin expanded rapidly during the 1940s, but expansion of groundwater irrigation was delayed until additional supplies of the resource were discovered and technological advancements in drilling and pumping were introduced. Thus, surface water continued to provide the primary source of irrigation water until the early- to mid-1950s.

### 4. Effects of Development

In other areas, beginning in the 1940s, seepage losses from surface water canals began to migrate into the Republican Basin groundwater system and introduced a significant new source of recharge. Land management practices (i.e., farming practices, habitat alterations, etc.) have also affected surface water runoff and aquifer recharge, in that these practices may increase surface water runoff into streams and reduce infiltration of water to the subsurface, or vice-versa. In general, the creation of new water infrastructure, expansion of irrigated acres, implementation of conservation practices, and climate variability have considerably affected groundwater levels and stream flows over time.

## E. Existing Water Supply Challenges and Activities

The water management issues in the Republican River Basin are extremely complex and involve a long history of stakeholder involvement and activities, a brief summary of which is described below. The Republican River Basin has many demands on its limited water supplies, including demands for irrigation, recreation, fish and wildlife, and municipalities. Declines in groundwater levels and streamflows have and continue to be widespread throughout the Basin, creating intense competition for limited water supplies and litigation.

Within the State of Nebraska, five Federal reservoirs (Swanson, Enders, Hugh Butler, Harry Strunk, and Harlan County Lake) are managed by Reclamation[6], and hold water rights that are administered by the Nebraska Department of Natural Resources (NDNR). The reservoirs, in addition to providing flood control, provide storage water to multiple irrigation districts including Frenchman-Valley (9,292 acres), Hitchcock & Red Willow (H&RW;11,662 acres), FCID (45,669 acres), and NBID (22,935 acres). Due to reduced surface water supplies, all Reclamation irrigation projects have decreased water deliveries in recent decades. For example, FCID delivered an average of approximately 18 inches per acre in the mid-1970s, 12 inches in the 1990s, and about seven inches on average currently. Enders Reservoir has not released water for irrigation since 2002. Individual surface water appropriators also experience water shortages and shutoffs during dry conditions. For three consecutive years, 2004, 2005, and 2006, Reclamation projects that utilize Swanson Lake irrigation storage did not receive project water due to the reduced inflows of the Republican River above Swanson Lake.

In addition to these Federal projects, private users divert water from the Republican River and its tributaries either directly through surface water pumping or via private canal diversions. A large number of groundwater wells have also been constructed in the Basin, providing water for the majority of the resource demands in the Basin. The depletions to surface water in the Basin created by these groundwater wells are estimated through the Republican River Compact Administration (RRCA) groundwater model. The RRCA groundwater model is also used to estimate positive groundwater accretions to the Republican River and its tributaries created by seepage from certain canals in the Platte River Basin to the north. Ultimately, output from the RRCA groundwater model is used, as outlined in the RRCA Accounting Procedures, to estimate groundwater pumping impacts (reductions to baseflow) for the three states and Imported Water Supply (IWS) credits (increases in baseflow) to Nebraska resulting from the Platte River Basin canal recharge. The RRCA Accounting Procedures also dictate how gaged surface water flows and consumptive uses are used – in conjunction with the IWS, groundwater pumping impacts, and other estimates – to determine each state’s level of compliance with the Compact. As a result, while a groundwater model is necessary as part of the process to determine Compact compliance, a surface water model is not currently required.

Within the State of Kansas, one Federal reservoir (Lovewell Reservoir) is managed by Reclamation, with water rights administered by the Kansas Department of Agriculture and held by the KBID (42,500 acres). Project water supplies diminished to the point in 2005 and 2006 where no irrigation deliveries were made to the KBID acres located above Lovewell Reservoir, and only minor deliveries were made to the KBID acres below Lovewell. Kansas also has

[6] While Harlan County Lake is owned by the U.S. Army Corps of Engineers, Reclamation is responsible for irrigation operations when water levels are below the flood pool.

established Minimum Desirable Streamflow (MDS) requirements at two locations on the Republican River. Water users who received a water right after the effective date of MDS requirements have water rights subject to administration during periods when MDS flows are not met. When the water supply is insufficient for all users, water right holders with junior rights may be restricted or shut-off.

## 1. Republican River Compact and Disputes

As previously mentioned, the Republican River is subject to an interstate compact between Colorado, Nebraska and Kansas. The Compact, established in 1943, divides the Basin's water supply across eastern Colorado, northwest Kansas, and southwest Nebraska. Reclamation manages irrigation storage water in Harlan County Lake for the Bostwick Irrigation Districts in Nebraska and Kansas. Typically, compact accounting requires five-year averaging of each State's water use. However, during water short years, the averaging is reduced to two years to protect Kansas' Republican water uses. Water short years are defined as when irrigation water supply at Harlan County Lake is less than 119,000 AF. During water short years, additional restrictions are placed on water users upstream of the Guide Rock, Nebraska, gage and Harlan County Lake releases are restricted to those users with water rights senior to February 26, 1948.

As the primary downstream user, Kansas looks to the Compact to prevent overuse by upstream users. As the state with the largest allocation, Nebraska uses the Compact requirements to protect its farmers' water supplies. In 1999, the Supreme Court granted Kansas' motion for leave to file a bill of complaint against Nebraska for violating the Compact by allowing the development of thousands of groundwater wells that connect to the Republican River. Kansas' complaint asserted that Nebraska was failing to prevent future violations, and it asked for damages and a decree commanding Nebraska to meet its delivery obligations under the Compact. Nebraska sought leave to file a motion to dismiss the complaint, questioning whether the Compact applied to groundwater consumptive use within Nebraska. Colorado responded that groundwater from alluvial aquifers was included within the Compact, but groundwater from the deeper Ogallala Aquifer was not.

The Court-appointed special master's report recommended that Nebraska's motion be denied, and in June 2000, the Supreme Court denied Nebraska and Colorado's exceptions. Following a series of memoranda by the special master, the States negotiated a Final Settlement Stipulation (FSS), approved by the U.S. Supreme Court in 2003. In 2007, following the first post-Settlement accounting period, Kansas petitioned this Court for monetary and injunctive relief, claiming that Nebraska had exceeded its water allocation. Nebraska responded that the Accounting Procedures improperly charged the State for using imported water and requested that the Accounting Procedures be modified accordingly. The

Court appointed a Special Master who concluded that Nebraska failed to comply with the Compact for the 2005-2006 period and recommended that Nebraska disgorge a portion of its gains in addition to paying damages for Kansas' loss, and recommended denying Kansas' request for an injunction. In addition, the Special Master's report recommended reforming the Accounting Procedures to prevent Nebraska from being charged for imported water. In February 2015, the U.S. Supreme Court concurred with the Special Master on all issues. Both sides viewed the ruling as a victory, while also recognizing that continued collaboration was necessary to avoid future conflict and to manage the Basin in a sustainable manner.

To this end, the States have been moving forward in cooperative efforts to manage the Basin's water supplies. Four agreements recently signed by the States reflect a change in the traditional ways the Compact has been interpreted and implemented, creating a more cooperative approach:

- On October 22, 2014, two agreements were signed at a Republican River Compact Administration (RRCA) meeting in Denver, Colorado. One ensures that KBID has a viable irrigation water supply for the 2015 growing season while confirming Nebraska's effectiveness of its Compact compliance efforts through full crediting of its augmentation project activities. The other agreement confirms that Colorado and Kansas will work towards improving Kansas' water supply on the South Fork Republican River and authorizes Colorado to receive credit in Compact accounting for water from its augmentation project on the North Fork Republican River.

- On November 19, 2014, the States signed an agreement addressing how water is administered for the benefit of irrigators in the Basin. It provides Nebraska with 100% credit for water delivered for exclusive use by Kansas irrigators to Harlan County Lake prior to June 1, 2015.

- On March 6, 2015, the States and Reclamation signed an agreement that provides additional flexibility for Nebraska to achieve its Compact obligations and lift closing notices pursuant to a Compact Call while ensuring Kansas water users' interests are also protected.

In addition to the RRCA, organizations such as the Republican River Riparian and Restoration Partners, are helping foster sustainable water resources management throughout the Basin. The Riparian and Restoration Partners, led by seven Resource Conservation and Development Programs, provides leadership in the planning and coordination of sound conservation practices, and brings Federal, State, and local entities together to implement a viable living Republican River Basin by 2037.

## 2. Summary of State Activities

### a. *Colorado*

The Republican River Water Conservation District (RRWCD) is an independent entity created by the Colorado State Legislature in 2004 to ensure local involvement in the State's efforts to comply with the Republican River Compact. The fifteen members of the Board of Directors are residents of the Basin appointed by the Commissioners of local counties, boards of groundwater management districts, and the Colorado Ground Water Commission.

The District promotes conservation through voluntary participation by offering, through a variety of Federal programs, financial incentives to producers who voluntarily retire water rights to reduce consumptive use. These water retirements support the District's efforts to conserve the Ogallala Aquifer for future generations.

RRWCD's most recent step toward Compact compliance was a $71 million locally funded pipeline project that was completed on April 4, 2014. The water source for the pipeline comes from existing irrigation wells with pumping limited to historic use. Water is delivered from wells located 8 to 15 miles north of the North Fork of the Republican River to that same stream at the Colorado/Nebraska border just above the measuring device. Colorado will get credit for this water delivery in the accounting for the Republican River Compact among Colorado, Kansas, and Nebraska.

### b. *Nebraska*

In April 2010, a 26-member Republican River Basin Water Sustainability Task Force was created with the passage of LB 1057 by the Nebraska Legislature to help define water sustainability for the Basin, develop and recommend a plan to reach that sustainability, and develop and recommend a plan to help avoid a water shortage in the Basin. The task force, comprised of Basin stakeholders – including water users, local and state policy makers, administrative officials, and residents of the Basin – released a final report on its findings in May 2012.

Within the state, the Department of Natural Resources (NDNR) is responsible for the use and permitting of the state's surface waters for irrigation, hydropower, industrial use, municipal use, domestic use, storage and other uses. Nebraska Legislative Bill 1098 (LB 1098) and Nebraska Revised Statute §46-755 (both approved April 2014), among other actions, required basin-wide water planning in areas where three or more Natural Resources Districts in a river basin are required to complete Integrated Management Plans (IMPs). Currently, the only river basin that the LB 1098 basin-wide planning requirements apply to is the Republican River Basin.

To address this requirement, the NDNR and local natural resources districts collaboratively created a stakeholder group to assist in developing this basin-wide plan. The Basin-Wide Water Management Plan for the Republican River aims to develop goals and objectives with the purpose of sustaining a balance between water uses and water supplies so the economic viability and social and environmental health of the Basin, sub-basin, or reach can be achieved and maintained for both the near term and long term, and ensure compliance with the Compact. The plan is being developed in consultation with over 40 representatives (the Stakeholder Advisory Committee) from a wide range of water users including but not limited to: irrigation districts, Reclamation districts, public power and irrigation districts, mutual irrigation companies, canal companies, surface and groundwater users, range livestock owners, the Game and Parks Commission, and municipalities that rely on water from within the Basin.

### c. *Kansas*

Through the Kansas Water Office, Basin Advisory Committees (BACs) were established to support the statewide Kansas Water Plan, focusing on core categories of agriculture, conservation/environment, fish and wildlife, industry/commerce, municipal public water suppliers, and recreation. Two of these BACs – the Upper Republican and the Kansas-Lower Republican – address Republican River system management within the state. (Note: As of April 15, 2015 the BAC structure is being converted from 12 basins to 14 regions under Regional Advisory Committees [RACs]. The new RACs related to the Republican River are known as the Upper Republican and Solomon-Republican.)

The Upper Republican BAC addresses the Compact and its associated Settlement Agreement requirement that requires Kansas to meet specific quantity goals (Minimum Desirable Streamflow [MDS]) for water leaving the Upper Republican Basin. Climatic conditions, lack of runoff, alluvial groundwater pumping, and reduced stream flows often limit water leaving the state. During the first accounting period (2003-2007) under the Settlement Agreement, Kansas met its obligations under the Compact. However, meeting these obligations in the future may prove to be challenging under future conditions. In this portion of the Basin, there is also a concerted effort among irrigators to slow the declines of the Ogallala-High Plains aquifer underway in Northwest Kansas Groundwater Management District No. 4 (GMD 4).

In anticipation of receiving water from Colorado’s pipeline project (mentioned above), the Upper Republican River Basin Conservation Projects Alliance was formed to develop ideas to use the water. The Kansas Water Office and GMD 4, using the Alliance’s ideas as a starting point, are investigating several water conservation ideas including a municipal pipeline with excess water delivered to Keith Sebelius Reservoir, a centralized, four-county, multipurpose water storage facility; a groundwater recharge project supporting one or more high priority areas; and alluvial recharge, provided there are significant surface diversions.

In 2009, the Kansas Lower Republican River Stakeholder Advisory Committee – consisting of representatives of local, State, and Federal water management agencies – was formed to provide advice on long term improvements in the Lower Republican Basin. The Committee reported its recommendations to the Kansas Water Authority which, in turn, made management of the Lower Republican River system a Kansas Water Plan priority issue.

The Kansas Water Office has also drafted a "Reservoir Roadmap" to provide a comprehensive overview of the current conditions and future impacts to areas currently or potentially served by Federal, State or municipal reservoirs in Kansas. Volume III of this report covers basin-wide approaches to reservoir sustainability including restoration, water conservation, and operational activities targeted to secure, protect and restore water supply availability. A chapter focuses on the Kansas-Lower Republican Basin with a discussion about approaches to improve water supply reliability through increased water supplies, a reduction in demand, or a combination of the two. Alternatives being evaluated for improving water supply reliability include sediment removal, reallocation of storage from one purpose to another, structural restoration, demand management, reservoir operational changes, new reservoirs, off-stream storage, and watershed management. In addition, this document includes discussion of Reclamation's Lovewell Reservoir on the Republican River which, although it does not directly provide public water supply, serves as an important source of irrigation water.

As part of the Republican River Basin Study, a pool rise at Lovewell Reservoir is being evaluated. (A pool rise is an option at a Federal reservoir in which allocated storage above the conservation pool exists, so flood pool storage may be reallocated to water supply storage.) To maintain the flood pool storage required by the USACE, additional conservation pool storage could be reallocated from the surcharge pool. Depending on the quantity of conservation pool storage gained by the pool rise, structural modifications to the existing dam and appurtenant structures may also be required. While the conservation pool at Lovewell Reservoir is used exclusively for irrigation purposes, this potential pool rise could benefit this portion of the Basin. See *Section 6.5: Description of Adaptation Strategies Evaluated* in this report for further discussion.

## 3. Summary of Previous Reclamation Activities and Studies

Reclamation has and continues to be involved in various aspects of water supply management in the Basin. This Republican River Basin Study builds on a number of previous and existing activities to better manage the Basin's existing water resources that are supported by stakeholders throughout the three States. Listed below are several studies and investigations conducted by Reclamation that are significant to the Basin:

- *Republican River Basin, Water Management Study, Special Report*, Bureau of Reclamation, February 1985.
- *Republican River Basin Flows; Flows Adjusted to 1993 Level Basin Development*, Bureau of Reclamation, Technical Service Center, Denver, Colorado, October 1995.
- *Resource Management Assessment, Republican River Basin, Water Service Contract Renewal*, Bureau of Reclamation, Great Plains Region, July 1996.
- *Technical Assistance to States Study, Lower Republican River, Kansas, Water Augmentation Analysis*, Bureau of Reclamation, May 2002.
- *Value Study Report, Proposals for More Efficient Management of Lower Republican River Water Supplies*, Bureau of Reclamation, Technical Service Center, Denver, Colorado, December 17, 2002.
- *Volume Analysis and Revised Flood Frequency Analysis for Comprehensive Facility Review, Lovewell Dam*, Bureau of Reclamation, Technical Service Center, Denver, Colorado, May 2003.
- *Analysis Addressing Hydrologic/Hydraulic Issues, Lovewell Dam*, Bureau of Reclamation, Technical Service Center, Denver, Colorado, September 2003.
- *Lower Republican River Basin Appraisal Report – Nebraska and Kansas*, Bureau of Reclamation, January 2005.

## 4. The Need for Federal Involvement

The need for Federal involvement, in particular Reclamation, stems from the nexus of Federal infrastructure and authorities, as well as the complexity and nature of interstate issues. While key Federal and State stakeholders have been working diligently to improve water management in the Basin, the Basin Study undertaken here was pursued in response to a need for a comprehensive assessment of current and future hydrologic and demand conditions, including risks associated with climate change/variability. Such an assessment is only made possible by coordination and development of modeling tools to quantify conditions and evaluate impacts, and by evaluating solutions within a basin-wide context, in an unbiased manner, and without binding any partner to a particular outcome or solution. Details are provided in the next section that describes this Study's purpose and objectives.

# II. Purpose and Objectives

## A. Study Purpose

The overall purpose of this Basin Study is to identify and help address current and future water supply and management challenges in the Republican River Basin, while also providing a mechanism that allows Colorado, Nebraska, and Kansas to coordinate with Reclamation using basin-wide modeling tools that quantify supplies and demands and consider impacts of climate change on overall system reliability. In doing so, the Study addresses the elements required under the WaterSMART Basin Study Program which are described in Reclamation's Directives and Standards (D&S). Each basin study must include the following: (1) Projections of future water supply and demand, considering specific impacts resulting from climate change; (2) Analyses of how existing water and power infrastructure and operations will perform given any current imbalances between water supply and demand and in the face of changing water realities due to climate change; (3) Development of appropriate adaptation and mitigation strategies to meet current and future water demands; and (4) A trade-off analysis of the strategies identified in terms of their ability to meet study objectives.

The specific manner by which study sponsors complete these elements must be described in a Plan of Study (POS) that outlines study objectives, scope, tasks, roles/responsibilities, and schedule. Study partners developed a POS, and on November 15, 2012, Reclamation and the States signed a Memorandum of Agreement (MOA) whereby they agreed to complete the Study within 24 months in accordance with the POS. Signatories of the MOA included the Director of the Colorado Division of Water Resources, the Secretary of the Kansas Department of Agriculture, the Chief Engineer of the Kansas Division of Water Resources, the Director of the Kansas Water Office, the Director of the Nebraska Department of Natural Resources, and the Area Manager of the Bureau of Reclamation's Nebraska-Kansas Area Office. Although the original schedule contemplated a study completion date within 24 months, or November 2014, modeling complications delayed the effort, so the Study completion date was extended 12 months to November 2015.

While this Study did include a robust process for evaluating conditions and identifying evaluating alternatives for each state, it stopped short of comparing/contrasting alternatives from one state against those from another or from making any recommendations with regards to basin-wide management and optimization. This enabled study partners to follow a more stream-lined process and complete the Study in a timely manner.

## B. Study Objectives

In accomplishing the purposes outlined above, the following objectives were established by study partners:

- Quantify Water Supply and Demand: Estimate current and future water supplies and demands at the Basin and sub-basin levels, and assess the effects of projected future climates on water resources, management, and availability for current and future water rights, and natural and ecological needs.

- Develop Basin Modeling Tools: Develop transparent and scientifically defendable hydrologic and economic models and compile the best available environmental information to aid in conjunctive surface and groundwater management planning. These tools would be used to assess system performance in the trade-off analysis of adaptation strategies.

- Evaluate the Impacts of No Action: Evaluate performance of existing infrastructure and operations under current and future climate conditions based on performance metrics developed by each state.

- Identify and Evaluate Adaptation Strategies: Identify structural and non-structural alternatives that address state-specific objectives described below; evaluate the alternatives based on performance metrics and benefit/cost ratios.

## C. Objectives of Study Partners

Furthermore, each partner put forth a specific list of objectives that each wanted to be addressed in accomplishing the overall Study Objectives described above.

### 1. Reclamation

Operate Bureau of Reclamation project facilities within the Republican River Basin, as well as the USACE Project, Harlan County Lake, to:

1. Maximize water storage in Reclamation and USACE storage facilities, as allowed under applicable State and Federal laws;

2. Consistently meet contractual delivery obligations to Reclamation contractors; and

3. Provide for secondary project benefits, including fish, wildlife, and recreation, as detailed in the Republican River Contract Renewal Final Environmental Impact Statement (June 2000) for the Preferred Alternative and any USACE requirements.

## 2. Colorado

The overall objective for Colorado is to better understand projected climate change in an effort to maintain compliance with the Republican River Compact and Final Settlement Stipulation (FSS). Colorado maintains Compact compliance by operation of the Compact Compliance Pipeline (CCP), reducing irrigated acreage, and curtailing junior water rights (including Bonny Reservoir which is currently operated as a pass through facility). Colorado has requested accounting changes to reflect the addition of CCP augmentation water and modeling adjustments for the occasions when Bonny Reservoir is empty. The RRCA must unanimously approve any accounting and modeling changes. To date, Kansas has refused to accept the proposed changes. Colorado and Kansas have been involved in ongoing negotiations to resolve this issue.
Given Colorado's objectives above, the scope of this Basin Study was limited to the Nebraska and Kansas sub-basins and associated water supply alternatives contained therein.

## 3. Nebraska

The overall objective for Nebraska is to maintain compliance with the Republican River Compact and FSS while maximizing the beneficial use of water for all Nebraska users in the Basin. The two primary components of this objective are:

1. Compact Compliance

    a. Nebraska must maintain compliance with the Compact and FSS, utilizing the jointly developed IMPs approved by the NDNR and the respective NRDs. The models developed under the Basin Study should include logic representative of the most important aspects of the IMP-driven actions, with the understanding that actual management decisions would be more responsive and complex than the simplified approximations included in the modeling structure.

    b. Compact compliance will be measured through the balance between consumptive water uses and water allocations as determined through a simplified version of Compact accounting, including consideration of two- and five-year averaging depending on water-short year status. The models constructed under this Basin Study will include simplified representations used to estimate this balance, which, while not including all the many variables used to determine Compact accounting, should help provide an overall sense of the general balance between uses and allocations. Nebraska's models will only consider the balances with respect to the State of Nebraska, and will not include evaluation of the other states' respective balances.

2. Maximization of Water Use

   a. A key modeling objective is to maximize the beneficial use of water in Nebraska's portion of the Republican River Basin, including the use of surface and groundwater for irrigation, recreation, and other purposes. Both the quantity and the timing of water availability will be considered while attempting to meet this objective.

   b. In the process of designing alternative structures, both physical and operational, to maximize beneficial use, the IMPs will serve as a management framework for determining how each alternative will be structured within the larger context of basin management. While the models will only incorporate a simplified version of the Compact Call Year processes contained within the IMPs, alternatives should be designed to not conflict with the intent and provisions of the IMPs.

### 4. Kansas

The overall objective for Kansas is to secure the State's share of the water it is entitled to under the Republican River Compact, with the ability to manage that water for the maximum benefit of Kansas water users. This includes maximizing the ability to meet the water demands for irrigation, recreation, wildlife areas, municipalities, industries, while also maintaining minimum desirable streamflows.

## D. Collaboration and Stakeholder Involvement

The collaboration and stakeholder involvement process was laid out and agreed by study partners in the MOA. Reclamation and the States of Colorado, Nebraska, and Kansas agreed to share responsibility for management of the Study. The Nebraska-Kansas Area Office represented Reclamation, and the Colorado Division of Water Resources, Nebraska Department of Natural Resources, Kansas Department of Agriculture and Kansas Water Office represented the individual States.

Three teams were responsible for various aspects of the Study: (1) the MOA team developed the MOA that guided the Study; (2) the Basin Study Work Group managed both technical and policy aspects of the Study; and (3) the Study Technical Team conducted technical evaluations and prepared technical memoranda and reports for review by the Basin Study Work Group. The MOA listed members of each team, although that list evolved throughout the Study for various reasons, including staff turnover, changing workload, etc. Despite changes in team membership, the teams were well represented and well engaged throughout the Study. Study managers maintained an administrative record of all electronic and paper documents that substantively recorded study progress and decision points. Copies of the administrative record are available upon request.

The Basin Study Work Group and/or Study Technical Team participated in conference calls either on a monthly, bi-weekly, or weekly basis depending on the scope and complexity of any particular activity. Decision-making was made on a consensus basis, usually orally on conference calls and followed up in emails. Technical Memoranda were shared among study partners at key milestones for review and comment. The type and extent of each review was determined by the type and authorship of each memorandum. Comments and responses were documented and included as part of the administrative record. Communication with stakeholders and the public varied across each agency.

## 1. Reclamation

Reclamation posted a study fact sheet on its website and provided study briefings to stakeholders at the following events:

- Annual Republican River Compact Administration Meeting
- Four States Irrigation Council Annual Meeting
- The Annual Southwest Water Conference
- Nebraska State Irrigation Association Annual Conference
- Various Irrigation Districts Annual Water User Meetings

A copy of the final Basin Study Report will be made available on Reclamation's Basin Study website (www.usbr.gov/WaterSMART/bsp/), as well as that of Nebraska-Kansas Area Office (www.usbr.gov/gp/nkao/).

## 2. Colorado

The State of Colorado engaged with stakeholders in the Basin to make them aware of the Study's objectives and scope. The majority of the Republican River Basin in Colorado makes up a large part of the Northern High Plains Designated Groundwater Basin and is subsequently administered by the Colorado Ground Water Commission (Commission). At several quarterly meetings of the Commission, the Deputy State Engineer gave a general study overview and discussed the Study objectives with those present. Upon completion of the Basin Study, Colorado will notify residents and interested parties in the Basin at a quarterly meeting of the Commission of the Study's completion and general findings. Based on the report's final format, Colorado will determine the most efficient method of making the document available to interested parties. As Colorado has no operational or structural study alternatives, there was minimal feedback received from potential stakeholders. Whenever possible, Colorado continues to periodically inform potential stakeholders of the Study's progress during Colorado Ground Water Commission meetings.

## 3. Nebraska

Stakeholder/public involvement was accomplished primarily through the Nebraska Republican River Management Districts Association (NeRRMDA), an organization consisting of the Lower Republican Natural Resources District (NRD), Middle Republican NRD, Upper Republican NRD, and Tri-Basin NRD, along with Nebraska Bostwick Irrigation District (NBID), Frenchman-Cambridge Irrigation District (FCID), Frenchman Valley Irrigation District (FVID), H&RW Irrigation District, and Pioneer Irrigation District (Pioneer ID); and in partnership with the NDNR. NeRRMDA and NDNR initiated a project in early 2011 to develop a conjunctive management plan for the Republican River Basin, in part through the creation of a surface water operations model, which could be linked to the existing groundwater model for the Basin. Although undertaken prior to the signing of the Basin Study MOA, the conjunctive management work for the NeRRMDA served as the foundation for the Nebraska stakeholder involvement efforts associated with this Basin Study, and included several public meetings to solicit input on model and plan development. Below is a short summary of NeRRMDA public meetings that supported the conjunctive management program, including highlights of the major topics and issues:

- July 26, 2010 – This meeting, held at the Tri-Basin NRD offices in Holdrege, Nebraska, included an update from NDNR staff on the conjunctive management project. Representatives from Tri-Basin NRD, Reclamation, FCID, and the Upper and Lower Republican NRDs were also in attendance, along with Senator Mark Christensen. Discussions included the possibility of switching between groundwater and surface water sources within Pioneer ID, Riverside ID, and FCID; the pros and cons of using natural flows versus storage flows; and issues concerning Harlan County Dam and its gate replacement. Public comment was also allowed as part of the open forum portion of the meeting.

- April 18, 2011 – This kickoff meeting was held at the Middle Republican NRD offices in Curtis, Nebraska, and included an update on the STELLA surface water model development, along with discussion of potential scenario concepts. Representatives from the Middle, Upper and Lower Republican NRDs, NDNR, NBID, FCID, Tri-Basin NRD, and FVID were also in attendance. There were discussions concerning the linkage between the groundwater and surface water models, as well as the use of Reclamation SCADA data for certain canal locations. Several alternatives were discussed, including the pump-back project with Swanson Reservoir, the construction of reservoirs below Harlan County Lake, and the use of canals for recharge purposes.

- October 11, 2011 – A conference call was held with representatives from the Upper, Lower and Middle Republican NRDs, Reclamation, NDNR, FCID, and FVID concerning the potential alternatives to be considered. An early discussion was also held in which geographic scope, and the timeframes for project completion were identified as potential evaluation criteria. Attendees discussed the possibility of combining alternatives to consider inter-project impacts and benefits, and alternatives including the use of canals for recharge, and addition of reservoir storage above and below Harlan County Lake, were mentioned.

- September 7, 2012 – This meeting was held at the Lower Republican NRD offices in Alma, Nebraska, and included an update on the Conjunctive Management project. Attendees included, but were not limited to, representatives from the Lower, Upper and Middle Republican NRDs, Reclamation, Tri-Basin NRD, FCID, NBID, USGS, and NDNR. Much of these discussions focused on potential alternatives, including the locations for new reservoirs, both above and below Harlan County Lake. Changing the storage capacity of existing reservoirs was also brought up as a potential alternative. Linkages between Meeker Canal and the Culbertson Canal were mentioned, as were potential reservoir sites on Turkey, Center, Cottonwood, Elk, Thompson, and Beaver Creeks. It was also mentioned that new reservoirs could provide new water supplies for the Superior Canal, potentially through exchanges with other water supplies such as Harlan County Lake storage to reduce necessary diversions at the Guide Rock Diversion Dam. There was considerable discussion concerning the practicality of various sites for new reservoirs, including features such as the reliability and quantity of available flows, the geographic features of potential sites, and linkages with existing surface water infrastructure. Time for public comment was also allowed during the meeting.

The NDNR plans to engage with the NRDs, cooperating irrigation districts, and other stakeholders to discuss the lessons and results learned through the Basin Study process, while turning its focus to more specific and targeted projects. Canal recharge opportunities such as those included in *Section 6.5: Description of Adaptation Strategies Evaluated*, and other conjunctive management options identified through dialogue with stakeholders, will be considered in the future as the State of Nebraska continues to work towards enhancing water supply reliability for its users, while ensuring compliance with the Republican River Compact in direct cooperation with the other Basin States.

### 4. Kansas

The State of Kansas engaged stakeholders through a variety of meetings and conferences from 2012 to present. Basin Study results will ultimately be shared through these similar forums:

- Upper Republican River Basin Advisory Committee Meetings
- Lower Republican River Management Advisory Committee Meetings
- Republican River Restoration Partnership Stakeholder Meetings
- Solomon-Republican Regional Advisory Committee Meeting
- Midwest Groundwater Conferences
- National Groundwater Association Groundwater Summits
- Association of Engineering Geologists Kansas Hydrology Seminars
- Northwest Kansas Groundwater Management No. 4 Board Meetings
- Kansas Lower Republican River Stakeholder Meetings
- HydroGeosphere User's meetings
- Annual Geological Society of America meetings
- Kansas Governor's Water Conferences

## E. Summary of Basin Study Technical Memoranda

Several technical memoranda and other deliverables were completed throughout key milestones in support of tasks outlined in the POS. For the sake of report brevity, these TMs are not included as appendices of this report; rather, only the most substantive and applicable TM content was inserted into the body of this report. A list is provided below, copies of which are available at Reclamation's Great Plains Regional Office in Billings, Montana upon request:

1. *Memorandum of Agreement No. R12MA60094 and Plan of Study on the Republican River Basin Study*. Prepared by Reclamation and the States of Colorado, Nebraska, and Kansas, November 2012.

2. *Republican River Basin Appraisal-Level Engineering and Cost Estimates on Structural Alternatives, Technical Memorandum No. RRB-8130-BSA-2014-1*. Prepared by the Bureau of Reclamation, Technical Service Center, August 2014. (Ref: Engineering TM [Reclamation 2014])

3. *Nebraska Modeling Methods for the Republican River Basin Study Project*. Prepared by the State of Nebraska, May 2015. (Nebraska Modeling Methods TM [TFG 2015a])

4. *Nebraska Modeling Results for the Republican River Basin Study Project*. Prepared by the State of Nebraska, June 2015. (Nebraska Modeling Results TM [TFG 2015b])

5. *Integrated Groundwater/Surface Water Model for the Lower Republican River Basin, Kansas: A Progress Report*. Prepared by the Kansas Geological Survey and Kansas Water Office, February 2015. (Kansas Modeling Methods TM [KGS and KWO 2015b])

6. *Republican River Basin Study: Kansas Modeling Results Technical Memorandum*. Prepared by the Kansas Geological Survey and Kansas Water Office, May 2015. (Kansas Modeling Results TM [KGS and KWO 2015a])

7. *Republican River Basin Study: Summary of Sub-Basin Model Coordination, Technical Memorandum No. 86-68210-2015-04*. Prepared by the Bureau of Reclamation, Technical Service Center, May 2015. (Coordination TM [Reclamation 2015c])

8. *Climate Change Analysis for the Republican River Basin Study, Technical Memorandum No. 86-68210-2015-07*. Prepared by the Bureau of Reclamation, Technical Service Center, June 2015. (Climate Change TM [Reclamation 2015b])

9. *Economics Technical Report for the Republican River Basin Study, Technical Memorandum No. EC-2015-02*. Prepared by the Bureau of Reclamation, Technical Service Center, June 2015. (Economics TM [Reclamation 2015a])

## F. Technical Sufficiency Review

Each technical memorandum underwent a technical sufficiency review pursuant to Reclamation's D&S WTR TRMR-65 on Basin Studies[7] to ensure that the technical information, data, models, analyses, and conclusions were technically supported and defensible. Reviews were conducted by reviewers who had relevant expertise and were not directly involved with conducting the portion of

[7] Even though the MOA was signed before finalization of the D&S, study partners agreed to follow the process described in the newer D&S.

the Basin Study they were reviewing. Table 2 below lists the reviewers assigned to the technical memoranda.

**Table 2. — Technical Sufficiency Review of Various Republican River Basin Study Components and Technical Memoranda**

| | | | |
|---|---|---|---|
| Reclamation's Appraisal-Level Engineering of Structural Alternatives | John Laboon, Waterways and Concrete Dams Group | Professional Engineer, Civil | 08/19/14 |
| Reclamation's Appraisal-Level Engineering of Structural Alternatives | Dennis Hanneman, Geotechnical Engineering Group | Professional Engineer and Group Manager, Geotechnical | 08/19/14 |
| Reclamation's Appraisal-Level Engineering of Structural Alternatives | Christopher Ellis, Geotechnical Engineering Group | Professional Engineer, Geotechnical | 08/19/14 |
| Reclamation's Appraisal-Level Cost Estimates | Tom Hanke, Estimating, Specifications, and Construction Management Group | Professional Engineer, Civil | 07/08/14 |
| Reclamation's Appraisal-Level Cost Estimates | Ngoc Dam, Estimating, Specifications, and Construction Management | Professional Engineer, Electrical | 07/08/14 |
| Reclamation's Economics Technical Report | Todd Gaston, Economics, Planning, & Technical Communications Group | Master of Science in Agricultural & Resource Economics | 06/09/15 |
| Reclamation Historical Climate/hydrology, Climate Change Analysis | Alan Harrison | Civil/Environmental Engineer with 23 years' experience with Reclamation, including 10 years working on climate and evapotranspiration projects. | 06/10/15 |
| Nebraska STELLA Surface Water Model Development and Operations | David Kracman<br>The Flatwater Group, Inc. | Master's Degree in Civil & Environmental Engineering, with a focus on Water Resources Management and Planning. Over 15 years' experience in constructing and using reservoir operation models (simulation and optimization). | 05/29/15 |
| Nebraska analyses of STELLA Surface | Tom Riley<br>The Flatwater Group, Inc. | Professional Engineer, Civil;<br>Master's Degree in Civil | 06/09/15 |

| Study Component | Reviewer Name | Qualifications and Expertise | Date Completed |
|---|---|---|---|
| Water Model Results and Review of Methods Tech Memo | | Engineering with over 25 years of experience in water resources planning, design, and management. | |
| Nebraska analyses of STELLA Surface Water Model Results and Use of CropSIM for derivation of Net Irrigation Requirement | Marc Groff<br>The Flatwater Group, Inc. | Professional Engineer, Civil | 06/17/15 |
| Nebraska analysis of STELLA Surface Water Model Results, and Review of Technical Memos on Modeling Methods and Modeling Results | Jesse Bradley<br>Nebraska Department of Natural Resources | Master's Degree in Hydrogeology. Over 10 years of experience in water management planning and groundwater modeling and hydrology. Specific experience with Republican River Compact accounting procedures and basin operations | 06/09/15 |
| Kansas Model Development (Linking of OASIS and HGS) and calibration | Jim Butler Jr. | Senior Scientist, Kansas Geological Survey<br>Hydrogeologist | 01/2015 |
| Kansas Model Development (Linking of OASIS and HGS) and calibration | Geoff Bohling | Associate Scientist, Hydrogeologist | 01/2015 |
| Kansas Hydrologic data (water use, demands, GIS coverages) | Chris Beightel | Program Manager, Kansas Dept. of Agriculture-Division of Water Resources (KDA-DWR)<br>Engineer | 01/2015 |
| Kansas Operational data (Kansas and Republican River Compact Administration administrative and legal framework for managing the Basin's water) | Chris Beightel | Program Manager, KDA-DWR<br>Engineer | 01/2015 |
| Kansas Model Development & Calibration (OASIS) | Matt Unruh | Environmental Scientist, Kansas Water Office<br>Water Resources Planner | 02/2015 |

# III. Current and Future Climate Conditions

The American Meteorological Society defines *climate* as “the slowly varying aspects of the atmosphere-hydrosphere-land surface system” (AMS 2012). The climate of a given region is generally described by the long-term average weather conditions over the region – for example, average precipitation and temperature – and the variability with respect to average conditions, including seasonal, interannual, and interdecadal fluctuations in regional weather patterns. Climate is typically considered over time-scales of decades, whereas weather is commonly considered on time-scales of days to weeks.

This section characterizes the current climate conditions in the Republican River Basin based on observed climate conditions, including average conditions for the period 1970-1999 and observed trends over the period 1960-2010. Future climate conditions are then characterized for the period 2030-2060 based on an ensemble of bias corrected and spatially disaggregated climate projections over the Basin. Lastly, this section describes the selection of three future climate scenarios for detailed analysis of system reliability under projected future climate conditions.

## A. Current Climate Conditions

### 1. Summary of Previous Studies

The Republican River Basin is located in the central portion of the Great Plains region of the U.S. The Great Plains region exhibits a continental climate characterized by extreme and variable weather and climate conditions (Rosenberg 1987). Key weather and climate features of the central Great Plains region and the Republican River Basin include: large range of daily, seasonal, and annual temperature and precipitation conditions; high solar radiation, strong winds, and low atmospheric humidity resulting in high ET rates; strong east-west gradients in annual mean precipitation and temperature; and frequent severe weather, including strong winds, hail, and tornadoes (Rosenberg 1987).

The Republican River Basin is characterized by semi-arid to humid climate conditions, with semi-arid conditions occurring in the western portion of the Basin and sub-humid to humid conditions occurring in the eastern portion of the Basin (NOAA 2011). Annual mean precipitation during the period 1970-1999 ranges from less than 15 inches per year near the western extent of the Basin in Colorado to more than 30 inches per year near the eastern extent of the Basin in Kansas (NDMC 2008). Temperatures within the Basin also exhibit a strong east-west gradient, with annual mean temperatures ranging from less than 48 degrees Fahrenheit (°F) in the west to approximately 55 °F in the east.

In addition to the strong east-west gradient over the Basin, the central Great Plains region also experiences large seasonal and interannual climate variability and extremes. Seasonal variability, for example, is illustrated by the uneven distribution of precipitation during the year: on average, 40% of annual precipitation falls during the months of May, June, and July, while between 5-7% of the annual total falls in the months of December, January, and February (Bathke et al. 2014). As one example of climate extremes in the region, portions of Nebraska experienced severe flooding in 2011, followed by extreme drought and persistent extreme heat events (heat waves) throughout much of the state in 2012 (Bathke et al. 2014).

Previous analyses of historical climate trends in the Great Plains region are summarized in Reclamation's 2013 literature synthesis (Reclamation 2013b). Several recent analyses of historical climate data from the U.S. Historical Climatology Network and other historical data sources indicate a slight increase in annual precipitation over much of the region during the 20$^{th}$ century. While the magnitude and statistical significance of historical precipitation trends vary between studies, several studies suggest a slight increase in wintertime precipitation, with more consistent precipitation trends in the southern Great Plains compared to the northern Great Plains. In addition, several studies indicate an increase in extreme precipitation events in the Great Plains during the 20$^{th}$ century, suggesting a warming-induced increase in thunderstorm activity (Reclamation 2013b).

As summarized by Reclamation (2013b), recent analyses indicate a relatively small increase in annual mean temperature over the Great Plains region during the 20$^{th}$ century. However, several studies cited in the literature synthesis found significant increases in seasonal mean temperature, with increases of up to 1.8 °F in spring (March-April-May) and 2.0 °F in winter (December-January-February). In contrast to precipitation trends, which are more consistent in the central Great Plains region, several studies suggest that the greatest warming occurred in the northern Great Plains region. Previous studies found an overall temperature increase of approximately 1.85 °F in the northern Great Plains and 0.63 °F in the southern Great Plains over the period 1901-2008. Similar trends were reported by Bathke et al. (2014). In addition to seasonal temperature trends, recent analysis of 20$^{th}$ century climate conditions indicates that the length of the frost-free season in Nebraska has increased anywhere from 5 to 25 days since 1895, and on average by more than one week (Bathke et al. 2014).

In addition to trends in precipitation and temperature, recent studies suggest that the Great Plains region has also experienced trends in snowpack and streamflow over the 20$^{th}$ century. Kunkel et al. (2009) found snowfall declines from 1920-1921 to 2006-2007 in the central Great Plains, contrasted by large increases in the lee of the Rocky Mountains and parts of the north-central Great Plains. Despite increases in annual snowfall in parts of the region, however, several studies cited by Reclamation (2013b) indicate a general decline in spring snowpack, reduced snowfall to precipitation ratios in winter, and earlier snowmelt runoff throughout much of the region. Other studies found that the fraction of annual streamflow occurring during late spring and summer has declined by 10-25% over recent decades in the northwestern portion of the region, and that snowmelt-driven runoff occurs 1-3 weeks earlier. Observed trends in snowpack and runoff were shown to result primarily from rising temperatures rather than changes in precipitation. While snowmelt is not a dominant source of runoff in the Republican River Basin, these studies highlight the important role of temperature in the hydrologic cycle and water resources of the region.

While numerous studies have evaluated historical trends in climate conditions in the central Great Plains region, including the Republican River Basin, it should be noted the magnitude and statistical significance of trends in precipitation differ strongly between studies depending on the dataset(s) and period of record considered. Trends in temperature, by contrast, are more consistent between studies. Differences in precipitation trends between studies are likely due to the larger temporal and spatial variability in precipitation over the region combined with the relatively large uncertainty in precipitation measurements (e.g., Legates and DeLiberty 1993).

In addition, it should be noted that trends in historical precipitation have not been clearly attributed to anthropogenic forcing (Hoerling et al. 2012). Global and regional temperature trends have been attributed to anthropogenic forcing of the climate system through human-induced changes in atmospheric composition and land cover (IPCC 2007, IPCC 2014). Worldwide trends in observed mean and extreme precipitation trends show signs of the influence of human forcing of the climate; however, climate models produce a notably weaker precipitation change signal than is seen in the observations. There is growing evidence of a linkage between the warming of the globe, arctic sea ice decline, and extreme winters across the eastern two-thirds of the U.S., including the Great Plains region (Reclamation 2013b). However, attribution of historical precipitation trends to anthropogenic forcing remains inconclusive.

In addition to climate conditions, previous studies have analyzed trends in streamflow and groundwater elevations in the Republican River Basin. The Nebraska Department of Natural Resources recently evaluated trends in the Nebraska portion of the Basin based on historical streamflow records from gages operated and maintained by the USGS and/or NDNR. Results demonstrate a notable decrease in the magnitude and interannual variability of streamflow throughout much of the Basin from the mid-1960s to the mid-2000s, with increasing streamflow declines during the latter portion of this period (HDR 2006). Previous studies suggest that streamflow declines occurred primarily due to widespread expansion of irrigated agriculture throughout the central and western portions of the Basin during the mid- to late-20$^{th}$ century (Szilagyi 2001). Streamflow declines occurred due to a combination of increased diversions of surface water for irrigation uses and increasing stream depletions from groundwater pumping for irrigation purposes. Further analysis of the causes of trends in the magnitude and variability of observed streamflow is beyond the scope of this analysis.

Nebraska DNR also evaluated trends in groundwater elevations in the Nebraska portion of the Basin for two periods: 1980-1999 and 1999-2005. During the period 1980-1999, groundwater levels declined through the western half of the Nebraska portion of the Basin (west of Gosper County, NE) and rose throughout the eastern half of the Nebraska portion of the Basin (HDR 2006). Declines in the western portion of the Basin near the Colorado-Nebraska state line exceeded 12 feet in some areas, while increases in groundwater elevations in the eastern portion of the Basin exceeded 12 feet in the areas north and west of Harlan County Lake. During the period 1999-2005, however, groundwater levels declined throughout the Nebraska portion of the Basin, with declines exceeding 12 feet in some areas during this period (HDR 2006). Increases in groundwater levels in the eastern portion of the Basin during the period 1980-1999 were attributed to importation of surface water from the Platte River for irrigation and subsequent recharge via deep percolation of irrigation water. No attempt was made to attribute declines in groundwater elevations; however, previous studies have attributed groundwater declines throughout the Republican River Basin to widespread expansion of irrigated agriculture (e.g., Szilagyi 1999, Wen and Chen 2006, Scanlon et al. 2012).

## 2. Analysis of Current Climate Conditions

### a. *Data and Methods Used*

Historical climate conditions over the Basin were characterized based on the gridded daily precipitation and temperature dataset developed by Maurer et al. (2002). Climate conditions were characterized with respect to spatial and temporal variability of precipitation and temperature. Spatial variability was characterized by evaluating climate statistics over the Basin for the period 1970-1999; temporal variability was characterized by evaluating seasonal and annual basin-averaged climate conditions over the period 1950-2010.

The historical climate dataset used in this Study was developed by Maurer et al. (2002) for the period 1949-2000 and later extended by Dr. Ed Maurer through the year 2010 (Maurer 2013). This dataset utilizes daily precipitation and temperature data from the National Weather Service (NWS) Cooperative Observer (Co-Op) network and Environment Canada. The station data are processed to remove spatial and temporal inconsistencies and then interpolated to a 1/8° degree grid (1/8° latitude by 1/8° longitude) covering the continental United States, as well as portions of Canada located in river basins that drain into the U.S. (e.g., the Columbia and Missouri river basins).

Gridded daily precipitation fields were constructed from records of daily total precipitation from the NWS Co-Op network and Environment Canada. The spatial density of precipitation stations varies widely throughout the continental United States, with an average of one station per 700 square-kilometer ($km^2$) (Maurer et al. 2002). Precipitation gauge data were interpolated to a 1/8° degree grid using the synergraphic mapping system (SYMAP) method. Gridded precipitation was then rescaled to match long-term average of the parameter-elevation regression on independent slopes (PRISM) precipitation climatology of Daly et al. (1994, 1997).

Gridded daily temperature fields were constructed for daily maximum and daily minimum temperature fields, respectively. The average spatial density of daily temperature stations is approximately one station per 1000 $km^2$. Daily maximum and minimum temperatures were interpolated to a 1/8° degree grid by the same method used to construct daily precipitation fields. Gridded temperature fields were then adjusted to account for elevation based on an assumed lapse rate of -6.5 °C per 1000m elevation.

The gridded daily precipitation and temperature datasets developed by Maurer et al. (2002) were previously verified by comparison to available station records, other gridded datasets, and by evaluation of hydrologic model simulations with these datasets used as meteorological inputs (Maurer et al. 2002). Results suggest that while the values at a given grid cell typically do not exactly match station records from gauges located within the cell, they do capture the daily, seasonal, and interannual variability of station records. In addition, the gridded datasets provide complete and consistent representation of climate conditions that is appropriate for analysis of spatial and temporal variability in climate conditions over large areas.

### b. *Current Precipitation*

As illustrated in Figure 3, climate conditions in the Basin exhibit a substantial east-west moisture gradient, with humid conditions in the eastern portion of the Basin and semiarid conditions in the western portion. Annual mean precipitation for the period 1970-1999 ranged from more than 35 inches per year near the eastern extent of the Basin in Kansas to less than 12 inches per year near the western extent of the Basin in Colorado. While the east-west precipitation gradient is evident in all seasons, it is strongest during summer (June-July-August, JJA). Average summer precipitation is greater than 15 inches in the eastern portion of the Basin in Kansas and less than 5 inches in the western portion of the Basin in Colorado.

In addition to the strong east-west gradient over the Basin, climate conditions also exhibit strong seasonal and interannual variability. Seasonal variability is characterized by hot, wet summers and cold, dry winters. The Basin typically receives most of its precipitation during spring and summer, with approximately 70% of the annual total precipitation occurring between April and September.

Figure 3 clearly illustrates the large differences in seasonal mean precipitation over the Basin. Seasonal variability in precipitation is further illustrated in Figure 4, which shows the median monthly basin-averaged precipitation for the period 1970-1999 (black line) along with the range of monthly values between the $10^{th}$ and $90^{th}$ percentiles (blue shading). Figure 4 clearly shows the distinct seasonal cycle of precipitation over the Basin, with dry conditions in winter and wet conditions from late spring through summer. The range of historical values between the $10^{th}$ and $90^{th}$ percentiles is large compared to the median value.

Two measures of interannual variability of annual precipitation are illustrated in Figure 5: the standard deviation and the inter quartile range (IQR). Both the standard deviation and IQR measure the dispersion (spread) of a given dataset; larger values of both metrics indicate greater variability (i.e., large variations from year to year) whereas smaller values indicated less variability (i.e., consistent conditions from one year to the next). Standard deviation of annual precipitation ranges from less than 3 inches in the western portion of the Basin to approximately 10 inches in the eastern portion. Similarly, IQR ranges from approximately 3 inches in the western portion of the Basin to approximately 12 inches in the east. Both metrics indicate that precipitation exhibits larger year-to-year variability in the wetter eastern portion of the Basin, with less interannual variability in the drier western portion.

At the basin scale, interannual variability in seasonal and annual precipitation is illustrated in Figure 6, which shows time series of seasonal and annual precipitation for the period 1950-2010. Basin-average annual precipitation ranges from less than 15 inches in dry years to nearly 30 inches in wet years. Basin-averaged precipitation exhibits large interannual variability for all seasons, with evidence of interdecadal variability in spring and summer. Trends in basin-averaged seasonal and annual precipitation (blue lines) indicate a slight increase in precipitation for all seasons; however, trends are not statistically significant for any season. The spatial distribution of trends in annual precipitation is illustrated in Figure 7; trends are statistically significant only over a small portion of the Basin.

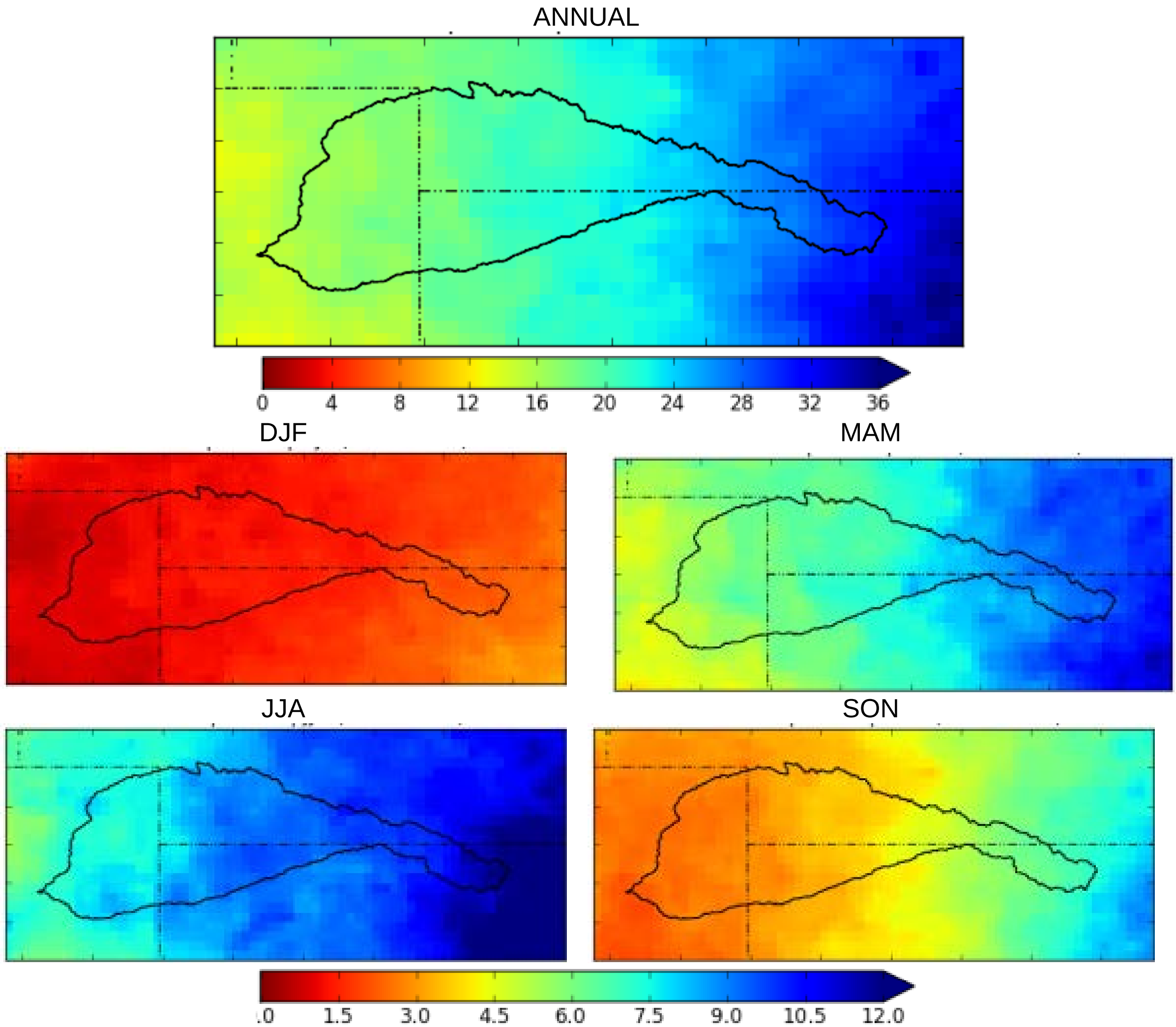



**Figure 3. — Spatial distribution of annual and seasonal mean precipitation. Seasonal precipitation shown for winter (December-January-February; DJF), spring (March-April-May; MAM), summer (June-July-August, JJA), and fall (September-October-November; SON). Colorbar indicates mean precipitation [inches/year]; black line delineates Republican River Basin.**

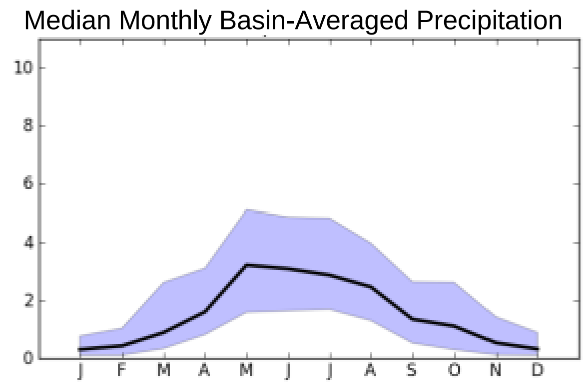



**Figure 4. — Monthly median of area-weighted basin-averaged precipitation over the Basin Study area (black line). Blue shaded area indicates the range between the 10th and 90th percentile basin-averaged precipitation for each month.**

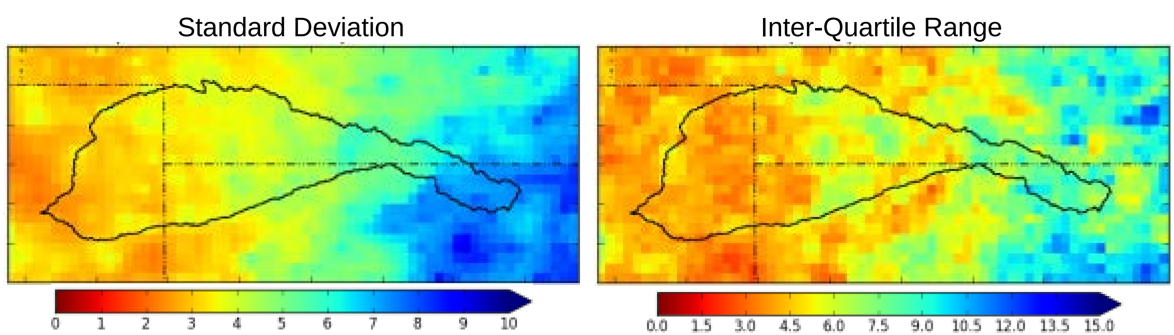



**Figure 5. — Spatial distribution of standard deviation (left) and inter-quartile range of annual precipitation. Colorbar indicates values in inches; black line delineates Republican River Basin.**

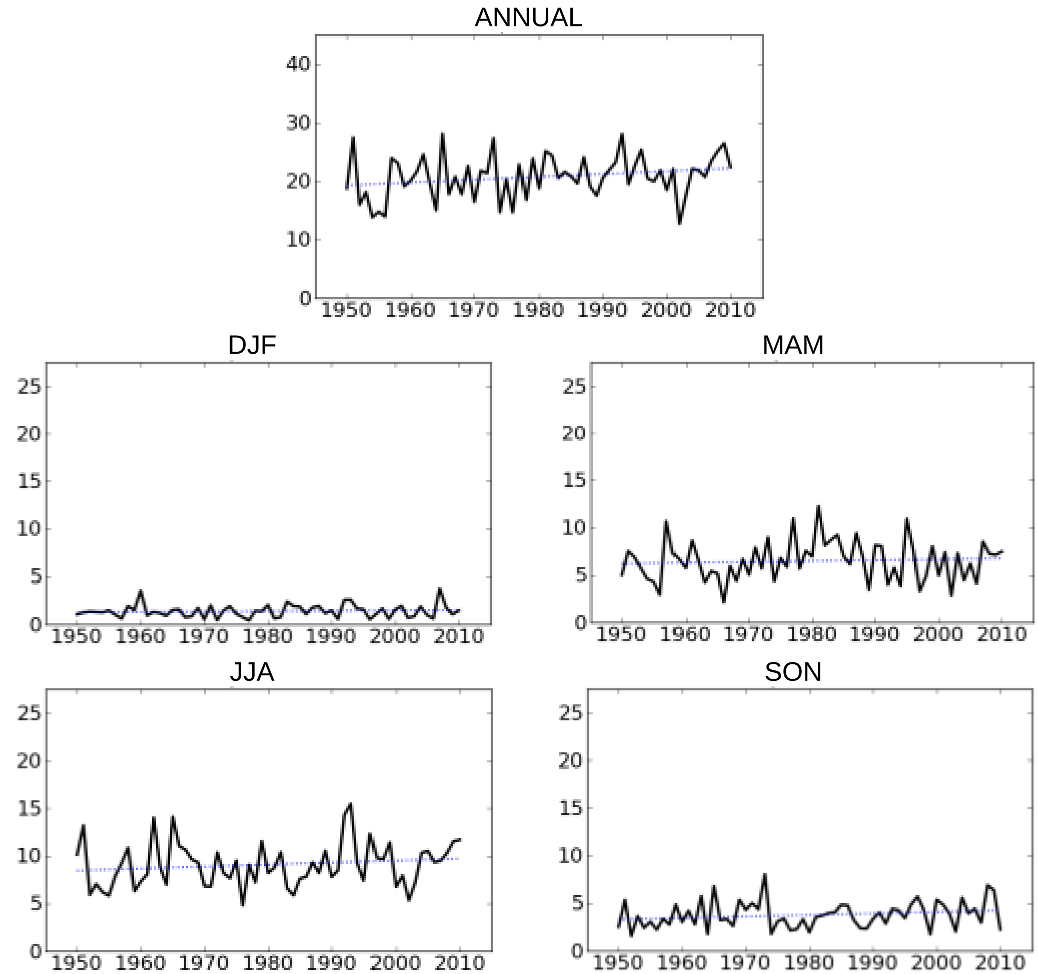



**Figure 6. — Timeseries of area-weighted basin-averaged precipitation over the Basin study area for the period 1950-2010. Black line shows basin-averaged precipitation [in]; blue dotted line shows trendline calculated over the period 1950-2010 (inclusive).**

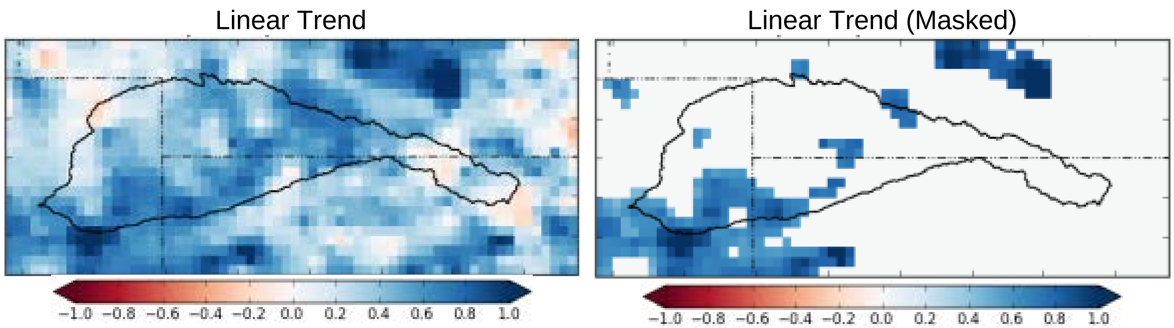



**Figure 7. — Spatial distribution of linear trends in annual precipitation for the period 2010-2050 (left); spatial distribution of linear trends in annual precipitation, masked where trends are not statistically significant (right). Colorbar indicates trend values in [inches/decade], with blue indicating positive (increasing) trends and red indicating negative (decreasing) trends; black line delineates Republican River Basin.**

### c. *Current Temperature*

Similar to precipitation, temperatures in the Basin exhibit a strong east-west gradient. Spatial distributions of annual and seasonal average temperatures over the Basin are illustrated in Figure 8, and median monthly basin-averaged temperatures for the period 1970-1999 are shown in Figure 9 (black line) along with the range of monthly values between the 10$^{th}$ and 90$^{th}$ percentiles (red shading). The spatial distribution of interannual temperature variability is illustrated in Figure 10, which shows the standard deviation and interquartile range of annual mean temperature over the region. Finally, interannual temperature variability is illustrated in Figures 11 and 12. Figure 11 shows time series of basin-averaged seasonal and annual mean temperatures for the period 1950-2010, and Figure 12 shows the spatial distribution of linear trends in annual mean temperature over this period.

Annual mean temperature ranges from less than 48 °F in the west to approximately 55 °F in the east. Seasonal temperature variability is also similar to precipitation, with large temperature variations consistent with cold winters and hot summers over the region. Interannual variability of mean annual temperatures is also large, similar to interannual variability of precipitation. Seasonal and annual mean temperatures do not exhibit statistically significant trends over the Basin for any season.

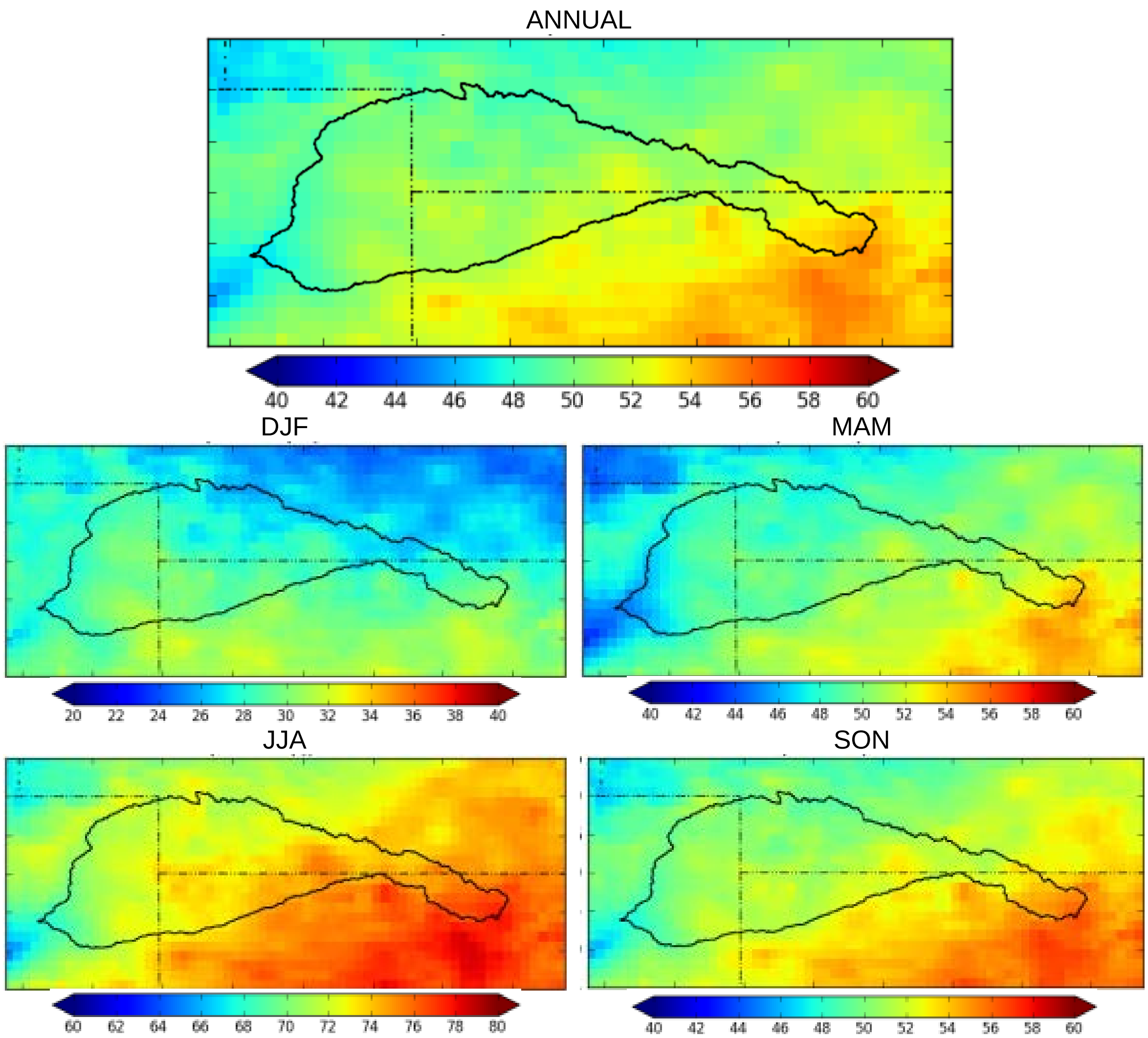



**Figure 8. — Spatial distribution of annual and seasonal mean temperature. Seasonal mean temperatures shown for winter (December-January-February; DJF), spring (March-April-May; MAM), summer (June-July-August, JJA), and fall (September-October-November; SON). Colorbar indicates mean temperature [°F]; black line delineates Republican River Basin.**

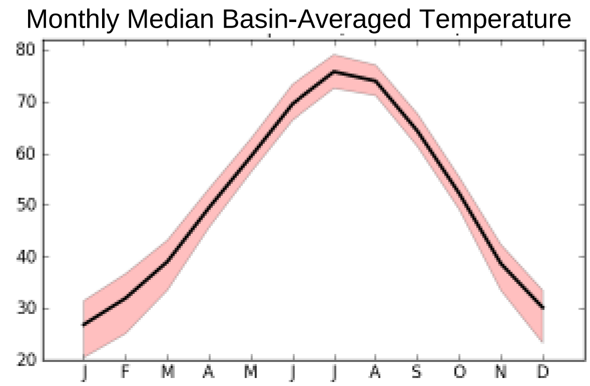



**Figure 9. — Monthly median of area-weighted basin-averaged temperature over the Basin Study area (black line). Red shaded area indicates the range between the 10th and 90th percentile basin-averaged temperatures for each month.**

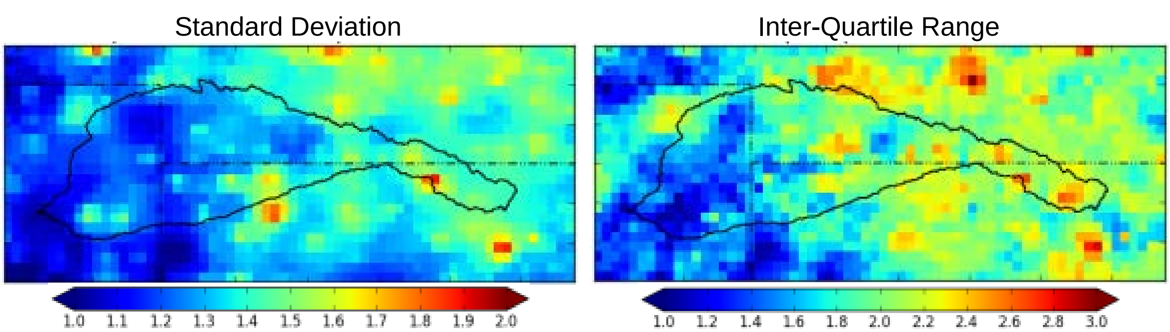



**Figure 10. — Spatial distribution of standard deviation (left) and inter-quartile range of annual mean temperature. Colorbar indicates values in [°F]; black line delineates Republican River Basin.**

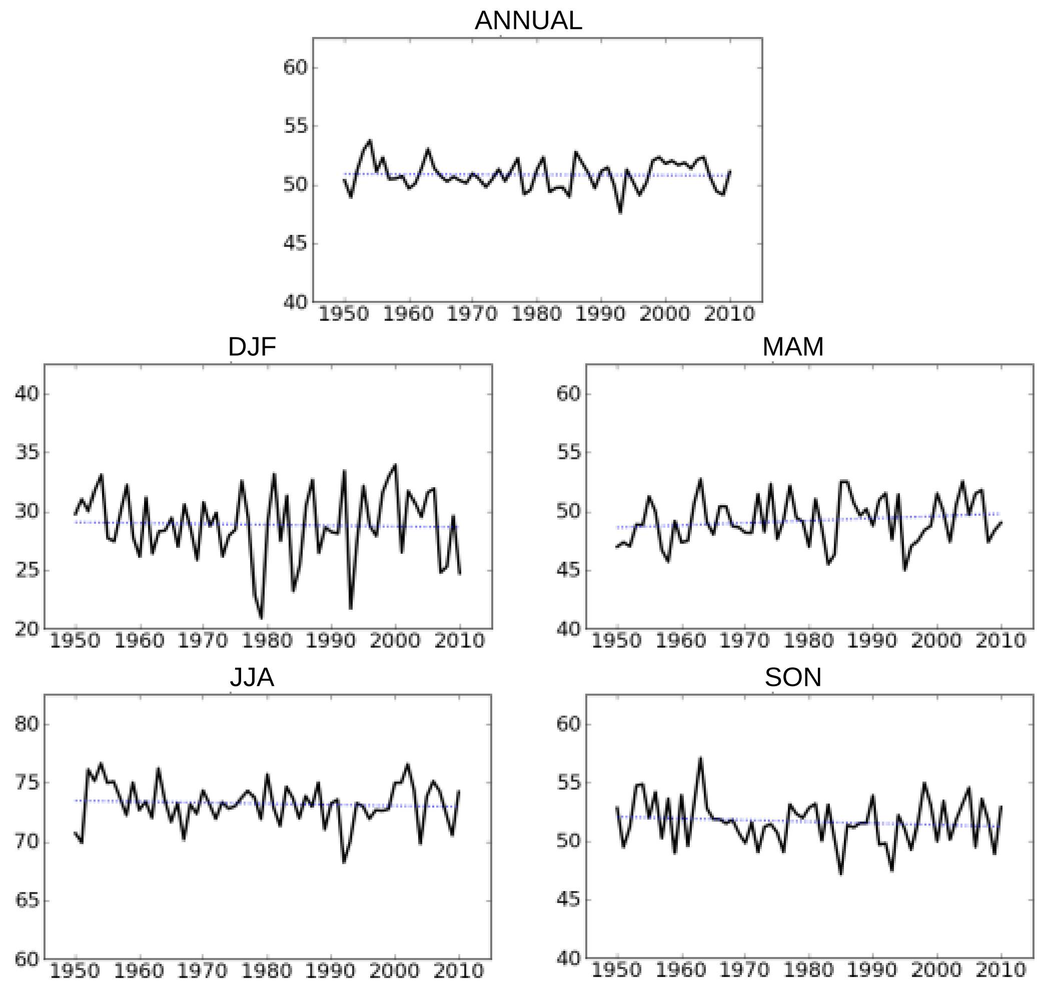



**Figure 11. — Timeseries of area-weighted basin-averaged seasonal and annual mean temperature over the Basin Study area for the period 1950-2010. Black line shows basin-averaged precipitation [in]; blue dotted line shows trendline calculated over the period 1950-2010 (inclusive).**

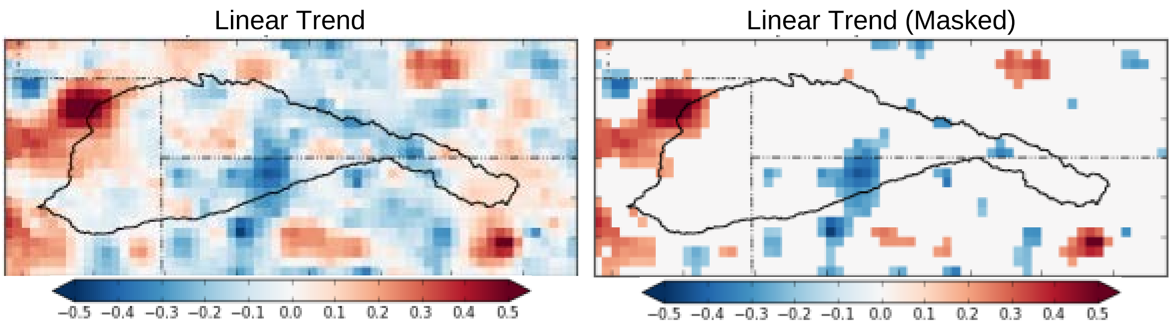



**Figure 12. — Spatial distribution of linear trends in annual mean temperature for the period 2010-2050 (left); spatial distribution of linear trends in annual mean temperature, masked where trends are not statistically significant (right). Colorbar indicates trend values in [°F/decade]; black line delineates Republican River Basin.**

# B. Future Climate Conditions

This section describes projections of future climate conditions in the Republican River Basin and the selection of climate projections used in developing climate scenarios for detailed analysis of future water supplies, demands, and operations in the Basin. Throughout this report, the term *climate projections* refers to raw or downscaled projections of future climate conditions produced by general circulation models (GCMs), whereas the term *climate scenarios* refers to climate and hydrologic datasets – including inputs to hydrologic, operations, and resource models – derived from climate projections in combination with historical, paleo, and/or other data sources. Climate projections are used to characterize the range of future climate change relative to historical conditions, while climate scenarios are used for detailed analysis of regional or basin-scale water supplies, demands, and operations under projected future climate conditions.

## 1. Summary of Previous Studies

A large body of research has been conducted over recent decades regarding climate change and its potential impacts on hydrology and water resources. Most of this research has focused on the large scale implications of global climate change, while providing limited information on impacts to water supplies and demands at regional and local scales. This section provides a brief summary of recent research relevant to climate change and its impacts in the Republican River Basin.

The World Climate Research Programme (WCRP) began the Coupled Model Intercomparison Project (CMIP) in 1995 to facilitate scientific collaboration towards better understanding the global climate system, including both natural (unforced) climate variability and climate change resulting from changes in radiative forcing (e.g., changes in greenhouse gases [GHG] concentrations).

CMIP provides standards and guidelines that allow for intercomparison of GCM results from multiple models developed by scientists and research groups from around the world. The multi-model datasets developed by each phase of the CMIP project are the primary datasets used by the global climate science community, including the Intergovernmental Panel on Climate Change (IPCC), to evaluate climate change.

Numerous studies have used climate projections from CMIP Phase 3 (CMIP3) and Phase 5 (CMIP5) to evaluate climate change at global and continental scales. The most recent report from the IPCC concludes that it is virtually certain that the Earth has warmed since the mid-20$^{th}$ century based on analysis of historical climate observations from around the globe (IPCC 2014). Based on extensive analysis of CMIP5 climate projections, the report concluded that it is likely that temperatures will continue to increase throughout the first half of the 21$^{st}$ century, and it is virtually certain that they will increase by the latter half of the 21$^{st}$ century (IPCC 2014). While the magnitude of warming is likely to vary among regions, it is virtually certain that all regions of the globe will experience warming during the 21$^{st}$ century. Climate projections indicate that changes in precipitation are expected to accompany changes in temperature; however, changes in precipitation are not expected to be uniform: it is likely that relatively wet regions will become wetter, while relatively dry regions become drier (IPCC 2014). Changes in both temperature and precipitation have the potential to disrupt water management operations by driving changes in quantity and timing of water supply and demand.

Analysis of climate projections from the CMIP5 multi-model archive by scientists at the University of Nebraska-Lincoln found that projected changes in temperature in Nebraska range from 4-5 °F (low emission scenarios) to 8-9 °F (high emission scenarios) by the late twenty-first century (2071-2099) (Bathke et al. 2014). The frequency of days with temperature exceeding 100 °F is projected to increase by an additional 13-16 days per year across the state, with a range from 10-21 days in the east to 21-37 days in the western part of the state. The number of warm nights with the nighttime low temperature above 60 °F is expected to increase by 20-25 nights per year for the lower emissions scenario and 25-40 nights per year for the higher emissions scenario. Changes in precipitation are expected to be relatively small over most of the state (Bathke et al. 2014).

Similar analysis of climate change in Colorado by scientists at the University of Colorado - Boulder and collaborating institutions found that temperatures in the northeastern portion of the state, including the Colorado portion of the Republican River Basin, are projected to increase by 3-4 °F during winter and spring and by 4-5 °F during summer by the middle of the 21$^{st}$ century (Lukas et al. 2014). Precipitation is projected to increase by approximately 5% in spring and as much as 20% during winter by mid-century, whereas summer and fall precipitation are projected to decrease by 5-10%.

Reclamation's West-Wide Climate Risk Assessments evaluated projected climate change and climate change impacts on water resources in eight major river basins in the Western U.S., including the Missouri River Basin, based on downscaled GCM projections from the CMIP3 multi-model archive (Reclamation 2011). The Missouri River Basin encompasses much of the northern and central Great Plains region, including the Republican River Basin. Analysis revealed that the Great Plains region is likely to continue to experience interannual and interdecadal variations in temperature and precipitation similar to historical conditions. For the next few decades, interannual and interdecadal variations are likely to be superimposed upon background trends that, in most cases, will be subtle compared to the magnitude of interannual variability (Reclamation 2011). Evapotranspiration demands and warm-season precipitation play a more prominent role in determining local hydrologic conditions in the Great Plains relative to water management, with less influence of headwaters snowpack and snowmelt timing. Future projections of precipitation for the central Great Plains are complicated by the limitations on the ability of GCMs to portray the frequency and intensity of warm-season convection events or tropical storm systems tracking into the region (Reclamation 2013b).

The Great Plains region frequently experiences a wide range of weather and climate hazards such as tornadoes, droughts, floods, and other severe weather events that result in significant economic losses and stresses to fragile ecosystems. Previous studies suggest that climate change will further exacerbate those stresses and increase economic losses in the future (Bathke et al. 2014). Gutowski et al. (2008) suggest that, in addition to trends in seasonal and annual total precipitation, climate change will likely affect precipitation frequency and intensity in many areas. Their results suggest that precipitation is likely to become less frequent but more intense, and further suggest that precipitation extremes are very likely to increase in the future. Their results are supported by observed trends in precipitation extremes over recent decades (Min et al., 2011).

In another study, projections of the Palmer Drought Severity Index (PDSI) over the 21$^{st}$ century indicates a semi-permanent state of severe drought over the Great Plains in coming decades due to rising temperatures and decreasing precipitation (Reclamation 2013b). Hoerling et al. (2012) looked at the difference between projections of PDSI and soil moisture through the 21$^{st}$ century and found that the PDSI projections indicate prolonged severe drought conditions. The soil moisture projections, however, suggest a more modest drying with a smaller change in drought frequency. In their view, if prolonged severe drought occurs in the near future, it will be due to lengthy periods of precipitation imbalances rather than increased temperatures.

It should be noted that uncertainties associated with hydrologic modeling and analysis may affect the results of climate change impacts studies. Vano et al. (2012) used multiple hydrologic models in the Colorado River Basin under a common set of climate change scenarios. Their results showed that the magnitude of runoff response to these scenarios varied considerably between the different models. Differences in runoff response were shown to stem from differences in how the models represented the physical processes governing infiltration, runoff, and soil moisture storage in the Basin. While these results are most applicable to the Colorado River Basin, similar dependence of runoff projections with respect to hydrologic model selection is expected for other basins in the Western U.S. (Reclamation 2013b).

## 2. Analysis of Future Climate Conditions

### a. *Data and Methods Used*

Analysis of future climate variability and change, and their corresponding implications for basin hydrology and water resources, requires reliable projections of future climate conditions. Projections of future climate are developed primarily through the use of global climate models (GCMs; also referred to as general circulation models). GCMs are complex numerical models that simulate large-scale weather and climate conditions over the globe based on the equations for fluid motion and energy transfer. GCMs have been used to simulate natural climate variability as well as the climate response to specified changes, including changes in atmospheric greenhouse gas (GHG) concentrations. The GCMs used to simulate climate change in response to changes in GHG concentrations include physically-based representations of ocean, land surface, and sea ice processes and their interactions with the atmosphere.

Climate projections for the Republican River Basin Study were obtained from an archive of bias-corrected and spatially-disaggregated (BCSD) CMIP3 climate projections developed by Reclamation in partnership with the USGS, USACE, Lawrence Livermore National Laboratory, Santa Clara University, Climate Central, and Scripps Institution of Oceanography. BCSD CMIP3 projections were developed by applying the BCSD downscaling methodology to an ensemble of 112 GCM climate projections from the CMIP3 multi-model archive, including projections from 16 GCMs developed by climate scientists from around the world. Previous studies have shown that the BCSD methodology provides downscaling capabilities comparable to other statistical and dynamical methods in the context of hydrologic impact studies (Reclamation 2013b). The BCSD projections used in this Study are publicly available through an online data portal[8].

Arguably the most common approach for evaluating climate change at regional and basin scales involves downscaling GCM climate projections, which typically have spatial resolutions on the order of 100 km, to a finer resolution suitable for watershed-scale analysis. Downscaling methods fall into two broad categories: dynamical downscaling, which involves using GCM output to define boundary conditions for a finer scale regional climate model, and statistical downscaling,

[8] http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html

which involves the use of historical climate data as the basis for statistically mapping GCM scale information to a finer resolution in space and/or time. Within each of these categories, numerous methods are available. Dynamical downscaling methods vary with respect to the regional climate model used, as well as to the processing of GCM output for use as boundary conditions for the regional climate simulation. Statistical downscaling methods vary with respect to the climate variables and statistical approach used to relate large-scale climate conditions from GCM projections to finer-scale climate conditions over a given region. The BCSD downscaling methodology used to develop the climate projections evaluated in this Study is summarized below; additional details are provided by Wood et al. (2004), Wood et al. (2006), and Reclamation et al. (2013).

The BCSD downscaling methodology is a two-step quantile mapping technique applied on a monthly and location-specific basis. The first step involves removing biases from the raw GCM projections. Climate conditions simulated by GCMs are commonly biased with respect to observed climate conditions – i.e., the probability distributions of simulated precipitation and temperature differ from the observed distribution. Biases vary by location, season, and climate variable, and represent limitations in a GCM's ability to simulate complex physical processes that affect regional climate conditions.

In the BCSD methodology, bias correction is carried out by first aggregating historical observations of precipitation and temperature to the GCM resolution. The gridded historical precipitation and temperature dataset of Maurer et al. (2002) was used as the basis for bias correction of GCM climate projections included in the BCSD CMIP3 archive. For each GCM grid cell over the target downscaling region, cumulative distribution functions (CDFs) are developed for observed and simulated precipitation and temperature for a historical reference period; the period 1950-1999 was used for development of the BCSD dataset used in this Study. A simple quantile-mapping procedure is then used to remove the bias in the GCM data such that the CDF of the bias-corrected GCM data matches the CDF of the observed data over the historical reference period. The CDFs and quantile mapping procedures are applied on a monthly basis.

The second step of the BCSD methodology involves spatially disaggregating GCM projections from the GCM resolution to the downscaling target resolution; a target resolution of 1/8° latitude by 1/8° longitude (approximately 12km by 12km at mid-latitudes) was used for the BCSD climate projections used in this Study. Spatial disaggregation is applied for each monthly time-step for the full target region by merging the historical spatial climatology with the spatially-disaggregated deviation for that time-step. An historical spatial climatology is developed for each month based on monthly means from the observed historical climate dataset – i.e., the dataset of Maurer et al. (2002) – at both the downscaling target resolution (1/8° latitude by 1/8° longitude) and the GCM resolution. Deviation factors are then computed at each monthly time-step for each GCM

grid cell. Precipitation factors are computed as the ratio of the bias-corrected GCM precipitation for each month divided by the precipitation value from the historical spatial climatology for the corresponding grid cell and month; temperature factors are computed as the difference between the corrected GCM temperature and the historical spatial climatology.
Deviation factors are then interpolated to the downscaling target resolution (1/8° latitude by 1/8° longitude), and then applied to the historical spatial climatology at the downscaling target resolution. Bias-corrected climate variability and change from the GCM are thus merged with the higher-resolution historical climatology, resulting in a bias-corrected and spatially-disaggregated climate projection.

It should be noted that this Basin Study uses the BCSD downscaled CMIP3 climate projections. New downscaled projections from the CMIP5 multi-model GCM archive were published shortly after this Study was initiated. While the CMIP5 projections are more recent, it has not been determined that they are a more reliable source of climate projections compared to existing CMIP3 climate projections. At this time, CMIP5 projections should be considered an addition to (not a replacement of) the existing CMIP3 projections unless the climate science community can offer an explanation as to why CMIP5 should be favored over CMIP3 (Reclamation et al. 2013).

All 112 BCSD projections of monthly precipitation and temperature were extracted from the CMIP3 BCSD archive for the area encompassing the Republican River Basin. Figure 13 shows the area over which BCSD climate projections were extracted from the archive, along with the spatial resolution of the BCSD dataset; the area extends from 38.5625°N to 41.4375°N latitude and from 104.1875°W to 96.3125°W longitude and encompasses the entire Republican River Basin above Clay Center, KS.

Projected changes in climate conditions over the Republican River Basin were analyzed by comparing seasonal and annual precipitation and temperature characteristics between selected historical and future periods for all BCSD grid cells over the area shown in Figure 13 and for area-weighted basin-averaged conditions. The period 1970-1999 was selected as the historical reference period and the period 2040-2059 was selected for the future period. The historical period was selected based on the availability of historical climate and hydrology data during this period, and the future period was selected to be consistent with the Basin Study period which extends through 2060.


**Figure 13. — Map of region encompassing Republican River Basin over which BCSD climate projections were extracted from the BCSD climate projection archive.**

## b. *Future Precipitation*

The range of projected basin-averaged seasonal and annual precipitation over the Republican River Basin over the 21$^{st}$ century is illustrated in Figure 14. In each panel of the figure, the black line indicates the ensemble median for that season. Dark blue shading indicates the range between ensemble 25$^{th}$ and 75$^{th}$ percentile values, and light blue shading indicates the range between ensemble 10$^{th}$ and 90$^{th}$ percentile values. The red line shows observed historical values. Ensemble median and percentile values were calculated for each season or year based on the distribution of basin-averaged precipitation for that season or year across all 112 BCSD CMIP3 climate projections.

Figure 14 suggests that precipitation over the Republican River Basin is likely to exhibit a slight positive trend over the 21$^{st}$ century. Projected trends are largest during fall and winter, with little change projected in spring and summer. However, approximately half of the BCSD CMIP3 climate projections project a slight increase in precipitation over the Basin while the other half project a slight decrease. These results highlight the large uncertainties in projected future precipitation changes over the Basin.

The spatial distribution of the ensemble-median projected changes in seasonal and annual mean precipitation between the historical and future periods used in this

Study are shown in Figure 15. The ensemble-median projected change was calculated by first computing the change in mean precipitation for each of the 112 BCSD CMIP3 climate projections, and then taking the median over the 112-member ensemble. Figure 15 thus represents the central tendency of the 112-member ensemble of BCSD projections. Note that the color scale in Figure 15 is oriented such that blue indicates a projected increase in precipitation while red indicates a decrease in precipitation between historical and future periods.

The ensemble-median (central tendency) indicates that seasonal mean precipitation is projected to increase over the entire Basin in winter relative to historical conditions, with increases exceeding 10% in the western portion of the Basin. Summer and fall precipitation are projected to increase slightly over the majority of the Basin, with a slight decrease projected over the western headwater area in Colorado. Spring precipitation is projected to increase over the northern and eastern portions of the Basin, with decreases up to 5% over the western portion of the Basin in Colorado, Kansas, and southwest Nebraska. Annual mean precipitation is projected to increase over most of the Basin, with increases approaching 5% in the eastern portion of the Basin.

As discussed above and in previous studies, there is considerable uncertainty in projected changes in precipitation over the 21$^{st}$ century. Figures 16 and 17 illustrate the 20$^{th}$ and 80$^{th}$ percentiles, respectively, of projected changes in precipitation from the BCSD CMIP3 projections. The 20$^{th}$ percentile represents the drier end of the range of projected change at each BCSD grid cell, whereas the 80$^{th}$ percentile represents the wetter end of the range of projected change.

In contrast to the ensemble median (central tendency), the ensemble 20$^{th}$ percentile (drier) shows widespread decreases in precipitation throughout the Basin during spring, summer, and fall seasons, with decreases of more than 10% over much of the Basin. In winter, the ensemble 20$^{th}$ percentile shows slight declines in precipitation over most of the Basin, with a slight increase over the western portion of the Basin in Colorado. The ensemble 80$^{th}$ percentile (wetter) shows widespread increases in precipitation throughout the Basin during all seasons, with increases exceeding 10% over the majority of the Basin. Comparison of Figures 16 and 17 again shows the large range – i.e., the large uncertainty – of projected changes in seasonal precipitation among the BCSD CMIP3 climate projections.

