8-2021

Development and Application of a Decision Framework to Support Improved River Basin Water Management

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DEVELOPMENT AND APPLICATION OF A DECISION FRAMEWORK TO

SUPPORT IMPROVED RIVER BASIN WATER MANAGEMENT

by

Leah Meeks

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

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2021

ABSTRACT

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Utah State University, 2021

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Water management decisions are often made at local scales and have the potential to change water supplies and uses throughout a basin. More research is needed to understand, help avoid unintended consequences that can arise in other parts of a base due to local-scale decisions and maximize basin-wide positives impacts. This dissertation presents a framework for water managers to support improved water resources management.

First, the Ranking Automation for NetworKs (RANK) tool was developed to identify water resources network nodes (e.g., reservoirs, junctions, services areas, sources, and sinks) that have high influence on the entire water resources network. RANK weighed node connections based on flow capacity and direction and an automated process to quantitatively rank nodes for three performance metrics: stability (nodes whose roles do not depend on other nodes), topological significance (nodes that cause other nodes to be unstable), and redundancy (node pair with similar connections). RANK was applied to the lower Bear River from southern Idaho to the

Great Salt Lake, Utah. RANK can inform decision-making regarding water transfers, dam siting, adopting water conservation measures, investigate alternative supplies, flow monitoring needs, and environmental protection strategies.

Second, a modeling methodology was developed to quantify the effects of reduced river return flow to reservoir storage, river flow, and irrigation diversions. Reducing the return flow decreases return flow from irrigation areas to the river system and increases consumptive use in an irrigation area. A 28-year daily simulation model of the Boise River Basin in Idaho was used to simulate a case study. Reducing return flows decreased river flow and increased stored reservoir water demand. To make up for river flow reductions, downstream users relied more on reservoir storage to meet irrigation demand than users in other locations in the basin. Irrigation shortages were larger in drier years due to less available reservoir storage.

Third, the return flow methodology was expanded to evaluate the impacts of storing water that was previously represented by reduced return flows. Flood control, intra-district operations, inter-district operations, recreation, and ecosystems were affected. Storing reduced diversions resulting from implementation of water conservation practices added management flexibility in a river basin. Water management for sustainable use of resources involves understanding how changes in one area affect water users throughout a river basin dependent on the same resources.

The framework presented in this dissertation can be applied to understand the hydrologic and the management relationships within a river basin to promote sustainable water use.

(215 pages)

PUBLIC ABSTRACT

Development and Application of a Decision Framework to Support Improved River Basin Water Management

Leah Meeks

Water management decisions made at local levels may have effects throughout an entire river basin. Water managers need better ways to help identify which decisions have broader implications and to quantify those effects to inform decision making. This dissertation presents a framework providing a basin-wide approach to water management using three studies. The first study developed a software tool to quantify how local changes within a water resources network affect the entire network. A case study was conducted on the Lower Bear River in Utah. The second study quantified the basin-wide effects of reducing return flows from irrigation areas to the river. The reduced return flow indirectly simulated the effects of implementing water conservation. The third study evaluated how storage of conserved water in reservoirs affects a river basin. A case study of the Boise River Basin in Idaho was used in the second and third studies. The first study developed a method to visualize large networks through simple graphics and identify critical water management locations. The second study found that reducing return flows causes decreased river flow, increased reservoir storage use to meet irrigation demands, and increased irrigation shortages. The third study found that storing conserved water can reduce irrigation shortages throughout a basin. A common finding was that downstream water users were the most affected by management changes. Impacts to the entire river basin should be considered when making management decisions at local levels.

DEDICATION

This dissertation is dedicated to Dr. Lynn Langer Meeks.

ACKNOWLEDGMENTS

This work would not have been possible without the motivation, support, and guidance of numerous wonderful people. My decade-long path has been full of frustration, elation, disappointment, and excitement. Constant encouragement was critical to complete this work.

I would like to thank my major advisor for his patience and understanding as I melded my academic, personal, and professional life during the time of conducting research and writing this dissertation. I also want to notice my committee members and the CEE graduate coordinator for flexibility and guidance.

The Utah Water Research Laboratory provided funding for the development of the RANK tool. Funding for the research of water conservation was provided through the Bureau of Reclamation’s Science and Technology Program as well as the Columbia-Pacific Northwest Region Planning Program. I would also like to thank some special colleagues at Reclamation for their support, time, expertise, and guidance.

Last and most important, I thank my family. My husband always believed in me. My mother provided steadfast support for my academic and personal endeavors. My children unknowingly motivated me with their constant quests to find answers.

Leah Meeks

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Water management decisions occur at many different levels and scales. Researchers and water management practitioners are becoming more interested in and concerned with how decisions made at one level affect other levels. Better understanding of the hydrologic and the management relationships within a river basin to promote sustainable water use supports more informed water management decisions. The interactions within a basin are very complex and often hard to determine and then quantify. This work advances the frameworks available to managers for supporting improved water resources management through local and regional scales. First, a software tool was developed to identify water resources network nodes (e.g., reservoirs, junctions, services areas, sources, and sinks) that have high influence on an entire water resources network to inform management and modeling decisions. The second part of this dissertation presents a modeling methodology to simulate the effects of water conservation measures via reduced river return flow to reservoir storage, natural flow in the river, and irrigation diversions.

Network Analysis. Water resources systems can be defined in terms of networks where locations such as reservoirs, services areas, and sensitive environmental sites are represented by network nodes that are connected via waterways such as canals, rivers, and pipelines represented by network links. Water resources networks are often large and connect numerous water supply, reservoir, diversion, and demand site nodes through multiple natural and engineered conveyance links. Identifying vulnerable, critical, and influential parts of a network is important to protect, manage, and understand the physical system being modeled (Barrat et al., 2008). One way to illustrate the effect of a node on the system (node influence) is to measure the effect of removing the node on the remaining network such as small node and link changes across important bridge nodes with few connections but that connect network branches (Barrat et al., 2008).

Singer and Greenshpan (2009) introduce a method called node extraction and visualization (NEVIS) that uses node extraction and parallel coordinate plotting to qualitatively show how nodes in networks with undirected links influence each other. Singer and Greenshpan (2009) define the terms *vulnerable*, *topologically significant*, and *backed up* to indicate, respectively, nodes that (1) are affected by removal of other nodes, (2) affect the centrality of other nodes in the network when removed, and (3) allow alternate paths to bypass a removed node. The authors describe how to visually identify nodes with these characteristics from the shapes of the traces on the parallel coordinate plot. These qualitative descriptions do not allow an analyst to compare or rank the relative importance of nodes nor consider large networks. Applying weights, such as node capacity and target flow, can help identify the relative importance of water system network features (Porse and Lund, 2015).

Parallel coordinate plots, used by Singer and Greenshpan (2009), show a very large number of dimensions side-by-side in one figure and reveal relationships among variables on adjacent axes (Inselberg, 1985). Limits to parallel coordinate analysis include (1) plots often have many lines and become busy and crowded (Edsall, 2003), (2) ordering of axes affects the interpretation of results (Edsall, 2003; Huh and Park, 2008; Albazzaz et al., 2005), (3) plots take time to construct (Albazzaz et al., 2005), (4) data analysis has not been automated (Albazzaz et al., 2005), (5) viewers cannot compare variables on distant axes (Edsall, 2003), and (6) plots only allow for qualitative data comparisons by visual inspection. To better identify high-influence nodes in water resources networks, Meeks and Rosenberg (2017) developed the Ranking Automation for NetworKs (RANK) tool to automatically and quantifiably define and rank nodes within a water resources network for three influence metrics: stability, topological significance, and redundancy. These rankings can then be used by water managers to identify candidate sites for specific management decisions. The Meeks and Rosenberg (2017) paper serves as Chapter 2 in this dissertation.

River Basin Effects of Water Conservation. Agriculture in the western United States is dependent on water delivery and irrigation systems to meet crop water needs. The agriculture sector has spent decades developing and implementing technologies and strategies to conserve water. Agricultural water conservation measures typically occur at two levels: field (e.g., converting surface irrigation to sprinkler or drip irrigation, reduced tillage, and recycling tailwater) and irrigation district (e.g., canal operation automation and earthen canal lining and piping). Water conserved at one location is usually used in another way or at a different location rather than not diverted or returned to the stream. Research has found that water savings from local changes may not be realized as expected (i.e., does not net additional water) at the watershed or basin scale (Grafton et al., 2018; Perry et al., 2009; Willardson 1985; Ahmad et al. 2014; Keller and Keller, 1995). Traditional definitions for irrigation design have considered the water diverted but not consumptively used as wasted or lost. In fact, “lost” water often becomes a source for another user to consumptively use downstream.

Irrigation return flows, either from the field or delivery scale, play an important role in basin scale water management (Bekkam et al., 2013). Conserved water can be consumptively used, stored in the system, or left instream. Many water conservation measures reduce return flows to rivers because a portion of the conserved water is often consumptively used instead of becoming return flow. Water conservation measures by upstream water users can reduce return flow that reduces the water available for downstream users because that conserved water is typically consumptively used by those upstream users instead of becoming return flow (Willardson, 1985; Venn et al., 2004; Simons et al., 2015). Water managers need additional methods to increase their understanding of to know more about where and how return flow interactions take place to make more informed decisions (Simons et al., 2015).