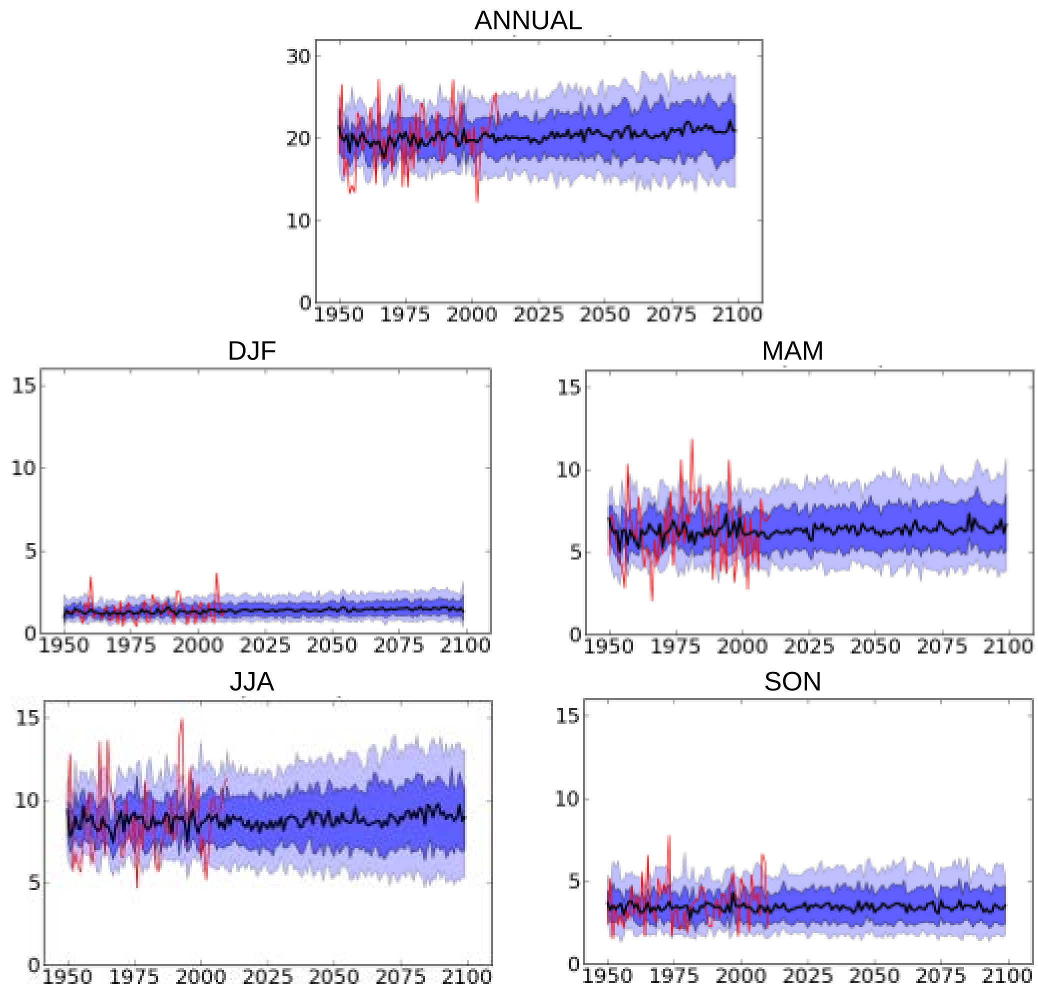



**Figure 14. — Timeseries of area-weighted basin-averaged seasonal and annual mean precipitation over the Basin Study area for the period 1950-2099 [in]. Black line shows the ensemble median; dark blue shading indicates range between ensemble 25th and 75th percentile values; light blue shading indicates range between ensemble 10th and 90th percentile values; red line shows observed historical values.**

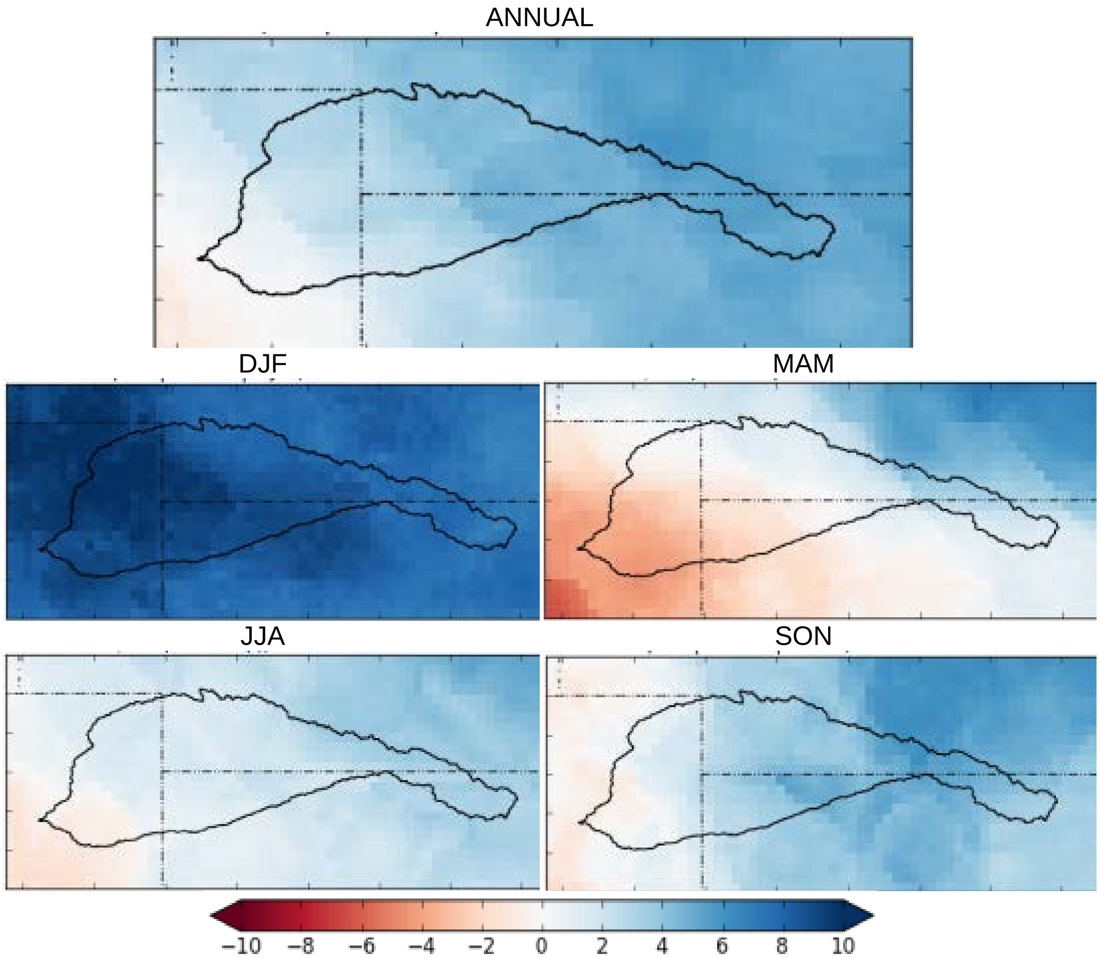



**Figure 15. — Spatial distribution the ensemble-median (central tendency) projected change in annual and seasonal mean precipitation between historical (1970-1999) and future (2030-2059) time periods. Color scale indicates ensemble-median percent change [%]; black line delineates Republican River Basin.**

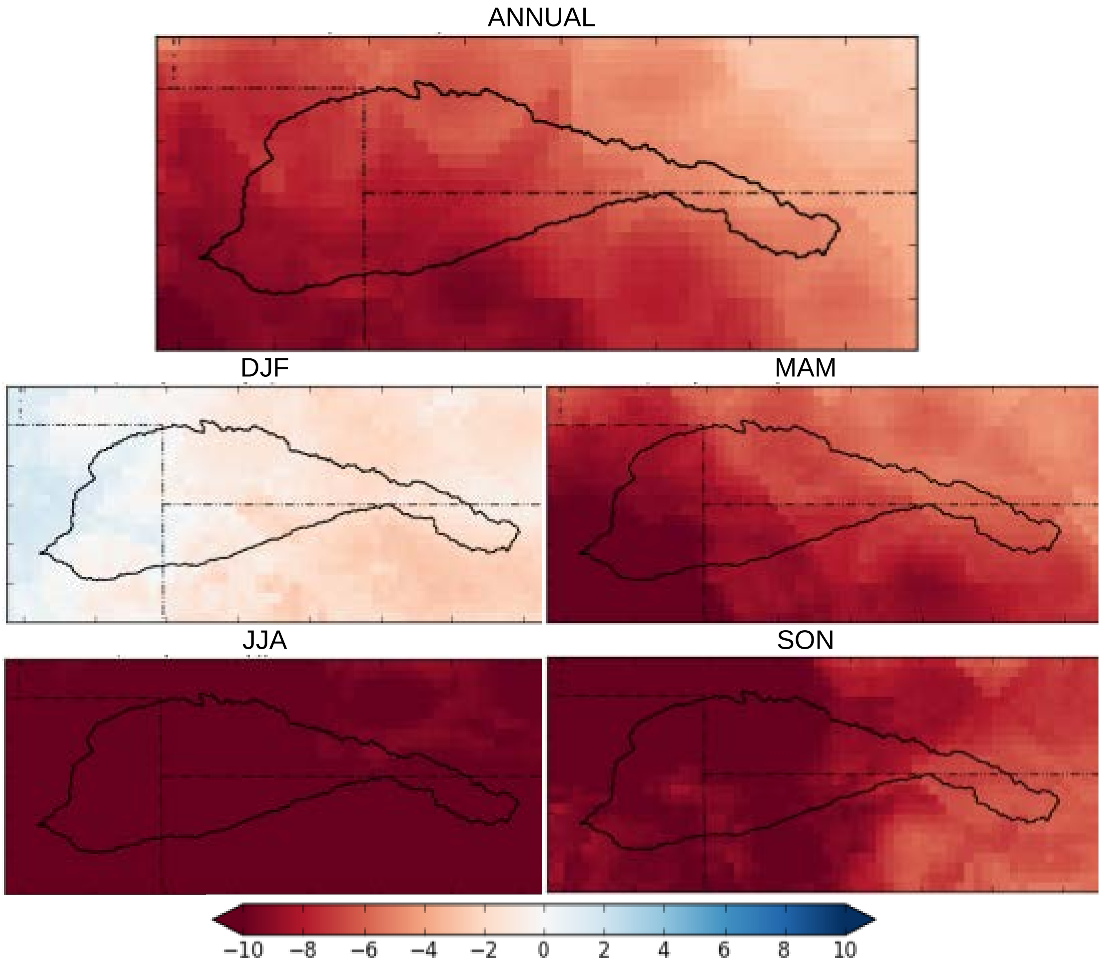



**Figure 16. — Spatial distribution the ensemble 20th percentile (drier) projected change in annual and seasonal mean precipitation between historical (1970-1999) and future (2030-2059) time periods. Color scale indicates ensemble 20th percentile percent change [%]; black line delineates Republican River Basin.**

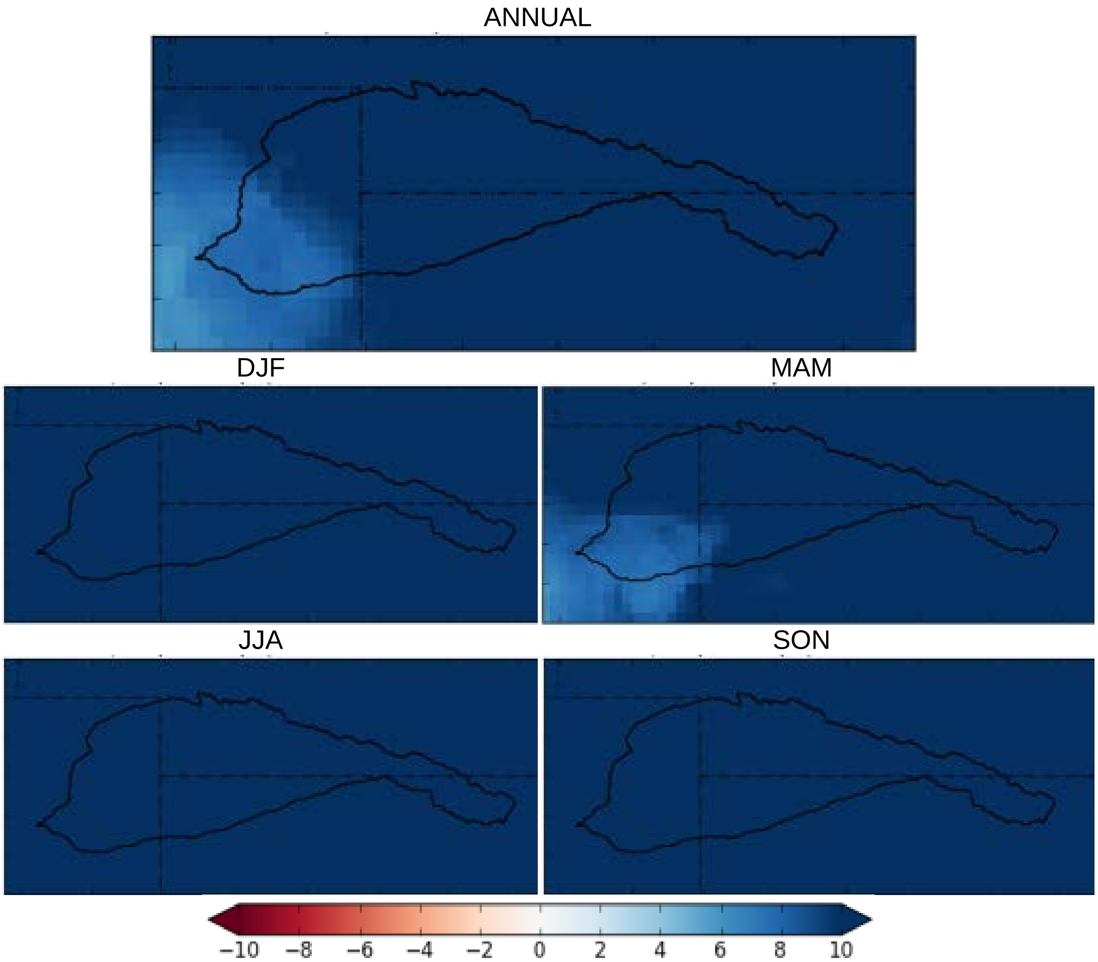



**Figure 17. — Spatial distribution the ensemble 80th percentile (wetter) projected change in annual and seasonal mean precipitation between historical (1970-1999) and future (2030-2059) time periods. Color scale indicates ensemble 80th percentile percent change [%]; black line delineates Republican River Basin.**

### c. *Future Temperature*

The range of projected basin-averaged seasonal and annual mean temperatures over the Republican River Basin is illustrated in Figure 18. In each panel of the figure, the black line indicates the ensemble median of projected basin-average temperature for that season. Dark red shading indicates the range between ensemble 25th and 75th percentile values, and light red shading indicates the range between ensemble 10th and 90th percentile values. The blue line shows observed historical values. Ensemble median and percentile values were calculated for each season or year based on the distribution of basin-averaged temperatures for that season or year across all 112 BCSD CMIP3 climate projections.

Figure 18 clearly shows a significant positive trend in projected future temperatures over the Republican River Basin during the 21st century. Projected trends are largest during summer and smallest during winter. In contrast to the large uncertainty in future precipitation trends across the ensemble of BCSD CMIP3 projections, all projections indicate warming over the Basin during the 21st century for all seasons.

The spatial distribution of the ensemble-median projected change in season and annual mean temperature between the historical and future periods is shown in Figure 19. The ensemble-median projected change in temperature was calculated in the same way as for precipitation: first, the change in mean temperature was computed for each of the 112 BCSD CMIP3 climate projections, then the median was taken over the 112-member ensemble. Figure 19 thus represents the central tendency of the 112-member ensemble of BCSD projections. Note that the color scale in Figure 19 is oriented such that red indicates a projected increase in temperature while blue indicates a decrease in temperature.

The ensemble-median (central tendency) shown in Figure 19 indicates that seasonal mean temperature is projected to increase over the entire Basin in all seasons relative to historical conditions, with increases exceeding 2 °F in winter and spring and exceeding 3.5 °F in summer and fall. Annual mean temperature is projected to increase by approximately 3.5 °F over the entire Basin. Projected warming is generally uniform over the Basin for each season.

Uncertainty in projected changes in temperature over the 21st century is substantially less than uncertainties in projected precipitation. Figures 20 and 21 illustrate the 20th and 80th percentiles, respectively, of projected change in temperature from the 112-member ensemble of BCSD CMIP3 climate projections. The 20th percentile represents the cooler (i.e., less warm), end of the range of projected change at each BCSD grid cell, whereas the 80th percentile represents the hotter (i.e., more warming) end of the range of projected change.

Figure 20 shows that the ensemble 20th percentile (less warming) change in temperature is generally 1-2 °F less than the ensemble-median change for all seasons, whereas Figure 21 shows that the ensemble 80th percentile (more warming) change is approximately 1-2 °F greater than the ensemble median. Similar to the ensemble-median, 20th and 80th percentile changes in temperature are largely uniform over the Basin. In contrast to projected change in precipitation, which for a given grid cell may decrease in some projections and increase in others, all projections indicate warming throughout the Study area between historical (1970-1999) and future (2030-2059) periods.

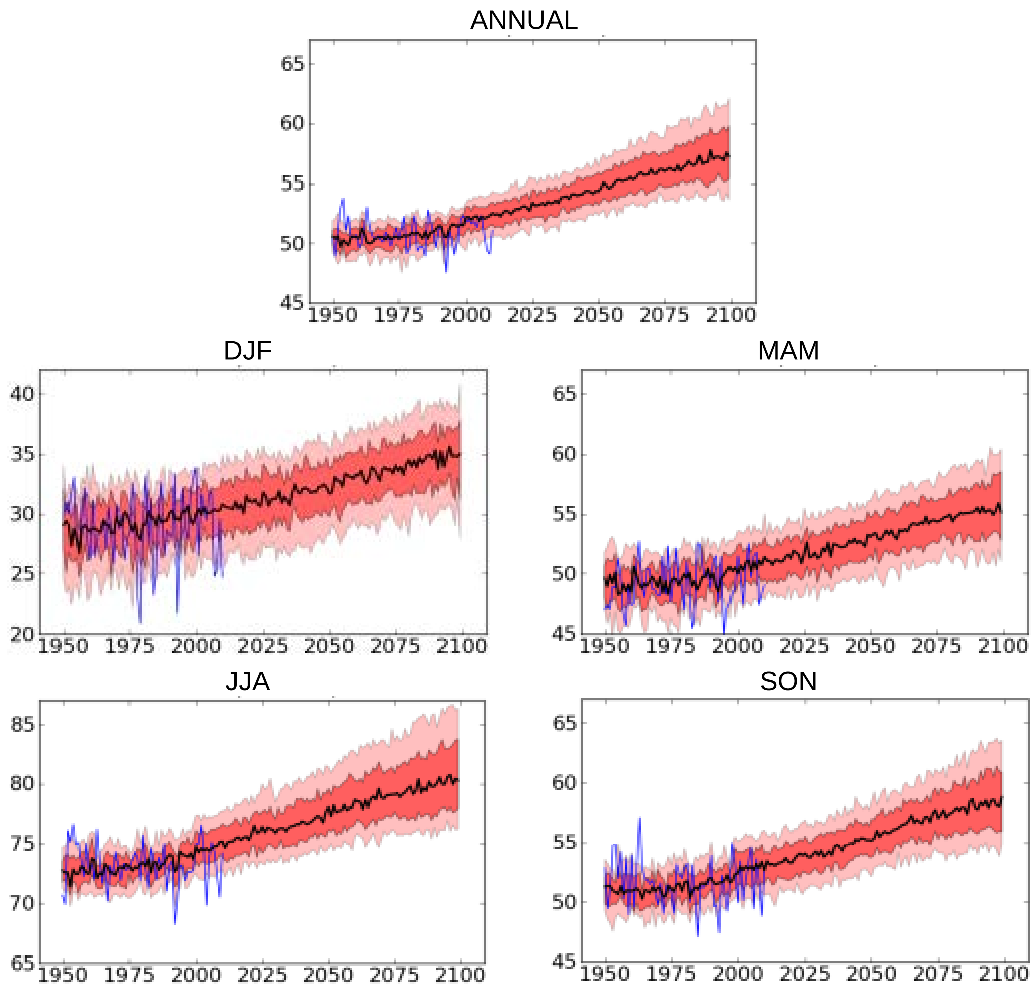



**Figure 18. — Timeseries of area-weighted basin-averaged seasonal and annual mean temperature over the Basin Study area for the period 1950-2099 [°F]. Black line shows the ensemble median; dark red shading indicates the range between ensemble 25th and 75th percentile values; light red shading indicates the range between ensemble 10th and 90th percentile values; blue line shows observed historical values.**

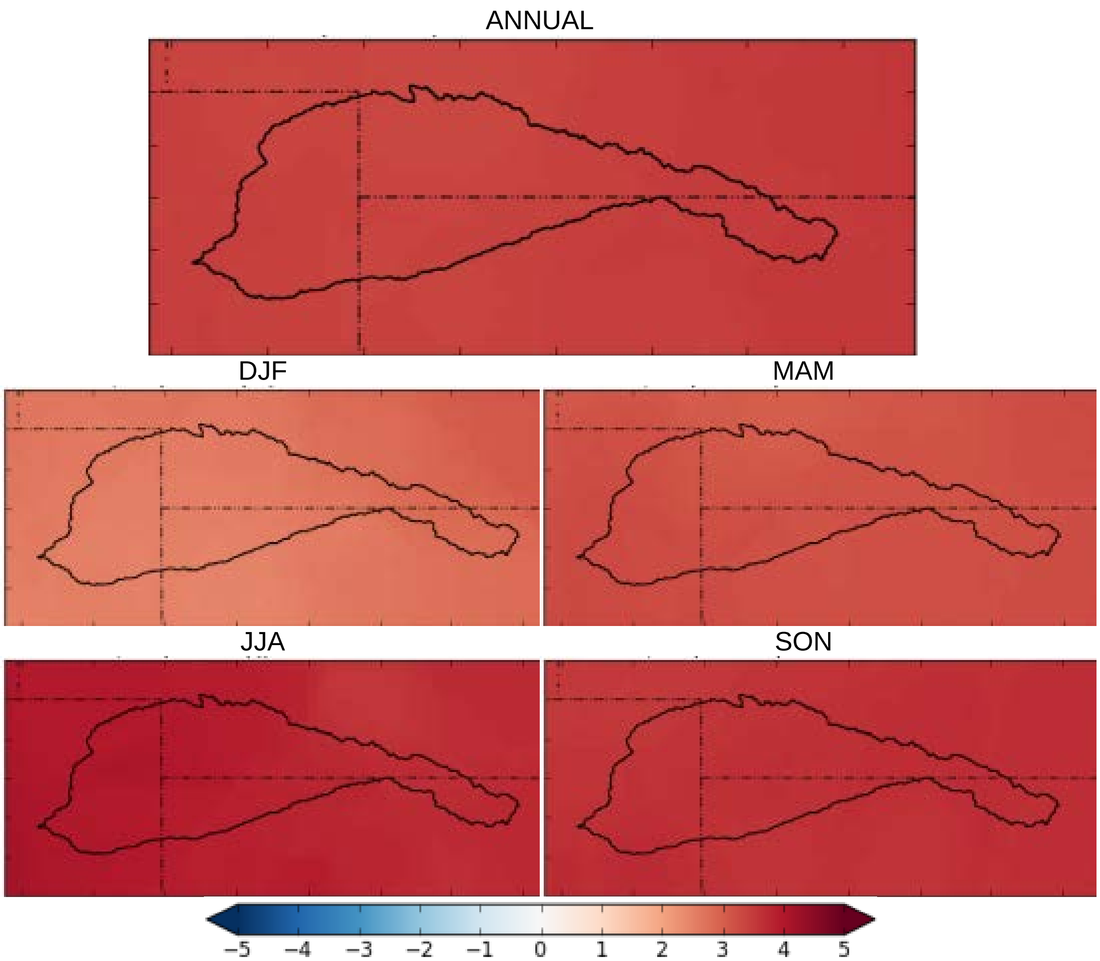



**Figure 19. — Spatial distribution the ensemble median (central tendency) projected change in annual and seasonal mean temperature between historical (1970-1999) and future (2030-2059) time periods. Colorbar indicates ensemble-median change [°F]; black line delineates Republican River Basin.**

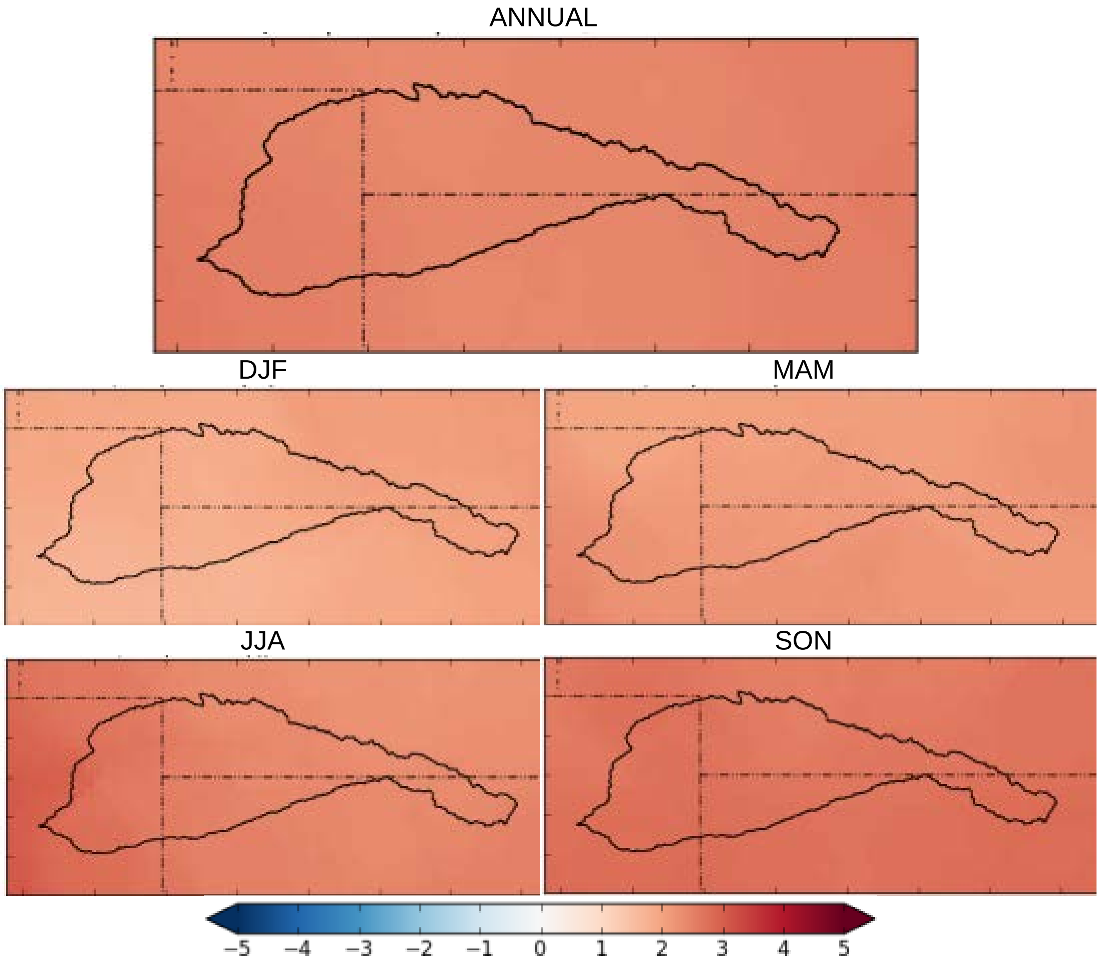



**Figure 20. — Spatial distribution the ensemble 20th percentile (cooler/less warming) projected change in annual and seasonal mean temperature between historical (1970-1999) and future (2030-2059) time periods. Color scale indicates ensemble 20th percentile percent change [°F]; black line delineates Republican River Basin.**

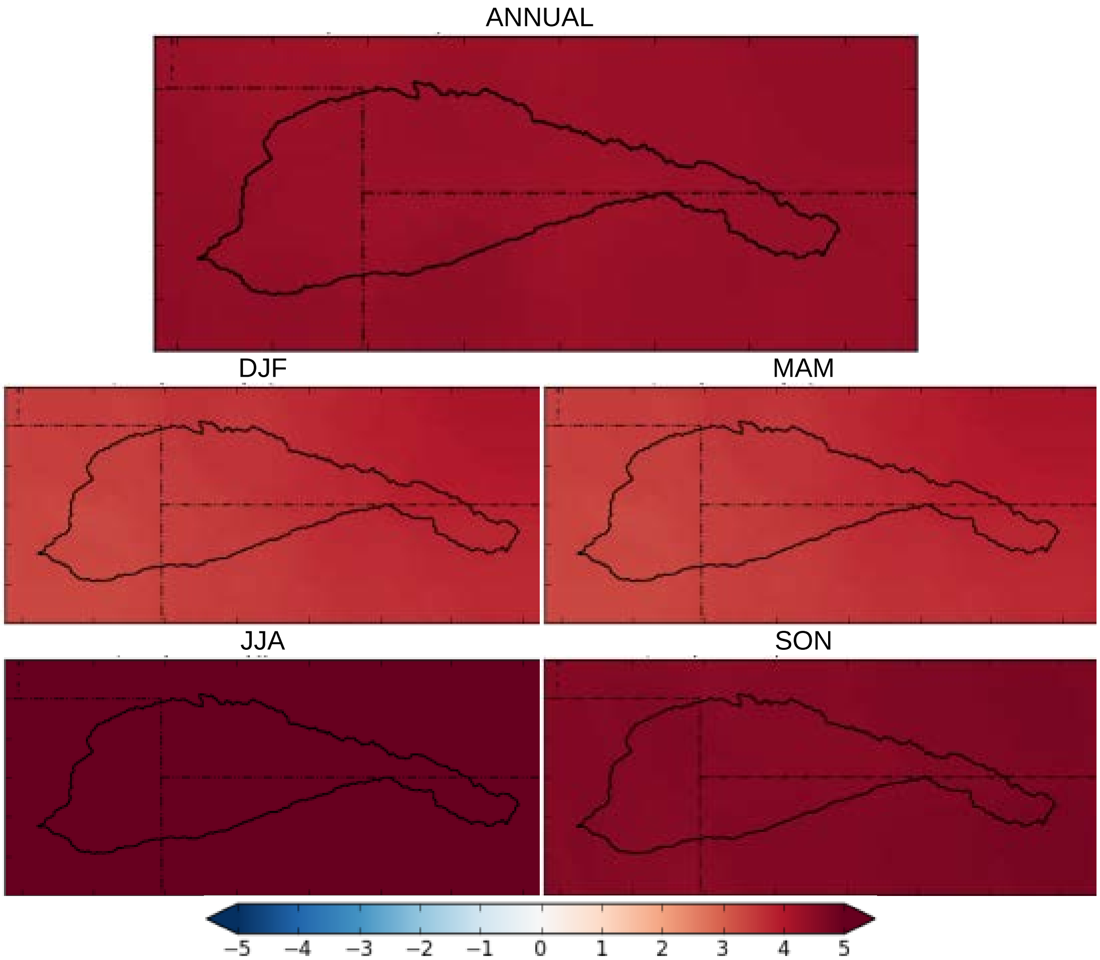



**Figure 21. — Spatial distribution the ensemble 80th percentile (hotter/more warming) projected change in annual and seasonal mean temperature between historical (1970-1999) and future (2030-2059) time periods. Color scale indicates ensemble 20th percentile percent change [°F]; black line delineates Republican River Basin.**

## 3. Selection of Climate Scenarios for Detailed Analysis

As in many complex planning studies, the Republican River Basin Study involves the use of numerous datasets and modeling tools to evaluate the watershed response to projected future climate conditions and to various water management alternatives. It is not feasible to carry out detailed analysis of water supply, demand, and operations in the Basin under all available climate projections, as this would require conducting and integrating the results from numerous simulations with each of the modeling tools used in the Study for each of the management alternatives considered – e.g., for the BCSD CMIP3 projection archive, this would result in 112 simulations multiplied with each modeling tool for each management alternative. Instead, there is a need to adequately represent the range of projected future climate conditions while also limiting the number of required simulations to maintain a manageable project scope.

To meet the needs of the Basin Study, three climate scenarios were developed as input to the hydrologic, water operations, and economic modeling tools used in the Study. A Baseline Climate Scenario was developed to represent current climate and hydrologic conditions in the Basin. Three future climate scenarios were then developed to represent the range of projected future climate conditions in the Basin. For the Baseline Scenario, model inputs were developed from historical observations of precipitation, temperature, pan evaporation, and streamflow; for each future climate scenario, climate-related inputs were developed by perturbing baseline inputs to reflect the on the projected change in each input variable between the periods 1970-1999 and 2030-2059 corresponding to each of the three selected future scenario. Baseline inputs were perturbed using a statistical procedure referred to as quantile-based perturbation. This procedure essentially superimposes the projected change in probability distribution of a given variable between two periods – e.g., between historical and future periods of a selected climate projection – onto that variable's probability distribution in a different dataset – e.g., the baseline input dataset. Projected changes in precipitation and temperature were obtained directly from the BCSD climate projections corresponding to each of the three scenarios selected for analysis in the Study.

This section describes the Baseline Scenario and development of future climate scenarios used for detailed analysis of system reliability and evaluation of alternatives.

### a. *Baseline Scenario*

All climate-related datasets and model inputs for the Baseline Scenario were developed directly from observed historical climate data for the period 1960-2010. Climate-related inputs include precipitation, temperature, and pan evaporation measurements. In addition, reference evapotranspiration (ET) and net irrigation requirement (NIR) datasets for the Baseline Scenario were computed directly from historical climate data.

Hydrologic datasets and model inputs for the Baseline Scenario were developed by adjusting observed historical streamflows to remove trends resulting from changes in hydrologic conditions in the Basin, including changes in surface water storage and diversions over time as well as surface water depletions resulting from changes in groundwater use. As conceptualized in this Study, the Baseline Scenario is intended to reflect current climate and hydrologic conditions in the Basin. Given the lack of significant trends in recent historical climate conditions, historical climate data are generally representative of current climate conditions in the Basin. By contrast, historical streamflows exhibit significant trends throughout much of the Basin and therefore are not representative of current hydrologic conditions. Hydrologic inputs for the Baseline Scenario were therefore developed by adjusting historical streamflows to remove trends and ensure that annual streamflow characteristics are consistent with recent observed conditions for the period 1995-2010.

The procedure used to develop baseline tributary inflow inputs is detailed in Reclamation's *Climate Change Technical Memorandum* (Reclamation, 2015b). The objective of the procedure is to develop a 50-year streamflow record that is consistent with (a) seasonal and interannual climate variability over the period 1961-2010, and (b) current hydrologic conditions in the Basin as characterized by streamflows during the period 1995-2010. Historical and baseline annual streamflows are illustrated below in Figure 22 for four selected gage locations. In each panel of Figure 22, the black line is the timeseries of observed historical annual streamflow [AF] at each location and the blue line is the corresponding computed baseline flow. As shown in this figure, the baseline flows reflect the timing and magnitude of historical streamflow variability, but without the significant trend in historical streamflow that is evident throughout much of the Basin.

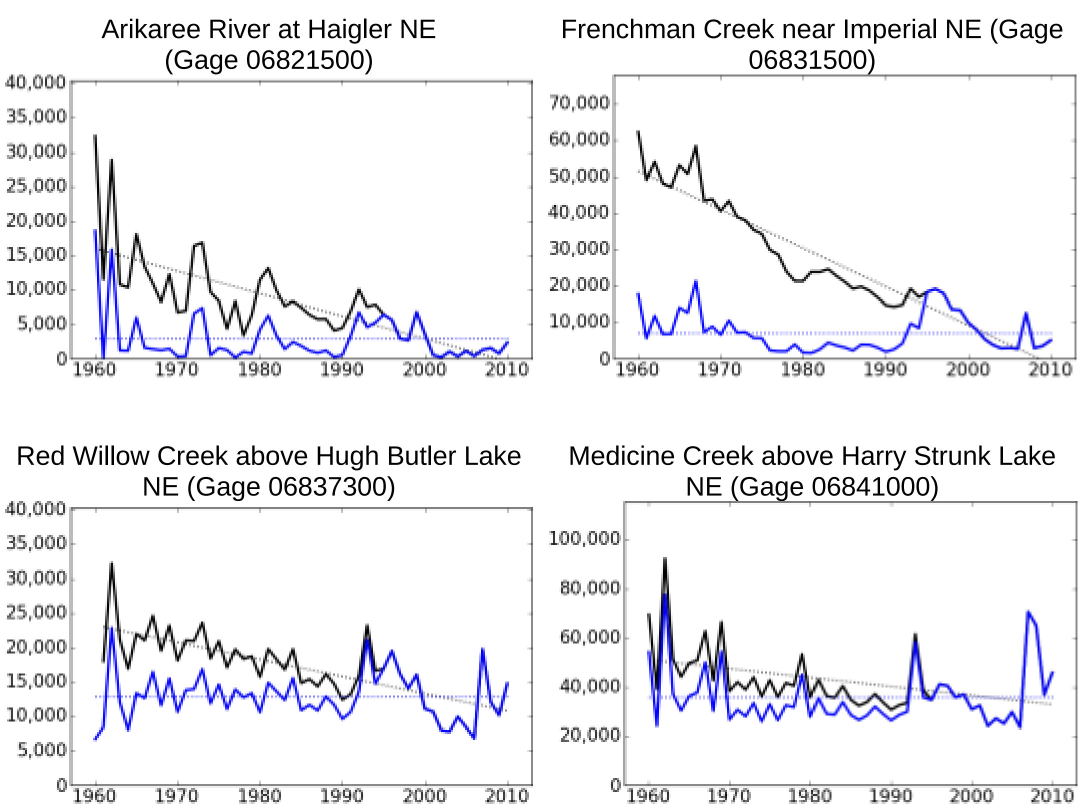



**Figure 22. — Timeseries of annual streamflow at selected stream gages throughout the Republican River Basin for the period 1960-2010 [AF]. Solid black lines shows observed historical streamflow for each gage; dashed black lines show linear trend in observed historical streamflow; solid blue lines show baseline (adjusted) streamflow for each gage; dashed blue lines show annual mean streamflow for baseline streamflow.**

### b. *Future Climate Scenarios*

Three climate scenarios were developed for this Study based on three individual climate projections selected from the BCSD CMIP3 projection archive. Datasets and model inputs for each future scenario were then developed by perturbing the baseline inputs based on the projected change in distribution of each variable between the historical reference period (1970-1999) and future period (2030-2059). The historical period was selected based on the availability of historical climate and hydrology data during this period, and the future period was selected to be consistent with the Basin Study period which extends through 2060.

As described at the beginning of this section and throughout this report, the term *climate projections* refers to raw or downscaled projections of future climate conditions derived from GCMs, whereas the term *climate scenarios* refers to climate and hydrologic datasets – including inputs to hydrologic, operations, and resource models – derived from climate projections in combination with historical, paleo, and/or other data sources. Climate projections are used to characterize the range of future climate change relative to historical conditions, while climate scenarios are used as the basis for detailed analysis of regional or basin-scale water supplies, demands, and operations under future climate conditions for a specific water resources planning study.

Three climate projections were selected from the ensemble of 112 BCSD CMIP3 projections as the basis for the three climate scenarios used in this Study. Projections were selected to represent the range of projected changes in three variables between historical (1970-1999) and future (2030-2059) periods. The three variables include:

1) Basin-averaged annual mean water availability

2) Basin-averaged annual mean precipitation

3) Basin-averaged annual mean temperature

Basin-averaged mean annual precipitation and temperature were computed directly from the BCSD CMIP3 projections, and changes in mean annual values were computed between the periods 2030-2059 and 1970-1999.

For the purpose of selecting climate projections for this Study, water availability is defined as the difference between annual total precipitation and annual total evapotranspiration. Basin-averaged mean annual water availability was computed based on a set of hydrologic projections using the Variable Infiltration Capacity (VIC) model. These hydrologic projections were previously developed by Reclamation's West-Wide Climate Risk Assessments (WWCRA) by using precipitation and temperature from the BCSD CMIP3 climate projections as inputs to the VIC model (Reclamation 2011).

The VIC model is a large-scale, semi-distributed hydrologic model that simulates the water balance at the land surface and shallow sub-surface, including infiltration, soil moisture storage, surface runoff, baseflow, and ET (Liang et al. 1994). Streamflow can be computed through a post-processing routing model that routes VIC surface runoff and baseflow through a defined stream network. The VIC model simulates unimpaired streamflow and does not account for reservoir storage, diversions, or depletions; as a result, the VIC model provides insight into hydrologic variability and change in response to climate forcings, but is not sufficient for detailed analysis of water supplies, demands, and operations for water resources planning purposes.

Depending on the preferences of a given study, the development of future climate scenarios may involve pooling of individual climate projections based on specified criteria or selection of individual climate projections for use as representative climate scenarios. Previous studies by Reclamation have explored the advantages and disadvantages of each approach (e.g., Reclamation 2010 and Reclamation 2011). For this Study, climate scenarios were developed based on three individual climate projections selected directly from the BCSD CMIP3 projection archive and corresponding VIC hydrology projections.

Three projections were selected to represent the range of variability in future climate and water availability. Projected change in basin-average mean annual water availability was used as the primary selection criteria, with projections selected corresponding to low ($10^{th}$ percentile), central tendency ($50^{th}$ percentile; i.e., median), and high ($90^{th}$ percentile) projected water availability relative to historical conditions. Projections selected based on water availability were then reviewed by the Study team to ensure that they also adequately represented the range of projected future precipitation and temperature over the Basin. Projected change in each variable was evaluated based on the area-weighted average of each variable over the Republican River Basin above Clay Center, KS. It should be noted that while BCSD climate projections were selected based on projected changes in basin-averaged conditions, the resulting climate scenarios maintain spatial variability across the domain; in other words, each scenario has potentially different projected climate changes from one portion of the watershed to another. The three climate projections selected as the basis of the climate scenarios used in this Study are detailed in Table 3.

**Table 3. — Description of Climate Projections Used for the Republican River Basin Study**

| Climate Scenario | Description |
|---|---|
| Scenario 1:<br>Warmer/Drier | miroc3_2_medres.1.sresa2<br>Low projected water availability (10th percentile)<br>Low projected precipitation (2nd percentile)<br>High projected temperature (93rd percentile) |
| Scenario 2:<br>Central Tendency | cccma_cgcm3_1.4.sresa1b<br>Central tendency projected water availability (50th percentile)<br>Central tendency projected precipitation (56th percentile)<br>Central tendency projected temperature (53rd percentile) |
| Scenario 3:<br>Less Warm/Wetter | ncar_ccsm3_0.7.sresb1<br>High projected water availability (90th percentile)<br>High projected precipitation (73rd percentile)<br>Low projected temperature (2nd percentile) |

The range of projected basin-averaged annual water availability (precipitation minus evapotranspiration) over the Republican River Basin is illustrated in Figure 23. The black line indicates the ensemble median of projected basin-average water availability; light blue shading indicates range between ensemble $10^{th}$ and $90^{th}$ percentile values, and dark blue shading indicates range between ensemble $25^{th}$ and $75^{th}$ percentile values. Gray shading indicates the historical (1970-1999) and future (2030-2059) periods considered in this Study. Figure 24 shows the probability distribution of mean annual water availability over the 112 hydrologic projections considered here for historical and future periods, along with the range of projected change in mean annual water availability between these periods. Probability distributions are illustrated as box-and-whiskers plots. Red, green, and blue stars on the right-hand panel of Figure 24 illustrate the projected change in annual mean water availability in the Scenarios 1-3, respectively (red = drier scenario; green = central tendency scenario; blue = wetter scenario).

Figure 25 illustrates the change in annual mean precipitation and temperature for each of the 112 BCSD CMIP3 climate projections. The red, green, and blue symbols again indicate the drier, central tendency, and wetter scenarios selected with respect to water availability. The drier scenario corresponds to the warmer and drier end of the range of projected changes in temperature and precipitation. The central tendency scenario corresponds to the central tendency of projected changes in temperature and precipitation. Similarly, the wetter scenario corresponds to the cooler and wetter end of the range of projected changes in temperature and precipitation. Projected changes in mean annual water availability, precipitation, and temperature for each of the three scenarios selected for detailed analysis in this Basin Study are provided in Table 4.

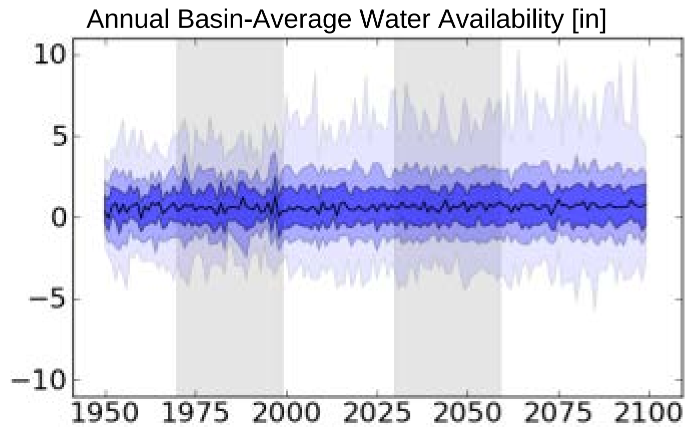



**Figure 23. — Projected annual basin-averaged water availability (precipitation minus evapotranspiration) over the Republican River [in]. Black line shows the ensemble median; dark blue shading indicates range between ensemble 25th and 75th percentiles; light blue shading indicates range between ensemble 10th and 90th percentiles; gray shading indicates historical (1970-1999) and future (2030-2059) periods considered in this Study.**

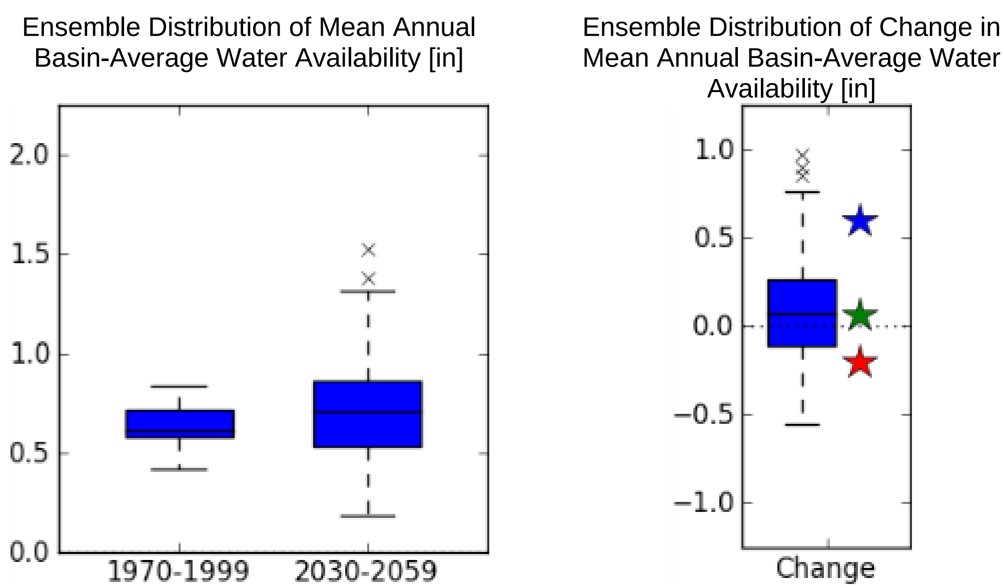



**Figure 24. — Distributions of historical and future annual mean basin-averaged water availability (left) and corresponding projected changes between historical and future periods (right). Red, green, and blue stars in the right-hand panel correspond to the projected change in annual mean water availability in the three scenarios selected for detailed analysis (red = drier, green = central tendency, blue = wetter).**

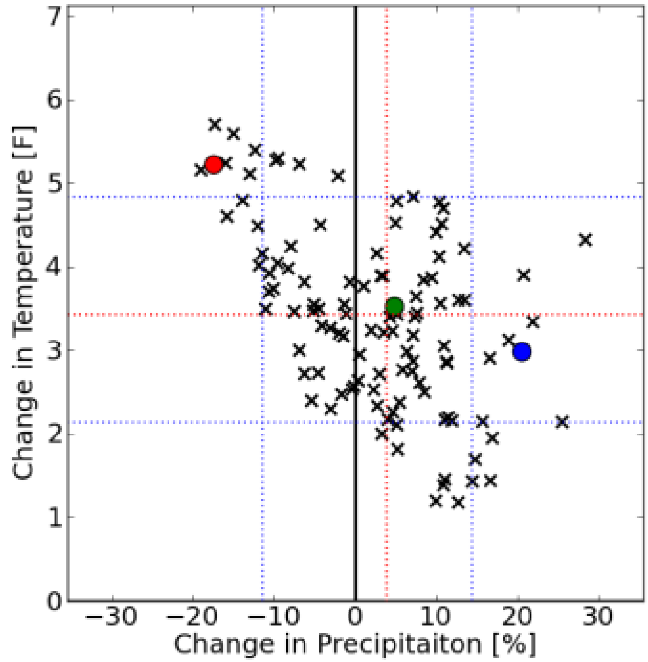



**Figure 25. — Projected change in mean annual temperature [°F] and precipitation [%] from 112 BCSD CMIP3 projections. Blue dashed lines indicate the 10th and 90th percentile projected changes; red dashed lines indicate the 50th percentile (median) projected change. Red circle indicates selected drier scenario; green circle indicates selected central tendency scenario; blue circle indicates selected high scenario with respect to water availability.**

**Table 4. — Summary of Projected Changes in Selected Scenario Variables**

| Variable | Projected Change by Scenario | | |
|---|---|---|---|
| | Scenario 1 Warmer Drier | Scenario 2 Central Tendency | Scenario 3 Less Warm Wetter |
| Mean Annual Water Availability | -0.20 in (-32.7%) | +0.01 in (+10.4%) | +0.60 in (+88.6%) |
| Mean Annual Temperature | +5.22 °F | +3.53 °F | +2.99 °F |
| Mean Annual Precipitation | -3.52 in (-17.4%) | +0.99 in (+4.8%) | +4.09 in (+20.6%) |

It should be noted that there are potential limitations associated developing future climate scenarios based on selection of individual climate projections. For example, Harding et al. (2012) suggest that impact analyses relying on one or a few climate projections are strongly influenced by the choice of individual projections used in the Study. Similarly, Deser et al. (2010) suggests including a large number of projections from a given model in an analysis of climate change impacts because each model realization may contain different superposition of unforced and forced trends. While these studies suggest that there are benefits to evaluating climate change risks and impacts based on numerous GCM projections, Figures 23 through 25 indicate that the scenario-based approach used in this Study balances the need to consider the range of projected changes in climate and water availability with the need to maintain a manageable project scope.

# IV. Current and Future Water Supplies and Demands

## A. Water Supplies

### 1. Description of Basin Water Supplies

Water supplies in the Republican River Basin include a combination of surface water and groundwater. Surface waters throughout the Basin are managed primarily for agricultural uses and flood control. Groundwater throughout the Basin is managed for agricultural, municipal, and industrial uses.

The primary surface water supplies within the Republican River Basin are illustrated in Figure 1. Surface water supplies include Republican River and its major tributaries, including the North and South Forks of the Republican River, Arikaree River, Frenchman Creek, Red Willow Creek, Medicine Creek, Beaver Creek, Sappa Creek, Prairie Dog Creek, and White Rock Creek. Smaller creeks and streams contribute to local surface water supplies in some areas of the Basin; however, smaller creeks and streams are a minor component of the overall surface water supply. Surface water supplies originate as a combination of direct runoff of precipitation and baseflow from groundwater discharge to streams; snowmelt runoff is not a significant component of surface water supplies in the Basin. Surface water is primarily managed for flood control and irrigation supply, and used largely for irrigated agriculture in the alluvial valleys bordering much of the Republican River and its tributaries in Nebraska and Kansas.

The Ogallala Aquifer is the primary groundwater supply throughout most of the Basin. The Ogallala Aquifer is the dominant geologic formation of the larger High Plains Regional Aquifer System and underlies the entire Republican River Basin, with the exception of the Lower Kansas sub-basin downstream of the Nebraska-Kansas state line near Hardy, Nebraska. The Ogallala Aquifer is composed primarily of alluvial and aeolian deposits of unconsolidated, poorly sorted clay, silt, sand, and gravel. Hydraulic properties vary widely across the aquifer, and the saturated thickness of the aquifer ranges from less than 50 feet in the western portion of the Basin to more than 400 feet in the northern portion of the Basin adjacent to the Platte River basin (McGuire et al. 2012). In addition to the Ogallala Aquifer, shallow alluvial aquifers along the Republican River and its tributaries are also important sources of groundwater within the Basin. These alluvial aquifers are hydraulically connected to the underlying Ogallala Aquifer, as well as to the overlying river channels. Groundwater is the primary water supply for most of the irrigated agriculture in the Basin, and the sole supply for municipal, industrial, and domestic uses throughout most the Basin.

Previous studies indicate a strong hydraulic connection between the Republican River and the underlying groundwater aquifers (e.g., Szilagyi 1999, Wen and Chen 2006, Scanlon et al. 2012). Groundwater pumping within the Basin results in capture (depletion) of surface-water supplies through reduced groundwater discharge to streams and/or increased seepage losses from stream channels. Conversely, surface water operations within the Basin affect the timing, distribution, and volume of groundwater recharge that occurs as seepage from surface-water channels, including the natural stream channels and unlined irrigation canals and laterals, and as deep percolation of applied irrigation water.

Surface water and groundwater resources within the Basin are managed by each of the Basin States: water management, use, and administration are subject to the laws and regulations of each respective state. In addition, the Republican River is subject to the Republican River Compact, an interstate compact that allocates the "virgin water supply"[9] of the Basin among the States. Following litigation in the U.S. Supreme Court, the States entered into a Final Settlement Stipulation, approved by the U.S. Supreme Court in 2003. Under the Final Settlement Stipulation, most stream flow depletions caused by surface water and groundwater diversions for beneficial consumptive use are included in the determination and allocation of the virgin water supply of the Basin. As a result, interaction between groundwater and surface water is a key component of water management within the Basin.

## 2. Approach to Water Supply Analysis

Modeling and analysis of current and future water supplies were carried out at the sub-basin scale, with each state leading the development of modeling tools and related datasets for its respective portion of the Basin. Basin-scale analysis was then carried out by integrating results across sub-basins. This sub-basin modeling approach was selected by the Basin Study partners to facilitate the use of best-available data, tools, and expertise in modeling and evaluating current and future water supplies and demands and system reliability, as well as in developing and evaluating management alternatives to improve water operations throughout the Basin.

[9] Per the Republican River Compact, the term "virgin water supply" is defined here as "the water supply within the Republican River Basin undepleted by the activities of man".

For the purpose of this Study, the Republican River basin was divided into four sub-basins (Figure 2). The Colorado and Nebraska sub-basins encompass all portions of the Basin within each of the respective states. The Upper Kansas sub-basin encompasses the portion of the Basin within Kansas that is upstream of Harlan County Lake, and the Lower Kansas sub-basin encompasses the portion of the Basin within Kansas downstream of Harlan County Lake. It should be noted that for modeling purposes, the modeling tools and related datasets developed to analyze water supplies, demands, and operations in the Lower Kansas sub-basin encompass the portion of the Basin from Harlan County Lake in Nebraska to Milford Lake in Kansas. As a result, modeling tools and datasets for the Lower Kansas sub-basin include the Nebraska portion of the Basin between Harlan County Lake and the Nebraska-Kansas state line, as well as areas downstream of Clay Center, Kansas that are outside of the Basin Study area. As shown in Figure 2, the portion of the Basin from Harlan County Lake to the Nebraska-Kansas state line lies within both the Nebraska and Lower Kansas sub-basin models; this area is referred to as the sub-basin overlap region.

New datasets representing current and projected future streamflow were developed for major tributaries in all sub-basins. In addition, new modeling tools were developed to simulate current and future surface water operations in the Nebraska and Lower Kansas sub-basins, including streamflows, reservoir storage and operations, surface water diversions and deliveries, and stream gains and losses (i.e., groundwater/surface-water interactions). Models developed for these sub-basins are summarized below in *Section 4.1.3: Current Surface Water Availability*; additional details are provided by TFG (2015a) and KGS and KWO (2015b). As discussed in *Section 1.2: Location and Description of the Study Area*, no new modeling tools were developed for the Colorado or Upper Kansas sub-basins.

Surface water supplies were characterized as the sum of annual gross surface water diversions, annual net change in reservoir storage, and annual streamflow leaving each sub-basin. This approach represents the quantity of surface water that is physically available within each sub-basin on an annual basis. It should be noted, however, that this approach does not reflect the sources of surface water within a given sub-basin (e.g., surface water originating as runoff or baseflow within the sub-basin versus inflows from upstream sub-basins) or any legal or regulatory constraints on its use (e.g., Compact obligations to downstream sub-basins, mandatory flow requirements, etc.). Specifically, this approach considers streamflow out of each sub-basin as a component of its surface water supply, without consideration of interstate obligations under the Republican River Compact. In addition, this approach does not account for re-use of surface water supplies, such as where operational spills and return flows from one canal service area contribute to subsequent surface water diversions to downstream canals.

Current surface water supplies in the Colorado and Upper Kansas sub-basins were characterized based on historical data for the period 1995-2010; data for more recent years were not readily available for use in this analysis. Recent changes to surface water uses within the Colorado and Upper Kansas sub-basins have resulted in decreased surface water diversions and decreased reservoir storage since approximately 2008. Based on the method used here to characterize surface water supplies, decreased diversions and storage would result in a corresponding increase in streamflow out of the sub-basin; however, these changes would not substantially affect the estimated total available surface water supply.

Current surface water supplies in the Nebraska and Lower Kansas sub-basins were characterized based on simulations of hydrology and water operations in the respective sub-basins under current climate and hydrologic conditions as defined by the Baseline Scenario (see *Section 3.2: Future Climate Conditions* for further detail) and current water management practices as defined by the No Action Alternative (see *Section 5.1: No Action – Future without Adaptation Strategies*). Each model represents the physical processes and major water infrastructure and operations affecting surface water supplies and management in the respective sub-basin. Model results incorporate recent changes in surface water management and operations, particularly in the Nebraska sub-basin, and therefore provide an improved representation of surface water supplies compared to historical data.

Future surface water supplies in each sub-basin were subsequently evaluated for each of the three future climate scenarios considered in the Basin Study (*Section 3.2: Future Climate Conditions*). The three future climate scenarios encompass the range of projected changes in climate and water availability over the Basin between a historical reference period (1970-1999) and selected future period (2030-2059). Future surface water supplies in the Colorado and Upper Kansas sub-basins were characterized based on the projected change in streamflow out of each sub-basin. Future surface water supplies in the Nebraska and Lower Kansas sub-basins were based on simulations of future hydrology and water operations in each sub-basin under each of the future climate scenarios for the No Action Alternative.

Current groundwater supplies in the Colorado, Upper Kansas, and Nebraska sub-basins were characterized based on computed groundwater recharge in each of these sub-basins. Groundwater recharge represents the inflow to the groundwater system over a given period, and thus the amount of groundwater that may contribute to baseflow, evapotranspiration from groundwater-dependent ecosystems, and well pumping for irrigation and other uses during the same period without depleting aquifer storage. Methods to estimate groundwater recharge throughout the portions of the Basin encompassed by the Republican River Compact Administration (RRCA) groundwater model were previously developed by the RRCA Groundwater Modeling Committee (RRCA 2003[10]). These methods provide estimates of recharge from precipitation, seepage from

[10] http://www.republicanrivercompact.org/v12p/RRCAModelDocumentation.pdf

irrigation canals and laterals, and deep percolation of irrigation water. Precipitation recharge is the dominant component of recharge in most years; precipitation recharge is calculated from a set of non-linear relationships between precipitation and recharge for different land cover and soil types. Recharge from surface water channels, including recharge by canal seepage, is calculated proportionately to net surface water diversions; recharge from irrigation, including deep percolation of surface water irrigation and groundwater irrigation, is also calculated proportionately to the gross irrigation, with different factors applied depending on irrigation source (surface water or groundwater), soil and crop types, and irrigation practices.

The RRCA groundwater model does not include the Lower Kansas sub-basin. Groundwater supplies in the Lower Kansas sub-basin were therefore characterized based on net recharge simulated by the hydrologic model of the Lower Kansas sub-basin developed in support of this Study. The Lower Kansas sub-basin hydrologic model simulates infiltration and recharge based on precipitation and evapotranspiration at the land surface. Recharge is not provided as a model output; instead, net recharge is computed from the simulated water budget aggregated over the model domain. Net recharge is the difference between recharge and evapotranspiration; net recharge is positive for periods when recharge exceeds evapotranspiration and negative for periods when evapotranspiration exceeds recharge.

Future groundwater supplies in all sub-basins are considered qualitatively based on projected changes in precipitation and surface water diversions under the No Action Alternative. Detailed analysis of future groundwater supplies was not carried out as part of this Study.

## 3. Current Surface Water Availability

### a. *Colorado Sub-Basin*

For the purposes of this Study, current surface water availability in the Colorado sub-basin is characterized based on the sum of annual streamflows out of the sub-basin, annual gross diversions within the sub-basin, and the annual net change in reservoir storage in the sub-basin for the period 1995-2010. Outflows are summed over the sub-basin's three primary tributaries: North Fork Republican River, Arikaree River, and South Fork Republican River. The Colorado sub-basin includes one storage facility, Bonny Reservoir on the South Fork Republican River. Surface water diversions within each sub-basin were compiled by the State of Colorado for the RRCA Groundwater Modeling Committee based on diversion records from the state's water rights database. Sub-basin outflows were estimated based on measured streamflow in each tributary at the gage nearest to the Colorado state line.

The North Fork Republican River flows from the Colorado sub-basin into the Nebraska sub-basin. Surface water availability in the North Fork Republican River drainage in the sub-basin is characterized using recent observed streamflows for the USGS stream gage at the Colorado-Nebraska state line (USGS Gage 06823000). The Arikaree River flows from the Colorado sub-basin through a short section of the Upper Kansas sub-basin and into the Nebraska sub-basin. Surface water availability in the Arikaree River drainage of the Colorado sub-basin is characterized using recent observed streamflows for the USGS stream gage near Haigler, Nebraska (USGS Gage 06821500). This stream gage is located approximately eight river miles downstream of the Colorado-Kansas state line, and no significant surface water inflows, impoundments, or diversions occur between the state line and the gage location. Lastly, the South Fork Republican River flows from the Colorado sub-basin into the Upper Kansas sub-basin. Surface water availability in the South Fork Republican River portion of the sub-basin is characterized using recent observed river releases from Bonny Reservoir. Bonny Reservoir is located approximately nine river miles upstream of the Colorado-Kansas state line. Diversions between Bonny Dam and the state line are accounted for in this analysis.

Figure 26 illustrates the total annual surface water supply of the Colorado sub-basin for the period 1995-2010, where total supply is represented as the sum of annual outflows and annual gross diversions for each of the primary tributaries in the sub-basin. The annual surface water supply in the sub-basin ranges from 30,050 AF to 55,100 AF, with an average of 38,500 AF for the period shown.

It should be noted that surface diversions make up a small portion of the total water use in the Colorado sub-basin. More importantly, since 2008, the majority of surface water diversions in the Colorado sub-basin have been abandoned or leased by the Republican River Water Conservation District. The remaining surface water diversions on the North Fork Republican River have averaged 950 AF/year since 2009, compared to an average of 9,100 AF/year over the period shown in Figure 26. Only one diversion remains active on the South Fork Republican River, which is Hale Ditch. Diversions to Hale Ditch since 2009 are typically less than 200 AF, with a minimum of 22 AF and a maximum of 1320 AF. Decreases in surface water diversions since 2008 allow a greater amount of surface water to flow out of the sub-basin, but do not affect the overall surface water supply.

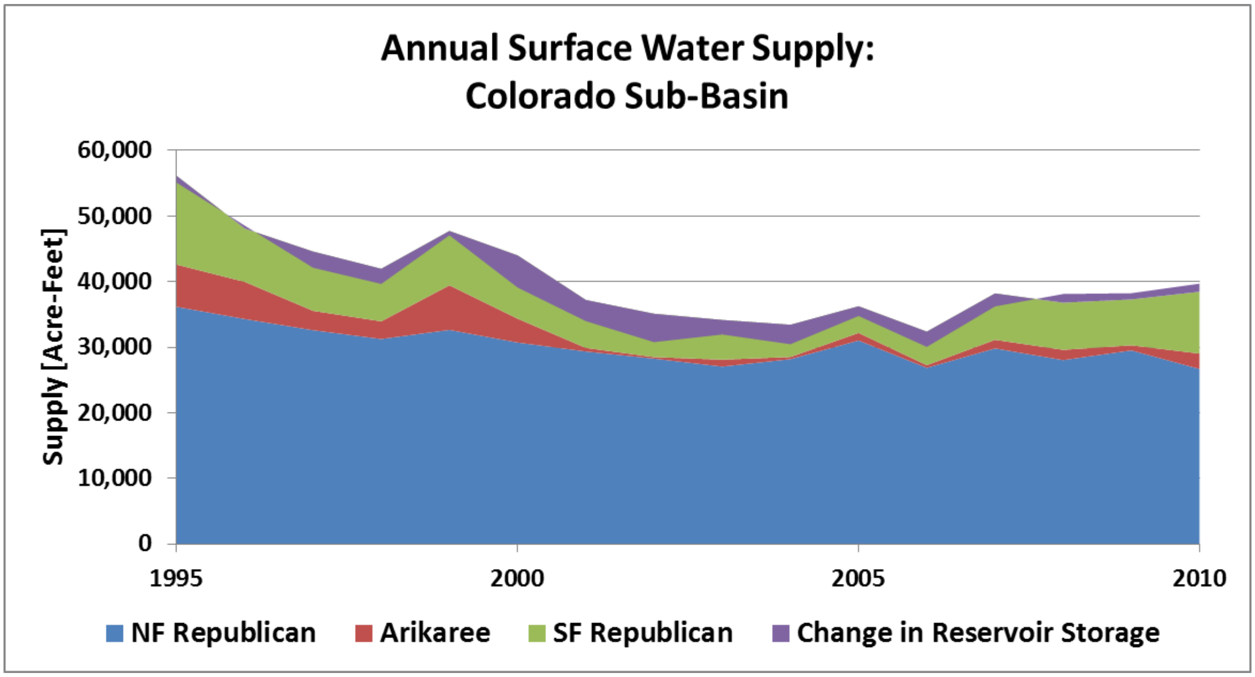



**Figure 26. — Annual surface water supply in the Colorado sub-basin for years 1995-2010.**

### b. *Upper Kansas Sub-Basin*

For the purposes of this Study, current surface water availability in the Upper Kansas sub-basin is characterized based on the sum of annual streamflows out of the sub-basin and the annual net change in reservoir storage in the sub-basin for the period 1995-2010. Outflows are summed over the sub-basin's four primary tributaries: South Fork Republican River, Beaver Creek, Sappa Creek, and Prairie Dog Creek. The Upper Kansas sub-basin includes one storage facility, Keith Sebelius Reservoir on Prairie Dog Creek, which serves irrigation demands in the Almena Unit and municipal demands for the city of Norton, Kansas. Similar to current conditions in the Colorado sub-basin, the majority of surface water rights in the Upper Kansas sub-basin have been abandoned, retired, or leased; as a result, annual surface water diversions in the sub-basin are less than 1,000 AF/year and are therefore omitted from this analysis.

The South Fork Republican River flows from the Colorado sub-basin through the Upper Kansas sub-basin and into the Nebraska sub-basin. Surface water availability in the South Fork Republican River drainage is characterized using recent observed streamflows in the South Fork Republican River at Benkelmann, Nebraska (USGS Gage 06827500), which is approximately one mile downstream of the Kansas-Nebraska state line. Beaver Creek, Sappa Creek, and Prairie Dog Creek each originate the Upper Kansas sub-basin and flow into the Nebraska sub-basin where they ultimately join the mainstem Republican River. Surface water supplies in the Beaver Creek drainage are characterized by recent observed streamflows in Beaver Creek at Cedar Bluffs, Kansas (USGS Gage 06846500), approximately two miles upstream of the Kansas-Nebraska state line. Supplies in

Sappa Creek and Prairie Dog Creek are characterized based on the USGS gages near Lyle, Kansas (USGS Gage 06845110) and Woodruff, Kansas (USGS Gage 06848500), respectively. The gage on Sappa Creek near Lyle, Kansas is located approximately at the Kansas-Nebraska state line and the gage on Prairie Dog Creek near Woodruff, Kansas, is located approximately 2.5 miles upstream of the state line. No significant inflows, impoundments, or diversions occur between any of the selected gages and the respective state line.

Figure 27 illustrates the total annual surface water supply of the Upper Kansas sub-basin for the period 1995-2010, where total supply is represented as the sum of annual outflows from the sub-basin in the South Fork Republican River, Beaver Creek, Sappa Creek, and Prairie Dog Creek. The annual surface water supply in the sub-basin ranges from a minimum of just 1,032 AF to a maximum of 126,462 AF, with an average of 31,710 AF per year for the period shown. Streamflows Beaver Creek, Sappa Creek, and Prairie Dog Creek are generally highest in summer and lowest in winter, with peak flows typically occurring during the month June-August. Flows in the South Fork Republican River peak in spring (April-May) and decrease through the summer, with low flows from August through January.

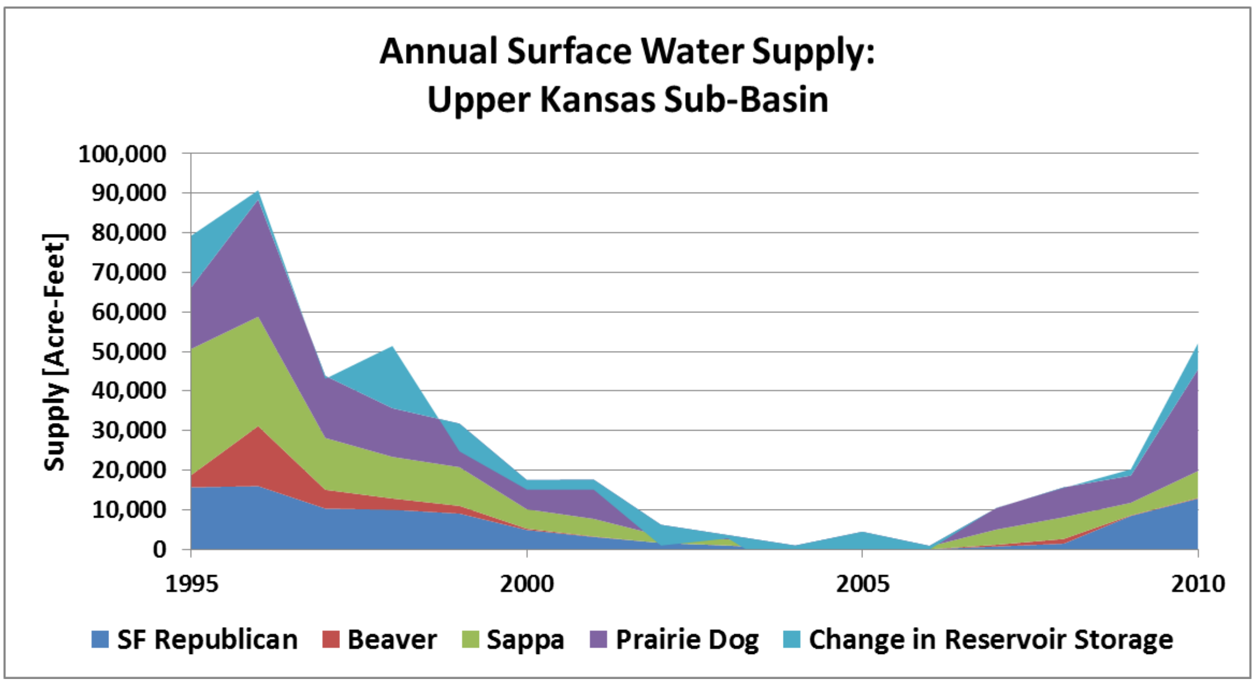



**Figure 27. — Annual surface water supply in the Upper Kansas sub-basin for years 1995-2010.**

### c. *Nebraska Sub-Basin*

For the purposes of this Study, annual surface water supply in the Nebraska sub-basin is characterized as the sum of simulated annual streamflows out of the sub-basin, annual gross diversions within the sub-basin, and the annual net change in reservoir storage in the sub-basin. Current surface water availability is characterized based on simulations of hydrology and water operations in the sub-basin under the Baseline Scenario and No Action Alternative. Simulations were carried out by The Flatwater Group, a technical consultant to State of Nebraska, using the STELLA Operations Republican River Model (STORRM) water operations model. STORRM was developed by The Flatwater Group, in collaboration with the Basin Study partners, in support of this Basin Study. As summarized in *Section 5.2: Approach to System Reliability Analysis*, STORRM explicitly represents all major surface water features within the sub-basin, including 16 Federal and non-Federal canals and five Federal storage facilities. Minor tributaries, diversions, and impoundments within the sub-basin are implicitly represented through the model's stream gain and loss terms and are thus accounted for in the simulated surface water budget. Surface water supply components represented in the STORRM model used to calculate annual surface water supply in the Nebraska sub-basin are listed in Table 5. Detailed documentation of the STORRM model is provided by TFG (2015a).

**Table 5. — Summary of Data Used to Estimate Surface Water Availability in Nebraska Sub-Basin**

| Data Type | Data Locations |
|---|---|
| Surface Water Diversions ($Q_{div}$) | Pioneer Ditch<br>Crews No. 1 Canal<br>Crews No. 2 Canal<br>Parks Canal<br>Meeker-Driftwood Canal<br>Culbertson and Culbertson Extension Canals<br>Riverside Canal<br>Red Willow Canal<br>Bartley Canal<br>Cambridge Canal<br>Franklin Canal<br>Naponee Canal<br>Franklin Southside Pump Canal<br>Superior Canal<br>Courtland Canal |
| Reservoir Storage ($\Delta S$) | Enders Reservoir<br>Swanson Reservoir<br>Hugh Butler Reservoir<br>Harry Strunk Reservoir<br>Harlan County Lake |
| Surface Water Outflow ($Q_{out}$) | Republican River near Hardy NE |

Figure 28 illustrates the total annual surface water supply of the Nebraska sub-basin based on a 50-year simulation under the Baseline Scenario and No Action Alternative. As summarized in *Section 3.2: Future Climate Conditions*, the Baseline Scenario represents historical climate conditions over the period 1960-2010 and current hydrologic conditions consistent with the period 1995-2010. Gross diversions, change in storage, and sub-basin outflow all exhibit significant interannual variability, including multi-year dry periods. Under current conditions, surface water supplies in the Nebraska sub-basin range from approximately 132,000 to 650,750 AF, with an average of 337,232 AF per year. Republican River outflow from the Nebraska sub-basin to the Lower Kansas sub-basin is the largest component of surface water supply in most years. Outflow ranges from 72,000 to 483,400 AF, with an average of approximately 217,700 AF per year. Gross diversions within the Basin range from a total of 21,600 to 280,750 AF per year and the annual change in reservoir storage ranges from a loss of 212,500 AF to a gain of 260,250 AF. Note that negative changes in storage are not illustrated to scale in Figure 28, but are reflected in the total supply shown in the figure.

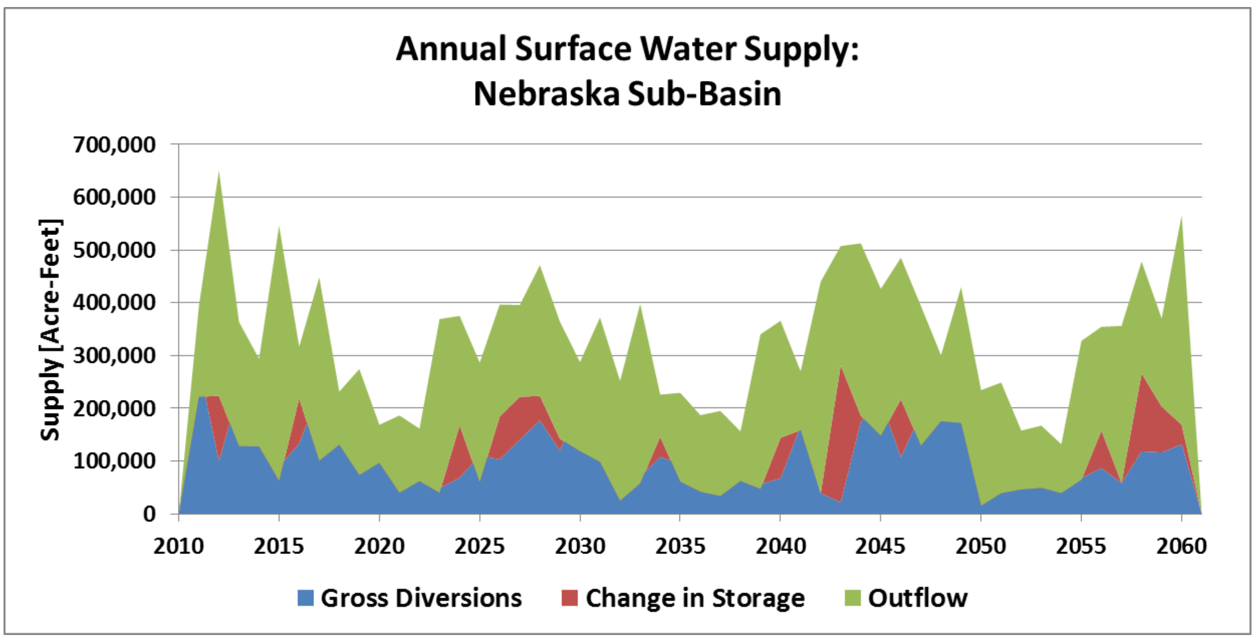



**Figure 28. — Annual surface water supply in the Nebraska sub-basin based on model results from a 50-year simulation under the Baseline Scenario – No Action Alternative.**

### d. *Lower Kansas Sub-Basin*

For the purposes of this Study, annual surface water supply in the Kansas sub-basin is characterized as the sum of simulated annual streamflows out of the sub-basin, annual gross diversions within the sub-basin, and the annual net change in reservoir storage in the sub-basin. Current surface water availability is characterized based on simulations of hydrology and water operations in the sub-basin under the Baseline Scenario and No Action Alternative. Simulations were carried out by the Kansas Geological Survey (KGS) and Kansas Water Office (KWO) using a linked hydrologic and water operations modeling platform. This new modeling platform was developed by KGS and KWO by linking the HydroGeoSphere (HGS) integrated hydrologic modeling software with the OASIS water operations modeling platform. As summarized in *Section 5.2: Approach to System Reliability Analysis*, HGS represents the physical hydrology of the Basin, including groundwater and surface water flows, while OASIS explicitly represents the operations of all major surface water features within the sub-basin. Surface water supply components represented in the OASIS model used to calculate annual surface water supply in the Lower Kansas sub-basin are listed in Table 6. Detailed documentation of the linked HGS-OASIS modeling approach is provided by KWO and KGS (2015b).

**Table 6. — Summary of Data Used to Estimate Surface Water Availability in Lower Kansas Sub-Basin**

| Data Type | Data Locations |
|---|---|
| Surface Water Diversiozdfsns ($Q_{div}$) | Upper KBID[11] and Lower KBID[12] |
| Reservoir Storage ($\Delta S$) | Lovewell Reservoir |
| Sub-Basin Outflow ($Q_{out}$) | Republican River at Clay Center KS |

Figure 29 illustrates the total annual surface water supply of the Lower Kansas sub-basin based on a 50-year simulation under the Baseline Scenario and No Action Alternative. As summarized in *Section 3.2: Future Climate Conditions*, the Baseline Scenario represents historical climate conditions over the period 1960-2010 and current hydrologic conditions consistent with the period 1995-2010. Gross diversions, change in storage, and sub-basin outflow all exhibit significant interannual variability, including multi-year dry periods. Under current conditions, surface water supplies in the Lower Kansas sub-basin range from approximately 135,000 to 2,850,000 AF, with an average of 651,150 AF per year. Republican River outflow from the sub-basin at Clay Center, Kansas, is by far the largest component of surface water supply in all years. Outflow ranges from 87,350 to 2,815,000 AF, with an average of approximately 600,000 AF per year. Gross diversions within the Basin range from a total of 10,300 to 95,850 AF per year and the annual change in reservoir storage ranges from a loss of 18,250 AF to a gain of 17,300 AF. Note that negative changes in storage are not

[11] Flow in Courtland Canal at NE-KS state line minus outflow from Courtland Canal to Lovewell Reservoir
[12] Gross diversion from Lovewell Reservoir to Courtland Canal

illustrated to scale in Figure 29, but are reflected in the total supply shown in the figure.

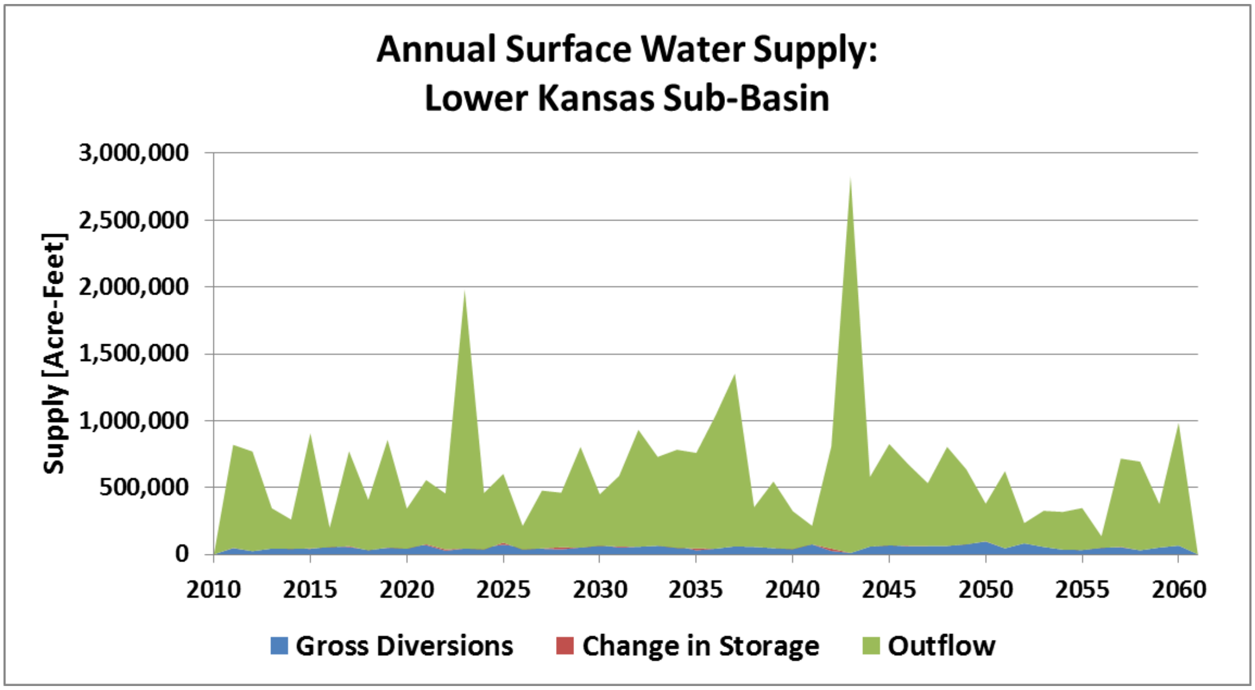



**Figure 29. — Annual surface water supply in the Lower Kansas sub-basin based on model results from a 50-year simulation under the Baseline Scenario – No Action Alternative.**

## 4. Current Groundwater Availability

### a. *Colorado Sub-Basin*

Current groundwater supply in the Colorado sub-basin was characterized based on the estimated annual recharge within the sub-basin. Recharge estimates were developed by the RRCA Groundwater Modeling Committee for use with the RRCA groundwater model and include the years 2001-2014. Recharge was aggregated over the sub-basin to compute annual average recharge rate and annual gross recharge.

Annual average recharge rate (inches) and annual gross recharge (AF) for the Colorado sub-basin are shown in Figure 30 for the period 2001-2014. The average recharge rate over the sub-basin ranges from 0.48 to 3.28 inches, with an average of 1.19 inches per year. Annual gross recharge within the sub-basin ranges from 200,000 to 1,350,000 AF, with an average of approximately 500,000 AF per year.

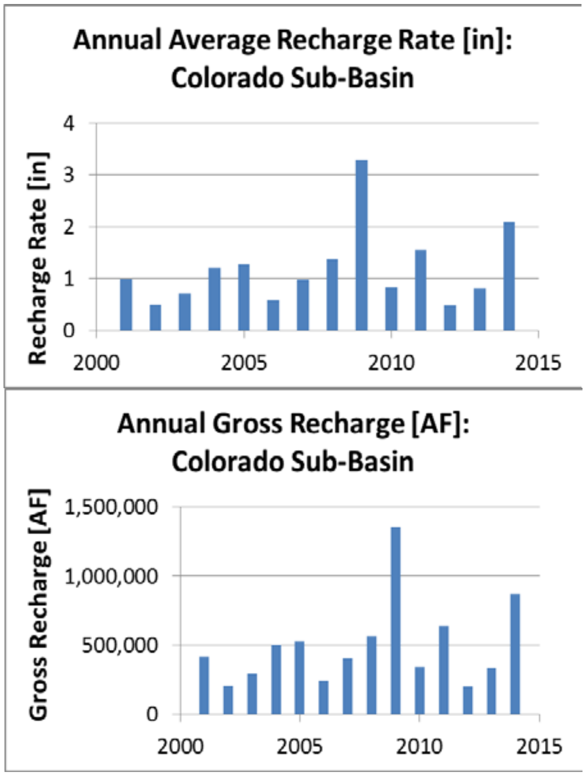



**Figure 30. — Estimated annual average recharge rate (left) and annual gross recharge (right) over the Colorado sub-basin for the period 2001-2014.**

## b. *Upper Kansas Sub-Basin*

Current groundwater supply in the Upper Kansas sub-basin was characterized based on estimated annual recharge within the sub-basin using the same approach as for the Colorado sub-basin. Annual average recharge rate (inches) and annual gross recharge (AF) for the Upper Kansas sub-basin are shown in Figure 31 for the period 2001-2014. The average recharge rate over the sub-basin ranges from 0.22 to 1.47 inches, with an average of 0.60 inches per year. Annual gross recharge within the sub-basin ranges from 58,000 to 385,000 AF, with an average of approximately 150,000 AF per year.

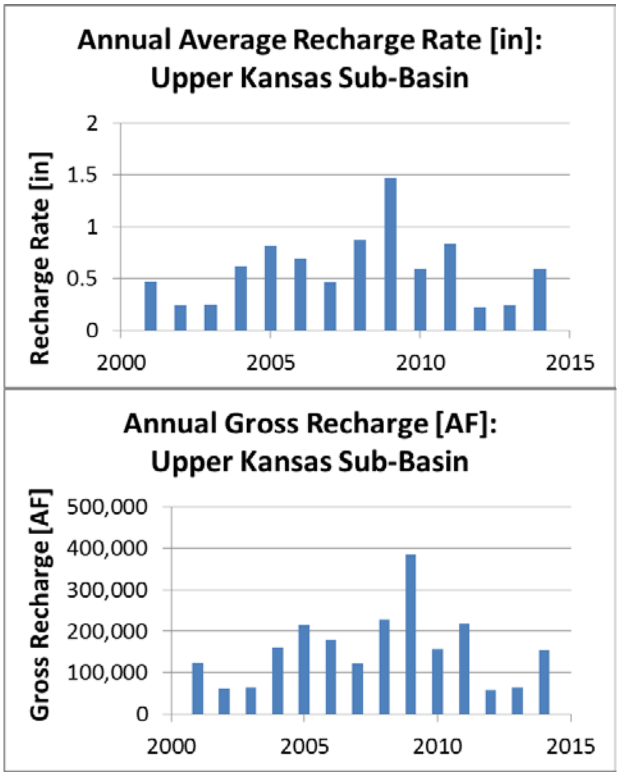
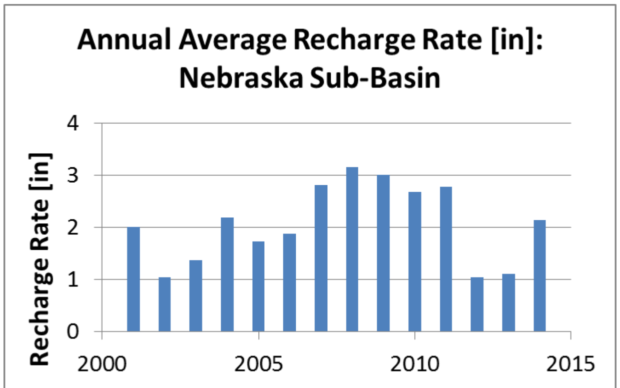



**Figure 31. — Estimated annual average recharge rate (left) and annual gross recharge (right) over the Upper Kansas sub-basin for the period 2001-2014.**

### c. *Nebraska Sub-Basin*

Current groundwater supply in the Nebraska sub-basin was characterized based on estimated annual recharge within the sub-basin using the same approach as for the Colorado sub-basin. Annual average recharge rate (inches) and annual gross recharge (AF) for the Nebraska sub-basin are shown in Figure 32 for the period 2001-2014. The average recharge rate over the sub-basin ranges from 1.03 to 3.16 inches, with an average of 2.07 inches per year. Annual gross recharge within the sub-basin ranges from 520,000 to 1,600,000 AF, with an average of approximately 1,000,000 AF per year.



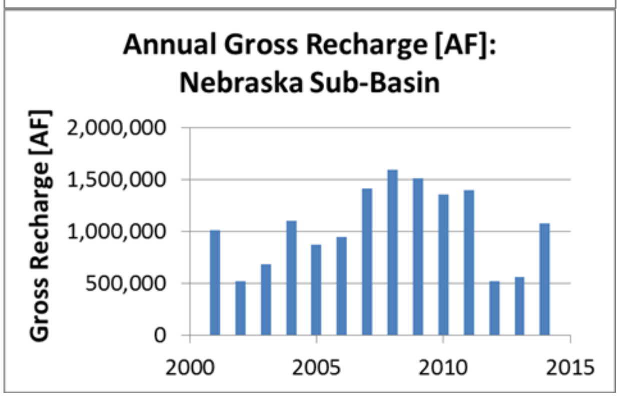




**Figure 32. — Estimated annual average recharge rate (left) and annual gross recharge (right) over the Nebraska sub-basin for the period 2001-2014.**

### d. *Lower Kansas Sub-Basin*

Current groundwater supply in the Lower Kansas sub-basin was characterized based on the estimated annual net recharge within the sub-basin. Net recharge estimates were developed by KGS based on simulations of hydrology and water operations in the Lower Kansas sub-basin under the Baseline Scenario and No Action Alternative. Net recharge was computed from the subsurface water balance simulated by the HGS component of the linked HGS-OASIS modeling platform (*see Section 5.2: Approach to System Reliability Analysis*). Net recharge is the difference between gross recharge into the subsurface and evapotranspiration of water out of the subsurface; net recharge is therefore positive over periods where recharge exceeds evapotranspiration, and negative over periods where evapotranspiration exceeds recharge.

Estimated annual net recharge rate (inches) and annual net recharge (AF) over the Lower Kansas sub-basin are shown in Figure 33. Data shown in Figure 33 are from a 50-year simulation of hydrology and water operations by the linked HGS-OASIS modeling platform developed by KGS and KWO in support of this Study. Annual net recharge rate averaged over the sub-basin ranges from a minimum of -4.5 inches to a maximum of 12.9 inches, with an average of 4.2 inches per year; annual net recharge aggregated over the sub-basin ranges from -580,000 to

1,650,000 AF, with an average of approximately 550,000 AF per year. As noted above, the occurrence of negative net recharge indicates that evapotranspiration from the sub-basin exceeds recharge in some years.

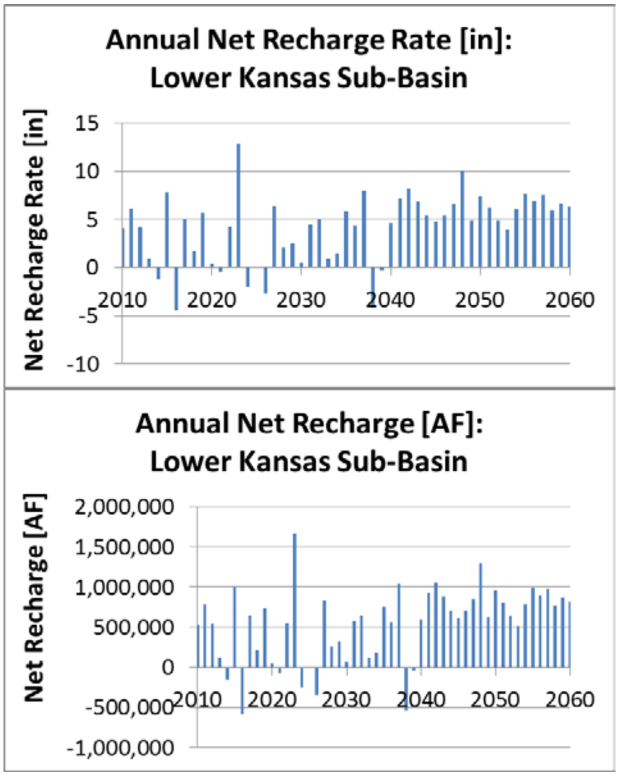



**Figure 33. — Estimated annual net recharge rate (left) and annual net recharge (right) over the Lower Kansas sub-basin for a 50-year simulation under the Baseline Scenario and No Action Alternative.**

## 5. Effects of Climate Variability and Change on Supply

### a. *Data, Models, and Methods Used*

Future surface water supplies in each sub-basin were evaluated for each of the three future climate scenarios considered in the Basin Study. The three future climate scenarios encompass the range of projected changes in climate and water availability over the Basin between a historical reference period (1970-1999) and selected future period (2030-2059). Development of the climate scenarios considered in this Study is summarized in *Section 3.2: Future Climate Conditions*; additional details are provided by Reclamation (2015b).

Future surface water supplies in the Colorado and Upper Kansas sub-basins were characterized based on the projected change in streamflow out of each sub-basin. Projections of future streamflows were developed for each of the sub-basin tributaries discussed in the previous section. Projected streamflows in the

Colorado sub-basin were developed for the North Fork Republican River at the Colorado-Nebraska state line; the Arikaree River at Haigler, Nebraska; and the South Fork Republican River below Bonny Dam. Projected streamflows in the Upper Kansas sub-basin were developed for the South Fork Republican River at Benkelman, Nebraska; Beaver Creek at Cedar Bluffs, Kansas; Sappa Creek at Lyle, Kansas; and Prairie Dog Creek at Woodruff, Kansas.

Projected future streamflows under each of the future climate scenarios considered in this Study were developed based on a combination of baseline streamflows and simulation of future streamflows under each scenario using the Variable Infiltration Capacity (VIC) hydrologic model. First, hydrologic simulations were carried out with the VIC model under the Baseline Climate Scenario and three future climate scenarios. Baseline streamflows at each of the locations listed above were then perturbed based on the change in simulated streamflow between VIC simulations for each scenario and VIC simulation under baseline climate conditions. Perturbations were applied using a quantile-based perturbation approach, which essentially consists of superimposing the projected change in probability distribution of a given variable between two periods — e.g., between selected historical and future periods — onto that variable's probability distribution in a different dataset. In this case, streamflow for each climate scenario was developed by superimposing the projected change in the probability distribution of monthly streamflow between VIC simulations under baseline and future climate scenarios onto the observed probability distribution of monthly streamflow. This procedure has been widely used to adjust historical climate and hydrologic datasets to reflect projected changes under future climate conditions.

Future surface water supplies in the Nebraska and Lower Kansas sub-basins were characterized based on simulations of future hydrology and water operations in each sub-basin under the No Action Alternative for each of the future climate scenarios considered in this Study. Climate and hydrologic inputs to the STORRM model of the Nebraska sub-basin and the linked HGS-OASIS model of the Lower Kansas sub-basin were perturbed to represent projected changes under each of the selected scenarios. Climate and hydrologic inputs to STORRM include tributary inflows at the upstream extent of the model domain, as well as net irrigation requirement for irrigated lands represented in the model; net irrigation requirement inputs were calculated based on projected future temperature and precipitation under each scenario. Climate and hydrologic inputs to the HGS-OASIS model include precipitation, temperature, and net irrigation requirement. As for current surface water supplies, future surface water supplies in each sub-basin are represented as the sum of annual gross diversions, net change in reservoir storage, and streamflow out of each sub-basin.

## b. *Future Surface Water Availability*

### i. Colorado Sub-Basin

Surface water supplies in the Colorado sub-basin under baseline and future climate scenarios are shown in Figure 34 for each of the sub-basin's three primary tributaries and for the sub-basin as a whole. Changes in the minimum, maximum, and average annual surface water supply under each scenario are summarized in Table 7.

Surface water supplies in the Colorado sub-basin are projected to decrease under Scenario 1 (warmer and drier) and increase substantially under Scenario 3 (less warm and wetter), with little change under Scenario 2 (central tendency). Projected changes are generally larger in the Arikaree River and South Fork Republican River, with smaller percent change in the North Fork Republican River. Projections suggest that high flows, as represented by the maximum annual surface water supply in each sub-basin, are more sensitive to changes in climate than average and low flows.

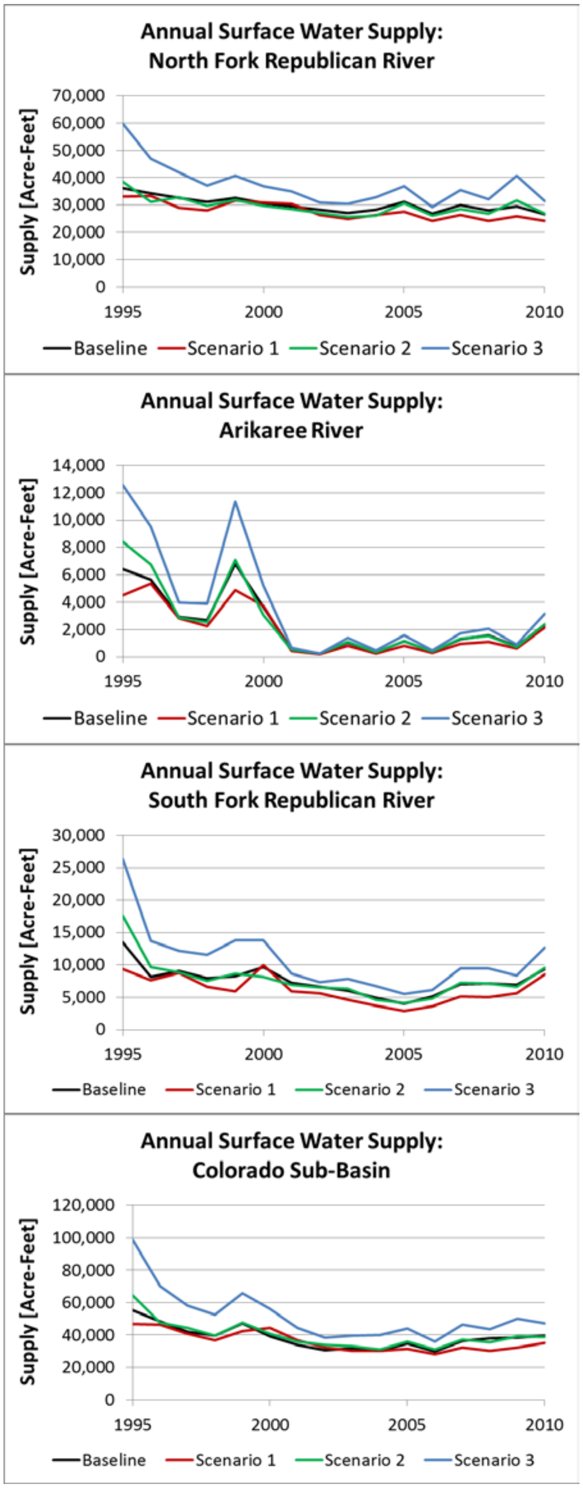



**Figure 34. — Surface water supplies in the Colorado sub-basin under baseline and future climate scenarios: North Fork Republican River (upper left); Arikaree River (upper right); South Fork Republican River (lower left); sub-basin total surface water supply (bottom right).**

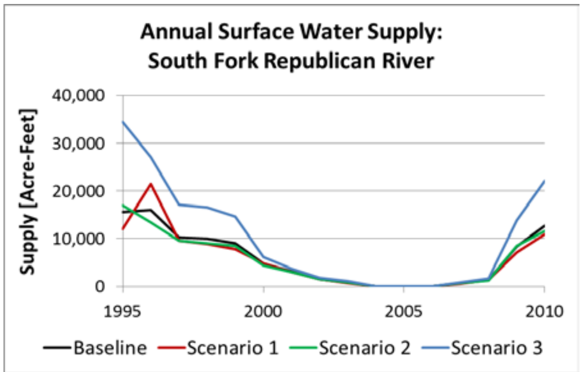
**Table 7. — Projected Percent Change in Minimum, Average, and Maximum Annual Surface Water Supply in Primary Tributaries of the Colorado Sub-Basin Under Future Climate Scenarios**

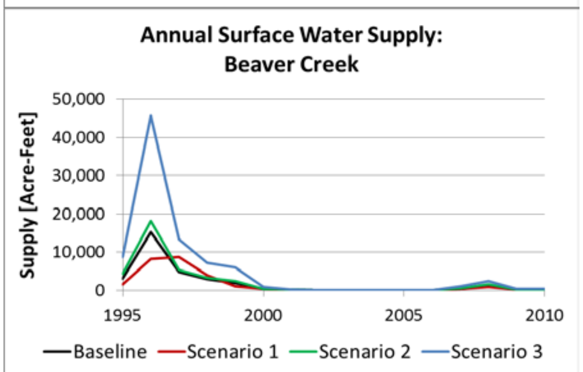
| | Scenario 1 (Warmer + Drier) | Scenario 2 (Central Tendency) | Scenario 3 (Less Warm + Wetter) |
|---|---|---|---|
| | Projected Change in Minimum Annual Streamflow | | |
| NF Republican | -7.1% | -4.1% | +9.4% |
| Arikaree | -14.5% | -1.5% | +11.2% |
| SF Republican | -29.0% | -0.5% | +36.4% |
| Sub-Basin Total | -6.0 | -3.5% | +7.0% |
| | Projected Change in Average Annual Streamflow | | |
| NF Republican | -7.6% | -2.0% | +24.9% |
| Arikaree | -17.6% | +6.8% | +56.4% |
| SF Republican | -18.0% | +2.7% | +43.3% |
| Sub-Basin Total | -7.3% | -1.24% | +22.3% |
| | Projected Change in Maximum Annual Streamflow | | |
| NF Republican | -8.4% | +6.6% | +65.4% |
| Arikaree | -21.4% | +23.6% | +84.8% |
| SF Republican | -26.2% | +30.6% | +95.2% |
| Sub-Basin Total | -10.0% | +8.6% | +56.3% |

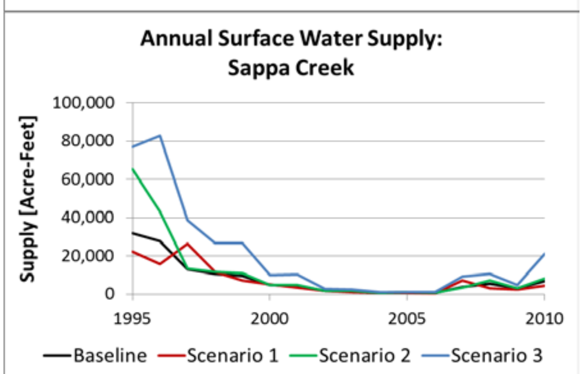
### ii. Upper Kansas Sub-Basin

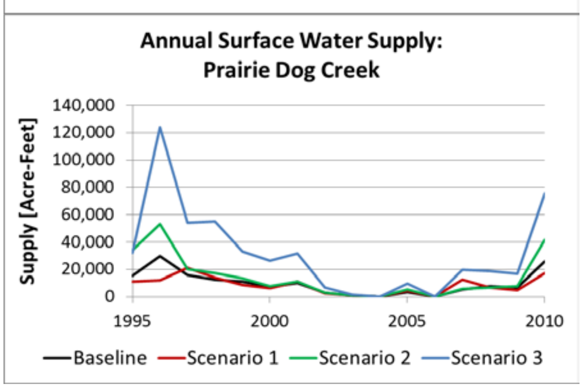
Surface water supplies in the Upper Kansas sub-basin under baseline and future climate scenarios are shown in Figure 35 for each of the sub-basin's four primary tributaries and for the sub-basin as a whole. Changes in the minimum, maximum, and average annual surface water supply under each scenario are summarized in Table 8.