Perry et al. (2007) found there are few studies or projects that quantify conserved water, and the "savings" are often assumed. The effects of water conservation measures are typically quantified by a calculation of irrigation efficiency. In general, efficiency is defined as the ratio of water used to the water applied. Efficiency terms related to water use can be difficult to compare without further clarifying the spatial and temporal scale (Burt et al., 1997; Jensen, 2007; Grafton et al., 2018; Perry et al., 2009).

Irrigation efficiency is usually limited to the delivery system and ignores the impacts of return flows (Cai, 2003; Scott et al., 2014). Due to this, increases in field-scale irrigation efficiency are often not realized at the basin scale (Willardson, 1985; Chen et al., 2018; Molden et al., 2001). For example, reducing runoff from a field would increase the field scale efficiency but more water is not necessarily available in the basin because more natural flow in the river would be needed to replace the water that previously returned to the river and was diverted by others. If a district lines a canal and then consumptively uses the conserved water within the district, there would be an increase the efficiency at the irrigation district scale. It could also increase a downstream user's extractions from a groundwater source or reservoir storage because that downstream user previously got return flow from the water that infiltrated though the canal. Clemmens et al. (2008) stated that water conservation at the irrigation district level may not be realized as "saved" water when considering the basin-wide perspective. Increases in classical efficiency may not lead to water savings on the basin scale but instead change flow paths, diversion points, and water use locations (Molden et al., 2001; Lankford, 2012; Scott et al., 2014). Basin-scale efficiency is affected by multiple factors, including local water use efficiency, return flows, and water reuse (Cai 2003). Irrigation efficiency and reservoir operation should be considered simultaneously to inform water management at the basin scale (Song et al., 2016; Karamouz and Araghinejad, 2008).

The effects of water conservation measures on basin-scale management need to be better understood and quantified since some users can benefit and some can be negatively affected by implementing the same water conservation measure (Willardson, 1985; Perry et al., 2017; Chen et al., 2018). Water rights and accounting should be included in analyzing the effects of water conservation on a river basin (Grafton et al., 2018; Reclamation, 2002). Rule-based simulation modeling with accounting procedures helps track return flows (Simons et al., 2015; McMahon and Farmer, 2009). Reduced return flows were incorporated into an accounting simulation model to quantify effects to reservoirs storage, river flow, and irrigation demands and management implications (Appendix B). The modeling methods presented can be used by water managers to identify how their decisions to implement water conservation measures may impact them and others to make more informed decisions.

Dissertation Organization

This dissertation presents a decision-support tool and two methods to improve understanding of river basin management. They are presented in three chapters:

1. **High Influence: Identifying and ranking stability, topological significance, and redundancies in water resource networks**

Water resources networks are often large and connect numerous water supply, reservoir, diversion, and demand-site nodes through multiple natural and engineered conveyance links. Chapter 2 is the development of a network analysis tool to quantify the effects of changes in water resources networks. The main contributions of this work include:

- Addressed some of the concerns of parallel coordinate visualization analysis by controlling for the order of the parallel coordinate axes representing extracted nodes and considering link direction and magnitude,
- Quantified classification and measurement of network node stability, topological significance, and redundancy,
- Applied magnitude (flow volume) and direction (flow downstream) methodology to an automated parallel coordinate visualization tool, and
- Applied this tool to the lower Bear River as a case study and identified how water resources node stability, topological significance, and redundancy can be used to inform water management decisions.

2. **Effects of Reducing Return Flow on Natural Flow, Reservoir Storage, and Meeting Diversion Requests in the Boise River Basin**

   Water conservation measures are applied at local levels while the effects to the basin are either discounted or vaguely qualified. Chapter 3 provides a method to quantify the basin-wide effects of conserving water while maintaining irrigation diversions, which effectively increases consumptive use. The main contributions of this work include:

   - Developed a method to simulate water conservation measure installation in an existing, rule-based accounting simulation model of the Boise River Basin by scaling return flow,
   - Quantified effects of simulating reduced return flows (to represent the implementation of water conservation measures) at local levels on natural river flow, reservoir storage, and meeting irrigation demand throughout a river basin, and
   - Applied the method and quantification to analyze natural river flow, reservoir storage, and irrigation demand shortage throughout the basin when return flow is altered.

3. **Evaluation of Storing Conserved Water to Increase River Basin Water Management Flexibility**

   Reservoir storage, water conservation effects, irrigation demands, and return flows all need to be examined together to better capture the interconnectedness of issues within a basin. Chapter 4 provides a method to quantify the basin-wide effects of storing conserved water in reservoirs for later use by holding consumptive use constant. The main contributions of this work include:

- Quantified how storing conserved water affects reservoir system storage, natural river flow, and irrigation delivery in an existing river basin, and
- Evaluated river basin metrics when using or storing conserved water and identified impacts to management decisions within a river basin regarding flood control, district operations, recreation, and ecosystems.

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CHAPTER 2

HIGH INFLUENCE: IDENTIFYING AND RANKING STABILITY, TOPOLOGICAL SIGNIFICANCE, AND REDUNDANCIES IN WATER RESOURCE NETWORKS

Meeks, L. and Rosenberg, D.E. 2017. High Influence: Identifying and Ranking Stability, Topological Significance, and Redundancies in Water Resource Networks. Journal of Water Resources Planning and Management, 143(6). DOI: 10.1061/(ASCE)WR.1943-5452.0000755.

Abstract

Modeling water resources networks is often input-intensive due to network size and complexity. This paper introduces a Ranking Automation for NetworKs (RANK) tool that weights node connections based on flow capacity and direction and automates the process to rank nodes that are stable, topologically significant, and redundant. Application to the 55-node, 73-link lower Bear River water system that stretches from southern Idaho to the Great Salt Lake, Utah shows that stable nodes do not depend on other nodes and are typically middle junctions; unstable nodes are located downstream. The most topologically significant nodes make other nodes unstable when added or removed and occur throughout the network. The most redundant node pairs have few but identical connections. Results can help water system modelers and planners identify and prioritize locations to (a) transfer water, (b) build, expand, remove, or abandon plans for dams, (c) adopt conservation measures, (d) develop alternative supplies, (e) monitor flows, and (f) protect environmental features. Network spatial resolution, link direction, and data used to weight links influence RANK results.

Introduction

Water resources networks are often large and connect numerous water supply, reservoir, diversion, and demand site nodes through multiple natural and engineered conveyance links. Classical schematics use arrows to visually show network connectivity in one figure while network analysis software such as UCINET (Borgatti et al., 2002) and Cytoscape (Shannon et al., 2003) readily quantify individual node characteristics such as degree (number of connections), nearness (normalization of distance between two nodes), shortest path to another node, or density (number of one-distance links divided by the total number of possible links) (Cohen and Havlin, 2010). These methods describe individual node attributes but have difficulty conveying how each node in the network influences the other nodes as well as what network changes are potentially significant versus inconsequential. Identifying vulnerable, critical, and influential parts of a network is important to protect, manage, and understand networks (Barrat, et al., 2008).

One way to show node influence is to measure how the removal of a node effects the rest of the network. For example, small node and link changes can severely damage network operation such as across important bridge nodes with low degree that connect network branches (Barrat, et al., 2008). Singer and Greenshpan (2009) introduce a method called node extraction and visualization (NEVIS) that uses node extraction and parallel coordinate plotting to qualitatively show how nodes in networks with undirected links influence each other. The NEVIS method, included in Inselberg's compilation textbook on parallel coordinates (Inselberg, 2009), systematically removes one node from a network, calculates how each node removal influences the centrality of remaining nodes (centrality is a measure of how connected a node is to the network), and plots all the extracted centrality results as ordinates on a parallel coordinate plot (Inselberg, 1985;

Wegman, 1990). On the plot, each parallel axis represents an extracted node while traces, one for each node, show how a node is affected by extracting the other nodes. Singer and Greenshpan (2009) further define the terms *vulnerable*, *topologically significant*, and *backed up* to indicate, respectively, nodes that (i) are affected by removal of other nodes, (ii) affect the centrality of other nodes in the network when removed, and (iii) allow alternate paths to bypass a removed node. The authors also qualitatively describe how to visually identify nodes with these characteristics from the shapes of the traces on the parallel coordinate plot. At present, these qualitative descriptions do not allow an analyst to compare or rank the relative importance of nodes nor consider a large number of nodes. Also, the undirected and un-weighted NEVIS network topology does not apply for networks like water resources systems where links typically have direction and magnitude.

Porse and Lund (2015) looked at the effects of network node removal in the California water system and used Cytoscape to calculate several individual node metrics. With a network of 596 nodes, they selected 11 nodes to remove individually and then as sets to represent cascading failures. Nodes were weighted for importance and demand; links were not weighted for capacity. Their work showed that applying weights, such as node capacity and target flow, can help identify the relative importance of network features.

Cohen and Havlin (2010) identify possible disadvantages to the node removal method for network analysis: (a) the removal of a central node (one with many connections) may have little influence in a well-connected network, (b) removal of a peripheral node that then disconnects other peripheral nodes thus classifying the removed node as important when it may not be, and (c) a node seeming to be important only because it is connected to a very central node. Visualization of results on a parallel coordinate plot (Singer and Greenshpan, 2009) presents further challenges such as: (1) plots often have many lines and become busy and crowded (Edsall, 2003), (2) ordering of axes affects the interpretation of results (Edsall, 2003, Huh and Park, 2008, Albazzaz et al., 2005), (3) plots take time to construct (Albazzaz et al., 2005), (4) data analysis has not been automated (Albazzaz et al., 2005), (5) viewers cannot compare values on distant axes (Edsall, 2003), and (6) plots only allow for qualitative data comparisons by visual inspection.