Similar to the Colorado sub-basin, surface water supplies in the Upper Kansas sub-basin are projected to decrease substantially under Scenario 1 (warmer and drier) and increase substantially under Scenario 3 (less warm and wetter). In contrast to the Colorado sub-basin, however, surface water supplies are projected to increase substantially under Scenario 2 (central tendency). Projected changes are generally consistent across tributaries, though Prairie Dog Creek exhibits slightly greater sensitivity to changes in climate than the other tributaries in the sub-basin. As for the Colorado sub-basin, projections suggest that high flows, as represented by the maximum annual surface water supply in each sub-basin, are more sensitive to changes in climate than average and low flows.


Annual Surface Water Supply:
South Fork Republican River
Supply [Acre-Feet]
40,000
30,000
20,000
10,000
0
1995
2000
2005
2010
Baseline
Scenario 1
Scenario 2
Scenario 3


Annual Surface Water Supply:
Beaver Creek
Supply [Acre-Feet]
50,000
40,000
30,000
20,000
10,000
0
1995
2000
2005
2010
Baseline
Scenario 1
Scenario 2
Scenario 3


Annual Surface Water Supply:
Sappa Creek
Supply [Acre-Feet]
100,000
80,000
60,000
40,000
20,000
0
1995
2000
2005
2010
Baseline
Scenario 1
Scenario 2
Scenario 3


Annual Surface Water Supply:
Prairie Dog Creek
Supply [Acre-Feet]
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
1995
2000
2005
2010
Baseline
Scenario 1
Scenario 2
Scenario 3

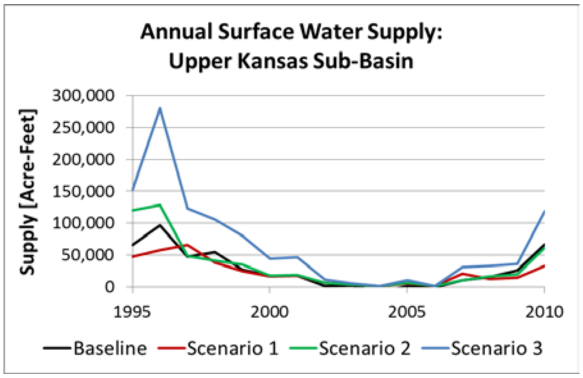



**Figure 35. — Surface water supplies in the Upper Kansas sub-basin under baseline and future climate scenarios: South Fork Republican River (upper left); Beaver Creek (upper right); Sappa Creek (middle left); Prairie Dog Creek (middle right); sub-basin total surface water supply (bottom center).**

**Table 8. — Projected Percent Change in Minimum, Average, and Maximum Annual Surface Water Supply in Primary Tributaries of the Upper Kansas Sub-Basin Under Future Climate Scenarios**

| | **Scenario 1 (Warmer + Drier)** | **Scenario 2 (Central Tendency)** | **Scenario 3 (Less Warm + Wetter)** |
|---|---|---|---|
| | Projected Change in Minimum Annual Streamflow | | |
| SF Republican | 0.0% | 0.0% | 0.0% |
| Beaver Creek | -11.2% | -2.0% | +37.7% |
| Sappa Creek | -21.1% | +1.45% | +30.9% |
| Prairie Dog Creek | -6.0% | -6.9% | +21.8% |
| Sub-Basin Total | -12.6% | +1.3% | +34.7% |
| | Projected Change in Average Annual Streamflow | | |
| SF Republican | -4.8% | -5.6% | +70.7% |
| Beaver Creek | -9.4% | +15.5% | +171.3% |
| Sappa Creek | -8.0% | +34.1% | +158.8% |
| Prairie Dog Creek | -13.6% | +47.5% | +226.8% |
| Sub-Basin Total | -9.5% | +28.2% | +165.5% |
| | Projected Change in Maximum Annual Streamflow | | |
| SF Republican | +34.6% | +6.5% | +116.3% |
| Beaver Creek | -12.2% | +19.4% | +200.4% |
| Sappa Creek | -5.5% | +56.2% | +199.3% |
| Prairie Dog Creek | -28.1% | +79.0% | +318.4% |
| Sub-Basin Total | -20.5% | +45.0% | +216.3% |

### iii. Nebraska Sub-Basin

Surface water supplies in the Nebraska sub-basin under baseline and future climate scenarios are shown in Figure 36. Consistent with previous descriptions, surface water supplies are shown as the sum of three components: gross diversions, net change in reservoir storage, and sub-basin outflows. Changes in the minimum, maximum, and average annual surface water supply under each scenario are summarized in Table 9.

The average annual surface water supply in the Nebraska sub-basin is projected to decrease moderately under Scenario 1 (warmer and drier) and increase under Scenarios 2 and 3 (central tendency and less warm and wetter, respectively). Gross diversions within the sub-basin are projected to decrease by 14% under Scenario 1 and increase by 14% and 31% under Scenarios 2 and 3, respectively; sub-basin outflow is projected to decrease by only 5% under Scenario 1 and increase by only 7% under Scenario 2, with a substantial increase of 75% under Scenario 3. Total reservoir storage in the sub-basin is projected to increase over the course of the 50-year simulation, relative to each simulation's initial condition, under all scenarios. Overall, the average annual total surface water supply within the Basin is projected to decrease by 8% under Scenario 1 and increase by 10% and 59% under Scenarios 2 and 3, respectively.

It should be noted that changes in surface water diversions depend on changes in both the amount of surface water available for diversion as well as the irrigated acreage and net irrigation requirement per acre in the Basin. The modeling approach used for the Nebraska sub-basin varies the irrigated acreage within each canal service area from year to year based on the available surface water supply: irrigated acreage increases in years of high surface water supply and decreases in years of low supply. Decreases in surface water diversions under Scenario 1 (more warm and drier) results from decreases in the available supply and corresponding decreases in irrigated acreage; by contrast, increases in average annual surface water diversion under Scenarios 2 and 3 generally results from an increase in available surface water supply and corresponding increase in irrigated acreage. The average net irrigation requirement for the sub-basin decreases under Scenarios 2 and 3 due to increased precipitation in the eastern portion of the Nebraska sub-basin under these scenarios; however, the increase in irrigated acreage due to increased surface water availability results in an overall increase in irrigation demands under these scenarios.

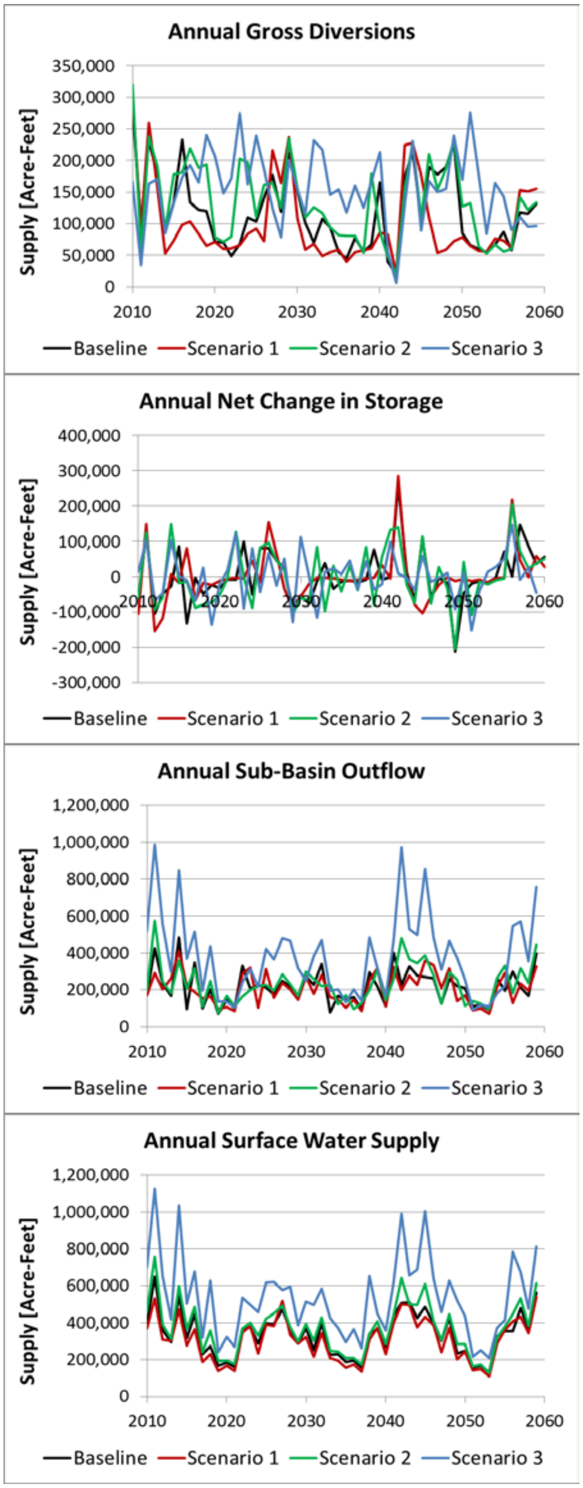



**Figure 36. — Surface water supplies in the Nebraska sub-basin under baseline and future climate scenarios: annual gross diversions (upper left); annual net change in reservoir storage (upper right); annual sub-basin outflow (lower left); annual total surface water supply (lower right).**

**Table 9. — Projected Percent Change in Minimum, Average, and Maximum Annual Surface Water Supply Components in the Nebraska Sub-Basin Under Future Climate Scenarios**

| | Scenario 1 (Warmer + Drier) | Scenario 2 (Central Tendency) | Scenario 3 (Less Warm + Wetter) |
|---|---|---|---|
| | Projected Change in Minimum Annual Streamflow | | |
| Gross Diversions | -10.4% | -2.8% | -71.8% |
| Change in Storage | -27.6% | -3.9% | -43.1% |
| Sub-Basin Outflow | -1.8% | +1.7% | +29.2% |
| Sub-Basin Total | -15.5% | -2.0% | +57.9% |
| | Projected Change in Average Annual Streamflow | | |
| Gross Diversions | -14.4% | +14.2% | +30.9% |
| Change in Storage | -51.1% | -9.5% | -11.8% |
| Sub-Basin Outflow | -4.7% | +7.3% | +74.7% |
| Sub-Basin Total | -8.2% | +9.7% | +59.1% |
| | Projected Change in Maximum Annual Streamflow | | |
| Gross Diversions | +7.1% | +14.3% | -1.8% |
| Change in Storage | +9.2% | -20.9% | -43.1% |
| Sub-Basin Outflow | -14.9% | +19.0% | +104.1% |
| Sub-Basin Total | -17.0% | +16.6% | +72.9% |

### iv. Lower Kansas Sub-Basin

Surface water supplies in the Lower Kansas sub-basin under baseline and future climate scenarios are shown in Figure 37. Similar to the Nebraska sub-basin, surface water supplies are shown as the sum of three components: gross diversions, net change in reservoir storage, and sub-basin outflows. Changes in the minimum, maximum, and average annual surface water supply under each scenario are summarized in Table 10.

The total surface water supply in the Lower Kansas sub-basin is projected to increase slightly under Scenarios 1 and 2 (warmer and drier and central tendency, respectively) and increase moderately under Scenario 3 (less warm and wetter). Increases under Scenario 1 result from a large projected increase in precipitation over the Lower Kansas sub-basin, despite a projected decrease in basin-average precipitation under this scenario. Gross diversions within the sub-basin are projected to increase under Scenarios 1 and 2, with decreases under Scenario 3 resulting from projected declines in net irrigation requirement due to increased precipitation under this scenario. In all scenarios, sub-basin outflow is the largest component of surface water supply in the Lower Kansas sub-basin. Projected changes in outflow are small under Scenarios 1 and 2, with a moderate increase of 12% in average annual sub-basin outflow under Scenario 3.

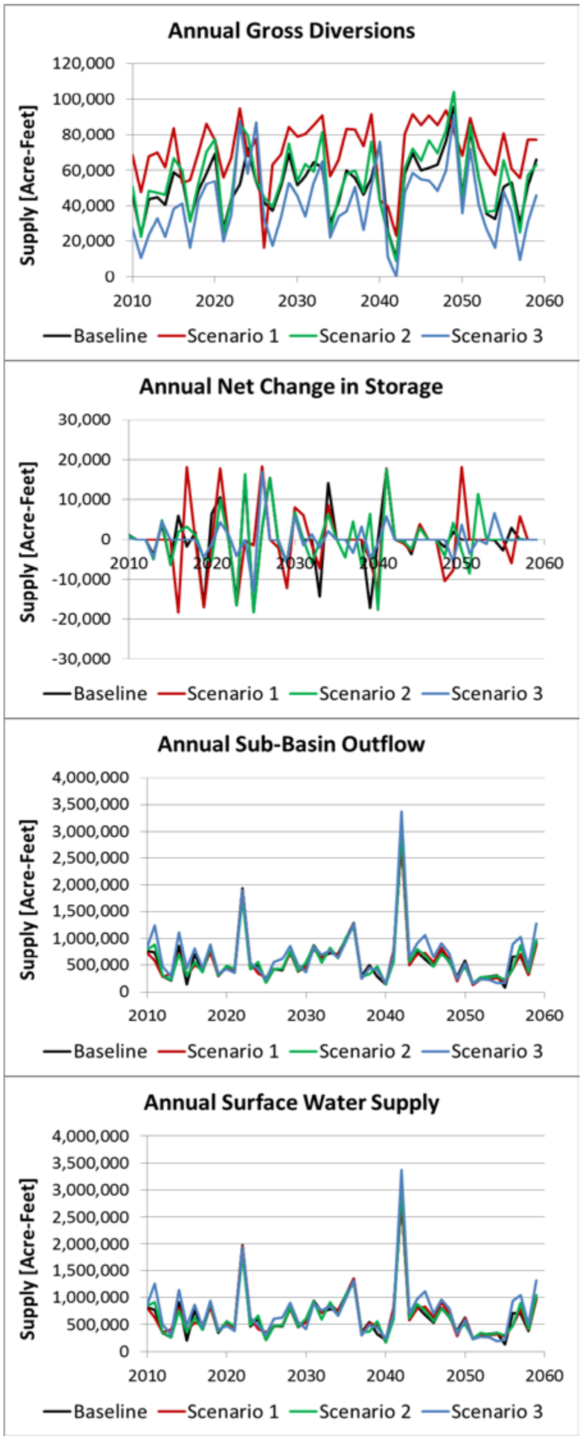



**Figure 37. — Surface water supplies in the Lower Kansas sub-basin under baseline and future climate scenarios: annual gross diversions (upper left); annual net change in reservoir storage (upper right); annual sub-basin outflow (lower left); annual total surface water supply (lower right).**

**Table 10. — Projected Percent Change in Minimum, Average, and Maximum Annual Surface Water Supply Components in the Lower Kansas Sub-Basin Under Future Climate Scenarios**

| | Scenario 1 (Warmer + Drier) | Scenario 2 (Central Tendency) | Scenario 3 (Less Warm + Wetter) |
|---|---|---|---|
| | Projected Change in Minimum Annual Streamflow | | |
| Gross Diversions | +60.0% | -14.9% | -100.0% |
| Change in Storage | +0.2% | +0.6% | -1.1% |
| Sub-Basin Outflow | +55.4% | +59.8% | +81.1% |
| Sub-Basin Total | +24.9% | +21.6% | +36.8% |
| | Projected Change in Average Annual Streamflow | | |
| Gross Diversions | +36.9% | +6.8% | -20.1% |
| Change in Storage | -19.7% | -11.7% | -69.9 |
| Sub-Basin Outflow | -2.3% | +0.3% | +15.2% |
| Sub-Basin Total | +.08% | +.08% | +12.4% |
| | Projected Change in Maximum Annual Streamflow | | |
| Gross Diversions | -1.2% | +8.8% | -5.0% |
| Change in Storage | +6.1% | +2.3% | -1.1% |
| Sub-Basin Outflow | -0.2% | +7.6% | +19.8% |
| Sub-Basin Total | +0.3% | +7.5% | +19.4% |

### c. *Future Groundwater Availability*

As described previously in this chapter, groundwater supplies in the Colorado, Upper Kansas, and Nebraska sub-basins are characterized based on estimated annual recharge in each sub-basin, while groundwater supplies in the Lower Kansas sub-basin are characterized based on estimated annual net recharge. Previous studies suggest that recharge from precipitation is the dominant component of recharge throughout the Basin in most years (RRCA 2003[13]), with recharge from surface water conveyance and from deep percolation of surface water irrigation also contributing to recharge in the Nebraska sub-basin. Deep percolation of groundwater irrigation also contributes to recharge in all three sub-basins.

In general, precipitation is projected to increase in the future in the eastern portion of the Basin and decrease in the future in the western portion of the Basin, with the magnitude and extent of projected increases and decreases varying between

[13] http://www.republicanrivercompact.org/v12p/RRCAModelDocumentation.pdf

future climate scenarios. Under Scenario 1, precipitation is projected to increase slightly in the eastern third of the Basin and decrease in the central and western portions of the Basin for an overall decrease of 17.4% over the Basin as a whole. Under Scenario 3, the magnitude and extent of projected increases in precipitation are much greater, with increases encompassing most of the Basin except for the headwaters in Colorado and Upper Kansas for an overall increase of 20.6% over the basin as a whole. Projected changes in precipitation under Scenario 2 are mixed, with an overall increase in annual average precipitation of just 4.8% over the Basin as a whole.

Projected changes in precipitation suggest that precipitation recharge is likely to decrease in the Colorado and Upper Kansas sub-basins under Scenarios 1 and 2, with little change under Scenario 3. Precipitation recharge is likely to increase in the Nebraska sub-basin under Scenarios 2 and 3, with little change under Scenario 1. Precipitation recharge is likely to increase to varying degrees over the Lower Kansas sub-basin under all scenarios, as all three scenarios project increased precipitation over the sub-basin. The effects of changes in surface water diversions, and corresponding seepage and deep percolation, on the total amount of recharge in each sub-basin is likely to be much smaller than the effects of changes in precipitation.

It should be noted that in addition to climate-driven changes in recharge, future groundwater storage and aquifer levels will depend on future changes in water demands, surface water operations, and groundwater management in the Basin.

# B. Water Demands

## 1. Description of Basin Water Demands

Irrigation is by far the dominant water demand throughout the Basin. The Basin contains over 2.7 million acres of irrigated agriculture. Corn is the dominant crop throughout the Basin, along with soybeans, alfalfa, sorghum, and a variety of other crops. As described in the previous section, irrigation demand is met by a combination of surface water and groundwater, with groundwater being the dominant supply in all sub-basins.

In addition to irrigation, water demands within the Basin include domestic, municipal, and industrial demands, as well as demands associated with recreation, and fish and wildlife uses. Domestic, municipal, and industrial demands in the Basin are met almost exclusively from groundwater whereas demands for recreation and fish and wildlife are met by surface water; however, demands for recreation, and fish and wildlife are non-consumptive and therefore do not significantly affect available surface water supplies in the Basin. Non-irrigation demands currently make up a small fraction of the total water demands in each sub-basin and are projected to remain at current levels in the future. For these reasons, non-irrigation demands are not discussed in detail.

## 2. Approach to Water Demand Analysis

Current water demands within each sub-basin were characterized based on county-level estimates of irrigated acreage and net irrigation requirement (NIR) during the period 2003-2008. These data were selected for this analysis because they were previously compiled by the RRCA groundwater modeling team for use in developing and verifying inputs to the RRCA groundwater model; annual acreage and NIR data are not available for all sub-basins prior to 2003 or after 2008. Agricultural practices during the period 2003-2008, as well as climate and hydrologic conditions during this period, are largely consistent with current conditions in each sub-basin and are therefore representative of current water demands. Non-irrigation demands are not considered in this analysis.

Irrigation demands are characterized based on the calculated NIR within each sub-basin. NIR is the amount of water that must be applied by irrigation, in addition to precipitation and soil moisture, to provide sufficient water for a crop to achieve full yield (Allen et al. 1998). NIR consists of the volume of water required by the crop to achieve full yield, exclusive of losses to surface runoff, deep percolation, and direct evaporation. NIR depends on crop evapotranspiration, which in turn depends on crop type and local meteorological conditions, including air temperature, wind speed, and humidity. In addition, NIR depends on local precipitation and soil characteristics, which govern the amount of moisture that reaches a crop's roots from local precipitation. NIR does not depend on water source, irrigation technology, or irrigation scheduling and management; as a result, NIR provides a common metric to evaluate irrigation demands across large areas.

Annual irrigated acreage and NIR were compiled for the Colorado, Upper Kansas, and Nebraska sub-basins for five years within the period 2003-2008. These data were used to characterize current water demands in each of these sub-basins. Data for each sub-basin were obtained from the respective state; data for the Colorado sub-basin are available for years 2003-2007; data for the Upper Kansas sub-basin are available for years 2003-2008; and data for the Nebraska sub-basin are available for years 2004-2008. It should be noted that the acreage data obtained for the Colorado sub-basin for years 2005-2007 only includes lands irrigated by groundwater. Based on data available for years 2001-2004, lands irrigated with surface water account for approximately 0.8% of all irrigated lands within the sub-basin; given the small amount of land irrigated with surface water and the lack of available data, this analysis omits lands irrigated with surface water for years 2004-2008.

Annual NIR was not available for the Lower Kansas sub-basin. In order to characterize current demand in the Lower Kansas sub-basin, annual NIR for each county in Kansas was developed based on recent estimates of annual median NIR developed by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) (NRCS 2014). NRCS estimates of median annual NIR were used in combination with irrigated acreage and cropping data to estimate the annual NIR for the Lower Kansas sub-basin for years 2004-2008.

## 3. Current Water Demands

Irrigated acreage, area-weighted NIR (acre-inches per acre), and annual total NIR (AF) are provided in Table 11 for each sub-basin. Annual irrigated acreage within the Colorado and Nebraska sub-basins were largely consistent from year-to-year over the period shown in Table 11; by contrast, irrigated acreage in the Upper and Lower Kansas sub-basins vary by more than 10% in some years compared to the average for the period. Area-weighted NIR is greatest in the Colorado and Upper Kansas sub-basins, where annual precipitation is lowest, compared to the Nebraska and Lower Kansas sub-basins which typically receive greater rainfall during spring and summer. Annual total NIR in the Nebraska sub-basin exceeds 2.1 million AF per year on average, with just one year (2008) having a total NIR less than 2 million AF. Annual total NIR in the Colorado sub-basin ranges from approximately 690,000 AF to almost 950,000 AF, and total NIR in the Upper Kansas sub-basin ranges from approximately 430,000 AF to 532,000 AF. Annual total NIR in the Lower Kansas sub-basin ranges from approximately 55,000 AF to 82,000 AF.

**Table 11. — Irrigated acreage, annual area-weighted NIR, and total annual NIR for each sub-basin**

| Sub-Basin | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | Average |
|---|---|---|---|---|---|---|---|
| | | | | Annual Irrigated Acreage (acres) | | | |
| Colorado | 572,649 | 572,378 | 577,953 | 572,409 | 549,199 | N/A | 568,918 |
| Upper Kansas | 532,180 | 466,467 | 456,490 | 459,387 | 472,745 | 431,160 | 469,738 |
| Nebraska | N/A[1] | 1,360,645 | 1,102,484 | 1,167,813 | 1,068,118 | 1,030,543 | 1,145,921 |
| Lower Kansas | 74,475 | 74,445 | 97,323 | 94,015 | 106,723 | 106,642 | 92,271 |
| | | | | Annual Area-Weighted NIR (inches) | | | |
| Colorado | 19.9 | 16.3 | 16.0 | 17.0 | 15.1 | N/A | 16.9 |
| Upper Kansas | 16.4 | 14.7 | 14.3 | 14.5 | 14.8 | 13.6 | 14.7 |
| Nebraska | N/A | 14.0 | 15.0 | 14.2 | 12.6 | 10.6 | 14.0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Lower Kansas | 9.0[2] | 9.0[2] | 9.2[2] | 9.2[2] | 9.2[2] | 9.2[2] | 9.1 |
| | | | | Annual Total NIR (acre-feet) | | | |
| Colorado | 947,706 | 777,269 | 771,365 | 811,389 | 691,785 | N/A | 799,903 |
| Upper Kansas | 532,180 | 466,467 | 456,490 | 459,387 | 472,745 | 431,160 | 469,738 |
| Nebraska | N/A | 1,588,635 | 1,378,769 | 1,385,438 | 1,121,264 | 911,202 | 1,588,635 |
| Lower Kansas | 55,804 | 55,733 | 74,502 | 72,112 | 82,171 | 82,149 | 70,412 |

[1] Data not available.
[2] Annual NIR estimated from median NIR values obtained from NRCS (2014) and annual cropping data provided by the State of Kansas.

## 4. Effects of Climate Variability and Change on Demands

### a. *Data, Models, and Methods Used*

Future groundwater demands in each sub-basin were evaluated for each of the three future climate scenarios considered in the Basin Study (*Section 3.2: Future Climate Conditions*). The three future climate scenarios encompass the range of projected changes in climate and water availability over the Basin between a historical reference period (1970-1999) and selected future period (2030-2059). Due to the limited modeling domains and range of alternatives, detailed analysis of the effects of climate variability and change on NIR within the Republican River Basin was carried out only for irrigation demands represented in the water operations models developed for the Nebraska and Lower Kansas sub-basins. Similar to supplies, projected future NIR was calculated for surface-water irrigation districts in the Nebraska sub-basin by The Flatwater Group, a technical consultant to the State of Nebraska, using the CropSIM crop water use model (TFG 2015a). Details are provided in *Section 5.2.1: Modeling Approach for Nebraska Sub-Basin*. Calculations of NIR for use in the STORRM model under baseline and future scenarios assumed a constant crop mix consisting only of corn, which is by far the dominant crop grown in the Nebraska sub-basin. Projected future NIR was calculated for irrigated lands in KBID in the Lower Kansas sub-basin by Reclamation in collaboration with KGS and KWO (Reclamation 2015b; KGS and KWO 2015a). NIR in the lower Kansas sub-basin was calculated by adjusting the estimated median NIR obtained from NRCS (2014) to account for projected changes in reference evapotranspiration and effective precipitation under each of the future climate scenarios considered in this analysis. Calculation of NIR under baseline and future scenarios for the Lower Kansas sub-basin assumed a constant crop mix representative of actual conditions for the year 2012. As noted in the previous section, non-irrigation demands make up a small portion of the total water demands in the Basin and are therefore omitted from this analysis.

### b. *Future Water Demands*

Figure 38 shows the median and range of annual NIR for lands served by each of the canals represented in the STORRM water operations model of the Nebraska sub-basin. Annual NIR values are shown for the Baseline Scenario and for each of the three future climate scenarios considered in this Study. The projected change in average annual NIR for each canal service area under the three climate scenarios is summarized in Table 12.

NIR ranges from approximately 7.5 to 22.5 inches per year in the western portion of the Nebraska sub-basin (Pioneer Canal service area) and from approximately zero to 15 inches per year in the eastern portion of the sub-basin (Courtland Canal service area) under the Baseline Climate Scenario. The range of annual NIR under future climate scenarios is similar to that under the Baseline Scenario, with a slight increase in the median annual NIR under Scenario 1 (warmer and drier), a slight decrease under Scenario 2 (central tendency), and a moderate decrease under Scenario 3 (less warm and wetter). Results suggest that projected increases in precipitation over the majority of the Nebraska sub-basin under Scenarios 2 and 3 more than offset temperature-driven increases in evaporative demand (reference evapotranspiration) under these scenarios.

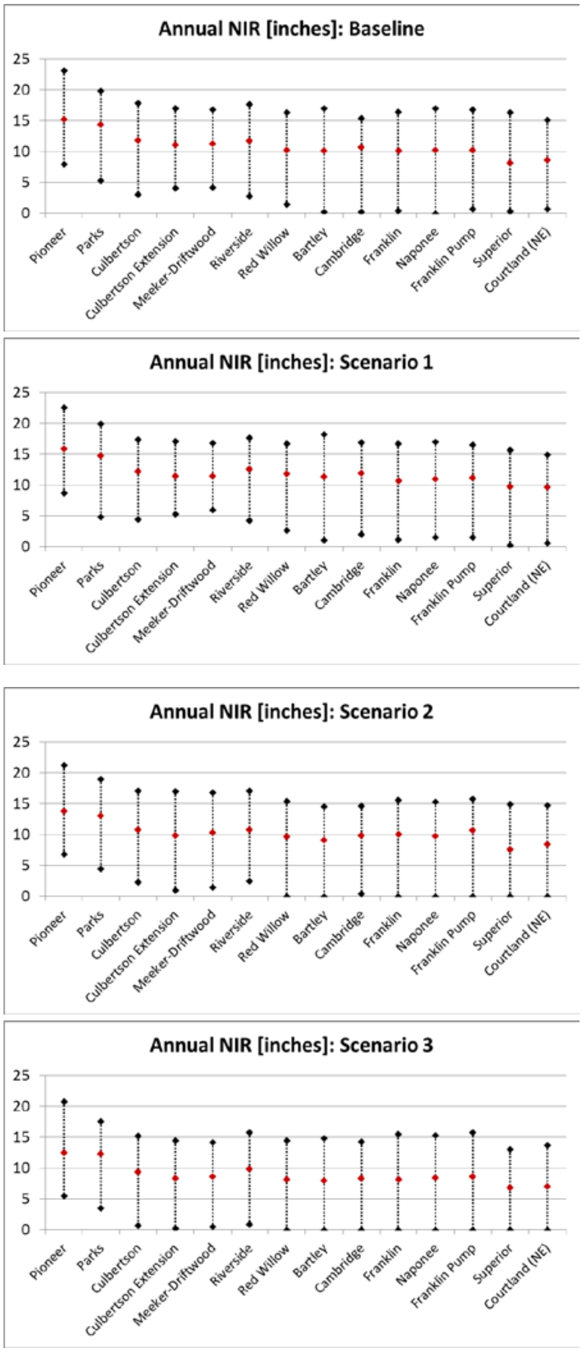



**Figure 38. — Annual NIR for canal service areas of surface water irrigation districts within the Nebraska sub-basin represented in STORRM under baseline and future climate scenarios.**

**Table 12. — Projected Change in Average Annual NIR for Canal Service Areas in the Nebraska Sub-Basin under future climate change scenarios.**

| Canal | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| Pioneer | +2% | -9% | -18% |
| Parks | +3% | -7% | -16% |
| Culbertson | +5% | -12% | -24% |
| Culbertson Extension | +7% | -11% | -26% |
| Meeker-Driftwood | +6% | -11% | -24% |
| Riverside | +5% | -11% | -21% |
| Red Willow | +8% | -11% | -25% |
| Bartley | +9% | -10% | -24% |
| Cambridge | +9% | -9% | -22% |
| Franklin | +10% | -7% | -21% |
| Naponee | +8% | -8% | -20% |
| Franklin Pump | +8% | -6% | -18% |
| Superior | +16% | -3% | -19% |
| Courtland (NE Only) | +11% | -4% | -18% |
| *Sub-Basin Average* | *+6.9%* | *-8.8%* | *-20.9%* |

The median and range of annual NIR for KBID in the Lower Kansas sub-basin is shown in Figure 39 for the baseline and future climate scenarios. Annual NIR for KBID ranges from approximately 2.5 to 17.5 inches per year under the Baseline Climate Scenario. Under Scenario 1 (warmer and drier), annual NIR for KBID ranges from approximately 3.5 to 20.5 inches; under Scenario 3 (less warm and wetter), annual NIR ranges from zero to 17.5 inches per year. On average, NIR for KBID increases by 41.4% under Scenario 1 due to a combination of temperature-driven increase in evaporative demand and decreased precipitation. Average NIR increases by 9.3% under Scenario 2 and decreases by 22.1% under Scenario 3.

It should be noted that projected changes in NIR for KBID are greater than corresponding projected changes in NIR for nearby lands in the Nebraska sub-basin served by the Courtland and Superior canals. Differences arise from the different methodologies used to calculate NIR in the Nebraska and Lower Kansas sub-basins. In particular, the methodology used to compute NIR for KBID in the Lower Kansas sub-basin is more sensitive to projected changes in precipitation than the method used compute NIR for canal service areas in the Nebraska sub-basin. Differences highlight known uncertainties regarding calculation of NIR.

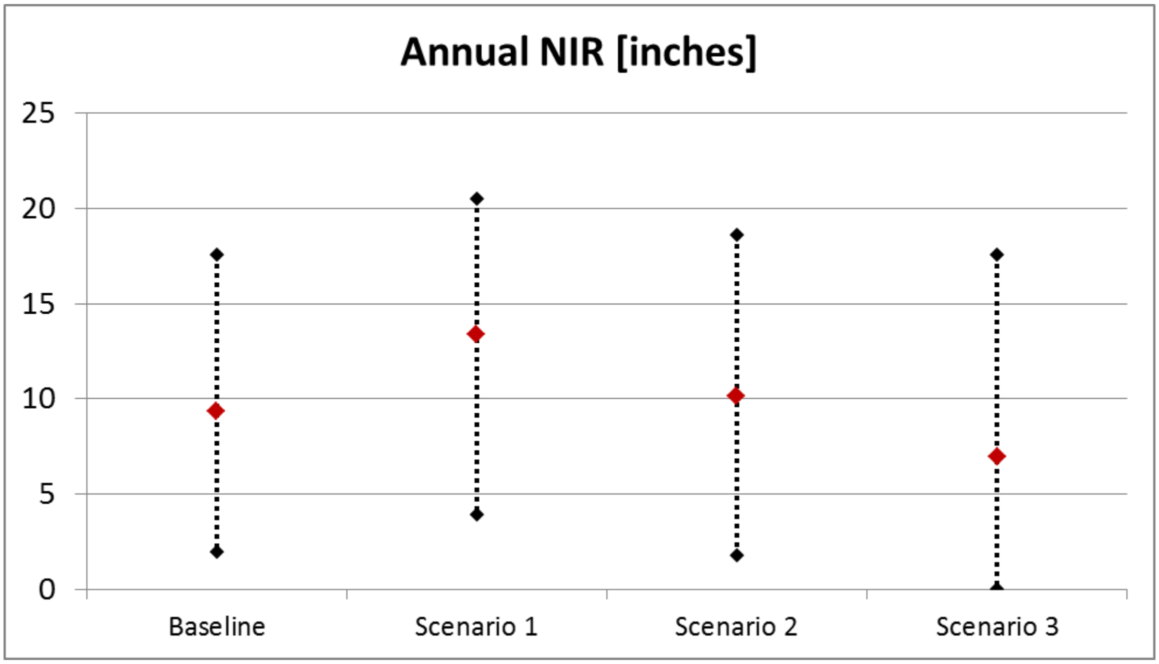



**Figure 39. — Annual NIR for KBID in the Lower Kansas sub-basin under baseline and future climate scenarios.**

## C. Water Supply Imbalances

Water supply imbalances occur when available supplies are not sufficient to meet demands. Water supply imbalances may occur due to physical or institutional constraints. Physical water supply imbalances occur when water demands in a given area exceed the quantity of water that is physically available in that area; such imbalances may result from insufficient water availability in a specific area, or from the lack of infrastructure to convey sufficient water to that area (e.g., insufficient capacity of a canal, pipeline, or groundwater well). Institutional water supply imbalances occur when water demands in a given area exceed the quantity of water that is legally available for use in that area under applicable Federal, State, and local laws and regulations, including individual water rights as well as interstate compacts. Water supply imbalances ultimately occur at the local level due to imbalances between demands of individual water users and the supplies that are physically and legally available to meet those demands. As a result, imbalances may occur in one area of a basin or sub-basin while surpluses occur in other areas and at different points in time.

This study attempted to assess the effects of these imbalances as part of the System Reliability Analysis (see next section). System reliability for the

Nebraska sub-basin evaluates the effects of water supply imbalances based on irrigated acreage, irrigation diversions and deliveries, and the frequency of Compact Call Years. System reliability for the Lower Kansas sub-basin evaluates the effects of water supply imbalances based on irrigation diversions and deliveries to KBID above and below Lovewell Reservoir. These results, combined with each partners' specific objectives, helped inform the adaptive strategies ultimately selected for further analyses. For reasons previously described, detailed analyses of water supply imbalances were not carried out for the Colorado and Upper Kansas sub-basins. Due to the significant groundwater storage in the Ogallala Aquifer and the heavy reliance on groundwater as the primary water supply in these sub-basins, current water supply imbalances in these sub-basins are primarily due to institutional constraints on water use. Analysis of institutional constraints was beyond the scope of this Basin Study.

# V. System Reliability and Impact Analysis

Section 9503(b)(3) of P.L. 111-11 requires that Basin Studies provide an analysis of how existing water and power infrastructure and operations will perform given any current imbalances between water supply and demand and in the face of changing water realities due to climate change (including extreme events such as floods and droughts) and population growth. This also includes an analysis of the extent to which changes in the water supply will impact Reclamation operations and facilities.

This analysis is typically performed on what is commonly called the "No Action Alternative," which represents the future condition if no strategies were undertaken to address water supply needs. It entails an evaluation of how the No Action Alternative is affected by various future climate conditions.

## A. No Action – Future without Adaptation Strategies

In general, the No Action Alternative is used to assess system performance of existing and anticipated water infrastructure and operations under current and future conditions, including projected climate change impacts on water supply and demand. Current and future conditions used to describe the No Action Alternative include operation of Reclamation reservoirs and facilities as described in the Republican River Contract Conversion and Renewal Final Environmental Impact Statement (2000) and associated Record of Decision. Anticipated actions include those that are currently in place, which represent current water resource development in the Basin, and those actions that have been approved or in the process of being implemented.

The No Action Alternative serves as the baseline for evaluating changes in the system performance and associated benefits of proposed structural and non-structural alternatives. It defines a specific level of development (fixed infrastructure) and associated operating practices (fixed operating conditions), but may differ from current or existing conditions in that it includes infrastructure or operation practices that are approved or being implemented but not yet in place. Simulation of the No Action Alternative under historical conditions may differ from actual historical operations in that the No Action Alternative assumes a fixed infrastructure and operating conditions, whereas, in reality, infrastructure and operations have changed over time.

For the purposes of this Study, the No Action Alternative represents future conditions over the 2011 to 2060 time period in which current management practices were maintained.

## 1. Nebraska

The No Action Alternative represents status quo management techniques and infrastructure, in the absence of any major changes beyond those already planned for incorporation. The Nebraska Modeling Methods TM (TFG 2015a) includes a more detailed explanation of the modeling structure for the No Action Alternative, but this section includes the highlights of the differences between historical conditions and the conditions assumed to be in place under the No Action Alternative.

1. Compact Call Year Operations – The No Action Alternative includes the use of Compact Call Year operations in the STELLA logic. This includes a determination at the beginning of each year if Compact Call Year administration will be required for the current year, and, if so, the procedures impose restrictions on surface water diversions and placing water into storage within reservoirs. Compact Call Years also involve separate tracking of Compact Water stored in Harlan County Lake, and require augmentation pumping for the Nebraska Cooperative Republican Platte Enhancement Project and Rock Creek projects at steady 60,000 and 15,000 AF per year levels, respectively.

2. Consistent Management of Stream Depletions – The No Action Alternative assumes that depletions to streamflow will be tracked by the NDNR and regional NRDs, and that pumping levels and other management actions within Nebraska's portion of the Basin will be managed and implemented to maintain stream depletions, per the directive of the current IMPs.

3. Colorado Compliance Pipeline Operations – Similar to Compact Call Year operations in Nebraska, Colorado Compliance Pipeline operations are included in the No Action Alternative, at a constant rate of 4,000 AF per year. While this simplified approach was used for modeling purposes, it is understood that different configurations of pumping operations may be preferable to this example.

4. Riverside Canal – Riverside Canal is not included within the No Action Alternative or the future alternative action scenarios, since 2011 was the last year the canal diverted water before the canal's irrigation rights were sold to Middle Republican NRD.

5. Harlan County Lake Flood Operations – As described in more detail in the Nebraska Modeling Results TM (TFG 2015b), Harlan County Lake releases increase to 2,975 AF/day when water levels intrude into the flood pool (314,111 AF) for the No Action Alternative representation of the STELLA model. For the historical calibration run, the trigger level was slightly higher, at 350,000 AF.

6. Meeker-Driftwood Spillback for Bartley and Cambridge Canals – The STELLA model for No Action conditions includes the ability to deliver water released from Swanson Reservoir through the Meeker-Driftwood Canal for downstream use by Bartley and Cambridge[14] Canals. This conveyance technique, used to reduce losses, is a more recent practice, and was not done in earlier years.

7. Bonny Reservoir Operations – Operations of Bonny Reservoir in the STELLA model involve using a simplified pass-through logic, with no deliveries to Hale Ditch. Bonny Reservoir is only able to store water temporarily to reduce downstream damages when inflows surpass an established flow rate.

8. Harlan County Lake Evaporation – The No Action Alternative included a small number of evaporation values during the winter months that were provided by Kansas to fill-in certain data gaps in the historical evaporation tables where the reported values from Reclamation were zero. These data were obtained after the Calibration model results were derived.

## 2. Kansas

The No Action Alternative includes all infrastructure and management plans that were in operation in 2010. New Compact compliance operations that were

[14] Since completing the model runs, it was learned that Meeker-Driftwood is probably not intentionally used as conveyance for Cambridge diversions. However, it is possible that extra water conveyed through Meeker-Driftwood may make its way to the Cambridge Canal diversion where it could be diverted for irrigation use.

implemented after 2010 were also included in all simulations since those new operations are expected to be used into the future. All No Action operations as simulated in the Kansas model are detailed in the Kansas Modeling Methods TM (KGS and KWO 2015b) as part of the model development and calibration.

## B. Approach to System Reliability Analysis

Analysis of system reliability focuses on surface water operations and deliveries throughout the Basin, including interstate surface water deliveries required under the Republican River Compact. As summarized in *Section 1.2: Location and Description of the Study Area*, no significant surface water operations occur within the Colorado or Upper Kansas sub-basins; water demands in these sub-basins are met almost exclusively by groundwater. Detailed analysis of system reliability is therefore limited to the Nebraska and Lower Kansas sub-basins.

System reliability was analyzed by simulating surface water operations within each sub-basin under the No Action Alternative, described above. Simulations were carried out for four scenarios: a Baseline Scenario representing current climate and hydrologic conditions in the Basin, and three future climate scenarios representing the range of projected future climate conditions in the Basin (see *Section 3.0: Current and Future Climate Conditions*). For reference, the three scenarios are described again below in Table 13.

**Table 13. — Summary of Projected Changes in Selected Scenario Variables**

| Variable | Projected Change by Scenario | | |
|---|---|---|---|
| | Scenario 1 Warmer Drier | Scenario 2 Central Tendency | Scenario 3 Less Warm Wetter |
| Mean Annual Water Availability | -0.20 in (-32.7%) | +0.01 in (+10.4%) | +0.60 in (+88.6%) |
| Mean Annual Temperature | +5.22 °F | +3.53 °F | +2.99 °F |
| Mean Annual Precipitation | -3.52 in (-17.4%) | +0.99 in (+4.8%) | +4.09 in (+20.6%) |

For the Baseline Scenario, model inputs were developed from historical observations of precipitation, temperature, pan evaporation, and streamflow. For each future climate scenario, climate-related inputs were developed by perturbing baseline inputs based on the projected change in each of these variables between the periods 1970-1999 and 2030-2059 under each scenario. Baseline inputs were perturbed using a statistical procedure referred to as quantile-based perturbation. This procedure essentially superimposes the projected change in probability distribution of a given variable between two periods – e.g., between historical and future periods of a selected climate projection – onto that variable's probability distribution in a different dataset – e.g., the baseline input dataset. Projected changes in precipitation and temperature were obtained directly from the BCSD climate projections corresponding to each of the three scenarios selected for analysis in the Study.

In order to simulate surface water operations in the Basin, new modeling tools and related datasets were developed for the Nebraska and Lower Kansas sub-basins. Modeling and analysis were carried out at the sub-basin scale, with each State leading the development of modeling tools and related datasets for its respective portion of the Basin. This sub-basin modeling approach was selected by the Basin Study partners to facilitate the use of best-available data, tools, and expertise in modeling and evaluating current and future water supplies and demands and system reliability, as well as in developing and evaluating management alternatives to improve water operations throughout the Basin.

Modeling tools developed for the Nebraska and Lower Kansas sub-basins in support of the Basin Study are summarized below. Details regarding the representation of physical hydrology and water operations differ between sub-basin models due to difference in the dominant characteristics and available data for each sub-basin, the management objectives of each State, and the experience and expertise of each State's modeling team. In order to ensure that results from sub-basin models can be integrated to provide a coherent basin-scale analysis, the Basin Study partners coordinated extensively to ensure consistent representation of water supplies, demands, and operations between sub-basins modeling tools. As detailed by Reclamation's Coordination TM (Reclamation 2015c), despite differences in the modeling approaches and implementation, modeling tools developed for the Nebraska and Lower Kansas sub-basins provide a consistent representation of hydrology and water operations in the Basin.

## 1. Modeling Approach for Nebraska Sub-Basin

The Nebraska sub-basin encompasses all of the Republican River Basin within the State of Nebraska. Surface water within the Nebraska sub-basin is managed primarily for agricultural uses and flood control. The sub-basin includes four Reclamation storage reservoirs (Swanson, Enders, Hugh Butler, and Harry Strunk) and one USACE reservoir (Harlan County) that provide water for irrigated agriculture, as well as five Reclamation diversion dams that divert water for irrigation purposes (Bartley, Cambridge, Culbertson, Red Willow, and Superior-Courtland). All Federal facilities within the sub-basin were authorized and constructed as part of the P-SMBP and are operated in accordance with their respective authorized purposes, as revised and amended, and in accordance with applicable Federal, State, and local laws and regulations.

Two new models were developed to simulate irrigation demands and water operations in the Nebraska sub-basin. Models for the Nebraska sub-basin are documented in detail in a technical memorandum prepared by The Flatwater Group, Inc. (TFG 2015a).

First, the CropSIM crop water use model was applied to evaluate NIR for surface water irrigation districts within the Nebraska sub-basin. CropSIM has been used widely by Nebraska in recent water resources planning efforts, including the Platte River Cooperative Hydrology Study (COHYST[15]) and the State's Integrated Water Management program[16]. CropSIM was selected for this Basin Study by the State of Nebraska based on the model's capabilities and previous successful applications of the model to evaluate NIR in Nebraska. Developed by Dr. Derrel Martin of the University of Nebraska-Lincoln, CropSIM simulates daily crop ET using a crop-coefficient approach, where daily crop ET is calculated by multiplying a daily reference ET by a crop- and condition-specific crop coefficient[17]. CropSIM then uses a soil water balance model to compute daily NIR as the amount of water that must be applied by irrigation, in addition to precipitation and soil moisture storage, for the crop to achieve full yield.

For the purposes of the Basin Study, CropSIM was used by the State of Nebraska to calculate NIR for each of the canal service areas represented in the State's water operations model of the upper portion of the Basin (above Nebraska-Kansas state line near Hardy, NE). CropSIM requires time-varying inputs for four meteorological variables: daily total precipitation, daily maximum air temperature, daily minimum air temperature, and daily reference ET. Similar to the VIC model, CropSIM also requires input values for numerous physical and hydrologic parameters, including parameters relating to soil and vegetation characteristics and hydraulic properties, as well as parameters relating to irrigation scheduling. Parameter values developed by The Flatwater Group, Inc. are provided as model input and are held constant over the duration of the simulation.

Second, a new water operations model was developed using the Systems Thinking Environment and Learning Laboratory Approach (STELLA) modeling platform to simulate surface water supplies, demands, and operations in the sub-basin under current and projected future conditions. STELLA is a generalized software tool for modeling a broad range of dynamic systems and has been widely used in fields ranging from biology to economics to water resources management. The State of Nebraska selected STELLA as the software tool for simulating water operations in the upper portion of the Republican River Basin (above the

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[15] See www.platteriverprogram.org/PubsAndData/ProgramLibrary/Cooperative%20Agreement%20for%20Central%20Platte%20River.pdf
[16] www.dnr.ne.gov/iwm
[17] Reference ET is a standardized method for characterizing the amount of energy available from the environment to evaporate water in terms of calculated ET from a hypothetical reference surface (see Allen et al 1998 for details).

Nebraska-Kansas state line near Hardy, NE) based on the State's previous use of STELLA in water resources planning, management, and administration. A new STELLA model of the upper portion of the Basin was developed for this Study by The Flatwater Group, Inc.

The STELLA model developed and used in this Basin Study is referred to as the STELLA Operations Republican River Model (STORRM). STORRM represents the physical and operational components of the Republican River Basin in Nebraska and simulates operation of six Federal reservoirs and diversions to 16 Federal and private canals, as well as tributary inflows and reach gains and losses throughout the sub-basin. STORRM includes a simplified representation of surface water administration under Nebraska's appropriative rights system including Nebraska's Compact Call Year operations, which are designed to ensure that the State meets its obligation to deliver water to Kansas under the Republican River Compact. STORRM is documented in detail in a technical memorandum prepared by The Flatwater Group, Inc. (TFG 2015a).

STORRM requires time-varying inputs for a number of hydrologic and meteorological variables on a daily timestep. Hydrologic inputs include: tributary inflows at the upstream model boundary; reach gains and losses within the model domain; and net irrigation requirement on a per-acre basis for each of the irrigation districts represented within the model domain. Meteorological inputs include precipitation and evaporation rates for each reservoir within the model domain. Additional hydrologic components are represented dynamically within the model, including diversion requirements for each irrigation district and return flows and spillback flows from canal operations.

## 2. Modeling Approach for Lower Kansas Sub-Basin

The Lower Kansas sub-basin encompasses the Republican River Basin from Harlan County Lake near Orleans, Nebraska, to Milford Lake downstream of Clay Center, Kansas. Similar to the Nebraska sub-basin, surface water within the Lower Kansas sub-basin is managed primarily for agricultural uses and flood control. The sub-basin includes one Reclamation storage reservoir (Lovewell) and one USACE reservoir (Harlan County Lake), as well as one Reclamation diversion dam that diverts water for irrigation purposes (Superior-Courtland). The sub-basin also includes Jamestown Wildlife Area, which is not currently operated as a reservoir, but has the potential to store water (see KGS and KWO 2015b). All Federal facilities within the sub-basin were authorized and constructed as part of the P-SMBP and are operated in accordance with their respective authorized purposes, as revised and amended, and in accordance with applicable Federal, State, and local laws and regulations.

One new model was developed by linking two modeling frameworks in support of the Basin Study to simulate hydrology and water operations, respectively, in

Lower Kansas sub-basin. These are documented in detail in a technical memorandum prepared by the Kansas Geological Survey and Kansas Water Office (KGS and KWO 2015b).

In order to simulate hydrologic conditions in the sub-basin, an integrated groundwater/surface water model was developed by the Kansas Geological Survey (KGS) for the State of Kansas using the HydroGeoSphere (HGS) modeling software (Therrien et al. 2007). HGS was selected for use in this Study by KGS based on the model's demonstrated ability to simulate complex interactions and feedbacks between surface water and groundwater under varying climate conditions. HGS was developed by researchers at the University of Waterloo and is capable of simulating two-dimensional depth-integrated overland flow and streamflow, as well as three-dimensional variably-saturated groundwater flow. The integrated surface and subsurface flow and transport equations are solved using a globally-implicit control-volume finite element method which allows for fully-integrated simulation of surface water and groundwater flows. HGS is also capable of simulating the effects of well pumping and of spatially and temporally variable evapotranspiration on groundwater and surface water flows, both of which are important components of the hydrologic system in the Republican River Basin.

Inputs to HGS include constant parameters specifying surface and subsurface properties as well as time-varying inputs representing climate and hydrologic conditions over the Basin. Constant parameters were developed by KGS through a detailed calibration and verification process; details of HGS calibration and verification are provided by KGS and KWO (2015b). Time-varying climate and hydrologic inputs include monthly mean precipitation rate (length per time) and monthly mean potential ET rate.

In addition to the HGS model, a water operations model was developed to simulate surface water operations within the Lower Kansas sub-basin using the Operational Analysis and Simulation of Integrated Systems (OASIS) modeling software (Hydrologics 2009). OASIS is a generalized software platform for simulation of surface water routing and operations. Water supply and demand components are represented as model inputs, and reservoir operations are governed by rules specified through the Operations Control Language, which defines physical and operational objectives and constraints on the system such as reservoir release schedules and criteria, target flows, and water rights priorities. The OASIS model developed for this Study simulates operation of Harlan County and Lovewell reservoirs and diversions to all Federal canals within the Basin downstream of Harlan County Lake. Diversions to smaller non-Federal canals are represented through model inputs but are not simulated explicitly. Climate and hydrologic inputs to OASIS include net evaporation (evaporation minus precipitation) at reservoir nodes, net irrigation requirement at demand nodes, and streamflows into junction nodes at the upstream boundaries of the model domain.

For the purposes of the Basin Study, OASIS is linked with HGS to allow for interactions between groundwater and surface water management and use within the sub-basin. To achieve this linkage, changes were made to both the HGS and OASIS source codes to allow information to be passed between the two models throughout the simulation period. HGS uses reservoir releases, irrigation district demands, and minimum desired streamflow (MDS) administration simulated by OASIS, whereas OASIS uses streamflow gains and losses in each model reach simulated by HGS.

## C. Impacts of Climate Change on Water Operations and Deliveries

Several metrics were selected to evaluate impacts of the No Action Alternative on system reliability. Table 14 below summarizes the results, details of which are provided in the discussion below. It is important to note that the differences in water deliveries between Nebraska and Kansas are due to the different methodologies used to compute irrigation demands as described in *Section 5.2.1* above. Under Scenario 1, for example, irrigation deliveries decrease in Nebraska and increase in Kansas. For Nebraska, the modeling approach used to calculate irrigation demands assumes that irrigated acreage varies year to year depending on the available surface water supply: irrigated acreage in Nebraska decreases under Scenario 1 in response to decreases in surface water supply; this results in a decrease in overall demand and a corresponding decrease in deliveries. For Kansas, irrigated acreage is held constant in all years; irrigation demands in Kansas increase due to decreases in precipitation and increases temperature, both of which result in increased crop irrigation requirements. This increase in demand drives an increase in water deliveries, despite an overall decrease in surface water supply. The ability for Kansas to deliver additional water despite an overall decrease in surface water supply results from two factors: first, less water is released for flood control purposes during the non-irrigation season; second, the Kansas modeling approach assumes that KBID will exercise its option to purchase up to 60,000 AF of additional water from Harlan County Lake during compact call years if available. It should be noted that despite increases in irrigation deliveries to Kansas, the proportionate increase in demands exceeds the increase in deliveries, resulting in an increase in shortages.

The other metrics included in Table 14 were selected by the Study partners as a means of measuring how well an alternative meets each state’s objectives. As previously discussed, Nebraska’s objective is to maintain compliance with the Republican River Compact and Final Settlement Stipulation while maximizing deliveries to all water users, as measured through FCID and NBID. Kansas’ objective is to secure Kansas’ share of the water under the Republican River Compact while maximizing the ability to meet the demands for KBID. Further explanation on the selection and use of the other metrics in the table below is provided below and in *Section 7.1* and *Section 7.3* below for Nebraska and Kansas, respectively.

**Table 14. — Results of the system reliability analysis evaluating impacts of future conditions on water deliveries in Nebraska and Kansas over a 50-year simulation period of 2011-2060**

<table>
<tr><th colspan="2" rowspan="2">Metric (2011-2060)</th><th colspan="4">Climate Condition</th></tr>
<tr><th>Baseline</th><th>Scenario 1: Warmer/Drier</th><th>Scenario 2: Central Tendency</th><th>Scenario 3: Less Warm/Wetter</th></tr>
<tr><td colspan="2">Nebraska</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Water Delivered (Acre-In/Acre)</td><td>7.4</td><td>6.3</td><td>8.9</td><td>8.2</td></tr>
<tr><td colspan="2">Acres Affected</td><td>45,521</td><td>30,847</td><td>53,953</td><td>75,504</td></tr>
<tr><td colspan="2">No. of Compact Call Determinations</td><td>23</td><td>33</td><td>16</td><td>0</td></tr>
<tr><td colspan="2">Harlan County Lake Levels (AF)</td><td>223,760</td><td>210,829</td><td>233,515</td><td>285,588</td></tr>
<tr><td colspan="2">Courtland Canal Flows (AF)</td><td>41,268</td><td>43,027</td><td>43,818</td><td>38,272</td></tr>
<tr><td rowspan="5">FCID</td><td>FCID Irrigation Diversions (AF)</td><td>36,960</td><td>28,293</td><td>43,600</td><td>58,359</td></tr>
<tr><td>Irrigated Acreage Reduction (No. of Years)</td><td>38</td><td>42</td><td>31</td><td>6</td></tr>
<tr><td>Cumulative Irrigated Acres Reduced</td><td>1,000,500</td><td>1,287,500</td><td>695,000</td><td>54,500</td></tr>
<tr><td>Delivery Shortage (No. of Years)</td><td>40</td><td>36</td><td>37</td><td>25</td></tr>
<tr><td>Cumulative Delivery Shortage (AF)</td><td>122,000</td><td>200,500</td><td>888,500</td><td>2,000</td></tr>
<tr><td rowspan="5">NBID</td><td>NBID Irrigation Diversions (AF)</td><td>25,204</td><td>17,098</td><td>30,709</td><td>38,685</td></tr>
<tr><td>Irrigated Acreage Reduction (No. of Years)</td><td>27</td><td>37</td><td>22</td><td>1</td></tr>
<tr><td>Cumulative Irrigated Acres Reduced</td><td>428,000</td><td>706,000</td><td>260,000</td><td>2,500</td></tr>
<tr><td>Delivery Shortage (No. of Years)</td><td>37</td><td>25</td><td>35</td><td>28</td></tr>
<tr><td>Cumulative Delivery Shortage (AF)</td><td>104,000</td><td>34,500</td><td>83,500</td><td>29,000</td></tr>
<tr><td colspan="2">Kansas</td><td></td><td></td><td></td><td></td></tr>
</table>

| Metric (2011-2060) | | Climate Condition: Baseline | Scenario 1: Warmer/Drier | Scenario 2: Central Tendency | Scenario 3: Less Warm/Wetter |
|---|---|---|---|---|---|
| Water Delivered (Acre-Inches/Acre ) | | 12.4 | 15.5 | 13.8 | 10.4 |
| KBID Up | Cumulative Water Shortage (AF) | 84,573 | 120,015 | 92,230 | 9,823 |
| | Percent of Demand Unmet | 11.3 | 11.4 | 11.3 | 1.6 |
| | No. of Water-Short Years | 8 | 14 | 9 | 1 |
| KBID Down | Cumulative Water Shortage (AF) | 56,812 | 149,734 | 57,364 | 1,366 |
| | Percent of Demand Unmet | 3.4 | 6.4 | 3.2 | 0.1 |
| | No. of Water-Short Years | 5 | 9 | 3 | 1 |

## 1. Nebraska

Nebraska's metrics measure the extent of compact compliance and gross surface water diversions to irrigation districts.

### a. *Overall Deliveries*

As part of the agricultural benefits analysis discussed in *Section 7.6: Benefits Evaluation*, combined overall irrigation deliveries were calculated on a basin-wide scale for both Nebraska and Kansas. For Nebraska, these included irrigated acres within NBID, FCID, FVID, and H&RW lands. For reasons described above, deliveries decrease under Scenario 1 and increase under Scenarios 2 and 3.

### b. *Compact Call Year Determinations*

Figure 40 shows the Compact Call Year operations for the No Action Alternative across all climate scenarios (including Baseline Climate). As shown, the wetter conditions of Climate Scenario 3 result in no Compact Call Years, whereas the drier conditions in Climate Scenario 1 result in the greatest number (33) of Compact Call Years. Climate Scenario 2 has 16 Compact Call Years, while the Baseline Climate results in 23.

### c. *Harlan County Lake Levels*

Figure 41 shows the Harlan County Lake (HCL) content for the No Action Alternative across all climate scenarios. As expected, the wetter conditions of Climate Scenario 3 result in the greatest reservoir content, including significant flood control during 2012, with content rising to nearly 700,000 AF. Reservoir levels are the least for the drier Climate Scenario 1, and Baseline Climate levels trail behind those of Climate Scenario 2. The average daily content for Harlan County Lake across the 50-year period was 223,760 AF, 210,829 AF, 233,515 AF, and 285,588 AF for Baseline Climate, Climate Scenario 1, Climate Scenario 2, and Climate Scenario 3, respectively.

### d. *Courtland Canal Flows*

Figure 42 shows the Courtland Canal flow at the state line for the No Action Alternative across all climate scenarios. Because the primary driver for the state line flow is the demand provided by the Kansas modeling team, the results must be interpreted with that demand in mind. In many instances, the Climate Scenario 1 state line flows are the highest, potentially due to the high water demand in KBID for that dry climate situation. Because the state line flows almost always meet the demands provided by Kansas, understanding the other variations across the climate scenarios would require turning to the methodologies used by the Kansas team in deriving the state line demands. The average annual state line flow for the Courtland Canal across the 50-year period was 41,268 AF, 43,027 AF, 43,818 AF, and 38,272 AF for Baseline Climate, Climate Scenario 1, Climate Scenario 2, and Climate Scenario 3, respectively. As a comparison, the average annual target flow provided by Kanas was 43,583 AF, 43,199 AF, 45,275 AF, and 38,291 AF for those same climate scenarios, respectively.

### e. *FCID Irrigation Diversions*

Figure 43 shows the FCID annual diversions for the No Action Alternative across all climate scenarios. The results show the tradeoff between irrigation demand and water availability with Climate Scenario 3 often indicating higher diversions likely when supply conditions were not as abundant in the other climate scenarios. In contrast, certain years, such as 2013, indicate that the lowest diversions would occur under Climate Scenario 3, potentially due to reduced crop irrigation demand in that year relative to the other climate scenarios. The average annual FCID diversion across the 50-year period was 36,960 AF, 28,293 AF, 43,600 AF, and 58,359 AF for Baseline Climate, Climate Scenario 1, Climate Scenario 2, and Climate Scenario 3, respectively.

### f. *NBID Irrigation Diversions*

Figure 44 shows the NBID (not including the Courtland Canal) annual diversions for the No Action Alternative across all climate scenarios. As with the FCID results, the tradeoff between irrigation demand and water availability is evident. The relative comparisons across climate scenarios for a given year are largely identical to the comparisons for FCID, likely for the same reasons indicated above. The average annual NBID diversion across the 50-year period was 25,204 AF, 17,098 AF, 30,709 AF, and 38,685 AF for Baseline Climate, Climate Scenario 1, Climate Scenario 2, and Climate Scenario 3, respectively.

### g. *FCID and NBID Shortages and Imbalances*

Reclamation requires an assessment of water supply imbalances as part of the system reliability analysis for all basin studies because water shortages can be an important metric for quantifying the effects of climate change on system operations and reliability. The modeling approach used for the Nebraska sub-basin calculates irrigated acreage within each canal service area prior to the irrigation season. Irrigated acreage is calculated based on the projected surface water supply available for the season and the historical relationship between surface water supply and irrigated acreage; in general, acreage is increased in years with high surface water supplies and decreased in years with low surface water supplies. The Nebraska model then simulates reservoir operations and surface water diversions and deliveries based on irrigation demands for the calculated acreage. To evaluate surface water imbalances, Reclamation staff used Nebraska's modeling results to calculate the amount of land irrigated relative to fully irrigated conditions, as well as the associated delivery shortage relative to what irrigation demands could potentially be for the fully irrigated condition. It is important to point out that this calculation is for hypothetical use only and is not representative of Nebraska's modeling approach.

The number of years during which irrigated acreages in NBID and FCID are reduced and the cumulative acreage reductions over the 50-year simulation period is shown in Table 14; the number of years during which surface water deliveries are less than irrigation demands and the cumulative delivery shortage are also shown in Table 14. Based on the historical relationship between surface water availability and irrigated acreage, NBID experiences reduced acreage during more than half of the simulation period under baseline (27 of 50 years) and Climate Scenario 1 (37 of 50 years), during slightly less than half of the simulation period under Climate Scenario 2 (22 of 50 years), and during just one year under Climate Scenario 3. Cumulative acreage reduction in NBID is 428,000 acres under the Baseline Climate Scenario; cumulative acreage reduction is greatest under Climate Scenario 1 at 706,000 acres and is less under Climate Scenarios 2 and 3 at 260,000 and 2,500 acres, respectively. For FCID, reduced acreage occurs in 38 of 50 years under the Baseline Scenario with a cumulative reduction of 345,000 acres over the 50-year simulation period. The frequency and magnitude of acreage reduction are greater under Climate Scenario 1 and are less under Climate Scenarios 2 and 3 compared to the Baseline Scenario.

Despite acreage reductions, delivery shortages in NBID occur in in more than half of all years under all scenarios. Shortages are greatest under the Baseline Climate Scenario, with shortages occurring in 37 of 50 years with a cumulative delivery shortage of 104,000 AF. The frequency and magnitude of shortages is smaller under all other climate scenarios compared to the Baseline Scenario. Surface water delivery shortages to FCID occur during 40 years under the Baseline Scenario with a cumulative shortage of 122,000 AF. Delivery shortages are less frequent under all climate scenarios compared to the baseline; however, the magnitude of shortages is greater under Climate Scenarios 1 and 2 and much less under Climate Scenario 3. It should be emphasized, however, that the frequency and magnitude of shortages do not depend on the available water supply but rather on the relationship between available water supply and water demands for the irrigated acreage calculated by the model.

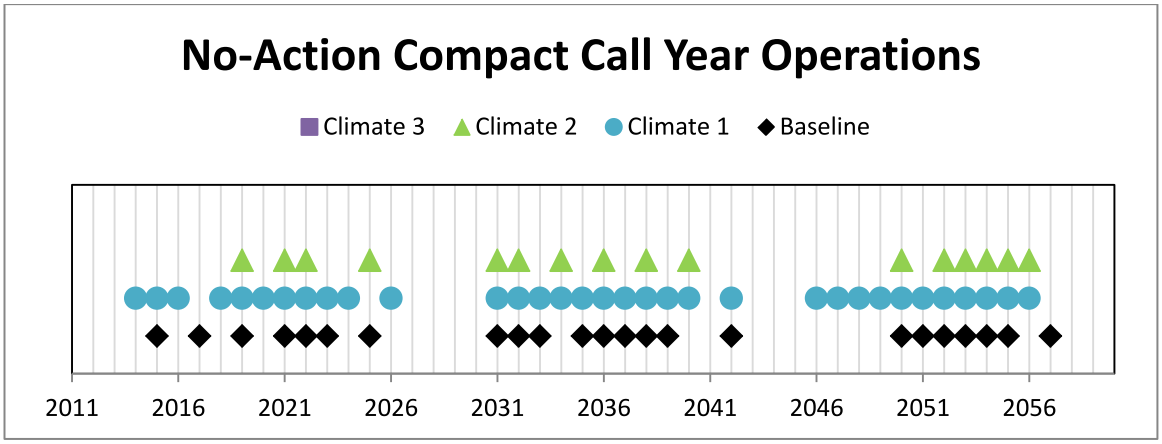


**Figure 40. — Compact Call Year Operations Under No Action Alternative for All Climate Scenarios**

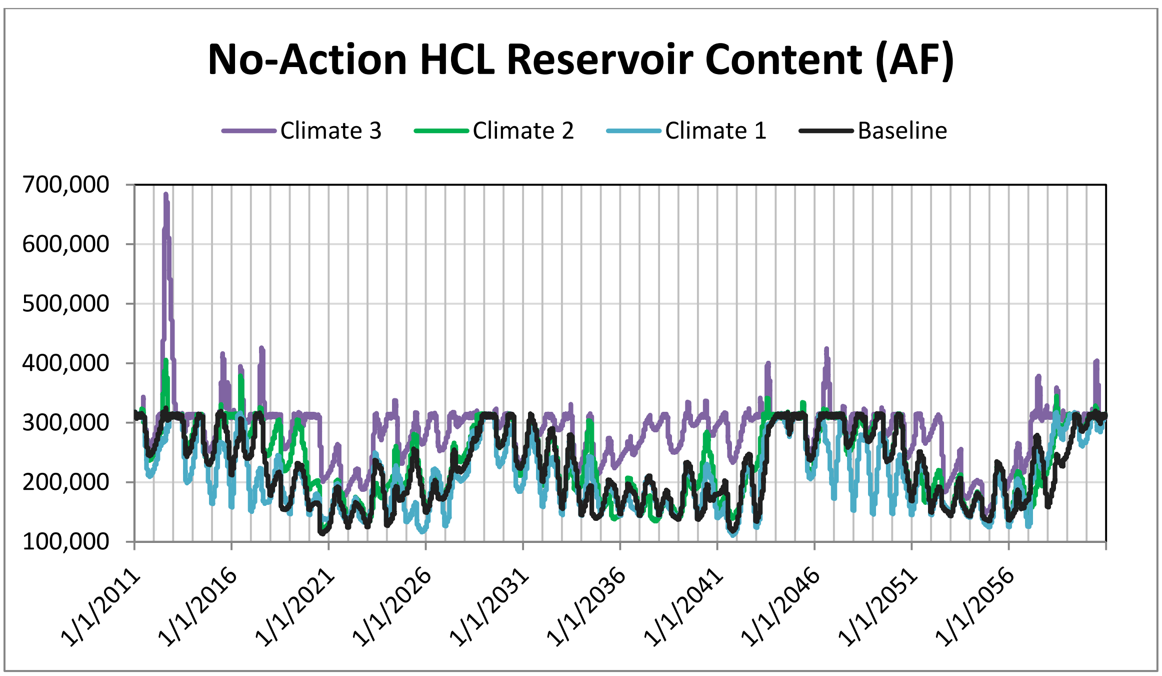


**Figure 41. — HCL Content Under No Action Alternative, for All Climate Scenarios**

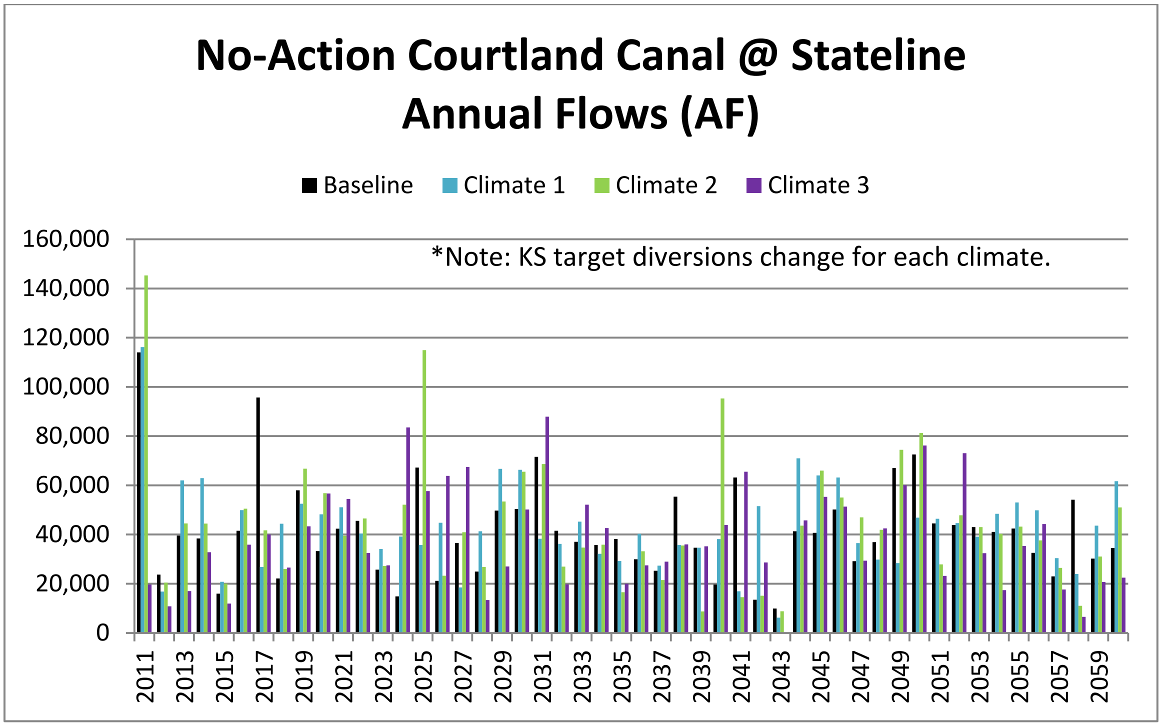


**Figure 42. — Courtland Canal at the Stateline Annual Flow Under No Action Alternative, for All Climate Scenarios**

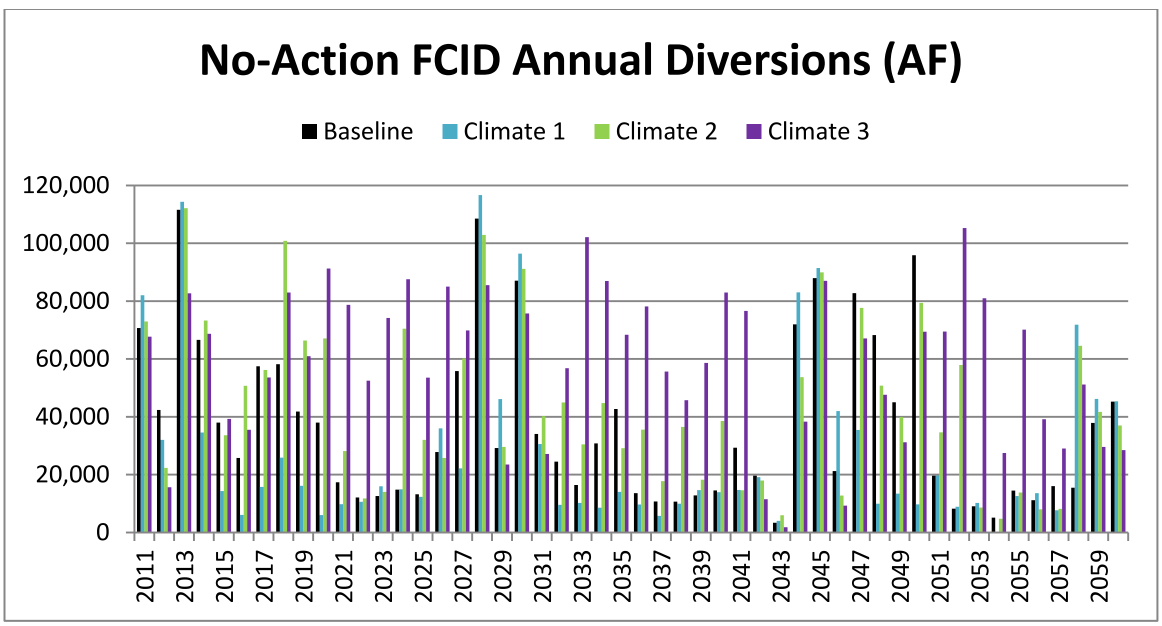


**Figure 43. — FCID Annual Diversions Under No Action Alternative, for All Climate Scenarios**

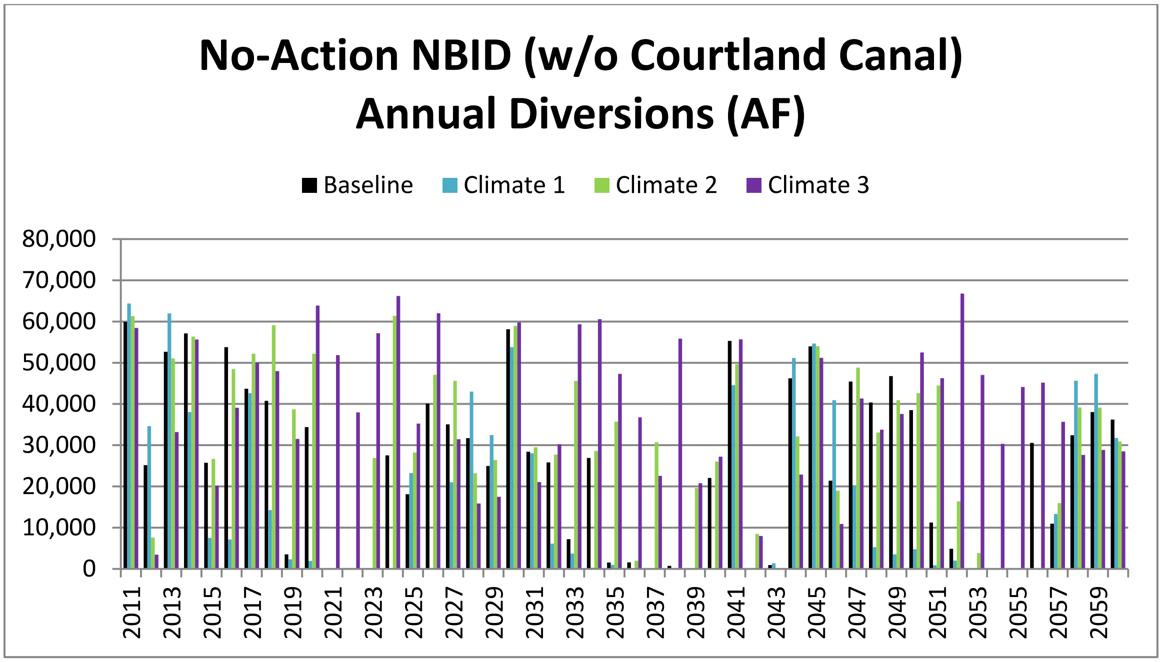


**Figure 44. — NBID (w/o Courtland Canal) Annual Diversions Under No Action Alternative, for All Climate Scenarios**

## 2. Kansas

Kansas' metrics measure the extent of impacts of climate change on deliveries and shortages to KBID both upstream and downstream of Lovewell Reservoir.

### a. *Overall Deliveries and Agricultural Benefits*

Table 14 above displays the effects of climate change on irrigation deliveries within KBID. For reasons described above, under the warmer/drier and central tendency climate scenarios (Scenario 1 and 2, respectively), irrigation deliveries increase in Kansas. Under the less warm/wetter climate scenario (Scenario 3), irrigation deliveries decrease.

### b. *Reservoirs and Stream Flows*

Two reservoirs were included in the model domain. Harlan County Lake represents the upstream boundary of the domain, and inflows to the reservoir are provided by the Nebraska STELLA model developed in conjunction with this work. The metric for reservoirs that guided the alternatives evaluation is storage volume (Figures 45 and 46). The warmer and drier climate (Scenario 1) resulted in the lowest volumes of water in both reservoirs for most months of the 50 year simulation. The volume of water stored within each reservoir determines the water elevation and surface area of water in the reservoirs. Results for elevation, surface area, reservoir inflows, and reservoir outflows are provided in the Kansas Modeling Results TM (KGS and KWO 2015a). The ability of the reservoir to meet water demands downstream is evaluated below. There are several stream gages along the simulated portion of the Lower Republican River Basin. Hardy gage, located upstream of the Nebraska-Kansas border, measures water flowing between states in the Republican River (Figure 47). The Courtland gage measures water flowing across the state line within the irrigation canal system (Figure 48). The Clay Center and Concordia gage stations are downstream of both reservoirs but are of concern because of MDS requirements administered at each gage (Figures 49 and 50). The gage results did not indicate consistent increases or decreases in flow for any one climate scenario because the streamflow at all gages is more dependent upon reservoir releases than climate.

### c. *KBID Demands and Shortages*

As stated previously, Kansas' objective is to ensure Compact compliance and minimize water shortages in the Lower Republican River Basin, in particular to the KBID. Operationally, KBID is divided into two areas: that portion located above Lovewell Reservoir referred to as upper KBID (or KBID-UP) and that portion below Lovewell Reservoir referred to as lower KBID (or KBID-DOWN). Of particular interest is the ability to meet demands of both the upper and lower KBID. Historically, KBID has experienced severe water shortages during droughts or periods of compact non-compliance. To assess impacts of climate change on water deliveries under the No Action Alternative, upper and lower KBID shortages were compared under the baseline climate and three climate scenarios over a 50-year simulation period (2011-2060).

The most important metrics for evaluating the alternatives is the ability to better meet water demands, thus reducing water shortages. Water demands under the various climate scenarios are provided in Figures 51 and 52 below. In all scenarios, significant water shortages for KBID are present under the No Action (Figures 53 and 54), although the greatest shortages occur under the warmer/drier climate (Scenario 1). Table 15 provides more specific data on the cumulative water shortages, percent of demands unmet, and instances in which water shortages to KBID occur under the various climate scenarios.