To better identify high-influence nodes in water resources networks, this paper introduces the Ranking Automation for NetworKs (RANK) tool to define, quantify, and automatically rank nodes for three influence metrics: (1) stable (their connectivity in the network does not depend on other nodes), (2) topologically significant (they cause other nodes to be unstable when removed from the network), and (3) redundant with other nodes. The ranking is done without need to qualitatively and visually interpret a parallel coordinate plot. RANK also further considers link (flow) direction and magnitude (e.g., a volume of water flowing downstream in a water resources network). The tool is used to identify promising locations for agriculture-to-urban water transfers and other water planning efforts in a in a 55-node, 73 link network for the lower Bear River basin, Utah. Described below are the steps of RANK, its application to the lower Bear River system, and implications for water systems modeling and management.

Methods

RANK follows four sequential steps to automate, rank, and identify stable, topologically significant, and redundant nodes in directed or undirected networks with or without link attributes and weights. Stability measures how much the extracted centrality value for a node changes across extracted networks. The roles of stable nodes do not depend on the existence of particular nodes. Topological significance measures how extracting a node affects the stability of other nodes in the network. When removed, topologically significant nodes cause instability in other nodes. Redundancy is a measure of connection similarity between a pair of nodes. The four steps are 1) create adjacency and weight matrices that describe the network topology, 2) calculate extracted centrality values for each node in each extracted network, 3) calculate pairwise differences among extracted centrality values, and (4) rank node stability, topological significance, and redundancy according to each performance metric. Each step is described and presented below. Steps 1 and 2 extend Singer and Greenhpan's (2009) NEVIS and parallel coordinate plotting work to include directed networks with weighted links while Steps 3 and 4 are unique to RANK.

Step 1: Create Adjacency and Weight Matrices. RANK uses a square input matrix A of size n by n to define the network topology (adjacency) where n is the number of nodes and a value of $A(i,j) = 1$ in the matrix means the node on row i has a directed edge (link) to the node indicated by column j. To define the adjacency matrix, the user can either a) manually enter values in a RANK worksheet or b) draw the directed graph in a program such as HydroPlatform (Harou et al., 2010) or UCINET (Borgatti et al., 2002) and export the calculated adjacency matrix to RANK. To include an undirected (bi-directional) link between a node pair, the user must specify two links in the adjacency matrix between the node pair, one link in each direction [$A(i,j) = 1$, $A(j,i) = 1$]. After specifying the adjacency matrix, the user then enters a second identically sized matrix of weights to quantitatively describe an attribute of each link such as flow capacity (Barrat et al., 2008). For an unweighted network, enter the same weight value of 1 for each link. RANK multiplies the adjacency and weight matrices element by element to generate a weighted adjacency matrix.

Step 2: Calculate Extracted Centrality and Create the Parallel Coordinate Plot. RANK calculates a connectivity matrix that transverses the weighted adjacency matrix by following the directed links; connectivity matrix values are the sum of the weighted links from one node to each other node. From the connectivity matrix, RANK calculates a weighted extracted centrality value for each node using the NEVIS centrality formula (see details in Singer and Greenshpan, 2009) and generates a parallel coordinate plot with weighted extracted centrality values as ordinates, extracted nodes as abscissa, and traces that show how each node's weighted extracted centrality values change across the abscissa.

From visual inspection of the parallel coordinate plot, the user can identify stable nodes as nodes whose traces have few or no vertical drops (changes in extracted centrality values) across the abscissa (extracted nodes). Topologically significant nodes are locations on the abscissa where extracting a node causes multiple traces to drop and/or large drops in traces. Nodes with similar horizontal traces are likely to be redundant. At this step, the order of the axes influences this qualitative visual interpretation of extracted centrality values.

Step 3: Calculate Pairwise Differences. To quantify the performance metrics and control for axes ordering on the parallel coordinate plot, RANK next calculates the difference between each of the (*n*-1)(*n*-2) pairs of weighted extracted network centrality values along a trace (extracted centrality is undefined on a node's trace at the abscissa where the node is extracted). These pairwise differences permit simultaneous comparison across each parallel coordinate axis. RANK quantifies node stability as the average of all pairwise differences associated with the trace. Higher average pairwise differences indicate nodes whose traces have larger drops and are more affected by node extractions. In contrast, each node's topological significance is determined by averaging the (*n*-1)(*n*-2) paired differences in weighted extracted centrality values generated from the *n*-1 locations where traces for each other node cross the abscissa for the extracted node.

Step 4: Rank Nodes. RANK averages the pairwise differences to determine node ranks for stability, topological significance, and redundancy. The most stable node has the lowest average pairwise difference across a trace and describes traces that do not have large or multiple drops. Topological significance is quantified by examining two factors associated with the traces of weighted extracted centrality values: the number of drops at an extracted network axis and the magnitude of each drop. Multiple traces that drop at the same extracted node indicate that extracting that node causes many nodes to become unstable. Extracted nodes that cause large numbers of traces to drop and large magnitude drops are topologically significant. The topological significance magnitude for a node is the average of all pairwise differences along the axis. RANK counts the number of pairwise differences for each axis which are equal to or greater than a user-specified threshold. Each node is ranked for number of and magnitude of drops. The node having the highest average rank for each is the most topologically significant.

To determine redundancy, the program identifies candidate redundant node pairs to avoid needlessly considering all possible node pairs and reduce calculation time. A histogram is created for each node with the number of pairwise differences in each of 15 histogram intervals. Candidate redundant node pairs are classified as nodes that have less than 0.5% different for each histogram interval. RANK then compares the row vectors from the connectivity matrix for each node in the candidate pair. Redundancy is expressed as a percentage and calculated as the number of common connectivity values divided by n-1 (maximum possible number of connections).

The end results from RANK are three lists that rank each node from n (most) down to 1 (least) for each performance metric. A user can go into the intermediate calculation spreadsheets and see the data which RANK uses to rank the nodes (e.g., to see how much more topologically significant the highest ranking node is compared to the second).

Implementation. RANK uses Excel's Visual Basic for Applications (VBA) macro programming capabilities to automate the entire analysis. Automation requires the user to provide four inputs: directed graph of the network in the format of the adjacency input matrix, a matrix of link weights, a value for the parallel coordinate drop threshold to determine topological significance, and the redundancy threshold RANK uses to screen redundant pairs to show to the user. RANK produces the parallel coordinate plot, ranks each node's stability and topological significance, and lists node pairs that are redundant. RANK can be accessed at https://github.com/lmeeks/RANK.

Applications

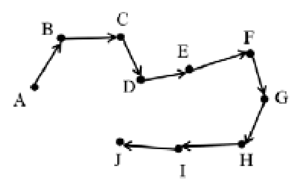
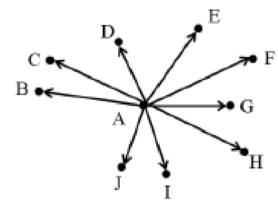
RANK is first demonstrated for two small illustrative networks. Then, it is applied to inform management of the much larger lower Bear River water system in Idaho and Utah.

Illustrative Networks. Illustrative (i) single branch and (ii) hub and spoke networks are presented because they are simple and uniform in construction but have very different structure. These networks introduce how RANK works, verify that outputs are correct, and illustrate the performance indicators that quantify stability, topological significance, and redundancy.

Single Branch. The single branch network has a single source node (A), multiple intermediary nodes connected by single links (B through I), and a single sink node (J) (Figure 2.1-A1). The adjacency input matrix for the single branch network has entries of 1 just above the primary diagonal. All links have the same weight. Running RANK yields a parallel coordinate plot where each horizontal trace is different but all follow a similar trend where the centrality of each node decreases as closer, upstream nodes are removed. The RANK analysis shows the most stable nodes are the most upstream in the network which receive water: B and C. Node A is the most topologically significant. There are no redundant node pairs because each of the nodes have different connections. The quantitative results confirm what may be apparent from visual inspection that upstream nodes are the most stable (longer, darker blue lines in Figure 2.1-A3 span more extracted nodes)while the most topological significant nodes are the nodes located upstream in an equally-weighted network.

Hub and Spoke. In this network, a single hub node (A) is the sole source for all exterior spoke nodes (B to J in Figure 22.1-B1). The adjacency matrix for this network has entries of 1 in the row for the hub node. Each of the hub-spoke links has a weight representing the flow rate along the link. The flow magnitude for links from hub A with destination node and magnitude are B-5, C-5, D-10, E-10, F-10, G-50, H-50, I-100, and J-100. The parallel coordinate plot shows that the hub (A) is stable as its trace has a weighted extracted centrality value that is constant and zero (pink line in Figure 2.1-B3). Values for all spoke traces drop at the A axis which represents extraction of the hub node. Since the traces for the spoke nodes drop (purple, blue, green, and red lines in Figure 2.1-B3), the spokes are unstable. Drops occur when the hub node is extracted making the hub topologically significant. The traces for all the spokes follow the same trend but having a higher flow rate (weight) corresponds with a higher extracted centrality (purple and blue lines above green and red lines in Figure 1-B3). Nodes having links with the same weights are redundant (overlapping solid and dashed purple, blue, green, and red lines in Figure 2.1-B3). The results confirm what is likely apparent from visual inspection that removing the hub node from a hub and spoke network decreases the stability of the other nodes the network connectivity. Also, results show that adding link weights changes the parallel coordinate plot extracted centrality and redundancy results.