**Table 15. — Simulated cumulative water shortages, percentage of water demands not met, and number of short months and years for KBID-UP and KBID-DOWN for 2011 through 2060**

| | Climate Scenario | KBID-UP | KBID-DOWN |
|---|---|---|---|
| Cumulative Water Shortage for 2011-2060 (AF) | Baseline | 84,573 | 56,812 |
| | Scenario 1: Warmer/Drier | 120,015 | 149,734 |
| | Scenario 2: Central Tendency | 92,230 | 57,364 |
| | Scenario 3: Less Warm/ Wetter | 9,823 | 1,366 |
| Percentage of Demand Not Met for 2011-2060 | Baseline | 11.3 | 3.4 |
| | Scenario 1: Warmer/Drier | 11.4 | 6.4 |
| | Scenario 2: Central Tendency | 11.3 | 3.2 |
| | Scenario 3: Less Warm/ Wetter | 1.6 | 0.1 |
| Instances of Water Shortage for 2011-2060 (# of years) | Baseline | 8 | 5 |
| | Scenario 1: Warmer/Drier | 14 | 9 |
| | Scenario 2: Central Tendency | 9 | 3 |
| | Scenario 3: Less Warm/ Wetter | 1 | 1 |

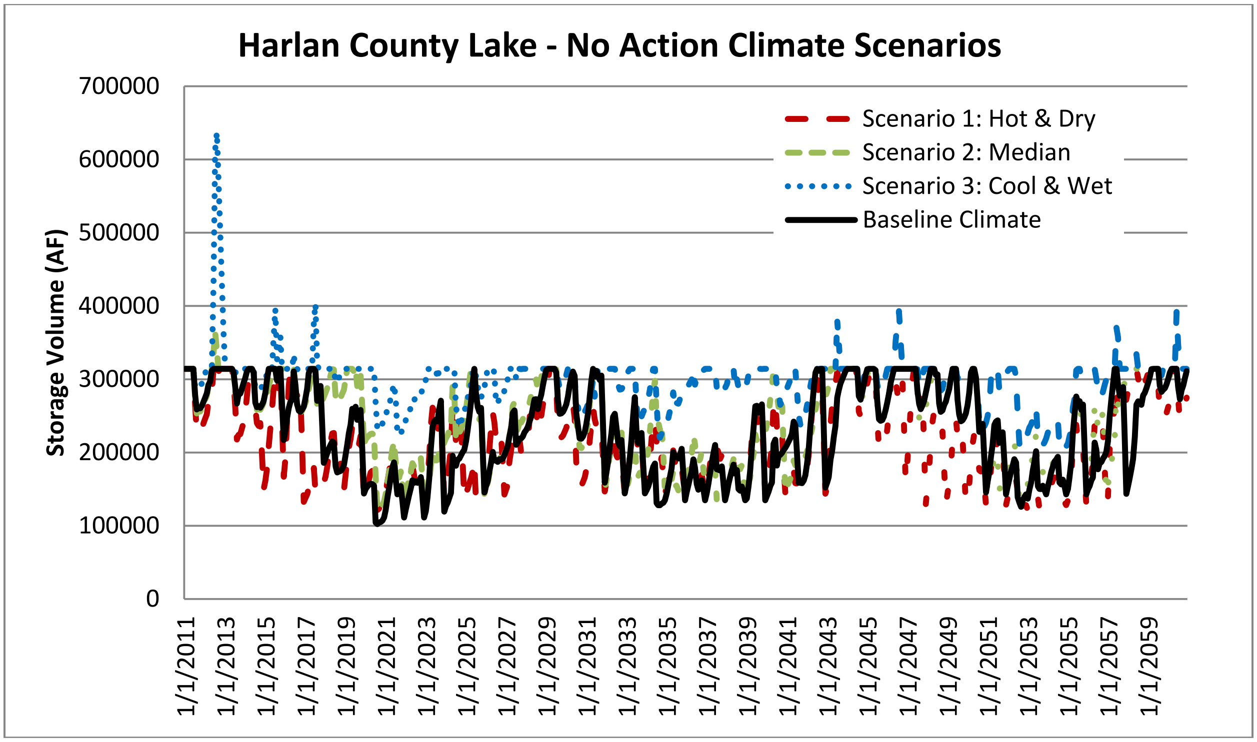


**Figure 45. — Storage volumes in Harlan County Lake for no action climate simulations from 2011-2060.**

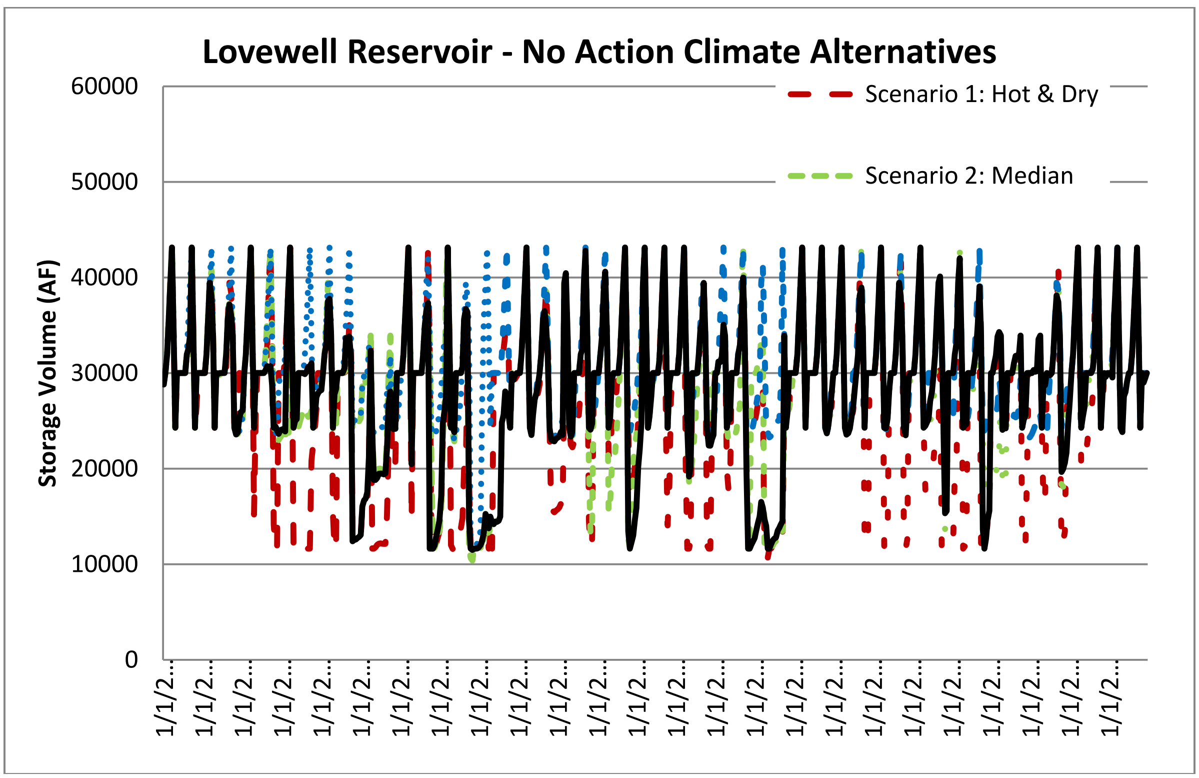


**Figure 46. — Storage volumes in Lovewell Reservoir for no action climate simulations from 2011-2060.**

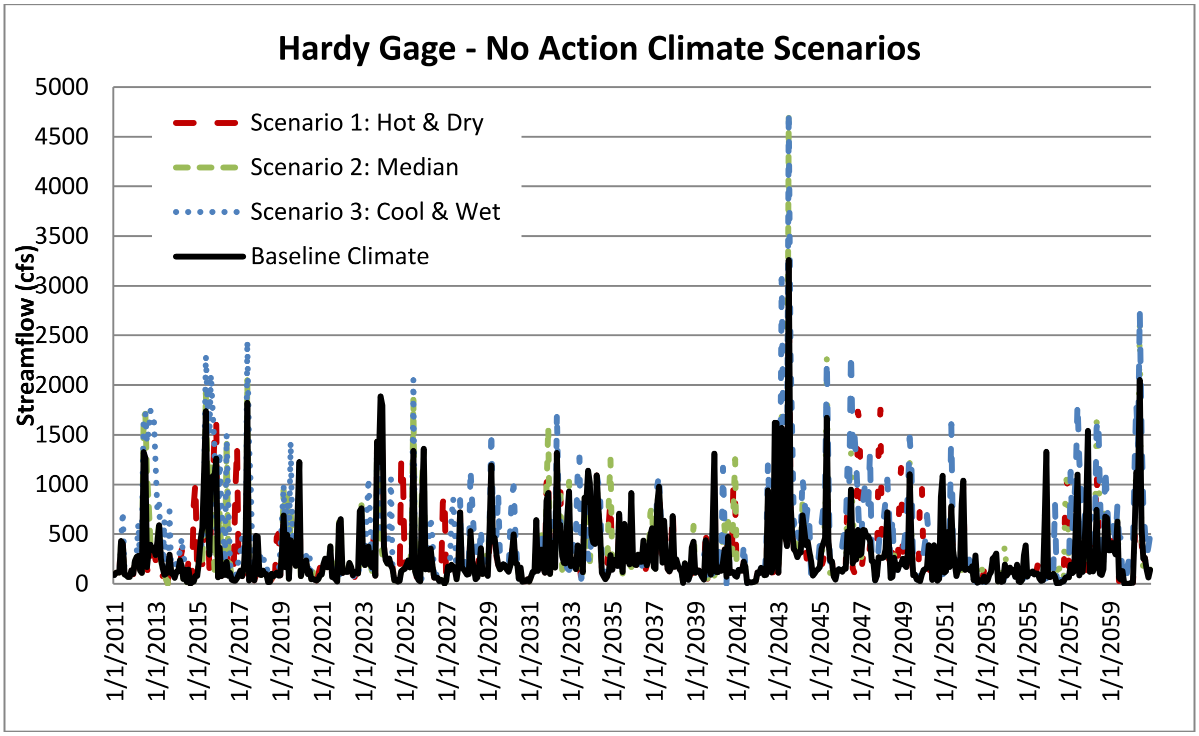


**Figure 47. — Streamflow at Hardy gage station for no action climate simulations from 2011-2060.**

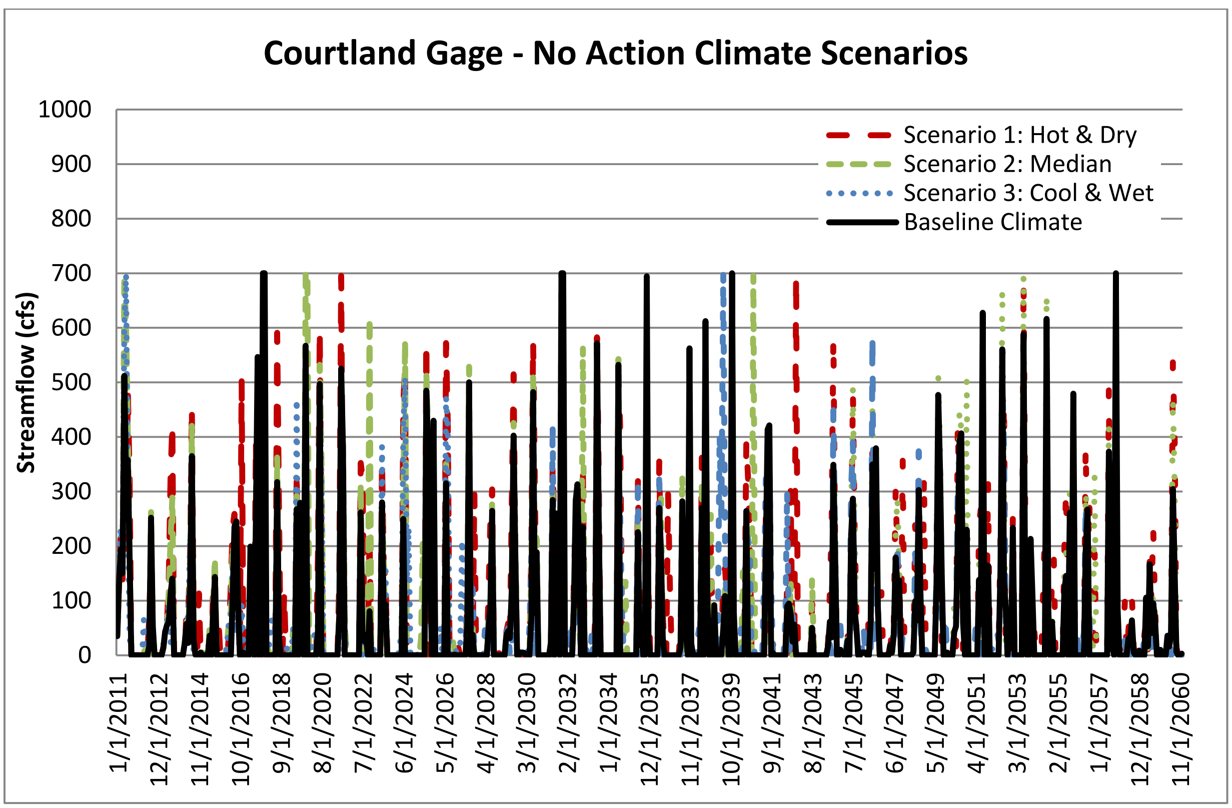


**Figure 48. — Streamflow at Courtland gage station for no action climate simulations from 2011-2060.**

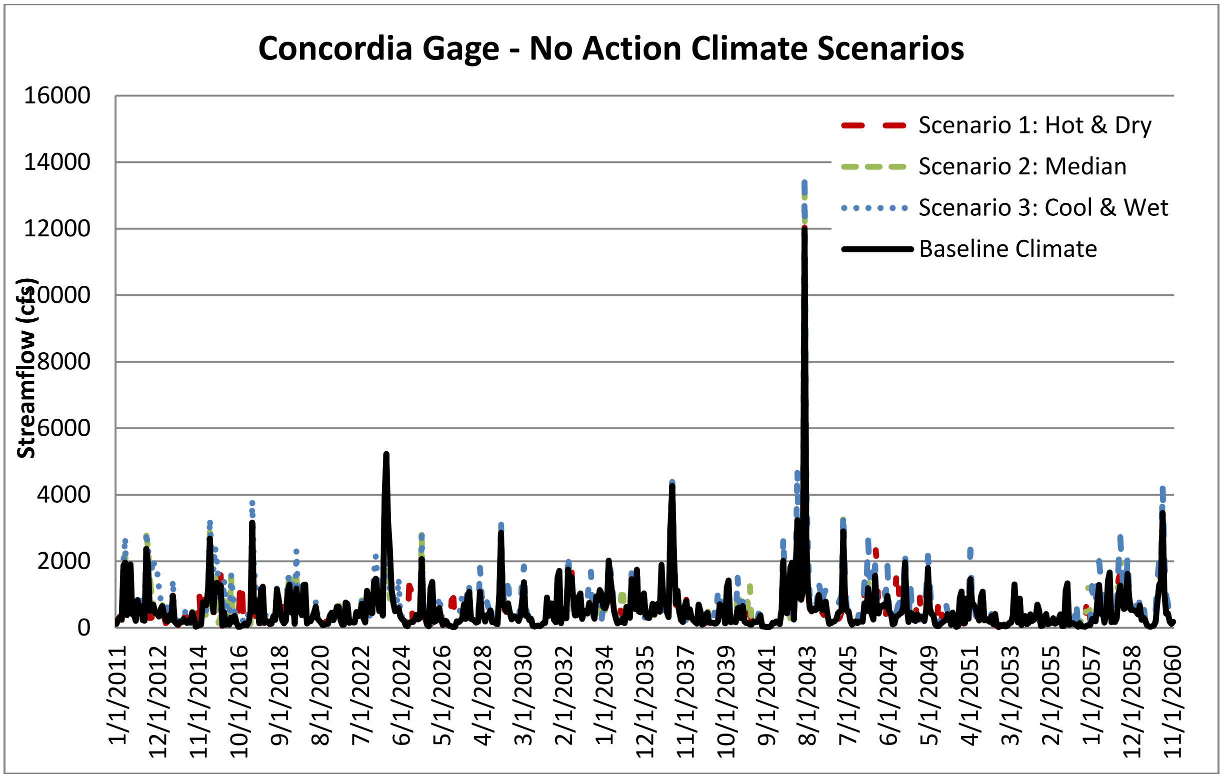


**Figure 49. — Streamflow at Concordia gage station for no action climate simulations from 2011-2060.**

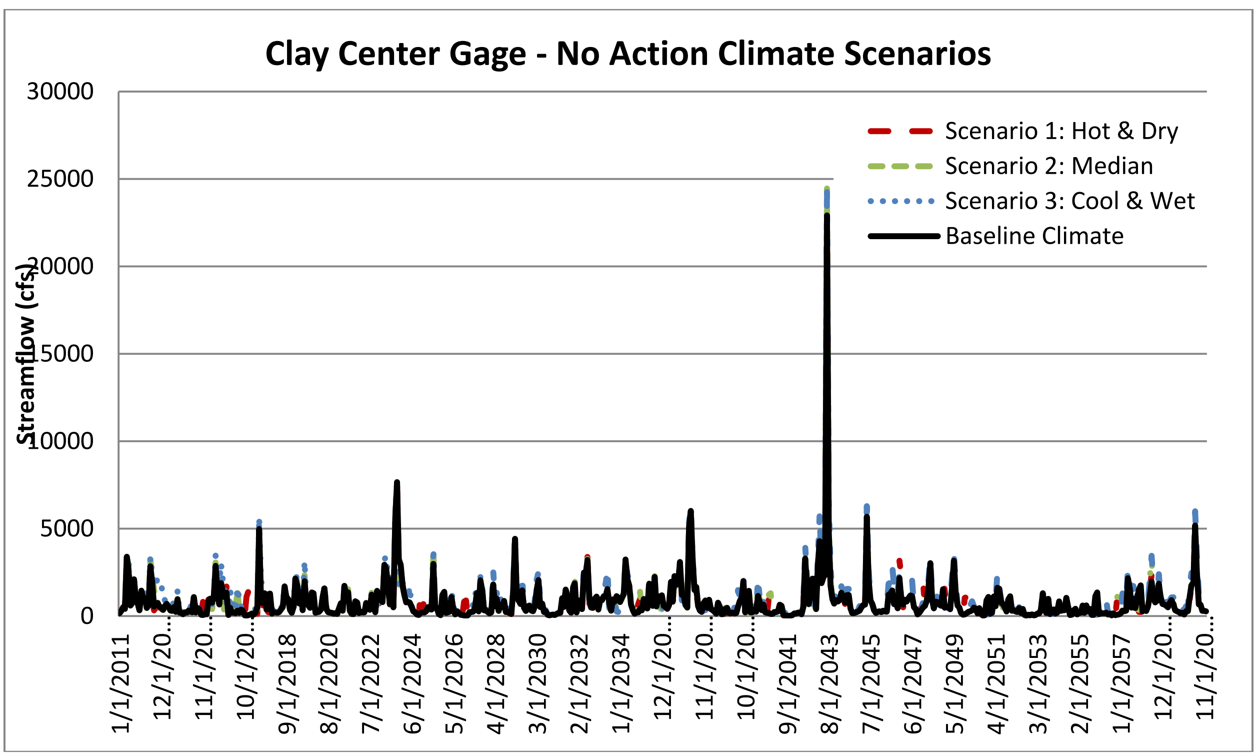


**Figure 50. — Streamflow at Clay Center gage station for no action climate simulations from 2011-2060.**

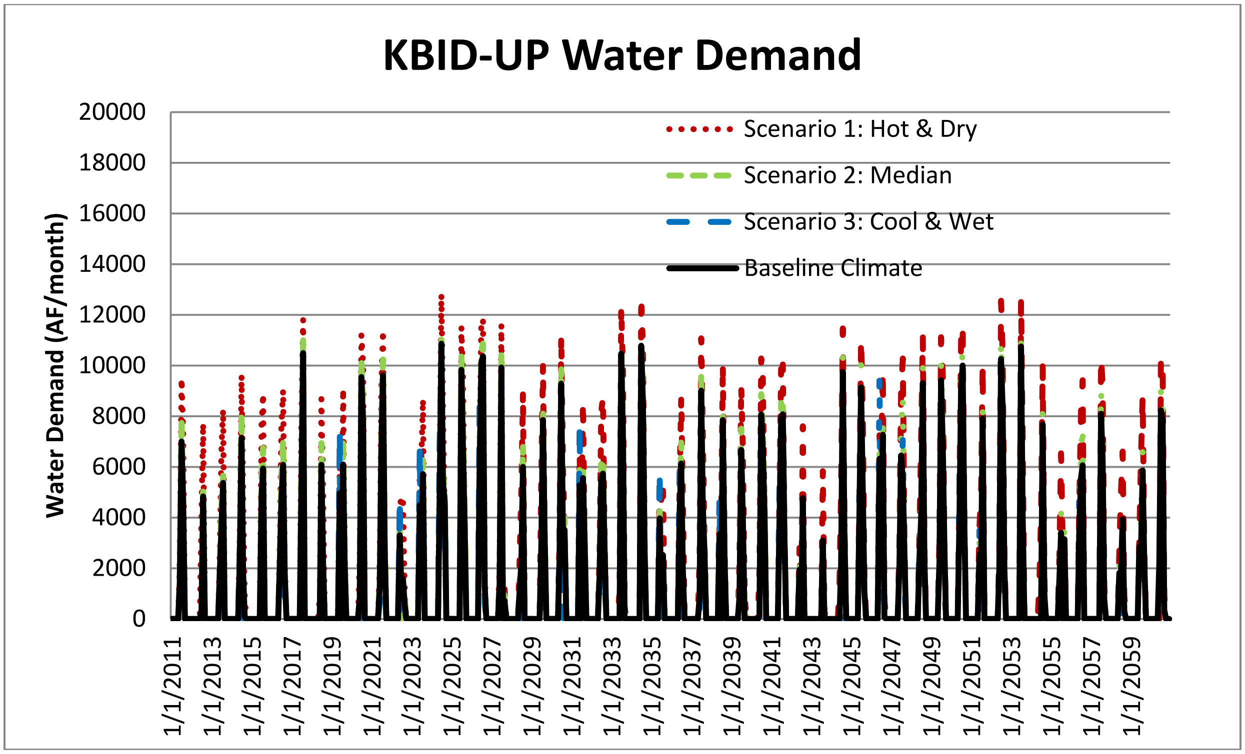


**Figure 51. — Water demands for KBID-UP for no action climate simulations from 2011-2060.**

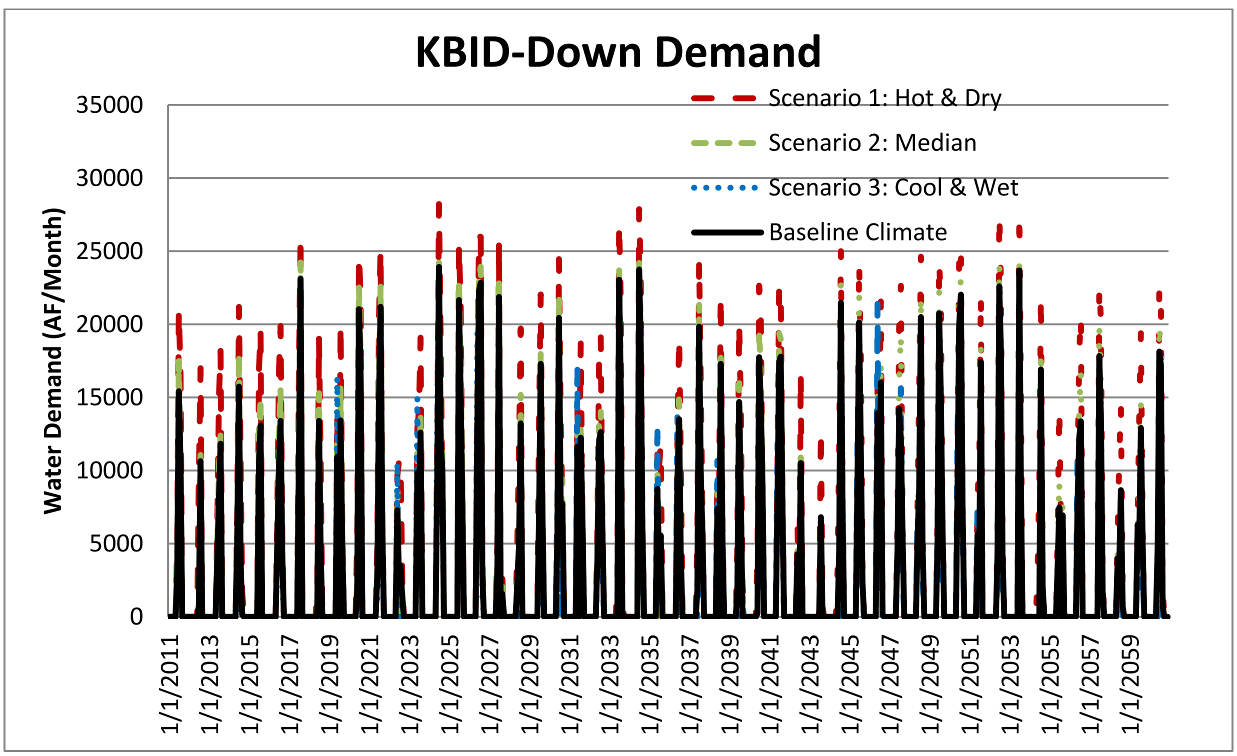


**Figure 52. — Water demands for KBID-DOWN for no action climate simulations from 2011-2060.**

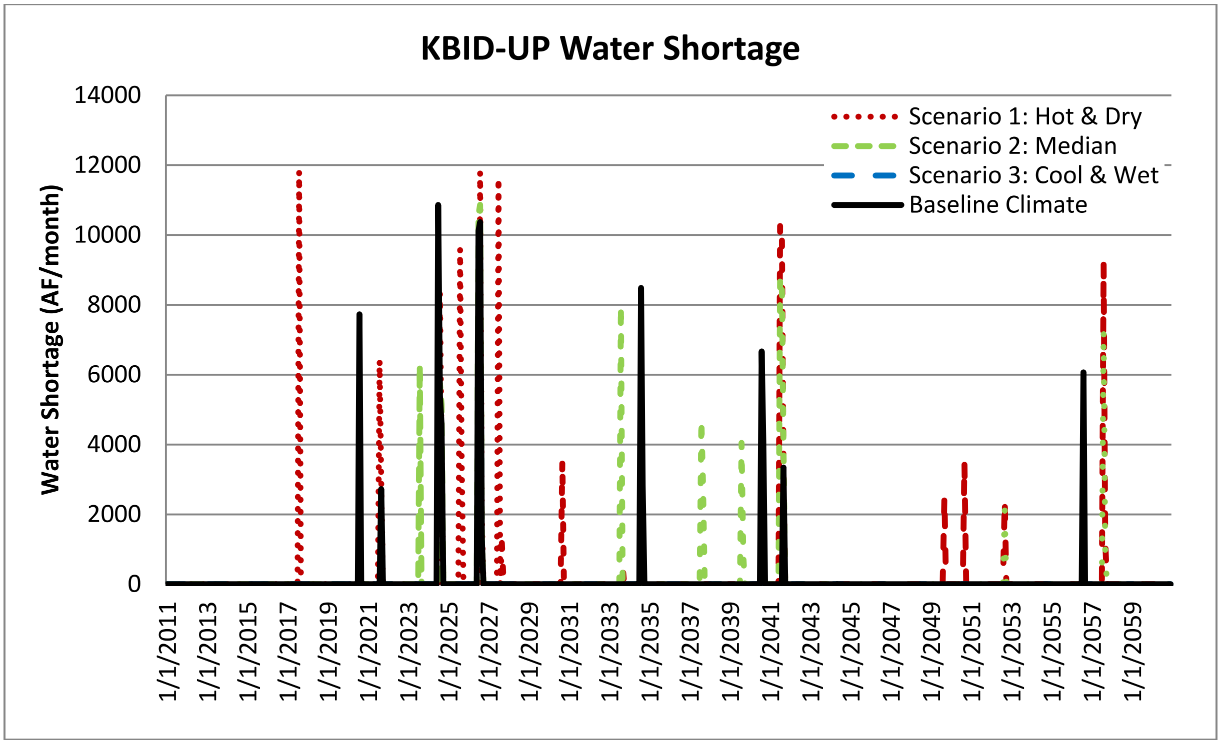


**Figure 53. — Water shortages for KBID-UP for No Action climate simulations from 2011-2060.**

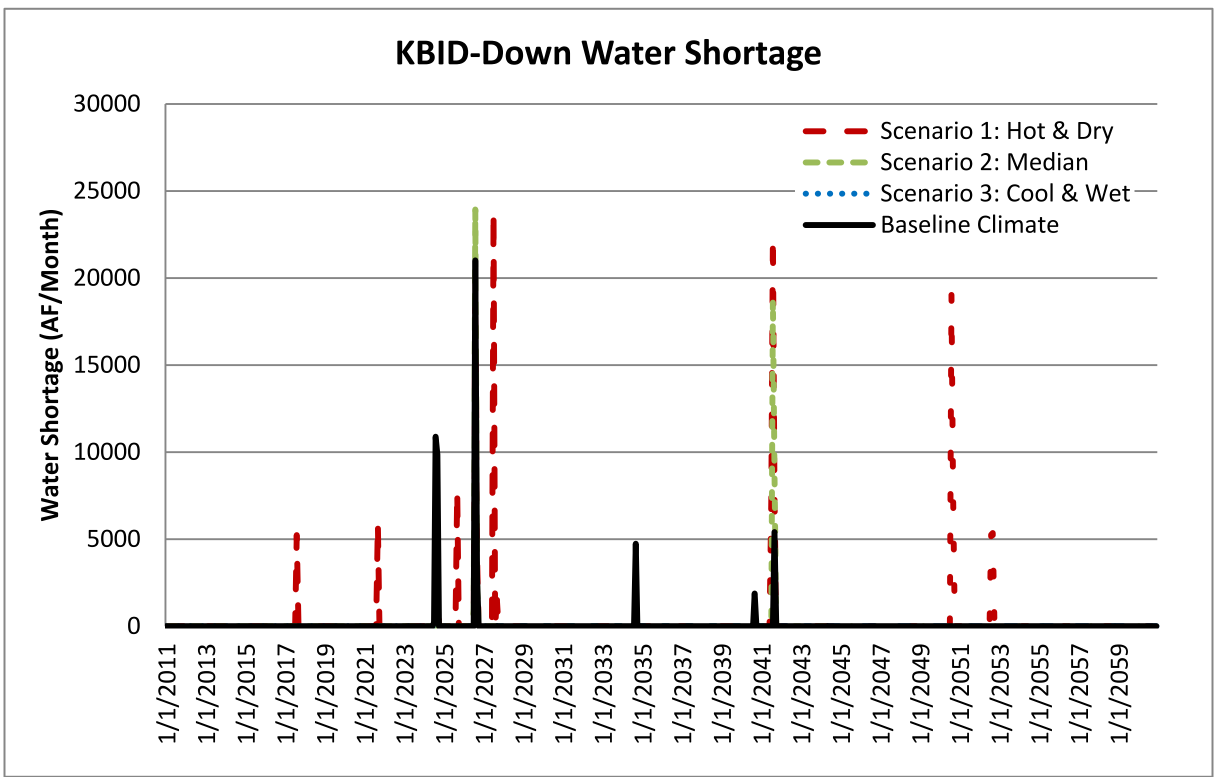


**Figure 54. — Water shortages for KBID-DOWN for No Action climate simulations from 2011-2060.**

# D. Impacts of Climate Change on Recreation Under the No Action Alternative

Table 16 displays the recreation economics of the No Action Alternative under the baseline climate and climate change scenarios. The Future No Action Alternative with climate change under each of the climate scenarios is compared to the single scenario Baseline No Action Alternative without climate change. The results in this table reflect the difference in the present value of the 50-year stream of recreation benefits for the No Action Alternative under each climate change condition.

As noted in the table's footnote, given that two sets of hydrologic data were provided for Harlan County Lake, two sets of results are presented for the combined recreation benefits across the six reservoirs. The first set includes Harlan County Lake recreation benefits based on hydrologic data provided by the Nebraska model, whereas the second set presents results with Harlan County recreation benefits based on Kansas hydrologic modeling output.

While certain reservoirs result in negative recreation benefits under the warmer/drier climate scenario (Scenario 1), overall, the recreation economic effect of climate change is positive for all three climate scenarios as compared to the baseline. Under the hot/dry and central tendency climate scenarios, Harlan County and Lovewell reservoirs generate the majority of the increase in recreation benefits. Under the less warm/wetter scenario, Swanson Reservoir also contributes heavily along with Harlan County and Lovewell.

The recreation visitation models for Swanson, Harlan County, and Lovewell are based on reservoir water levels and air temperatures. The coefficients of the models are positively correlated for both water level and temperature implying that increases (or decreases) in water levels and temperatures should lead to increases (or decreases) in recreation visitation. Note that similar changes in water levels across alternatives at different reservoirs can lead to dramatically different results upon recreation visitation due to reservoir size and bathymetry. For example, a one-foot change in water level at Harlan County Lake would lead to a substantially larger change in surface area as compared to a similar change in water levels at all the other much smaller reservoirs included in this Study.

The large $49.2 million increase in recreation benefits at Swanson Reservoir under Climate Scenario 3 is primarily due to the large change in water levels and, to a lesser degree, air temperatures. The monthly change in average water levels was estimated in the 14.4 ft to 15.6 ft range which equates to a loss in surface area ranging from 1,537 to 1,764 acres. The monthly change in temperature ranged from 1.9 °F to 4.5 °F. At Harlan County Lake, the large increases in recreation benefits under the warmer/drier and central tendency climate scenarios are due primarily to the increases in average monthly air temperatures (increased temperature ranges from 3.8 °F to 8.2 °F for Scenario 1 and 3.8 °F to 4.9 °F for

Scenario 2). Climate Scenario 3 is driven by both changes in water levels (4.2 ft to 5.3 ft equating to a change in surface area of 1,257 to 1,612 acres) and temperatures (1.6 °F to 3.9 °F). Finally, at Lovewell Reservoir, the increases in recreation benefits under all three climate scenarios is primarily due to air temperature increases in the 1.6 °F to 8.3 °F range. The largest loss (-$7.5 million) in recreation benefits is seen at Swanson Reservoir under Scenario 1. This is due to the consistent reduction in average monthly water levels across the May to November high recreation use season ranging from -9.1 ft to -10.1 ft which corresponds to a reduction in surface area of 925 to 1070 acres.

For some scenarios and reservoirs, there may be a sizable reduction in water levels which are offset in the visitation estimates by increases in air temperatures. For example, at Harry Strunk Reservoir, the alternative/scenario Future No Action results in an increase of $2.3 million in recreation values over Baseline No Action. Water levels across the April to September high recreation use season were estimated to decline from a low of 4.0 ft to a high of 8.1 ft (157 to 359 surface acres) while temperatures were estimated to increase from 3.8 °F to 8.1 °F. The increases in temperature outweighed the losses in water levels resulting in an increase in recreation benefits.

Overall, compared to the Baseline Scenario, the effects of Climate Scenarios 1, 2, and 3 result in an approximate increase of recreation benefits by 14%, 18%, and 29%, respectively.

**Table 16. — Recreation benefits comparison of the Baseline Climate Scenario versus the three future climate scenarios, all under the Future No Action Alternative**

| | | | | | |
|---|---|---|---|---|---|
| Enders | Nebraska | | -1.12 | 7.97 | 11.80 |
| Harry Strunk | Nebraska | | 2.35 | 7.22 | 13.27 |
| Hugh Butler | Nebraska | | -1.77 | 3.94 | 8.06 |
| Swanso n | Nebraska | | -7.47 | 8.82 | 49.22 |
| Harlan County (*) | ***Nebraska*** | | 49.28 | 37.04 | 37.84 |
| Lovewell | Kansas | | 27.91 | 25.04 | 25.53 |
| Total: | | 507.12 | +69.18 | +90.04 | +145.72 |
| Enders | Nebraska | | -1.12 | 7.97 | 11.80 |
| Harry Strunk | Nebraska | | 2.35 | 7.22 | 13.27 |
| Hugh Butler | Nebraska | | -1.77 | 3.94 | 8.06 |
| Swanso n | Nebraska | | -7.47 | 8.82 | 49.22 |
| Harlan County (*) | ***Kansas*** | | 47.77 | 37.66 | 39.45 |
| Lovewell | Kansas | | 27.91 | 25.04 | 25.53 |
| Total: | | 508.85 | +67.67 | +90.66 | +147.33 |

(*) Two versions of hydrologic output for Harlan County Lake were provided, one from the Nebraska model and one from the Kansas model. The total reservoir recreation effect of climate change as compared to the without climate change baseline is presented using Harlan County Lake results based on both the Nebraska and Kansas input data.

# VI. Impacts of Climate Change on Environmental Resources Under the No Action Alternative

A detailed inventory of environmental resources is provided in *Section 8.0* of this report. This inventory provides the basis for the impacts documented below.

## A. Fish and Wildlife

The amounts and functionality of streams, reservoirs, wetland, and riparian habitats would remain unchanged. Swanson, Harlan County, and Lovewell Reservoirs would continue to provide ample habitat for the current population of walleye, white bass, wipers, channel catfish, and crappie. Like most reservoir environments, the abundance and food available is largely dictated by the changing reservoir elevations during the spring and fall months. White bass, wipers, and catfish can also be found in the Republican River just downstream of the dams. Reservoir level fluctuations would continue to have an impact on the reservoir fishery.

High water temperatures and low flows in Frenchman Creek during the summer months would continue to be a limiting factor to the fish community. Thompson Creek supports a fish population of central stonerollers, red shiners, orangethroat darters, creek chubs, suckermouth minnows, flathead minnows and northern plains killifish. Under the No Action Alternative, all these species would have the ability to persist in Thompson Creek. The Kansas MDS would also remain unchanged.

## B. Federal and State Threatened, Endangered, and Species of Concern

Federal and State-listed species would not be impacted further than under historic conditions. Whooping cranes, eskimo curlews, peregrine falcons, Interior least terns and piping plovers would still have access to the areas that are currently used today. The amount of riverine and riparian habitat for these species would not be altered. Impacts to the American burying beetle would not be expected due to the absence of ground disturbing activities under the No Action Alternative.

### 1. Invasive Species

Invasive species such as Canadian thistle, musk thistle, European buckthorn and garlic mustard would continue to persist throughout the area. No ground disturbing actions would take place under the No Action Alternative that would increase the spread these species. Reservoirs are would continue to be stocked with non-native game species for recreation. Under the No Action, these species would continue to persist in the reservoir environments and could spread into the Republican River and Frenchman Creek.

### 2. Water Quality

Under the No Action Alternative, all impairments are expected to continue. Headwater tributaries into Lovewell Reservoir would continue to be impaired for water supply and aquatic life by arsenic, selenium and total phosphorus. White Rock Creek upstream and downstream from Lovewell Reservoir would continue to have water supply impaired by arsenic and an impaired aquatic life due to total phosphorus and total suspended solids.

Much of Frenchman Creek is impaired by E. coli and naturally high water temperatures. Although not documented, it is assumed that dissolved oxygen would also be a problem due to the high water temperatures in the summer and fall months. One segment of Frenchman Creek is impaired by selenium. Thompson Creek is also impaired by E. coli and naturally high water temperatures due to reduced summer and fall flows. All these impairments would continue to exist.

### 3. Ecological Resiliency

Decreased flows and altered hydrographs are the primary limiting factors throughout the Basin which would continue under the No Action Alternative. Fish populations would continue to shift towards species that are benthic spawners rather than pelagic spawners due to the decrease in spawning and drift distance for larval fish. The Basin could also continue to see an increased shift towards non-native species.

# VII. Development of Adaptation Strategies

Section 9503(b)(3) of P.L. 111-11 requires development of appropriate adaptation and mitigation strategies (including both structural and nonstructural alternatives) to meet current and future water demands. Adaptation strategies (i.e. alternatives) were formulated to improve system reliability based on impacts associated with No Action (described above) on metrics considered important to meeting each State's purposes and objectives described in *Section 2.0*. As described in that section, Colorado maintains Compact compliance by operation of the Compact Compliance Pipeline, reducing irrigated acreage, and curtailing junior water rights (including Bonny Reservoir which is presently operated as a pass through facility). Given Colorado's objectives above, the scope of this Basin Study was limited to the Nebraska and Kansas sub-basins and associated water supply alternatives contained therein. The purposes and objectives of Nebraska and Kansas are briefly summarized again here in terms of their approach in identifying adaptation strategies for consideration. As discussed below, the ability of an alternative to meet these objectives was only one of the criteria used to determine whether an alternative would be eliminated from consideration. The elimination of alternatives itself, is an iterative process that has occurred over the course of decades of investigations. In the context of this Basin Study, time and funding constraints, along with the availability of data, were key limiting factors in assessing which, how many, and when to consider and/or advance alternatives.

## A. Nebraska Approach

Alternatives were formulated to meet Nebraska's objective of maintaining compliance with the Republican River Compact and FSS while maximizing the beneficial use of water for all Nebraska users in the Basin. Maximizing the beneficial use of water in Nebraska's portion of the Basin must not conflict with the intent and provisions of the NRD's IMPs. Furthermore, this includes managing the timing, magnitude, and frequency of reservoir storage to maximize diversions to FCID and NBID.

## B. Kansas Approach

Alternatives were formulated to meet Kansas' overall objective to secure the share of the water Kansas is entitled to under the Republican River Compact with the ability to manage that water for the maximum benefit of Kansas water users. This includes maximizing the ability to meet water demands for irrigation, recreation, wildlife areas, municipalities, and industries, while also maintaining minimum desirable streamflows, along with appropriate management of the timing, magnitude, and frequency of reservoir storage to minimize shortages to KBID.

## C. Nebraska Adaptation Strategies Considered But Eliminated

Using the No Action Alternative as a baseline, four alternatives were considered for evaluation: Non-Irrigation Canal Recharge, Swanson Reservoir Augmentation via New Frenchman Creek Pipeline, Swanson Reservoir Augmentation via New Republican River Pipeline, and Exchange Downstream Supplies for Harlan County Releases (new Thompson Creek Dam or new Beaver Creek Dam). The choice of alternatives was a collaborative process that took place over the course of years, and which involved early input from stakeholders in Nebraska's portion of the Basin. Basic configurations of potential alternatives for Hugh Butler and Harry Strunk reservoirs were also considered during the early part of the study process, but a choice was made to focus on the remaining list of alternatives based on budget and time constraints, modeling and data considerations, and input from Reclamation staff. No specific project involving Enders Reservoir was identified as part of the early process of alternative identification. Below is a brief description of the rationale behind eliminating non-irrigation canal recharge and Beaver Creek Dam from further consideration under this Basin Study.

Non-irrigation canal recharge would involve the use of specific Federal canals in Nebraska's portion of the Republican River Basin to provide recharge through diversions of non-irrigation stream flow. The diversions would be allowed to permeate the unlined canals, providing additional recharge to the alluvial aquifer, and enhancing stream flows through delayed accretion returns. For operational purposes, the administration of these diversions could be structured to allow for upstream recharge diversions during times where Harlan County Lake would normally call-out junior upstream water rights. If actually carried out in practice, these operational changes would involve consultation with Reclamation and with other parties as needed. A full description is provided in Nebraska's Modeling Results TM (TFG 2015b). In the TM, this alternative was evaluated but discontinued for several reasons, mostly due to limitations with the modeling platforms and time constraints. Because this was the only alternative that required use of the RRCA Groundwater Model for a complete analysis, it presented extra challenges in terms of transferring results between the groundwater model and the STELLA surface water model. Several assumptions were made concerning the base conditions used with the groundwater model, which meant that the stress conditions and other inputs used in the groundwater model did not always line up, or correlate with, corresponding inputs in the STELLA model. Extra time was also required to transfer data results back and forth between the models until some level of convergence could be obtained. Due to all these factors, it was determined that a more thorough examination of the canal recharge alternative would be more appropriate outside the Basin Study processes, and to focus instead on the remaining alternatives. The preliminary results for the canal recharge options do, however, show great promise in terms of the ability to conduct future recharge projects across the Basin, and the potential for consistent available flows for diversion during years when Compact Call Year operations are not required.

The development of a new dam on Beaver Creek in Nebraska (known in previous reports as Alternative 3B) would involve exchanging water supplies originating downstream of Harlan County Lake for stored water in the lake. Multiple sources and infrastructure configurations are possible, but two examples were considered for the purposes of this alternative, both of which included bringing in exchange water from the north side of the Republican River downstream of Harlan County Lake: a new reservoir on Thompson Creek, and a new reservoir on Beaver Creek. While the Beaver Creek location had advantages in terms of being located downstream of the Guide Rock Diversion Dam, and closer to the state line with Kansas, the spotty historical flow record on Beaver Creek made it difficult to estimate available supplies and potential reservoir sizes, so this option was eliminated. Instead, the Thompson Creek location was targeted for the purposes of this Study, while acknowledging that future consideration of the Beaver Creek location – perhaps including synthesis of the historical flow record using appropriate hydrologic techniques – could be warranted.

## D. Kansas Adaptation Strategies Considered But Eliminated

Kansas focused its analysis on management alternatives within the Lower Republican Basin downstream of Harlan County Lake. As stated in the POS, although the Upper Republican Basin in Kansas was identified as an area of concern for meeting water needs, due to uncertainties as to the future delivery of water in the South Fork of the Republican River, management alternatives, including those related to Keith Sebelius Reservoir, would not be evaluated in this Study.

Initially, Kansas proposed several alternatives to evaluate as part of this Basin Study, but time and funding constraints required a reduction in alternatives before model development began. These included elimination of:

- Development of aquifer storage and recovery within the alluvial aquifer system to store flood water for later baseflow or municipal well field augmentation.

- Development of a new reservoir storage facility within the Basin at Beaver Creek in Kansas.

The focus was then set on expanding the storage capacity of Lovewell Reservoir (known as "Alternative 1" in previous reports), an option that was studied extensively by Reclamation in a 2005 Appraisal Investigation, and off season storage of surplus water from Lovewell Reservoir or the Courtland Canal at Jamestown Wildlife Area, a 5,000-acre wetland complex in Kansas. The latter alternative would entail the release of the water stored at Jamestown in the late spring and/or into the summer for alluvial aquifer recharge and to meet the MDS in the Republican River at Concordia, Kansas while also providing important ecosystem benefits. However, this option was eliminated from further review in this Study because Kansas questioned whether this option could effectively augment flows upstream of Concordia; as well, the spatial and temporal resolution of the modeling tools for this Study was not sufficient to meaningfully evaluate the low flow conditions that trigger MDS administration.

The process of refining these alternatives even further was based on modeling runs and assessing the potential benefits in terms of meeting Kansas' objectives, as described in *Section 7.0: Evaluation of Adaptation Strategies* of this report.

# E. Description of Adaptation Strategies Evaluated

Four alternatives were selected for further evaluation in this Study – one in Kansas and three in Nebraska. A brief description of the alternatives, including prominent features, is below[18]. More detailed information can be found in the report "*Republican River Basin Appraisal-Level Engineering and Cost Estimates on Structural Alternatives*" (August 2014).

- Alternative 1 – Expansion of Lovewell Reservoir, KS
- Alternative 3A – Swanson Reservoir Augmentation via New Frenchman Creek Pipeline, NE
- Alternative 3B – Swanson Reservoir Augmentation via New Republican River Pipeline, NE
- Alternative 5A – New Thompson Creek Dam, NE

## 1. Alternative 1 – Expansion of Lovewell Reservoir, Kansas

This alternative proposes to increase storage in Lovewell Reservoir located eight miles south of Superior, Nebraska on White Rock Creek. This alternative is subdivided into three options of increasing storage by 16,000, 25,000, or 35,000 AF. It includes winterization and automation of the Superior-Courtland Diversion Dam, the Courtland Canal, and appurtenant features which would allow canal diversions whenever water is needed and available during the winter months.

[18] The naming/numbering convention was derived from previously completed reports and was left unchanged in this Study for the purposes of staying consistent with previous reports and avoiding confusion.

These improvements would then result in Lovewell Reservoir filling earlier in the spring and would provide additional water to the reservoir, when available, if additional storage space were provided by raising the top of active conservation pool level. A brief description of the prominent features of this alternative follows. An illustration is provided in Figure 55.

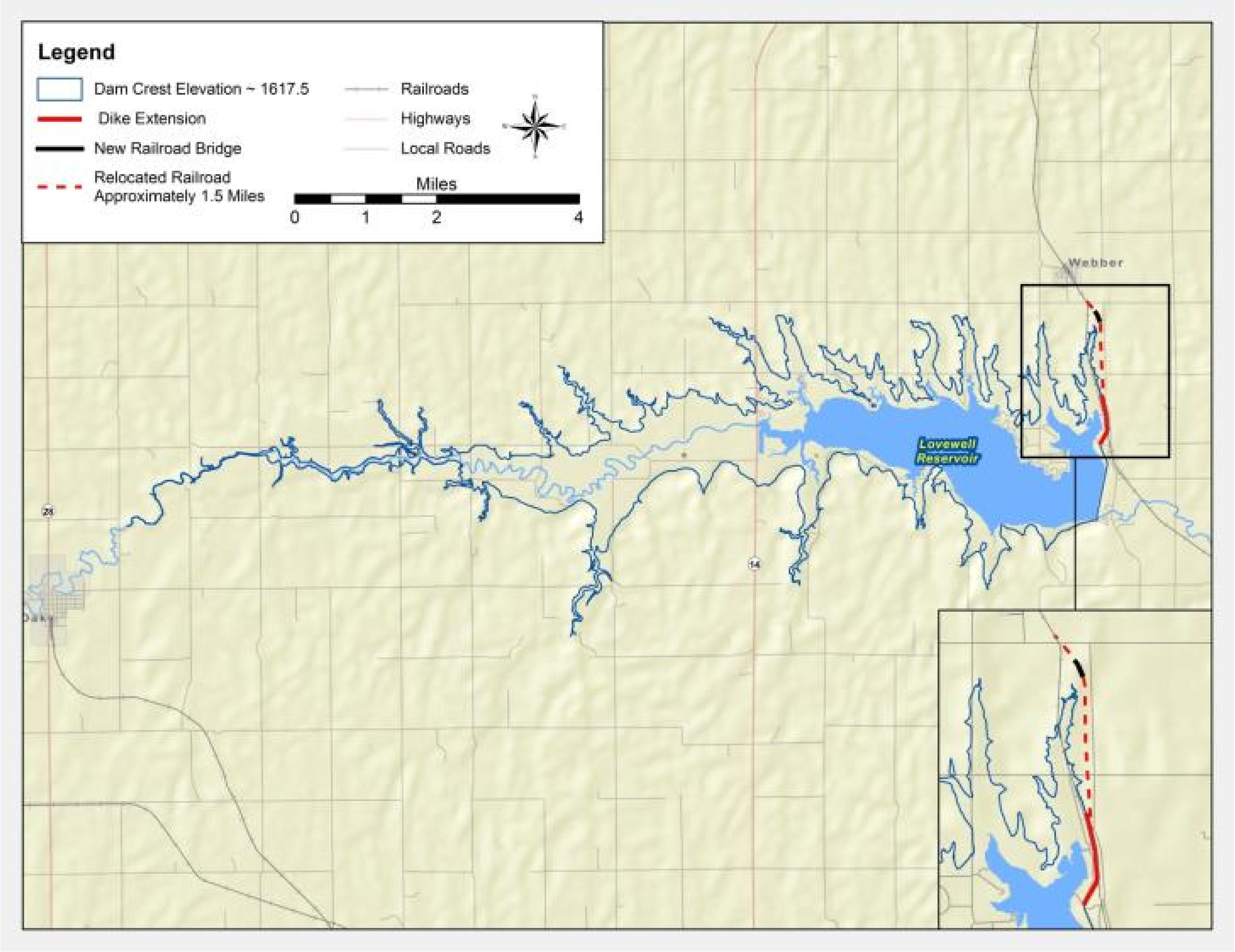


**Figure 55. — Conceptual illustration of Alternative 1, Expansion of Lovewell Reservoir. For simplicity, only one of the three expansion options (1C) is included.**

### a. *Lovewell Dam and Courtland Canal*

Located on White Rock Creek three miles northwest of Lovewell, Kansas, the Bureau of Reclamation's Lovewell Dam, constructed in 1957, stores water from the Creek and from Republican River diversions via the Superior-Courtland Diversion Dam through the Courtland Canal. The dam is a 3-million cubic-yard earthfill structure, 8,500 feet long that extends 81 feet above streambed.

State Highway 14 crosses the upper portion of Lovewell Reservoir approximately five miles west of the dam. The highway is a paved 28-foot-wide roadway and crosses White Rock Creek with a 371-foot-long bridge with raised embankment approaches. The top of the road is at approximate elevation 1603. The State of Kansas has provided a flood easement to the United States up to elevation 1595.3.

A State Park near the reservoir offers camping, fishing, wildlife watching and a full-service marina. There are 62 privately owned cabins in an area west of the State Park on the north side of Lovewell Reservoir on lots leased from the Kansas Division of Wildlife and Parks. All of the cabins have been constructed above the existing top of active conservation pool (elevation 1582.6). A single-lane boat ramp and about 12 boat docks are maintained by the cabin owners but are designated for public use. Increasing the conservation storage in Lovewell Reservoir may impact some of the private cabins. Although the exact number of cabins to be affected is unknown at this time, an estimate was made based on information provided by the Lovewell State Park manager for the purpose of determining mitigation costs.

The recreation facilities at Lovewell include a marina, leased cabins, approximately 56 trailers, numerous campsites, boat ramps, boat docks, fuel storage and distribution, picnic shelters, shower and restroom facilities, and parking lots. Recreation mitigation costs included in this Study are based on recreation mitigation costs developed as part of the previous 2005 studies.

#### i. Courtland Canal

Constructed from 1949 to 1959, the Courtland Canal system originates at the Superior-Courtland (Guide Rock) Diversion Dam. From the Diversion Dam, located about 17 miles west of Superior, Nebraska, the Courtland Canal flows generally southeast along the west side of the Republican River. About midway along its length, the canal discharges into Lovewell Reservoir which regulates the combined flows of the canal and White Rock Creek. The canal includes 19.7 miles (15.1 miles in Nebraska) of open ditch canal above Lovewell Reservoir with a discharge capacity of 685 cfs and service to 13,445 acres. The lower end of the canal diverts from Lovewell Reservoir and extends southeast to the vicinity of Courtland, Kansas. Below Lovewell Reservoir, the canal includes 21.6 miles of open ditch canal with a discharge capacity of 635 cfs and service available to 29,620 acres.

### b. *Alternative 1B[19] Description – 16,000 AF Expansion of Lovewell Reservoir*

Alternative 1B includes raising the crest elevation of the existing dam and dike embankment sections to elevation 1616.0 and would increase the total reservoir storage capacity by approximately 16,000 AF. The additional storage would be allocated to active conservation storage capacity by raising the top of active conservation pool 4.7 feet from elevation 1582.6 to elevation 1587.3. To maintain the existing flood control storage capacity, the top of the flood control pool would be raised 3.0 feet from elevation 1595.3 to elevation 1598.3. The current reservoir volume above the top of flood control pool elevation 1595.3 would increase from approximately 123,900 AF to approximately 125,500 AF with the dam and dike embankments raised to elevation 1616.0. As a result, existing overtopping risks, that are reported to be relatively low with an annualized failure probability of $7x10^{-6}$, would not be expected to increase significantly as a result of this alternative; however, actual risks would need to be estimated by a risk analysis team based on the results of additional flood routing studies, which is beyond the scope of this Study.

The appraisal level design and cost estimates for increasing the reservoir storage capacity by 16,000 AF include raising the dam crest elevation by 1.5 feet, raising the dike section crest by 3.5 feet, raising the spillway ogee crest by 3.0 feet, and extending the left end of the dike about 100 feet at the new crest elevation.

This alternative includes provisions for winterizing and automating the existing Courtland Canal. In general, winterization involves installing measures to prevent ice formation during the winter. Specifically, this alternative includes a bubbler system for each of the radial gates at the 11 check structures on the Courtland Canal and the canal headworks at the Superior-Courtland (Guide Rock) Diversion Dam in order to allow winter operations of the Canal. The bubbler system would prevent the buildup of ice at the gates, thereby maintaining necessary flow control in the canal during the winter season. The cost estimate for winterization of the canal also includes installing and furnishing power.

The power would also be used to automate the radial gates at 11 check structures and the canal headworks at the Diversion Dam. A local control mode would be used, based on upstream and downstream water depths to control each radial gate. A remote terminal unit (RTU) would provide the control at the individual radial gates. The RTU would consist of a PC-based controller that would receive input regarding gate position and water depth from sensors. The RTU would provide local control of the radial gate based on control algorithms and software. Power would be provided to the RTU to allow the RTU to automatically raise or lower the gates.

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[19] To avoid confusion, the naming/numbering convention used here is consistent with those used in previous reports.

Stilling wells would be installed at the 11 check structures for monitoring the depth upstream and downstream of the radial gate. Stilling wells would be located approximately 50 to 100 feet upstream and 100 to 200 feet downstream of the check structures. A pressure transducer would be placed in each stilling well for water depth measurement. The pressure transducer would transmit water depth data to the RTU. Details, including schematics, are provided in "*Republican River Basin Appraisal-Level Engineering and Cost Estimates on Structural Alternatives*" (August 2014).

### c. *Alternative 1C Description – 25,000 AF Expansion of Lovewell Reservoir*

Alternative 1C includes raising the crest elevation of the existing dam and dike embankment sections to elevation 1617.5 and would increase the total reservoir storage capacity by approximately 25,000 AF. The additional storage would be allocated to active conservation storage capacity by raising the top of active conservation pool 7.0 feet from elevation 1582.6 to elevation 1589.6. To maintain the existing flood control storage capacity, the top of the flood control pool would be raised 4.6 feet from elevation 1595.3 to elevation 1599.9. The current reservoir volume above the top of flood control pool elevation 1595.3 would increase from approximately 123,900 AF to approximately 130,000 AF with the dam and dike embankments raised to elevation 1617.5. As a result, existing overtopping risks, that are reported to be relatively low with an annualized failure probability of $7x10^{-6}$, would not be expected to increase significantly as a result of this alternative; however, actual risks would need to be estimated by a risk analysis team based on the results of additional flood routing studies, which is beyond the scope of this Study.

The appraisal level design and cost estimates for increasing the reservoir storage capacity by 25,000 AF include raising the dam crest elevation by 1.5 feet, raising the dike section crest by 3.5 feet, raising the spillway ogee crest by 4.6 feet, and extending the left end of the dike about 200 feet at the new crest elevation. Details, including schematics, are provided in "*Republican River Basin Appraisal-Level Engineering and Cost Estimates on Structural Alternatives*" (August 2014).

Relocation of an existing Santa Fe railroad line near the left end of the dike section may be necessary for this alternative. Options other than relocating the railroad line could be explored as part of future studies and risk analyses, but were not considered as part of this Study. Specifically, based on available topographic mapping, relocation of the railroad line appears to be necessary in order to join the raised dike embankment crest with the existing grade at the left abutment. While inundation of the railroad line during extreme flood events could potentially be acceptable to both Reclamation and railroad decision-makers, the need to relocate the railroad is assumed to be driven by accepted dam engineering practice to have a uniform dam crest elevation spanning from abutment to abutment. In addition, there would likely be a need to raise or protect the existing

Highway 14 roadway crossing at the upper end of the reservoir. Costs for addressing impacts to the railroad are included in the developed cost estimates for this Study based on historical data and estimator judgment. These impacts would need more detailed evaluation as part of future studies. Costs for raising or protecting the existing Highway 14 roadway crossing were assumed to be a part of the design contingencies allowance since quantities have not been evaluated and defined. Modifications to the existing outlet works are not required.

Similar to Alternative 1B, this alternative would include provisions for winterizing and automating the existing Courtland Canal, and installing monitoring equipment upstream and downstream of the canal's check structures.

### d. *Alternative 1D Description – 35,000 AF Expansion of Lovewell Reservoir*

Alternative 1D includes raising the crest elevation of the existing dam and dike embankment sections to elevation 1619.0 and would increase the total reservoir storage capacity by approximately 35,000 AF. The additional storage would be allocated to active conservation storage capacity by raising the top of active conservation pool 9.4 feet from elevation 1582.6 to elevation 1592.0. To maintain the existing flood control storage capacity, the top of the flood control pool would be raised 6.3 feet from elevation 1595.3 to elevation 1601.6. The current reservoir volume above the top of flood control pool elevation 1595.3 would increase from approximately 123,900 AF to approximately 133,973 AF with the dam and dike embankments raised to elevation 1619.0. As a result, existing overtopping risks, that are reported to be relatively low with an annualized failure probability of $7x10^{-6}$, would not be expected to increase significantly as a result of this alternative; however, actual risks would need to be estimated by a risk analysis team based on the results of additional flood routing studies, which is beyond the scope of this Study.

The appraisal level design and cost estimates for increasing the reservoir storage capacity by 35,000 AF include raising the dam crest elevation by 3.0 feet, raising the dike section crest by 5.0 feet, raising the spillway ogee crest by 6.3 feet, and extending the left end of the dike about 700 feet at the new crest elevation. Details, including schematics, are provided in "*Republican River Basin Appraisal-Level Engineering and Cost Estimates on Structural Alternatives*" (August 2014).

### e. *Engineering Assumptions*

The following engineering assumptions were considered in development of this alternative:

- The existing embankment crest width for the dam can be reduced from 30 feet to 20 feet for the purpose of raising the existing dam crest.

- The spillway radial gates would be removed for concrete placement of the modified (raised) ogee crest and re-installed after placement is completed.

- There would be no change in the operation of the modified spillway. Specifically, the re-installed radial gates would be operated as currently specified in the standing operating procedures relative to the reservoir water level above the new ogee crest elevation.

- Flood overtopping risks as presented in the 2010 Comprehensive Facility Review (CFR) for Lovewell Dam appear to be relatively low with an estimated annualized life loss of $7 \times 10^{-6}$, which is a value well below Reclamation's Public Protection Guidelines. As long as the adjusted reservoir storage volume between the modified top of exclusive flood control pool and the modified dam crest is equal to or greater than the existing storage volume between the existing top of exclusive flood control pool and the existing dam crest, then the overtopping risks would not be expected to significantly increase.

- Static risks for internal erosion of the embankment into the foundation as presented in the 2010 CFR for Lovewell Dam are well below Reclamation's Public Protection Guidelines with an estimated annualized life loss of $6 \times 10^{-5}$. Even with slightly higher seepage gradients, the increased reservoir head would be expected to have a minimal effect on the existing internal erosion risk estimates; however, this assumption would have to be validated by completing a formal team risk analysis. Based on this assumption, it is then further assumed for the purpose of this Study that additional modifications, such as enhancements to the toe drain, are not required to accommodate the increased reservoir water surface elevations associated with these alternatives.

- Water surface profiles to evaluate chute wall overtopping, increase in cavitation potential, and increase in stilling basin sweepout potential are beyond the scope of this Study.

- Potential borrow areas for construction of the raised embankments (dam and dike) would be located within 20 miles of the dam site locations.

- Potential commercial sources for gravel surfacing are assumed to be located within 20 miles of the dam site locations.

- Potential commercial sources for riprap are assumed to be approximately 200 miles (one-way) from the dam site locations.

Costs are summarized in the *Section 7.0: Evaluation of Adaptation Strategies*. Cost estimate worksheets with details are presented in Reclamation's Engineering TM.

## 2. Alternatives 3A and 3B – Swanson Reservoir Augmentation, Nebraska

These alternatives involve augmentation of Swanson Reservoir by taking advantage of existing available storage and diverting water from either Frenchman Creek or the Republican River. In recent years, Swanson Reservoir has consistently had available storage capacity. This alternative would divert water directly from Frenchman Creek (Alt 3A) or just downstream of the confluence of Frenchman Creek and the Republican River (Alt 3B) into Swanson Reservoir when storage space is available. A brief description and illustration of features is below; more detailed information can be found in Reclamation's Engineering TM.

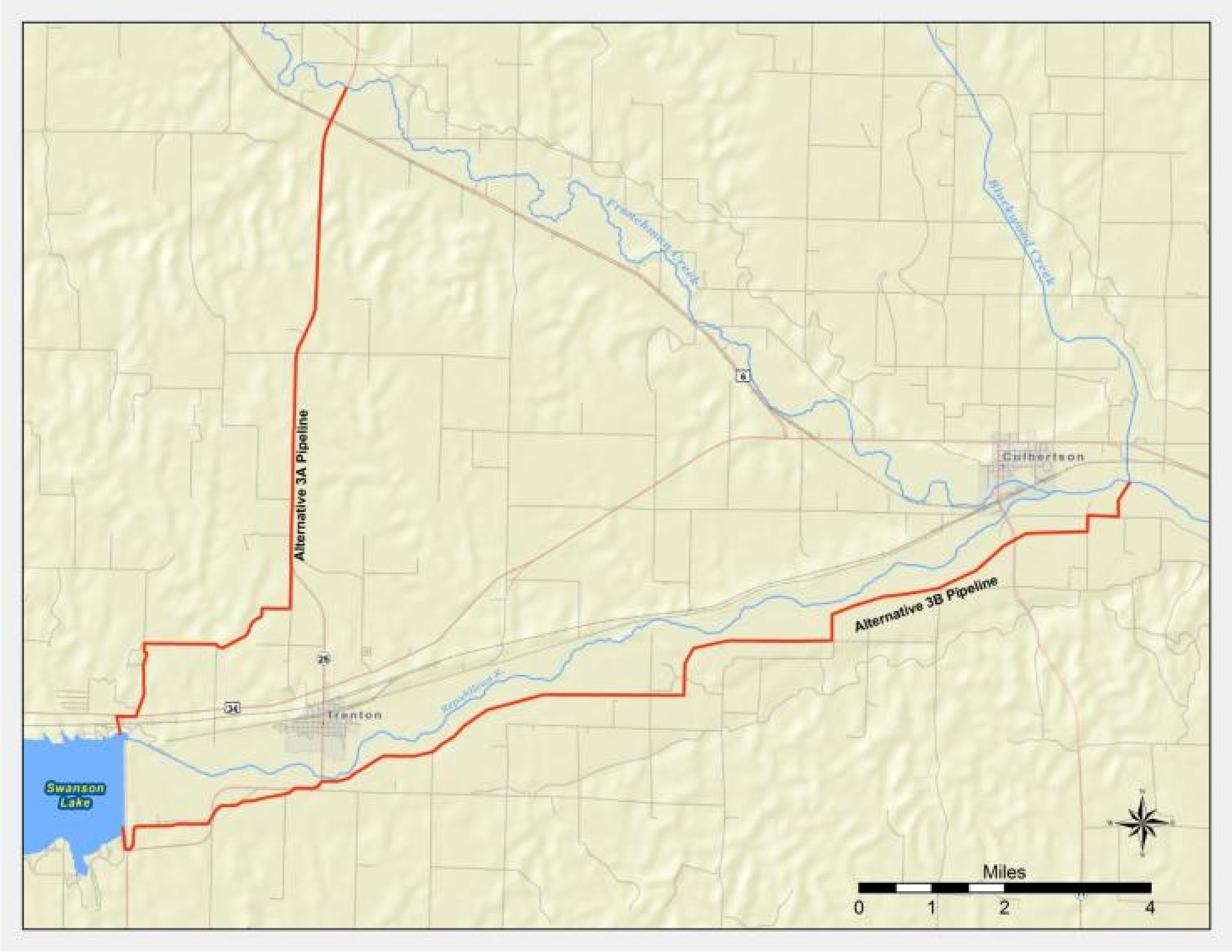


**Figure 56. — Conceptual illustration of Alternatives 3A and 3B, Swanson Reservoir Augmentation.**

### a. *Trenton Dam/Swanson Reservoir*

Trenton Dam, a major feature of the Frenchman-Cambridge Division of the P-SMBP, is located on the Republican River approximately 22 miles west of McCook, Nebraska. Constructed by Reclamation between 1949 and 1953, the dam provides irrigation water storage and flood control for the Republican River. The project also provides incidental benefits for recreation, fish, and wildlife.

Trenton Dam impounds the Republican River to form Swanson Lake. The lake has an active conservation volume of 99,784 AF between elevations 2752.0 and 2720.0, an inactive storage volume of 10,312 AF between elevations 2720.0 and 2710.0, and a dead storage volume of 2,118 AF between elevation 2710.0 and the streambed at elevation 2693.0. The reservoir has an exclusive flood control volume of 134,077 AF between elevations 2773.0 and 2752.0, and a surcharge volume of 107,610 AF between elevations 2785.0 (maximum design reservoir water surface) and 2773.0. Since the project's completion in 1953, reservoir water levels in Swanson Reservoir have never exceeded the top of the exclusive flood control pool elevation 2773.0. The historical maximum reservoir water surface elevation of 2757.4 feet, which occurred on August 3, 1962, only utilized just under 29% of the total exclusive flood control pool volume.

Engineering assumptions used to develop Alternatives 3A & 3B include:

- There are no structural modifications planned for the Trenton Dam embankment as part of these alternatives.
- The existing top of active conservation pool elevation 2752.0, top of exclusive flood control pool elevation 2773.0, and top of dam elevation 2793.0 for Swanson Reservoir will not be changed.
- The maximum design pumping rate for Alternative 3A is 3,000 gallons per minute (gpm) (6.7 cfs).
- The maximum design pumping rate for Alternative 3B is 5,000 gpm (11.1 cfs).
- Pipeline alignments are developed to limit potential impacts to private land owners and, as a result, existing easements associated with county roads will be used, when possible.
- Controlled low-strength material is used for pipe trench backfill.
- For cost estimating purposes, pipe trench excavation is assumed to be 20% in rock and 80% in soil.

- Pumping plant costs are developed using Reclamation historical cost data for pumping plant structures.

- Costs for fish screens are conservatively included in the cost estimates based on historical cost data from previous projects utilizing fish screen structures.

- Winterization for pump-back operations during the non-irrigation season is considered.

Costs are summarized in *Section 7.0: Evaluation of Adaptation Strategies*. Cost estimate worksheets with details are presented in Reclamation's Engineering TM.

### b. *Alternative 3A – New Frenchman Creek Pipeline*

Google Earth software was used to determine the alignment and profile for Alternative 3A. A direct, straight line from Frenchman Creek to Swanson Reservoir had multiple hills and valleys to cross. As a result, the alignment used for this Study paralleled Highway 25 before heading southwest to Swanson Reservoir. This alignment, with a length of 11.3 miles, has fewer hills to cross and is approximately one mile longer than the straight alignment.

The highest point along the alignment is approximately 2.8 miles from the intake. A 50,000 gallon regulating tank (24-foot diameter by 28 feet high) would be required to control the pumps on the hill. The design flow, 3000 gpm (6.7 cfs), would then flow by gravity along the remaining 8.5 miles to the reservoir. The pipe was determined to be 18-inch diameter PVC pipe from the intake pumping plant to the regulating tank. On the gravity side, in order to maintain pressurized pipe over the final hill about 1.5 miles from the reservoir, the pipe design was determined to be 18-inch and 16-inch diameter PVC pipe. The flow is to be controlled prior to entering the reservoir with a 16-inch flow control valve. Since the alignment is above the reservoir water surfaces of both Frenchman Creek and Swanson Reservoir, no dewatering was assumed for the pipeline construction.

Intake and outlet structures would be constructed, and a series of three pumps would be provided to pump up to 6.7 cfs from Frenchman Creek to the pipeline's high point.

A preliminary plan of the pipeline alignment and corresponding profile is shown in the 2014 Engineering TM.

### c. *Alternative 3B – New Republican River Pipeline*

Google Earth software was used to determine the alignment and profile for Alternative 3B. A direct, straight line from the Republican River to Swanson Reservoir crossed multiple farms and fields. As a result, the alignment used for this Study followed the boundaries of the fields, where possible, to minimize the potential difficulties in obtaining right-of-way. This alignment, with a length of 17.4 miles, is approximately two miles longer than the straight alignment.

The alignment is fairly flat with minor high and low points until approaching the reservoir. The design flow of 5,000 gpm (11.1 cfs) would be pumped from the intake to the reservoir. The pipe was determined to be 30-inch PVC pipe. The velocity in the pipe is only estimated to be 2.3 feet per second. As a result, additional hydraulic analyses would be required to determine the minimum velocities required in the pipe to carry the anticipated sediment load of the water and to evaluate the pumping units static to dynamic head limitations. Since the pipeline alignment is below the water surface of Swanson Reservoir, this estimate assumes that 30% of the pipe trench would require dewatering.

Similar to Alternative 3A, intake and outlet structures would be constructed, and a series of three pumps would be provided to pump up to 6.7 cfs from the Republican River to the pipeline's high point.

A preliminary plan of the pipeline alignment and corresponding profile is shown in the 2014 Engineering TM.

### 3. Alternative 5A – New Thompson Creek Dam, Nebraska

This alternative involves construction of a new dam on Thompson Creek, a tributary to the Republican River, and conveying the water to the Franklin Canal for delivery to NBID in exchange for allowing water to be stored in Harlan County Lake. An illustration is provided below.

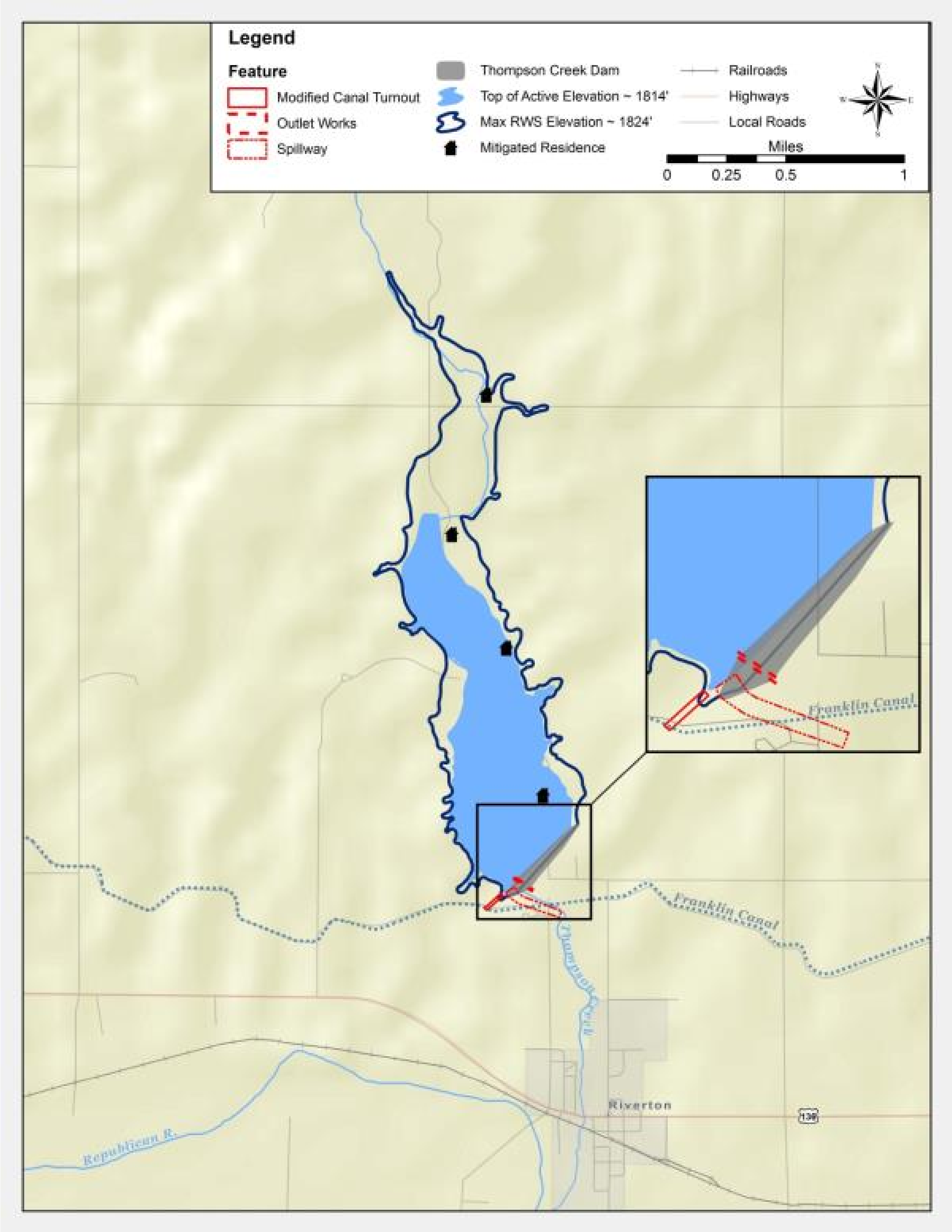


**Figure 57. — Conceptual illustration of Alternative 5A, New Thompson Creek Dam.**

## a. *Franklin Canal*

Constructed from 1952 to 1956 as part of the P-SMBP, Bostwick Division, the Franklin Canal originates at Harlan County Dam. From Harlan County Dam the canal flows generally east along the north side of the Republican River to five miles east of Red Cloud, Nebraska. The canal has a length of approximately 48 miles with a diversion discharge capacity of 230 cfs. The majority of the canal is unlined with a bottom width of 14 feet and 1:5H:1V side slopes.

## b. *Alternative Description*

This alternative involves exchanging water supplies originating downstream of Harlan County Lake for stored water in the reservoir. Multiple sources and infrastructure configurations are possible, but two examples were considered in this Study, one of which (New Beaver Creek Dam) was eliminated from further consideration as previously discussed.

Specifically, Alternative 5A includes development of a 5,000 AF reservoir one mile north of Riverton, Nebraska on Thompson Creek, a tributary to the Republican River. To impound 5,000 AF, a new embankment would need to be constructed about 50 feet high with a crest length of about 2,200 feet. It appears that, based on results of preliminary site studies using the available topography and aerial mapping, locating the new reservoir on the lower reach of Thompson Creek would result in inundating some homes, agricultural lands, roadways, and utilities. Figure 22 in the Engineering TM (Reclamation 2014) presents the preliminary selected dam alignment and approximate inundated areas at the top of active conservation pool and estimated maximum reservoir water surface elevation. Flood storage at the maximum reservoir water surface is about 9,300 AF. A preliminary storage capacity curve also is provided.

Layout and earthwork quantity estimates were completed using the preliminary alignment and dam cross section. A preliminary spillway was sized based on flood routing results using scaled flood frequency hydrographs developed previously by Reclamation for other dams located within the limits of the Republican River Basin. The outlet works, located 400 feet from the right abutment of the dam near the maximum section of the embankment, consists of a reinforced concrete trashracked intake structure, a 48-inch diameter steel conduit encased in reinforced concrete on either side of the gate structure, a 50-foot tall reinforced concrete (wet well) gate structure, and an impact basin type terminal structure. The outlet works gate structure houses two manually operated 48-inch by 48-inch stainless steel sluice gates that control downstream releases. Details of these components are provided in Reclamation 2014.

The Franklin Canal passes the proposed reservoir site less than a ¼-mile downstream of the new dam. To deliver water stored in new Thompson Creek Reservoir to the existing Franklin Canal, a new pumping plant would be required. Specifically, the Franklin Canal currently crosses the Thompson Creek valley via an existing siphon structure. Both the upstream inlet and downstream exit of the siphon are higher in elevation than the top of active pool elevation of Thompson Creek Reservoir. As a result, water must be lifted approximately 50 feet from the reservoir rim to the canal connection point located just upstream of the siphon inlet. To achieve this, three duty pumps and one standby pump would be provided to pump up to 11.1 cfs from the reservoir to the discharge canal. An existing canal turnout adjacent to the proposed new delivery pipe could be modified to allow water deliveries from the canal to the reservoir should this become an advantageous feature for this particular alternative.

Plans and drawings are shown in the Engineering TM (Reclamation 2014).

Engineering assumptions used to develop Alternative 5A include:

- The reservoir water supply volume below top of active conservation pool is 5,000 AF for new Thompson Creek Dam.

- The spillways for the new embankment dams will be sized based on an estimated inflow design flood developed using basin size scaling factors applied to flood frequency hydrographs for existing Reclamation dams in the Republican River watershed and using estimated consequences based on available census data for downstream towns and Lovewell Dam estimated consequences.

- The outlet works are sized in accordance with Reclamation's ACER Technical Memorandum No. 3 – Criteria and Guidelines for Evacuating Storage Reservoirs and Sizing Low-Level Outlet Works.

- Four feet of freeboard between the estimated maximum reservoir water surface elevation and the dam crest is included in the design of the new embankment dams.

- Potential borrow areas for construction of the new embankment dams are located within 20 miles of the dam site location.

- Potential commercial sources for filter sand, drain gravel, riprap bedding and gravel surfacing are located within 20 miles of the dam site location.

- Potential commercial sources for riprap are assumed to be approximately 200 miles (one-way) from the selected dam site location.

- Depth to rock for embankment cutoffs are estimated based on existing available regional geological information. No field investigations have been performed.

Costs are summarized in the *Section 7.0: Evaluation of Adaptation Strategies*. Cost estimate worksheets with details are presented in Reclamation's Engineering TM.

# VIII. Evaluation of Adaptation Strategies

Section 9503(b)(3) of P.L. 111-11 requires a quantitative or qualitative trade-off analysis of the adaptation and mitigation strategies identified. Such analyses are to examine all proposed strategies in terms of (1) their ability to meet study objectives; (2) the extent to which they minimize imbalances between water supply and demand, and address potential impacts of climate change; (3) level of stakeholder support; (4) relative costs; and (5) environmental impacts.

## A. Nebraska Approach

The evaluation of the alternatives was based on several metrics developed to measure, in different ways, the ability of the alternative to help maximize water use and ensure Compact compliance. These metrics included the number of Compact Call Years predicted by the model, reservoir storage levels, irrigation diversions, and diversions made for project-specific purposes. In each case, the metrics as measured under the No Action Alternative were compared with the metrics for the action alternative, for Baseline Climate conditions and for the warmer/drier, central tendency, and less warm/wetter climate scenarios developed by Reclamation. In this way it was possible to consider how well the given alternative improved the metrics, or if they in fact, led to less desirable results than the No Action alternative in some cases.

Regarding Compact compliance, STELLA included a simplified set of calculations used to estimate Nebraska's Compact balance using principles from the RRCA Accounting Procedures. Through the results of modeling, it was determined that these estimates indicated Compact compliance for almost every year, in every alternative (including No Action). For the few instances that indicated a potential negative balance, incorporation of the recently approved accounting changes concerning the consumption of Imported Water Supply (the simplified STELLA accounting estimates did not include this change) would likely result in all these negative balances being shifted to positive balances, with perhaps one or two exceptions out of the entire time horizon for all alternatives. Given this situation, it was determined that a better way to consider Compact accounting considerations was by considering the number of Compact Call Years as an indication of conditions requiring special management actions in order to maintain Compact compliance.

This section includes descriptions of these alternatives, including information on their purposes and objectives, operational considerations, general information on how they would be incorporated into the modeling platforms, and information on what metrics were used to evaluate their effectiveness in meeting management objectives.

## 1. Alternative 3A – Swanson Reservoir Augmentation Via Frenchman Creek Pipeline

### a. *Purpose and Objective*

One of the main objectives for this alternative would involve increasing the water supply reliability for Frenchman-Cambridge Irrigation District (FCID). Increased storage within Swanson Reservoir would potentially be available to FCID irrigators, based on their storage contracts with Reclamation. The additional storage could also be used to assist with Compact compliance efforts, by providing additional supplies that could be made available downstream to the State of Kansas. Recreation interests could also benefit from increased storage levels.

### b. *Changes in Operation*

Pumping from Frenchman Creek would be allowed during the non-irrigation season when Compact Call Year operations were not required. Pumping would be allowed up to the 3,000 gpm (about 13.3 AF/day) limit, or up to the estimated available flow in the river – whichever is less. As a simplification, it was assumed that pumping would be allowed regardless of Harlan County Lake conditions, preventing the reservoir from "calling out" the pumping diversions as might otherwise be expected for a junior water right. This arrangement would require agreements with Reclamation, and potentially other parties, to allow pumping by the project during the non-irrigation season. The additional supplies provided by the pumping operations would also require special consideration with respect to contract obligations with FCID and management of the reservoir pools. While there are many potential ways in which this might be implemented, for the purposes of this Study it was assumed that the new supply would be treated as if it was natural flow entering the reservoir from the mainstem Republican River, and stored for later release as part of the overall FCID supply.

### c. *Model Implementation*

In order to implement the alternative in the STELLA model, a new flow element was added between from the diversion point on Frenchman Creek to Swanson Reservoir. Logic was added such that pumping would occur during the non-irrigation season, in years other than Compact Call Years, up to the lesser of the pipeline capacity or the available flow at the diversion point. Pumping was also not allowed if Swanson Reservoir levels entered the flood pool. The appropriation system logic was altered to allow pumping regardless of Harlan County Lake conditions. Otherwise, the STELLA logic concerning determination of available storage supplies for FCID users was unchanged.

#### d. *Evaluation Metrics*

The metrics used for this alternative included Compact Call Year determinations, annual pump-back diversions, Swanson Lake levels, Harlan County Lake levels, irrigation diversions by the FCID canals, and total NBID irrigation diversions (without the Courtland Canal).

### 2. Alternative 3B – Swanson Reservoir Augmentation Via Republican River Pipeline

#### a. *Purpose and Objective*

The purpose and objective would be identical to that for Alternative 3A.

#### b. *Changes in Operation*

Pumping from Frenchman Creek would be allowed during the non-irrigation season when Compact Call Year operations were not required. Pumping would be allowed up to the 5,000 gpm (about 22 AF/day) limit, or up to the estimated available flow in the river, whichever is less. Otherwise, the changes in operation would be the same as with Alternative 3A.

#### c. *Model Implementation*

In order to implement the alternative in the STELLA model, a new flow element was added between from the diversion point on the Republican River to Swanson Reservoir. Otherwise, the implementation methods were identical to those used in Alternative 3A.

#### d. *Evaluation Metrics*

As with Alternative 3A, the metrics used for this alternative included Compact Call Year determinations, annual pump-back diversions, Swanson Lake levels, Harlan County Lake levels, irrigation diversions by the FCID canals, and total NBID irrigation diversions (without the Courtland Canal).

### 3. Alternative 5A – New Thompson Creek Dam, NE

#### a. *Purpose and Objective*

This alternative, with its corresponding new reservoir and new tie-in with the Franklin Canal, could be used to serve multiple objectives. By drawing from sources downstream of Harlan County Lake, demands for Harlan County releases could be decreased, improving water supply reliability for NBID users. Retaining storage in Harlan County Lake could also assist with Compact compliance activities, by reducing instances of Water-short Year Administration and Compact Call Years, and enhancing supply reliability for KBID as well. Regulating north-side tributary flows would provide flexibility and operational benefits by making it possible to capture high tributary flows during periods of excess, and using those stored supplies when water supplies are scarce and of greater beneficial value. The resulting higher reservoir levels in Harlan County Lake could also benefit recreation uses in the reservoir, while benefiting the community that relies on the economic opportunities provided by Harlan County Lake. Recreational benefits could also be realized for the new smaller dam as well.

### b. *Changes in Operation*

The Thompson Creek Reservoir would store water during the non-irrigation season, for years when Compact Call Year operations were not required, for release to the Franklin Canal during the irrigation season to supplement its supplies. The connection between Thompson Creek Reservoir and the Franklin Canal would be at a point on the canal where about half of Franklin Canal's service area would be above, and half below, the tie-in location. Water delivered to the Franklin Canal from Thompson Creek would reduce the demand for Harlan County releases to Franklin Canal. As with Federal canals, a maximum river release rate would apply (in this case, 833 AF/day, based on a simple evaluation of the historical gage record on the Creek) for all situations unless larger releases were required to prevent overtopping. For simplification, no changes to the contract language between Reclamation and NBID were assumed for operational purposes. The reservoir content did not factor into determinations of available water supply for NBID or KBID. No changes were made to the methodology used in calculations involving the Harlan County Lake Consensus Plan between Reclamation and the USACE (which provides for sharing the decreasing water supply into the lake) or any calculations of Compact accounting balances. In reality, if a new reservoir were to be constructed on Thompson Creek, some or all of these operational arrangements may have to be adjusted to take into account the new storage capacity of the reservoir.

### c. *Model Implementation*

Incorporating the new reservoir into the STELLA model involved several modifications. A new STELLA stock element was added to represent the reservoir, along with new flow elements for both the river release and the pumping release to Franklin Canal. Logic was added to STELLA concerning reservoir operations. An added constraint on reservoir releases to the Franklin Canal prevented releases above those needed to service irrigation demands in the portion of the Franklin Canal's service area below the Thompson Creek connection.

### d. *Evaluation Metrics*

The primary metrics considered for the Thompson Creek Reservoir alternative included Compact Call Years, Franklin Canal diversions/releases from Thompson Creek Reservoir, Thompson Creek Reservoir levels, Harlan County Lake levels, total diversions by all NBID canals except the Courtland Canal (including Franklin Canal), total combined diversions by upstream FCID canals, diversions by the Courtland Canal from the Republican River, Guide Rock flows, and flows in the Courtland Canal at the state line. This wide range of metrics provided several ways to maximize water uses and evaluate Compact compliance.

# B. Nebraska Results

Before discussing the individual alternatives, it is important to note the measurement of Compact compliance, as this was one of the primary modeling objectives for Nebraska. As mentioned earlier, STELLA included a simplified set of calculations used to estimate Nebraska's Compact balance, using principles from the RRCA Accounting Procedures. Through the results of modeling, it was determined that these estimates indicated Compact compliance for almost every year, in every alternative (including No Action). For the few instances that indicated a potential negative balance, incorporation of the recently approved accounting changes concerning the consumption of Imported Water Supply (the simplified STELLA accounting estimates did not include this change) would likely result in all of these negative balances being shifted to positive balances, with perhaps one or two exceptions out of the entire time horizon for all alternatives. Given this situation, it was determined that a better way to consider Compact accounting considerations was by considering the number Compact Call Years as an indication of conditions requiring special management actions in order to maintain Compact compliance.

## 1. Alternative 3A – Swanson Reservoir Augmentation via Frenchman Creek Pipeline

As mentioned earlier, the key metrics used to evaluate Nebraska Alternative 3A (Swanson Reservoir Augmentation via New Frenchman Creek Pipeline) were Compact Call Year determinations, annual pump-back diversions, Swanson Lake levels, Harlan County Lake levels, irrigation diversions by the FCID canals, and total NBID irrigation diversions (without Courtland Canal). The end of this section includes the graphical representations/figures of the STELLA results pertaining to these metrics that are referred to in the discussion below.

### a. *Compact Call Year Determinations*

Information on Compact Call Year determinations for Baseline Climate conditions is included in Figure 58. As shown, Alternative 3A has the same number of Compact Call Years as the No Action Alternative (23), but the years 2034 and 2035 are switched in terms of which is a Compact Call Year. Climate Scenario 1, depicted in Figure 59, shows there were 33 Compact Call Years for both the No Action and Alternative 3A, with all Compact Call Years coinciding.

For Climate Scenario 2, as shown in Figure 60, there were 16 Compact Call Years for the No Action Alternative, and 19 for Alternative 3A. In addition, many of the Compact Call Years did not coincide. Climate Scenario 3 results are shown in

Figure 61, where only one year (2055) is a Compact Call Year for Alternative 3A, with none in the No Action Alternative.

In summary, Alternative 3A has the same number of Compact Call Years as the No Action Alternative under Baseline Climate and Climate Scenario 1 (warmer/drier conditions), and both No Action and Alternative 3A have at or near zero Compact Call Years under Climate Scenario 3 (less warm/wetter conditions). The most significant difference between No Action and Alternative 3A is under Climate Scenario 2 (central tendency climate), where operations under Alternative 3A result in three additional Compact Call Years beyond No Action levels. Overall, the impact of Alternative 3A on the number of Compact Call Years appears to be minimal, and slightly negative. This may be due to increased consumptive use on FCID lands, as described later in this section.

### b. *Annual Pump-back Diversions*

The amount of water pumped from Frenchman Creek into Swanson Lake under Baseline Climate conditions, over a calendar year, is shown in Figure 62. Since the pumps can pump for a maximum of 241 days (242 for leap years), and the pump capacity is about 13.3 AF/day, the maximum pumping amount over a calendar year is about 3,202 AF (3,216 AF for a leap year). As shown in Figure 62, for Baseline Climate conditions, pump-back diversions into Swanson Lake under Alternative 3A always approach maximum pumping levels during years that are not Compact Call Years.

Looking at Figures 63 through 65, similar conditions occur for Climate Scenarios 1 through 3. As long as a Compact Call Year is not in place (refer again to Figures 59 through 61), pump-back levels always approach the maximum pumping volume.

In summary, Alternative 3A pump-back operations are able to pump at or near maximum pumping rates consistently, regardless of climate scenario, for all years that are not Compact Call Years, under the constraints of the 3,000 gpm (13.3 AF/day) pumping limitation.

### c. *Swanson Lake Levels*

Alternative 3A Swanson Lake content is shown in Figure 66 for Baseline Climate conditions. Compared to No Action conditions, Swanson Lake levels are generally higher under Alternative 3A, due to the pump-back operations. There are a few exceptions, such as during calendar year 2034, but this can be explained by the shift in Compact Call Years between the No Action and 3A alternatives (2034 is a Compact Call Year under Alternative 3A, but not under the No Action Alternative). During Compact Call Years, not only are pump-back operations not permitted, but natural flow must also pass through the reservoir without being stored during the non-irrigation season. Reservoir levels on the order of 7,000 AF higher are common during non-Compact Call Years, when comparing Alternative 3A to No Action. This is possible, despite the fact that pumping is limited to around 3,200 AF per/year, since carryover can occur if a portion of the pumped water is not released during the irrigation season.

Under Climate Scenario 1 conditions for Swanson Lake, as shown in Figure 67, similar effects are apparent, with reservoir levels under Alternative 3A higher than the No Action Alternative for years that are not Compact Call Years, again on the order of 7,000 AF in difference. For Climate Scenario 2, shown in Figure 68, the comparison is more complex, largely due to the differences in Compact Call Years between Alternative 3A and No Action under these climate conditions. Focusing on the period prior to 2023, when Compact Call Years began to differ, the general trend of higher lake levels for Alternative 3A is apparent, as it is during later years when Compact Call Years, and non-Compact Call Years, are common between Alternative 3A and the No Action Alternative.

For Climate Scenario 3, as shown in Figure 69, the same pattern of higher levels under Alternative 3A continues, but there are several years in which levels reach the flood pool elevation, and flood releases cap off the level of the reservoir and hide differences between the alternative and No Action. The effects of the Compact Call Year in 2055 under Alternative 3A are also apparent, as lake levels drop considerably compared to No Action, which does not experience a Compact Call Year that year.

In summary, Swanson Lake levels are consistently higher under Alternative 3A than for the No Action Alternative for those years in which Compact Call Years do not preclude pump-back operations (or require pass-through of natural flow). Reservoir content is on the order of 7,000 AF greater during periods of consistent Compact Call Year status, unless levels are high enough so that flood pool operations come into play, as occurs periodically under Climate Scenario 3.

### d. *Harlan County Lake Levels*

Differences in Harlan County Lake levels between Alternative 3A and the No Action Alternative are more difficult to identify than with Swanson Lake levels, in part due to the larger capacity of Harlan County Lake relative to the pumping levels. Figure 70 shows Harlan County Lake content for Alternative 3A compared to No Action. As shown, it is often difficult to discern any major differences, although there are periods, such as 2041, when it is more apparent that levels are lower under Alternative 3A. This may be due to the fact that flows that otherwise may reach Harlan County Lake are being intercepted at the pump site, and brought back to Swanson Lake, where they may later be diverted by upstream FCID users for irrigation use. The shift in Compact Call Years between 2034 and 2035 is again apparent as well.

For the Climate 1 Scenario, shown in Figure 71, the differences in lake levels are even more difficult to see. However, close inspection in years such as 2025, when Compact Call Years are not in effect in either the No Action Alternative or Alternative 3A, reveals that Harlan County Lake levels are slightly lower, by a few thousand AF, under Alternative 3A. The same observation is true under Climate 2 conditions, as shown in Figure 72, and under Climate 3 conditions, depicted in Figure 73: for common non-Compact Call Years, Harlan County Lake levels are slightly lower under Alternative 3A than with the No Action Alternative. Figure 73 also shows the effects of flood pool operations, as content rarely exceeds the top of the irrigation pool. One notable exception is the content level during 2012, when very large inflows required temporary flood storage to prevent excessive downstream high flows.

In summary, Harlan County Lake levels are slightly lower under Alternative 3A than under No Action conditions during years in which both alternatives share a common Compact Call Year status. The difference in storage content for those years appears to be on the order of a few thousand AF. This difference may be attributable to increased diversion and consumptive use on FCID irrigated lands, as described below.

### e. *FCID Irrigation Diversions*

Figure 74 shows the sum of irrigation diversions for all FCID canals under Baseline Climate conditions, including under the No Action Alternative and Alternative 3A. Across many of the years, FCID diversions are slightly higher under Alternative 3A than No Action, by a few thousand AF. There are several complex timing effects involved when comparing the No Action against the alternative condition in this case. Part of this is due to the delayed impacts to Swanson Reservoir from the non-irrigation season pumping. For example, while pump-back operations take place during 2011, the first modeled year, FCID diversions are basically the same under the alternative for that year, since Swanson Lake supplies were only beginning to be supplemented by the pump-back flows. The year 2012, however, does show higher FCID diversions under Alternative 3A. High Swanson Lake levels also may preclude pump-back operations at times, or may reach levels high enough that the additional pump-back water does not lead to changes in the calculations for available irrigation supply or for the number of irrigated acres.

The general responses seen under Baseline Climate conditions also apply to the climate scenarios. Figure 75 shows that under the warmer/drier Climate Scenario 1, FCID diversions are usually slightly higher for Alternative 3A than the No Action Alternative during the year after a non-Compact Call Year, due to the delayed benefits of the pump-back operations. During stretches of Compact Call Years, there is virtually no difference between No Action and Alternative 3A FCID diversions. For Climate Scenario 2, as shown in Figure 76, the comparison is again more complex due to offsets in the Compact Call Years between the No Action Alternative and Alternative 3A. Careful examination still shows the delayed benefits through the pump-back operations, on the order of a few thousand AF. For Climate Scenario 3, shown in Figure 77, there are only a few years when differences in FCID diversion are apparent between No Action and Alternative 3A – despite pump-back operations occurring at near maximum levels for all years except 2055. In these instances, the available water supplies in storage were high enough for both the No Action Alternative and Alternative 3A conditions that, in both cases, the regression predicting the number of irrigated acres in FCID suggested maximum levels. This resulted in equal NIR demands, which were met in both situations by equal levels of canal diversions.

One additional issue concerning the FCID diversions involves the overall impact of consumptive use in the Basin on Compact accounting and the distribution of Basin water supplies. Since operations under Alternative 3A often lead to increased irrigation diversions by FCID canals, compared to No Action diversion levels, the resulting increase in consumptive use appears to have an adverse impact to inflows into Harlan County Lake downstream. The slightly lower Harlan County Lake levels that result are likely the cause for there being a few additional Compact Call Years under Alternative 3A than the No Action Alternative for Climate Scenarios 2 and 3.

In summary, Alternative 3A produces slightly higher FCID diversions compared to No Action conditions over the 50-year time horizon for Baseline Climate conditions, and under the alternative climate scenarios. Climate Scenario 3 shows the smallest impacts due to the overall abundance of available stored water supplies, and maximization of irrigated acres.

### f. *NBID Irrigation Diversions*

While the pump-back operations under Alternative 3A are designed to enhance water supplies for the FCID canals, there could also be impacts downstream to NBID water users. Figure 78 shows projected NBID diversions (for all NBID canals except Nebraska's portion of Courtland Canal) for Baseline Climate conditions, and includes the No Action Alternative and Alternative 3A results. As shown, the differences from No Action are usually small, but tend to be negative impacts on the order of a few thousand AF. The connection between the Compact Call Years and the years in which greater differences appear between No Action and Alternative 3A is not as strong as with diversions to upstream FCID users, but a delayed response resulting from lower Harlan County Lake levels is discernable.

Turning to Climate Scenario 1 in Figure 79, there is a mix of small changes to diversions in some years – mostly small decreases compared to No Action, but including a few small increases such as in 2030. Overall there seems to be a slight reduction in diversions under Alternative 3A when compared to the No Action Alternative. As usual, it is difficult to discern the pump-back impacts for Climate Scenario 2 (see Figure 80) due to the changes in Compact Call Years relative to those under No Action conditions. However, the overall trend again points to slightly lower NBID diversions resulting from the pump-back operations. For the less warm/wetter Climate Scenario 3 conditions, shown in Figure 81, even the overall impact is difficult to interpret, as diversions are slightly higher, and slightly less, depending on the particular year, when comparing No Action to the action alternative. As with FCID diversions under the wet climate scenario, small changes to water supply during periods of abundant reservoir storage appear to result in small differences in NBID diversions between the No Action Alternative and Alternative 3A.

In summary, under Baseline Climate and Climate Scenarios 1 and 2, there appears to be a negative impact – on the order of a few thousand AF – to NBID diversions under Alternative 3A when compared to the No Action Alternative. Under Climate Scenario 3, the impact is particularly difficult to discern. In general, there appears to be a small negative impact to NBID resulting from increased consumptive use on the FCID irrigated acres upstream.

In terms of whether Alternative 3A meets or exceeds its purpose and objectives, there were mixed findings. From the perspective of increasing the water supply reliability for FCID, the results indicate that there would likely be additional diversions made by the FCID canals as a result of the pump-back operations. Swanson Lake levels also would benefit from the new supply of water from Frenchman Creek. However, in terms of Compact compliance efforts, there may be a slight negative impact, largely due to a slight decrease in inflows to, and storage levels in, Harlan County Lake. A small increase in the number of Compact Call Years may be expected under Alternative 3A. In addition, there appears to be a tradeoff in terms of FCID and NBID water supplies, as NBID diversions may decrease slightly under the alternative.

Other lessons learned through the evaluation of Alternative 3A include a potential for considering different configurations of the alternative. It is very clear from the results that the pumping level of 3,000 gpm could be increased, since pump-back operations were almost always able to operate at full capacity for those years in which pumping was allowed. Higher pumping levels would also make it easier to evaluate the impacts from pump-back operations, since the relatively small impacts under the current pumping capacity are sometimes difficult to tease from the model output. However, it is likely that the impacts would be greater – both positive and negative – under higher pumping levels. In addition, there may be alternate ways in which to manage the pump-back operations, and storage of the new supplies in Swanson Lake. Information produced by FCID[20] suggested operations in which Swanson Lake storage releases would be made for storage in Harlan County Lake, instead of for consumptive use by FCID users. The Alternative 3A results provide helpful information on some of the operational and modeling considerations that would be required for a Swanson Lake pump-back project, and alternative configurations could be considered in the future, building on these initial findings.

[20] Frenchman-Cambridge Irrigation District, Swanson Reservoir Pumpback Project, April 20, 2012 PowerPoint by Brad Edgerton, accessed on May 30, 2015 at www.fcidwater.com/Swanson Project/Swanson Project.pdf

## 2. Alternative 3B – Swanson Reservoir Augmentation via Republican River Pipeline

As with Alternative 3A, the key metrics used to evaluate Nebraska Alternative 3B (Swanson Reservoir Augmentation via New Republican River Pipeline) were Compact Call Year determinations, annual pump-back diversions, Swanson Lake levels, Harlan County Lake levels, irrigation diversions by the FCID canals, and total NBID irrigation diversions (without Courtland Canal). This section includes graphical representations of the STELLA results pertaining to these metrics.

### a. *Compact Call Year Determinations*

Information on Compact Call Year determinations for Baseline Climate conditions is included in Figure 58. As shown, Alternative 3B has the same number of Compact Call Years as the No Action Alternative (23), but the years 2033 and 2034 are switched in terms of which is a Compact Call Year. Climate Scenario 1, depicted in Figure 59, shows there were 33 Compact Call Years for both the No Action and Alternative 3B, with all Compact Call Years coinciding.

For Climate Scenario 2, as shown in Figure 60, there were 16 Compact Call Years for the No Action Alternative, and 18 for Alternative 3B. In addition, several of the Compact Call Years did not coincide. Climate Scenario 3 results are shown in Figure 61, where there are no Compact Call Years for either Alternative 3B or the No Action Alternative.

In summary, Alternative 3B has the same number of Compact Call Years as the No Action Alternative under Baseline Climate and Climate Scenario 1 (warmer/drier conditions), and both No Action and Alternative 3B have zero Compact Call Years under Climate Scenario 3 (less warm/wetter conditions). The most significant difference between No Action and Alternative 3B is under Climate Scenario 2 (central tendency climate), where operations under Alternative 3B result in two additional Compact Call Years beyond No Action levels. Overall, the impact of Alternative 3B on the number of Compact Call Years appears to be minimal, and slightly negative. This may be due to increased consumptive use on FCID lands, as was suggested for Alternative 3A.

### b. *Annual Pump-back Diversions*

The amount of water pumped from Frenchman Creek into Swanson Lake under Baseline Climate conditions, over a calendar year, is shown in Figure 62. Since the pumps can pump for a maximum of 241 days (242 for leap years), and the pump capacity is about 22.0 AF/day, the maximum pumping amount over a calendar year is about 5,306 AF (5,329 AF for a leap year). As shown in Figure 62, for Baseline Climate conditions, pump-back diversions into Swanson Lake under Alternative 3B always approach maximum pumping levels during years that are not Compact Call Years.

Looking at Figures 63 through 65, similar conditions occur for Climate Scenarios 1 through 3. As long as a Compact Call Year is not in place (refer again to Figures 59 through 61), pump-back levels always approach the maximum pumping volume.

In summary, Alternative 3B pump-back operations are able to pump at or near maximum pumping rates consistently, regardless of climate scenario, for all years that are not Compact Call Years, under the constraints of the 5,000 gpm (22.0 AF/day) pumping limitation.

### c. *Swanson Lake Levels*

Alternative 3B Swanson Lake content is shown in Figure 66 for Baseline Climate conditions. Compared to No Action conditions, Swanson Lake levels are generally higher under Alternative 3B, due to the pump-back operations. There are a few exceptions, such as during calendar year 2034, but this can be explained by the shift in Compact Call Years between the No Action and 3B alternatives (2034 is a Compact Call Year under Alternative 3B, but not under the No Action Alternative). During Compact Call Years, not only are pump-back operations not permitted, but natural flow must also pass through the reservoir without being stored during the non-irrigation season. Reservoir levels on the order of 10,000 AF higher are common during non-Compact Call Years, when comparing Alternative 3B to No Action. This is possible, despite the fact that pumping is limited to around 5,300 AF per/year, since carryover can occur if a portion of the pumped water is not released during the irrigation season. The pumping differences are slightly greater than those between No Action and Alternative 3A (pump-back from Frenchman Creek), which is understandable given the higher pumping levels under Alternative 3B versus Alternative 3A.

Turning to Climate Scenario 1 conditions for Swanson Lake, as shown in Figure 67, similar effects are apparent, with higher reservoir levels under Alternative 3B than the No Action Alternative for years that are not Compact Call Years – again on the order of 10,000 AF in difference. For Climate Scenario 2, shown in Figure 68, the comparison is more complex, largely due to the differences in Compact Call Years between Alternative 3B and No Action under these climate conditions. Focusing on the period prior to 2023, when Compact Call Years began to differ, the general trend of higher lake levels for Alternative 3B is apparent, as it is during later years when Compact Call Years and non-Compact Call Years are common between Alternative 3B and the No Action Alternative.

For Climate Scenario 3, as shown in Figure 69, the same pattern of higher levels under Alternative 3B continues, but there are several years in which levels reach the flood pool elevation, and flood releases cap off the level of the reservoir and hide differences between the alternative and No Action.

In summary, Swanson Lake levels are consistently higher under Alternative 3B than for the No Action Alternative for those years in which Compact Call Years do not preclude pump-back operations (or require pass-through of natural flow). Reservoir content is on the order of 10,000 AF greater during periods of consistent Compact Call Year status, unless levels are high enough so that flood pool operations come into play, as occurs periodically under Climate Scenario 3.

### d. *Harlan County Lake Levels*

Differences in Harlan County Lake levels between Alternative 3B and the No Action Alternative are more difficult to identify than with Swanson Lake levels, in part due to the larger capacity of Harlan County Lake relative to the pumping levels. Figure 70 shows Harlan County Lake content for Alternative 3B compared to No Action. As shown, it is often difficult to discern any major differences, although there are periods, such as 2041, when it is more apparent that levels are lower under Alternative 3B. This may be due to the fact that flows that otherwise may reach Harlan County Lake are being intercepted at the pump site, and brought back to Swanson Lake, where they may later be diverted by upstream FCID users for irrigation use. The shift in Compact Call Years between 2033 and 2034 is again apparent as well.