These illustrative networks provide a way to verify the accuracy of RANK to both visualize and quantify stable, topologically significant, and redundant nodes in simple networks. The parallel coordinate plot for the Single Branch network does not readily convey that the near-upstream nodes are most stable and shows the importance of RANK's quantification. The results also show that the performance metrics of stability, topological significance, and redundancy are not mutually exclusive – for example nodes can be both unstable and redundant (spokes in a Hub and Spoke network) or stable but not topologically significant (nodes in Single Branch network). Each of these quantified and ranked characteristics can have important implications for modeling and managing larger and irregular networks such as the lower Bear River water system.

Network Characteristic	A. Single Branch	B. Hub & Spoke
1. Directed Graph		

2. Weighted Adjacency Matrix

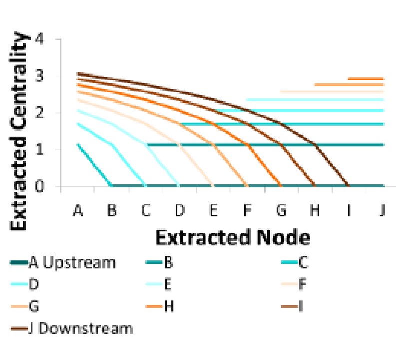
A. Single Branch — Destination Node

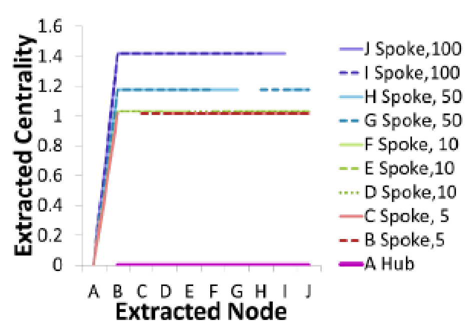
	A	B	C	D	E	F	G	H	I	J
A		1								
B			1							
C				1						
D					1					
E						1				
F							1			
G								1		
H									1	
I										1
J										

B. Hub & Spoke — Destination Node

	A	B	C	D	E	F	G	H	I	J
A		5	5	10	10	50	50	50	100	100
B										
C										
D										
E										
F										
G										
H										
I										
J										

3. Parallel Coordinate Plot





Network Characteristic	A. Single Branch	B. Hub & Spoke
4. Stability Rank	1:A, 2:B	1:A (Hub)
5. Topological Significance Rank	1:A	1:A (Hub)
6. Redundant Pairs	none	B-C, D-E, D-F, E-F, G-H, I-J

Figure 2. 1. Illustrative networks and RANK results.

Bear River Network. Here, RANK is applied to inform water systems modeling and planning in the lower Bear River system of Idaho and Utah including potential locations for agricultural to urban water transfers. The Bear River watershed comprises 7,500 square miles of agricultural, urban, federal, and state lands in southeastern Idaho, northeastern Utah, and southwestern Wyoming and is the largest tributary of the Great Salt Lake with an average annual inflow of 1.2 million acre feet (Mesner and Horsburgh 2012). The primary water uses in the basin are for agriculture, urban, industrial, power generation, recreation, and the environment.

The lower Bear River system used in this analysis stretches from Southeastern Idaho to the Great Salt Lake, Utah. The Utah Division of Water Resources (UDWR) developed a Bear River simulation model to examine water system sustainability over a 50-year historical record (Utah Division of Water Resources, 2004). The schematic represents the system with 55 nodes (10 reservoirs [6 existing and 4 proposed], 11 urban, agricultural, and environmental service areas, 13 flow junctions) and 73 linkages (Figure 2.2). The system's largest environmental wetland service area is the Bear River Migratory Bird Refuge while other incidental riparian water uses occur at various junctions along the main stem of the Bear River. Network links were weighted by the flow capacity from one node to another (UDWR, 2004, Figure 2.3) and all links were unidirectional except the bi-directional canal between Willard Bay Reservoir and Junction 32-55. Water quality and mixing is not addressed in RANK; it is assumed that water from a source or branch can serve any service area or environmental area.

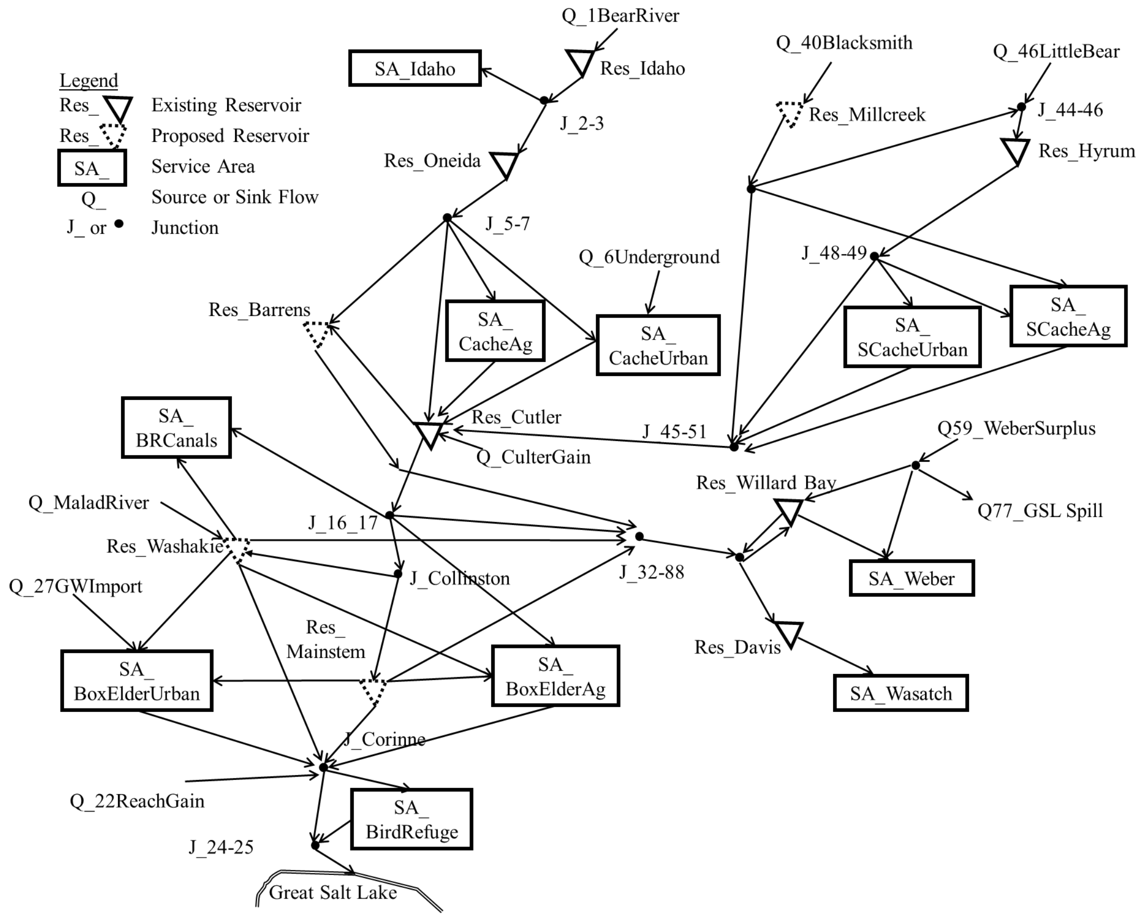


Figure 2. 2. Schematic of Bear River Network for application of RANK.

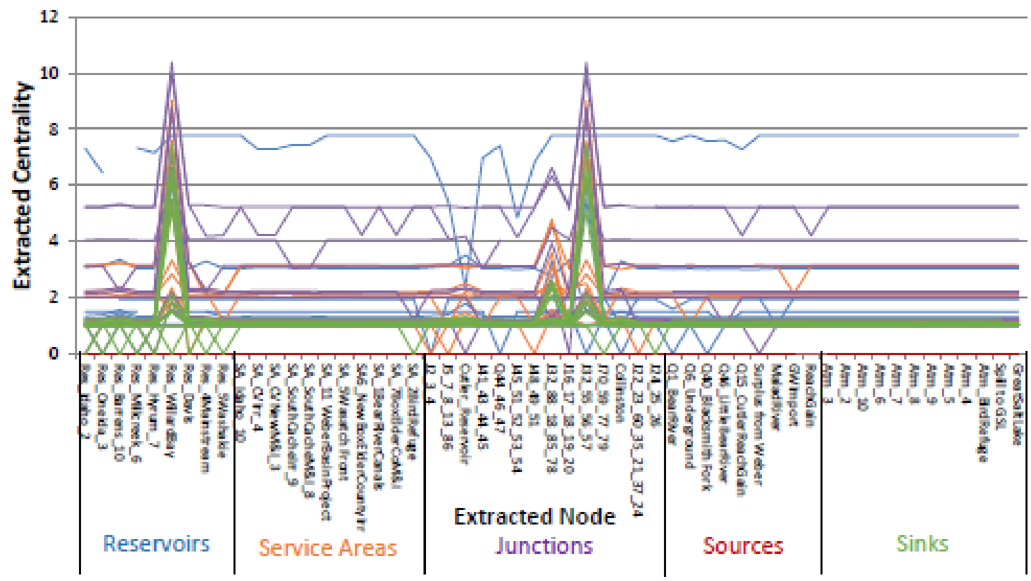


Figure 2. 3. RANK resulting parallel coordinate plot for Bear River Network. Traces showing extracted centrality values for reservoirs, service areas, junctions, sources and sinks, and node groups are blue, orange, purple, red, and green, respectively.

As Utah's urban population continues to grow along the Wasatch front in Salt Lake, Davis, and Weber counties, planners project the need to transport Bear River water to these areas (Mesner and Horsburgh 2012). Water transfers from agricultural to urban uses could change how the water system functions. The water system is complex and managers have numerous options to implement changes. Some pressing questions include from what agricultural areas should managers transfer water to meet future urban demands and where might it be appropriate to build additional dams, remove existing dams, abandon proposed dams, implement conservation measures, develop new local resources, monitor flows, or protect environmental and ecosystem services?

Running RANK for the Bear River network gives a parallel coordinate plot where the (i) extracted node axes are ordered and grouped from left to right by reservoirs, service areas, junctions, sources and sinks, and (ii) traces showing extracted centrality values for these node groups are similarly colored (respectively, blue, orange, purple, red, and green in Figure 3). Visual inspection of the plot identifies reservoirs and junctions as the extracted node axes where traces have the largest and most number of drops in extracted centrality values and indicates these nodes are the most topologically significant. Reservoir removal typically causes the centrality of a single green trace to drop to zero which is the reservoir's corresponding evaporation sink. In contrast, traces are generally flat (few drops) across the abscissa axes that represent extracting service area, source, and sink nodes and show these nodes have little topological significance. Visual and qualitative observations allow the user to generally classify nodes.

Calculating pairwise differences among centrality values and ranking nodes using the quantitative performance metrics proposed in this work controls for axes order in Figure 2.3 and shows the most stable nodes are sources like the headwaters of the Bear, Blacksmith Fork, and Little Bear rivers while the most unstable nodes are Junctions 24-25 and Corrine which are located far downstream in the network directly upstream of the Great Salt Lake Terminus and New Box Elder Irrigation service area (Figure 2.4 and Table 1). These results occur even though unstable downstream junctions have incoming and outgoing links of high capacity and the service areas have relatively low capacity links.

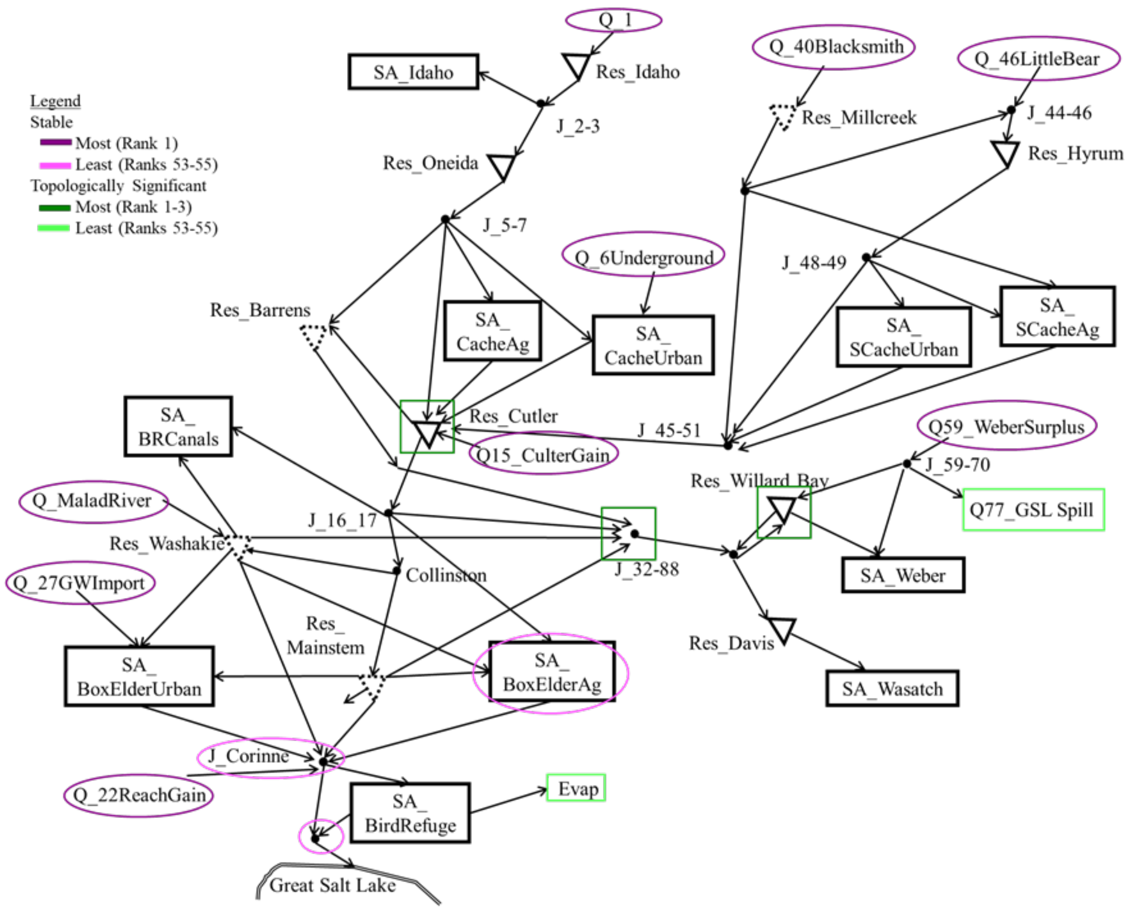


Figure 2. 4. Schematic of Bear River Network with RANK results of stability and topological significance shown in purple and green.

Table 2. 1. RANK stability results for the Bear River network.

Rank	Weighted, Directed Network	Unweighted, Undirected Network
55	Reach Gain, Groundwater Import, Malad River, Surplus from Weber, Q15 Cutler Gain, Q46 Little Bear RiverQ46, Q40 Blacksmith Fork, Q6 Groundwater, and Q1 Flow from Bear Lake	Washakie Reservoir
54	Evaporation from Washakie	Junction 22-60
53	Junction 70-59	SA7 Box Elder M&I Users
3	Junction 24-25	Evaporation from Hyrum Reservoir
2	Junction Corrine	Q61 Malad River
1	New Box Elder Irrigation	Great Salt Lake

The most topologically significant node, Cutler Reservoir, has links with the highest weights entering and leaving of all nodes but is also the 6th most unstable node. The Corrine area junction has the same node degree as Cutler and 10% less flow capacity yet is one of the least topologically significant and 2nd most unstable (Figure 2.4 and Tables 2.1 and 2.2). The other topologically significant nodes have a variety of degrees and incoming and outgoing flows (Table 2.2). These observations show that several factors beyond node degree and link density affect node topological significance.

Table 2. 2. RANK topological significant results for the Bear River network.

Rank	Weighted, Directed Network	Unweighted, Undirected Network
55	Cutler Reservoir	Cutler Reservoir
54	Willard Bay Reservoir	Junction 45-51
53	Junction 32-88 (potential Bear River diversions to Wasatch Front)	Junction 32-88
3	Q15 Cutler Reach Gain	Q15 Cutler Reach Gain
2	Cache Valley Irrigation	Collinston
1	All nodes which have no downstream connections (all reservoir evaporation nodes, Great Salt Lake, WeberBasin, Wasatch, BearRiverCanals, BirdRefuge, BoxElderM&I, and NewBoxElderIrrigation)	Bear River Canals

The lower Bear River has several highly redundant node pairs that are the same type (Table 2.3). Cache Agriculture and Cache Urban service areas differ only in that Cache Urban can additionally receive water from Q6-Groundwater. South Cache Agriculture and South Cache Valley Urban service areas are also highly redundant because they both connect to the same diversion and return flow points on the Little Bear River except that South Cache Agriculture can additionally divert water from the

Blacksmith Fork River below Millcreek Reservoir.

Table 2. 3. Highly redundant node pairs of the same node type in the weighted, directed Bear River network.

Redundancy Value	Node 1	Node 2
98%	South Cache Agriculture Service Area	South Cache Urban Service Area
98%	Cache Valley Irrigation	Cache Valley Urban
88%	Hyrum Reservoir	Millcreek Reservoir
86%	Idaho Reservoir	Oneida Reservoir
84%	Malad River	Groundwater Import

The Bear River network was also analyzed using undirected and unweighted links to test effects of link direction and weighting (Table 2.3). With these settings, the least stable nodes connected to only one other node and were the Great Salt Lake, Malad River, and Evaporation from Hyrum Reservoir. Cutler and the junction (J32-88) that bridges to the Weber basin still had high topological significance, but the junction (J45-51) that bridges to the South Cache valley had higher topological significance than Willard Bay Reservoir. In the weighted, directed network, most unstable nodes are located downstream and topologically significant nodes are more likely to be located upstream. The top three topological significant nodes when not considering direction or magnitude are in the top 15 when the analysis considers link weight and direction. There are five highly redundant node pairs with over 96% of the same connections including the Cache Valley Irrigation and Cache Valley Urban service areas. For comparison, the Cache Valley service areas were 98% redundant with the directed and weighted version of RANK.