For the Climate Scenario 1, shown in Figure 71, the differences in lake levels are even more difficult to see. However, close inspection in years such as 2025, when Compact Call Years are not in effect in either the No Action Alternative or Alternative 3B, reveals that Harlan County Lake levels are slightly lower, by a few thousand AF, under Alternative 3B. The same observation is true under Climate Scenario 2 conditions, as shown in Figure 72, and under Climate Scenario 3 conditions, depicted in Figure 73: for common non-Compact Call Years, Harlan County Lake levels are slightly lower under Alternative 3B than with the No Action Alternative. Figure 74 also shows the effects of flood pool operations, as content rarely exceeds the top of the irrigation pool. One notable exception is the content level during 2012, when very large inflows required temporary flood storage to prevent excessive downstream high flows.

In summary, Harlan County Lake levels are slightly lower under Alternative 3B than under No Action conditions during years in which both alternatives share a common Compact Call Year status. The difference in content for those years appears to be on the order of a few thousand AF, and slightly more than the difference for Alternative 3A. This difference may be attributable to increased diversion and consumptive use on FCID irrigated lands.

### e. *FCID Irrigation Diversions*

Figure 74 shows the sum of irrigation diversions for all FCID canals under Baseline Climate conditions, including under the No Action Alternative and Alternative 3B. Across many of the years, FCID diversions are slightly higher under Alternative 3B than No Action, by a few thousand AF. As is the case with Alternative 3A, part of this is due to the delayed impacts to Swanson Reservoir from the non-irrigation season pumping. High Swanson Lake levels also may preclude pump-back operations at times, or may reach levels high enough that the additional pump-back water does not lead to changes in the calculations for available irrigation supply or for the number of irrigated acres.

The general responses seen under Baseline Climate conditions also apply to the climate scenarios. Figure 75 shows that under the warmer/drier Climate Scenario 1, FCID diversions are usually higher for Alternative 3B than the No Action Alternative during the year after a non-Compact Call Year, due to the delayed benefits of the pump-back operations. During stretches of Compact Call Years, there is virtually no difference between No Action and Alternative 3B FCID diversions. For Climate Scenario 2, as shown in Figure 76, the comparison is again more complex due to offsets in the Compact Call Years between the No Action Alternative and Alternative 3B. Careful examination still shows the delayed benefits through the pump-back operations, on the order of a few thousand AF (and usually, but not always, a few thousand AF of diversions greater than the level obtained under Alternative 3A). For Climate Scenario 3, shown in Figure 77, there are only a few years when differences in FCID diversion are apparent between No Action and Alternative 3B – despite pump-back operations occurring at near maximum levels for all years (see Figure 65). In these instances, the available water supplies in storage were high enough for both the No Action Alternative and Alternative 3B conditions that, in both cases, the regression predicting the number of irrigated acres in FCID suggested maximum levels. This resulted in equal NIR demands, which were met in both situations by equal levels of canal diversions.

As was the case with Alternative 3A, operations under Alternative 3B often lead to increased irrigation diversions by FCID canals, compared to No Action diversion levels. The resulting increase in consumptive use appears to have an adverse impact to inflows into Harlan County Lake downstream. The slightly lower Harlan County Lake levels that result are likely the cause for there being a few additional Compact Call Years under Alternative 3B than the No Action Alternative for Climate Scenario 2.

In summary, Alternative 3B produces generally higher FCID diversions compared to No Action conditions over the 50-year time horizon for Baseline Climate conditions, and under the alternative climate scenarios. Climate Scenario 3 shows the smallest impacts due to the overall abundance of available stored water supplies, and maximization of irrigated acres.

#### f. *NBID Irrigation Diversions*

While the pump-back operations under Alternative 3B are designed to enhance water supplies for the FCID canals, there could also be impacts downstream to NBID water users. Figure 78 shows projected NBID diversions (for all NBID canals except Nebraska's portion of Courtland Canal) for Baseline Climate conditions, and includes the No Action Alternative and Alternative 3B results. As shown, the differences from No Action are usually small, but tend to be negative impacts on the order of a few thousand AF. The connection between the Compact

Call Years and the years in which greater differences appear between No Action and Alternative 3B is not as strong as with diversions to upstream FCID users, but a delayed response resulting from lower Harlan County Lake levels is discernable.

Turning to Climate Scenario 1 in Figure 79, there is a mix of small changes to diversions in some years – mostly small decreases compared to No Action, but including a few small increases such as in 2041. Overall there seems to be a slight reduction in diversions under Alternative 3B when compared to the No Action Alternative. As usual, it is difficult to discern the pump-back impacts for Climate Scenario 2 (see Figure 80) due to the changes in Compact Call Years relative to those under No Action conditions. However, the overall trend again points to slightly lower NBID diversions resulting from the pump-back operations. For the less warm/wetter Climate Scenario 3 conditions, shown in Figure 81, even the overall impact is difficult to interpret, as diversions are slightly higher, and slightly less, depending on the particular year, when comparing No Action to the action alternative. As with FCID diversions under the wet climate scenario, small changes to water supply during periods of abundant reservoir storage appear to result in small differences in NBID diversions between the No Action Alternative and Alternative 3B.

In summary, under Baseline Climate and Climate Scenarios 1 and 2, there appears to be a negative impact – on the order of a few thousand AF – to NBID diversions under Alternative 3B when compared to the No Action Alternative. The impact also appears to be of a slightly higher magnitude than that observed for Alternative 3A, which is understandable given the higher pumping capacity under Alternative 3B. Under Climate Scenario 3, the impact is particularly difficult to discern. In general, there appears to be a small negative impact to NBID resulting from increased consumptive use on the FCID irrigated acres upstream.

In terms of whether Alternative 3B meets or exceeds its purpose and objectives, the results point, as they did for Alternative 3A, to a mixed decision. From the perspective of increasing the water supply reliability for FCID, the results indicate that there would likely be additional diversions made by the FCID canals as a result of the pump-back operations. Swanson Lake levels also would benefit from the new supply of water from Frenchman Creek. However, in terms of Compact compliance efforts, there may be a slight negative impact, largely due to a slight decrease in inflows to, and storage levels in, Harlan County Lake. A small increase in the number of Compact Call Years may be expected under Alternative 3B, although less than under Alternative 3A. In addition, there appears to be a tradeoff in terms of FCID and NBID water supplies, as NBID diversions may decrease slightly under the alternative.

As was the case with Alternative 3A, it is very clear from the results that the pumping level of 5,000 gpm could be increased, since pump-back operations were almost always able to operate at full capacity for those years in which pumping was allowed. Higher pumping levels would also make it easier to evaluate the impacts from pump-back operations, since the relatively small impacts – although usually greater than those under Alternative 3A – are sometimes difficult to tease from the model output. However, it is likely that the impacts would be greater – both positive and negative – under higher pumping levels. The same alternative management techniques that could be considered for Alternative 3A, including different uses of the water stored in Swanson Lake from pump-back operations, also apply to Alternative 3B.

## 3. Alternative 5A – New Thompson Creek Dam

The key metrics used to evaluate Nebraska Alternative 5A (New Thompson Creek Dam) were Compact Call Year determinations, Franklin Canal diversions/releases from Thompson Creek Reservoir, Thompson Creek Reservoir levels, Harlan County Lake levels, total diversions by all NBID canals except Courtland Canal (including Franklin Canal), total combined diversions by upstream FCID canals, diversions by the Courtland Canal from the Republican River, Guide Rock flows, and flows on the Courtland Canal at the state line. This section includes graphical representations of the STELLA results pertaining to these metrics.

Before beginning the discussion on the evaluation of the alternative, it should be mentioned that an error was recently noted in the STELLA model with respect to the maximum capacity of the proposed Thompson Creek Reservoir. While the engineering specifications produced by Reclamation indicated a maximum capacity of about 9,300 AF, the capacity constraint in STELLA was inadvertently set at 7,167 AF. This error should have minor effects on the overall alternative evaluation, since it would only come into play during flood operations when water in the flood pool is evacuated as quickly as possible.

### a. *Compact Call Year Determinations*

Information on Compact Call Year determinations for Baseline Climate conditions is included in Figure 58. As shown, Alternative 5 has the same number of Compact Call Years as the No Action Alternative (23), but the years 2033 and 2034 are switched in terms of which is a Compact Call Year. Climate Scenario 1, depicted in Figure 59, shows there were 33 Compact Call Years for both the No Action and Alternative 5, with all Compact Call Years coinciding. Similarly, for Climate Scenario 2, as shown in Figure 60, there were 16 Compact Call Years for both the No Action Alternative and Alternative 5, with all Compact Call Years coinciding. Climate Scenario 3 results are shown in Figure 61, with no Compact Call Years in either the No Action Alternative or Alternative 5.

In summary, Alternative 5 has the same number of Compact Call Years as the No Action Alternative under the Baseline Climate and all three Climate Scenarios. The only difference in all instances was in 2033 and 2034 for the Baseline Climate, where the Compact Call Years were switched between the No Action

Alternative and Alternative 5. Overall, there appears to be little to no impact on Compact Call Year determinations resulting from Alternative 5 operations.

### b. *Franklin Canal Diversions/Releases from Thompson Creek Reservoir*

Figure 86 shows Baseline Climate Scenario results for Alternative 5 with respect to Franklin Canal Diversions. Under the No Action Alternative, the only source for Franklin Diversions is from Harlan County Lake releases of Republican River water via the outlet structure to Franklin Canal. Under Alternative 5, water can also be diverted to Franklin Canal via the pipeline from Thompson Creek Reservoir. Figure 86 shows all these elements for Baseline Climate conditions. As shown, total Franklin Canal diversions are consistently higher under Alternative 5 conditions compared to No Action conditions, except for 2034 – which was the single year in which Compact Call Year administration was in place in the Alternative 5 conditions but not in No Action conditions. For all other years, total Franklin Canal diversions with the pipeline from Thompson Creek Reservoir were always greater than or equal to Franklin Canal diversions under No Action.

Besides total diversions, Figure 86 also shows diversions from Thompson Creek Reservoir. For those years in which pipeline releases are made from the new reservoir, the amounts range from about 550 AF/year to a maximum of 2,035 AF/year. The capacity of the pipeline is 11.1 cfs, or about 22.0 AF/day. Since the irrigation season used for these purposes in STELLA varies from year to year, depending on the first day of positive crop NIR, the annual capacity of the pipeline also varies. However, assuming a 125-day irrigation season as an upper limit, the maximum capacity of the pipeline would be about 2,750 AF/year. In terms of the years in which Franklin Canal diversions from Thompson Creek Reservoir do or do not take place, there are several variables involved. One is the storage available in Thompson Creek Reservoir (described below). Compact Call Years determine when Thompson Creek Reservoir can store water, but not when it can release water already stored. Another factor is the storage available at Harlan County Lake. For example, if supplies in Harlan County Lake are so low that the regression determining the number of acres planted (and irrigated) within the Franklin Canal service area suggests zero acres, then no diversions to the Franklin Canal would occur. This is the case for 2021 through 2023 under Baseline Climate conditions. While there is water available in Thompson Creek Reservoir for release, no acres were planted within the Franklin Canal service area for those years. This may suggest an opportunity to either modify the regression or to modify the calculation of available storage supplies with respect to the Franklin Canal.

Also of note is the amount of diversions from Harlan County Lake (Republican River) under Alternative 5 versus No Action. Compared to No Action conditions, releases from Harlan County Lake to the Franklin Canal are lower under

Alternative 5. This indicates a benefit to Harlan County Lake, discussed further later, generated from the new supply source for Franklin Canal.

Results for Climate Scenarios 1, 2, and 3 are shown in Figures 87, 88, and 89, respectively. The same principles that applied to Baseline Climate conditions also apply to these climate scenarios, with total Franklin Canal diversions being higher under Alternative 5 than No Action conditions, and releases from Harlan County Lake to Franklin Canal lower under Alternative 5 than under the No Action Alternative. Maximum releases to Franklin Canal from Thompson Creek are a little over 2,000 AF/year for all three climate scenarios, with average releases slightly over 1,200 AF/year for those years when releases to Franklin Canal from Thompson Creek Reservoir occur. The number of years in which releases from Thompson Creek to Franklin Canal can be made also increase under wetter climate scenarios, which is evident in comparing Figure 89 to Figure 91.

In summary, total Franklin Canal diversions are consistently higher under Alternative 5 than under No Action conditions, due to the new source of water supply from Thompson Creek. Releases to Franklin Canal from Harlan County Lake decrease under the alternative, as the Thompson Creek water serves as a substitute for Republican River water from Harlan County Lake. These general principles apply across all climate scenarios.

### c. *Thompson Creek Reservoir Levels*

Figure 90 shows a composite graph, for Baseline Climate and all three climate scenarios, showing predicted Thompson Creek Reservoir levels. The individual climate scenarios (including Baseline Climate) are depicted separately in Figures 91 through 94. Focusing first on Baseline Climate conditions, Figure 91 shows the varying storage content in Thompson Creek Reservoir over time. The cyclical nature of the graph shows the changes to reservoir volume created by storage of Thompson Creek flows during the non-irrigation season, and releases made to the Franklin Canal and Thompson Creek during the irrigation season. It is also apparent that the reservoir is able to fill up to the top of its conservation pool (5,000 AF total storage) every year during which storage is allowed (non-Compact Call Years). For Compact Call Years, as shown in Figure 58, reservoir levels steadily fall as evaporation and releases to the Franklin Canal reduce the storage content. This is particularly apparent in periods such as 2034 through 2039.

Similar effects can be seen under Climate Scenarios 1 through 3, as depicted in Figures 92 through 94, respectively. Average storage volumes are highest under the wetter Climate Scenario 3 and lowest under Climate Scenario 1, as would be expected. Under Climate Scenario 3, storage volumes during most years rise to the maximum capacity level, suggesting that a larger reservoir size could be preferable for this location under wetter climate conditions. This effect may be exacerbated by the inadvertently smaller maximum capacity value used in the STELLA model, as described earlier in this document. However, since the

STELLA logic requires that water be released from the flood pool as soon as possible, with the constraint of the maximum release rate, the impacts of the error are likely minimal.

In summary, Thompson Creek Reservoir volumes show expected seasonal variations across the climate scenarios, as water is stored during the non-irrigation season for non-Compact Call Years and released during the irrigation season for Franklin Canal (and to Thompson Creek as needed). The effect of Compact Call Years is clearly visible, as reservoir levels steadily decline in those periods. The results also suggest that a larger reservoir size – both in terms of conservation/irrigation pool and flood pool – could be beneficial.

### d. *Harlan County Lake Levels*

Baseline Climate Harlan County Lake content is shown in Figure 95, comparing Alternative 5 to the No Action Alternative. The most obvious difference is that during 2033 and 2034, which corresponds to the years in which Compact Call Years were "switched" between No Action and Alternative 5. Otherwise, careful inspection shows that there are multiple periods throughout the 50-year period when Harlan County Lake levels are slightly higher – on the order of a few thousand AF – for Alternative 5 than for the No Action Alternative. This is consistent with the expected impacts from Thompson Creek serving as a substitute supply to Harlan County Lake. In fact, in comparing the timing of when Harlan County Lake levels under Alternative 5 slightly exceed those of the No Action Alternative, such as the 2012 to 2020 period; those conditions coincide almost exactly with the period of releases from Thompson Creek Reservoir to Franklin Canal shown in Figure 96.

These same principles apply to Climate Scenarios 1 through 3, shown in Figures 96 through 98, respectively. The years of Compact Call Years between the No Action Alternative and Alternative 5 match exactly across all three climate scenarios, which makes it easier to compare impacts. The differences still require careful examination, due to the relatively small difference in overall Harlan County Lake content between No Action and the alternative, but the years in which higher Harlan County Lake levels occur for Alternative 5 than for the No Action Alternative continue to correspond to the years in which Thompson Creek Reservoir releases are made to Franklin Canal. The differences are more numerous under Climate Scenario 2 than under Climate Scenario 1, since pumping from Thompson Creek Reservoir also occurs more often. While pumping occurs most often under Climate Scenario 3 (as shown in Figure 99), since there are no Compact Call Years, the impacts to Harlan County Lake, shown in Figure 98, are muted when levels reach the flood pool and flood operations in STELLA require rapid evacuation of excess storage.

In summary, Harlan County Lake levels are slightly higher – on the order of a few thousand AF – for many years under Alternative 5 than they are under the No Action Alternative, for all climate scenarios (including Baseline Climate). These years are highly correlated to the years in which releases from Thompson Creek Reservoir are made to Franklin Canal. This indicates a tangible benefit to Harlan County Lake from substitute Thompson Creek supplies being applied to Franklin Canal irrigated acres.

### e. *Total NBID Diversions (Excluding Courtland Canal)*

Diversions from NBID canals are also impacted by Thompson Creek Reservoir under Alternative 5. For this metric, Nebraska's portion of the Courtland Canal has been excluded to simplify the modeling analysis and because of the relatively small number of acres serviced by that portion of the canal. Figure 99 compares NBID diversions under Alternative 5 relative to baseline conditions. As would be expected, NBID diversions are higher – usually by a few thousand AF – under the alternative than No Action for many of the years, and those years again correspond with those in which pumping from Thompson Creek Reservoir to Franklin Canal took place, as shown in Figure 86. An exception again can be seen in 2033 and 2044, when Compact Call Years were "switched" between the No Action Alternative and Alternative 5.

The same principles again apply for Climate Scenarios 1 through 3, shown in Figures 100 through 102. NBID diversions are slightly higher on average, by a few thousand AF, for the years in which pumping from Thompson Creek to Franklin Canal took place. The differences between the No Action Alternative and Alternative 5 NBID diversions are probably the least under Climate Scenario 3. However, close inspection of Figure 102 indicates that NBID diversions are slightly higher under alternative conditions for years in which Thompson Creek Reservoir releases are made to Franklin Canal (see Figure 89). For example, for 2014, No Action NBID irrigation diversions under Climate Scenario 3 were 55,630 AF while Alternative 5 diversions were 109 AF higher at 55,739 AF. This agrees well with the difference in total Franklin Canal diversions between No Action levels (35,587 AF) and Alternative 5 diversions (35,697 AF), which was about 110 AF.

In summary, the difference between total NBID diversions (excluding Nebraska's portion of the Courtland Canal) under No Action and Alternative 5 closely parallel the differences between Franklin Canal total diversions for the same years, for all climate scenarios (including Baseline Climate). While Franklin Canal itself is able to divert more total irrigation water under Alternative 5 than under No Action conditions, diversions for the remainder of the NBID canals appear to remain mostly unchanged.

### f. *Total FCID Diversions*

The model evaluation also considered potential impacts from Thompson Creek Reservoir operations on upstream FCID users. Figure 103 shows Baseline Climate results for the No Action Alternative and Alternative 5 for all FCID diversions. Initial inspection indicates little to no difference between No Action and Alternative 5 levels of FCID diversions, except again for the switched

Compact Call Years under Baseline Climate during 2033 and 2034. Closer inspection also shows little to no differences, with some cases of slightly higher No Action level diversions than Alternative 5, and some years where the opposite is true – but always at very low magnitudes in terms of the differences (often only a few AF).

Figures 104 through 106 show the results under the three climate scenarios. In all instances, the differences between No Action FCID diversions and Alternative 5 diversions are negligible. Even under Climate Scenario 2, where the differences between No Action and alternative Compact Call Years are the greatest, there are still only a few instances when differences between No Action and Alternative 5 FCID diversions are apparent.

In summary, operations of Thompson Creek Reservoir appear to have negligible impact on FCID diversions upstream. This is to be expected, since activities downstream of the FCID service area should have little to no impact on FCID irrigation activities unless those actions influence Compact Call Year determinations, which would result in management changes upstream of Harlan County Lake as well.

#### g. *Courtland Canal Diversions from the Republican River*

Courtland Canal diversions from the Republican River, as measured at the 0.7 Courtland Canal gage just downstream from the Guide Rock Diversion Dam, are shown for Baseline Climate conditions in Figure 107. As shown, differences between No Action and alternative conditions are very minimal, and mainly occur in the period around 2033 and 2034, when the Compact Call Years are switched between the No Action Alternative and Alternative 5. The overall average diversions across the 50-year period are 48,655 AF/year for the No Action Alternative and 48,690 AF/year for Alternative 5. The very slight average increase (less than 50 AF/year) is probably negligible.

Under the climate scenarios, the results are similar, with only very small differences in Courtland Canal diversions for Alternative 5 compared to No Action, as shown in Figures 108 through 110. The average differences across the 50-year period are less than 20 AF/year for all three climate scenarios, and are sometimes greater for No Action and sometimes vice versa.

In summary, Courtland Canal diversions from the Republican River appear basically unchanged as a result of Thompson Creek Reservoir operations when compared against the No Action Alternative. These results lead naturally to the question of whether there are any changes to flows at the Guide Rock gage on the Republican River, just downstream from the Courtland Canal diversion, which is the next metric under consideration.

### h. *Guide Rock Flows*

Republican River flows at the Guide Rock gage, which are critically important in determining Compact allocations and balances, are shown for Baseline Climate conditions in Figure 111. Once again, differences between No Action and alternative flow rates are small – except for the 2033 and 2034 dates involving switched Compact Call Years. Over the 50-year period, average flows were 179,999 AF for the No Action Alternative and 178,743 AF for Alternative 5.

Results are similar for the climate scenarios, as depicted in Figures 112 through 114. For Climate Scenario 1, average Guide Rock flows over the 50-year period were 171,075 AF for No Action and 170,342 AF for Alternative 5. Under Climate Scenario 2, the 50-year averages were 196,004 AF and 195,200 AF, respectively. Under Climate Scenario 3, they were 347,249 AF and 346,776 AF, respectively. As evident in the 50-year averages, and through inspection of the graphs, there appears to be a very small reduction in Guide Rock flows between No Action and alternative conditions. For all climate conditions, there also was a slight decrease in Guide Rock flows under Alternative 5.

In summary, Republican River flows at Guide Rock appear to experience a small decrease from Thompson Creek Reservoir operations, for all climate scenarios (including Baseline Climate). The differences, however, are small relative to the overall flow at the Guide Rock gage.

### i. *Courtland Canal Flows at State Line*

Earlier it was shown that Courtland Canal diversions from the Republican River are basically unchanged as a result of Thompson Creek Reservoir operations. Figure 115 shows that this is also the case when looking downstream on the Courtland Canal, near the state line between Nebraska and Kansas. Figure 115 for Baseline Climate, and Figures 116 through 118 for the climate scenarios, also include information on the target flows provided by Kansas, which were used as demands at the state line in the STELLA model. Normally it was possible to meet Kansas' target flows, but in some instances where the target flows were very high, such as in 2017 and 2031 under Baseline Climate, available flows were not sufficient. In terms of differences between the No Action Alternative and Alternative 5 flows, there is little to no difference observed. That is also borne out with the 50-year average flows, where No Action and alternative flows differ by less than 30 AF.

Climate Scenarios 1 through 3, shown in Figures 116 through 118, reveal the same overall results, with little to no differences between No Action and Alternative 5 Courtland Canal flows at the state line. As with the Baseline Climate conditions, 50-year average differences between the No Action Alternative and Alternative 5 Courtland Canal flows at the state line are less than 30 AF for all three climate scenarios.

In summary, as is the case with the Courtland Canal diversions from the Republican River, flows in the canal downstream at the state line appear basically unchanged as a result of Thompson Creek Reservoir operations when compared against the No Action Alternative.

In terms of whether Alternative 5 meets or exceeds its purpose and objectives, there are again mixed results, as was the case with Alternatives 3A and 3B. From the perspective of increasing the water supply reliability for NBID, the results indicate that there would likely be additional diversions made by the Franklin Canal as a result of Thompson Creek Reservoir operations. The remaining NBID demands likely would be unaffected, as would FCID canals upstream of Harlan County Lake. Harlan County Lake levels would likely improve for those years when Thompson Creek Reservoir pumping to Franklin Canal occurred, with perhaps a few thousand AF of additional storage supply within Harlan County Lake for some years over the 50-year period. This does indicate a potential benefit to Harlan County Lake resulting from the substitute supply originating from Thompson Creek.

In terms of Compact-related impacts, there appears to be little to any impacts to the number of Compact Call Years as a result of Thompson Creek operations compared to No Action conditions. The small benefit to storage levels in Harlan County does not directly result in reductions in Compact Call Years. This may be in part due to the increased consumptive use on Franklin Canal lands, which negatively affects Nebraska's Compact balance, but that same consumption would provide benefits to NBID irrigators on the Franklin Canal. The small size of the Thompson Creek Reservoir alternative may also be a factor, and it may be beneficial to consider larger reservoir sizes in future analyses. The consistent ability of Thompson Creek Reservoir to fill its conservation pool each year, and the regular incursion of water into the flood pool when climate conditions are wetter, both indicate that the reservoir could benefit from greater conservation and flood storage. Finally, while Guide Rock flows show a slight decrease in overall flows under the alternative, flows on the Courtland Canal at the state line are basically unchanged, with both gages having impacts on Compact balances for Nebraska. As with Alternatives 3A and 3B, different management options, such as modifying the water supply calculations in NBID contracts and possibly the language in the Consensus Plan and RRCA Accounting Procedures to reflect the new storage supply from the Thompson Creek Reservoir may also be worth considering if water planners wish to conduct future analyses of the potential reservoir site.

# 4. Figures of Nebraska Results

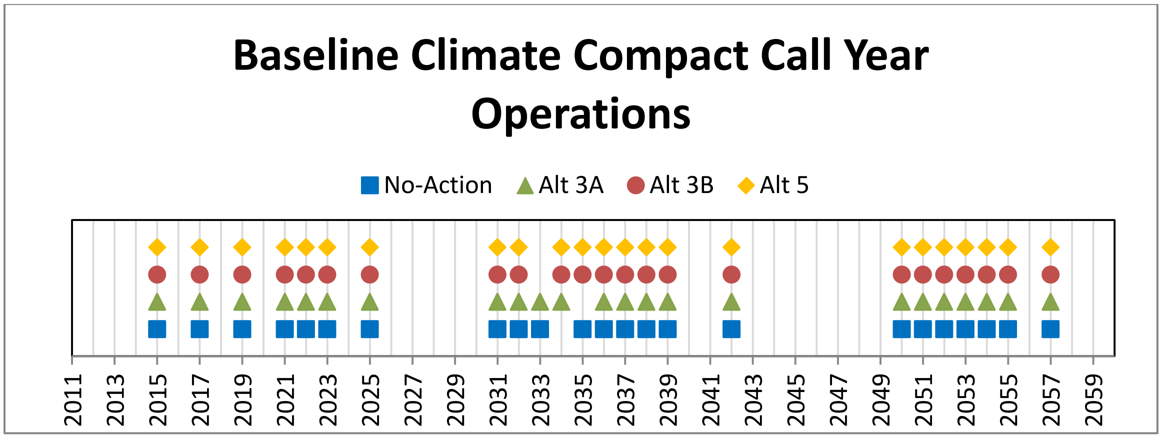


**Figure 58. — Baseline Climate Compact Call Year Operations**

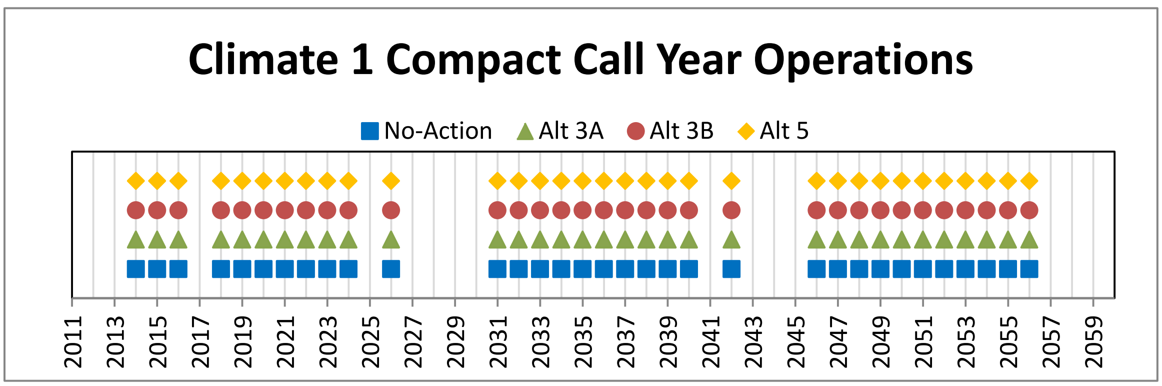


**Figure 59. — Climate Scenario 1 Compact Call Year Operations**

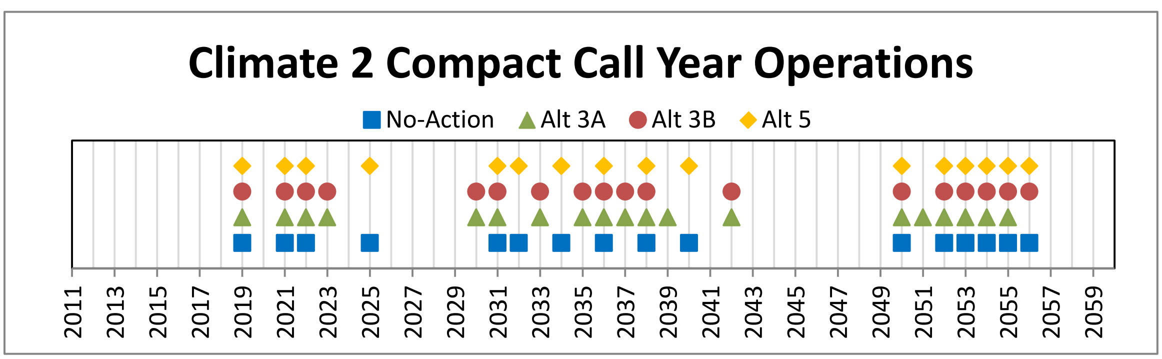


**Figure 60. — Climate Scenario 2 Compact Call Year Operations**

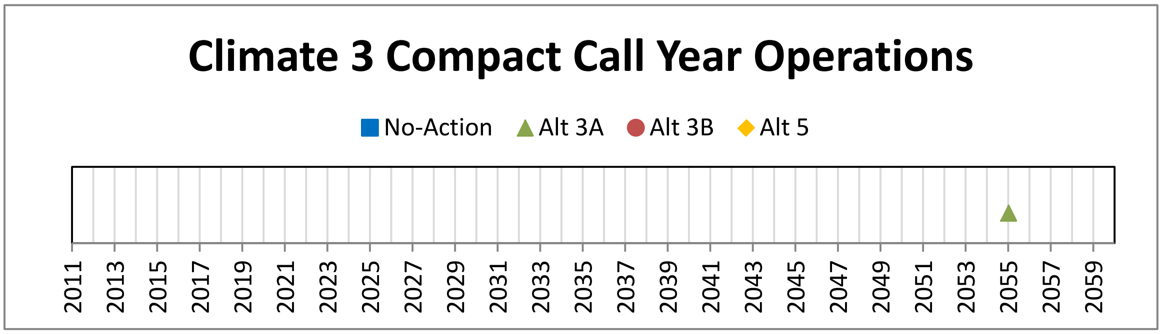


**Figure 61. — Climate Scenario 3 Compact Call Year Operations**

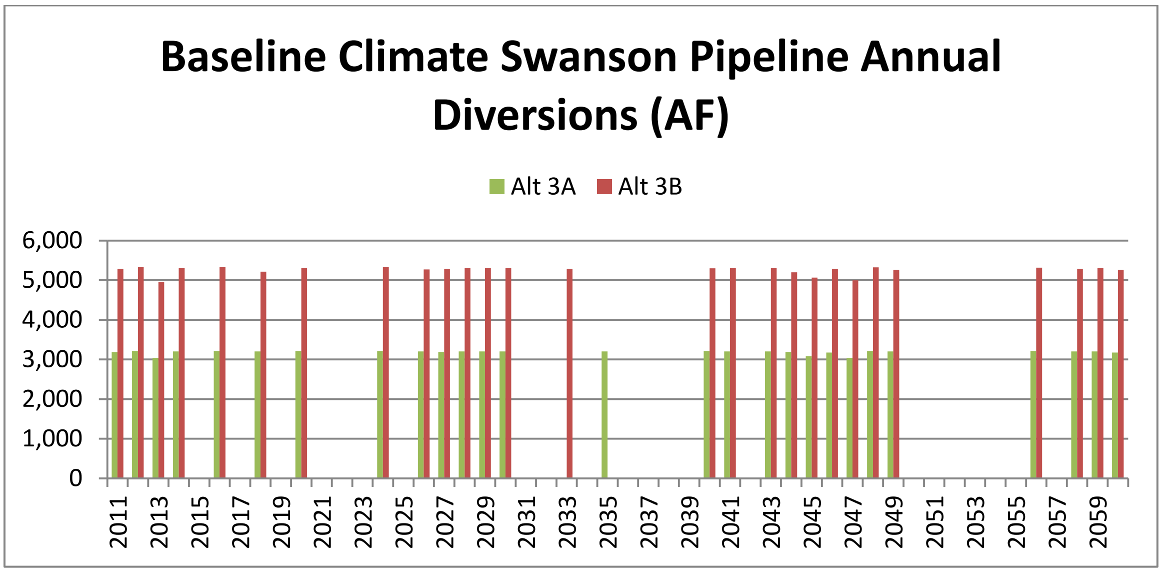


**Figure 62. — Baseline Climate Swanson Pipeline Annual Diversions for Alt 3A & 3B**

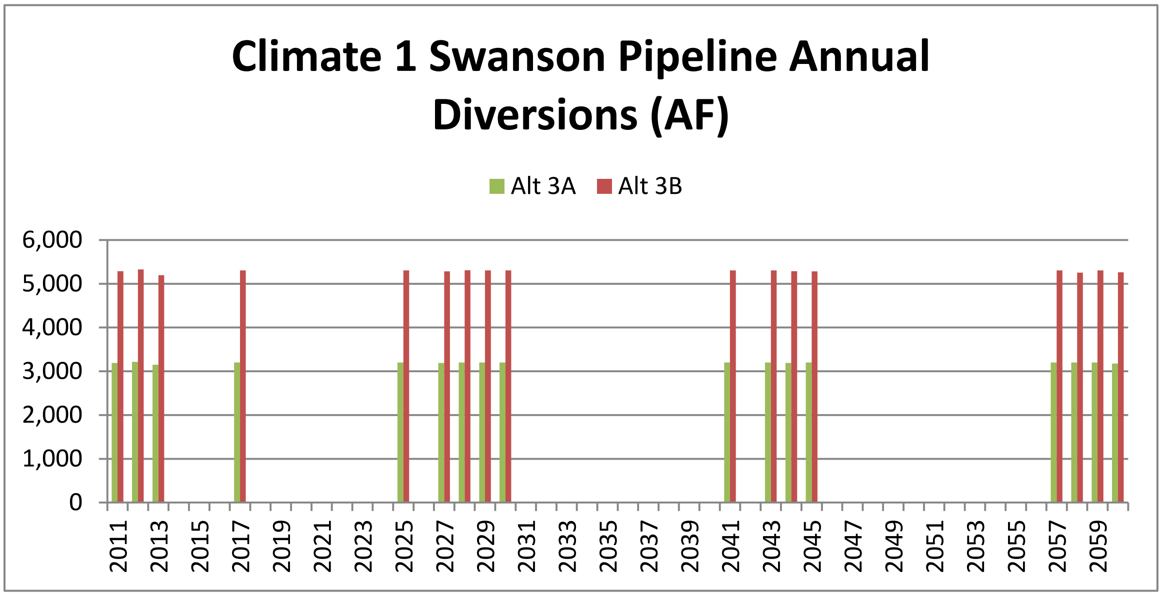


**Figure 63. — Climate Scenario 1 Swanson Pipeline Annual Diversions for Alt 3A & 3B**

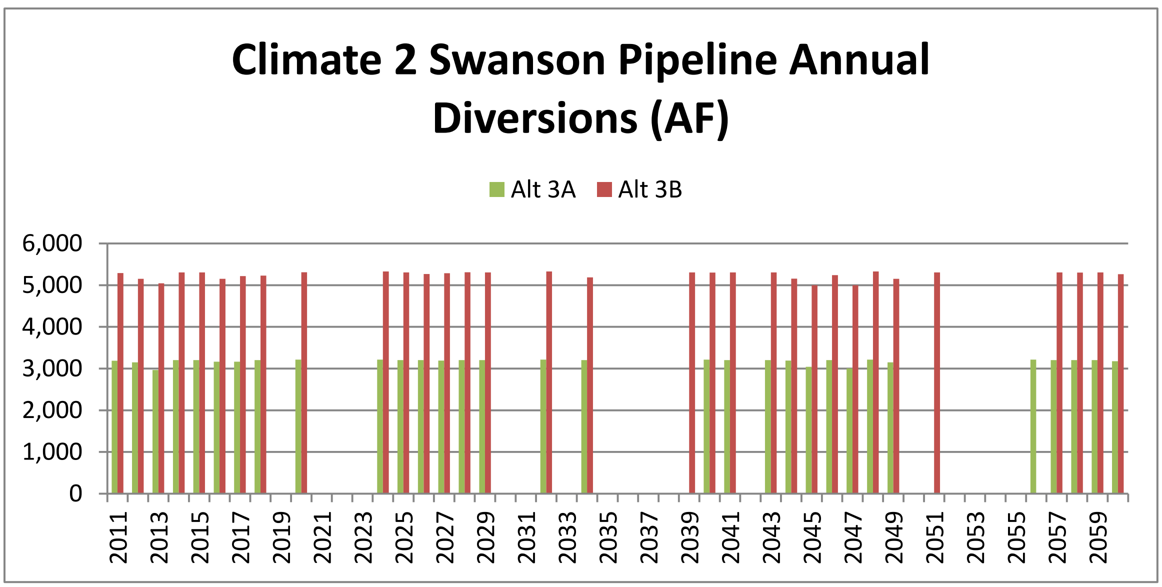


**Figure 64. — Climate Scenario 2 Swanson Pipeline Annual Diversions for Alt 3A & 3B**

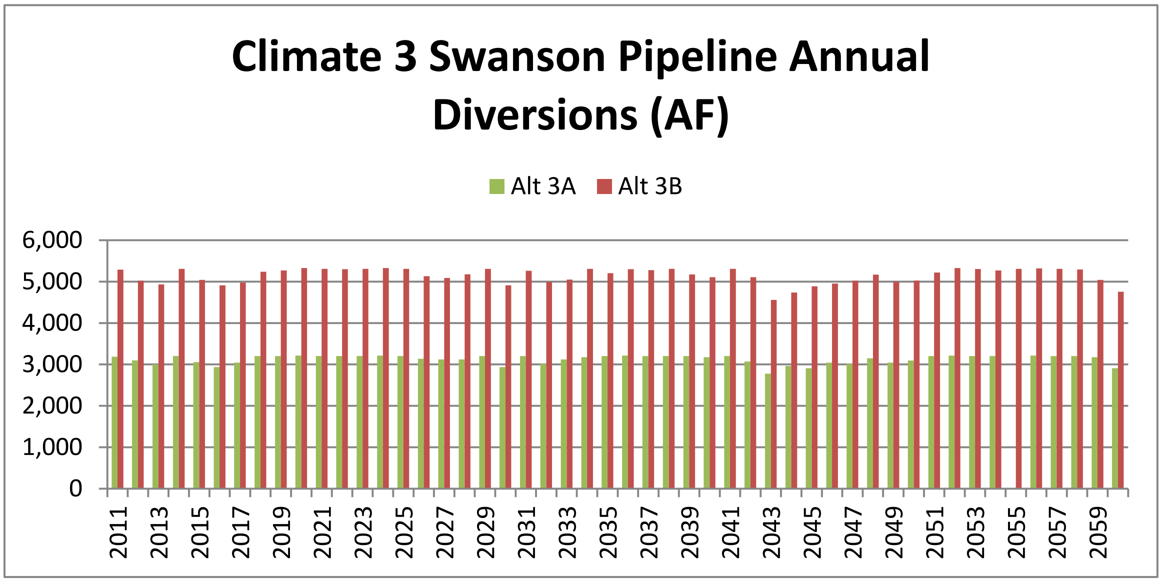


**Figure 65. — Climate Scenario 3 Swanson Pipeline Annual Diversions for Alt 3A & 3B**

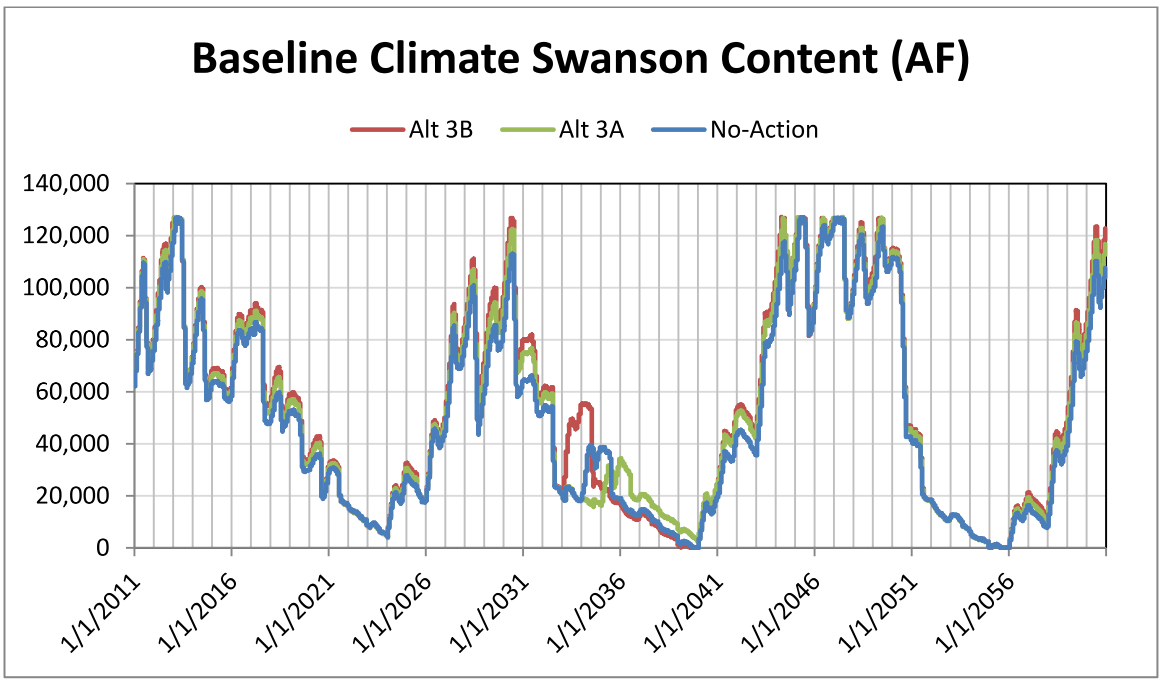


**Figure 66. — Baseline Climate Swanson Content for Alt 3A & 3B**

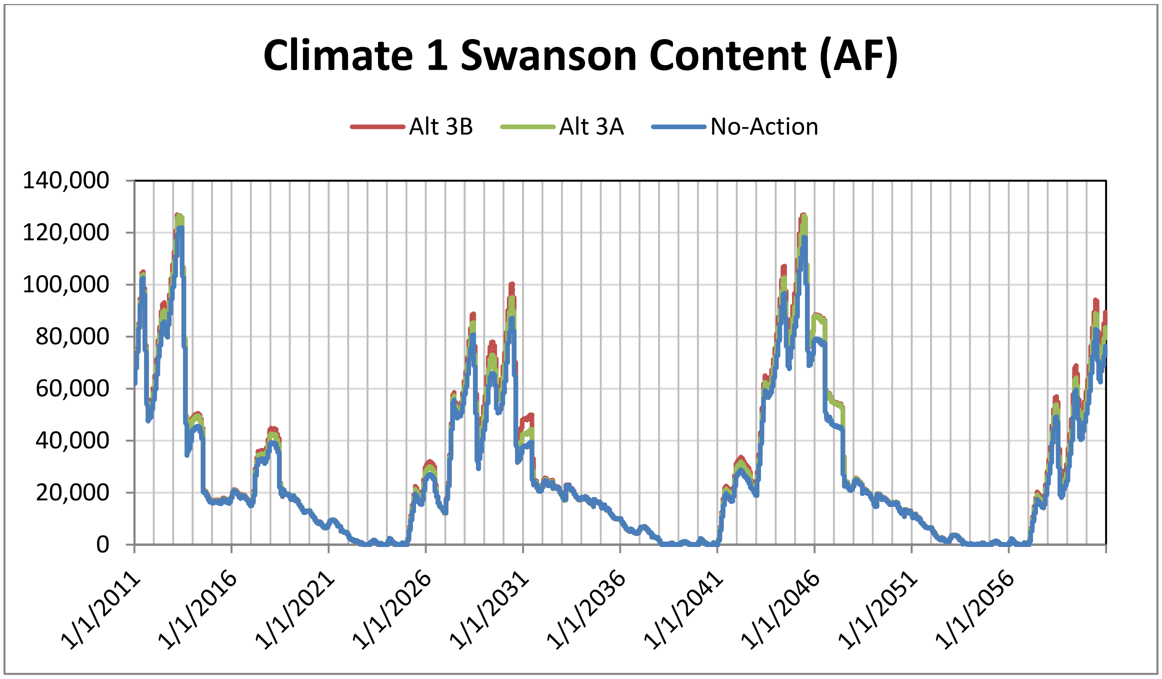


**Figure 67. — Climate Scenario 1 Swanson Content for Alt 3A & 3B**

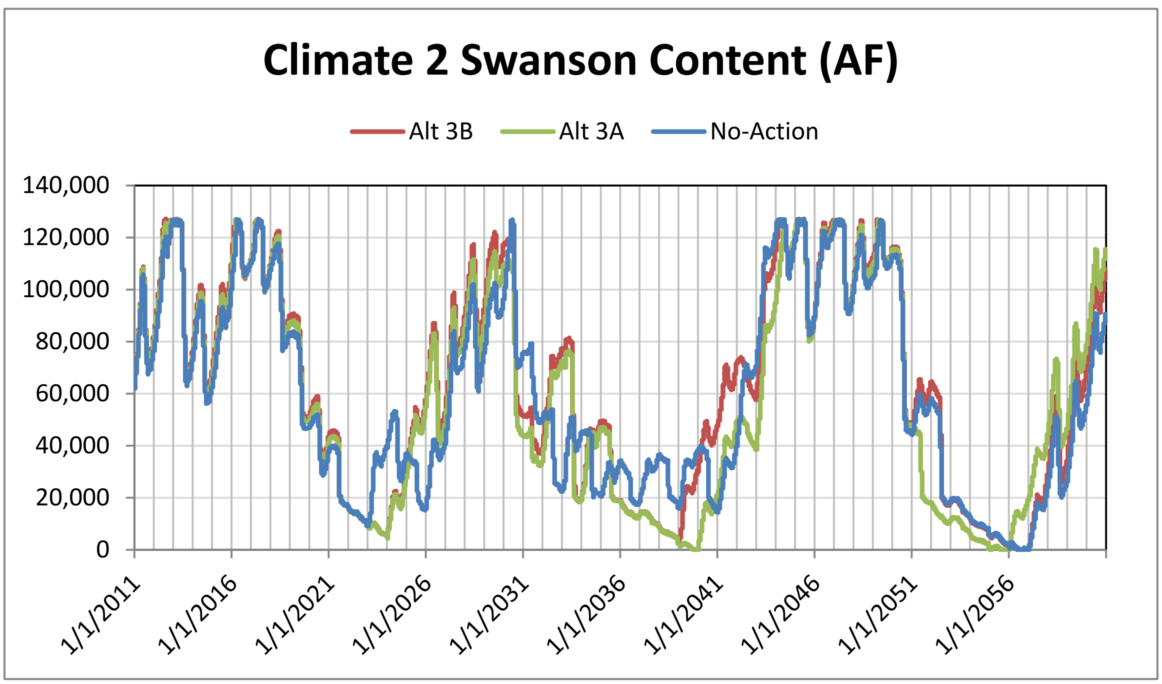


**Figure 68. — Climate Scenario 2 Swanson Content for Alt 3A & 3B**

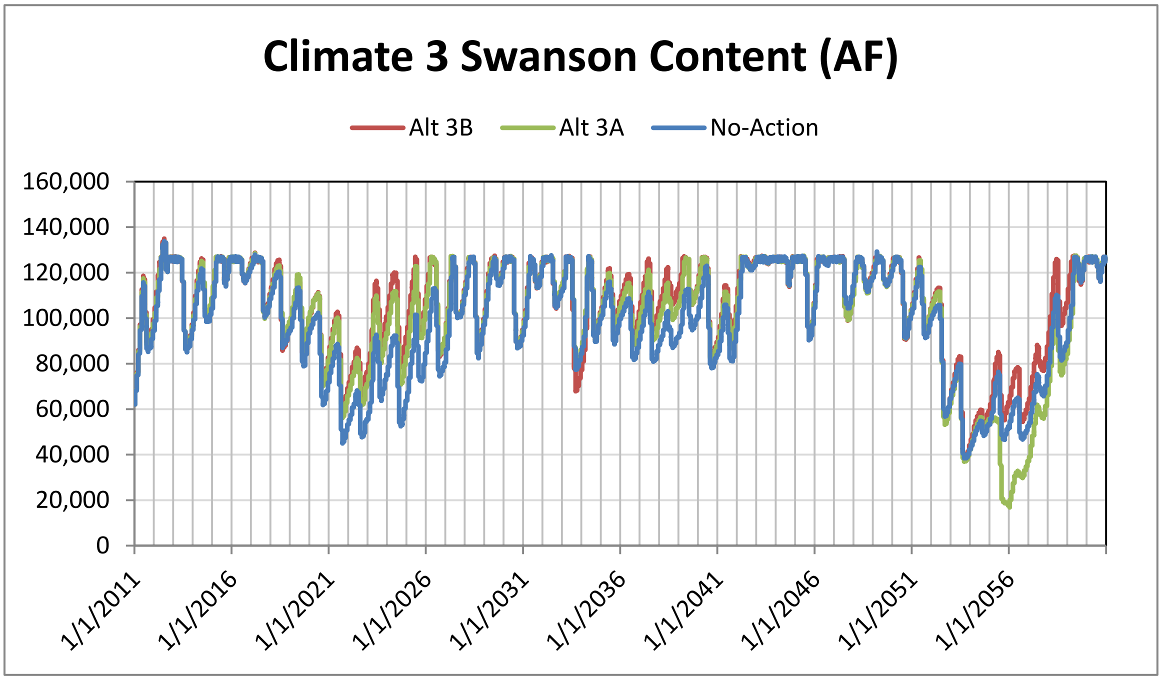


**Figure 69. — Climate Scenario 3 Swanson Content for Alt 3A & 3B**

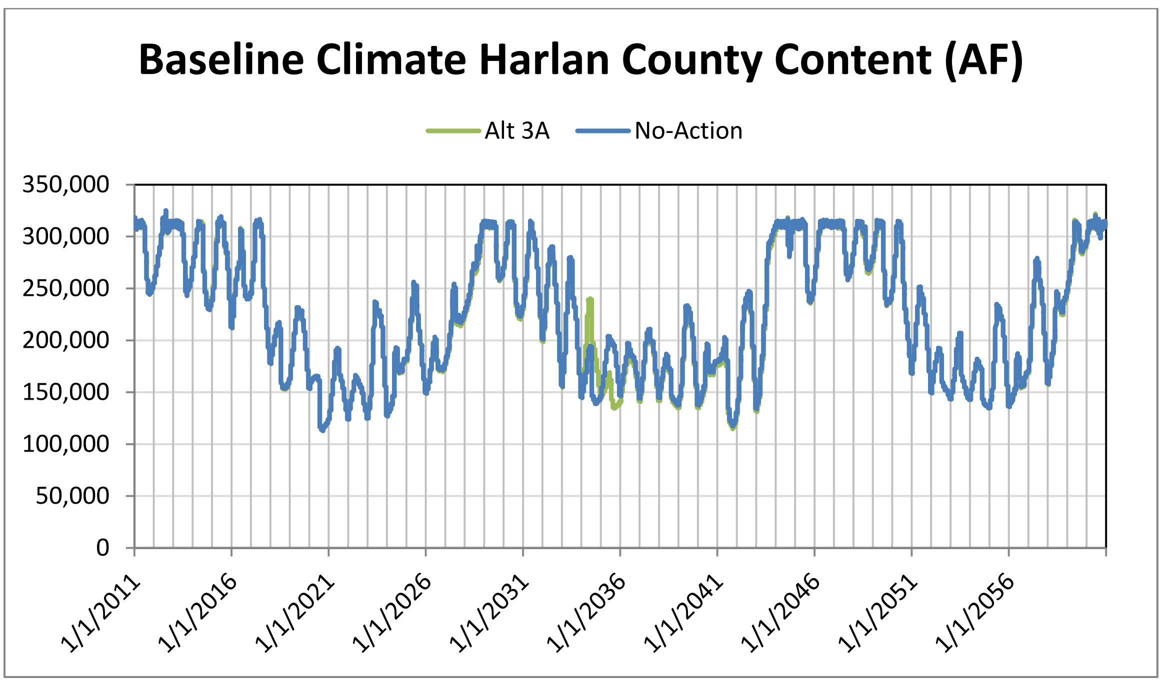


**Figure 70. — Baseline Climate Harlan County Content for Alt 3A**

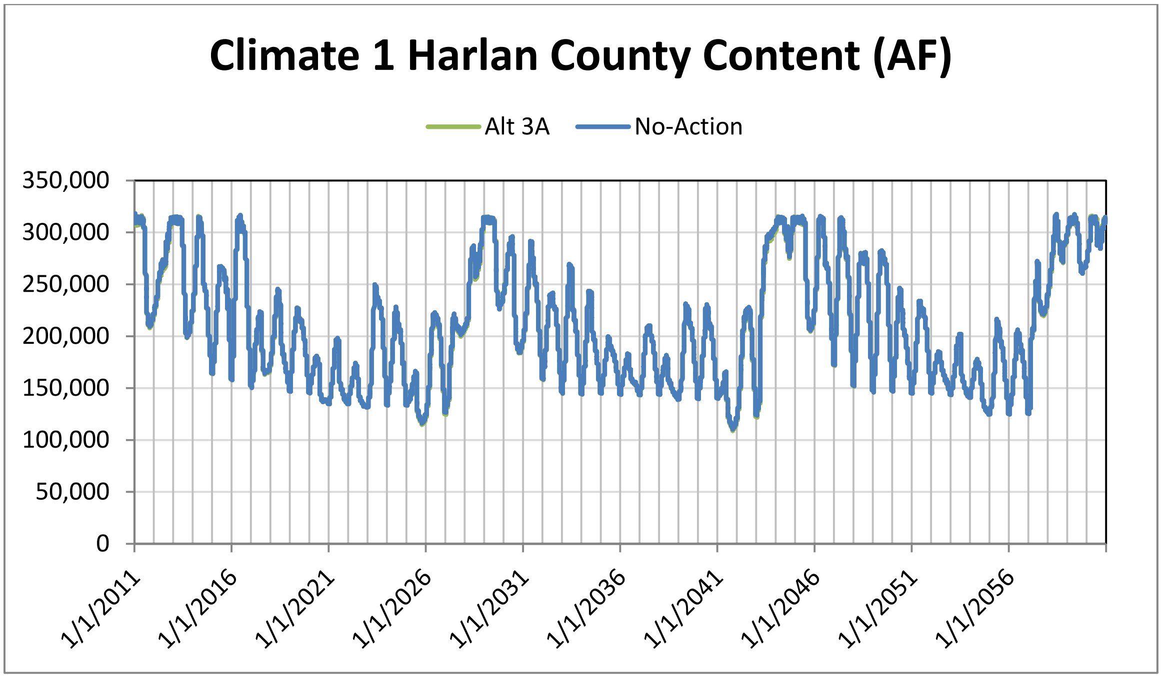


**Figure 71. — Climate Scenario 1 Harlan County Content for Alt 3A**

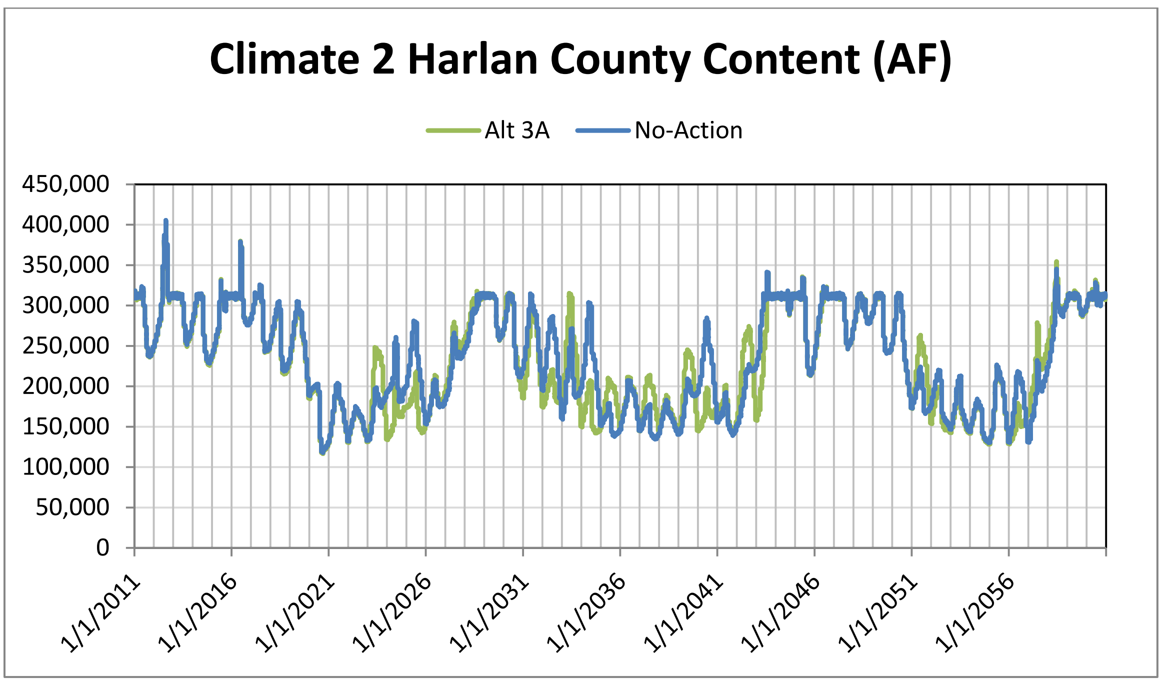


**Figure 72. — Climate Scenario 2 Harlan County Content for Alt 3A**

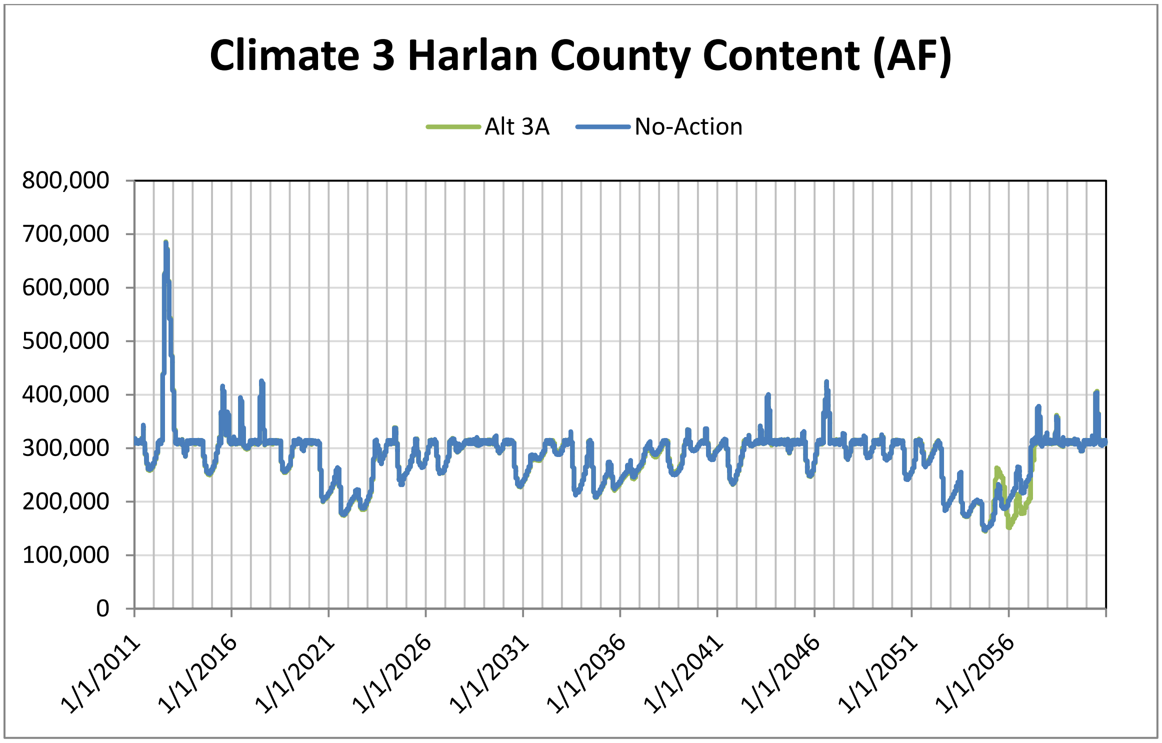


**Figure 73. — Climate Scenario 3 Harlan County Content for Alt 3A**

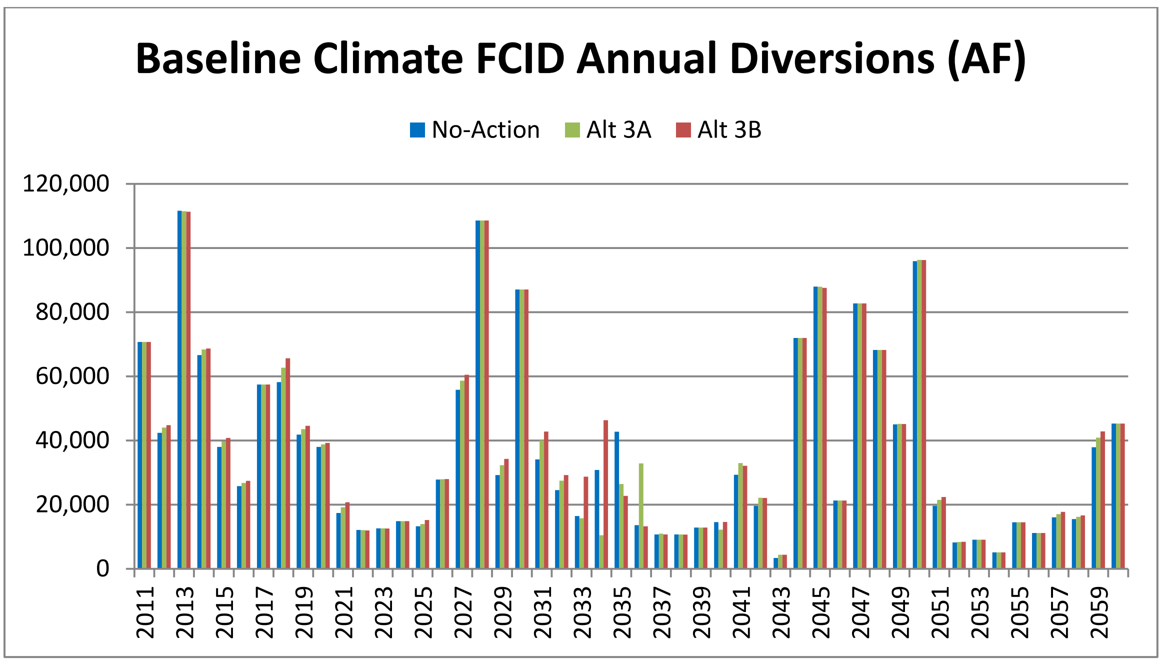


**Figure 74. — Baseline Climate FCID Annual Diversions for Alt 3A & 3B**

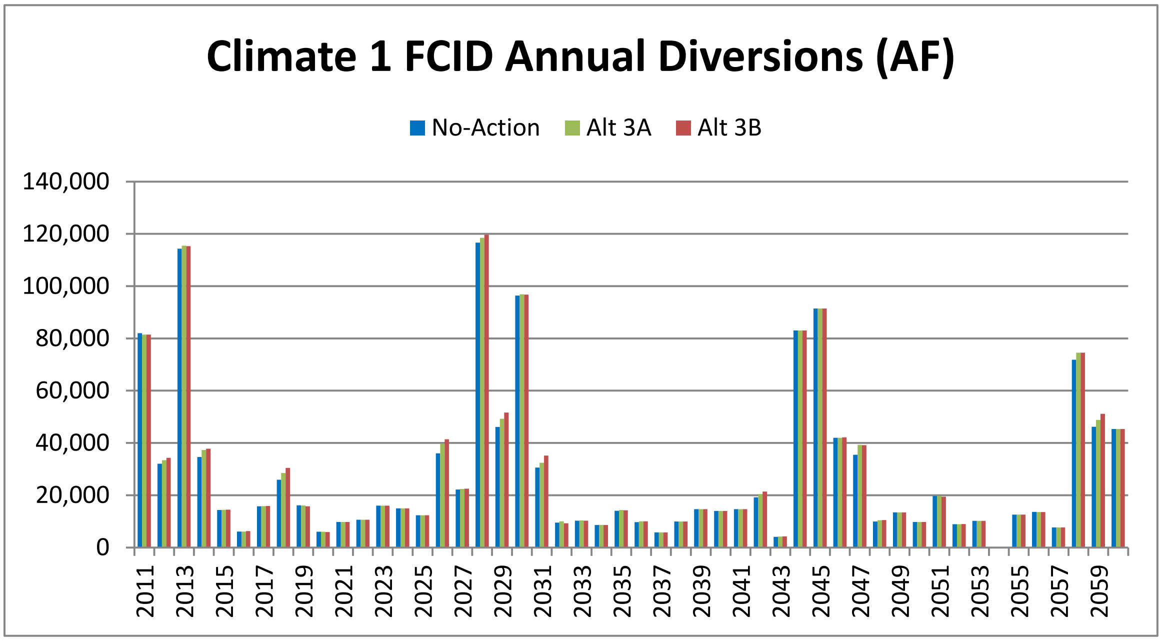


**Figure 75. — Climate Scenario 1 FCID Annual Diversions for Alt 3A & 3B**

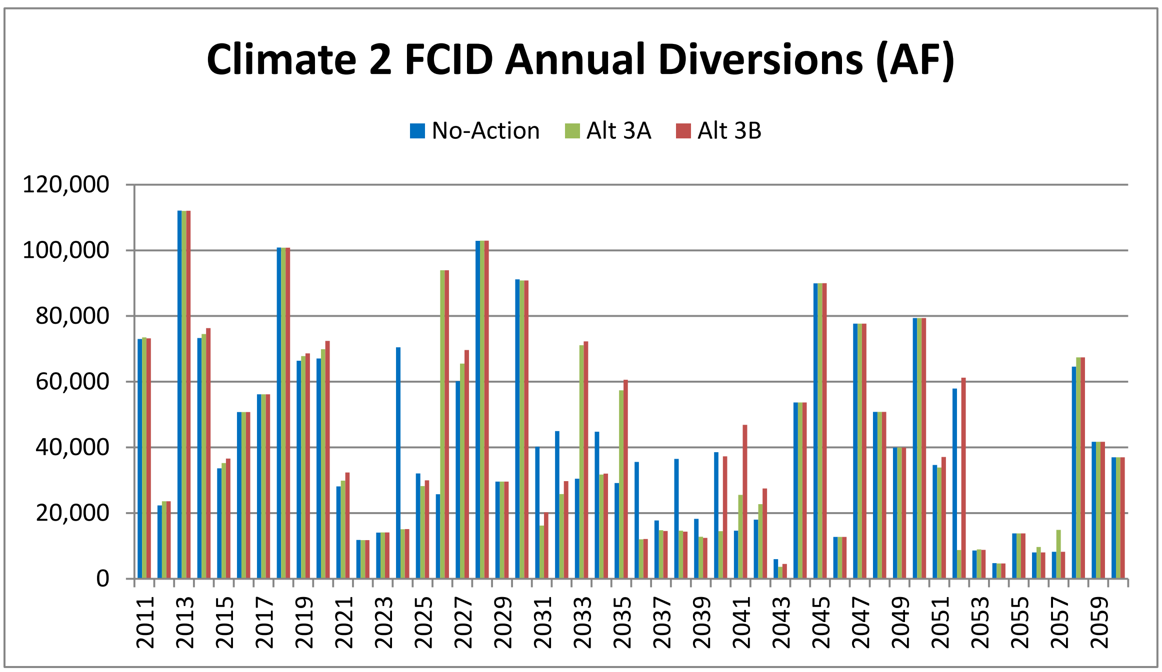


**Figure 76. — Climate Scenario 2 FCID Annual Diversions for Alt 3A & 3B**

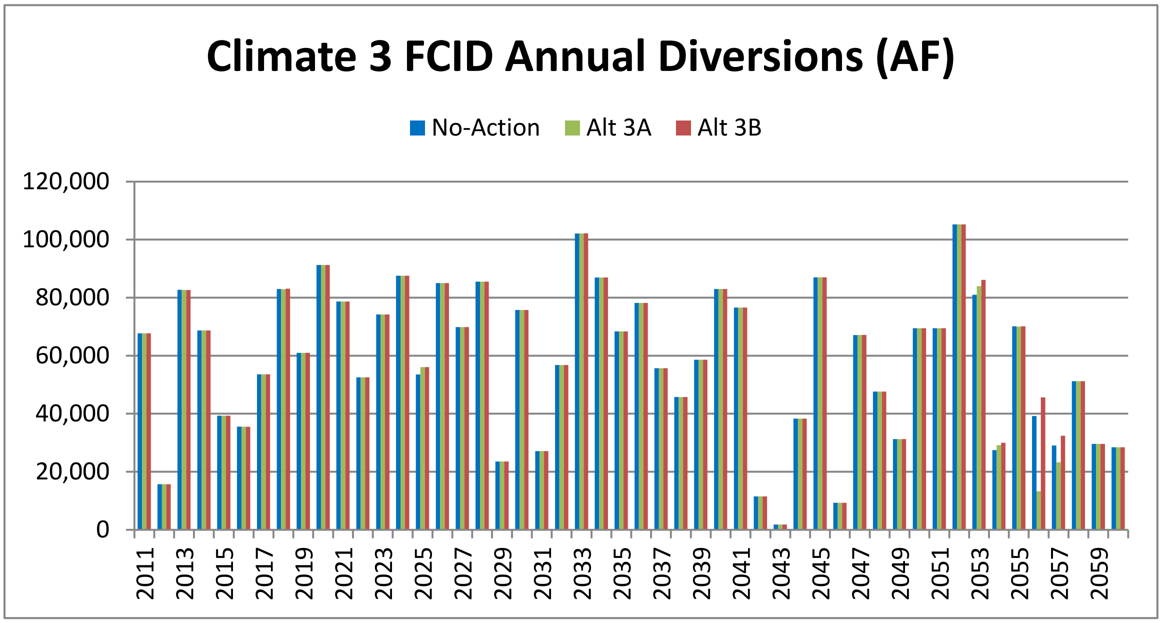


**Figure 77. — Climate Scenario 3 FCID Annual Diversions for Alt 3A & 3B**

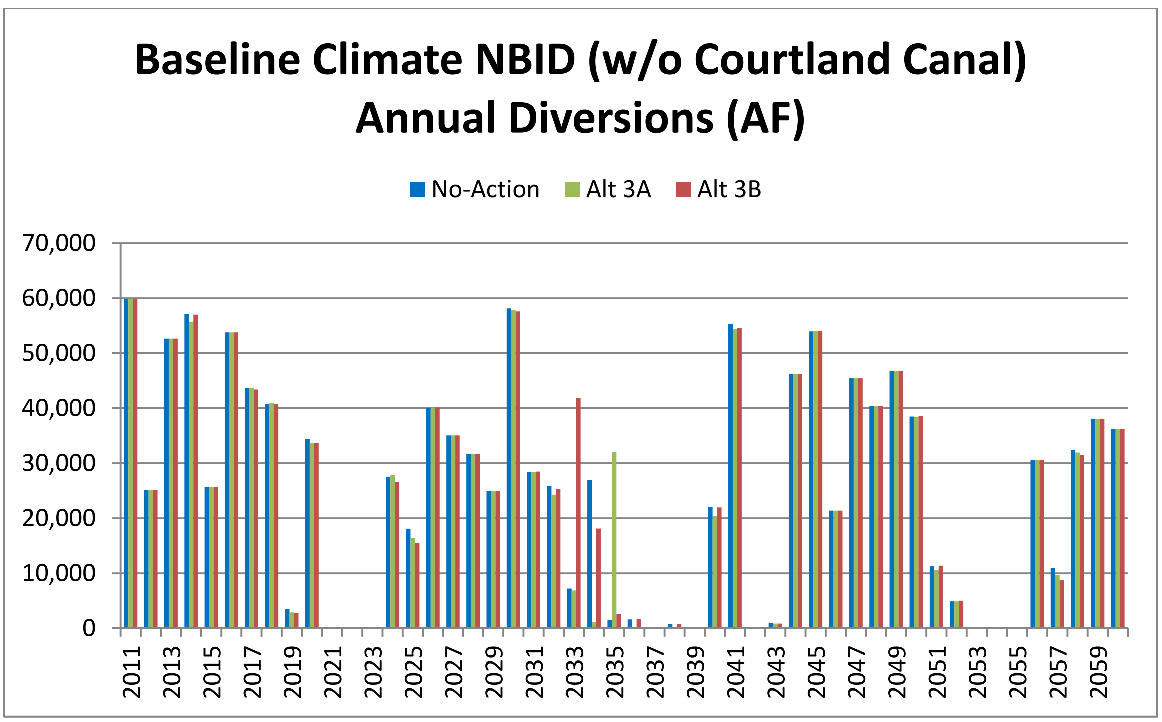


**Figure 78. — Baseline Climate NBID (w/o Courtland Canal) Annual Diversions**

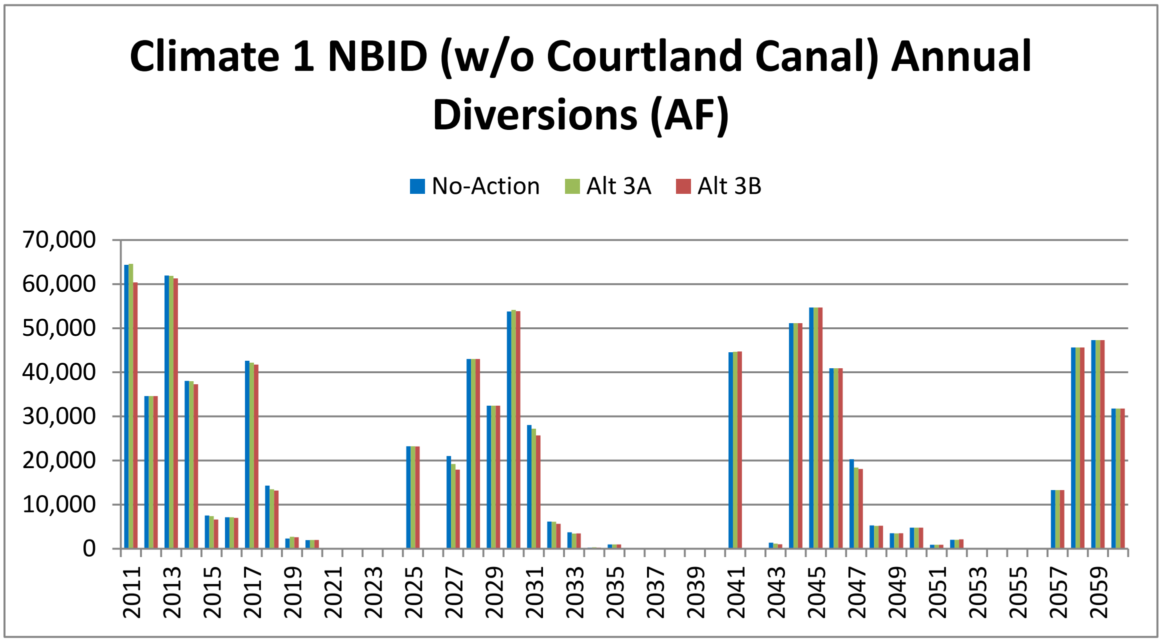


**Figure 79. — Climate Scenario 1 NBID (w/o Courtland Canal) Annual Diversions**

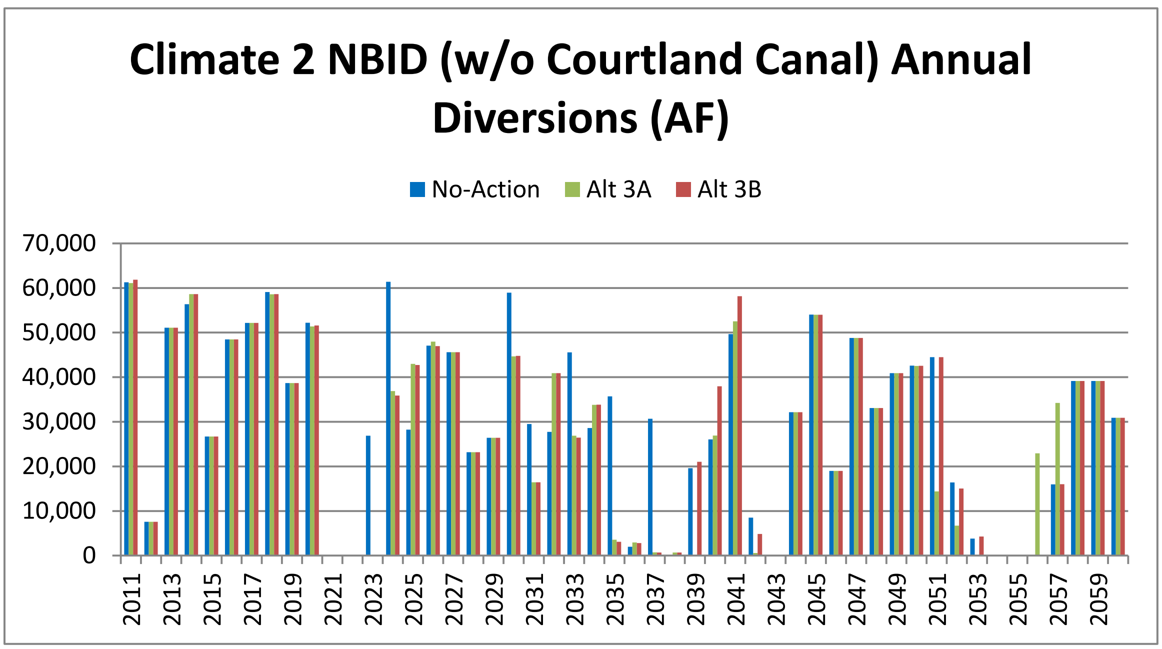


**Figure 80. — Climate Scenario 2 NBID (w/o Courtland Canal) Annual Diversions**

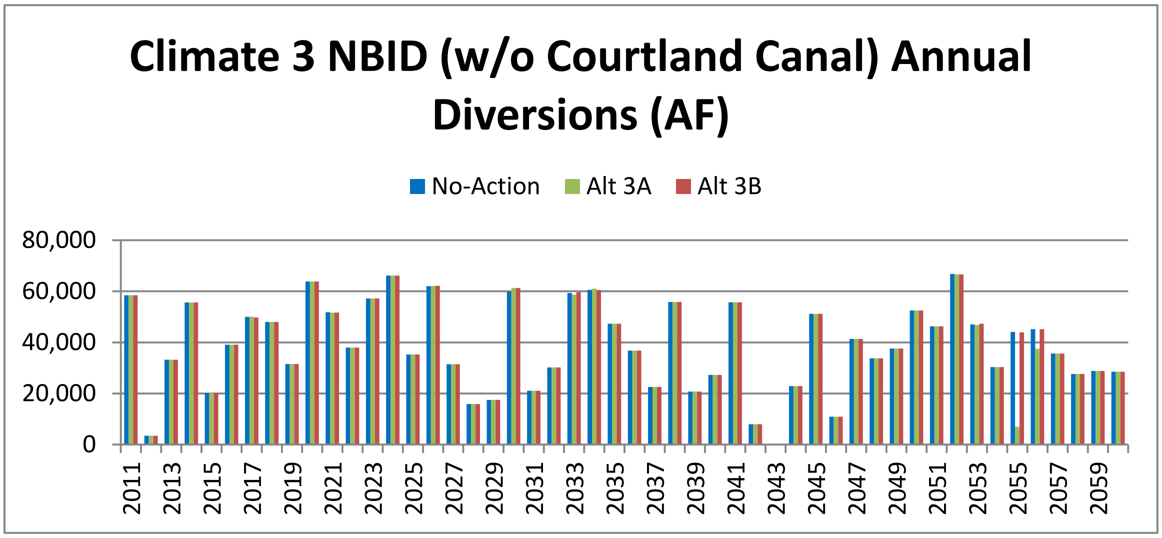


**Figure 81. — Climate Scenario 3 NBID (w/o Courtland Canal) Annual Diversions**

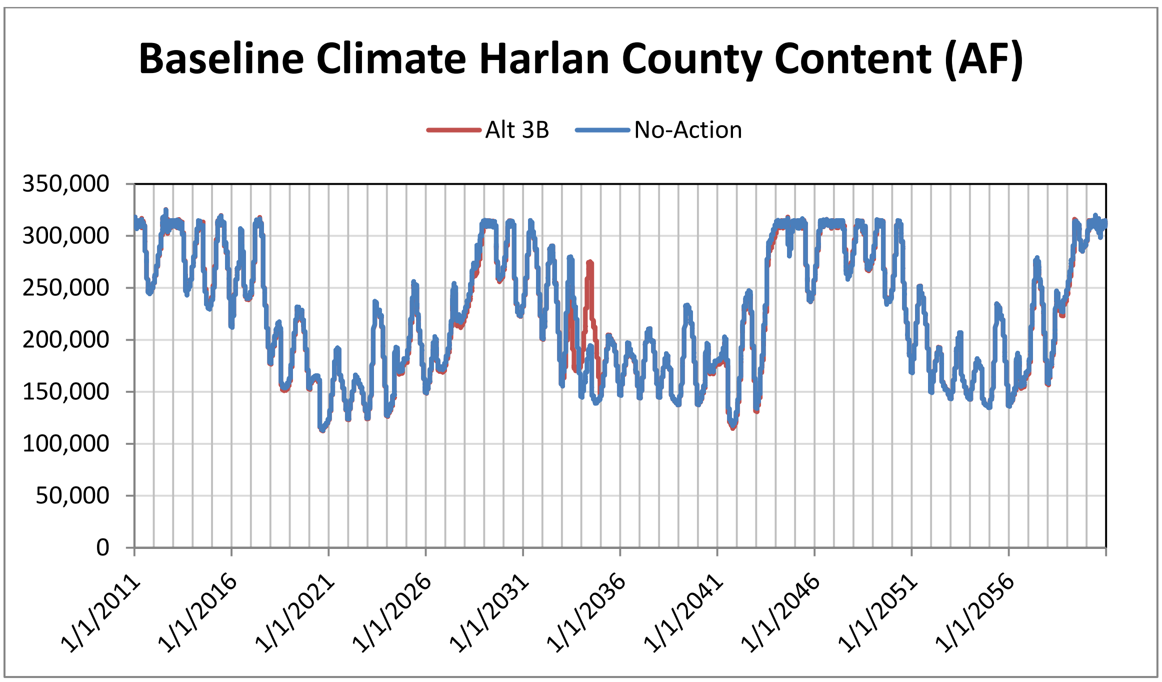


**Figure 82. — Baseline Climate Harlan County Content for Alt 3B**

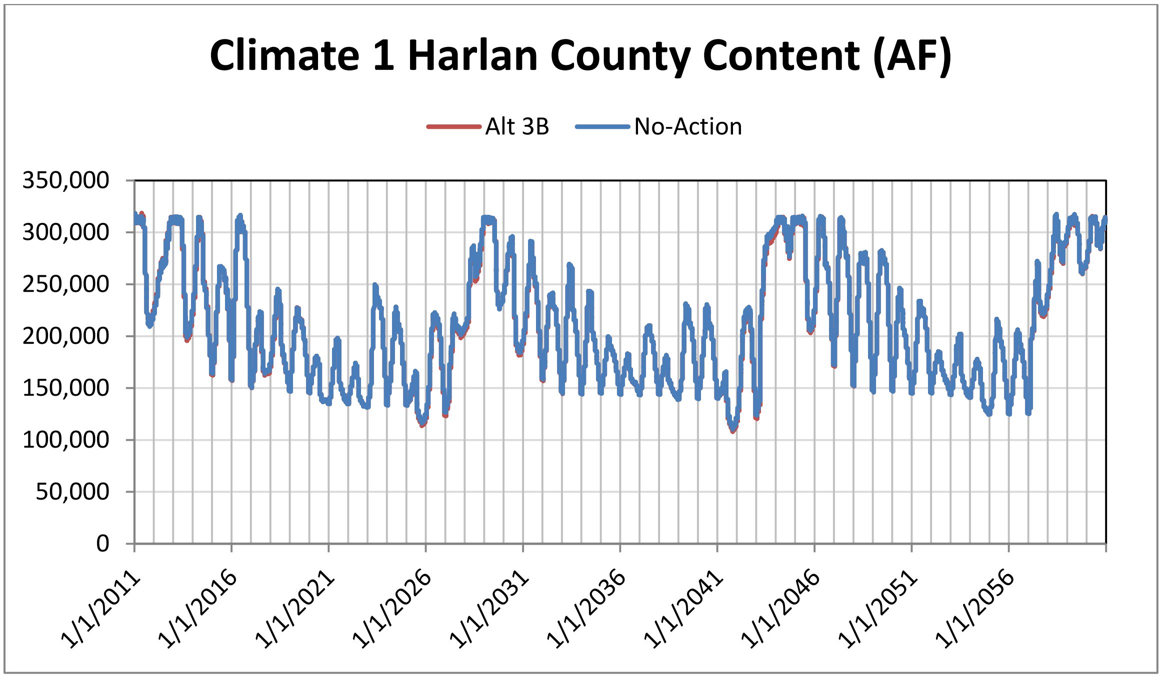


**Figure 83. — Climate Scenario 1 Harlan County Content for Alt 3B**

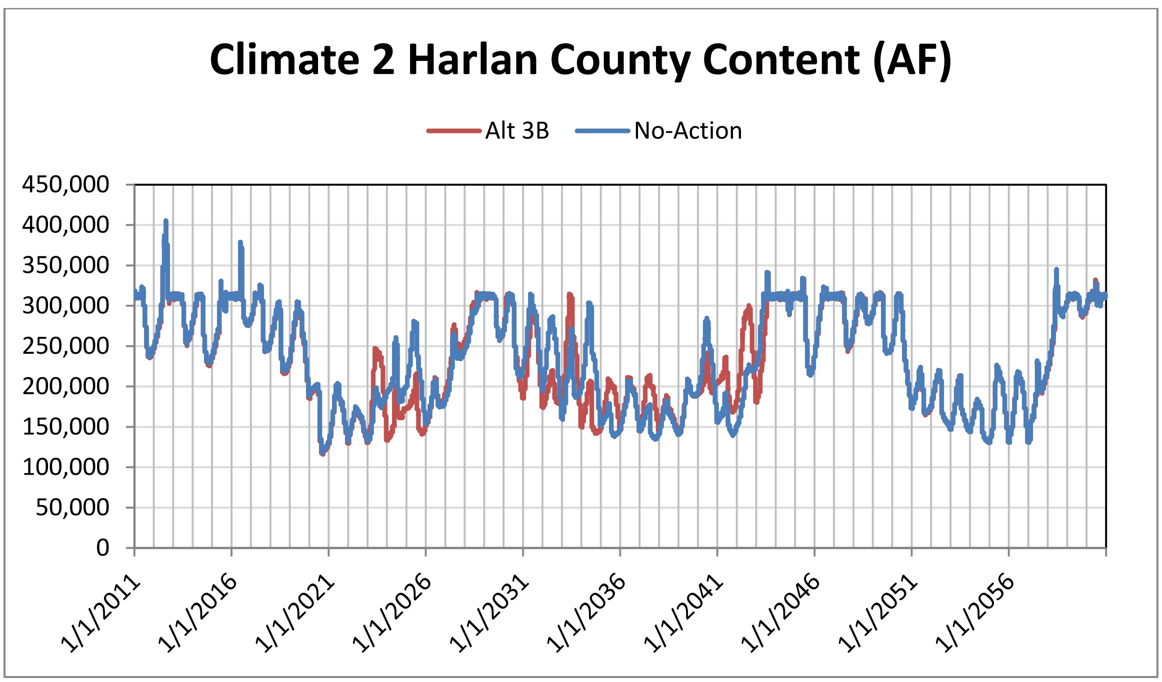


**Figure 84. — Climate Scenario 2 Harlan County Content for Alt 3B**

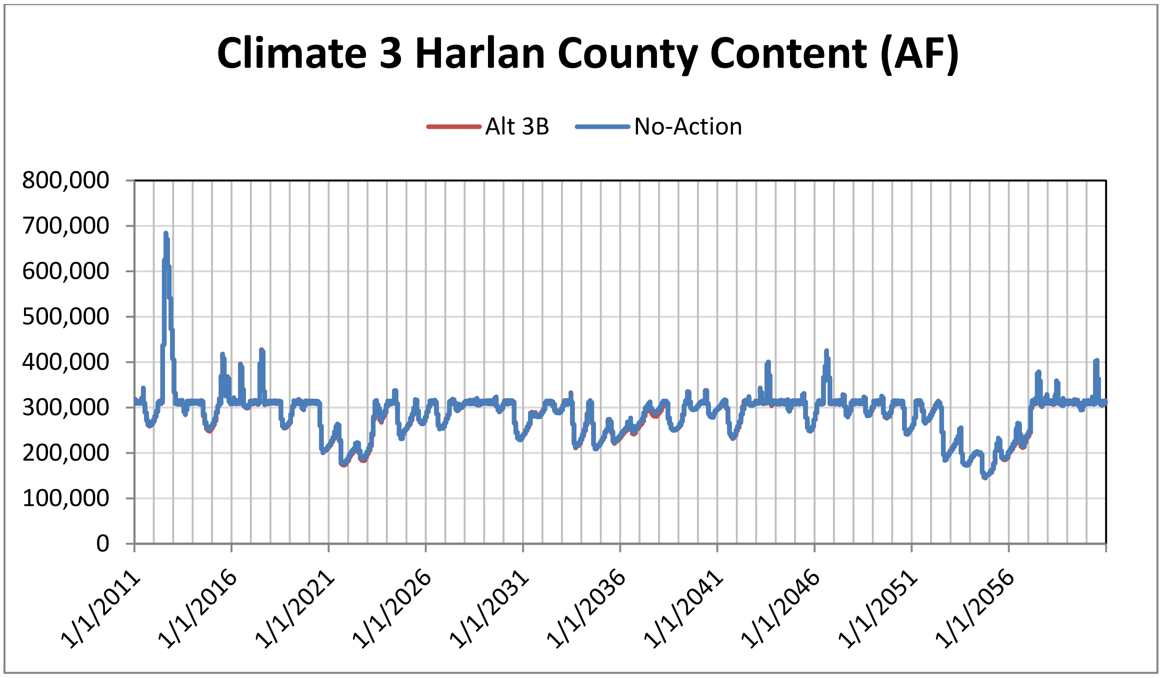


**Figure 85. — Climate Scenario 3 Harlan County Content for Alt 3B**

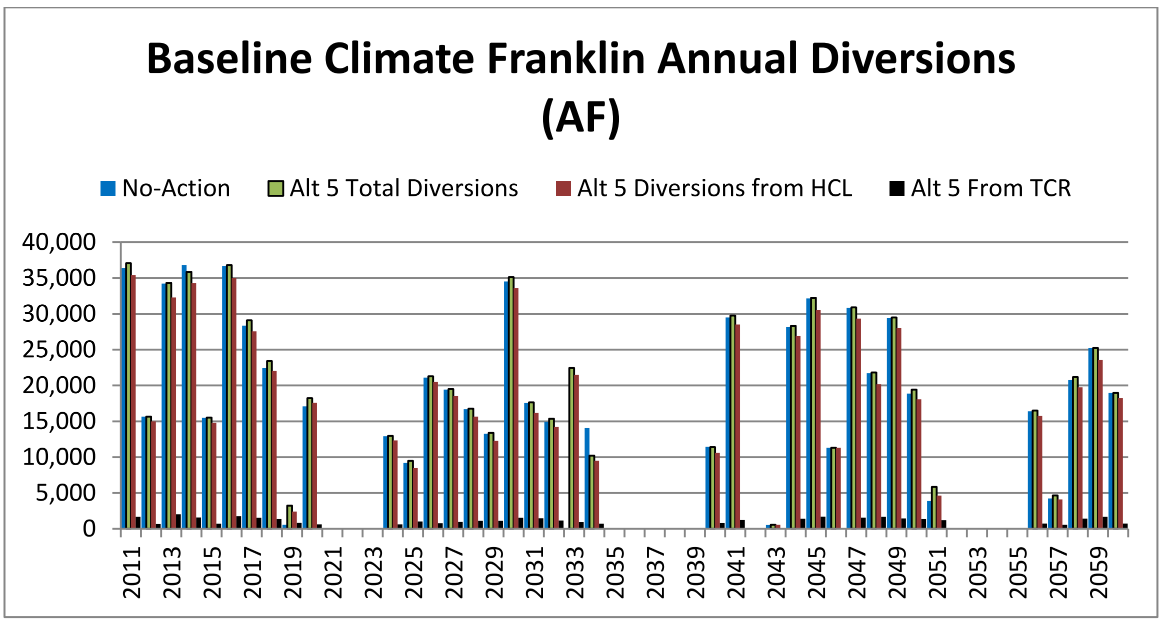


**Figure 86. — Baseline Climate Franklin Canal Annual Diversions for Alt 5**

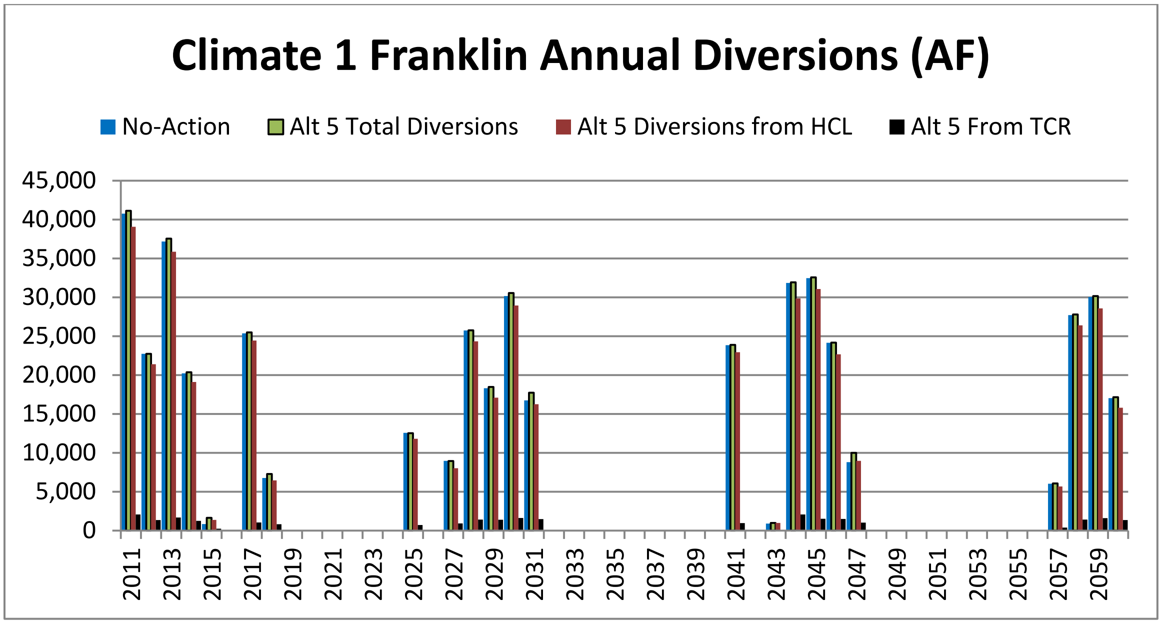


**Figure 87. — Climate Scenario 1 Franklin Canal Annual Diversions for Alt 5**

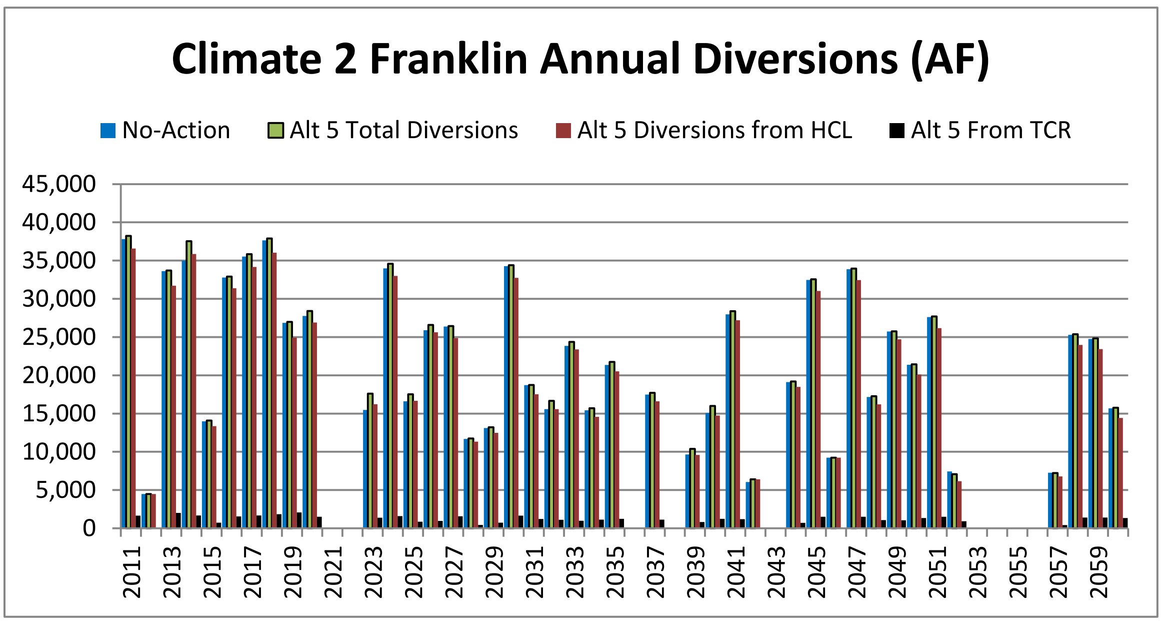


**Figure 88. — Climate Scenario 2 Franklin Canal Annual Diversions for Alt 5**

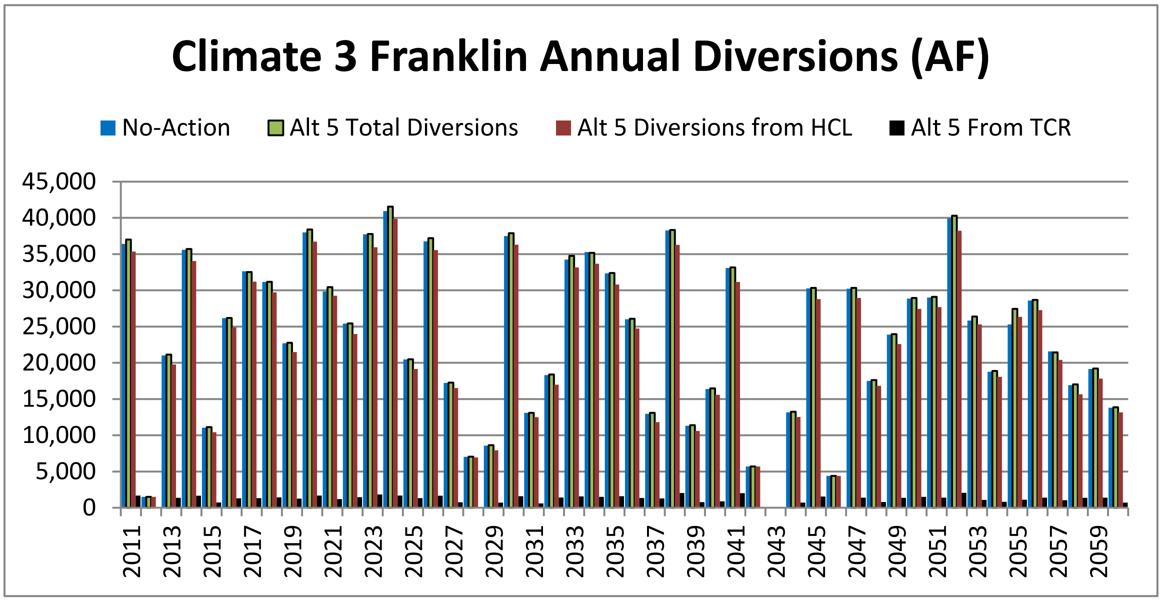


**Figure 89. — Climate Scenario 3 Franklin Canal Annual Diversions for Alt 5**

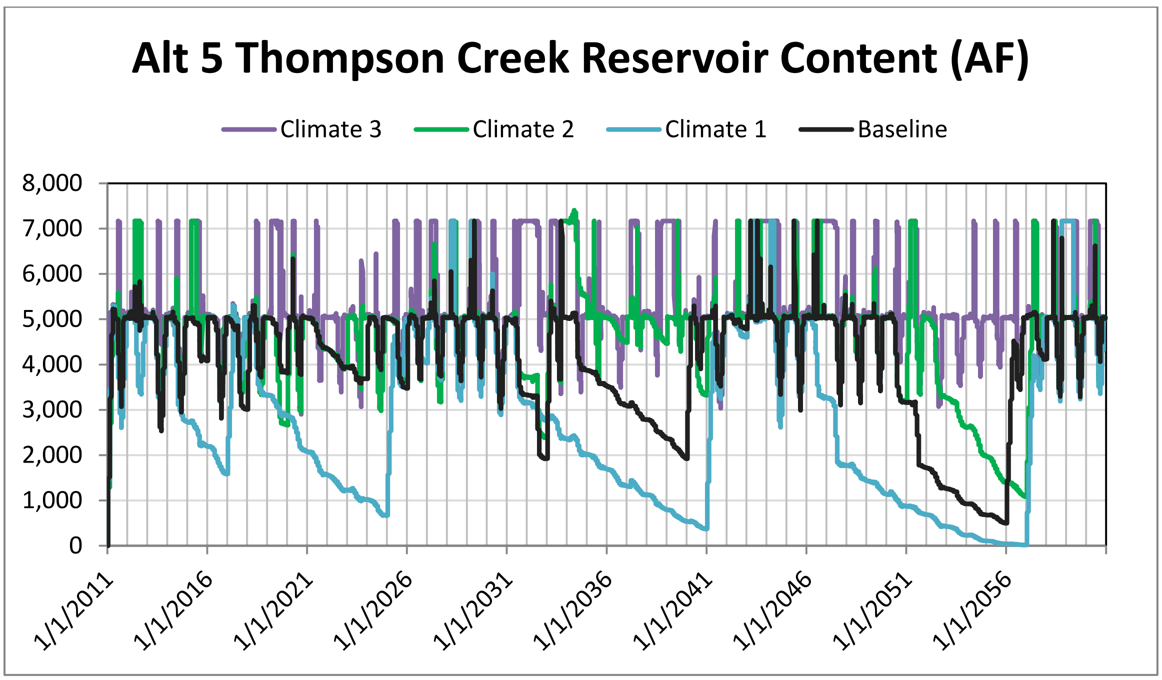


**Figure 90. — Alt 5 Thompson Creek Reservoir Content**

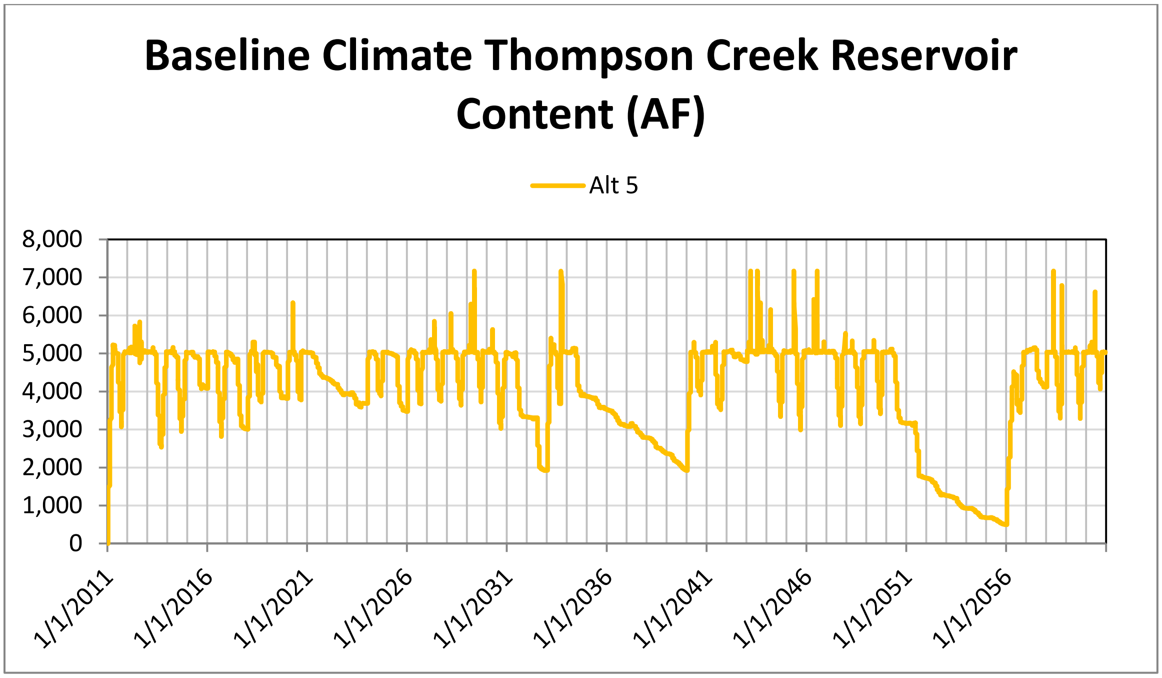


**Figure 91. — Baseline Climate Thompson Creek Reservoir for Alt 5**

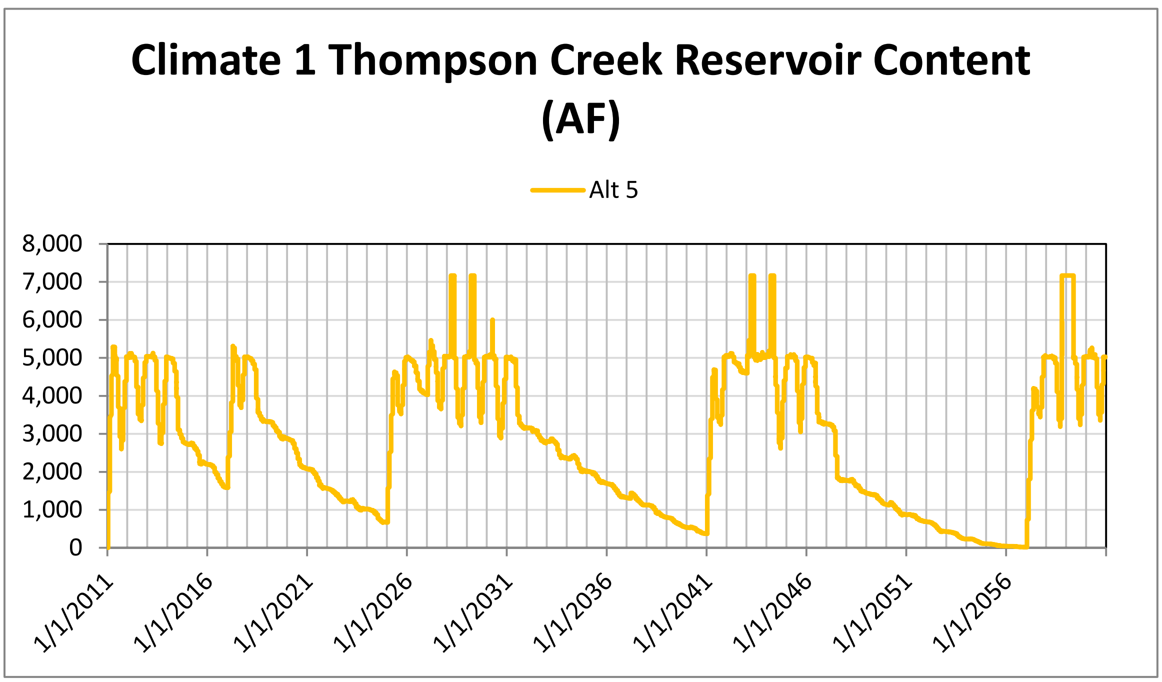


**Figure 92. — Climate Scenario 1 Thompson Creek Reservoir for Alt 5**

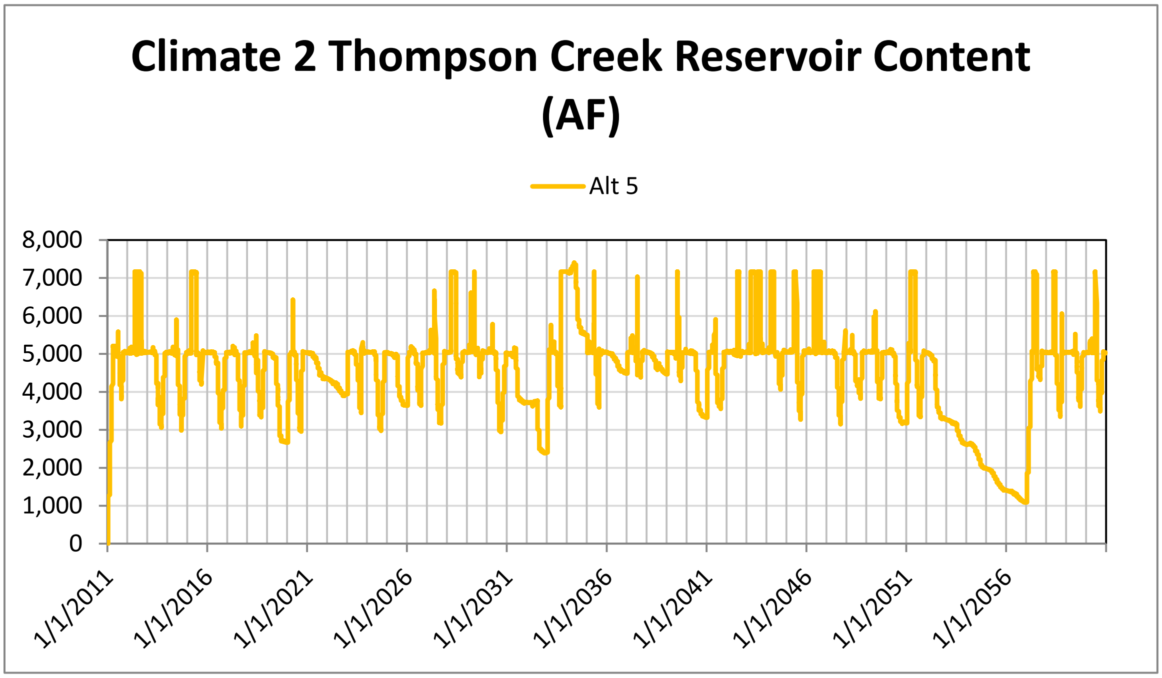


**Figure 93. — Climate Scenario 2 Thompson Creek Reservoir for Alt 5**

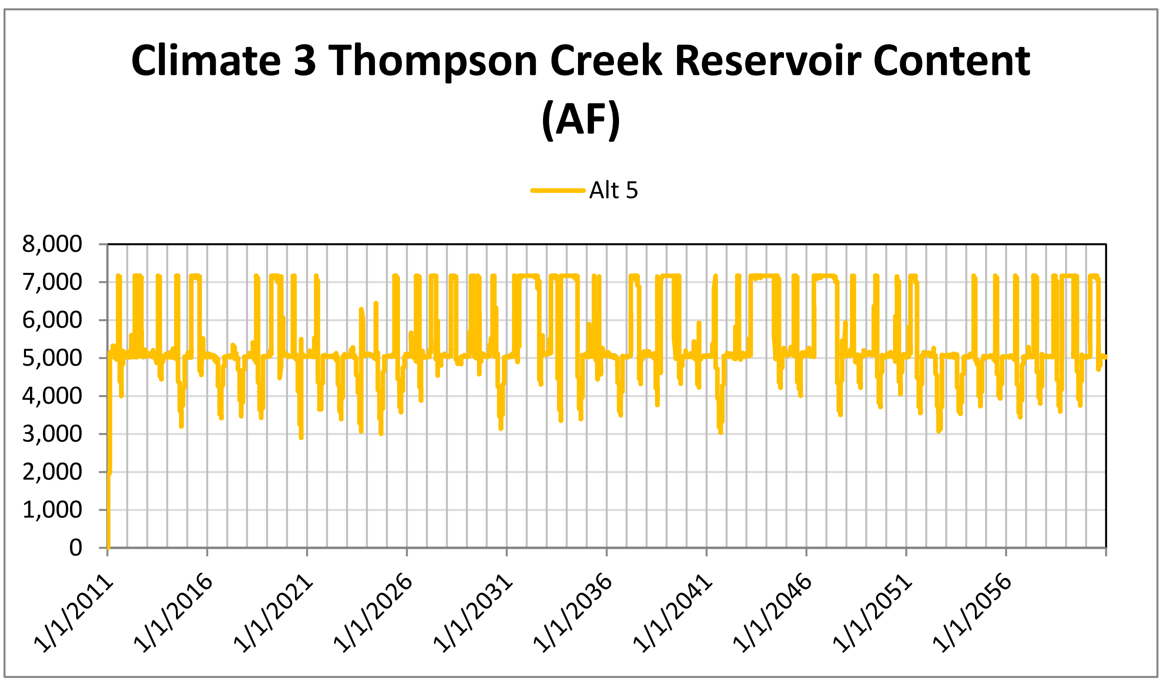


**Figure 94. — Climate Scenario 3 Thompson Creek Reservoir for Alt 5**

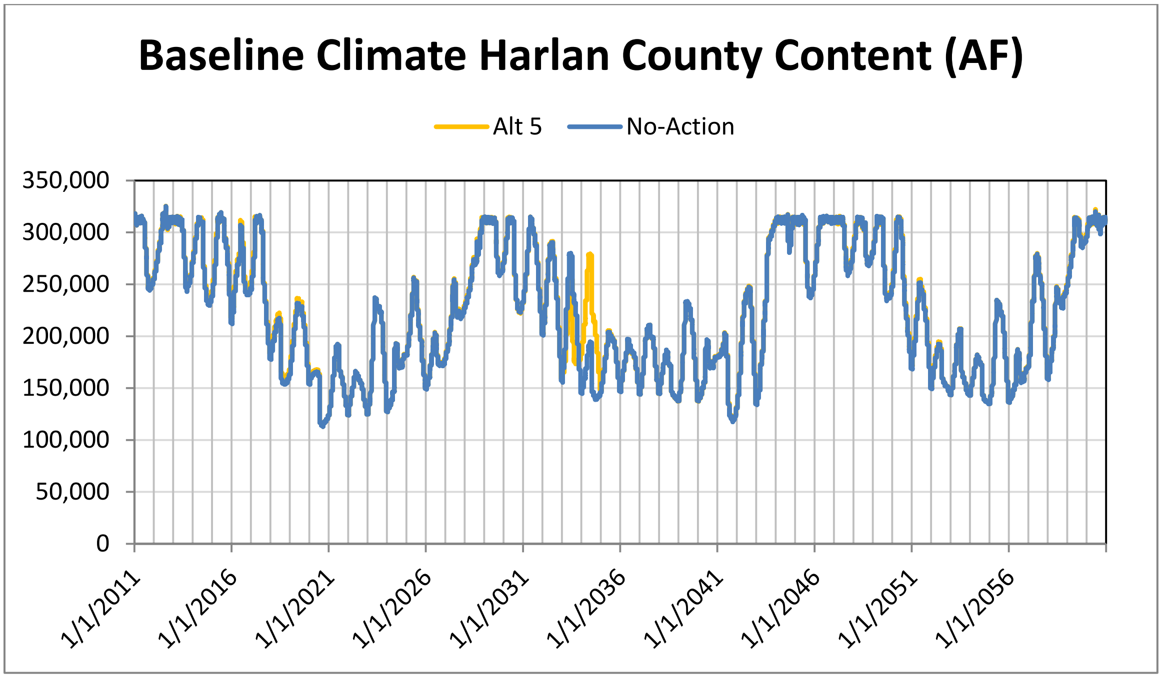


**Figure 95. — Baseline Climate Harlan County Content for Alt 5**

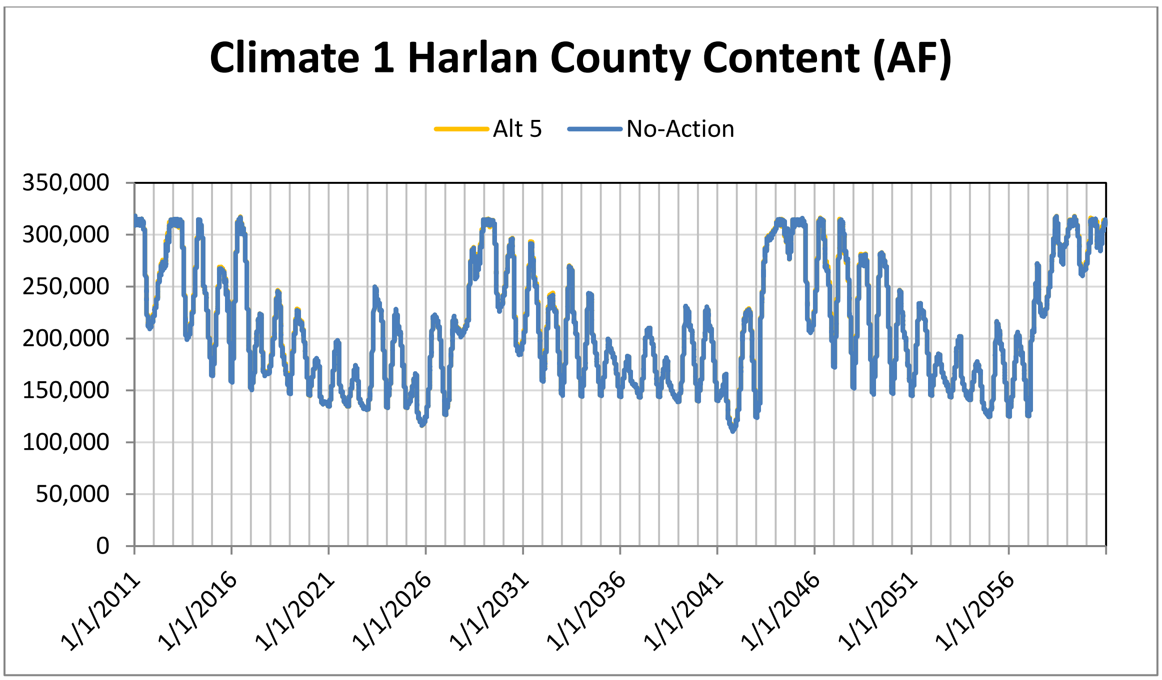


**Figure 96. — Climate Scenario 1 Harlan County Content for Alt 5**

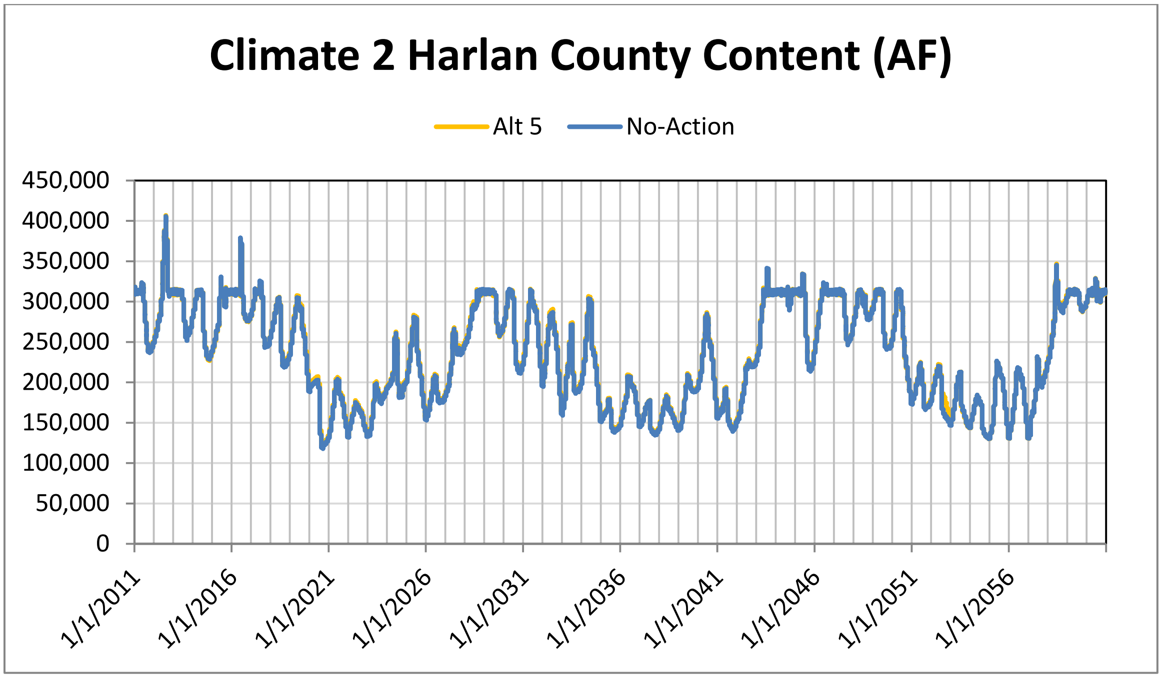


**Figure 97. — Climate Scenario 2 Harlan County Content for Alt 5**

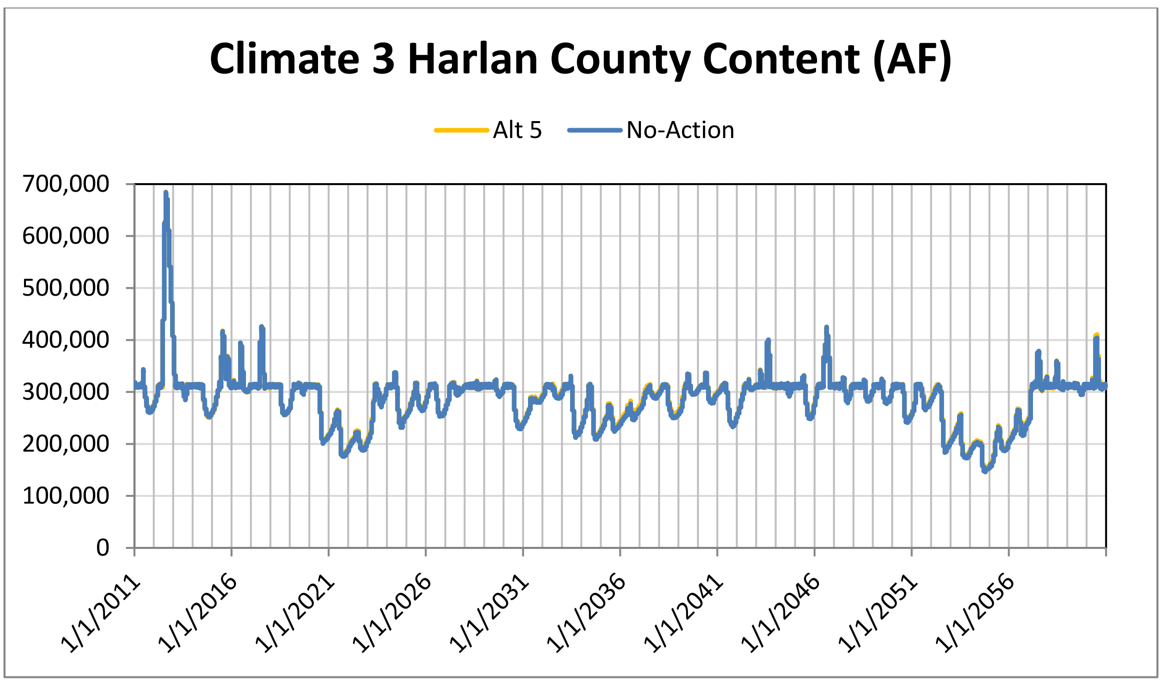


**Figure 98. — Climate Scenario 3 Harlan County Content for Alt 5**

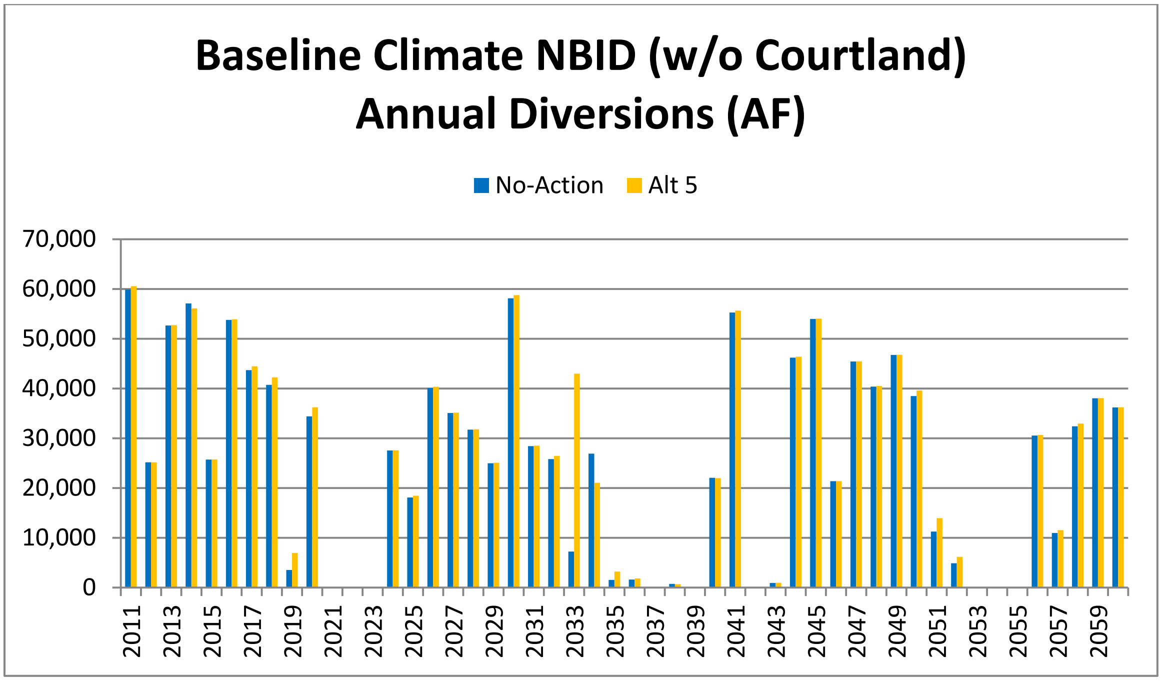


**Figure 99. — Baseline Climate NBID (w/o Courtland Canal) Annual Diversions for Alt 5**

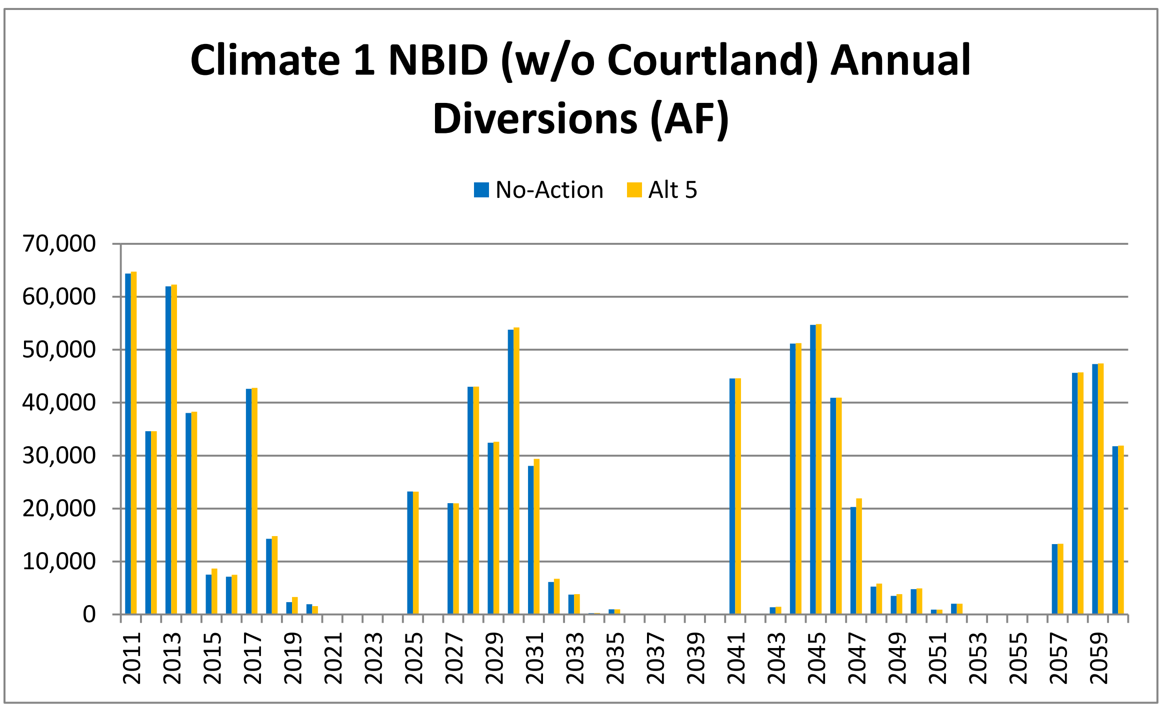


**Figure 100. — Climate Scenario 1 NBID (w/o Courtland Canal) Annual Diversions for Alt 5**

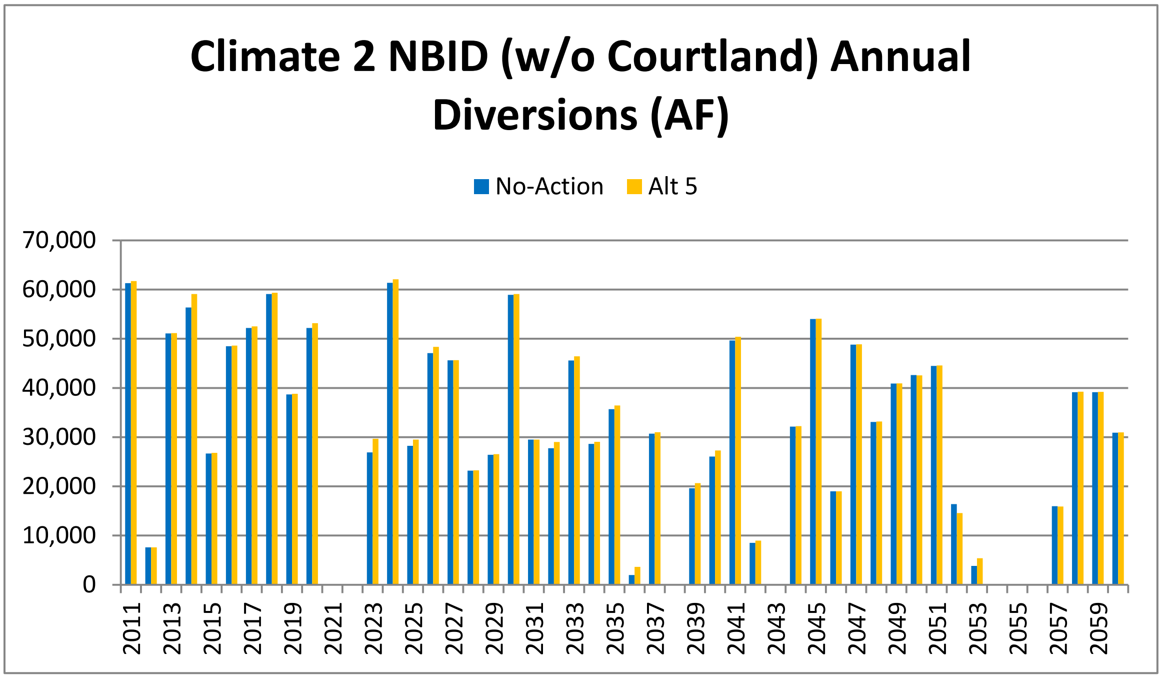


**Figure 101. — Climate Scenario 2 NBID (w/o Courtland Canal) Annual Diversions for Alt 5**

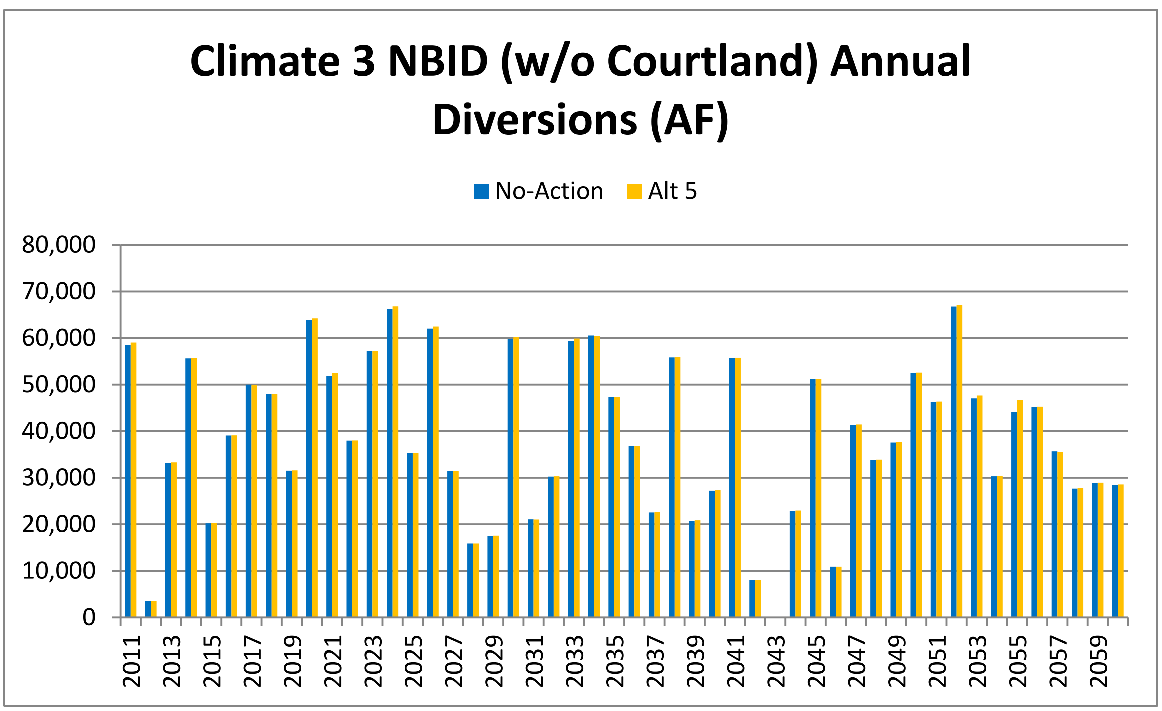


**Figure 102. — Climate Scenario 3 NBID (w/o Courtland Canal) Annual Diversions for Alt 5**

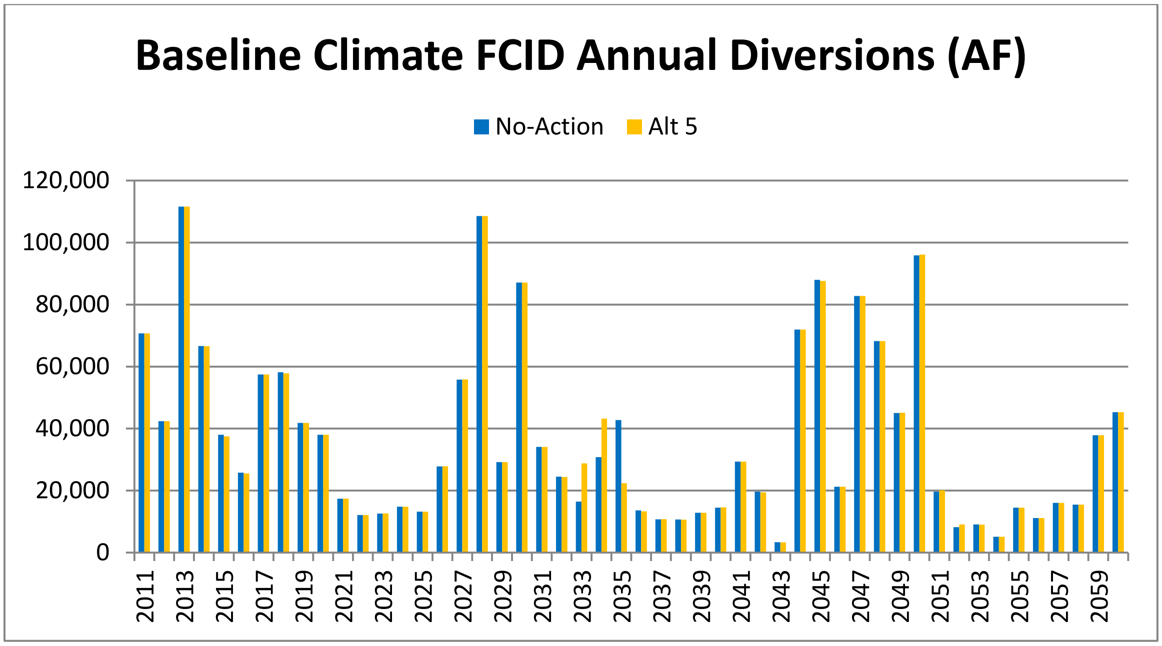


**Figure 103. — Baseline Climate FCID Annual Diversions for Alt 5**

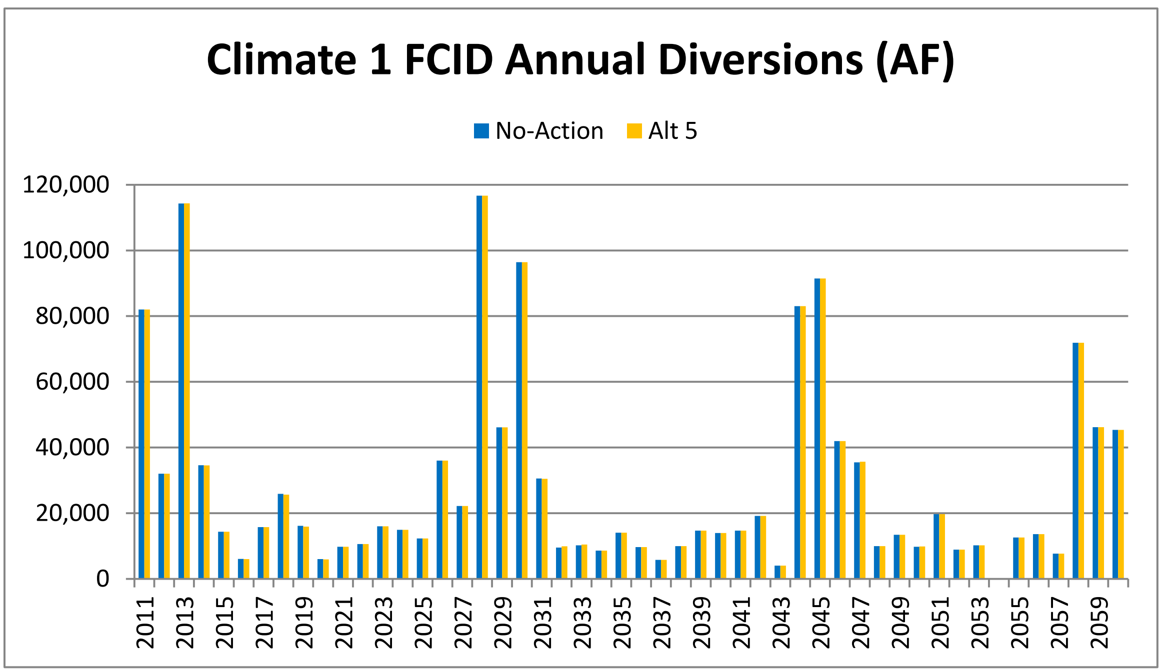


**Figure 104. — Climate Scenario 1 FCID Annual Diversions for Alt 5**

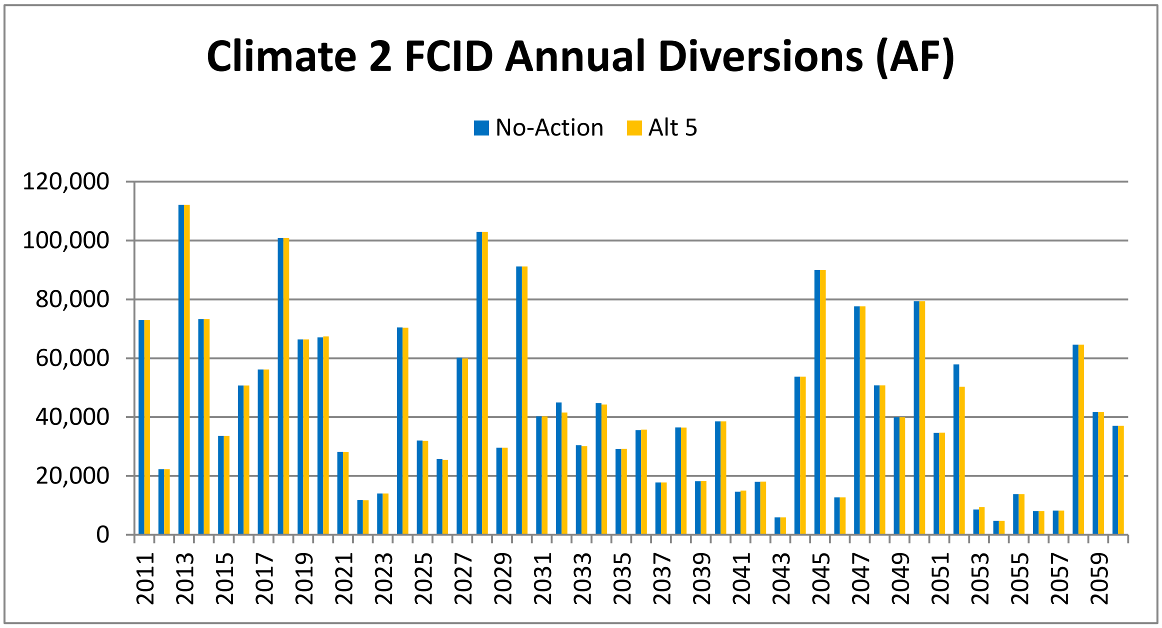


**Figure 105. — Climate Scenario 2 FCID Annual Diversions for Alt 5**

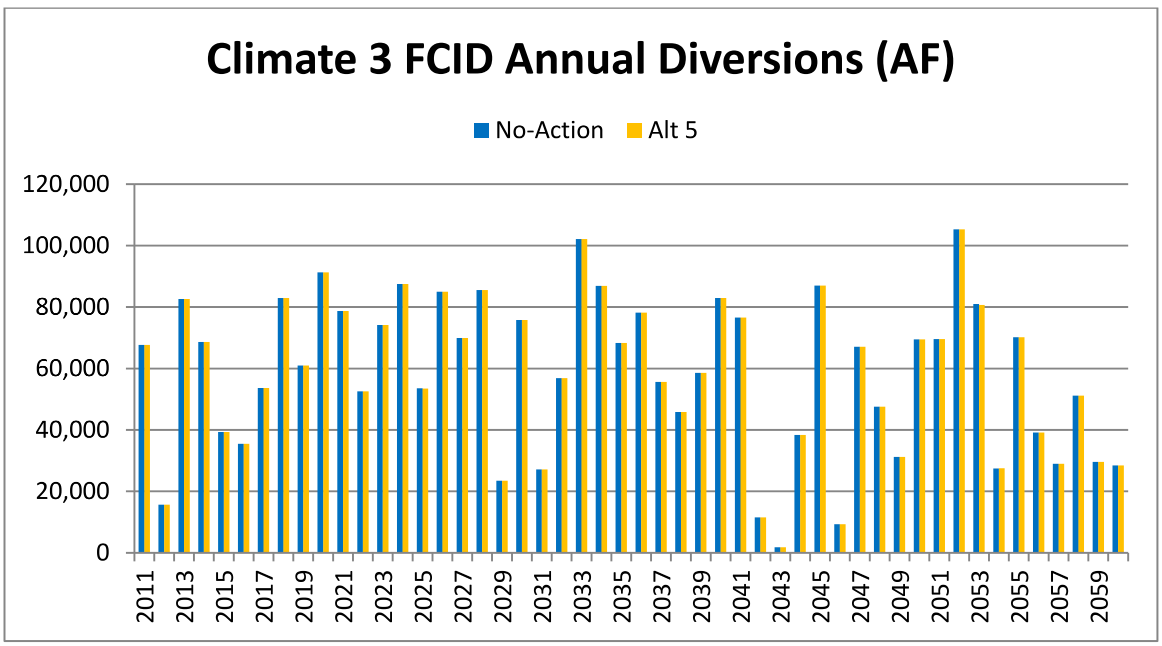


**Figure 106. — Climate Scenario 3 FCID Annual Diversions for Alt 5**

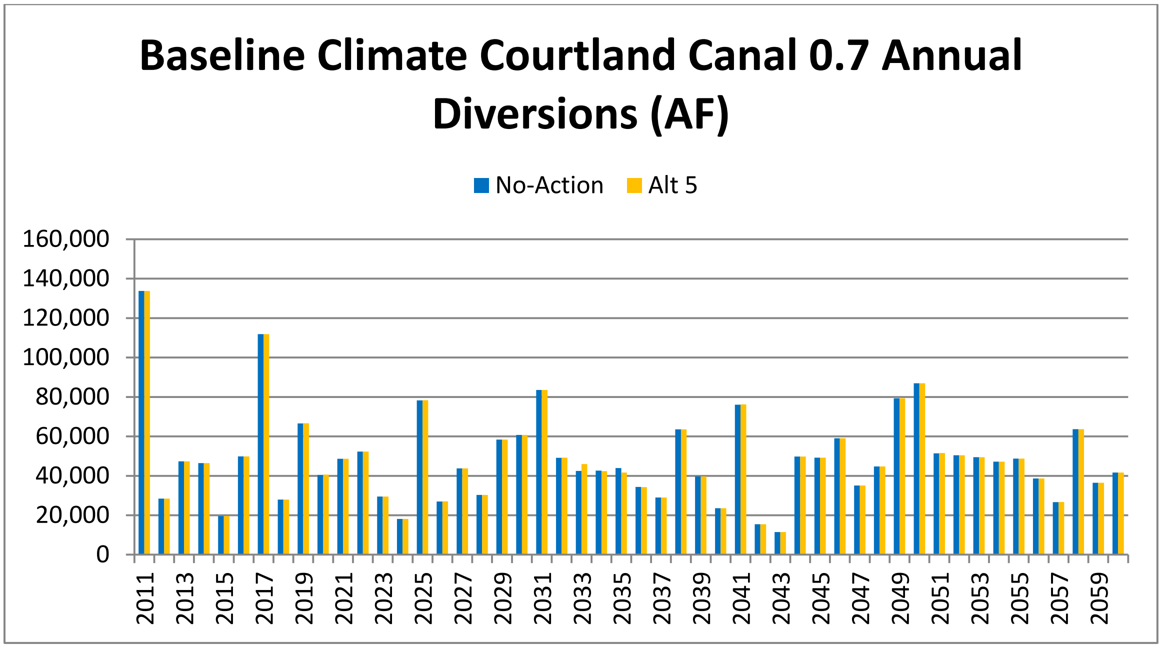


**Figure 107. — Baseline Climate Courtland Canal 0.7 Annual Diversions for Alt 5**

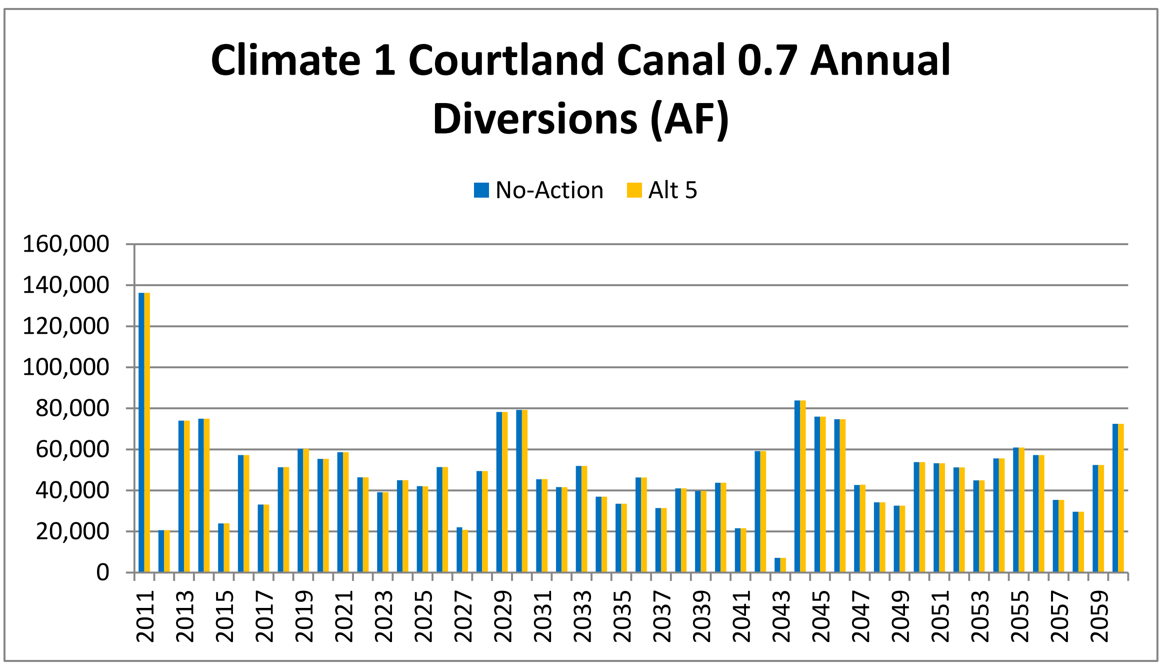


**Figure 108. — Climate Scenario 1 Courtland Canal 0.7 Annual Diversions for Alt 5**

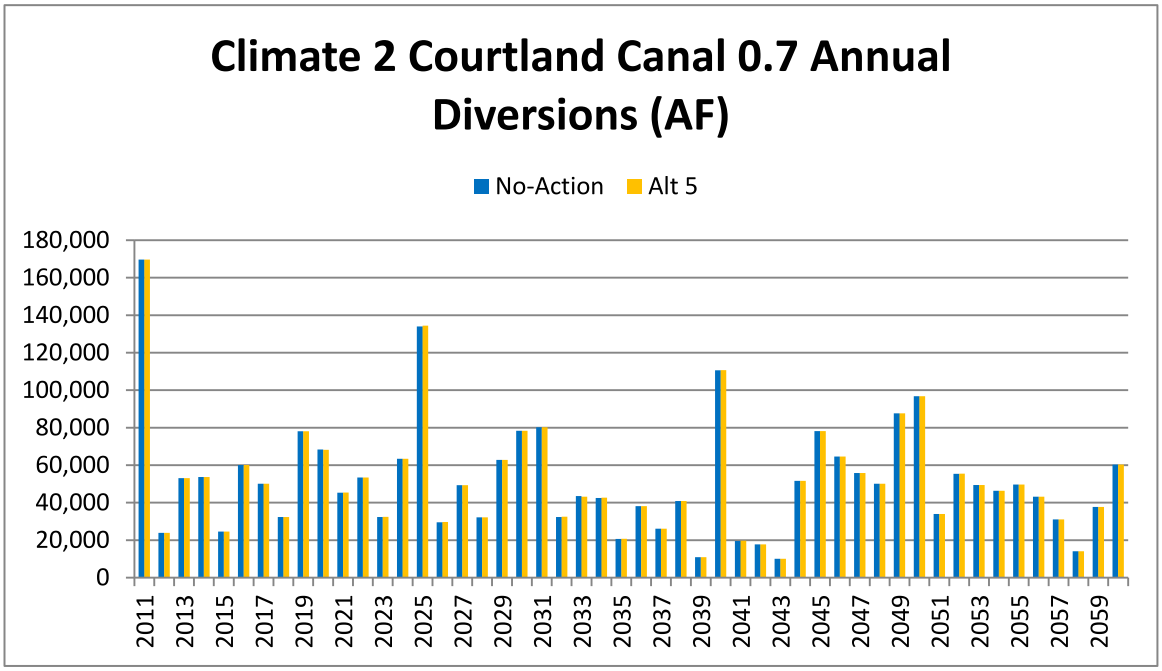


**Figure 109. — Climate Scenario 2 Courtland Canal 0.7 Annual Diversions for Alt 5**

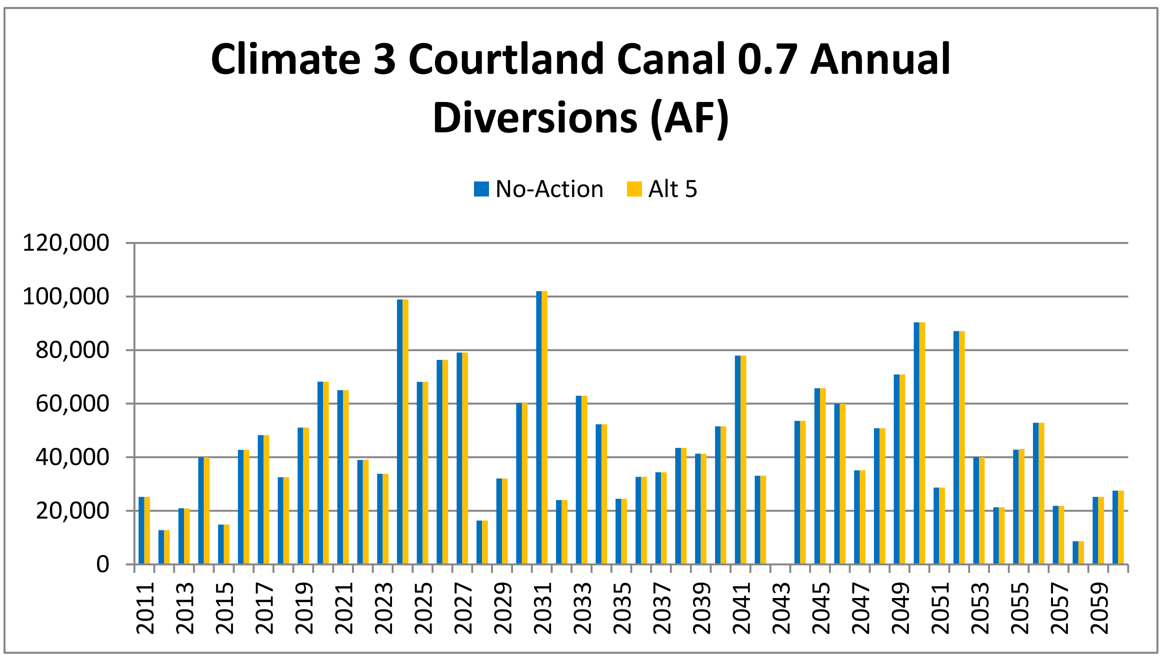


**Figure 110. — Climate Scenario 3 Courtland Canal 0.7 Annual Diversions for Alt 5**

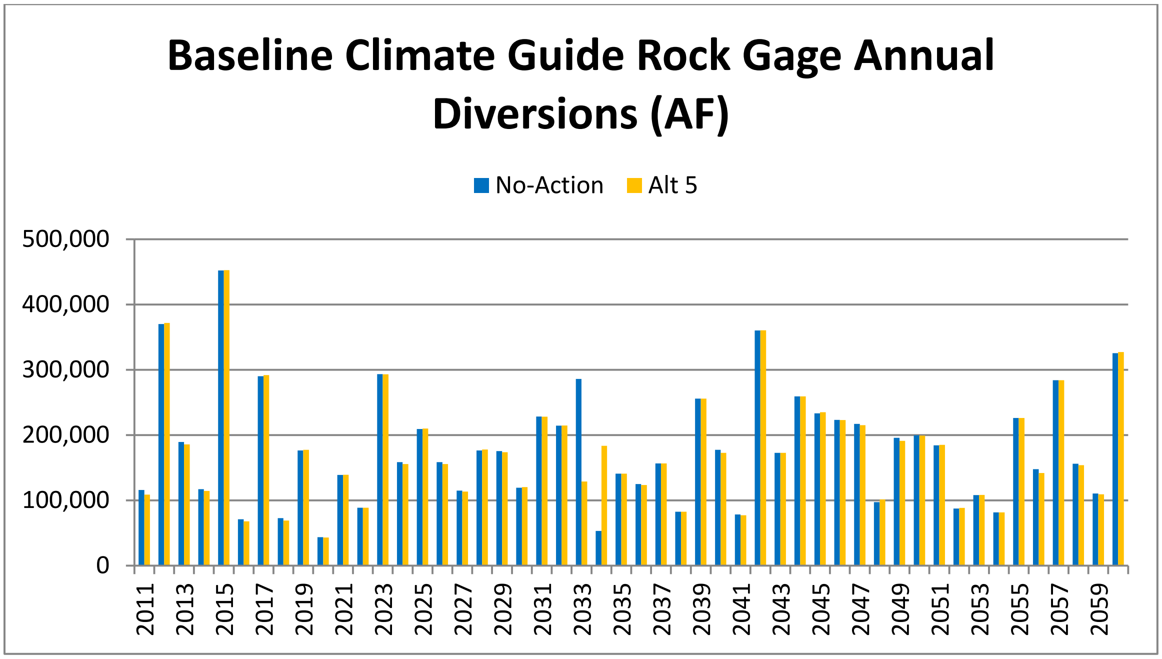


**Figure 111. — Baseline Climate Guide Rock Gage Annual Diversions for Alt 5**

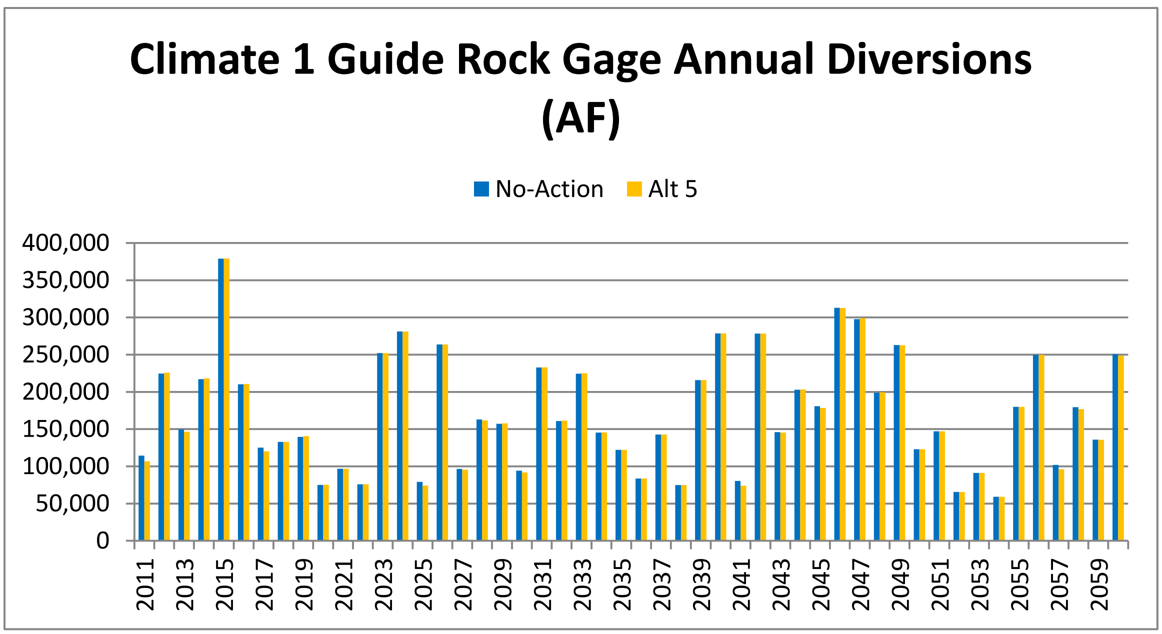


**Figure 112. — Climate Scenario 1 Guide Rock Gage Annual Diversions for Alt 5**

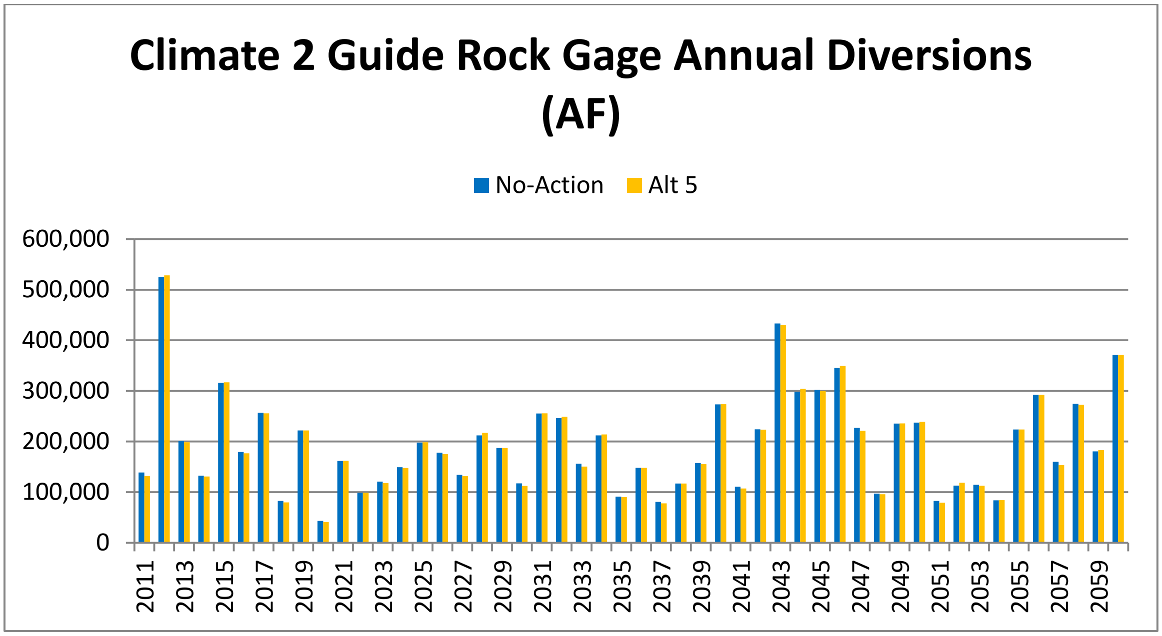


**Figure 113. — Climate Scenario 2 Guide Rock Gage Annual Diversions for Alt 5**

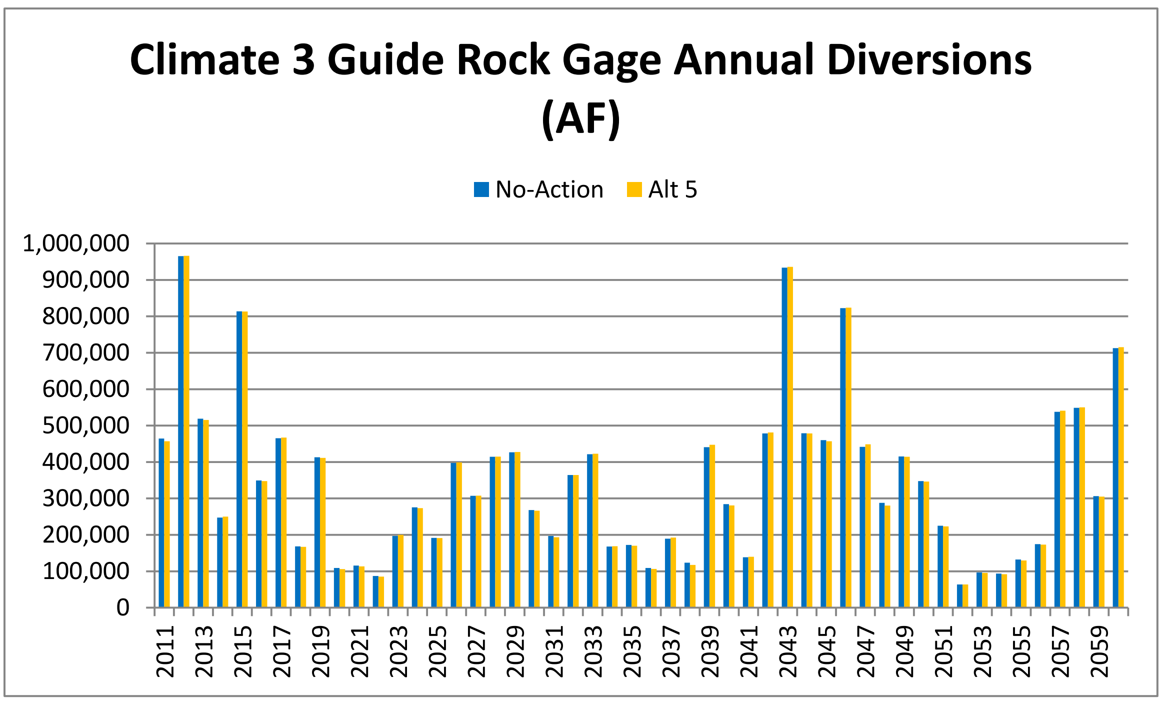


**Figure 114. — Climate Scenario 3 Guide Rock Gage Annual Diversions for Alt 5**

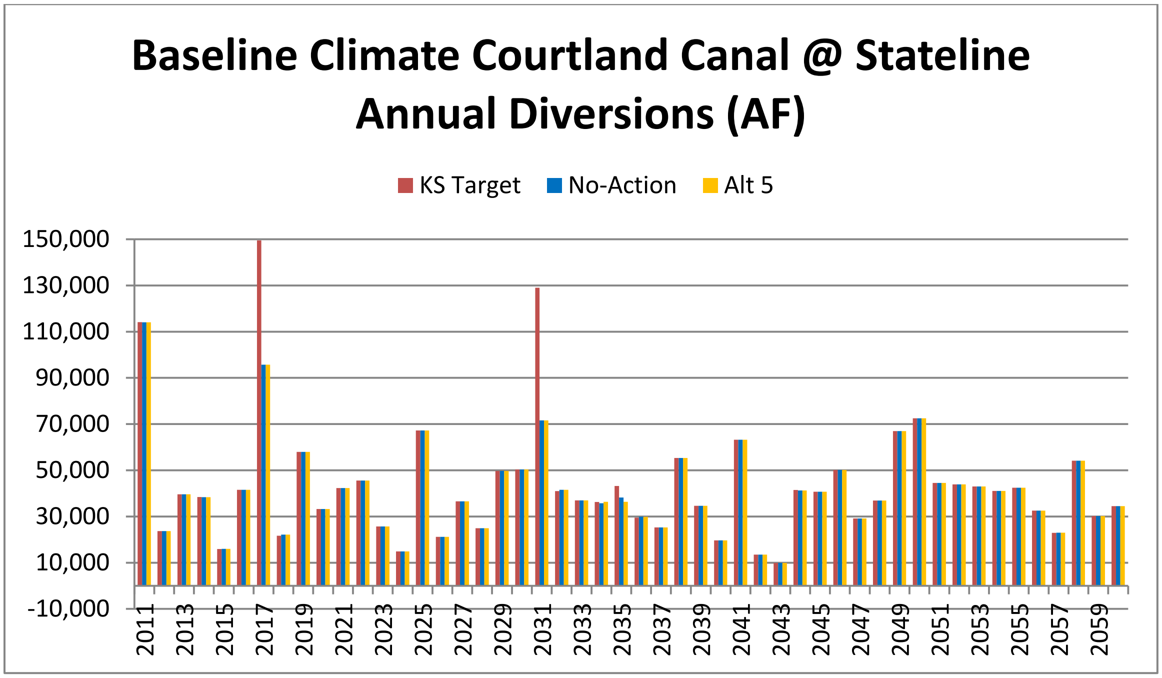


**Figure 115. — Baseline Climate Courtland Canal at Stateline Annual Diversions for Alt 5**

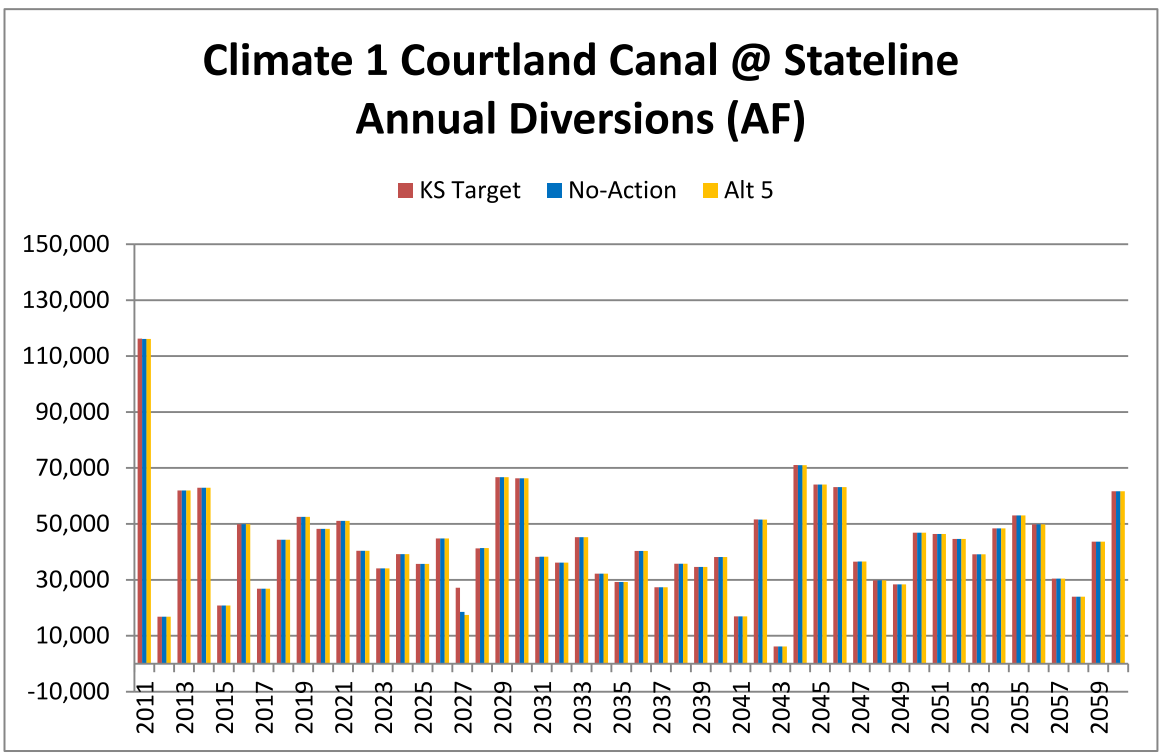


**Figure 116. — Climate Scenario 1 Courtland Canal at Stateline Annual Diversions for Alt 5**

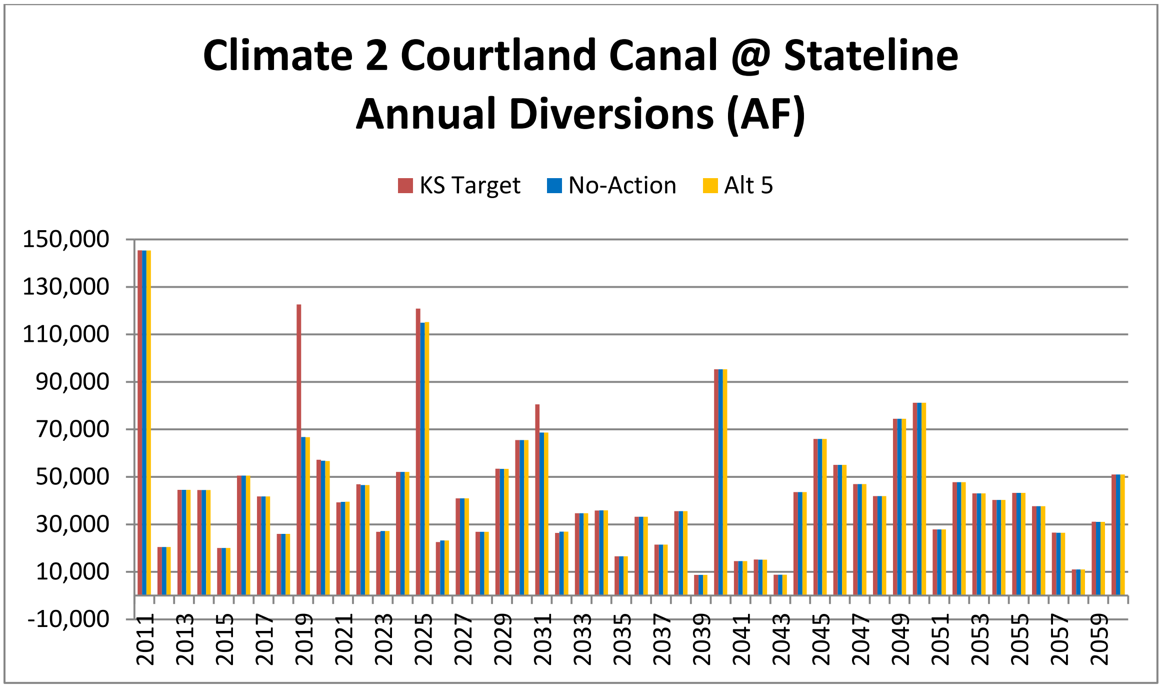


**Figure 117. — Climate Scenario 2 Courtland Canal at Stateline Annual Diversions for Alt 5**

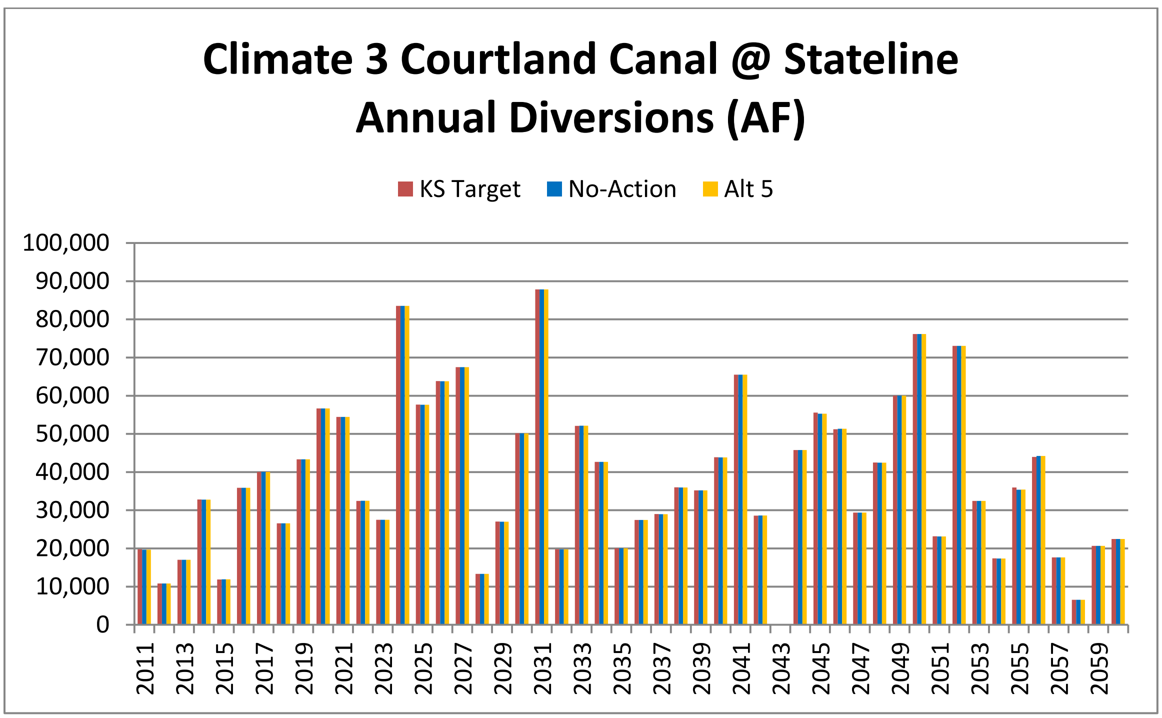


**Figure 118. — Climate Scenario 3 Courtland Canal at Stateline Annual Diversions for Alt 5**

## C. Kansas Approach

As stated previously, Kansas' objective is to ensure Compact compliance and minimize water shortages in the Lower Republican River Basin, in particular in the Kansas-Bostwick Irrigation District (KBID). Operationally, KBID is broken into two areas: that portion located above Lovewell Reservoir referred to in this document as upper KBID (or KBID-UP) and that portion below Lovewell Reservoir referred to as lower KBID (KBID-DOWN). Of particular interest is the ability to meet demands of both the upper and lower KBID. Historically, KBID has experienced severe water shortages during droughts or periods of Compact non-compliance.

To assess the effectiveness of each alternative, upper and lower KBID shortages were compared between the No Action Alternative and Action Alternatives using an iterative process for optimization. First, as presented in *Section 5.0: System Reliability and Impact Analysis*, the No Action Alternative was run with all climate scenarios, including the baseline to identify the climate scenario that caused the most water shortages throughout the 50-year simulation period. Based on that analysis, only the warmer/drier Scenario 1, along with the Baseline Scenario, was selected for the Action Alternatives Analysis.

## D. Kansas Results

### 1. Baseline Climate – Reservoirs

Based on model simulations, Harlan County Lake is not predicted to change significantly with the expansion of Lovewell Reservoir (Figure 119); however, there are significant changes to Lovewell Reservoir's storage as capacity is increased (Figure 120). The volume of water stored within each reservoir determines the water elevation and surface area of water in the reservoirs. Results for elevation, surface area, reservoir inflows and reservoir outflows are provided in the Kansas Modeling Results TM (KGS and KWO 2015a).

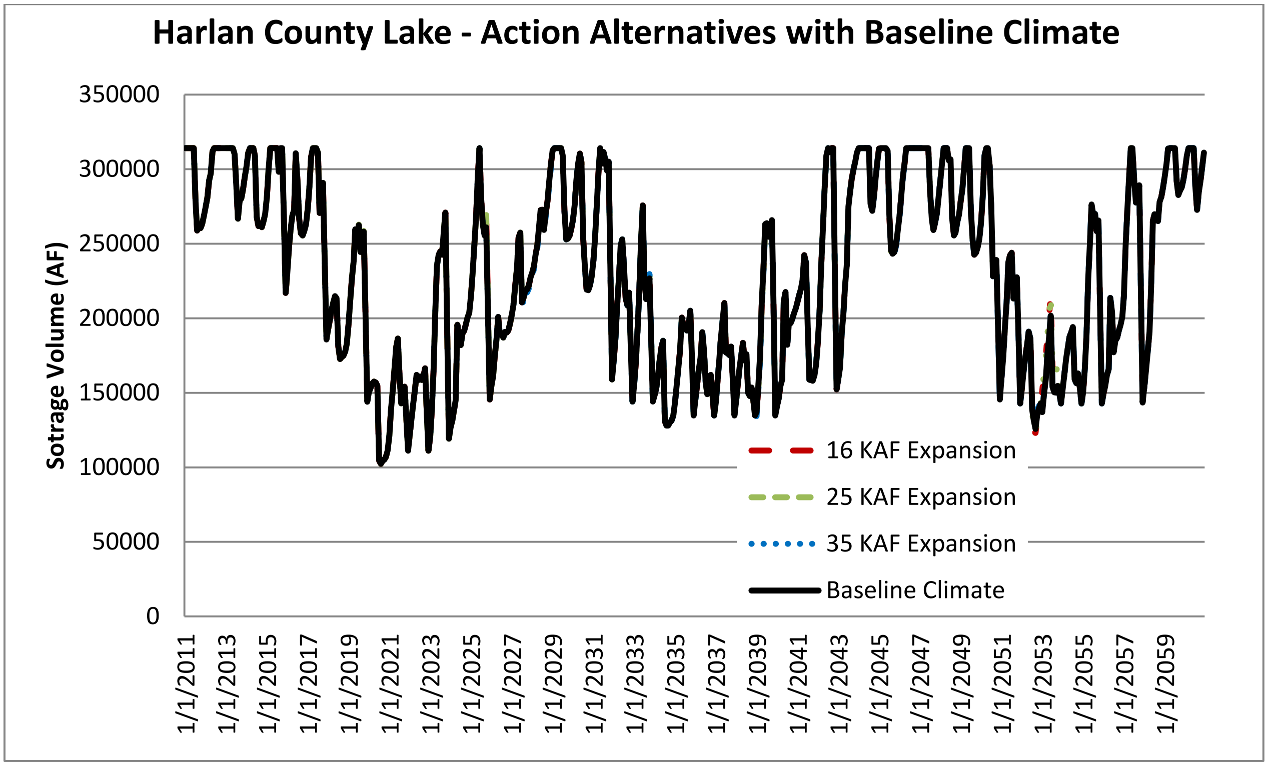


**Figure 119. — Storage volumes in Harlan County Lake for action alternatives with Baseline Climate from 2011-2060.**

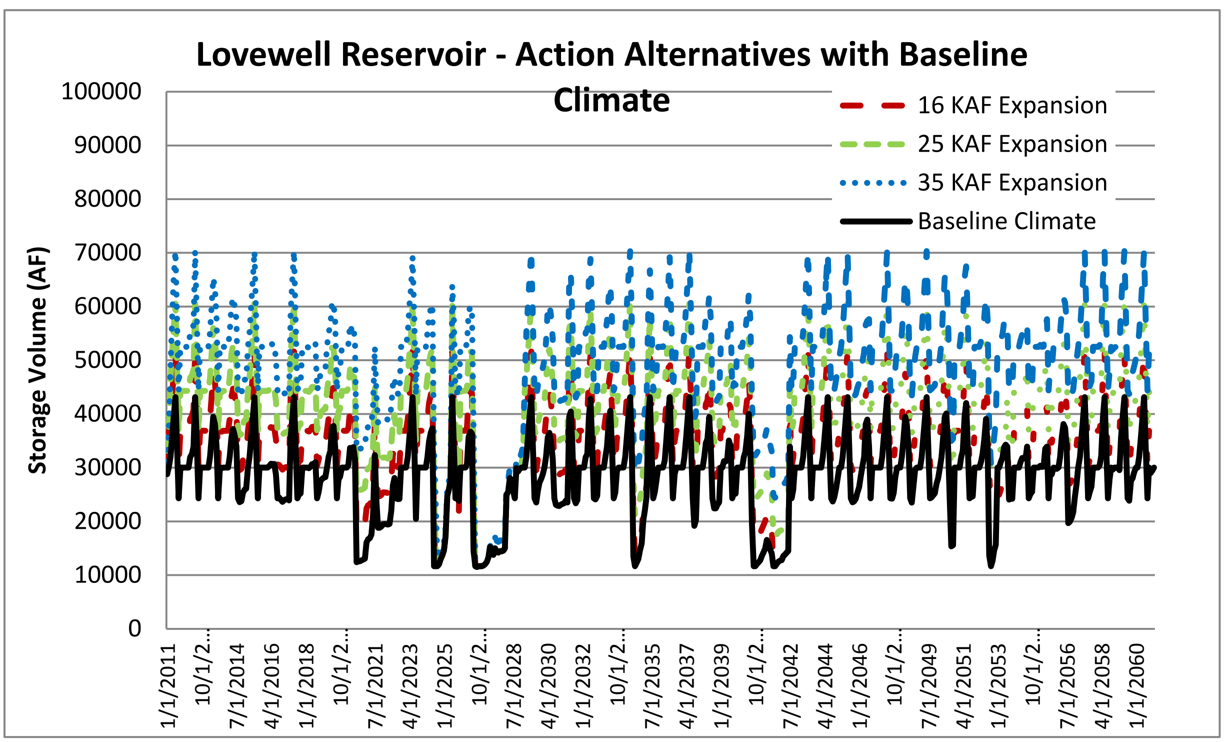


**Figure 120. — Storage volumes in Lovewell Reservoir for action alternatives with Baseline Climate from 2011-2060.**

## 2. Baseline Climate – Stream Gages

As illustrated in Figures 121 through 124, the streamflow at the Hardy, Courtland, Clay Center, and Concordia gages are not significantly altered due to the expansion of Lovewell under the Baseline Climate Scenario.

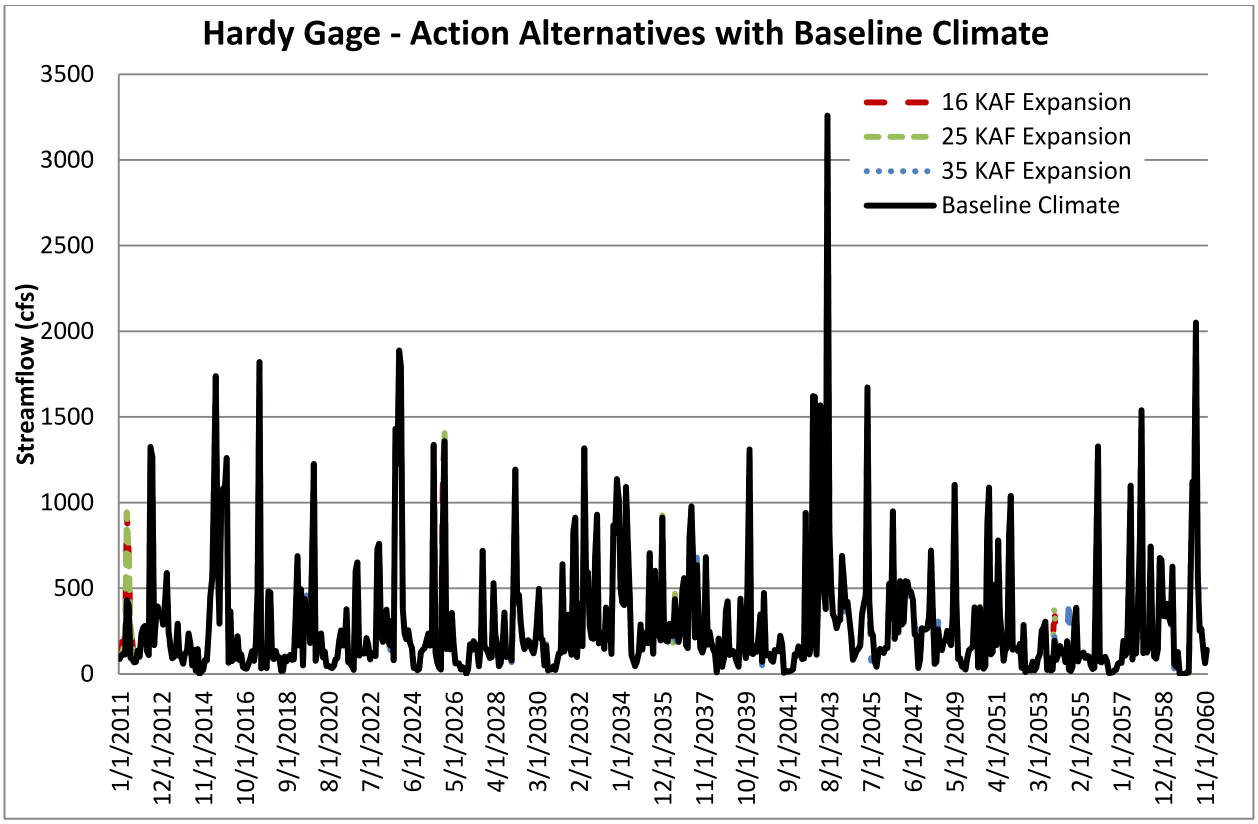


**Figure 121. — Streamflow at Hardy gage for action alternatives with Baseline Climate from 2011-2060.**

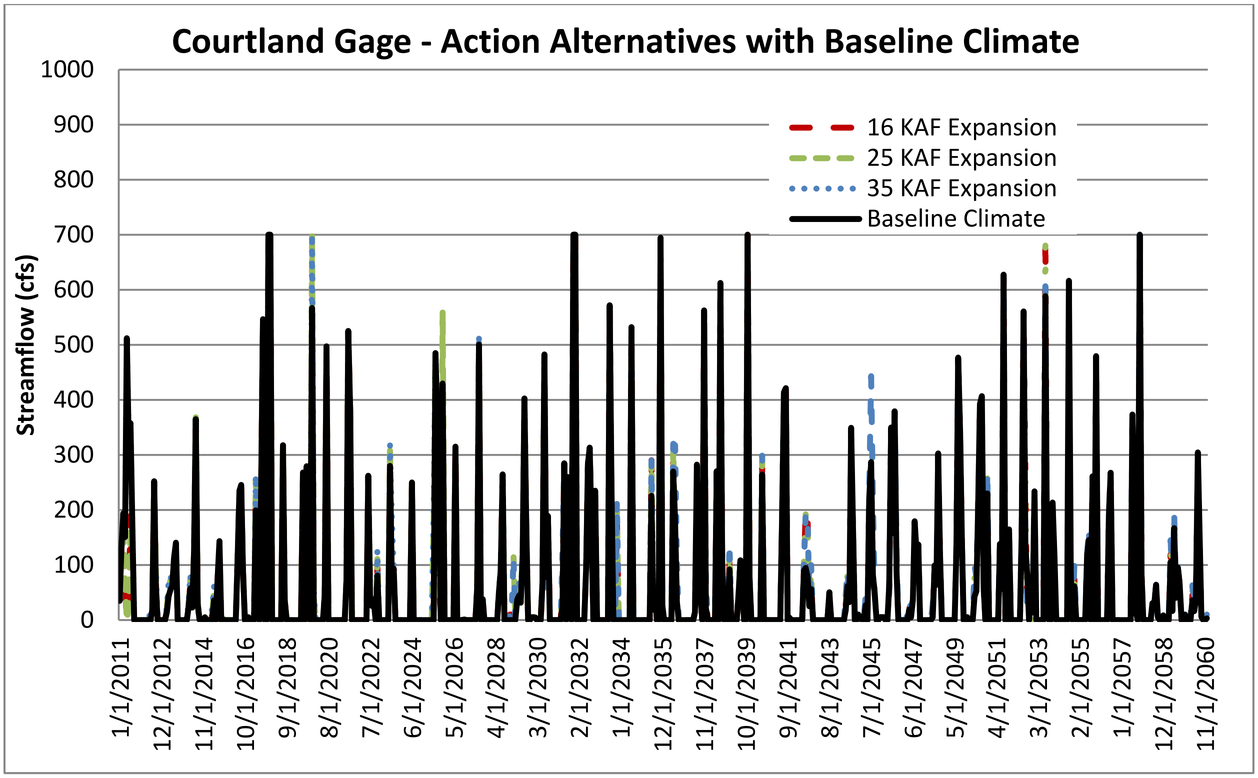


**Figure 122. — Streamflow at Courtland gage for action alternatives with Baseline Climate from 2011-2060.**

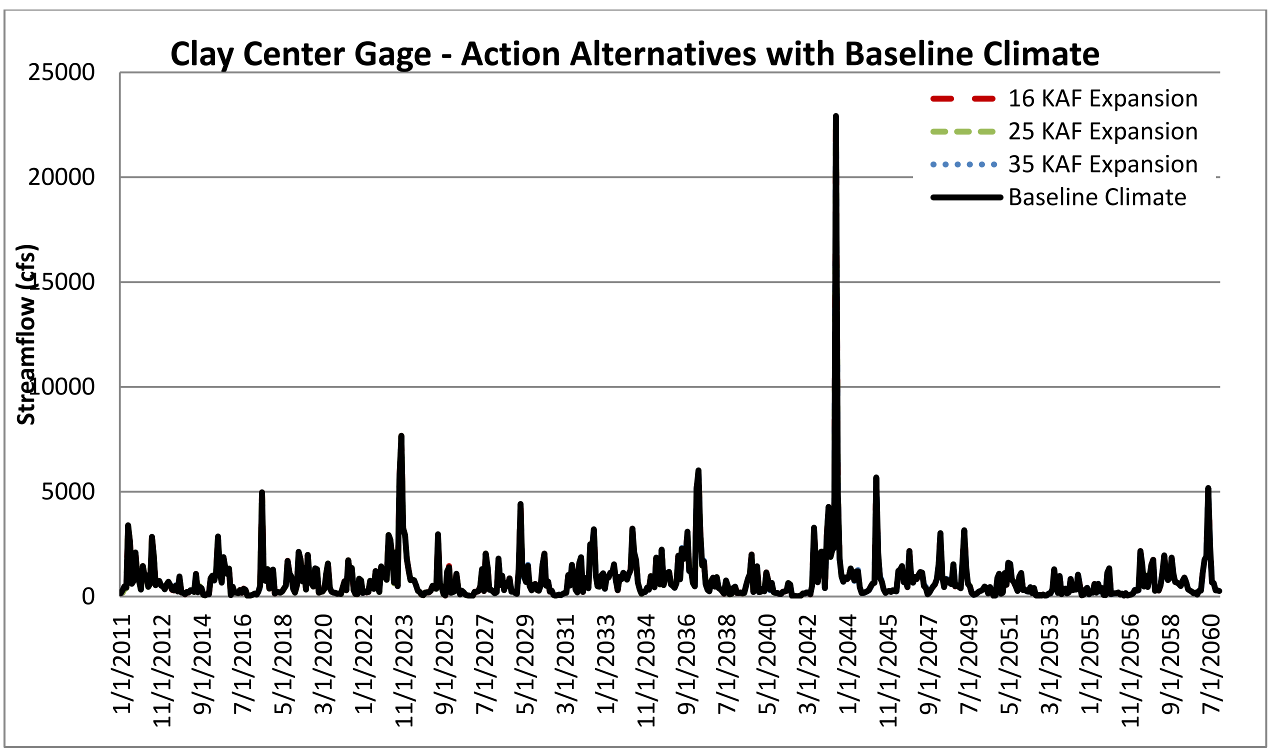


**Figure 123. — Streamflow at Clay Center gage for action alternatives with Baseline Climate from 2011-2060.**

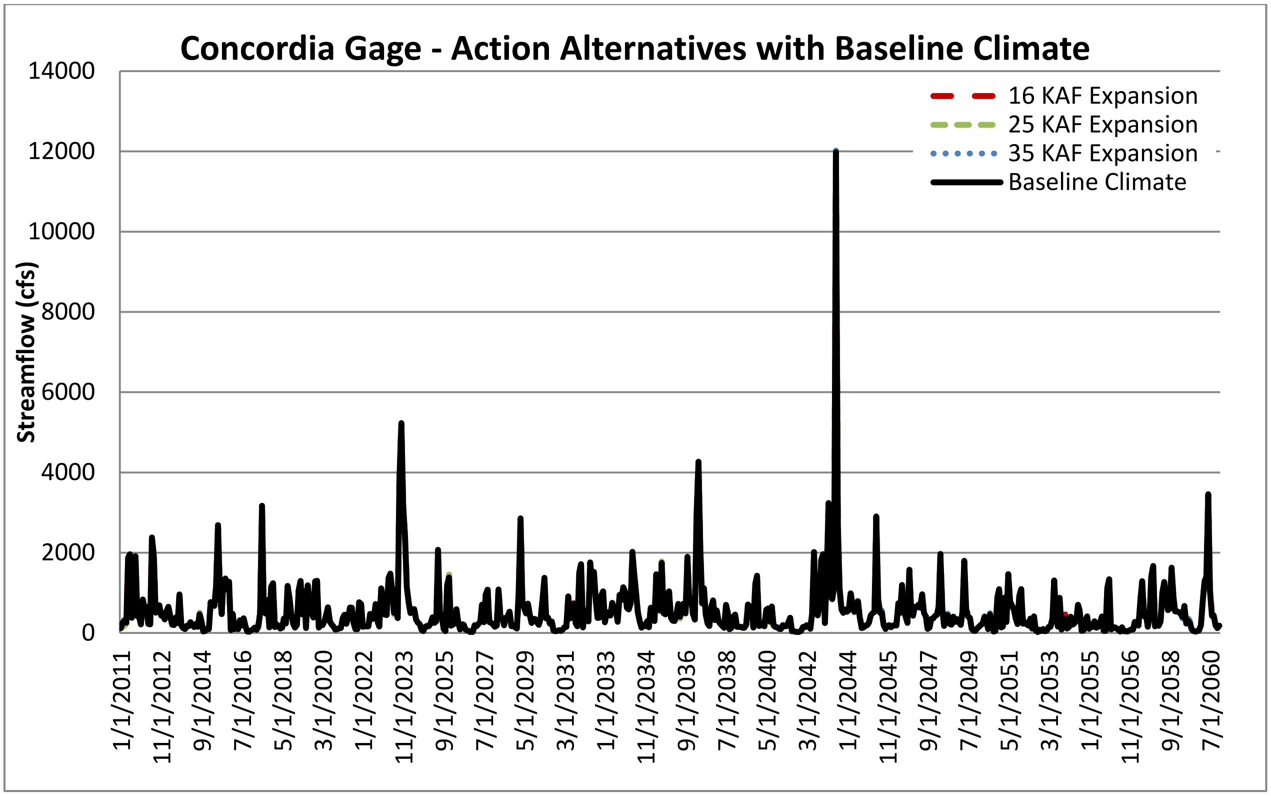


**Figure 124. — Streamflow at Concordia gage for action alternatives with Baseline Climate from 2011-2060.**

## 3. Baseline Climate – Water Demands and Shortages

Irrigation demands under the Baseline Climate Scenario are illustrated in Figures 125 and 127 below.