Discussion

RANK can identify and rank the most stable, topologically significant, and redundant nodes in a network considering both link direction and weight. In the directed, weighted analysis for the Bear River network, unstable nodes are typically located downstream. Sources located at more upstream locations are more topologically significant than sources located more downstream even if the downstream source contributed more inflow (e.g., Blacksmith Fork is more topologically significant than the Reach Gain at Cutler Reservoir even with 16% less flow at Blacksmith Fork). Nodes with more connections are less likely to be redundant because there is a lower likelihood that another node will have the same relationships with other network nodes.

Link weight and direction affect the performance metrics. In the unweighted and undirected case, the best predictor of instability was a nodes with few connections. Adding flow direction caused more downstream nodes to be unstable. Topological significant nodes were junctions that link branches of the network. In the case of weighted and directed links, there was not a standard rule-of-thumb to identify the location or characteristics of topologically significant nodes. Cutler Reservoir remained the most topologically significant node in both analyses. Below, we suggest how to use the RANK results to inform water system modeling and planning.

Potential Water Transfers. Managers can identify potential sources of water transfers as nodes with high redundancy and low topological significance. For example, RANK results for the lower Bear River system show the Cache Valley Irrigation service area is 98% redundant with the Cache Valley Urban service area. This redundancy suggests that moving water from Cache Valley Irrigation to Cache Valley Urban has little influence on network connectivity. Cache Valley Urban and Cache Valley Irrigation have topological significance values of 23 and 22, respectively, which further supports their similar influence on the network. Similarly, the South Cache Irrigation and the South Cache Urban service areas are 98% redundant with topological significance ranks of 35 and 36, respectively. Together, the redundancy and topological significance metrics suggest the Cache Valley and South Cache service areas are two promising sources of agricultural to urban transfers if the goal of the transfer is to leave intact the connectivity of the remaining parts of the lower Bear River water system.

Reservoir Siting. The RANK results for reservoirs compare favorably to recent Bear River reservoir siting efforts (Table 2.4). For example, the existing Cutler, Willard Bay, Idaho, and Oneida reservoirs have the highest topological significance ranks which suggest priorities to build these reservoirs first. The proposed Barrens and Millcreek reservoirs have the lowest topological significance ranks and will likely go unbuilt because the two sites were recently excluded from a UDWR short list of Bear River storage project sites to further study (Bowen, Collins & Associates and HDR Engineering, 2014). The proposed on-stream Mainstem and off-stream Washaskie reservoirs have topological significance ranks interspersed with several existing reservoirs. Washakie was shortlisted while the Mainstem site was not. Interestingly, Washakie has very high financial costs and environmental impacts, and is unlikely to be built. In contrast, the UDWR also shortlisted another recently proposed on-stream site, the Above Cutler Reservoir (omitted from Bear River model schematic but proposed location is at J5-7 junction). The J5-7 node has a topological significance rank of 41/55 similar to many existing reservoirs; the result suggests the proposed Above Cutler reservoir site merits further study. This discussion of RANK results in reference to current Bear River reservoir siting efforts suggests that existing or proposed reservoirs with high topological significance should be retained or further studied as potential projects. Managers may abandon proposals for reservoirs with low topological significance while existing reservoirs with very low topological significance may be candidate sites for dam removals.

Table 2. 4. RANK results for Bear River Reservoirs and Current Status

Reservoir	RANK Topological Significance		Current status
	Weighted, Directed	Unweighted, Undirected	
Cutler	55	55	Existing
Willard Bay	54	48	Existing
Idaho	40	38	Existing
Oneida	39	49	Existing
Mainstem	38	44	Proposed, not short listed
Davis	37	42	Existing
Washakie	33	45	Proposed, short listed
Hyrum	29	17	Existing
Barrens	28	30	Proposed, not short listed
Millcreek	24	43	Proposed, not short listed

Additional Water System Planning and Modeling. In addition to identifying promising sources of water transfers and reservoir sites, RANK results can inform other water system planning and modeling activities. Nodes with high topological significance should be monitored because of their high impact on other nodes. Water supply to unstable nodes is easily affected by changes at other network nodes. At unstable nodes, managers should implement water conservation measures, develop new alternative supplies, and monitor flows. In the Bear River system, the least stable service areas are the Box Elder County New Irrigation, Box Elder County New M&I, and Bear River Canals. These service areas would benefit most from conservation and alternate supplies particularly in times when there is low surface water availability, limited reservoir storage, or breaks in water transmission lines. As an example, managers of the Weber Basin Water Conservancy District, who oversee the Weber Basin Project (30/55 for stability), have steadily promoted water conservation programs over the last decade (Weber Basin Water Conservancy District, 2010). Additionally, managers should also monitor conditions at unstable nodes like Junction 24-25, Junction 23-23, and Cutler Reservoir because conditions at these nodes are subject to activities at many other nodes in the network.

Managers should protect nodes with low stability or high topological significance that provide environmental services because degradation or removal of these areas will negatively impact ecosystem services at the location and other nodes in the network. RANK results can also identify which environmental areas would benefit most from further management. The Bird Refuge, a critical environmental site both in the Bear River system as well as the entire region, has low stability (51/55) and low topological significance rank. In contrast, Junction 5-7 Diversions to Cache Valley is a riparian service area with a high topological significance rank of 41/55 and medium stability of 26/55.

Focusing the redundancy analysis on node pairs that are of the same type and share similar management options (e.g., reservoirs, service areas, junctions, etc.), managers can use the redundancy of Cache and South Cache Valley Irrigation districts as well as Cache and New Cache Urban districts to reroute water in the event of system failure at one node. Redundancy, therefore, identifies operational flexibility in the system. At the same time, the redundancy results also identify system components that serve identical (or nearly identical) functions; managers can use these results to identify nodes that if removed from the system will save money and other resources but otherwise have little effect on the overall system performance.

In addition to informing water system planning, RANK results can be used to inform model design and resolution. For example, RANK can help with model reduction as follows: 1) apply RANK to the existing network, 2) use RANK's redundant pair results to select node pairs to combine into one node, 3) rerun RANK with the simplified network, and 4) compare RANK results for the original and simplified networks. If there are few changes, then retain the simplified network, and lastly, 5) repeat steps 1 to 4 for other redundant node pairs. In contrast, nodes with high topological significance may be locations to focus additional data collection or enhancements to improve model spatial resolution. Modelers may also benefit by recognizing unstable nodes as network locations where model results will be sensitive to scenario or other changes. Application of RANK in these ways is highly dependent on the model scope and application.

Limitations. RANK requires input data describing network connectivity, link weights, and threshold values for the calculations of node topological significance and redundancy. The spatial resolution of the network connectivity data will affect node rankings of stability, topological significance, and redundancy as well as the interpretation of the results to inform water system modeling and planning. Similarly, the type of data used for the link weights may influence outcome (i.e., analysis using mean annual flow versus peak flow rates, channel capacity, or concentration for a water quality constituent). The source and type of link weight data used may obscure what is actually happening in the network and particular link weighting data is likely better suited for specific modeling and planning applications.

Conclusions

Water resources systems comprise complex networks for which modeling to inform management typically requires significant computational effort. Difficulties are exacerbated when removing individual nodes to study effects on other nodes in the system. In this paper, a Ranking Automation for NetworKs (RANK) tool was developed for both directed and undirected networks with weighted and unweighted links to identify and rank key network nodes that are (1) stable: their roles do not depend on the existence of particular nodes, (2) topologically significant: when removed or added to the network, these nodes cause other nodes to be unstable, and (3) redundant: node pairs that have similar connections. RANK goes beyond first-order network analysis tools which analyze networks based on the number of nodes and links and paths between nodes. RANK instead quantifies how the relationships among nodes change when a particular node is removed. Node ranks are calculated by taking pairwise differences in centrality values on the parallel coordinate plot that represents network-wide effects of node extractions. These paired differences further control for the ordering of axes on the plot as well as quantify the visual and qualitative interpretation of the plot. Water managers can use RANK results to help inform several water system modeling and planning activities.

RANK was applied to two small illustrative weighted, directed networks as well as the larger 55-node, 73-link lower Bear River water system. The analysis shows that unstable nodes generally are more likely to be located downstream but have a variety of incoming and outgoing link weights. There is not a simple rule to identify topologically significant nodes. Redundant nodes typically have few but identical connections and similar geographic locations. These results suggest investigating: (a) highly redundant, low topological significant nodes as candidate sources for water transfers to urban areas; (b) building or expand dams at reservoir sites with high topological significance; (c) removing existing or abandoning proposed dams at reservoir sites with low topological significance; (d) adopting conservation measures or developing alternative supplies at unstable service areas; and (e) monitoring flows and protect environmental features at unstable and topologically significant nodes. Modelers can also use RANK redundancy, topological significance, and stability results to identify locations within the model network to simplify the schematic, add data and spatial resolution, or find sensitive results.

Acknowledgements

This research was funded by Utah Mineral Lease funds. The authors thank the several anonymous reviewers for constructive feedback on earlier drafts.

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CHAPTER 3

EFFECTS OF REDUCING RETURN FLOW ON NATURAL FLOW, RESERVOIR STORAGE, AND MEETING IRRIGATION DIVERSION REQUESTS IN THE BOISE RIVER BASIN

Abstract

As water demands increase, more pressure is put on the agriculture sector to implement water conservation measures. Water conservation measures are applied at local (field or irrigation) level while effects to the basin are often not fully considered. This study developed a method to model and quantify the effects of water conservation measures on an existing river basin. Water conservation measures were simulated in the model by reducing the return flow from irrigated areas to the river. Reducing the return flow and keeping the diversion demands constant represented an increase in consumptive use for an irrigation area. The results quantify how system reservoir storage, meeting irrigation demands, and flow in the river change as water conservation measures are introduced in a 28-year simulation of the Boise River Basin. Reducing return flows while maintaining historical irrigation diversion requests decreased the natural river flow available for diversion, which increased demands for stored reservoir water. The basin irrigation demand shortage increased 2.6 times on average throughout the system with no return flow. To make up for the reduction in natural river flow as return flows to the river were reduced, downstream users relied more heavily on reservoir storage to meet irrigation demand than other users. Reducing return flow while keeping the irrigation diversion request, which effectively increased the consumptive use, resulted in more reservoir storage used and more irrigation demand shortages. Irrigation shortages

increased in drier years due to less reservoir storage being available. During the driest year of the simulation, the total system shortage nearly doubled when going from current conditions to no return flow. Future studies should investigate long-term effects of water conservation measures on groundwater and management implications of water conservation measures.

Subject Headings: water efficiency, water conservation, return flows, basin management, water management, simulation modeling, rule-based simulation

Introduction

Agriculture in the western United States is dependent on water delivery and irrigation systems to meet crop water needs. The agriculture sector has spent decades developing and implementing technologies and strategies to conserve water. Billions of dollars of public and private money have been spent on installing water conservation technologies (Grafton, 2018).

Water conservation measures typically occur at two levels: field (e.g., converting surface irrigation to sprinkler or drip irrigation, reduced tillage, and recycling tailwater) and irrigation district (e.g., canal operation automation and lining or piping earthen canals). Water conservation measures can reduce field runoff, deep percolation (irrigation that travels below the crop rootzone), system spill, and canal water infiltration. Most of the technologies do not change the consumptive use of the water diverted but instead change the location of the consumptive use. For example, an irrigation district may be concerned that they are losing water that they divert to seepage out of an earthen canal and may consider lining it. That infiltrated water is currently percolating to an aquifer or returned to the river and may be consumptively used by other users downstream. By lining their canal, the district could make that previously infiltrated water available for consumptive use in its district (to water land under its water right that is not currently irrigated or to expand serviced acreage if allowed under the water right) while the water users that previously relied on return flows have less water available and one less source of water. Research has found that water savings from local changes may not be realized as expected because the water that becomes conserved was already used as a source for another water user (Grafton et al., 2018; Perry et al., 2009; Willardson, 1985; Ahmad et al., 2014; Keller and Keller, 1995). In fact, water that was previously considered “lost” by one water user was often a source for another user to consumptively use downstream.

A mass balance is a good way to analyze what is happening to irrigation water. A mass balance shows the inputs and outputs to a defined control volume. Figure 3.1 shows a generic water mass balance for a canal (top) and a three-canal basin (bottom) with definitions in Table 3.1. The three-canal system mass balance diagram shows the relationships of how changes at upstream canals can impact downstream canals. As shown in the three-canal system, the Spill and Infiltration terms may provide water to downstream canals via the Spill or Surface & Subsurface Flow as well as being return flow to the river. Reducing the Spill and Infiltration by implementing water conservation measures would reduce or eliminate water availability to users downstream.

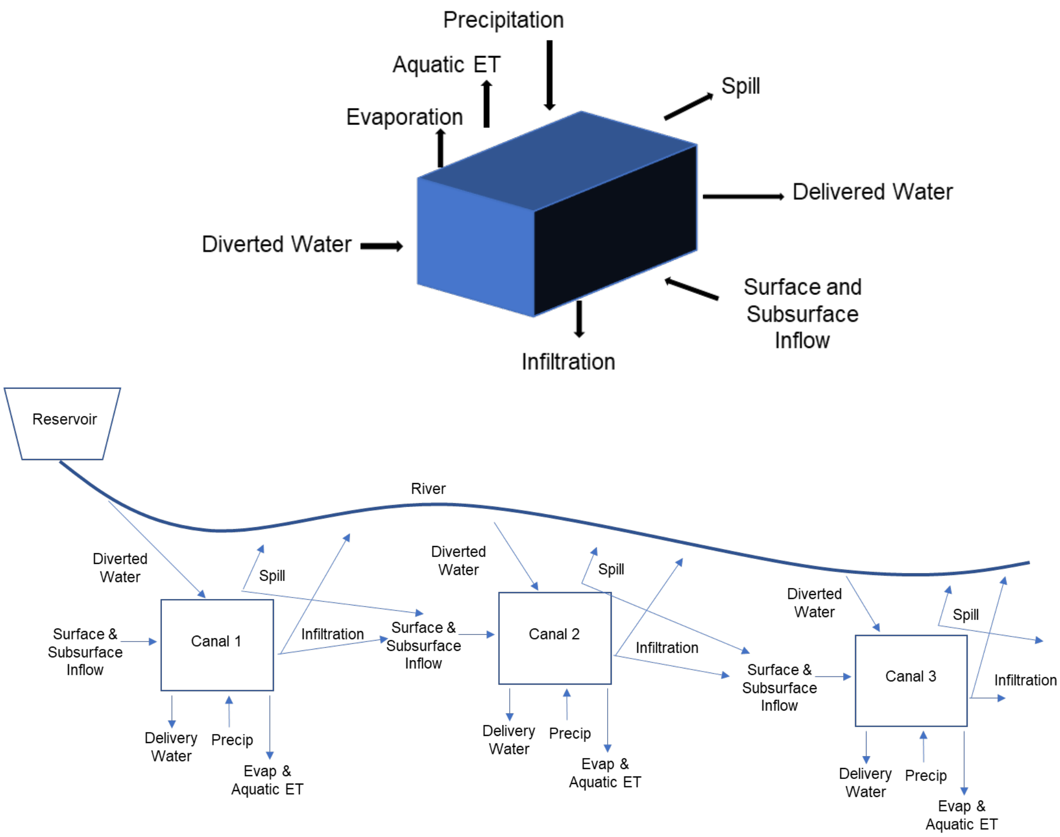

Figure 3. 1. Mass balance for a single canal (top) and river system with a reservoir and three canals (bottom). The three-canal system shows the relationships between upstream and downstream canals related to water use.

Table 3. 1. Mass balance terms for the Figure 3. 2. diagram of canal mass balance.

Canal mass balance term	**Inflow or outflow**	**Definition**
Diverted Water	Inflow	Water diverted from the sources (river, reservoir, groundwater) to the canal
Precipitation	Inflow	Rainfall that lands in the canal
Surface and Subsurface Inflow	Inflow	Water that enters the canal via surface flow (e.g., overland flow, field runoff) or subsurface through the soil, including groundwater or water table or water that returns to the river
Evaporation and Aquatic EvapoTranspiration	Outflow	Water that evaporates from the canal surface and evapotranspiration (ET) of aquatic species growing in and along the canal channel

Delivery Water	Outflow	Water that leaves the canal through irrigation diversion structures to deliver irrigation water (including crop ET)
Infiltration	Outflow	Water the seeps through the canal and infiltrates into the subsurface
Spill	Outflow	Water that leaves the canal at the end of the canal when not all of the water diverted is delivered

Mass balance terms can be increased, reduced, or eliminated by the implementation of water conservation measures (Table 3.2). These water conservation measures can be at the field or delivery scale.

Table 3. 2. Examples of how water mass balance can be affected by some commonly used water conservation measures.

Mass balance term	**Water conservation measure**	**Scale**	**How water conservation measures can alter this mass balance term**
Evaporation	Lining	District	Can change surface area for evaporation
	Piping	District	Eliminates evaporation by enclosing water
	Conversion to sprinkler irrigation	Field	Increases during spray evaporation
	Conversion to drip or subsurface irrigation	Field	Reduce or eliminates wetted soil area
Canal Aquatic ET	Lining or Piping	District	Eliminates growth of aquatic species in channel banks
Delivery Water	Conversions to sprinkler, drip, or subsurface irrigation	Field	May increase water use if yields increase (e.g., plant crops with higher consumptive use, get an additional alfalfa cutting)
	Tailwater recycling	Field	May reduce water removed from the canal by water user because some water already delivered is reused
Infiltration	Lining or Piping	District	Reduces infiltration because lining or pipe is a barrier between water and the soil

Spill	Automation and SCADA (supervisory control and data acquisition)	District	Reduces spill by better timing diverted water and delivery water
Surface and Subsurface Inflow	Lining	District	Reduces subsurface flow by being a barrier between canal water and soil
	Piping	District	Eliminates surface and subsurface flow by being a barrier between canal water and soil or overland flow
Field Runoff	Conversions to sprinkler, drip, or subsurface irrigation	Field	Can reduce the amount of water applied to field that is more than what infiltrates into the soil
	Tailwater recycling	Field	Can reduce runoff by recirculating local runoff to the head of the field
	Reduced tillage	Field	Can increase water infiltration into soil
Deep Percolation	Conversions to sprinkler, drip, or subsurface irrigation	Field	Can reduce the amount of water applied to a field that is not consumptively used
	Reduced tillage	Field	Can increase water holding capacity of soil in crop root zone

Irrigation return flows, either from the field or delivery scale, play an important role in basin scale water management (Bekkam et al., 2013). Traditional definitions for irrigation design have considered the water diverted, but not consumptively used, as wasted or lost. Many water conservation measures reduce return flows to rivers because they reduce the system losses that are generated from inefficient practices. If the conserved water is consumptively used in the area in which it is conserved, water conservation measures by upstream water users can reduce return flow that reduces the water available for downstream users (Willardson, 1985; Venn et al., 2004; Simons et al., 2015). Water managers need to know more about where and how return flows are used to better manage their resources (Simons et al., 2017).