As presented in Figure 127, KBID-UP does not experience any significant change in water shortages because of its location above Lovewell Reservoir; however, KBID-DOWN water shortages are reduced by the expansion of Lovewell Reservoir (Figure 128).

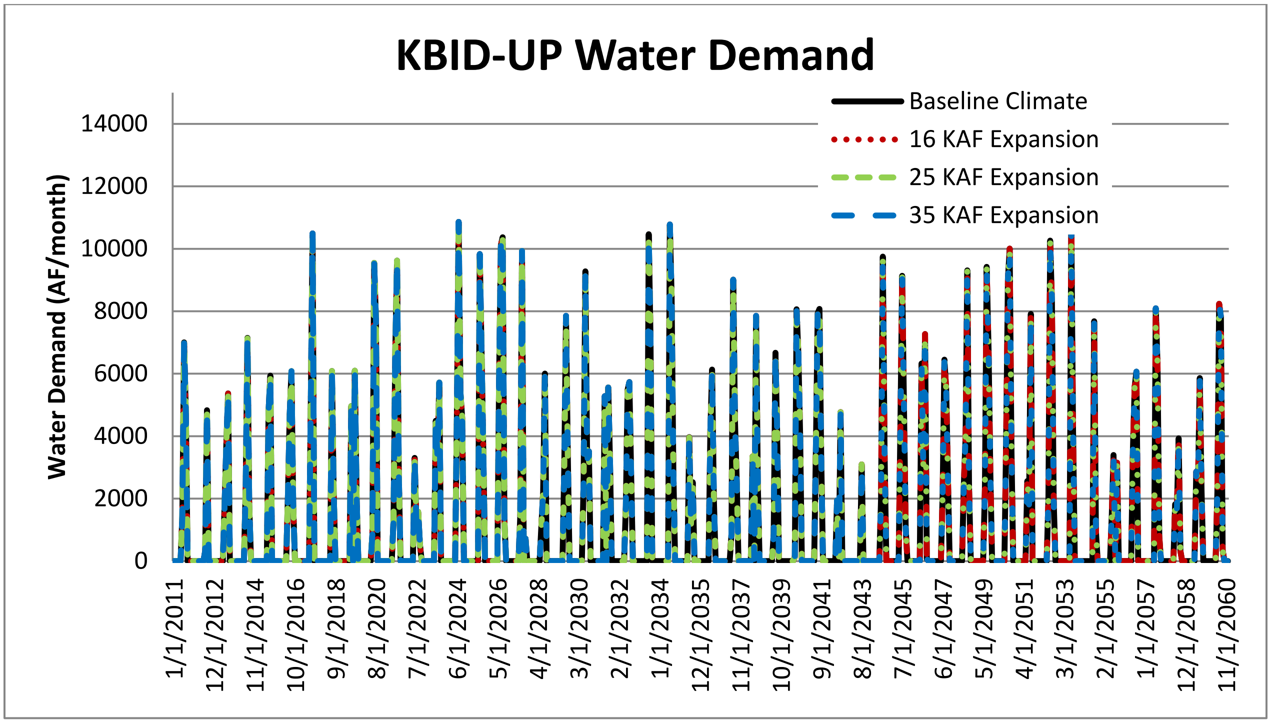


**Figure 125. — Water demands for KBID-UP for action alternatives under Baseline Climate from 2011-2060.**

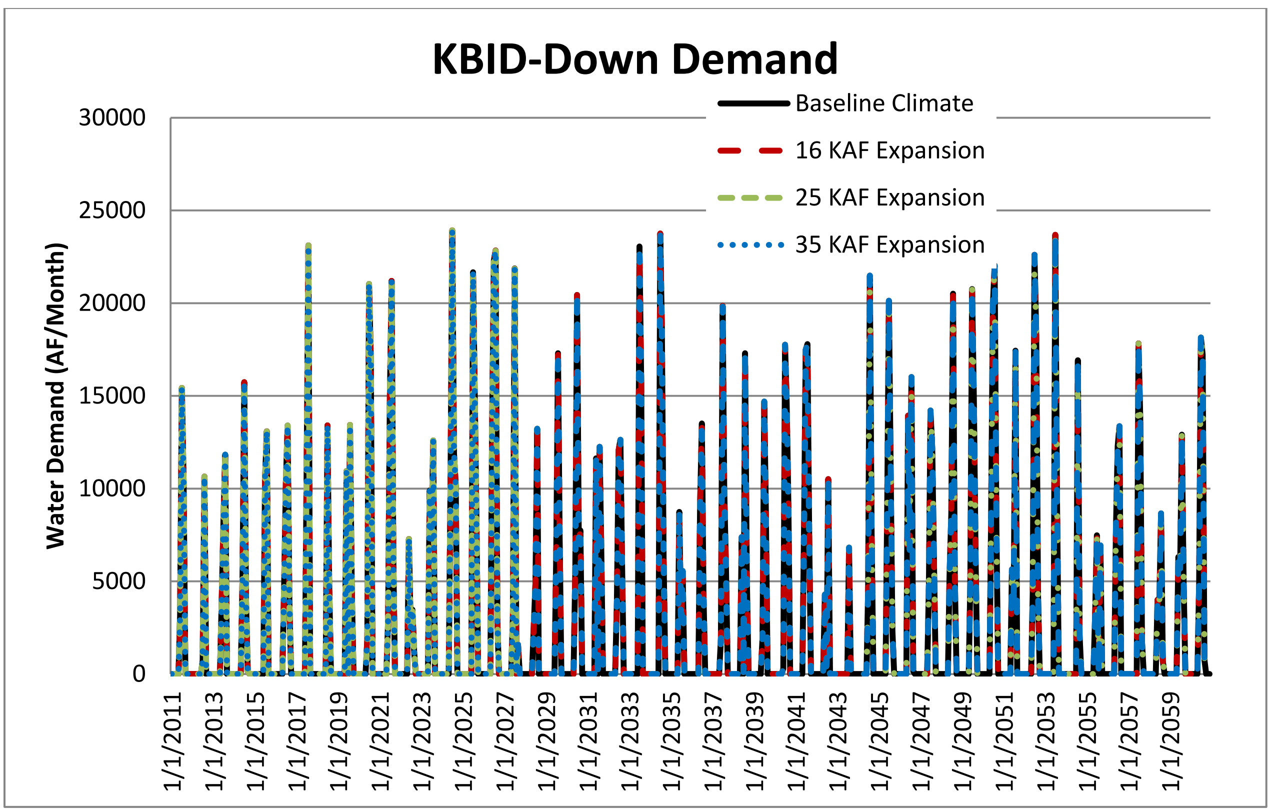


**Figure 126. — Water demands for KBID-DOWN for action alternatives under Baseline Climate from 2011-2060.**

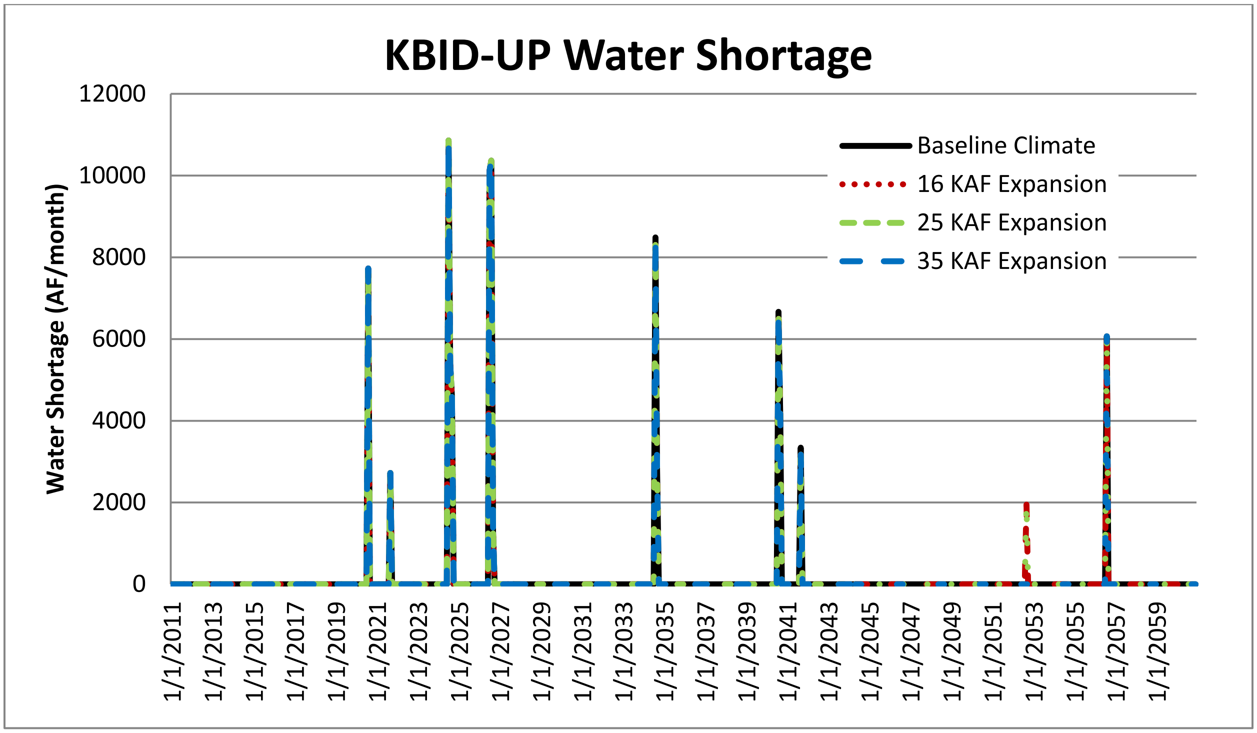


**Figure 127. — KBID-UP water shortages for action alternatives with Baseline Climate from 2011-2060.**

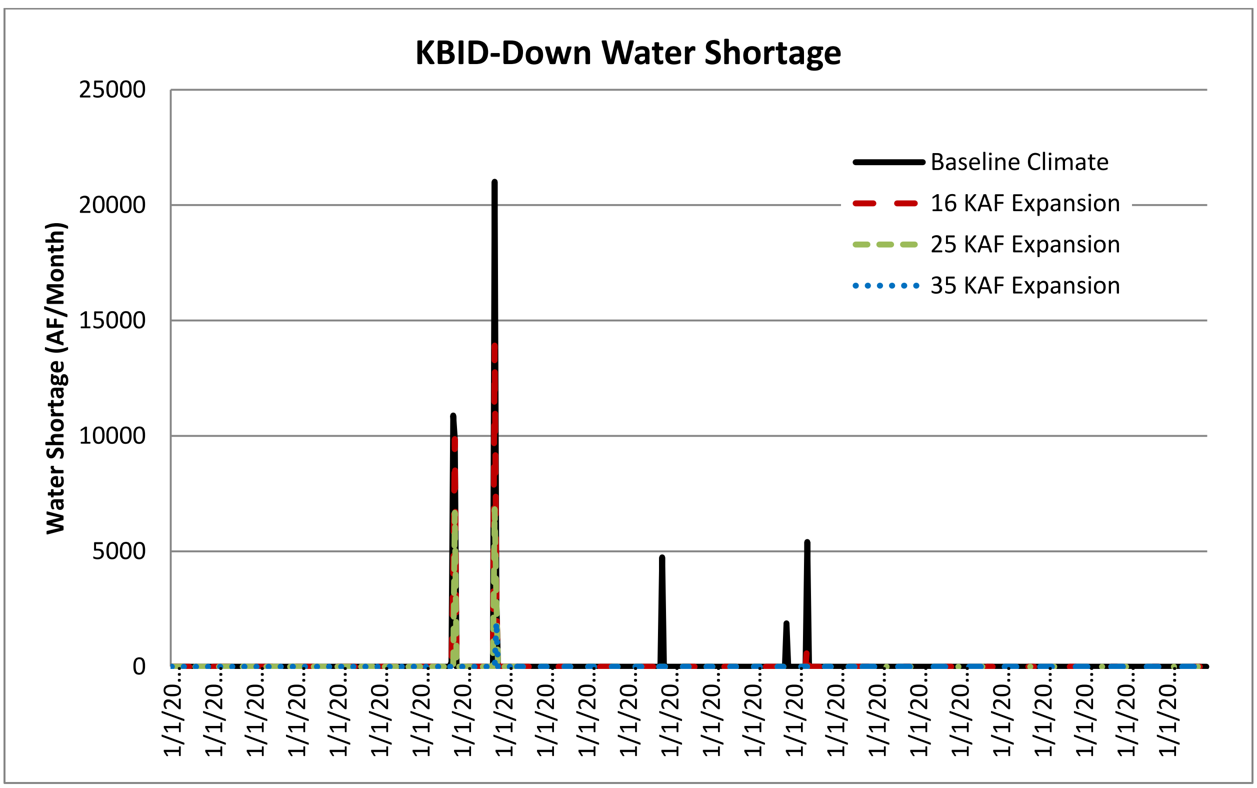


**Figure 128. — KBID-DOWN water shortages for action alternatives with Baseline Climate from 2011-2060.**

## 4. Hot and Dry Climate – Reservoirs

The environmental metric for reservoirs that guides the alternatives evaluation is storage volume (Figures 129 and 130). As with the Baseline Climate action scenarios, Harlan Reservoir is not predicted to change significantly with the expansion of Lovewell (Figure 129); however there are significant changes to Lovewell reservoir's storage as capacity is increased (Figure 130). The volume of water stored within each reservoir determines the water elevation and surface area of water in the reservoirs. Results for elevation, surface area, reservoir inflows and reservoir outflows are in Kansas Modeling Results TM.

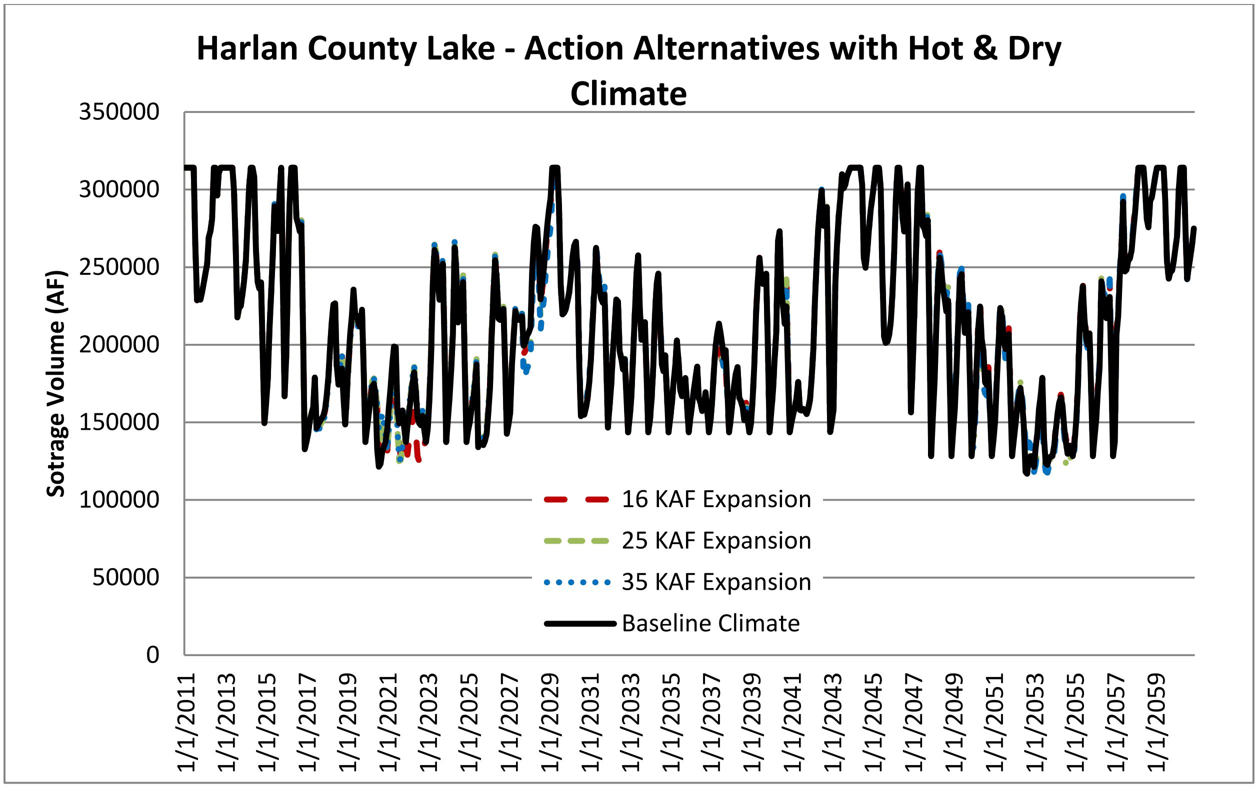


**Figure 129. — Storage volumes in Harlan County Lake for action alternatives with hot and dry climate from 2011-2060.**

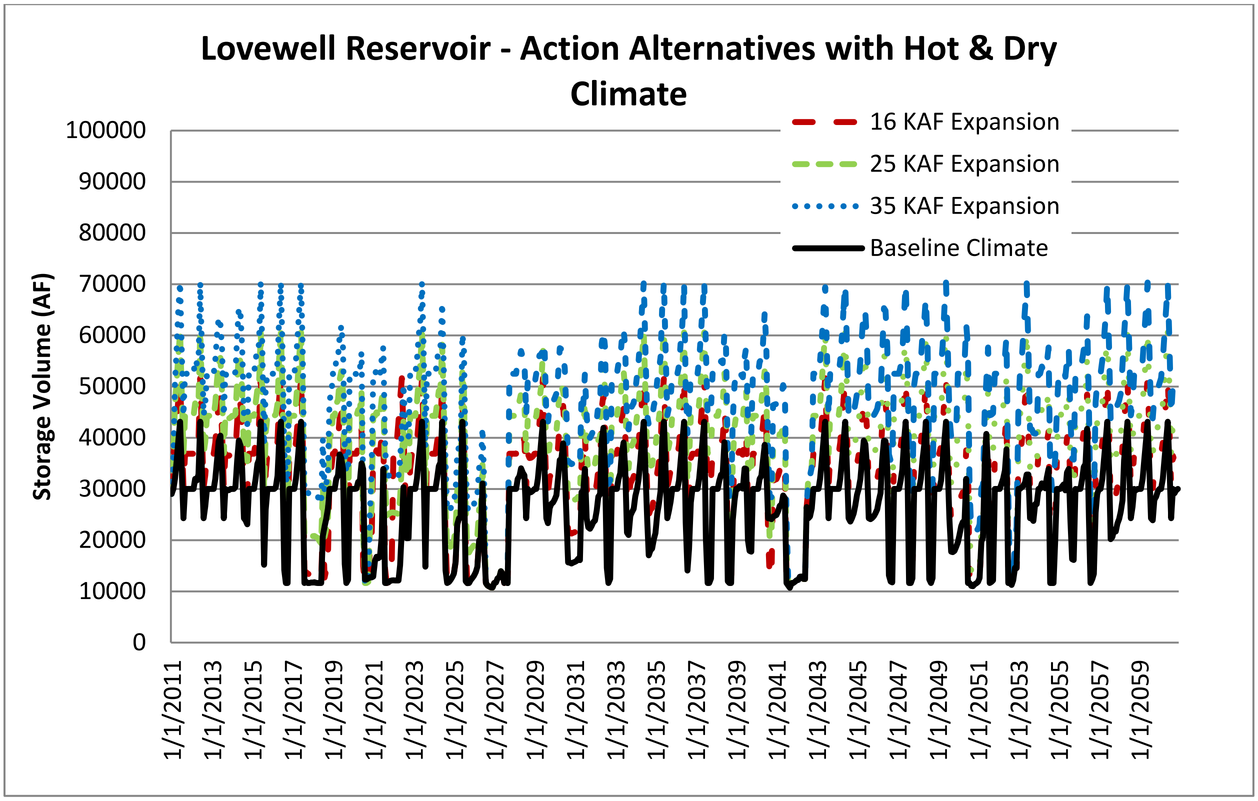


**Figure 130. — Storage volumes in Lovewell Reservoir for action alternatives with hot and dry climate from 2011-2060.**

## 5. Warmer and Drier Climate – Stream Gages

Hardy gage, located upstream of the Nebraska-Kansas border, measures the water flowing in the Republican River between states (Figure 131). Courtland gage data represents the water flowing across the state line within the irrigation canal system (Figure 132). Clay Center and Concordia gage stations are downstream of both reservoirs, but are of concern because of MDS requirements administered at each gage (Figures 133 and 134). Under the Baseline Climate, streamflows at the gages are not significantly altered due to the expansion of Lovewell.

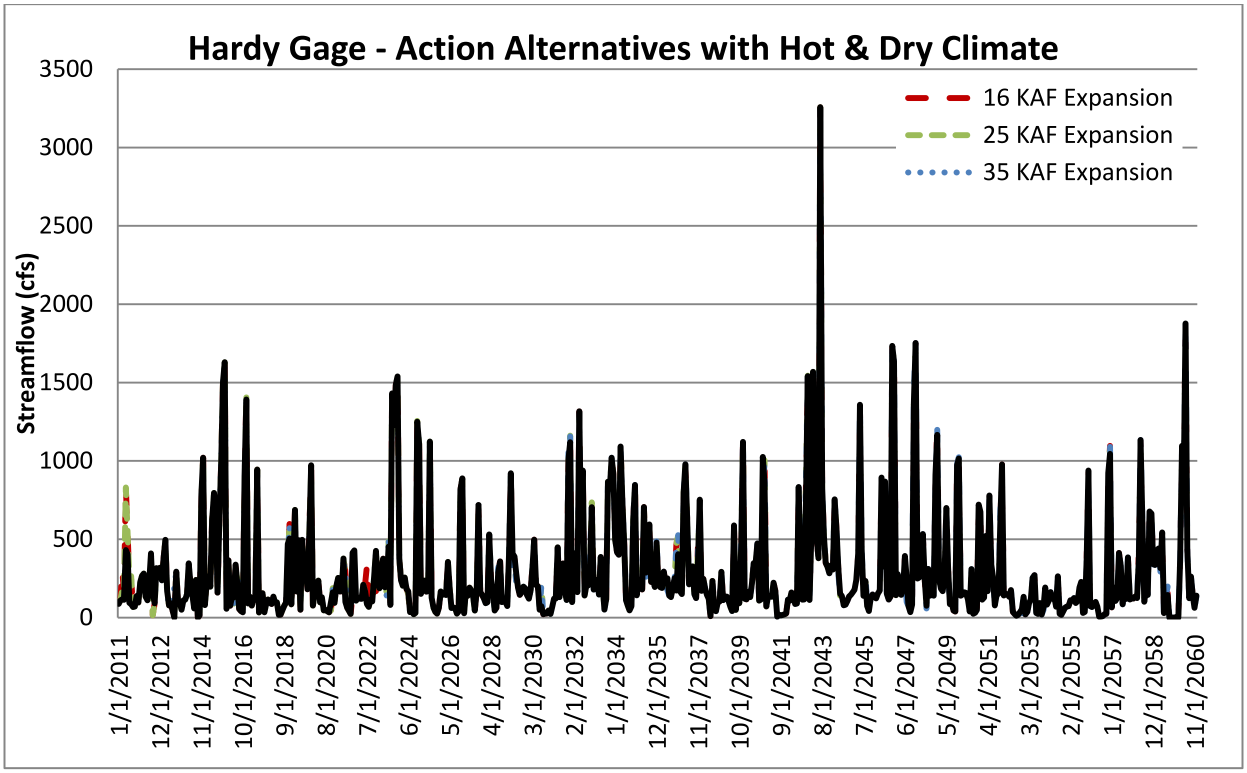


**Figure 131. — Streamflow at Hardy gage for action alternatives with hot and dry climate from 2011-2060.**

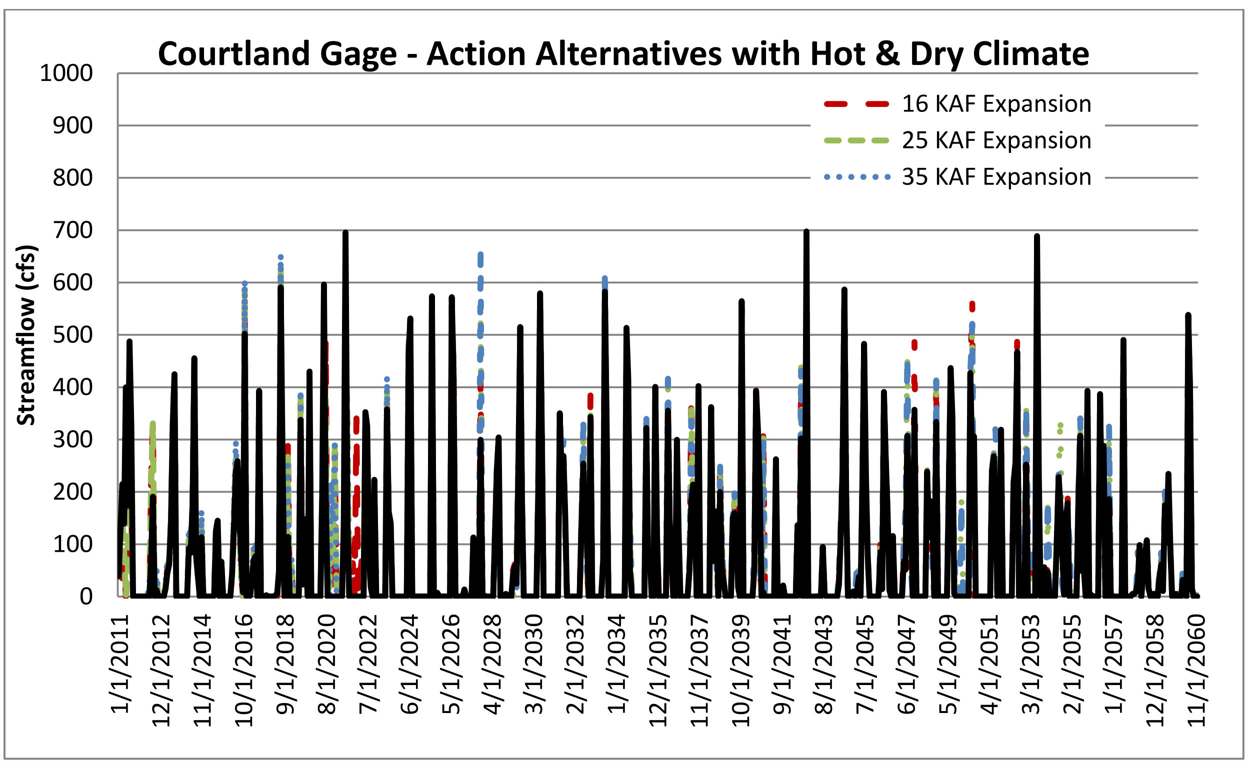


**Figure 132. — Streamflow at Courtland gage for action alternatives with hot and dry climate from 2011-2060.**

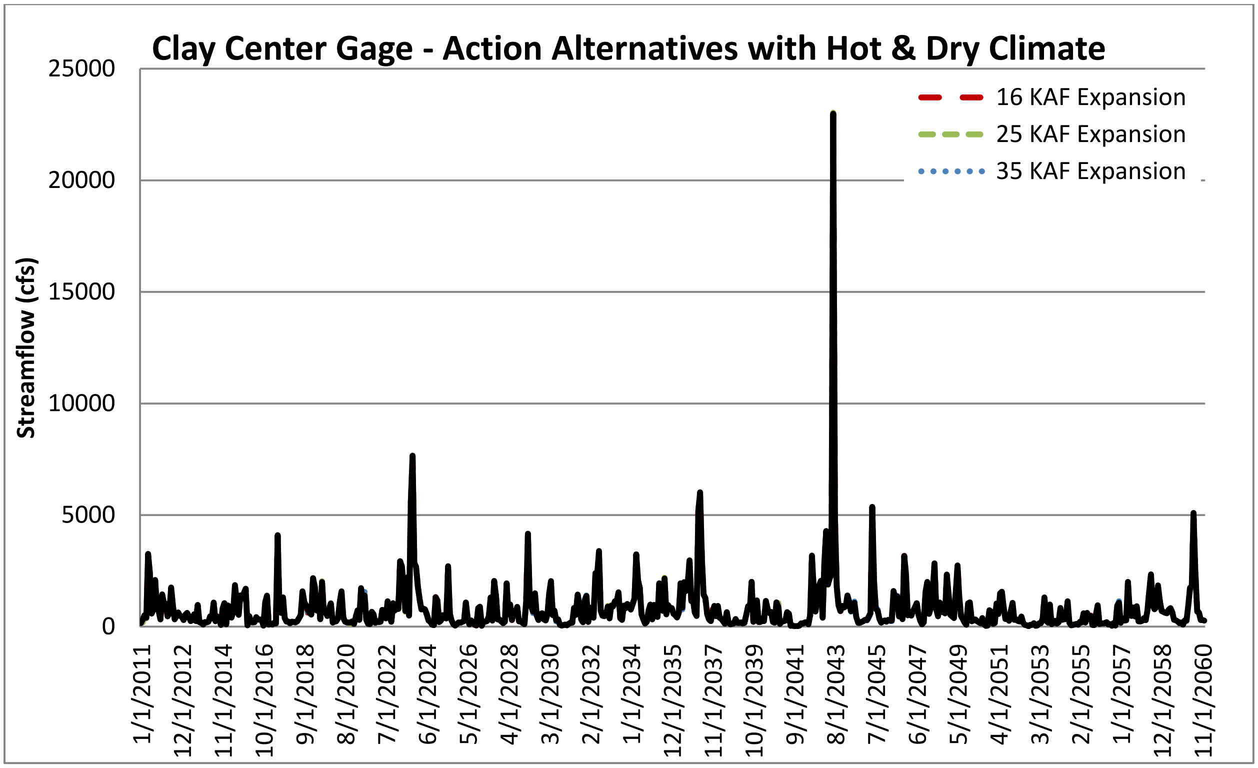


**Figure 133. — Streamflow at Clay Center gage for action alternatives with hot and dry climate from 2011-2060.**

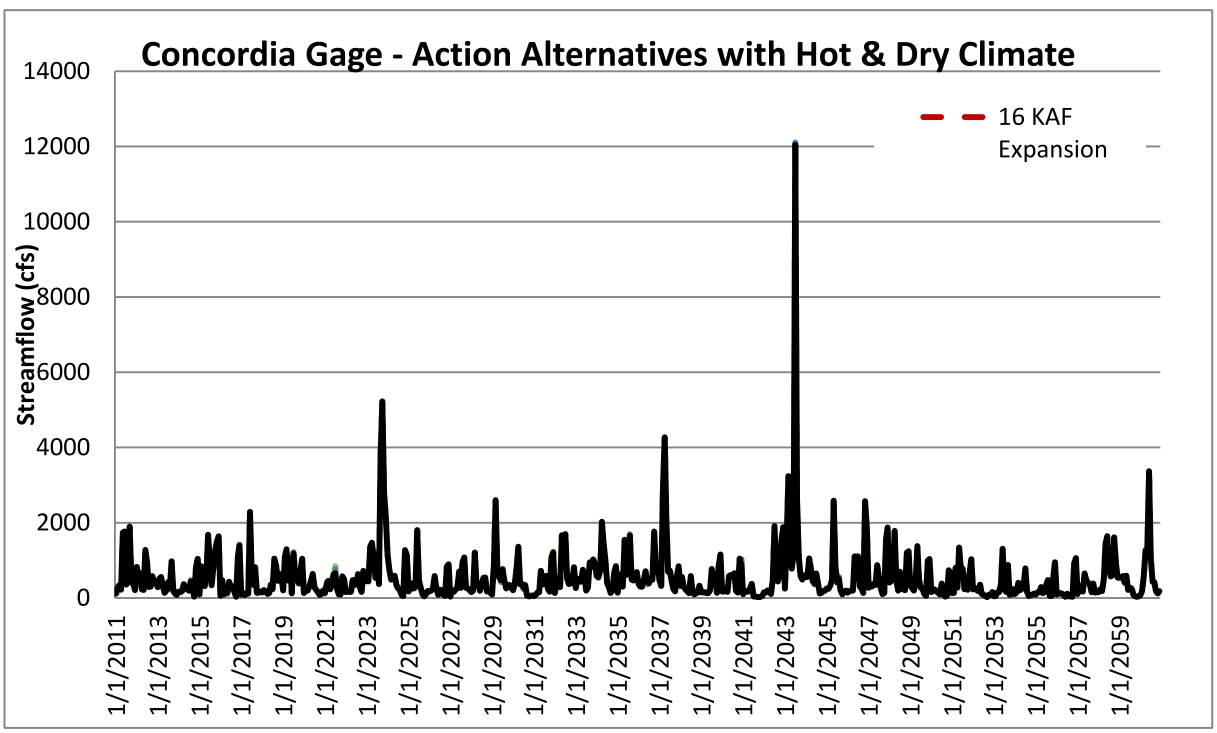


**Figure 134. — Streamflow at Clay Center gage for action alternatives with hot and dry climate from 2011-2060.**

## 6. Warmer and Drier Climate – Water Demands and Shortages

The evaluation of irrigation demands under the warmer/drier Scenario 1 is presented in Figures 135 and 136 below. Contrary to the Baseline Climate action simulations, KBID-UP does have changes in water shortages with the expansion of Lovewell Reservoir (both reductions and increases; Figure 137), in addition to the reductions in shortages predicted for KBID-DOWN (Figure 138).

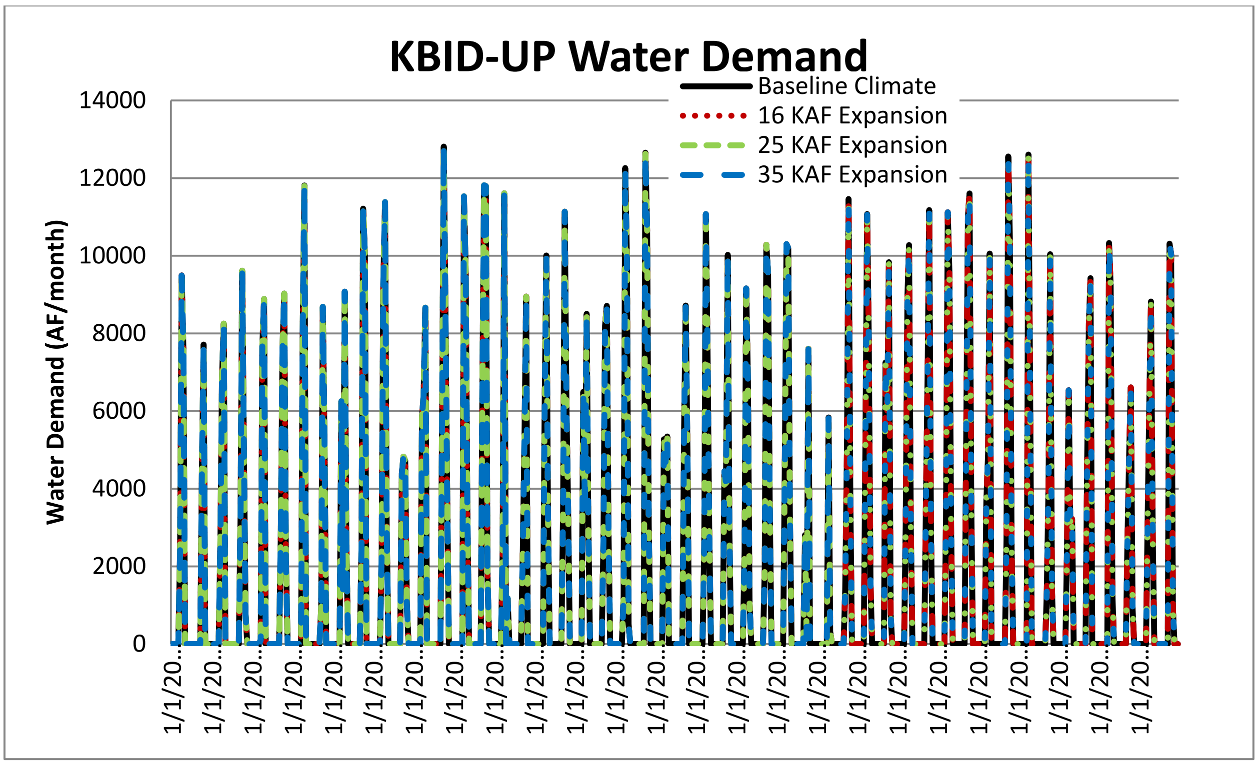


**Figure 135. — Water demands for KBID-UP for action alternatives under hot and dry climate from 2011-2060.**

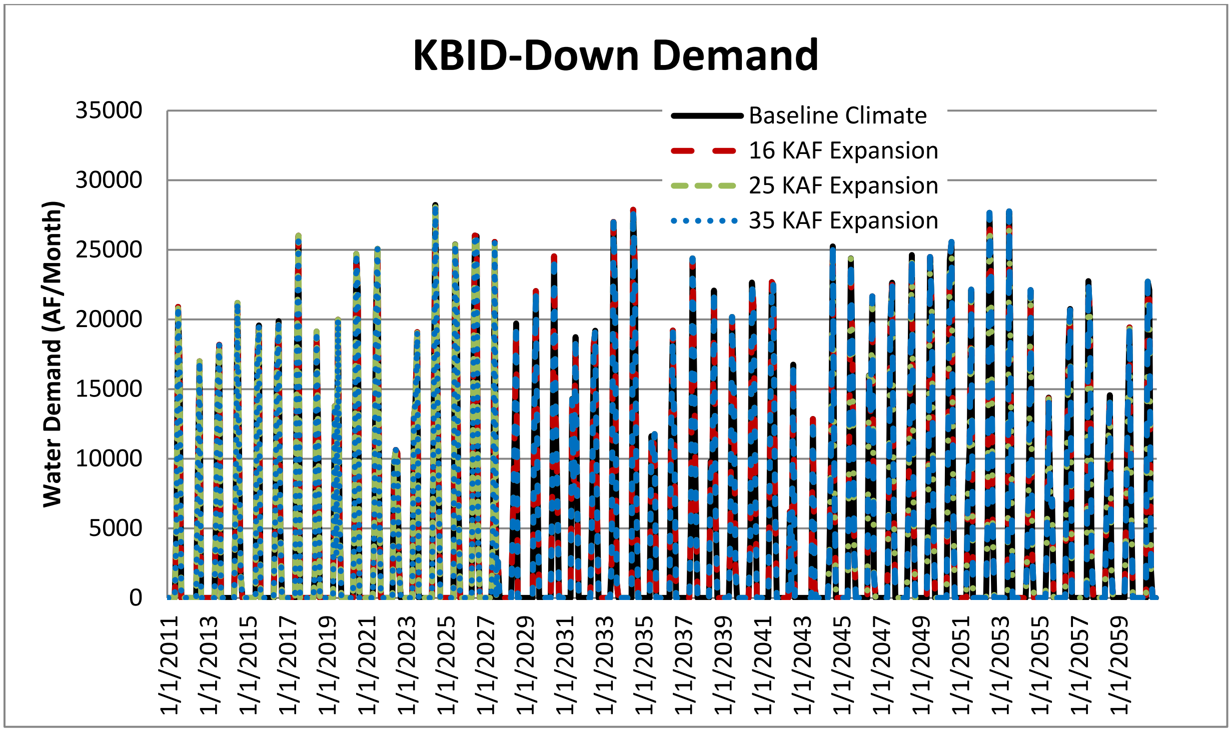


**Figure 136. — Water demands for KBID-DOWN for action alternatives under hot and dry climate from 2011-2060.**

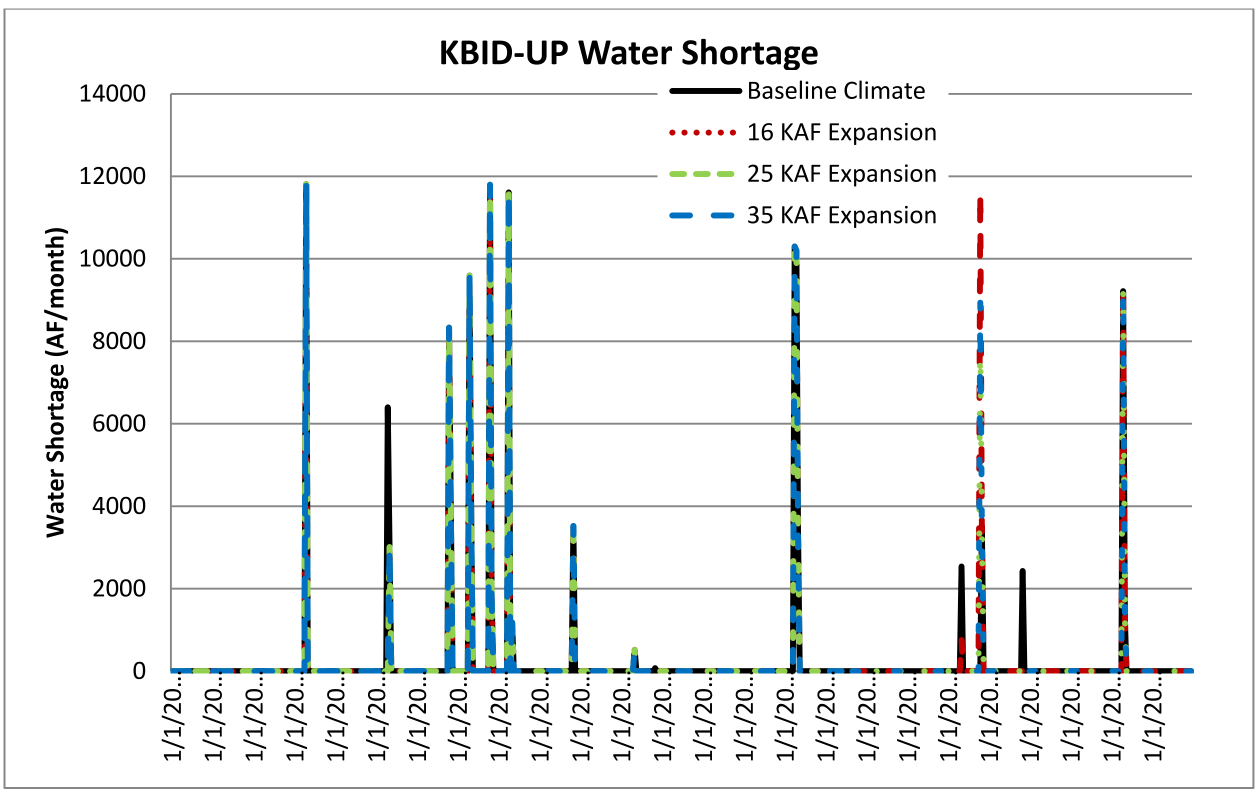


**Figure 137. — KBID-UP water shortages for action alternatives with hot and dry climate from 2011-2060.**

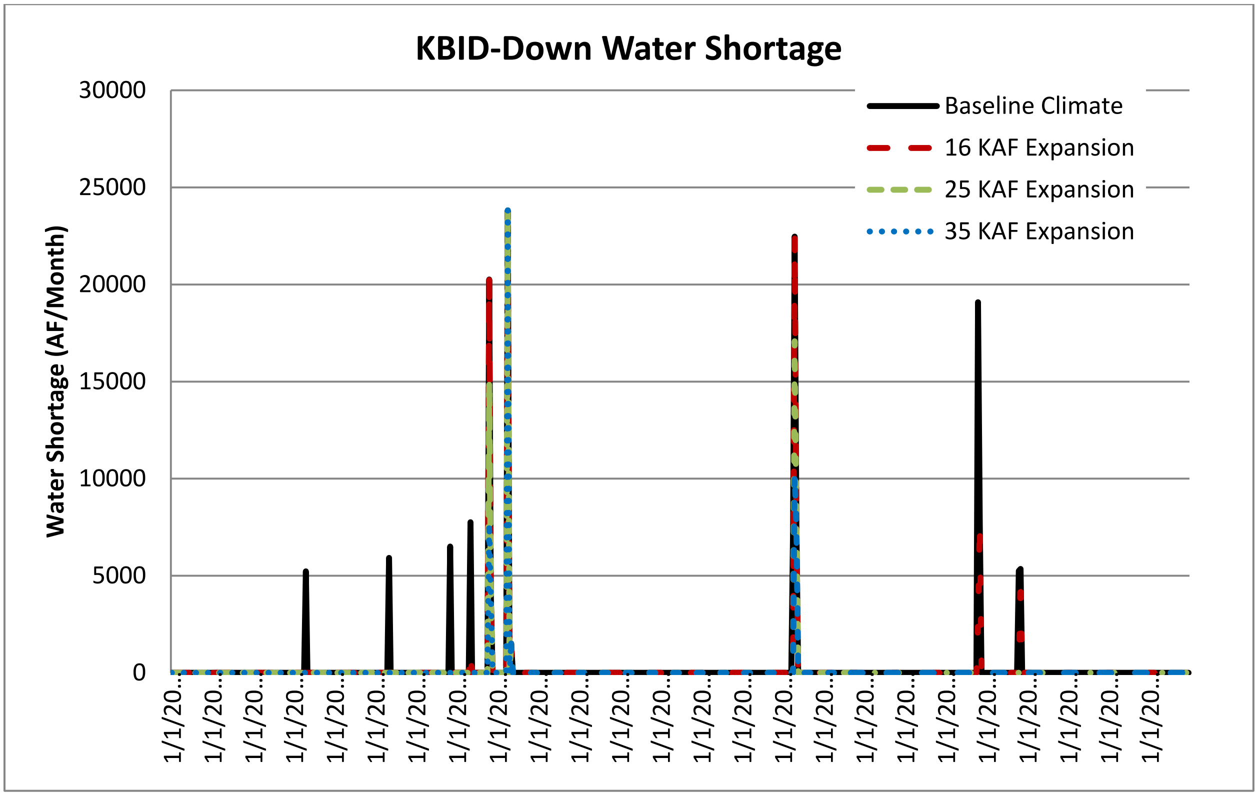


**Figure 138. — KBID-DOWN water shortages for action alternatives with hot and dry climate from 2011-2060.**

## 7. Discussion

Upon reviewing the results of the alternatives evaluation, it was observed that with the inclusion of Compact Call operations in the simulation, the frequency of KBID-DOWN shortages was quite low, and that an annual shortage for the Baseline Climate, No Action scenario was observed in only five of the 50 of the simulation years. Shortage years are summarized in Table 17 below. In three of the five shortage years, annual shortages were relatively small in magnitude (i.e., less than two inches and less than 11% of the total crop irrigation demand). The anticipated impact to crop yields/acre for those three shortage years is assumed to be small. The summary of shortage years for Action Alternatives is also provided in Table 17 below. Indeed, increasing the storage at Lovewell Reservoir reduces the frequency and magnitude of shortages for KBID-DOWN; however, the reduction in the frequency and magnitude of shortages relatively low considering the fact that the baseline No Action scenario was already quite low. Therefore, the Lovewell Reservoir storage alternatives do very little to reduce the frequency or magnitude of KBID-UP shortages. As a result, the benefits of increasing storage at Lovewell Reservoir appear limited under the Baseline Climate Scenario, especially considering the costs (discussed in the next section).

**Table 17. — Summary of Kansas water shortage years for Action Alternatives under Baseline Climate**

| KBID-Down: Base Climate | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | No Action | | LVWL + 16KAF | | LVWL + 25KAF | | LVWL + 35KAF | |
| Sim Yr | Irr Demand (in/acre) | Irr Deliv (in/acre) | Shortage (in/acre) | Irr Deliv (in/acre) | Shortage (in/acre) | Irr Deliv (in/acre) | Shortage (in/acre) | Irr Deliv (in/acre) | Shortage (in/acre) |
| 2024 | 16.1 | 10.1 | 6.0 | 12.1 | 4.0 | 14.2 | 1.9 | 16.1 | 0.0 |
| 2026 | 17.5 | 10.7 | 6.8 | 12.7 | 4.8 | 14.8 | 2.8 | 17.0 | 0.6 |
| 2034 | 14.0 | 12.6 | 1.4 | 14.0 | 0.0 | 14.0 | 0.0 | 14.0 | 0.0 |
| 2040 | 12.0 | 11.4 | 0.5 | 12.0 | 0.0 | 12.0 | 0.0 | 12.0 | 0.0 |
| 2041 | 14.6 | 13.0 | 1.6 | 14.3 | 0.3 | 14.6 | 0.0 | 14.6 | 0.0 |

Kansas next ran the worst case climate scenario (Scenario 1: warmer and drier climate). The shortage summary results for KBID-DOWN are shown in Table 18 (in inches/acre). As expected, the frequency and magnitude of shortages increased over the Baseline Scenario for the No Action run with shortages occurring in nine of the 50 simulation years. The shortages in four of the nine years were comparatively larger (seven inches or more) than the shortages in the remaining five years. The Action Alternatives reduce the frequency and magnitude of the shortages over the No Active alternative, with the 16K AF storage increase reducing the shortage frequency to KBID-DOWN by seven years during the 50-year simulation. Three of the seven shortage years are relatively larger than the remaining four. The 25K AF storage increase reduces the shortage frequency to three years during the 50-year simulation, and the 35K AF increase also has three shortage years during the 50-year simulation.

**Table 18. — Summary of Kansas water shortage years for Action Alternatives under a warmer/drier climate**

| KBID-Down: Climate Scen 1 (Warmer, Drier) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | No Action | | LVWL + 16KAF | | LVWL + 25KAF | | LVWL + 35KAF | |
| Sim Yr | Irr Demand (in/acre) | Irr Deliv (in/acre) | Shortage (in/acre) | Irr Deliv (in/acre) | Shortage (in/acre) | Irr Deliv (in/acre) | Shortage (in/acre) | Irr Deliv (in/acre) | Shortage (in/acre) |
| 2017 | 12.5 | 11.0 | 1.5 | 12.5 | 0.0 | 12.5 | 0.0 | 12.5 | 0.0 |
| 2021 | 16.5 | 14.8 | 1.7 | 16.5 | 0.0 | 16.5 | 0.0 | 16.5 | 0.0 |
| 2024 | 19.7 | 17.8 | 1.9 | 19.6 | 0.1 | 19.7 | 0.0 | 19.7 | 0.0 |
| 2025 | 15.6 | 13.4 | 2.2 | 15.3 | 0.3 | 15.6 | 0.0 | 15.6 | 0.0 |
| 2026 | 20.5 | 13.5 | 7.0 | 13.5 | 7.0 | 15.0 | 5.4 | 17.1 | 3.4 |
| 2027 | 9.6 | 2.3 | 7.3 | 2.3 | 7.3 | 2.3 | 7.3 | 2.3 | 7.3 |
| 2041 | 18.2 | 7.5 | 10.7 | 9.4 | 8.8 | 11.1 | 7.1 | 13.1 | 5.1 |
| 2050 | 19.8 | 12.1 | 7.7 | 16.8 | 3.0 | 19.8 | 0.0 | 19.8 | 0.0 |
| 2052 | 17.8 | 14.7 | 3.0 | 16.3 | 1.5 | 17.8 | 0.0 | 17.8 | 0.0 |

Although the Lovewell storage increase alternatives do not directly influence the shortages of KBID-UP, under the warmer/drier climate scenario (Scenario 1), expansion of Lovewell Reservoir reduced or eliminated KBID-UP shortages in two of the 13 water shortage years. This is because the additional water availability freed up a portion of the KBID-DOWN demand on Harlan County Lake which benefited KBID-UP in the form a modest reduction in its shortage. However, interestingly, the expansion of Lovewell Reservoir can also *increase* the shortage of KBID-UP. In one of the 13 simulation years where shortages were noted for KBID-UP, the KBID-UP shortage increased over the No Action run for all action alternatives. In this case, although the increase in storage at Lovewell reduced the shortage of KBID-DOWN (the particular simulation year was 2050 in Table 18), the trade-off was to increase the shortage of KBID-UP. However, the total shortage between KBID-UP and KBID-DOWN was reduced slightly in that simulation year.

Nevertheless, considering the high cost of Lovewell storage expansion and the small relative reductions to the frequency of shortages under the warmer, drier climate scenario, the only expansion alternative that was selected for further evaluation was the 25K AF storage increase to Lovewell Reservoir (Alternative 1C in previous reports). The 16K AF storage increase was not selected because the differences in shortages were much smaller than the 25K AF, and the 35K AF increase was not selected because the frequency and magnitude of shortage differences between Action and No Action were similar to the 25K AF increase, and at a much higher cost.

To substantiate the selection of the 25K AF alternative, simulation shortages were compared for each alternative under the warmer, drier Climate Scenario 1 using a nonparametric Wilcoxon rank-sum test. The results provided in the Kansas Modeling Results TM (KGS and KWO 2015a) indicate that both the 25K AF and 35K AF shortage distributions differ (alpha = 0.05) from the No Action alternative. No other statistical differences were noted between any of the other alternative comparisons. Again, considering the costs, the selection of 25K AF remains the best alternative for further evaluation for the warmer, drier climate scenario.

In conclusion, it was determined that only Alternative 1C would be carried forward to an economics analysis. Therefore, although costs for all four Lovewell storage options are provided in the Engineering TM (Reclamation 2014), only costs for Alternative 1C are provided in the cost evaluation presented in this report.

# E. Cost Evaluation

## 1. Purpose and Scope

Based on Kansas' modeling results described above, and because Alternatives 1A, 1B, and 1D were eliminated from further consideration, only the costs of Alternative 1C are presented here (Reclamation's 2014 TM includes costs for all four storage options). Costs for all three Nebraska alternatives were developed.

These estimates were prepared by Reclamation's Technical Service Center Estimating Group (Denver, Colorado). The estimates are in accordance with Reclamation Manual Directives and Standards FAC 09-01 and FAC 09-03. The cost estimates are considered "appraisal-level", as defined by D&S FAC 09-01, which states: "appraisal cost estimates are used in appraisal reports to determine whether more detailed investigations of a potential project are justified. These estimates may be prepared from cost graphs, simple sketches, or rough general designs which use the available site-specific design data." Appraisal-level costs estimates are developed at an early stage of project development and are therefore <u>not</u> suitable for requesting project authorization or construction fund appropriations from Congress. All costs are in April 2014 dollars.

## 2. Methods

The cost estimates are based on the following key elements:

**Field Costs:** capital costs of project features from award to construction closeout. The field cost is broken down into the contract costs and construction contingencies.

- Contract Costs: estimated cost of the contract at the time of bid or award, and include the following:
    - Mitigation costs: Applicable to Alternatives 1C and 5A, mitigation costs were based on previous mitigation quantities presented in the 2005 Appraisal Study and/or on recent quantity information obtained from Lovewell State Park or Kansas Department of Wildlife personnel; these costs were generated based on historical data and/or estimator judgment. Mitigation costs regarding potential land acquisition were estimated with the use of U.S. Department of Agriculture Land Values 2013 Summary (August 2013) report. Approximate land values from that report were escalated to April 2014 price level. Details are provided in Reclamation's Engineering TM.

- Mobilization: A value of 5 +/- percent was used for mobilization. This includes costs of contractor bonds, and mobilizing contractor personnel and equipment to the project site during initial project start-up. The assumed 5 +/- percent value in the cost estimate is based upon past experience on similar projects.
- Design Contingency: A value of 25 +/- percent was used for (i) unlisted items; (ii) design and scope changes; and (iii) cost estimating refinements.
- Allowance for Procurement Strategies: A value of 3 +/- percent was used for procurement strategies to account for potential additional costs when the solicitation is advertised and awarded under other than full and open bid competition. These include solicitations that will be set aside under socio-economic programs, along with solicitations that may limit competition or allow award to other than the lowest bid or proposal. This estimate assumes a Request for Proposals from qualified contractors with selection based on a combination of project approach, contractor experience, and the proposed price.

- Construction Contingency: A value of 25 +/- percent was used for construction contingencies based upon the completeness and reliability of the engineering design data, geological information, projected quantities, and general knowledge of the conditions at the site. It covers minor differences in actual and estimated quantities, unforeseeable difficulties at the site, changed site conditions, possible minor changes in plans, and other uncertainties.

***Non-Contract Costs:*** these costs were estimated to be 35 +/- percent of the Total Field Costs based on typical non-contract cost percentage ranges from past large Reclamation projects. Land acquisition and relocation of property by others is not included in this percentage. Non-contract costs include, but are not limited to, the following:

- Cultural resources preservation.
- Services facilities: camps, construction roads, utility systems, temporary plants used for construction, etc.
- Planning (Investigations): studies and surveys (collection, assembly, analysis of data, and preparation and review of reports such as environmental impact studies, cultural resources studies, mitigation studies, etc.).
- Engineering and other costs: designs and specifications, construction engineering and management, other costs such as general office

salaries, supplies and expenses, general transportation expenses, security, environmental oversight, legal services, etc.

***Escalations:*** There are two distinct periods of time that must be considered with escalation: first, the time from when the estimate is prepared until notice to proceed, and second, the duration of the construction contract. The cost estimates only include escalation during construction in the unit prices. An allowance for escalation from the April 2014 price level to the Notice to Proceed milestone was not included in the estimates. For projects which are to be developed over an extended period of time, or at some distant time in the future, it is prudent to incorporate some consideration of the time value of money in the cost estimates.

## 3. Results

Table 19 summarizes the construction cost estimates. Costs for operations and maintenance were not evaluated. Cost estimate worksheets with detailed breakdowns of quantities, unit prices, and amounts, for the proposed structural alternatives, are presented in the Engineering TM. Details regarding the basis and scope of cost estimates are described below.

**Table 19. — 2014 Appraisal Level Cost Estimates[1]**

| Alternative Description | Field Cost | Noncontract[2] Cost | Construction Cost |
|---|---|---|---|
| 1C: 25,000 AF Expansion of Lovewell Reservoir | $44,000,000 | $15,000,000 | $59,000,000 |
| 3A: Swanson Reservoir Augmentation – New Frenchman Creek Pipeline | $27,000,000 | $9,000,000 | $36,000,000 |
| 3B: Swanson Reservoir Augmentation – New Republican River Pipeline | $61,000,000 | $21,000,000 | $82,000,000 |
| 5A: New Thompson Creek Dam | $68,000,000 | $24,000,000 | $92,000,000 |

[1] All costs are in April 2014 dollars.
[2] Non-Contract Costs were estimated to be approximately 35% of the Total Field Costs based on percentage ranges from past large Reclamation projects.

To complete the cost estimation process, interest during construction (IDC) was estimated for each alternative based on an allocation of total construction costs across presumed construction periods for each alternative. The costs by alternative and year are presented in Table 20. IDC was calculated annually, using a compound interest procedure, based on the FY2015 planning rate of 3.375 percent. Combining construction and IDC costs provides an estimate of the total construction costs by alternative (exclusive of annual operations, maintenance, replacement and power [OMR&P] costs) as of the end of the construction period for each alternative. Given that construction periods varied across the alternatives, total construction costs by alternative were then compounded to the end of Year 5 (end of construction for the alternative with the longest construction period) so as to measure all costs and benefits at the same point in time for use in the benefit cost analysis. Total compounded construction costs range from $41.1 million (3A - Swanson Reservoir Enhanced Storage - Frenchman Creek Intake and Pipeline) to $100.1 million (5A - New Thompson Creek Dam and Franklin Canal Connection). These costs by alternative were used as the basis for the benefit-cost analysis provided in the *Section 7.7: Benefit/Cost Evaluation*.

**Table 20. — Annual Construction Breakdown of 2014 Appraisal Level Cost Estimates**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1C – 25,000 AF Lovewell Reservoir Expansion & Winterization/Automation of Courtland Canal | 15.7 | 27.6 | 15.7 | – | – | 59.0 | 3.0387 | 66.297 |
| 3A – Swanson Reservoir Enhanced Storage – Frenchman Creek Intake and Pipeline | 18.0 | 18.0 | – | – | – | 36.0 | 1.2253 | 41.1229 |
| 3B – Swanson Reservoir Enhanced Storage – Republican River Intake and Pipeline | 12.3 | 28.7 | 28.7 | 12.3 | – | 82.0 | 5.6815 | 90.6408 |
| 5A – New Thompson Creek Dam and Franklin Canal Connection | 11.0 | 22.1 | 25.8 | 22.1 | 11.0 | 92.0 | 8.053 | 100.053 |

a All costs reported in April 2014 dollars.

b Annualized cost breakdowns are based on estimated construction durations for each project and an expenditure rate that assumes 15% of the work is completed in the first 25% duration of the project, the next 70% of the work is completed in the next 50% of the project duration, and the final 15% of the work is completed in the final 25% duration of the project.

c IDC is calculated using the FY2015 planning rate of 3.375 percent (Reclamation, 2014a).

d Sum of total construction costs and IDC compounded to Year 5; therefore, this exceeds sum of total construction costs and IDC column values.

# 4. Considerations for Development of More Detailed Cost Estimates

The alternatives presented were developed to appraisal-level design in accordance with Reclamation's D&S. Costs were developed without any engineering data other than topographic mapping, satellite imagery, and design drawings of existing Reclamation features. The following additional engineering tasks should be considered if more detailed cost estimates are desired. This list of items should not be considered comprehensive and would vary depending on the alternative and level of design considered:

- Site Studies
  - Site visits
  - Detailed topographic mapping and inundation mapping site selection
  - Detailed mitigation analyses
    - Railroad relocation and railroad bridge (type and size)
    - Highway 14 roadway crossing protection or raise (scope of work and quantities)
    - Land, recreation, and homeowner (e.g., cabins) impacts, and specific quantities developed for each element
- Geotechnical and Geology Studies
  - Field Investigations
    - Surface studies including material classification
    - Collection and review of existing data
    - Borrow area investigations including test pits
    - Foundation investigations including borings, test pits, and trenches
    - Pipeline alignment borings
    - Coring of existing concrete features
    - Corrosivity testing
    - Laboratory testing
  - Geologic Mapping
- Hydrologic and Hydraulic Studies
  - Flood frequency studies including paleo-flood investigations
  - Tailwater studies

  - Flood routings
  - Water surface profiles
  - Model studies
  - Dam break studies and inundation mapping
- Risk Analyses
  - Consequence studies
  - Potential failure modes development
  - Team design-based risk analyses
- Constructability Reviews
  - Materials availability
  - Construction access
  - Construction schedule
- Non-Contract Costs
  - Developed to the same level of detail as the contract costs
  - Technical expert input (from many different disciplines) will be needed to develop non-contract costs at a feasibility level
  - Environmental Studies on endangered and protected species, water quality, and permitting compliance

## F. Benefits Evaluation

Based on Kansas' modeling results described in *Section 7.0: Evaluation of Adaptation Strategies* section of this report, and because Alternatives 1B and 1D were eliminated from further consideration, only economic benefits for Alternative 1C were developed. The economic benefits of all three Nebraska alternatives (3A, 3B, and 5A) were evaluated.

Study partners decided to limit the scope of the economic benefits used in the benefit-cost analysis (BCA) to agriculture and recreation, as these categories are expected to comprise the majority of economic benefits associated with the Republican River Basin Study's alternatives. The decision also was made to limit the scope of costs exclusively to construction activities. Therefore, the primary objective of the economic analysis was to estimate the net economic benefits (i.e., benefits minus costs) for each proposed alternative as compared to the No Action Alternative based on construction costs, including interest during construction, and agricultural and recreation benefits. A secondary objective of the analysis was to evaluate the economic effect of climate change associated with the various climate scenarios.

# 1. Purpose and Scope

The BCA presented in this report comprises an appraisal-level analysis consistent with the *Principles, Requirements, and Guidelines for Water and Land Related Resources Implementation Studies* (PR&Gs), which provide a common framework for evaluating Federal water resources investments (USCEQ, 2014) (DOI, 2015).

The purpose of a BCA is to compare the monetized benefits of a proposed project to its monetized costs. The total costs of the proposed project are subtracted from the total benefits to measure net benefits. The BCA in this Study is conducted using a "with" versus "without" approach. The "with" condition reflects the situation *with* a given proposed alternative in place, while the "without" condition reflects the situation *without* the given proposed alternative in place. The alternative representing the "with" condition is referred to as the Action Alternative and the alternative representing the "without" condition is referred to as the No Action Alternative. A "with" versus "without" analysis compares estimates of the net benefits under each proposed Action Alternative to estimates of net benefits under the No Action Alternative. The Action Alternative with the greatest increase in net benefits in excess of those under the No Action Alternative is the preferred alternative from an economics perspective. Should the net benefits for each of the proposed action alternatives fail to exceed those of the No Action Alternative, then the No Action Alternative would be the preferred alternative from an economics standpoint.

Before comparisons can be made between costs and benefits, they must be converted to the same dollar year. Dollar year adjustments – typically using some form of price index – attempt to ensure that all cost and benefit estimates are measured at the same price level. In addition, costs and benefits will occur at different points in time, implying different time values. The concept of the time value of money suggests that a dollar of benefits or costs incurred in the future is worth less than a dollar of benefits or costs incurred today because all benefits and costs have an opportunity cost. That is, one could put today's dollar in a bank (or some alternative investment) and earn interest over time resulting in a total value in the future greater than the original dollar. For example, if one could earn 3 percent interest over the year, $1.00 today would be equivalent to $1.03 a year from now, therefore $1.00 a year from now is only worth $0.97 today (1/1.03). When conducting a BCA, the analyst selects a point in time for measuring all costs and benefits. It makes no difference to the results of the BCA whether the selected year is in the past, current, or future. Costs and benefits which occur prior to the selected year are increased (compounded up) to the selected year. Conversely, costs and benefits which occur after the selected year are decreased (discounted back) to the selected year.

## 2. Methods

As previously stated, only action alternatives 1C (submitted by Kansas), 3A, 3B and 5A (submitted by Nebraska) were carried forward into the economic analysis. Three future climate scenarios were analyzed for each proposed action alternative (except for Alternative 1C):

1. Scenario 1: Warmer/Drier (*low* water availability);
2. Scenario 2: Central Tendency (*median* water availability); and
3. Scenario 3: Less Warm/Wetter (*high* water availability).

For Alternative 1C, for reasons previously discussed, the decision was made to only consider the warmer/drier Climate Scenario 1. In addition, a without climate change condition was evaluated for each proposed action alternative. This results in fourteen combinations of climate scenarios and alternatives to be evaluated for the economics analysis.

Two versions of the No Action Alternative were developed for comparison purposes: one based on historical climate/hydrologic conditions (without climate change) and the other based on the three future climate scenarios. The Baseline No Action Alternative models historical climate with no climate change and no structural modifications. The Future No Action Alternative models the following: (1) Scenario 1 with no structural modification (FNA 1); (2) Scenario 2 with no structural modification (FNA 2); and (3) Scenario 3 with no operational modification (FNA 3). Table 21 below displays the four or five alternatives associated with each climate scenario for a total of eighteen alternatives/climate scenarios (alternative/scenario) that were used for comparison purposes within this economics analysis.

**Table 21. — Alternatives and climate scenarios analyzed in the Republican River Basin Study economics analysis**

| | | | |
|---|---|---|---|
| Baseline | No Action | Historical (no climate change) | BLNA |
| Baseline | 1C | Historical (no climate change) | BL1C |
| Baseline | 3A | Historical (no climate change) | BL3A |
| Baseline | 3B | Historical (no climate change) | BL3B |
| Baseline | 5A | Historical (no climate change) | BL5A |
| Future | No Action | Scenario 1 | FNA 1 |
| Future | 1C | Scenario 1 | F1C 1 |
| Future | 3A | Scenario 1 | F3A 1 |
| Future | 3B | Scenario 1 | F3B 1 |
| Future | 5A | Scenario 1 | F5A 1 |
| Future | No Action | Central Tendency | FNA 2 |
| Future | 3A | Central Tendency | F3A 2 |
| Future | 3B | Central Tendency | F3B 2 |
| Future | 5A | Central Tendency | F5A 2 |
| Future | No Action | Scenario 3 | FNA 3 |
| Future | 3A | Scenario 3 | F3A 3 |
| Future | 3B | Scenario 3 | F3B 3 |
| Future | 5A | Scenario 3 | F5A 3 |

As stated above, BCAs are conducted using a “with” versus “without” approach – the “with” condition reflecting the situation with a proposed Action Alternative in place and the “without” condition reflecting the situation with the No Action Alternative in place.

Three additional net benefits comparisons are made solely for the purpose of evaluating the economic effects of the three future climate scenarios without operational/structural changes. In this case, the Baseline No Action Alternative “without” climate change is compared to the Future No Action Alternative “with” climate change such that the “with” versus “without” comparison is maintained. FNA 1, FNA 2, and FNA 3 are compared to Baseline No Action to assess the climate scenario economic effects.

As noted above, before comparisons can be made between costs and benefits, they must be converted to the same dollar year and point in time. For this Study, regardless of when they were expected to be incurred, all the costs and benefits are calculated in either 2013 or 2014 dollars, with such a minor difference, no dollar year/price level adjustment was pursued.

Furthermore, to account for the time value of money, all costs and benefits need to be converted to the same point in time. Reclamation BCAs typically convert all costs and benefits to the end of the construction period which is equivalent to the beginning of the benefit period or period of analysis. In the analysis developed for this Study, costs incurred prior to the end of the construction period were compounded (increased) to the end of the construction period and benefits incurred during the period of analysis were discounted (reduced) to the start of the period of analysis (equivalent to the end of the construction period). Note that the point of reference for the measurement of benefits and costs has no bearing on the results of the BCA.

The construction period for the various action alternatives under consideration varies from two to five years. Total construction costs by action alternative were measured as of the end of Year 5, which represents the end of construction for the alternative with the longest construction period. Therefore, construction costs for alternatives with less than a five-year construction period were compounded to the end of Year 5. Since IDC reflects the procedure for measuring costs at the end of the construction period, those alternatives with less than a five-year construction period required further compounding (beyond the IDC calculation) to measure costs as of the end of Year 5

Benefits were calculated across a 50-year planning horizon. The stream of annual benefits occurring after the construction period (end of Year 5) under each alternative/scenario was discounted to a present value. For alternatives with less than a five-year construction period, agricultural and recreation benefits were assumed to begin immediately after construction was completed. Benefits under these alternatives were compounded up to the end of the overall construction period (Year 5). All compounding and discounting was performed using the fiscal year 2015 (FY2015) Federal discount rate of 3.375 percent (Reclamation, 2014a).

## 3. Agricultural Benefits Analysis

### a. *Purpose and Scope*

For the purpose of this analysis, *agricultural benefits* under a defined alternative/scenario are estimated as *irrigation benefits* accrued to irrigated lands in Nebraska and Kansas under the hydrologic conditions specified by each alternative/scenario. *Irrigation benefits* are measured as the change in net farm income (NFI) received from the use of irrigation water to produce agricultural commodities (Reclamation, 2004a).

A number of simplifying assumptions were made to facilitate the agricultural benefits analysis for this appraisal-level study:

1. The agricultural benefits analysis is based solely on irrigated lands falling within the boundaries of the Lower Republican River Basin;

2. Groundwater pumping used to supplement any surface water deliveries under any alternative/scenario was held constant between scenarios;

3. The irrigation benefits are based on averages of the hydrology output for irrigation deliveries. The changes in estimated yield in the irrigation benefits study come solely from a change in irrigation water deliveries.;

4. Changes in NFI were driven by estimated changes in yield; and

5. Hydrologic model estimates of changes in irrigation water deliveries and the number of acres affected by each alternative were used as an input in estimating crop yields and the change in irrigation benefits for each alternative.

### b. *Methods*

Benefit values for irrigated agriculture were estimated following the criteria for measuring National Economic Development (NED) benefits defined in the PR&Gs (USCEQ, 2014) (DOI, 2015). A PR&G analysis of NED agricultural benefits is based on a "with" versus "without" approach (see *Section 7.6.3: Agricultural Benefits Analysis* for further detail). Annual agricultural benefits under a given alternative/scenario are estimated as NFI subject to the hydrologic conditions specified by each alternative/scenario. The present value of annual agricultural benefits under each alternative/scenario is then calculated using a 50-year planning horizon and the FY2015 Federal discount rate of 3.375 percent (Reclamation, 2014a).

The agricultural benefits portion of this appraisal-level study estimates the economic benefits accruing from the projected changes in water deliveries.

Irrigated acres in the Lower Republican River Basin located in Kansas and Nebraska were included in the agricultural benefits study. For Nebraska, only the most dominant crop for the area, corn, is modeled. For Kansas, corn and soybeans are modeled.

The methodology employed to calculate NFI under a given alternative/scenario is:

1. The farm budgets prepared for this analysis account for gross revenues, variable costs, and fixed costs of operation;

2. Prices received are held constant for all alternatives;

3. All costs of production, except harvest costs, are held constant between alternatives/scenarios (harvest costs are allowed to change as changes in yield are experienced);

4. Historical cropping patterns for Kansas were obtained from the Kansas Bostwick Irrigation District Number 2 (KBID) crop census reports (Kansas, 2015) and were assumed to hold for all affected acres in Kansas (irrigated corn and soybeans were the only crops included in the Kansas farm budgets);

5. Historical cropping patterns for Nebraska counties were provided by the state of Nebraska (Nebraska, 2015) (corn was the only crop included in the Nebraska typical farm, based on the recommendation of the state of Nebraska); and

6. The change in NFI under a given alternative/scenario is driven by a change in crop yields. Crop yields for each alternative/scenario are estimated using the *Water Optimizer* computer application (Yield Estimation Model) developed by the University of Nebraska, Lincoln (UNL) (Martin, Supalla, & Nedved, 2005).

Relatively small changes in the water deliveries were projected for the action alternatives included in this Study. UNL agricultural economists have published articles and provided the Yield Estimation Model, which estimates yields for varying water delivery levels, several crops, and some of the more prominent soil types in Nebraska (Martin, Supalla, & Nedved, 2005). Included in the UNL publications are model coefficients for different regions of the state and the ability to modify the models to a particular range of water deliveries.

The Yield Estimation Model incorporates plant growth dynamics with respect to soil and water. Thus, the model can predict yield changes assuming all other plant requirements such as fertilizer, etc. are met. The model includes factors for the type of irrigation system used (e.g., furrow or sprinkler), the maximum yield that could be obtained, and ET rates. Input factors also include the ET and yield for dryland crops. The model estimates incremental yields starting from the dryland yield average and up to the suggested maximum yield.

For this Study, published average plant growth dynamic values for south-central Nebraska were used in the Yield Estimation Model for estimating changes in crop yields for both the Nebraska and the Kansas irrigated lands. The plant growth values used in the Yield Estimation Model include average irrigated corn yields from KBID crop census reports (Kansas, 2015) and county-average irrigated and dry land corn yields from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA-NASS, 2015), irrigation efficiency rates, effective precipitation, and crop irrigation requirements.

### i. Historical Cropping Pattern

Historical cropping data for 22 counties in Nebraska was provided by the state of Nebraska for four predominant crops grown in the Nebraska portion of the Lower Republican River Basin: corn, soybeans, sorghum, and wheat (Nebraska, 2015). However, the state of Nebraska recommended that only one crop, corn, be included in this analysis, so that was done in this analysis.

Historical cropping pattern data for KBID was provided by the state of Kansas and used for the Kansas portion of this analysis (Kansas, 2015). Predominant crops grown in the KBID included corn, soybeans, sorghum, and alfalfa. Corn and soybeans were selected as the representative crops for KBID, since these two crops account for almost 88% of all irrigated lands in the district. The acreages for corn and soybeans were extrapolated to all Kansas irrigated lands affected the proposed action alternatives. Additionally, cropping pattern data and average yield data was available for irrigated lands both above and below Lovewell Reservoir. Therefore, a weighted average base yield was calculated for use in the farm budgets.

### ii. Farm Income

Farm Income is a product of crop yields and prices received. Weighted averages of corn and soybean yields were calculated for KBID. On average, 13,269 acres (31.2 percent) were irrigated above Lovewell and 29,231 acres (68.8 percent) were irrigated below Lovewell Reservoir. The maximum reported corn yield for KBID acres was 231 bushels per acre, while the maximum reported soybean yield was 66 bushels per acre.

For Nebraska, the average corn yield was 160.3 bushels per acre and the maximum reported yield for 2006–10 was 168.9 bushels per acre. The average yields used as base inputs for the Yield Estimation Model are presented in Table 22 below.

**Table 22. — Average Irrigated Yields, 2006-2010**

| | UNIT | 2006 | 2007 | 2008 | 2009 | 2010 | AVG |
|---|---|---|---|---|---|---|---|
| *KBID Above Lovewell* | | | | | | | |
| Corn | Bushels/Acre | 146.9 | 169.0 | 189.0 | 197.0 | 173.5 | 175.1 |
| Soybeans | Bushels/Acre | 51.0 | 55.0 | 59.0 | 60.0 | 55.3 | 56.1 |
| *KBID Below Lovewell* | | | | | | | |
| Corn | Bushels/Acre | 167.1 | 185.0 | 190.0 | 231.0 | 158.6 | 186.3 |
| Soybeans | Bushels/Acre | 55.6 | 55.0 | 58.0 | 66.0 | 53.1 | 57.5 |
| *Nebraska (22 County avg.)* | | | | | | | |
| Corn | Bushels/Acre | 149.5 | 159.2 | 160.4 | 168.9 | 163.7 | 160.3 |

Prices received for this analysis were provided by the states of Kansas and Nebraska (Kansas, 2015) (Nebraska, 2015). Prices received were held constant throughout the comparisons of alternatives/scenarios. A three-year average of prices received was used in this analysis.

#### iii. Farm Expenses

Farm expenses were obtained from a previous study performed in the Lower Republican River Basin (Reclamation, 1997). Expenses for those earlier studies were taken from UNL Extension crop budgets and then indexed to 2013 dollars – the year in which all values are reported.

#### iv. Crop Expenses

Crop expenses include custom work, herbicides, insect control, disease control, fertilizer, seed, and miscellaneous crop expenses. Custom work includes the application of chemicals and fertilizer, and custom harvest. Chemicals are used on the representative farms to control weeds, insects, and gophers. All crop related expenses were indexed to 2013 using the *Index of Prices Paid* (USDA-NASS, 2014).

### c. *Results*

This economic analysis separately evaluates the economic effects of the proposed action alternatives and the economic effects of climate change. Thus, the Agricultural Benefits are presented in separate sections to present the results of alternative/scenario comparisons and the economic effects of climate change.

#### i. Agricultural Benefits Comparisons by Alternative/Scenario

The first step in determining the irrigation benefits was to calculate the changes in yields based on the changes in water deliveries to irrigated acres. Inputs to the Yield Estimation Model include maximum expected yield, maximum crop water use (ET), dryland crop water use, and factors for irrigation system efficiency. The average crop water use (ET) parameter for south-central Nebraska (24.4 inches of water) was obtained from NebGuide G98-1354-A (Benham, 1998). Effective rainfall coefficients and crop irrigation requirements for sandy loam soils in Central Nebraska were also obtained from the NebGuide (Benham, 1998) and were not adjusted. The Yield Estimation Model had default coefficients for irrigation system efficiencies that were not modified for this analysis. Once the Yield Estimation Model accounted for the range of water deliveries estimated by the hydrology models, a range of corresponding yields was output. These yield estimates are used in the Farm Budget Tool to calculate the change in NFI for the Kansas whole-farm and the Nebraska whole-farm budgets by alternative/scenario. NFI is calculated by subtracting variable and fixed costs of production from the estimated gross revenues.

The agricultural economic effects of the proposed action alternatives are presented under both without climate change and with climate change scenarios. For the without climate change comparison, estimated irrigation benefits for each action alternative without climate change are compared to the estimated irrigation benefits for the No Action Alternative without climate change. Similarly, for the with climate change comparison, estimated irrigation benefits for each proposed action alternative for each of the three climate scenarios are compared to the estimated irrigation benefits for the No Action Alternative under the same climate scenario. This comparison is provided for each alternative under each climate scenario (with the exception of Alternative 1C where hydrologic results were only provided for the without climate change condition and warmer/drier climate scenario).

### ii. Effects of Climate Change on Agriculture Benefits

*No Action versus Action Alternatives under Baseline Climate Scenario*

The changes in water deliveries, subsequent changes in yields, and changes in the present value of NFI for the action alternatives compared to the No Action Alternative – all under the Baseline Climate Scenario – are shown in Table 23.

**Table 23. — Agricultural benefits comparison of No Action Alternative versus action alternatives, all under Baseline Climate Scenario**

| | Base Case Alternative | Comparison Alternative | | | |
|---|---|---|---|---|---|
| | No Action | 1C | 3A | 3B | 5A |
| **Kansas** | | | | | |
| Water Deliveries (Acre-Inches/Acre) | 12.7 | +1.1 | n/a | n/a | n/a |
| Acres Affected | 42,500 | 42,500 | n/a | n/a | n/a |
| Corn Yield (bushels/acre) | 182.8 | +5.8 | n/a | n/a | n/a |
| Soybeans Yield (bushels/acre) | 56.4 | +1.3 | n/a | n/a | n/a |
| NFI Present Value ($ million) | | +$19.12 | n/a | n/a | n/a |
| **Nebraska** | | | | | |
| Water Deliveries (Acre-Inches/Acre) | 7.42 | n/a | -0.14 | -0.03 | +.05 |
| Acres Affected | 42,521 | n/a | 43,109 | 43,860 | 43,029 |
| Corn Yield bushels/acre | 163.7 | n/a | -0.7 | -0.02 | +0.2 |
| NFI Present Value ($ million) | | n/a | -$3.08 | -$0.84 | +$0.80 |

As displayed in Table 23, the estimated weighted-average yield for the Baseline No Action Alternative came to 182.8 bushels of corn and 56.4 bushels of soybeans per acre for Kansas and 163.7 bushels per acre for Nebraska. In Kansas, water deliveries increased by 1.1 acre-inches from the Baseline No Action delivery. In Nebraska, water deliveries were relatively constant across action alternatives/scenarios compared to the Baseline No Action delivery with slightly lower deliveries in two of the three alternatives/scenarios. There was no change in the number of affected acres in Kansas, but an increased number of acres were affected in Nebraska under the action alternatives/scenarios.

*No Action versus Action Alternatives under Future Climate Scenarios*

For the with climate change comparison, estimated irrigation benefits for each proposed alternative for each of the three climate scenarios are compared to the estimated irrigation benefits for the No Action Alternative under the same climate scenario. This comparison is provided for each alternative under each climate scenario (with the exception of Alternative 1C where hydrologic results were only provided for the without climate change condition and warmer/drier climate scenario). Tables 24 through 26 present the results under the three climate scenarios for each alternative.

**Table 24. — Agricultural benefits comparison of No Action Alternative versus action alternatives, all under Climate Scenario 1 (warmer/drier)**

| | Base Case Alternative | Comparison Alternative | | | |
|---|---|---|---|---|---|
| | No Action | 1C | 3A | 3B | 5A |
| **Kansas** | | | | | |
| Water Deliveries (Acre-Inches/Acre) | 17.5 | +0.50 | n/a | n/a | n/a |
| Acres Affected | 42,500 | 42,500 | n/a | n/a | n/a |
| Corn Yield (bushels/acre) | 201.8 | +4.9 | n/a | n/a | n/a |
| Soybeans Yield (bushels/acre) | 60.3 | +0.7 | n/a | n/a | n/a |
| NFI Present Value ($ million) | | +$7.72 | n/a | n/a | n/a |
| **Nebraska** | | | | | |
| Water Deliveries (Acre-Inches/Acre) | 6.29 | n/a | +0.03 | +0.01 | 0 |
| Acres Affected | 30,847 | n/a | 31,182 | 31,345 | 30,939 |
| Corn Yield (bushels/acre) | 157.8 | n/a | +0.2 | +0.1 | 0 |
| NFI Present Value ($ million) | | n/a | +$0.64 | +$0.30 | 0 |

Table 24 shows results when comparing the No Action under Climate Scenario 1 to the action alternatives under the same scenario. For Kansas, water deliveries to 42,500 acres averaged 17.5 acre-inches under no action. Water deliveries increased by one half inch under Alternative 1C, resulting in increases in corn and soybean yields. The increase in water deliveries and crop yields caused an increase in NFI of $7.72 million for Alternative 1C under Climate Scenario 1 in present value terms.
There were slight to no increases in water deliveries in Nebraska, resulting in slight increases in corn yields under Alternatives 3A and 3B. Increases in the present value of NFI occurred for 3A and 3B over 335 and 498 more acres, respectively.

No change in water deliveries were observed for Alternative 5A. Therefore, no change in yield or NFI resulted.

**Table 25. — Agricultural benefits comparison of No Action Alternative versus action alternatives, all under Climate Scenario 2 (central tendency)**

| | Base Case Alternative | Comparison Alternative | | |
|---|---|---|---|---|
| | **No Action** | **3A** | **3B** | **5A** |
| **Nebraska** | | | | |
| Water Deliveries (Acre-Inches/Acre) | 7.74 | -0.5 | -0.1 | -0.03 |
| Acres Affected | 53,953 | 50,500 | 52,677 | 54,188 |
| Corn Yield (bushels/acre) | 165.3 | -2.3 | -0.6 | -0.1 |
| NFI Present Value ($ million) | | -$11.85 | -$3.02 | -$1.0 |

Table 25 shows results when comparing the No Action under Climate Scenario 2 to the action alternatives under the same scenario. There were slight decreases in water deliveries to Nebraska irrigated lands, resulting in decreased corn yields ranging from -0.1 bushels/acre to -2.3 bushels/acre under all three action alternatives. The present value of NFI decreased for all action alternatives compared to the No Action Alternative under Climate Scenario 2.

**Table 26. — Agricultural benefits comparison of No Action Alternative versus action alternatives, all under Climate Scenario 3 (less warm, wetter)**

| | Base Case Alternative | Comparison Alternative | | |
|---|---|---|---|---|
| | **No Action** | **3A** | **3B** | **5A** |
| **Nebraska** | | | | |
| Water Deliveries (Acre-Inches/Acre) | 8.51 | -0.1 | +0.01 | +0.01 |
| Acres Affected | 75,504 | 74,638 | 75,834 | 75,531 |
| Corn Yield (bushels/acre) | 169.0 | -0.6 | 0 | 0 |
| NFI Present Value ($ million) | | -$5.33 | 0 | 0 |

Table 26 shows results when comparing the No Action under Climate Scenario 3 to the action alternatives under the same scenario. There was a slight decrease in water deliveries to Nebraska irrigated lands under Alternative 3A, resulting in a decreased corn yield of six tenths of a bushel. The present value of NFI decreased for Alternative 3A by $5.33 million compared to the No Action.
No change in water deliveries, yields, or present value of NFI was observed for Alternatives 3B or 5A.

# 4. Recreation Benefits Analysis

## a. *Purpose and Scope*

Recreation benefits were evaluated for six reservoirs within the Republican River Basin – five in Nebraska (Enders, Swanson, Hugh Butler, Harry Strunk, and Harlan County) and one in Kansas (Lovewell). Hydrologic effects were not evaluated for Bonny Reservoir in Colorado or Keith Sebelius Reservoir in Kansas, resulting in an exclusion of those reservoirs from the recreation economic analysis.

While there may be some recreation activity on the Republican River itself, the focus of the recreation analysis is on the six impacted reservoirs which generate a sizable amount of recreation use. As shown Table 27, total recreation use across the six reservoirs averaged nearly 950,000 visits annually across the 2000–2011 time period. Harlan County and Lovewell provide nearly 80% of this total visitation.

**Table 27. — Recreation Data by Affected Reservoir**

| Reservoir | Dam | Location State | Surface Acreage (Top of Conservation Pool) | Average Annual Visitation (2000-2011)* |
|---|---|---|---|---|
| Swanson | Trenton | Nebraska | 4,794 | 51,403 |
| Enders | Enders | Nebraska | 1,707 | 39,105 |
| Hugh Butler | Red Willow | Nebraska | 1,628 | 44,715 |
| Harry Strunk | Medicine Creek | Nebraska | 1,850 | 60,017 |
| Harlan County | Harlan County | Nebraska | 13,250 | 527,361 |
| Lovewell | Lovewell | Kansas | 2,986 | 226,149 |
| | | | **Total:** | **948,750** |

(*) Data Sources: Nebraska Game and Parks Commission, Kansas Department of Wildlife, Parks and Tourism.

## b. *Methods*

To estimate recreation economic benefits under each alternative at each reservoir, information was developed or obtained in terms of both annual visitation and value per visit. As discussed below, annual visitation estimates were developed by alternative, but the value per visit is not alternative specific. Multiplying the annual visitation estimates by alternative times values per visit results in estimates of annual recreation economic value by alternative and reservoir. Compounding/discounting and summing the range of annual values estimated across each year of the 50-year planning horizon results in a present value by alternative and reservoir. Summing the present values across reservoirs results in the recreation value by alternative for use in the benefit-cost analysis.

### i. Reservoir Visitation Modeling

Attempts were made to statistically estimate a relationship between end-of-month water levels and monthly visitation at each of the six reservoirs. Each reservoir provides a wide range of recreational activities including fishing, boating/waterskiing, camping, picnicking, swimming, hunting, etc. Some of these activities are water-based (boating/waterskiing, fishing, swimming) since they directly make use of the water while others are water-influenced (camping, picnicking, hunting, birding/wildlife viewing), given that they make use of the water indirectly.

The relationship of visitation to water levels is fairly straightforward for water-based activities (e.g., boating and boat-based fishing) since, as water levels decline, boating and boat-based fishing tends to decline due to limited access as boat ramps become unusable and as increases in exposed and unexposed obstructions hamper boat movement. Also, shoreline fishing tends to decrease as mud flats widen, making water access more difficult. For some water-influenced activities (e.g., camping, picnicking), while they do not require access to the water, they are generally influenced by water levels due to aesthetic reasons – the development of "bath tub rings" and mud flats around a reservoir creates a less attractive setting. For other water-influenced activities (e.g., hunting, birding/wildlife viewing), depending on the species targeted, bird/wildlife populations can vary significantly with the presence or quantity of water. Typically, fish and wildlife populations increase as water levels and surface area increases. In addition, visitation normally increases as these populations increase - with certain exceptions (e.g., certain types of bird watching where visitation may actually increase as populations decrease and become rarer at the site). Exceptions aside, it is generally the case for water based and water influenced activities that visitation tends to increase as water levels rise and vice versa. As a result, visitation levels for most water based and water influenced recreational activities typically moves in unison with water levels. Above and below the typical water level range, most water based and water influenced activities decline as facilities become unusable due to extremely low water levels or flooding.[21]

Monthly visitation data for each reservoir from 2000-2012 was obtained from the Nebraska Game and Parks Commission and Kansas Department of Wildlife, Parks and Tourism. Data on end of month (EOM) water levels and total monthly precipitation for each reservoir was obtained from Reclamation's Nebraska-Kansas Area Office. Average monthly temperature data was obtained from the High Plains Regional Climate Center (Historical Climate Data Summaries for each reservoir with missing information supplemented with data from closest data

[21] The potential for optimal water levels within the available range of data were tested using a quadratic model. This model proved statistically insignificant and was therefore not used to estimate changes in visitation.

point in the High Plains Regional Climate Center database) (HPRCC, 2015). Finally, annual population data for Nebraska and Kansas was obtained from the U.S. Census Bureau.

Prior to the modeling efforts, a visitation-based monthly outlier analysis was conducted for each reservoir. Data was sorted by month and average visitation was calculated for each month. A standard deviation was calculated for each month and a high and low end visitation thresholds were developed using two standard deviations from the mean (reflects 95% of the data). If a given monthly visitation observation fell outside of the two standard deviation ranges, either on the high or low end, that observation was dropped from the data set.

Using data across all months from 2000 through 2012, the visitation or use estimating model seen below in Equation 1 was proposed for each reservoir.

**Equation 1. — Basic water level model with seasonality**

$$\underset{}{Visits_{mj}} = f\,(\underset{(+)}{EOM\ WL_{mj}},\ \underset{(+)}{Temp_{mj}},\ \underset{(-)}{Precip_{mj}},\ \underset{(+)}{Pop_{y}},\ \underset{(+)}{Spring},\ \underset{(+)}{Summer},\ \underset{(+)}{Fall})$$

where:

| | |
|---|---|
| Month: | m = January,…,December |
| Reservoir: | j = 1,…,6 |
| Year: | y = 2000,…,2012 |

Dependent Variable ($Visits_{mj}$): Total visits associated with each month at each reservoir.

Explanatory Variables:

| | |
|---|---|
| EOM $WL_{mj}$: | End of month water level in feet above mean sea level (msl) by month and reservoir |
| $Temp_{mj}$: | Average monthly air temperature (degrees F) by month and reservoir |
| $Precip_{mj}$: | Total monthly precipitation in inches by month and reservoir |
| $Pop_{y}$: | Annual state population |
| Spring: | Spring (March–May) qualitative (0/1) variable |
| Summer: | Summer (June–August) qualitative (0/1) variable |
| Fall: | Fall (September–November) qualitative (0/1) variable |

The dependent variable reflects total monthly visits. The positive and negative signs under each explanatory variable represent the direction of the expected relationship between the explanatory variable and the dependent variable (visits or ln visits[22]). For example, the positive sign under the EOM water level and temperature variables reflect the expectation that average EOM water

[22] Note in some cases the natural log of the dependent variable was used to improve the modeling results. Taking the natural log of visits is a standard transformation used in recreation modeling.

levels/temperatures and total monthly visits would move in the same direction such that an increase (decrease) in water levels/temperatures is expected to result in an increase (decrease) in total monthly visits. The logic of the expected relationship between reservoir water levels and visitation was described above - for temperature, the logic may be less obvious but generally relates to the idea that recreationists may want to be on the water more as temperatures rise due to the cooling effects and increased interest in swimming. Consideration was given to expanding the basic model to include seasonality terms (spring, summer, and fall dummy variables) until it was discovered that the average monthly temperature (Temp) variable essentially picks up the effect of both temperature and summer season on visitation since the Temp variable was highly correlated with the Summer dummy variable at each reservoir. Since the Temp variable is also a climate change measure, it can be used to differentiate between the climate scenarios. Explanatory variables with a negative sign suggest that visits would move in the opposite direction (e.g., an increase in total monthly precipitation is expected to result in a decrease in total monthly visits). All models were run using an ordinary least squares statistical regression approach.

When attempting to address seasonality within the all month modeling efforts, it became apparent that the relationship between water levels and visitation during the low use months did not mirror the relationship during the high use months. Therefore, models were also attempted using what was deemed to be the high recreation season at each reservoir. In looking at the breakdown of average visitation by month, varying high recreation seasons were selected for each reservoir. Outliers were also removed from the high season data set based on the outliers identified in the full data set evaluation. With the exception of the seasonal dummy variables, the same model as estimated above under the all month perspective was also estimated for each reservoir using data for the high recreation season. Results of the modeling efforts are presented in Reclamation's Economics TM for each reservoir both in terms of a brief description and in tabular format.

### ii. Reservoir Values per Visit

The Republican River reservoirs provide a wide range of recreational activities including fishing, boating/waterskiing, camping, picnicking, swimming, hunting, bird/wildlife watching, etc. Based on information in Reclamation's Recreation Use Data Report for each reservoir (Johanson, 2013), the top four recreation activities at each reservoir are boating, fishing, camping, and hunting. Without data on the percentage breakdown by activity, the assumption was made that each of the four activities are equally likely. A value per visit for each reservoir was developed based on information for these four activities.

A value per visit was calculated from existing recreation economic studies using a procedure referred to as benefit transfer. Rosenberger (2011) developed a meta-analysis of outdoor recreation studies obtained from across the U.S. The results of 188 freshwater fishing studies, 32 motorized boating studies, 3 camping studies, and 26 waterfowl hunting studies were gathered and presented for the Midwestern U.S. region which includes Kansas and Nebraska. Rosenberger (2011) reports an average value of $39.30 per visit for fishing, $30.84 for boating, $9.85 for camping, and $31.76 for hunting in 2010 dollars. These four values average to $27.94 per visit in 2010 dollars. Indexing the $27.94 value up to April 2014 dollars (to be consistent with the cost estimates) using the Midwest Urban Consumer Price index results in a value of $30.38 for those activities. The $30.38 value per visit was used for all reservoirs.

## c. *Results*

### i. Recreation Benefits Comparisons by Alternative/Scenario

The recreation economic effects of the proposed action alternatives are presented under both baseline and climate scenarios. For the baseline comparison, estimated recreation benefits for each of the action alternatives are compared to the estimated recreation benefits for the No Action Alternative. Similarly, estimated recreation benefits for each of the proposed action alternatives in each of the three climate scenarios are compared to the estimated recreation benefits for the No Action Alternative under the same climate scenario. This comparison is provided for each alternative under each climate scenario (with the exception of Alternative 1C where hydrologic results were only provided for the without climate change condition and hot/dry climate scenario).

As shown in Table 28 below, by far the largest difference in recreation benefits is for Alternative 1C ($49.5 million under baseline and $65.0 million for Climate Scenario 1). This is due to the increase in recreation benefits at Lovewell Reservoir. As noted above, for Alternative 1C, climate change effects were only estimated for Scenario 1. Since climate factors, which include air temperatures, do not vary across alternatives for the same climate scenario, the increase in recreation benefits at Lovewell are due exclusively to changes in average monthly water levels. Under the Baseline Scenario, average monthly water levels were estimated to increase from 4.2 ft. to 4.6 ft. (associated with increases in surface area ranging from 632 to 673 acres) whereas under Climate Scenario 1, average monthly water levels were estimated to increase from 4.3 ft. to 5.1 ft. (646 to 722 acres).

The only other notable change in recreation benefits is the $7.6 million increase at Swanson Reservoir under Alternative 3B, Climate Scenario 3. Again, since average monthly air temperature is the same, the change in water levels drives the estimate of increased recreation benefits. The change in average monthly water levels ranges from 1.2 ft. to 1.4 ft. or 136 to 179 acres of surface area. While this difference may not appear dramatic, it shows how sensitive recreation visitation and value can be to changing water levels.

**Table 28. — Recreation Benefits Comparisons by Scenario**

| Present Value of the Change in the 50-Year Stream of Reservoir Recreation Benefits (Million $) | | | | | | |
|---|---|---|---|---|---|---|
| | | | Climate Change Condition | | | |
| | | | | Climate Scenarios | | |
| Alternative | Reservoir | State Providing Hydrologic Modeling | Baseline Climate Condition | Scenario 1 | Scenario 2 | Scenario 3 |
| 1C | Harlan County | Kansas | 0.08 | -0.02 | n/a | n/a |
| | Lovewell | Kansas | 49.40 | 65.00 | n/a | n/a |
| | Total: | | 49.48 | 64.98 | n/a | n/a |
| 3A | Enders | Nebraska | -0.16 | 0.00 | -1.55 | -0.16 |
| | Harry Strunk | Nebraska | -0.05 | -0.03 | -1.26 | -0.34 |
| | Hugh Butler | Nebraska | 0.02 | 0.02 | -1.36 | 0.13 |
| | Swanson | Nebraska | 1.64 | 0.45 | -2.11 | 2.51 |
| | Harlan County | Nebraska | -0.31 | -0.17 | -0.35 | -0.18 |
| | Total: | | 1.14 | 0.27 | -6.63 | 1.95 |
| 3B | Enders | Nebraska | 0.29 | 0.00 | -0.95 | 0.00 |
| | Harry Strunk | Nebraska | -0.16 | -0.04 | -0.82 | 0.01 |
| | Hugh Butler | Nebraska | -0.23 | 0.01 | -0.97 | 0.15 |
| | Swanson | Nebraska | 1.81 | 0.67 | 1.13 | 7.62 |
| | Harlan County | Nebraska | -0.10 | -0.25 | -0.13 | -0.19 |
| | Total: | | 1.62 | 0.39 | -1.74 | 7.59 |
| 5A | Enders | Nebraska | 0.29 | 0.00 | -0.01 | 0.00 |
| | Harry Strunk | Nebraska | -0.04 | -0.01 | -0.01 | 0.01 |
| | Hugh Butler | Nebraska | -0.17 | 0.00 | 0.00 | -0.04 |
| | Swanson | Nebraska | 0.04 | -0.01 | -0.03 | 0.18 |
| | Harlan County | Nebraska | 0.46 | 0.16 | 0.41 | 0.39 |
| | Total: | | 0.57 | 0.15 | 0.37 | 0.54 |

### ii. Effects of Climate Change on Recreation Benefits

Table 29 displays the recreation economic effects of climate change. The No Action Alternative under each climate scenario is compared to the Baseline No Action Alternative. The results in this table reflect the difference in the present value of the 50-year stream of recreation benefits for the No Action Alternative under each climate change condition.

As noted in the table's footnote, given that two sets of hydrologic data were provided for Harlan County Lake, two sets of results are presented for the combined recreation benefits across the six reservoirs. The first set includes Harlan County Lake recreation benefits based on hydrologic data provided by the Nebraska model whereas the second set presents the reservoir's benefits based on Kansas hydrologic modeling output.

While certain reservoirs result in negative recreation benefits under Climate Scenario 1, overall the recreation economic effect of climate change is positive for all three climate scenarios compared to the Baseline No Action. Under Scenarios 1 and 2, Harlan County and Lovewell reservoirs generate the majority of the increase in recreation benefits. Under Scenario 3, Swanson Reservoir also contributes heavily along with Harlan County and Lovewell.

The recreation visitation models for Swanson, Harlan County, and Lovewell are based on reservoir water levels and air temperatures. The coefficients of the models are positive for both water level and temperature implying that increases (or decreases) in water levels and temperatures should lead to increases (or decreases) in recreation visitation (see *Section 7.6.4: Recreation Benefits Analysis* for more details). Note that similar changes in water levels across alternatives at different reservoirs can lead to dramatically different impacts upon recreation visitation due to reservoir size and bathymetry. For example, a one-foot change in water level at Harlan County Lake would lead to a substantially larger change in surface area as compared to a similar change in water levels at all the other much smaller reservoirs included in this Study.

The large $49.2 million increase in recreation benefits at Swanson Reservoir under Scenario 3 is primarily due to the large change in water levels and to a lesser degree air temperatures. The monthly change in average water levels was estimated in the 14.4 ft to 15.6 ft range which equates to a gain in surface area ranging from 1,537 to 1,764 acres. The monthly change in temperature ranged from 1.9 °F to 4.5 °F. At Harlan County Lake, the large increases in recreation benefits under Scenario 1 and Scenario 2 are due primarily to the increases in average monthly air temperatures (increased temperature ranges from 3.8 °F to 8.2 °F for Scenario 1 and 3.8 °F to 4.9 °F for Scenario 2). Climate Scenario 3 (less warm/ wetter) is driven by both changes in water levels (4.2 ft to 5.3 ft equating to a change in surface area of 1,257 to 1,612 acres) and temperatures (1.6 °F to 3.9 °F). Finally at Lovewell Reservoir, the increases in recreation benefits under all three climate scenarios is primarily due to air temperature increases in the 1.6 °F to 8.3 °F range. The largest loss (-$7.5 million) in recreation benefits is seen at Swanson Reservoir under Scenario 1. This is due to the consistent reduction in average monthly water levels across the May to

November high recreation use season ranging from -9.1 ft to -10.1 ft which corresponds to a reduction in surface area of 925 to 1,070 acres.

For some scenarios and reservoirs, there may be a sizable reduction in water levels which are offset in the visitation estimates by increases in air temperatures. For example, at Harry Strunk Reservoir, No Action, Scenario 1 results in an increase of $2.3 million in recreation values over the Baseline No Action. Water levels across the April to September high recreation use season were estimated to decline from a low of 4.0 ft to a high of 8.1 ft (157 to 359 surface acres) while temperatures were estimated to increase from 3.8 °F to 8.1 °F. The increases in temperature outweighed the losses in water levels resulting in an increase in recreation benefits.

Overall, compared to the Baseline No Action, the effects of Climate Scenarios 1, 2, and 3 result in an approximate increase of recreation benefits by 14%, 18%, and 29%, respectively.

**Table 29. — Recreation benefits comparison of the Baseline Climate Scenario versus the three future climate scenarios, all under the Future No Action Alternative**

| Present Value of the Change in the 50-Year Stream of Recreation Benefits (Million $) | | | | | |
|---|---|---|---|---|---|
| | | | ***Climate Scenario Comparisons*** | | |
| **Reservoir** | **State Providing Hydrologic Modeling Results** | **Baseline No Action** | **Scenario 1** | **Central Tendency** | **Scenario 3** |
| Enders | Nebraska | 19.31 | -1.12 | 7.97 | 11.80 |
| Harry Strunk | Nebraska | 22.52 | 2.35 | 7.22 | 13.27 |
| Hugh Butler | Nebraska | 37.36 | -1.77 | 3.94 | 8.06 |
| Swanso n | Nebraska | 16.36 | -7.47 | 8.82 | 49.22 |
| Harlan County (*) | ***Nebraska*** | 301.82 | 49.28 | 37.04 | 37.84 |
| Lovewell | Kansas | 109.75 | 27.91 | 25.04 | 25.53 |
| Total: | | 507.12 | +69.18 | +90.04 | +145.72 |
| Enders | Nebraska | 19.31 | -1.12 | 7.97 | 11.80 |
| Harry Strunk | Nebraska | 22.52 | 2.35 | 7.22 | 13.27 |
| Hugh Butler | Nebraska | 37.36 | -1.77 | 3.94 | 8.06 |
| Swanso n | Nebraska | 16.36 | -7.47 | 8.82 | 49.22 |
| Harlan County (*) | ***Kansas*** | 303.55 | 47.77 | 37.66 | 39.45 |
| Lovewell | Kansas | 109.75 | 27.91 | 25.04 | 25.53 |
| Total: | | 508.85 | +67.67 | +90.66 | +147.33 |

(*) Two versions of hydrologic output for Harlan County Lake were provided, one from the Nebraska model and one from the Kansas model. The total reservoir recreation effect of climate change as compared to the without climate change baseline is presented using Harlan County Lake results based on both the Nebraska and Kansas input data.

# G. Economics Analysis

## 1. Purpose and Scope

As previously stated, the primary purpose of the economic analysis was to estimate the net economic benefits (i.e., benefits minus costs) for each action alternative as compared to the No Action Alternative based on construction costs, including interest during construction, and agricultural and recreation benefits. A secondary objective of the analysis was to evaluate the economic effect of climate change associated with the various climate scenarios.

## 2. Methods

Agricultural and recreation benefits were estimated independently under the conditions specified for each of the eighteen alternatives/scenarios defined in Table 30. The sum of agricultural and recreation benefits under a given alternative/scenario yields the *combined benefits*. The costs associated with each alternative/scenario are then subtracted from *combined benefits* to yield *net benefits* under each alternative/scenario.

## 3. Results

### a. *Benefit/Cost Comparisons by Alternative/Scenario*

Table 30 presents the net benefit results of the action alternatives under each climate scenario (including Baseline). Alternative 1C yielded the largest agricultural and recreation benefits of all four alternatives; this is due to the increased water deliveries and higher lake levels associated with reservoir expansion. Furthermore, relative to total costs, Alternative 1C was the only alternative to yield positive net benefits. These benefits were driven primarily by recreation as opposed to agricultural production from water deliveries. The agricultural and recreation benefits of Alternatives 3A, 3B, and 5A were mixed depending on the climate scenario, but overall, the net benefits were all negative relative to costs. Results are considered preliminary; a more complete economics analysis would include operations, maintenance, replacement, and power (OMR&P) costs and address the data gaps and assumptions provided in Section 7.7.4 of the Basin Study Report. For instance, adding OMR&P costs would reduce net benefits across all alternatives; in the case of Alternative 1C, this reduction could be substantial enough to result in net benefits becoming negative

**Table 30. — Present value of net benefits of alternatives under different climate scenarios, Republican River Basin Study. Scenario 1 = warmer/drier; Scenario 2 = central tendency; Scenario 3 = less warm/wetter**

| | | *All benefits, costs, and net benefits reported in millions of dollars* | | | | |
|---|---|---|---|---|---|---|
| **Base Case Alternative / Scenario** | **Comparison Alternative/ Scenario** | **Incremental Agricultural Benefits[a]** | **Incremental Recreation Benefits[a]** | **Incremental Combined Benefits[a,b]** | **Incremental Costs[c]** | **Net Benefits[a,d]** |
| No Action/ Baseline | 1C / Baseline | 19.12 | 49.48 | 68.60 | 66.30 | 2.30 |
| No Action/ Baseline | 3A / Baseline | -3.08 | 1.14 | -1.94 | 41.12 | -43.06 |
| No Action/ Baseline | 3B / Baseline | -0.84 | 1.62 | 0.78 | 90.64 | -89.86 |
| No Action/ Baseline | 5A / Baseline | 0.80 | 0.57 | 1.37 | 100.05 | -98.68 |
| No Action / 1 | 1C / 1 | 7.72 | 64.98 | 72.70 | 66.30 | 6.40 |
| No Action / 1 | 3A / 1 | 0.64 | 0.27 | 0.91 | 41.12 | -40.21 |
| No Action / 1 | 3B / 1 | 0.30 | 0.39 | 0.69 | 90.64 | -89.95 |
| No Action / 1 | 5A / 1 | 0.00 | 0.15 | 0.15 | 100.05 | -99.90 |
| No Action / 2 | 3A / 2 | -11.85 | -6.63 | -18.48 | 41.12 | -59.60 |
| No Action / 2 | 3B / 2 | -3.02 | -1.74 | -4.76 | 90.64 | -95.40 |
| No Action / 2 | 5A / 2 | -1.00 | 0.37 | -0.63 | 100.05 | -100.68 |
| No Action / 3 | 3A / 3 | -5.33 | 1.95 | -3.38 | 41.12 | -44.50 |
| No Action / 3 | 3B / 3 | 0.00 | 7.59 | 7.59 | 90.64 | -83.05 |
| No Action / 3 | 5A / 3 | 0.00 | 0.54 | 0.54 | 100.05 | -99.51 |

[a] 50-year stream of benefits discounted at the FY2015 Federal Discount rate of 3.375% (Reclamation, 2014).

[b] The sum of agricultural benefits and recreation benefits.

[c] Costs are associated with action alternatives/scenarios but not the No Action Alternative/scenarios; includes capital costs and interest during construction and excludes operations, maintenance, replacement, and power costs.

[d] Combined Benefits minus Costs.

### b. *Effects of Climate Change on Benefit/Cost Analysis*

Table 31 reports the results of the No Action Alternative under each of the three future climate scenarios compared to the No Action Alternative under Baseline conditions. Since project operations are identical, the difference in economic value is exclusively due to the physical effects of climate change.

Hydrologic inputs in terms of reservoir water levels were provided for Harlan County Lake from both the Kansas and Nebraska modeling efforts. As a result, separate recreation benefit estimates were calculated using the Nebraska data (option 1 in Table 31) and the Kansas data (option 2 in Table 31).

Net benefits under all three future climate scenarios under the No Action Alternative exceed those associated with the comparative Baseline Climate condition. Both total benefits and net benefits (note zero costs for the No Action Alternatives) are dominated by recreation under Scenarios 2 and 3 (recreation reflects 72 to 98 % of total and net benefits). Under Scenario 1, agricultural benefits are considerably higher compared to the other two scenarios such that recreation only reflects 57% of the total and net benefits. Recreation benefits increase under each No Action climate scenario due to increased temperatures under all three scenarios and increased water elevations under Scenarios 2 and 3.

**Table 31. — Present value of net benefits of alternatives under different climate scenarios, Republican River Basin Study**

| | | *All benefits, costs, and net benefits reported in millions of dollars* | | | | |
|---|---|---|---|---|---|---|
| **Base Case Alternative/ Scenario** | **Comparison Alternative/ Scenario** | **Incremental Agricultural Benefits[a]** | **Incremental Recreation Benefits[a]** | **Incremental Combined Benefits[a,b]** | **Incremental Costs[c]** | **Net Benefits[a,d]** |
| *Option 1: Recreation Results for Harlan County Lake based on Nebraska modeling* | | | | | | |
| No Action / Baseline | No Action / 1 | $50.37 | $69.18 | $119.55 | $0.00 | $119.55 |
| No Action / Baseline | No Action / 2 | $29.38 | $90.04 | $119.42 | $0.00 | $119.42 |
| No Action / Baseline | No Action / 3 | $2.57 | $145.72 | $148.29 | $0.00 | $148.29 |
| *Option 2: Recreation Results for Harlan County Lake based on Kansas modeling* | | | | | | |
| No Action / Baseline | No Action / 1 | $50.37 | $67.67 | $118.04 | $0.00 | $118.04 |
| No Action / Baseline | No Action / 2 | $29.38 | $90.66 | $120.04 | $0.00 | $120.04 |
| No Action / Baseline | No Action / 3 | $2.57 | $147.33 | $149.90 | $0.00 | $149.90 |

[a] 50-year stream of benefits discounted at the FY2015 Federal Discount rate of 3.375% (Reclamation, 2014).

[b] The sum of agricultural benefits and recreation benefits.

[c] No costs are associated with any of the No Action Alternative options.

[d] Combined Benefits minus Costs.

# 4. Assumptions and Data Gaps

This section summarizes the assumptions, uncertainties, and data gaps associated with economic analyses conducted for this Republican River Basin Study. In addition, recommendations for future basin studies are discussed.

While the analysis for this Basin Study had only to meet the level of detail and analytical rigor of an appraisal level study, some of the discussion below examines what might be required for a more detailed analysis if such is pursued by the States.

## a. *Agricultural Benefits*

The agricultural benefits analysis was simplified by including only one crop (corn) in Nebraska. Historical cropping data for 22 counties in Nebraska was provided by the state of Nebraska for five predominant crops grown in the Nebraska portion of the Lower Republican River Basin: corn, hay, sorghum, soybeans, and wheat. The average percentage split of the four predominant crops was: corn (55 percent), hay (9 percent), soybeans (17 percent), sorghum (2 percent), and wheat (17 percent) across all 22 counties. This data was obtained from USDA-NASS.

The agricultural benefits analysis was simplified by including only two crops (corn and soybeans) in Kansas. Historical cropping pattern data for KBID was provided by the state of Kansas and used for the Kansas portion of this analysis. Predominant crops grown in the KBID included corn, soybeans, sorghum, and alfalfa. Corn and soybeans were selected as the representative crops for KBID, since these two crops account for almost 88% of all irrigated lands in the district. The acreages for corn and soybeans were extrapolated to all Kansas irrigated lands affected by the proposed action alternatives. A comparison between the cropping pattern exhibited within KBID and other counties in Kansas was not conducted.

Changes in NFI, and thus, irrigation benefits were driven by estimated changes in yield in this appraisal analysis. Crop prices, yields, and input costs would affect the agricultural benefits in the Republican River Basin. In general, when input costs increase, all else being equal, agricultural benefits would decrease. The effects of crop price changes would depend on the direction and magnitude of the changes. Higher crop prices, all else equal, would be expected to increase net agricultural revenues. Higher crop yields, all else equal, would also be expected to increase net agricultural revenues.

## b. *Recreation Benefits*

Application of recreation use models assumes the historic statistical relationship between water levels/air temperature and visitation will hold into the future. However, there is no guarantee that the estimated relationships will continue to hold. Perhaps the only way to potentially address changes in the water level/temperature to visitation relationship would be to conduct surveys where recreationists are directly asked to react to water level/air temperature changes.

Use estimation models were assumed to be applicable beyond the range of underlying data. The average monthly water levels/air temperatures for some months and alternatives fell outside the range of the underlying data used to estimate the models (especially for the warmer/drier climate scenario, low water availability). The fact that water levels and air temperatures fell outside the historical range is not surprising given the study objective to measure the effects of climate change. Despite this issue, the models were still used to forecast visitation for all months and alternatives. It may not be possible to avoid this potential problem with climate change studies. Even if surveys were conducted in an attempt to gather information on recreationists' reactions to water level/temperature conditions outside the historical range, those survey results could be questionable since by definition they are based on conditions beyond the visitor experience.

Measures of recreation visitation by reservoir, alternative, and climate change scenario have an inherent level of uncertainty due to the statistical analysis. In addition to the results based on averages, statistically based confidence intervals around the average estimates could have been developed and used in the analysis. Given the substantial increase in alternative and climate change scenario comparisons which would result from the use of confidence intervals, only the average estimates were used in the analysis.

Values per trip by activity were calculated based on a benefits transfer of information obtained from recreation economic studies at other sites within the region (Rosenberger, 2011). Transferred values from other sites are often used in feasibility studies as well as appraisal studies. It was assumed that the indexed values per trip by activity from other regional sites would be reflective of the current value per trip for the same activity at the reservoirs included in this Study. There is always the potential for error when transferring values from other sites. Such error could be avoided if data were available (e.g., via surveys) to estimate values separately for each of the impacted reservoirs.

Given the lack of data on the percent of visitation by activity for each reservoir, it was assumed the top four activities at each site were equally likely for purposes of estimating an average recreation value per trip. Had the percent of visitation by activity for each reservoir been available, a weighted average value per trip could have been estimated for each reservoir. Since values per trip vary across the top four activities used in the benefits transfer application, it is possible that the weighted average might vary significantly from the applied straight average. With data on the percent of visitation by activity at each reservoir, it is also possible that the weighted average would be based on a different number of activities as opposed to the top four. To avoid these potential problems, visitation by activity could be estimated by collecting data (e.g., via head counts by activity or as a result of a survey).

### c. *Benefit-Cost Analysis*

The BCA focused on the top two potentially impacted benefit categories (agriculture and recreation) as decided by study team management. It is possible that other benefit categories might also be impacted, which could affect the BCA results.

Annual operations, maintenance, replacement, and power (OMR&P) costs were excluded from the benefit-cost analysis under the assumption that they would be minor in comparison to construction costs. If the impact to annual OMR&P costs proved higher than expected, excluding them from the BCA may have affected those alternatives with positive net benefits.

As is standard practice, benefits were assumed to begin in the year after construction was completed for each alternative. If it was determined that benefits started later for whatever reason, that could affect the present value estimate of the benefits. Even if this was the case, it is unlikely that the impact would be substantial.

### d. *Future Investigations*

- A consistent method for developing cropping patterns across states could be implemented, such as using irrigation district information for both states or use only USDA-NASS data for both states.

- More detailed groundwater pumping evaluation across climate scenarios is needed.

- Changes in NFI were driven by estimated changes in yield in this appraisal analysis. Other drivers of changes in NFI might include changes in cropping patterns (acreage of one crop increases while another decreases) and/or changes in pumping costs. A more detailed analysis might examine additional factors of production and include them in the agricultural benefits analysis.

- Collect additional data and conduct surveys on travel costs and/or contingent valuation modeling where both visitation and value could be derived from the same model.

- Annual OMR&P costs could be estimated to provide a more complete benefit-cost analysis.8.0 Environmental Resources Evaluation

# H. Existing Environmental Resources

Reclamation (2000) prepared an environmental impact statement (EIS) for water service contract renewal for irrigation districts in the Republican River Basin in Nebraska and Kansas in the 1990s. Though somewhat dated, much of the material in that EIS represents the best available information related to Basin environmental resources and much is incorporated in the following evaluation without citation.

## 1. Stream Habitats

Aquatic resources in the Republican River Basin consist of plants and animals that require open water to complete some portion of their life cycle. This includes organisms like fish and submerged aquatic plants, but also includes invertebrates, reptiles, amphibians, birds, and mammals that feed or reproduce in the water or periodically inhabit aquatic or riparian habitats. The most important aquatic resources in the Basin - the Republican River and its tributaries - have been substantially altered since 19th century settlement with long-lasting effects on aquatic resources.

Native aquatic organisms in the Basin adapted and evolved under connected stream habitats and extremes of drought and floods characteristic of most Great Plains watercourses (Dodds et al. 2004). Only those organisms that could tolerate and reproduce under widely fluctuating ranges of temperature, dissolved oxygen, turbidity, current velocity, and discharge were able to survive and adapt to such conditions. The ability of these organisms to withstand such environmental extremes resulted in a highly-resilient aquatic ecosystem. Although resilient, native fish in Great Plains' streams are currently vulnerable to mortality by being stranded in streambed pools with highly-elevated water temperatures for extended periods or being entrained into reservoirs and canals (Durham et al., 2006).

Dam construction, diversions, and groundwater pumping in the Basin have moderated these extreme conditions and created environments favorable for less-resilient organisms to inhabit and sometimes dominate Basin streams. Basin impoundments have altered stream flow discharge and flow patterns. The pre-settlement hydrograph has changed from flood flows in late winter and spring with lower flows or ponding in summer and fall to a new pattern where flood flows are impounded and released during the growing season to accommodate irrigation demands. Quist et al. (2005), Perkin and Gido (2012), Hubert and Gordon (2006), and Perkin et al. (2015) found impoundments on Great Plains streams alter aquatic community structure both upstream and downstream with some species being extirpated. Stocked impoundments provide a source of non-native fish species that are able to move upstream and downstream and outcompete native species in altered habitats. Impoundments were also responsible for modifying the hydrograph and water clarity downstream to the detriment of native fish species.

Reductions in the volume of water conveyed through Basin streams along with habitat fragmentation caused by impoundment and diversion structures have become significant threats to native aquatic resources and biodiversity. In-stream diversions, groundwater pumping, on-farm soil and water conservation practices, upstream irrigation development, and extended drought in the Basin have significantly decreased stream flows and inflows to most reservoirs. These activities and conditions have transformed pre-settlement riverine habitats to highly-variable, inhospitable habitats in which long-term persistence of native stream fishes is questionable (Falke et al. 2011). Reservoir levels are lower than planned, and less water is available to release during the non-irrigation season. Only in those reaches of Basin streams where irrigation return flows, groundwater discharge, and canal or dam seepage occur have flows been somewhat sustainable.

In 1980, the Kansas Legislature amended the Water Appropriation Act to include the concept of minimum desirable streamflows (MDS). MDS are instream flow rates that balance aquatic life needs, water quality concerns, and the interests of downstream users. MDS requirements were made part of the Kansas Water Appropriation Act by the Kansas Legislature to ensure base surface flows in certain streams to protect existing water rights and to meet in-stream water uses related to water quality, fish and wildlife, and recreation. MDS have been established at two locations on the Republican River: one at the stream gage near Concordia and another at a stream gage near Clay Center (Table 32). The MDS target flows vary by month and location, ranging from a high of 250 cfs (Clay Center, April through June) to a low of 65 cfs (Concordia, October). Water rights issued after April 12, 1984 are junior to MDS and subject to being administered if the flow levels are not met for seven days or more. As noted above, just since 2000, there have been six years that river flows did not meet MDS for extended periods of time. In 2002, groundwater diversions junior to MDS were shut off, which contributed about 10% of the total streamflow.

**Table 32. — Minimum desirable streamflows (cfs) on the Republican River in Kansas**

| Gage | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Republican River at Concordia | 100 | 125 | 150 | 150 | 150 | 150 | 150 | 150 | 80 | 65 | 80 | 100 |
| Republican River at Clay Center | 125 | 150 | 200 | 250 | 250 | 250 | 200 | 200 | 100 | 90 | 100 | 125 |

## 2. Reservoir Habitats

Harlan County Lake supports a variety of aquatic resources typical for a reservoir, dominated by open-water fish species such as walleye, white bass, wipers (white bass/striped bass hybrid), and white crappie. Fishery management activities at the reservoir are the responsibility of the Nebraska Game and Parks Commission. Depending on runoff conditions and species, white bass, walleye, and channel catfish migrate up the Republican River from the reservoir in the spring. High spring flows in the river are necessary to facilitate upstream spawning migrations of white bass.

Swanson Reservoir is located on the Republican River above Harlan County Lake about two miles west of the Town of Trenton, Nebraska. The reservoir's water clarity has a special appeal for both boaters and anglers. High water years in the early 1980s reduced swimming opportunities, but they provided a boost to the fishery. Trophy-size northern pike are found among the submerged willows and along the face of the dam. Swanson Reservoir is also known for its large walleye and a growing population of black, smallmouth, and largemouth bass. Crappie are found in the shallows during spawning season, and large schools of white bass are common from July through September.

Lovewell Reservoir is situated in the Chalk Hills region of the Smoky Hills of Kansas. Chalk bluffs, oak-covered hillsides, and upland prairies characterize the area. Migrating waterfowl and shorebirds use the reservoir and associated wetlands. On the north side of the reservoir are areas of short-grasses inhabited by thirteen-lined ground squirrels and black-tailed prairie dogs. Bobwhite quail can be found associated with shrub thickets. Ring-necked pheasants are found in the grasslands, croplands, and along the roads. Wild turkey, both white-tailed and mule deer, coyotes, opossums, raccoons, and bobcats are also found in the area. In addition to migratory songbirds, cormorants, white pelicans, gulls, and herons use the reservoir and surrounding uplands. Mourning doves, red-tailed hawks, turkey vultures, and bald eagles are becoming more common at the reservoir.

## 3. Wetlands Habitat

Wetlands in the Republican River Basin provide a variety of public benefits. Depending on their location, wetlands capture and store flood flows, improve water quality through filtration and percolation, recharge groundwater, stabilize shorelines, provide fish and wildlife habitat, contribute to primary productivity, and provide recreational and educational opportunities. Many of these functions and values contribute to the Basin's economic well-being. Where wetlands are present in the flood plain, flood damage is reduced. Riparian wetlands also eliminate the need for engineered solutions for shoreline protection. Deer and turkey frequent riparian forests and wetlands, and associated hunting provides recreational and economic benefits.

The most common wetlands in the Basin consist of depressional wetlands (i.e., marshes) and those associated with abandoned stream channels. These wetlands provide similar functions and values and support much of the same types of plants and animals. Common wetland plants that are important for fish and wildlife include bulrushes, sedges, smartweeds, cattails, and rooted submerged aquatic plants. Wet meadows supported by high groundwater in the flood plain or irrigation become more common in the lower reaches of the Basin.

Harlan County Lake supports about 2,000 acres of wetlands according to the National Wetlands Inventory. Although this acreage includes some adjacent lands, the majority of wetlands are on lands adjacent to Harlan County Lake. Wetlands adjacent to Harlan County Lake provide important wildlife habitat, fish breeding and foraging habitat, nutrient/sediment trapping, and recreation. Fluctuating reservoir levels have affected the abundance, distribution, and species composition of wetland and riparian habitat adjacent to the reservoir. The majority of wetland habitat associated with the reservoir is located upstream adjacent to Republican River/Prairie Dog Creek and on their deltas. Smaller wetlands are located adjacent to the main body of the reservoir and in the upper cove areas.

Swanson Reservoir supports approximately 780 acres of wetlands scattered along the periphery of the reservoir which varies in size depending on reservoir operations.

Proposed Thompson Creek Reservoir contains a footprint of approximately 97 acres of forested riparian habitat and approximately seven acres of wetlands.

Lovewell Reservoir supports approximately 2,800 acres of forested riparian habitat and approximately 1,000 acres of wetlands depending on the fluctuating reservoir surface elevation.

## 4. Riparian Habitat

Riparian communities in the Basin range from grasses and forbs in the more arid headwater areas to galleries of cottonwood, willow, green ash, burr oak, American elm, and hackberry in the moister, lower reaches of the Basin. Riparian communities are important as cover, forage, and breeding habitat for neotropical migratory birds. Streamside vegetation also provides food, cover, and shade for fish and other aquatic organisms. The amount of riparian vegetation in the Basin increased following flooding in the 1930s, but the development of irrigation and flood-control impoundments has reduced these flood events and promoted colonization of flood-scoured channels by pioneering riparian species. Of the approximately 65,000 acres of riparian habitat estimated in the Basin, approximately 5,000 acres are adjacent to Federally-developed flood control and irrigation reservoirs. These riparian areas are a direct result of reservoir development and can be affected both positively and negatively by short- and long-term changes in operations.

Shoreline stabilization, wildlife habitat, water quality, and aesthetic values can be attributed to reservoir riparian habitats. Like riverine riparian habitat, reservoir riparian areas support a relatively high diversity of plant and animal species. Approximate acreages for the individual reservoirs are: Swanson Lake (947); Harlan County Lake (24,030); and Lovewell Reservoir (2,883).

## 5. Terrestrial and Avian Wildlife

The Republican River Basin supports terrestrial and avian wildlife common throughout much of the Great Plains ecosystem. A mosaic of agricultural lands, shelterbelts, grasslands, wetlands, and riparian areas provides a diversity of habitat conditions that meet life cycle requirements for large and small mammals; migratory waterfowl, shorebirds, and wading birds; ground-nesting birds; neotropical migratory birds; reptiles; and amphibians. Common mammals in the Basin include white-tailed and mule deer, coyote, bobcat, opossum, raccoon, rabbits and hares, beaver, muskrat, mink, prairie dogs, skunks, ground squirrels, mice, and bats. Aquatic and terrestrial turtles, lizards, and snakes are found in suitable habitats. Resident birds, such as owls, turkeys, pheasant, quail, doves, and grouse are widespread and are generally associated with agricultural lands, shelterbelts, and adjacent grasslands.

The Basin lies within the Central Flyway and provides important migration and breeding habitat for neotropical migratory birds and migratory waterfowl, shorebirds, and wading birds. Neotropical migratory birds include swallows, wrens, robins, vireos, sparrows, blackbirds, flycatchers, kingbirds, and warblers. Migratory water birds migrating through or breeding in the Basin include mallards, teal, northern shoveler, scaup, coots, Canada and snow geese, herons, egrets, sandpipers, phalaropes, gulls, terns, and sandhill and whooping cranes. Other migratory birds include bald and golden eagles, hawks, osprey, and falcons. Bald eagles have been confirmed at Swanson and Harlan County Lakes.

## 6. Federal and State Threatened, Endangered, and Species of Concern

The Endangered Species Act of 1973, as amended (ESA), was enacted to protect and recover imperiled species and the ecosystems upon which they depend. Under the ESA, species may be listed as either endangered or threatened. “Endangered” means a species is in danger of extinction throughout all or a significant portion of its range. “Threatened” means a species is likely to become endangered within the foreseeable future. Section 7 of the ESA requires Federal agencies to use their legal authorities to promote the conservation purposes of the ESA and to consult with the U.S. Fish and Wildlife Service to ensure that effects of actions they authorize, fund, or carry out are not likely to jeopardize the continued existence of listed species.

Nebraska has enacted the Nebraska Nongame and Endangered Species Conservation Act (NNESCA) that prohibits take, exportation and possession, and imposes severe penalties on violators. The intent of the NNESCA is to conserve species of wildlife for human enjoyment, for scientific purposes, and to insure their perpetuation as viable components of their ecosystems. Projects that would be authorized, funded, or carried out by state agencies are reviewed annually as part of a mandatory consultation process designed to prevent a state action from jeopardizing the existence of an endangered or threatened species. State recovery plans for endangered or threatened species identify, describe, and schedule the actions necessary to restore populations to a more secure status. Plans are implemented on a priority basis, dealing first with species in the most immediate danger, whose life requirements are best known, and those which offer the best opportunity for success.

State and Federally- listed species are protected in Kansas as designated by the Kansas Nongame and Endangered Species Conservation Act of 1975 (KNESCA). The KNESCA places responsibility for identifying and undertaking appropriate conservation measures for listed species directly upon the Department of Wildlife, Parks and Tourism through statutes and regulations. Regulations require the department to issue special action permits for activities that affect species listed as threatened and endangered in Kansas. Recovery plans are a designated strategy with the objective to guide research and management aimed at enhancing the listed species' population. Ultimately, the goal is to be able to remove the species from threatened and endangered status in Kansas. Plans are developed based on a species priority list established by the Threatened and Endangered Species Task Force, through public comment, and in accordance with the amount of funds appropriated for this purpose.

Several Federally- and State-listed threatened or endangered species may be present throughout the Republican River Basin. The following species rely upon surface waters associated with basin streams and impoundments, adjacent riparian habitats, and/or wetlands for some portion of their life cycles.

### a. *Aquatic and Wetland Species*

- Topeka shiner (*Notropis topeka*) Federal endangered
- Sturgeon chub (*Macrhypbopsis gelida*) KS threatened
- Flathead chub (*Piatygobio gracilis*) KS threatened
- Plains minnow (*Hybognathus placitus*) KS threatened

- Shoal chub (*Macrhybopsis hyostoma*) KS threatened
- Western silvery minnow (*Hybognathus argyritis*) KS threatened
- Silver chub (*Macrhybopsis storeriana*) KS endangered

### b. *Avian Species*

- Whooping crane (*Grus americana*) Federal/NE/KS endangered
- Eskimo curlew (*Numenius borealis*) Federal/NE/KS endangered
- Interior least tern (*Sterna antillarium athalassos*) Federal/KS endangered
- Piping plover (*Charadius melodis*) Federal/KS threatened
- Snowy plover (*Charadrius alexandrinus*) KS threatened
- Western prairie fringed orchid (*Piatanthera praeclora*) Federal/NE threatened
- Bald eagle (*Haliaeetus luecocephalus*) NE/KS threatened

### c. *Terrestrial species*

- Peregrine falcon (*Falco peregrinus*) NE/KS endangered
- White-faced ibis (*Piegadis chihi*) KS threatened
- Black-footed ferret (*Mustela nigripes*) Federal/NE/KS endangered
- Swift fox (*Vulpes velox*) NE endangered
- American burying beetle (*Nicrophorus americanus*) Federal/NE/KS endangered

American burying beetle is found in Nebraska in areas with loose or sandy soils to facilitate burial of nursery prey. Pipeline construction has potential to affect such habitat and/or directly affect beetles. Reclamation conducted surveys for American burying beetles at Swanson, Medicine Creek, and Red Willow reservoirs in 2006 (Reclamation 2014). No beetles were collected during these surveys.

## 7. Invasive Aquatic Species

The Republican River Basin supports a variety of invasive and/or noxious aquatic or water-dependent plant species. Nebraska has designated the following water-dependent plant species as either invasive, noxious, or both (http://neinvasives.com/species/plants/):

- Tamarisk (*Tamarix spp.*)
- Common reed (*Phragmites australis*)
- Purple loosestrife (*Lythrum salicaria*)
- Reed canarygrass (*Phalaris arundinacea*)

Nebraska has designated the zebra mussel (*Dreissena polymorpha*) as an aquatic invasive species.

Kansas has designated the following water-dependent plant species as invasive, noxious, or both:

- Tamarisk
- Purple loosestrife
- Hydrilla (*Hydrilla verticillata*)
- Curly-leaf pondweed (*Potamogeton crispus*)
- Eurasian watermilfoil (*Myriophyllum spicatum*)

In addition, Kansas has designated the following species as the greatest threats to Kansas waters:

- Zebra mussel
- Asian carp – three species
  - *Mylopharyngodon piceus*
  - *Hypophthalmichthys molitrix*
  - *H. nobilis*
- White perch (*Morone americana*)

Other unwanted aquatic species in Kansas include:

- New Zealand mudsnail (*Potamopyrgus antipodarum*)
- Round goby (*Neogobius melanostomus*)

- Ruffle (*Gymnocephalus cernuus*)
- Rudd (*Scardinius erythrophthalmus*)
- Rusty crawfish (*Orconectes rusticus*)

## 8. Invasive Terrestrial Species

Nebraska has designated the following terrestrial plant species as invasive, toxic, or both:

- Canada thistle (*Cirsium arvense*)
- Musk thistle (*Carduus nutans*)
- European buckthorn (*Rhamnus cathartica*)
- Lespedeza (*Lespedeza cuneata*)
- Garlic mustard (*Alliaria petiolata*)

Kansas has designated the following terrestrial plant species as invasive, toxic, or both:

- Canada thistle
- Musk thistle
- Johnsongrass (*Sorghum halepence*)
- Field bindweed (*Convolvulus arvensis*)
- Lespedeza

Other non-native terrestrial species known to occur in the Basin in either Nebraska or Kansas include:

- Russian olive (*Elaeagnus angustifolia*)
- Eastern red cedar (*Juniperus virginiana*)
- Smooth brome (*Bromus inermis*)
- Black locust (*Robina psuedoacacia*)
- Kentucky bluegrass (*Poa pratensis*)
- Tall wheatgrass (*Thinopyrum ponticum*)
- Siberian elm (*Ulmus pumila*)
- Cheatgrass (*Bromus tectorum*)

- Common burdock (*Arctium minus*)
- Common mullein (*Verbascum thapsus*)
- Japanese silverberry (*Elaeagnus umbellate*)
- Crown vetch (*Coronilla varia*)
- Tree of heaven (*Ailanthus altissima*)

## 9. Water Quality

### a. *Surface Water*

Surface waters in the Basin are generally turbid and contain a moderate concentration of dissolved minerals. Streams generally provide oxygen concentrations sufficient to support warm-water aquatic life. Surface watercourses carry fairly high levels of nutrients evidenced by high concentrations of nitrates and phosphates. Water quality analysis conducted during contract renewal for the irrigation districts indicated that water quality is generally good with the possible exception of selenium (Reclamation 2000). The following information is derived from that activity's 2000 environmental impact statement.

Within the upper basin, water quality parameter values are affected by addition of water of lesser quality from Frenchman, Red Willow, and Medicine creeks. Agricultural practices and agricultural runoff contribute to increased fecal coliform, turbidity, suspended solids, and nitrates throughout the Basin. Additionally, sewage treatment plant and industrial discharges, along with animal feedlot runoff, contribute to increases in suspended solids, fecal coliform, and biochemical oxygen demand (BOD).

The major factor determining surface water quality conditions in this Basin correlates with flow volumes. Nutrients, BOD, bacterial numbers, and turbidity are at their lowest levels during periods of low flow. During high flows, most surface waters are at their poorest quality with significant increases in these parameters. Agricultural runoff is the largest contributor of BOD and nutrients to streams.

High levels of nitrates and phosphates in agricultural runoff have been shown to cause a significant loss of forest-derived carbon (i.e., leaves, twigs, etc.) from stream ecosystems and reduce the ability of streams to support aquatic life (Rosemond et al. 2015). Additional nutrients in the form of nitrates and phosphates were found to reduce forest-derived carbon in stream reaches by one-half. The loss of forest-derived carbon and the microbes they support further reduces the stream's capacity to assimilate nutrients with more nutrients flowing downstream to concentrate in lakes, reservoirs, and estuaries.

Water quality trends in the Basin have been altered by the major reservoirs in the Basin. Within these storage facilities, suspended solids, BOD, chemical oxygen demands (COD), turbidity levels, and total dissolved solids (TDS) have decreased. Biological and chemical reactions have contributed to the reduction in BOD, COD, and TDS as well as small changes to acidity and/or alkalinity (pH). Water storage reduces flow velocity and allows particulate matter to settle out resulting in reduced turbidity and suspended solid concentrations in some reservoirs. Lovewell and Swanson Reservoirs are characterized as eutrophic (i.e., nutrient rich). Pesticides have been detected in Lovewell Reservoir. Diminished streamflow has generally reduced water quality with the higher quality low flows being depleted. The filling of reservoirs has become more dependent on higher flows of lower quality causing their water quality to further deteriorate.

### b. *Impaired Surface Waters*

Section 303(d) of the Clean Water Act (CWA) requires states, territories, and authorized tribes to identify and establish a priority ranking for all waterbodies where technology-based effluent limitations required by Section 301 of the Act are not stringent enough to attain and maintain applicable water quality standards. Once identified, these entities are to establish total maximum daily loads (TMDLs) for the pollutants causing impairment in those waterbodies and submit the list of impaired waterbodies and TMDLs to the Environmental Protection Agency (EPA). Section 303(d) requires that TMDLs be established for all identified impaired waters and set at levels to achieve the applicable water quality standards and assigned beneficial uses. States are also required to categorize surface waterbodies. Categories 1-4A are not considered impaired and generally do not require TMDLs, or they are impaired but have an established TMDL(4A). Category 5 includes waterbodies where one or more beneficial uses are determined to be impaired by one or more pollutants and all of the TMDLs have not been developed.

**Nebraska**: The source of the following water quality information is Nebraska's 2014 Water Quality Integrated Report to the EPA (Nebraska Water Quality Division 2014):

- In the Republican River Basin, 31 of the 102 stream segments have been identified as impaired (Category 5) – the most of any basin in Nebraska. Only one stream segment on the mainstem Republican River located near the Kansas border has been identified as impaired for which a TMDL has been established (4A). Two stream segments tributary to the Republican River (Crooked Creek and Rock Creek) are categorized as 4C meaning they are impaired by contributions from natural sources.

- Of the 20 reservoirs located in the Basin, twelve have been categorized as impaired (Category 5) and include Harlan County and Swanson reservoirs. No reservoirs in the Basin have established and approved TMDLs.

- Much of the mainstem Republican River is impaired by E coli. Two mainstem stream segments are also impaired by selenium and low levels of dissolved oxygen, and one mainstem stream segment is impaired by the herbicide atrazine.

- Much of Frenchman Creek is impaired by E. coli and naturally high water temperatures, and one segment is impaired by selenium. Enders Reservoir is located on Frenchman Creek and is impaired by nutrients, chlorophyll a, and mercury. There is a fish consumption advisory for Enders Reservoir. Swanson and Harlan County Lakes are impaired by total phosphorus, total nitrogen, and chlorophyll a.

- Thompson Creek is impaired by E. coli and naturally high water temperatures. One segment of Beaver Creek is impaired by E. coli and low dissolved oxygen. Courtland Canal in Nebraska is impaired by E. coli.

- Section 314 of the CWA requires states submit information on the eutrophic condition of publicly owned lakes and reservoirs. Swanson Reservoir was found to be eutrophic.

**Kansas:** To comply with Section 303(d) of the CWA, Kansas prepared a list of all impaired or potentially impaired waters in the state (Kansas Department of Health and Environment 2014):

- Headwater tributaries of the Basin in Kansas are impaired for water supply and aquatic life by arsenic, selenium, and total phosphorus. Insufficient data exist to determine whether some tributaries may be impairing aquatic life and water supply from eutrophication, fluoride, sulfate, and lead. When the Republican River flows back into Kansas, the river is impaired for aquatic life by total phosphorus. Further downstream, the river is impaired for aquatic life by total suspended solids and total phosphorus. A TMDL has been established and approved for E. coli for the Republican River near Clay Center and Rice.

- White Rock Creek and Courtland Canal flow into and out of Lovewell Reservoir, respectively. Upstream of Lovewell Reservoir, White Rock Creek is impaired for water supply by arsenic and for aquatic life by total phosphorus and total suspended solids. White Rock Creek also has relatively high levels of E. coli, sulfate, and selenium; however, TMDLs have been established and approved for these constituents.

Currently, White Rock Creek downstream of Lovewell Reservoir does not have established TMDLs for beneficial uses.

- Lovewell Reservoir has TMDLs established and approved for all beneficial uses for eutrophication and pH.

### c. *Impaired Groundwater*

The Ogallala Formation is the largest supply of groundwater in the Basin containing water of good to excellent quality. Water pumped from the Ogallala Formation tends to be a calcium-magnesium-bicarbonate type when the formation overlies Pierre shale and a calcium-bicarbonate type when it overlies Niobrara chalk. Alluvium and terrace groundwater is declining in quality. A high proportion of samples from these groundwater sources exceed the maximum contaminant levels for TDS, sulfate, chloride, and nitrate-nitrogen. When compared to Ogallala water, water from alluvial groundwater shifts to a sodium-bicarbonate-sulfate type. Selenium concentrations above toxic levels in water may have occurred historically from the natural weathering process of these seleniferous marine shales.

## 10. Ecological Resiliency

Section 4(a) of the SECURE Water Act (P.L. 111-11) requires the "Secretary [of the Interior] to establish a climate change adaptation program (1) to assess each effect of, and risk resulting from, global climate change with respect to the quantity of water resources . . . and (2) to ensure, to the maximum extent possible, that strategies are developed at watershed and aquifer system scales to address potential water shortages, conflicts, and other impacts to water users . . . and the environment . . . ." One of the required elements of this section requires the Secretary to analyze the extent to which changes in the water supply of the United States will impact flow and water dependent ecological resiliency.

The responses of natural systems to progressive changes in climatic conditions are not linear. Instead, natural systems tend to be stable within a limited range of change, as determined by the system's resilience (or resiliency), and then rapidly change when the system's level of tolerance is exceeded. For this reason, ecological resilience is a useful concept for understanding the responses of ecological systems to climate change. Ecological thresholds are transition points at which small changes in physical or chemical parameters elicit a large, or non-linear, response of a natural or social-ecological system. A threshold represents the endpoint of ecological resilience – the point at which a system switches to a different system. Avoiding such thresholds is a key management goal in climate change adaptation.

Native fish that inhabit plains and prairie streams have been found to be incredibly resilient and are able to withstand unusually low levels of dissolved oxygen, high water temperatures, and flooding (Wohl et al. 2009). Fish species living in smaller prairie streams have developed strategies to compress their reproduction and growth into the unpredictable and short periods of higher flows and to maximize their mobility through a patchy habitat. Many possess unique strategies for survival and reproduction in their harsh native environment and are generally small in size to survive in small habitat patches prairie streams provide. However, water withdrawals have exacerbated stream drying and eliminated many springs and pools. Impoundments restrict fish movement and further fragment fish populations. Such alterations to prairie stream habitats have had substantial effects on an otherwise resilient fish community and have pushed some fish species to their thresholds for survival (Dodds et al. 2004).

# I. Effects of Adaptation Strategies on Environmental Resources

## 1. No Action – Future without Adaptation Strategies

### a. *Fish and Wildlife*

The amounts and functionality of streams, reservoirs, wetland, and riparian habitats would remain unchanged. Swanson, Harlan County, and Lovewell Reservoirs would continue to provide ample habitat for the current population of walleye, white bass, wipers, channel catfish, and crappie. Like most reservoir environments, the abundance of food available is largely dictated by the changing reservoir elevations during the spring and fall months. White bass, wipers, and catfish would continue to be found in the Republican River just downstream of the dams. Reservoir level fluctuations would continue to have an impact on the reservoir fishery.

High water temperatures and low flows in Frenchman Creek during the summer months would continue to be a limiting factor to the fish community. Thompson Creek supports a fish population of central stonerollers, red shiners, orangethroat darters, creek chubs, suckermouth minnows, flathead minnows and northern plains killifish. Under the No Action all of these species would have the ability to persist in Thompson Creek. The Kansas MDS would remain unchanged under the No Action.

### b. *Federal and State Threatened, Endangered, and Species of Concern*

Federal and State-listed species would not be impacted further than under historic conditions. Whooping cranes, eskimo curlews, peregrine falcons, Interior least terns and piping plovers would still have access to the areas that are currently used today. The amount of riverine and riparian habitat for these species would not be altered. Impacts to the American burying beetle would not be expected due to the absence of ground disturbing activities under the no action alternative.

### c. *Invasive Species*

Invasive species such as Canadian thistle, musk thistle, European buckthorn and garlic mustard would continue to persist throughout the area. No ground disturbing actions would take place under the No Action that would increase the spread these species. Reservoirs are currently stocked with non-native game species for recreation. Under the No Action, these species would continue to persist in the reservoir environments and could spread into the Republican River and Frenchman Creek.

### d. *Water Quality*

Under the No Action, all impairments may or may not continue depending on the outcome of management strategies recommended in the TMDLs.

### e. *Ecological Resiliency*

Decreased flows and altered hydrographs are the primary limiting factors throughout the Basin which would continue under the No Action alternative. Fish populations would continue to shift towards species that are benthic spawners rather than pelagic spawners due to the decrease in spawning and drift distance for larval fish. The Basin could also continue to see an increased shift towards non-native species.

## 2. Alternative 1C – 25,000 AF Expansion of Lovewell Reservoir

The proposed action would include increasing the storage capacity of the reservoir by 25,000 AF by raising the dam 1.5 ft and the dike surrounding the dam by 3.5 ft.

### a. *Fish and Wildlife*

Lovewell Reservoir would still provide habitat to waterfowl and shorebirds for migration and nesting. Species such as song birds, cormorants, white-pelicans, gulls, and herons would continue to use the area. The large areas of short-grass habitat to the north of the reservoir could be impacted by the increase in water surface elevations, which would have a negative impact on the current population of black-tailed prairie dogs.

Higher reservoir elevations would reduce the amount of wetlands that currently exist. The reservoir would continue to provide ample habitat for the current population of walleye, white bass, wipers, channel catfish, and crappie. The current habitat and carrying capacity of the reservoir would increase due to the increased storage. Inundation of new riparian and wetland habitat would have a positive impact on productivity and habitat within the reservoir in the short term.

White bass, wipers, and catfish would continue to be found in the Republican River just downstream of the dam.

The MDS flow in the lower Republican River would still need to be met to ensure that aquatic species are not impacted downstream of Lovewell Reservoir.

### b. *Federal and State Threatened, Endangered, and Species of Concern*

Current Federally listed species in Kansas including the whooping crane, eskimo curlew, Interior least tern, piping plover, peregrine falcon, black-footed ferret, and the American burying beetle would not be affected. The expansion of shoreline may enhance nesting habitat of the piping plover.

Also Kansas State-listed species including the white-faced ibis, snowy plover, bald eagle, sturgeon chub, flathead chub, plains minnow, western silvery minnow and silver chub, are not expected to be impacted under this action alternative.

### c. *Invasive Species*

This alternative would require a large area of upland habitat to be disturbed with the raising of the dam and diking system. This ground disturbance could increase the spread of invasive species such as Canadian thistle, musk thistle, Johnson grass, bindweed and lespedeza. Although not identified as invasive, cheatgrass and smooth broom may become established in these areas.

The increase in reservoir habitat could increase the populations of non-native species that currently exist. This could have a negative impact on the native fish population in the Republican River upstream and downstream of the reservoir.

### d. *Water Quality*

Under the No Action, all impairments may or may not continue depending on the outcome of management strategies recommended in the TMDLs.

### e. *Ecological Resiliency*

Decreased flows and altered hydrographs are the primary limiting factors throughout the Basin. The state of Kansas has implemented a MDS for the protection of instream flows for water quality, fish, wildlife, aquatic life, recreation, general aesthetics and domestic uses which would continue under the action alternative. Fish populations in the Republican River would continue to shift towards species that are benthic spawners rather than pelagic spawners due to the decrease in spawning and drift distance for larval fish. The Basin could also continue to see an increased shift towards non-native species.

## 3. Alternative 3A – Swanson Reservoir Augmentation via Frenchman Creek Pipeline

The action alternative would divert water out of Frenchman Creek to be stored in Swanson Reservoir. Currently Swanson Reservoir has existing available storage that is not being used on a yearly basis.

A new 11.3-mile long pipeline would begin in Frenchman Creek and be routed along Highway 25 south, before heading southwest to Swanson Reservoir. The intake structure would have fish entrainment protection and divert approximately 6.7 cfs into the new pipeline.

The effects on each resource described below are general in nature and are subject to change if the alternative is modified.

### a. *Fish and Wildlife*

Under the proposed action, Swanson Reservoir would continue to provide ideal habitat for migrating waterfowl, shorebirds, and wading birds that are moving through the area during spring and fall migrations. Approximately 4,000 acres of adjacent public lands would still be accessible for the public and wildlife. Swanson Reservoir would continue to support the introduced populations of walleye, white bass, wipers, largemouth bass, channel catfish, bullheads and crappie. Additional reservoir habitat would be created if additional water is stored throughout the year due to diversions out of Frenchman Creek. Water level fluctuations would still have an impact on the reservoir fishery.

With additional diversions out of Frenchman Creek into Swanson Reservoir, it is likely that these conditions would continue in the future. Also, dewatering may become an increased issue in Frenchman Creek which would be detrimental to the current fish populations.

### b. *Federal and State Threatened, Endangered, and Species of Concern*

Threatened and endangered species such as whooping cranes, eskimo curlew, peregrine falcons, Interior least terns and piping plovers would still persist throughout the area. Because the new diversion will only remove 6.7 cfs out of Frenchman Creek, it is not expected to have a large impact on habitat and water conditions downstream in the Republican River. If Swanson Reservoir elevations were increased due to the additional diversion, piping plover habitat on the reservoir margins could be impacted.

The American burying beetles' range includes some of the upland habitat around Enders Reservoir and Frenchman Creek. Impacts to this species could be possible with the installation of the new water pipe from Frenchman Creek to Swanson Reservoir. As proposed, the new pipeline would be routed along existing roadways that would reduce the chance of impacts. Reclamation conducted surveys in 2014 and did not find any beetles in area, but if this alternative were to move forward, additional surveys would be needed.

### c. *Invasive Species*

This alternative would require approximately 11.3 miles of upland habitat to be disturbed. This ground disturbance could increase the spread of invasive species such as Canadian and musk thistles. Although not identified as invasive, cheatgrass and smooth broom may become established along the disturbed route.

Increased storage levels in Swanson Reservoir could increase the population of non-native species that currently exists. This could have a negative impact on the native fish population in the Republican River upstream and downstream of the reservoir.

### d. *Water Quality*

Some minor water quality impacts would be expected with this alternative. High water temperatures and low flow conditions in Frenchman Creek that currently exist would not likely improve but could become worse with additional diversions.

Water quality impairments in Swanson Reservoir due to elevated levels of phosphorus, nitrogen, chlorophyll a, and mercury would still persist. With additional water being stored in Swanson Reservoir, some of these elements could become diluted and have less of an impact on the current fishery. It is likely that the fish consumption advisories would not be lifted.

### e. *Ecological Resiliency*

As mentioned above decreased flows and timing of peak flows are the primary limiting factors within the Basin. Diverting more water out of Frenchman Creek could increase these effects. It is expected that the species composition in Frenchman Creek would continue to shift to benthic spawners rather than pelagic spawners due to the decrease in spawning and drift distance for larval fish.

## 4. Alternative 3B – New Republican River Pipeline

The action alternative would divert water out of the Republican River to be stored in Swanson Reservoir. Currently, Swanson Reservoir has existing available storage that is not being used on a yearly basis.

The new pipeline would follow boundaries of existing fields, where possible, to minimize potential difficulties in obtaining right-of-way access. The alignment is approximately 17.4 miles in length. The intake would be screened to prevent fish entrainment and would pump approximately 11.1 cfs from the Republican River to Swanson Reservoir.

The effects to each resource described below are general in nature and are subject to change if the alternative is modified.

### a. *Fish and Wildlife*

Under the proposed action, Swanson Reservoir would continue to provide ideal habitat for migrating waterfowl, shorebirds, and wading birds that are moving through the area during spring and fall migrations. Approximately 4,000 acres of adjacent public lands would still be accessible to the public and wildlife. Swanson Reservoir would continue to support the introduced populations of walleye, white bass, wipers, largemouth bass, channel catfish, bullheads and crappie. Additional reservoir habitat would be created if additional water is stored throughout the year due to diversions out of the Republican River. Water level fluctuations would still have an impact on the reservoir fishery.

### b. *Federal and State Threatened, Endangered, and Species of Concern*

Threatened and endangered species such as whooping cranes, eskimo curlew, peregrine falcons, Interior least terns and piping plovers would still persist throughout the area. Because the new diversion would only remove 11.1 cfs out of the Republican River, it is not expected to have a large impact on habitat and water conditions downstream in the Republican River. Like the previous alternative, if Swanson Reservoir elevations are increased, it could negatively impact the amount of piping plover habitat along the reservoir margins.

The American burying beetle range does not extend down to Swanson Reservoir or the proposed pipeline route, so impacts to the species would not be expected.

### c. *Invasive Species*

This alternative would disturb approximately 17.4 miles of upland habitat. This ground disturbance could increase the spread of invasive species such as Canadian and musk thistles. Although not identified as invasive, cheatgrass and smooth broom may become established along the disturbed route.

Increased storage levels in Swanson Reservoir could increase the population of non-native species that currently exists. This could have a negative impact on the native fish population in the Republican River upstream and downstream of the reservoir.

### d. *Water Quality*

Water quality impairments in Swanson Reservoir due to elevated phosphorus, nitrogen, chlorophyll a, and mercury would not be expected to worsen. With additional water being stored in Swanson Reservoir, some of these elements could become diluted and have less of an impact on the current fishery. It is likely that the fish consumption advisories would not be lifted.

### e. *Ecological Resiliency*

As mentioned above decreased flows and timing of peak flows are the primary limiting factors within the Basin. Diverting more water out of the Republican River could increase these effects. It is expected that the species composition in the Republican River would continue to shift to benthic spawners rather than pelagic spawners due to the decrease in spawning and drift distance for larval fish.

## 5. Alternative 5A – New Thompson Creek Dam

This alternative includes the construction of a new reservoir on Thompson Creek about one mile north of Riverton, Nebraska. This new reservoir would provide for the storage of approximately 5,000 AF of water. The new dam would be approximately 50 ft high with a crest length of approximately 2,200 ft. The dam would be designed for a maximum reservoir water surface area of 9,300 acres. The outlet works would be designed to have a capacity of 420 cfs.

The Franklin Canal passes the proposed reservoir less than ¼ mile downstream. A pumping plant would be constructed to deliver water stored in the new Thompson Creek Reservoir to the Franklin Canal. Approximately 11.1 cfs would be pumped from the proposed reservoir into the Franklin Canal for irrigation purposes.

The effects to each resource described below are general in nature and are subject to change if the alternative is modified.

### a. *Fish and Wildlife*

The construction of a new reservoir to capture Thompson Creek flows would eliminate approximately 97 acres of forested riparian habitat and approximately seven acres of wetlands. However, the new reservoir would provide for approximately 5,000 AF of new reservoir habitat. This new habitat would have a positive impact on migrating waterfowl, shore birds and wading bird species.

It is likely that the existing fish population of central stonerollers, red shiners, orangethroat darters, creek chubs, suckermouth minnows, flathead minnows and northern plains killifish would be negatively impacted. Most of these species are specialized and best suited to riverine environments and are unable to survive in a reservoir habitat. It is likely that the reservoir would turn into a recreation fishery with introduced non-native species being the primary focus.

### b. *Federal and State Threatened, Endangered, and Species of Concern*

Threatened and endangered species such as whooping cranes, eskimo curlews, peregrine falcons, Interior least terns, and piping plovers would continue to utilize the areas. With the creation of a new reservoir, piping plover habitat along the reservoir margins could increase. The amount of increased habitat would depend highly on reservoir elevations.

### c. *Invasive Species*

This alternative would require a large area of upland habitat to be disturbed with the construction of a new dam and diking system. This ground disturbance could increase the spread of invasive species such as Canadian and musk thistles. Although not identified as invasive, cheatgrass and smooth broom may become established in these areas.
The creation of a reservoir habitat could increase the population of non-native species that currently exists. This could have a negative impact on the native fish population in the Thompson Creek upstream and downstream of the reservoir.

### d. *Water Quality*

Currently, Thompson Creek is impaired by E. coli and naturally high water temperatures due to reduced summer and fall flows. These impairments would likely worsen due to decreased flow in Thompson Creek downstream of the dam.

### e. *Ecological Resiliency*

Decreased flows and altered hydrographs are the primary limiting factors throughout the Basin which would worsen under this alternative. Flows in Thompson Creek are expected to change dramatically with the construction of a new storage reservoir. The new reservoir would likely decrease spring flows and increase late summer flows due to irrigation demands downstream. Native fish populations would likely decline with the introduction of non-native game fishes for the reservoir fishery. Fish populations would continue to shift towards species that are benthic spawners rather than pelagic spawners due to the decrease in spawning and drift distance for larval fish. Water quality as mentioned above would become a major factor in determining what fish species are able to survive in Thompson Creek.

## 6. Assumptions, Risks, and Unknowns, Recommendations for Future Investigation

- All alternatives discussed above would be subject to National Environmental Protection Act, National Historic Preservation Act, and ESA requirements. This document does not alleviate these requirements.

- Surveys for endangered and threatened species would need to be completed before an alternative could move forward. For example if Alternative 3A or 3C was selected, American burying beetle surveys would need to be completed before the final pipeline route is identified.

- To fully understand all environmental effects, a more in-depth hydraulic analysis would need to be completed.

# IX. Findings and Conclusions

## A. Disclaimers

- This Study is a technical assessment and does not provide recommendations or represent a statement of policy or position of the Bureau of Reclamation, the Department of the Interior, or the funding partners. The Study does not propose or address the feasibility of any specific project, program or plan. Nothing in the Study is intended, nor shall the Study be construed, to interpret, diminish, or modify the rights of any participant under applicable law. Nothing in the Study represents a commitment for provision of Federal funds. All cost estimates included in this Study are preliminary and intended only for comparative purposes only.

- The States participating in this Basin Study understand that this Study provides multi-state collaborative opportunities to explore management alternatives in the context of sustaining a long-term balance between water uses and supplies in the Republican River Basin. The findings of the Study do not and will not compromise any State's position in litigation or any other dispute between or among the States, nor will they be binding upon any state as a result of that state's participation. No statements made or positions taken by any state's representatives may be used in any way as part of any present or future dispute between or among the States. However, data, study results, and potential projects generated or exchanged as part of this Study may be used by any state for any purpose.

- These findings and analyses do not constitute a position of the Federal government to support or recommend for implementation any adaptation strategies/alternatives identified and evaluated in this report. Although Reclamation will continue to work within its authorities to collaborate with the States as it relates to Federal projects/interests within the Basin, unless otherwise directed by Congress, it is the responsibility and at the discretion of the States to undertake additional investigations and/or implement the adaptation strategies/alternatives identified in this report.

- As described in *Sections 6.0: Adaptation Strategies Considered but Eliminated* of this report, evaluations on system reliability and associated adaption strategies were not conducted for the Colorado or upper Kansas sub-basins. Study partners chose to focus on meeting the water supply needs of three irrigation districts within the Basin: Frenchman-Cambridge Irrigation District (FCID), Bostwick Irrigation District of Nebraska (NBID), and Kansas Bostwick Irrigation District No. 2 (KBID). To evaluate water supplies and operations for these districts, new modeling tools and related datasets were developed for the Nebraska and Lower-Kansas sub-basins. These tools simulate the hydrology and water operations of these sub-basins and provide the basis for detailed analysis of current and future water supplies and demands, as well as for an analysis of system reliability under various alternatives and under a range of projected future climate scenarios. No new modeling tools were developed for the Colorado or Upper Kansas sub-basins. The findings described below reflect these considerations.

## B. Baseline versus Future Climate Conditions

- All climate-related datasets and model inputs for the Baseline Scenario were developed directly from *observed* historical climate data for the period 1960-2010. Three climate scenarios were developed for this Study based on three individual climate projections selected from the BCSD CMIP3 projection archive, as summarized below in Table 33.

**Table 33. — Water availability, temperature, and precipitation projections associated with three climate scenarios evaluated in the Republican River Basin**

| Name | Climate Condition | Mean Annual Water Availability | Mean Annual Temperature | Mean Annual Precipitation |
|---|---|---|---|---|
| Scenario 1 | Warmer/Drier | -0.20 in (-33%) | +5.2 °F | -3.5 in (-17%) |
| Scenario 2 | Central Tendency | +0.01 in (+10%) | +3.5 °F | +0.9 in (+5%) |
| Scenario 3 | Less Warm/Wetter | +0.60 in (+89%) | +2.9 °F | +4.1 in (+21%) |

## C. Impacts of Climate Variability and Change Under No Action

### 1. Water Supplies

- Surface water supplies in the Colorado sub-basin are projected to decrease under Scenario 1 and increase substantially under Scenario 3, with little change under Scenario 2.

- Similar to the Colorado sub-basin, surface water supplies in the Upper Kansas sub-basin are projected to decrease substantially under Scenario 1 and increase substantially under Scenario 3. In contrast to the

Colorado sub-basin, however, surface water supplies in the Upper Kansas are projected to increase substantially under Scenario 2.

- The total surface water supply in the Nebraska sub-basin is projected to decrease moderately under Scenario 1 and increase under Scenarios 2 and 3. The total surface water supply in the Lower Kansas sub-basin is projected to increase slightly under Scenarios 1 and 2 and increase moderately under Scenario 3. Increases under Scenario 1 result from a large projected increase in precipitation over the Lower Kansas sub-basin, despite a projected decrease in basin-average precipitation under this scenario.

- Regarding groundwater supplies, projected changes in precipitation suggest that precipitation recharge is likely to decrease in the Colorado and Upper Kansas sub-basins under Scenarios 1 and 2, with little change under Scenario 3. Precipitation recharge is likely to increase in the Nebraska sub-basin under Scenarios 2 and 3, with little change under Scenario 1. Precipitation recharge is likely to increase to varying degrees over the Lower Kansas sub-basin under all scenarios, as all three scenarios project increased precipitation over the sub-basin. The effects of changes in surface water diversions, and corresponding seepage and deep percolation, on the total amount of recharge in each sub-basin is likely to be much smaller than the effects of changes in precipitation.

## 2. Water Demands

- For Nebraska, average NIR for canal service areas increases by 6.9% under Scenario 1 due to a combination of temperature-driven increase in evaporative demand and decreased precipitation. Average NIR decreases by 8.8% under Scenario 2 and decreases by 20.9% under Scenario 3. Results suggest that projected increases in precipitation over the majority of the Nebraska sub-basin under Scenarios 2 and 3 more than offset temperature-driven increases in evaporative demand (reference evapotranspiration) under these scenarios.

- For Nebraska, when applying district acreages and applying an area weighted average, the NIR decreases by 21% for Scenario 1 and increases by 15% and 44% for Scenarios 2 and 3, respectively. This result is based on Nebraska's modeling approach which estimates irrigated acreage based on available supply (i.e., more water is available under the cool/wet scenario, so acreage is increased and total demand [acres x NIR] increases). Under Scenario 1, acreage is reduced due to low supply, resulting in a decrease in overall demand.

- For Kansas, average NIR for KBID increases by 41.4% under Scenario 1 due to a combination of temperature-driven increase in evaporative demand and decreased precipitation. Average NIR increases by 9.3% under Scenario 2 and decreases by 22.1% under Scenario 3.

- It should be noted that projected changes in NIR for KBID are greater than corresponding projected changes in NIR for nearby lands in the Nebraska sub-basin served by the Courtland and Superior canals. Differences arise from the different methodologies used to calculate NIR in the Nebraska and Lower Kansas sub-basins.

## 3. Water Supply Imbalances

- This study attempted to assess the effects of these imbalances as part of the System Reliability Analysis, the results of which are summarized in Section 9.3.4 below. System reliability for the Nebraska sub-basin evaluated the effects of water supply imbalances based on irrigated acreage, irrigation diversions and deliveries, and the frequency of compact call years. System reliability for the Lower Kansas sub-basin evaluated the effects of water supply imbalances based on irrigation diversions and deliveries to KBID above and below Lovewell Reservoir.

## 4. Water Operations and Deliveries

- Impacts of climate change on water operations and deliveries indicate mixed results depending on the state and their respective assumptions on irrigated acres. For Nebraska, the modeling approach used to calculate irrigation demands assumes that irrigated acreage varies year to year depending on the available surface water supply: irrigated acreage in Nebraska decreases under Scenario 1 in response to decreases in surface water supply; this results in a decrease in overall demand and a corresponding decrease in deliveries. For Kansas, irrigated acreage is held constant in all years; irrigation demands in Kansas increase due to decreases in precipitation and increases in temperature, both of which result in increased crop irrigation requirements. This increase in demand drives an increase in water deliveries, despite an overall decrease in surface water supply.

- To evaluate surface water imbalances, Reclamation staff used Nebraska's modeling results to calculate the amount of land irrigated relative to fully irrigated conditions, as well as the associated delivery shortage relative to the potential irrigation demands for the fully irrigated condition. It is important to point out that this calculation is for hypothetical use only and is not representative of Nebraska's modeling approach. Based on the historical relationship between surface water availability and irrigated acreage, NBID experiences reduced acreage in all years under all climate scenarios. Cumulative acreage reduction in NBID is 428,000 acres under the Baseline Climate Scenario; this increases to 706,000 acres under Scenario 1 and decreases to 260,000 and 2,500 acres under Scenarios 2 and 3, respectively. For FCID, reduced acreage occurs in 38 of 50 years under the Baseline Scenario with a cumulative reduction of 345,000 acres over the 50-year simulation period. The frequency and magnitude of acreage reduction are greater under Climate Scenario 1 and are less under Climate Scenarios 2 and 3 compared to the Baseline Scenario.

- Despite acreage reductions, delivery shortages in NBID occur in in more than half of all years under all scenarios. Shortages are greatest under the Baseline Climate Scenario, with shortages occurring in 37 of 50 years with a cumulative delivery shortage of 104,000 AF. The frequency and magnitude of shortages is smaller under all other climate scenarios compared to the Baseline Scenario. Surface water delivery shortages to FCID occur during 40 of 50 years under the Baseline Scenario with a cumulative shortage of 122,000 AF. Delivery shortages are less frequent under all climate scenarios compared to the baseline; however, the magnitude of shortages is greater under Climate Scenarios 1 and 2 and much less under Climate Scenario 3. It should be emphasized, however, that the frequency and magnitude of shortages do not depend on the available water supply but rather on the relationship between available water supply and water demands for the irrigated acreage calculated by the model.

- One of the significant factors affecting water management in the Basin is the occurrence of Compact Call Years. During Compact Call Years, special provisions are imposed on reservoir releases and canal diversions throughout the Nebraska portion of the Basin to ensure that compact compliance is achieved. Under the No Action Alternative, the frequency of Compact Call determinations made by Nebraska goes up 43% and down 100% under the drier versus wetter climate scenarios, respectively.

- Cumulative shortages to KBID are projected to exceed 140,000 AF over the 50-year simulation period under the No Action Alternative assuming the Baseline Climate condition. Under the warmer/drier climate change scenario, these shortages almost double to 270,000 AF. The frequency of shortages, however, is quite low (5 out of 50 simulated years [10%]). This is largely due to modeling operational assumptions under the No Action Alternative made by Nebraska during

Compact Call Years which require measures to be taken to ensure Compact compliance, thereby minimizing shortages to KBID.

## 5. Recreation Benefits

- Overall, compared to the Baseline No Action Alternative, Climate Scenarios 1, 2, and 3 result in an approximate increase of recreation benefits by 14%, 18%, and 29%, respectively for both Nebraska and Kansas.

- While certain reservoirs result in negative recreation benefits under Scenario 1, the overall recreation economic effect of climate change on the No Action Alternative is positive for all three climate scenarios as compared to the Baseline No Action. Under Scenarios 1 and 2, Harlan County and Lovewell reservoirs generate the majority of the increase in recreation benefits. Under Scenario 3, Swanson Reservoir also contributes heavily along with Harlan County and Lovewell.

- The reason for increased benefits under the climate scenarios is the positive correlation of air temperatures and water levels with recreation visitation. Note that similar changes in water levels across alternatives at different reservoirs can lead to dramatically different results upon recreation visitation due to reservoir size and bathymetry.

## 6. Net Economic Benefits

- Net economic benefits of action alternatives under all future climate scenarios exceeded net benefits under the Baseline Climate Scenario. The net benefits are dominated by the recreational benefits which reflect 72 to 98% of the net benefits depending on the climate scenario.

- The increase in recreation benefits is driven by increases temperatures under all three scenarios and increased water elevations under Scenarios 2 and 3.

## 7. Environmental Resources

- High water temperatures and low flows in Frenchman Creek during the summer months would continue to be a limiting factor to the fish community. Thompson Creek supports a fish population of central stonerollers, red shiners, orangethroat darters, creek chubs, suckermouth minnows, flathead minnows and northern plains killifish. Under No Action, all these species would have the ability to persist in

Thompson Creek. The Kansas MDS would remain unchanged under the No Action.

- Federal and State-listed species would not be impacted further than under historic conditions.

- Invasive species such as Canadian thistle, musk thistle, European buckthorn and garlic mustard would continue to persist throughout the area. No ground disturbing actions would take place under the no action that would increase the spread these species. Reservoirs that are currently stocked with non-native game species for recreation. These species would continue to persist in the reservoir environments and could spread into the Republican River and Frenchman Creek.

- All water quality impairments may continue depending on the outcome of water management strategies recommended in the TMDLs. Headwater tributaries into Lovewell Reservoir would continue to be impaired for water supply and aquatic life by arsenic, selenium and total phosphorus. White Rock Creek upstream and downstream from Lovewell Reservoir would continue to have impaired water supply by arsenic and an impaired aquatic life due to total phosphorus and total suspended solids.

- Decreased flows and altered hydrographs are the primary limiting factors throughout the Basin which would continue. Fish populations would continue to shift towards species that are benthic spawners rather than pelagic spawners due to the decrease in spawning and drift distance for larval fish. The Basin could also continue to see an increased shift towards non-native species.

# D. Nebraska Findings For Action Alternatives

## 1. Alternative 3A – Swanson Reservoir Augmentation via Frenchman Creek Pipeline

- In terms of whether Alternative 3A meets or exceeds the purpose and objectives laid forth in this Study, findings were mixed. From the perspective of increasing the water supply reliability for FCID, the results indicate that there would likely be additional diversions made by the FCID canals as a result of the pump-back operations. Swanson Lake levels also would benefit from the new supply of water from Frenchman Creek. However, in terms of Compact compliance efforts, there may be a slight negative impact, largely due to a slight decrease in inflows to, and storage levels in, Harlan County Lake. A small increase in the number of Compact Call Years may be expected under Alternative 3A. In addition, there appears to be a tradeoff in terms of FCID and NBID water supplies, as NBID diversions may decrease slightly under the alternative.

- Other lessons learned through the evaluation of Alternative 3A include a potential for considering different configurations of the alternative. It is very clear from the results that the pumping level of 3,000 gpm could be increased, since pump-back operations were almost always able to operate at full capacity for those years in which pumping was allowed. Higher pumping levels would also make it easier to evaluate the impacts from pump-back operations since the relatively small impacts under the current pumping capacity are sometimes difficult to assess from the model output. However, it is likely that the impacts would be greater – both positive and negative – under higher pumping levels. In addition, there may be other options in which to manage the pump-back operations and storage of the new supplies in Swanson Lake. Information produced by FCID suggested operations in which Swanson Lake storage releases would be made for storage in Harlan County Lake instead of for consumptive use by FCID users. The results from Alternative 3A provide helpful information on some of the operational and modeling considerations that would be required for a Swanson Lake pump-back project, and alternative configurations could be considered in the future, building off of these initial findings.

- Regarding climate change impacts on FCID deliveries, Alternative 3A produces slightly higher FCID diversions compared to No Action conditions over the 50-year time horizon for Baseline Climate conditions, as well as under the alternative climate scenarios. Climate Scenario 3 shows the smallest impacts due to the overall abundance of available stored water supplies and maximization of irrigated acres.

- Regarding climate change impacts on NBID deliveries, under Baseline Climate and Climate Scenarios 1 and 2, there appears to be a negative impact, on the order of a few thousand AF, to NBID diversions under Alternative 3A when compared to the No Action Alternative. Under Climate Scenario 3, the impact is particularly difficult to discern. In general, there appears to be a small negative impact to NBID resulting from increased consumptive use on the FCID irrigated acres upstream.

## 2. Alternative 3B – Swanson Reservoir Augmentation via Republican River Pipeline

- In terms of whether Alternative 3B meets or exceeds its purpose and objectives, the results point, as they did for Alternative 3A, to mixed findings. From the perspective of increasing the water supply reliability for FCID, the results indicate that there would likely be additional diversions made by the FCID canals as a result of the pump-back operations. Swanson Lake levels also would benefit from the new supply of water from Frenchman Creek. However, in terms of Compact compliance efforts, there may be a slight negative impact, largely due to a slight decrease in inflows to, and storage levels in, Harlan County Lake. A small increase in the number of Compact Call Years may be expected under Alternative 3B, although less than under Alternative 3A. In addition, there appears to be a tradeoff in terms of FCID and NBID water supplies, as NBID diversions may decrease slightly under the alternative.

- As was the case with Alternative 3A, it is very clear from the results that the pumping level of 5,000 gpm could be increased, since pump-back operations were almost always able to operate at full capacity for those years in which pumping was allowed. Higher pumping levels would also make it easier to evaluate the impacts from pump-back operations, since the relatively small impacts – although usually greater than those under Alternative 3A – are sometimes difficult to tease from the model output. However, it is likely that the impacts would be greater – both positive and negative – under higher pumping levels. The same alternative management techniques that could be considered for Alternative 3A, including different uses of the water stored in Swanson Lake from pump-back operations, also apply to Alternative 3B.

- Regarding climate change impacts on FCID deliveries, Alternative 3B produces generally higher FCID diversions compared to No Action conditions over the 50-year time horizon for Baseline Climate conditions, as well as under the alternative climate scenarios. Climate Scenario 3 shows the smallest impacts due to the overall abundance of available stored water supplies and maximization of irrigated acres.

- Regarding climate change impacts on NBID deliveries, under Baseline Climate and Climate Scenarios 1 and 2, there appears to be a negative impact – on the order of a few thousand AF – to NBID diversions under Alternative 3B when compared to the No Action Alternative. The impact also appears to be of a slightly higher magnitude than that observed for Alternative 3A, which is understandable given the higher pumping capacity under Alternative 3B. Under Climate Scenario 3, the impact is particularly difficult to discern. In general, there appears to be a small negative impact to NBID resulting from increased consumptive use on the FCID irrigated acres upstream.

## 3. Alternative 5A – New Thompson Creek Dam

- In terms of whether Alternative 5 meets or exceeds its purpose and objectives, there are again mixed results, as was the case with Alternatives 3A and 3B. From the perspective of increasing the water supply reliability for NBID, the results indicate that there would likely be additional diversions made by the Franklin Canal as a result of Thompson Creek Reservoir operations. The remaining NBID demands likely would be unaffected, as would FCID canals upstream of Harlan County Lake. Harlan County Lake levels would likely improve for those years when Thompson Creek Reservoir pumping to Franklin Canal occurred, with perhaps a few thousand AF of additional storage supply within Harlan County Lake for some years over the 50-year period. This does indicate a potential benefit to Harlan County Lake resulting from the substitute supply originating from Thompson Creek.

- In terms of Compact-related impacts, there appears to be little to no impacts to the number of Compact Call Years as a result of Thompson Creek operations compared to No Action conditions. The small benefit to storage levels in Harlan County does not directly result in reductions in Compact Call Years. This may be in part due to the increased consumptive use on Franklin Canal lands, which negatively affects Nebraska's Compact balance, but that same consumption would provide benefits to NBID irrigators on Franklin Canal. The small size of the Thompson Creek Reservoir alternative may also be a factor, and it may be beneficial to consider larger reservoir sizes in future analyses. The consistent ability of Thompson Creek Reservoir to fill its conservation pool each year, and the regular incursion of water into the flood pool when climate conditions are wetter, both indicate that the reservoir could benefit from greater conservation and flood storage. Finally, both Guide Rock flows and flows on the Courtland Canal at the state line, which have direct impacts on Compact balances for Nebraska, would appear to be unchanged as a result of Thompson Creek Reservoir operations. As with Alternatives 3A and 3B, different management options, such as modifying the water supply calculations in NBID contracts and possibly the language in the Consensus Plan and RRCA Accounting Procedures to reflect the new storage supply from the Thompson Creek Reservoir, may also be worth considering if water planners wish to conduct future analyses of the potential reservoir site.

- Impacts of climate change have negligible impacts on FCID and NBID deliveries under Alternative 5A.

- Regarding Republican River flows at the Guide Rock gage, which are critically important in determining Compact allocations and balances, differences between No Action and Action flow rates are small under all climate scenarios. As evident in the 50-year averages, and through inspection of the graphs, there appears to be little to any difference in Guide Rock flows between No Action and alternative conditions. For all climate conditions, there was a slight decrease in Guide Rock flows under Alternative 5, but the magnitude and variability over the course of the study period indicate little to no impacts.

### 4. Other Management Strategies to Consider

As described earlier in this report, other management strategies were considered but eliminated from additional investigation as it relates to this Study, namely the off-season canal recharge and the impoundment of Beaver Creek in Nebraska.

#### a. *Non Irrigation Canal Recharge*

- Preliminary findings on the canal recharge options do indicate great promise in terms of the ability to conduct future recharge projects across the Basin, and maintain consistent available flows for diversion during years when Compact Call Year operations are not required.

- A more thorough examination of the canal recharge alternative would be more appropriate outside the basin study process.

#### b. *New Beaver Creek Dam*

- While the focus on this Study was on Thompson Creek, findings indicate that a synthesis of the historical flow record using appropriate hydrologic techniques could be warranted for Beaver Creek.

## E. Kansas Findings For Action Alternatives

### 1. Alternative 1: Expansion of Lovewell Reservoir

- Largely due to operational assumptions under No Action made by Nebraska during Compact Call years, Kansas' modeling results indicate that increasing the storage at Lovewell Reservoir reduces the frequency and magnitude of shortages to KBID downstream of the reservoir, but not by much relative to the No Action Alternative. As well, increasing storage at Lovewell Reservoir does very little to reduce the frequency or magnitude of shortages to KBID upstream of Lovewell Reservoir. Therefore, the benefits of increasing storage at Lovewell Reservoir appear limited under the Baseline Climate Scenario. These findings do not consider the quantitative analysis of recreation benefits completed by Reclamation.

- Under Climate Scenario 1, the frequency and magnitude of shortages to KBID downstream of Lovewell Reservoir increased over the Baseline Scenario for the No Action run with shortages occurring in nine of the 50 simulation years. The expansion alternatives reduce the frequency and magnitude of the shortages over the No Active alternative, with the 16K AF storage increase reducing the shortage frequency to seven years, the 25K AF storage increase reducing the shortage frequency to three years during the 50-year simulation, and the 35K AF increase also reducing the shortage to KBID to three years.

- Considering the high cost of expansion alternatives and the small relative reductions to shortage frequencies under the warmer, drier climate scenario, the only expansion alternative that was selected for further evaluation was the 25K AF storage increase to Lovewell Reservoir (Alternative 1C in previous reports).

## F. Economics Analysis of Action Alternatives

- The action alternatives were developed to appraisal-level design in accordance with Reclamation's D&S, and project costs were developed without any engineering data other than topographic mapping, satellite imagery, and design drawings of existing Reclamation features. Capital costs ranged from $36 million to $92 million.

- The largest difference in recreation benefits for action versus no action was for Alternative 1C ($49.5 million without climate change and $65.0 million for Climate Scenario 1). This is due to the increase in recreation benefits at Lovewell Reservoir. As noted above, for Alternative 1C, climate change effects were only estimated for Scenario 1. Because climate factors, which include air temperatures, do not vary across alternatives for the same climate scenario, the increase in recreation benefits at Lovewell are due exclusively to changes in average monthly water levels. Under the Baseline Scenario, average monthly water levels were estimated to increase from 4.2 ft to 4.6 ft (associated with increases in surface area ranging from 632 to 673 acres) whereas under Climate Scenario 1, average monthly water levels were estimated to increase from 4.3 ft to 5.1 ft (646 to 722 acres).

- The only other notable change in recreation benefits is the $7.6 million increase at Swanson Reservoir under Alternative 3B for Climate Scenario 3 (increase of $7.6 million). Again, since average monthly air temperature is the same between alternative/scenarios, the change in water levels drives the increased recreation benefits. The change in average monthly water levels for Alternative 3B, Scenario 3 ranges from 1.2 ft to 1.4 ft or 136 to 179 acres of surface area. While this difference may not appear dramatic, it shows how sensitive recreation visitation and value can be to changing water levels.

- Alternative 1C yielded the largest agricultural and recreation benefits of all four alternatives; this is due to the increased water deliveries and higher lake levels associated with reservoir expansion. Furthermore, relative to total costs, Alternative 1C was the only alternative to yield positive net benefits. These benefits were driven primarily by recreation as opposed to agricultural production from water deliveries. The agricultural and recreation benefits of Alternatives 3A, 3B, and 5A were mixed depending on the climate scenario, but overall, the net benefits were all negative relative to costs. Results are considered preliminary; a more complete economics analysis would include OMR&P costs and address the data gaps and assumptions provided in Section 7.7.4. For instance, adding OMR&P costs would reduce net benefits across all alternatives; in the case of Alternative 1C, this reduction could be substantial enough to result in net benefits becoming negative

## G. Ongoing Negotiations and Agreements

The findings of this Basin Study should be considered in the context of the ongoing negotiations and agreements among Colorado, Nebraska, and Kansas pertaining to the management of the Republican River Basin. An agreement was signed in October 2014 between Colorado and Kansas helping improve the reliability of water supplies in the South Fork Republican River in Kansas by authorizing Colorado to receive credit in Compact accounting for water from its augmentation project on the North Fork Republican River. Yet other agreements recently signed during the conduct of this Basin Study include provisions between Nebraska and Kansas to integrate more flexibility into achieving Compact compliance while maximizing surface water use by irrigators. For instance, in March 2015, the RRCA, Reclamation, and the Bostwick Irrigation Districts reached a short-term agreement that allowed surface water rights to remain open during Compact Call Years, thereby providing surface water users with more certainty in their water supplies. At the same time, Nebraska was allowed to offset any current-year shortfalls through augmentation pumping (as described in Nebraska's IMPs) the following year outside the irrigation season. The States are currently working on a long-term agreement similar to the framework agreed to in 2015. If the States can reach agreement, it would minimize Nebraska's need to issue Compact Calls, help administer surface water rights for Compact compliance, and limit the need to make water releases from Reclamation reservoirs outside the irrigation season.

In addition to the RRCA, organizations and programs, such as the Republican River Riparian and Restoration Partners, are helping foster sustainable water resources management throughout the Republican River Basin. The Partners, led by seven Resource Conservation and Development Programs, help provide leadership in the planning and coordination of sound conservation practices, and bring Federal, State, and local entities together to implement a viable living Republican River Basin by 2037. These local and Federal projects are managed cooperatively to help ensure a healthy Basin in the years to come.

## H. Other Programs and Opportunities

Although the Basin Study Program provides an avenue to conduct planning on a basin-wide scale to identify and evaluate adaptation and mitigation strategies, as previously stated, it does <u>not</u> provide the means to construct or otherwise implement those strategies. Funding for construction/implementation may be provided under other WaterSMART programs, namely through Water and Energy Efficiency Grants (WEEG) or Water Conservation Field Services Grants. The irrigation districts in Nebraska and Kansas are no doubt familiar with these programs, as demonstrated by their recent successes in being awarded grants under these programs for the conversion of open laterals into pipelines. As these districts are aware, the administration of Reclamation's construction grant funding follows strict program requirements and is subject to Congressional appropriations, both of which may change in any given year.

### 1. Water and Energy Efficiency Grants

Prospective non-Federal project sponsors are encouraged to visit: www.usbr.gov/WaterSMART/weeg/ to learn about program developments and funding opportunities relating to WEEGs. A brief list of important program elements includes:

- Eligible entities include irrigation and water districts with water or power delivery authority, as well as States and Tribes.
- Eligible projects are those that improve the conservation and/or management of water and energy, include lining or piping of canals, installation of advanced measuring devices, irrigation system automation, installation of residential water meters, and activities that reduce urban water use, among other types of projects. Many projects also accomplish important program goals beyond water efficiency, including increasing the use of renewable energy, protecting endangered species, or facilitating water markets.
- Funds must be cost-shared, with at least 50% of the total project costs being provided by the non-Federal sponsor.

- Funds are awarded on a competitive basis in response to a Funding Opportunity Announcement that is typically posted on www.grants.gov in the fall.

- Different funding amounts may be available for smaller (up to $300,000 Federal award) or larger (up to $1,000,000 Federal award) implementation projects.

- Projects are typically completed within two to three years depending on the funding group awarded.

## 2. Water Conservation Field Services Program

To learn more about Water Conservation Field Services, contact should be made with Reclamation's Nebraska-Kansas Area Office. A brief list of important program elements includes:

- Eligible entities include irrigation and water districts with water or power delivery authority, as well as States and Tribes.

- Projects are typically smaller-scale than those considered for WEEGs described above. However, similar to WEEGs, eligible projects are those that improve the conservation and/or management of water and energy, include lining or piping of canals, installation of advanced measuring devices, irrigation system automation, installation of residential water meters, and activities that reduce urban water use, among other types of projects. Many projects also accomplish important program goals beyond water efficiency, including increasing the use of renewable energy, protecting endangered species, or facilitating water markets.

- Funds must be cost-shared, with at least 50% of the total project costs being provided by the non-Federal sponsor.

- Funds are awarded on a competitive basis in response to a Funding Opportunity Announcement that is typically posted on www.grants.gov in the fall.

- Funding is typically capped at $100,000 per project.

- Projects are typically completed within one to two years.

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