The scale and geology of a river basin can affect how return flows are utilized. The hydrology of a basin or its subbasins influences of the impacts of water conservation measures (Giordano et al., 2017). Chen et al. (2018) simulated water conservation measures under different field scales ranging from a single field (317 ha) to an entire river basin (100800 ha). The water conservation measures simulated included canal lining and changing the irrigation method. Chen et al. (2018) found that more water was recycled and diverted by multiple users as the scale increased, indicating that increasing the magnitude of water users leads to more return flow being used and that return flow is a critical source of water within a basin. Molden et al. (2001) defined six water management zones to categorize water management strategies. One particular zone, the natural recapture zone, is defined as self-conserving because the drainage returns to the distribution system. Water conservation improvements in the natural recapture zones that recaptured irrigation scale and field scale changes result in little real water savings and may only be beneficial in very localized cases (Molden, et al., 2001).

Many of the technologies used for water conservation measures have multiple benefits that are not solely related to conserving water. The following are examples of water conservation measures used for other benefits: canal lining and piping used to eliminate animal burrowing and thus increasing canal safety, converting from flood to sprinkler irrigation to reduce labor, canal lining and piping to reduce aquatic species and herbicide use to eradicate those species, converting to drip irrigation to add more precision for irrigation and fertigation for high-value crops, and adding remote control (e.g., SCADA) and automated turnouts to reduce irrigation district labor. Water managers should consider the full range of benefits and effects when implementing these technologies.

The effects of water conservation measures on basin-scale management need to be better understood and quantified since some users can benefit and some can be negatively affected by the same implementation activity (Willardson, 1985; Perry et al., 2017; Chen et al., 2018). Water conservation measures can reduce surface and subsurface return flows. Simulating a range of return flow reductions is a way to explore the potential net effects of water conservation measures, without having to simulate how specific conservation measures might alter return flows. Rule-based simulation modeling helps track return flows (McMahon and Farmer, 2009). A basin-wide accounting model that tracks river flow, diversions, reservoirs, and use of return flows spatially and temporally is needed to evaluate the basin-wide impacts of various local water conservations efforts (Simons et al., 2015; McMahon and Farmer, 2009). An accounting model allows for the tracking of water right priority in water right allocation under the prior appropriation doctrine. Methods to quantify return flows that include spatiotemporal tracking need to be established to provide information to water managers and water policy makers (Simons et al., 2015). These methods would support further study into how water conservation measures at field and irrigation delivery scales influence water availability in the basin.

The objective of this work was to develop a method to simulate changes in return flows, which represent the implementation of water conservation measures, in an existing model and quantify the effects on system reservoir storage, delivery shortage, and natural flow. Natural flow is the water in the river that can be diverted by natural flow water rights and excludes reservoir water that is released from storage specifically for diversions. The Boise River Basin was used as a case-study river basin because it has multiple canals, an extensive return flow system, and ample historical data.

Methods

A RiverWare surface water model of the Boise River Basin system originally developed by Reclamation (Appendix A) was used to simulate the basin-scale effects of reductions in return flow due to increasing installation of water conservation measures. The return flows within the system were incrementally scaled from current conditions to no return flow (Appendix B). Sensitivity of storage in the basin's reservoirs, irrigation shortages, and Boise River flow were assessed.

<u>Boise River Basin Site Description</u>

The Boise River Basin is located in southwest Idaho. The Boise River is fed by rain and snow in the mountains and flows west to the urban and agricultural area of the Treasure Valley. The Boise City-Nampa, Idaho metropolitan statistical area has a population approaching 800,000 and about 224,000 acres of irrigated agriculture (Reclamation, 2014). The Boise River Basin consists of three reservoirs, one off-stream storage facility, approximately 1,170 miles of canals that deliver about 1.5 million acre-feet of water a year for agricultural irrigation, and major water gages along the river. The reservoirs, with a total available storage of 949,000 acre-feet, are operated to provide irrigation water, flood control, recreation, and power generation (Reclamation, 2014). The Boise River terminates where it flows into the Snake River. Return flows from the diversions return to the river at various points along the river via a drain system (Figure 3.2). A shallow aquifer underlying the Treasure Valley is recharged by precipitation, canal seepage, and deep percolation from irrigated fields with canal seepage being largest single source (Urban, 2004).

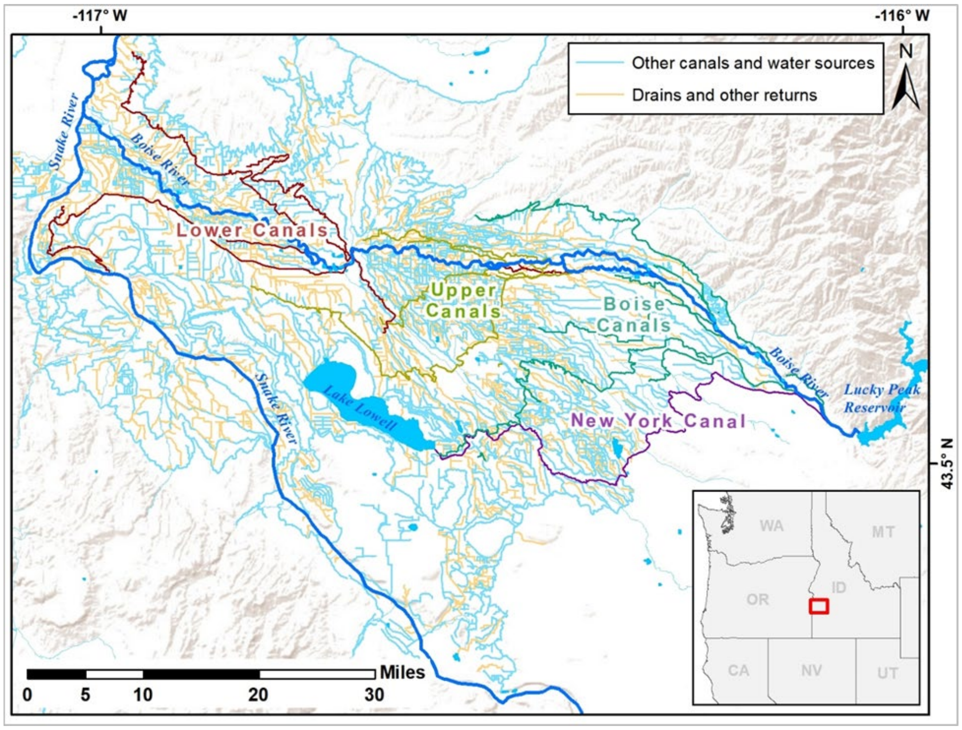

Figure 3. 3. Map of Boise River System with aggregated canal group: New York Canal (purple), Boise Canals (blue-green), Upper Canals (yellow-green), and Lower Canals (red).

The irrigation system altered the natural hydrology within the Boise River system. The irrigation practices changed the way and locations that water drained and infiltrated. The shallow aquifer is recharged by irrigation water runoff and canal seepage that raised the water table (Urban, 2004). Field irrigation methods in the Treasure Valley include gravity flood irrigation, sprinkler systems, and drip irrigation. Typical water conservation projects (e.g., replacing flood with sprinkler or drip irrigation and canal lining) may change how the river management system needs to be operated. The amount of runoff and deep percolation depends on the type of irrigation, management, and soil conditions which them impact the groundwater recharge and river return flows.

Boise River Basin Modeling

The U.S. Bureau of Reclamation developed a RiverWare accounting model of the Boise River system to simulate the operations of the Boise Project support the analysis of changes to the Boise Project (Appendix A). RiverWare (Zagona et al., 2001) is a river and reservoir simulation platform that uses a network of objects representing physical conditions and constraints along with a series of user-written rules to represent operation policies. The model distributes water through the system using RiverWare's defined SolveWaterRights function based on natural flow priorities following the prior appropriation doctrine, available natural flow, and the irrigation request. Each reservoir has a storage account for water users. Storage accounts fill to varying degrees based on runoff conditions. The model uses water from a storage account to attempt to meet the irrigation diversion request if there is not enough natural flow available. The model also approximates the basin's rental pool operation by assuming excess reservoir storage could be rented by water users. If a water user's irrigation diversion request is not met with natural flow and storage accounts, the water user object requests rental pool water, as it is assumed that a water user would do so in practice to avoid a physical shortage. The model releases rental pool water to the water user if there is excess storage water available. In practice, water users must buy rental pool water. The model assumes a water user will always use rental pool water if it is available. In this analysis, rental pool water was included in the storage delivery.

Figure 3.3 is a schematic of the model showing the three reservoirs (Anderson Ranch, Arrowrock, and Lucky Peak) and three river gages (Glenwood, Middleton, and Parma) in the river basin connected with river reaches and showing water user objects.

The three river reaches below the reservoir system (LuckyToGlenwood, GlenwoodToMiddleton, and MiddletonToParma) have surface gains from small streams, gains from groundwater return flows, losses to ground water, and diversions for irrigation. In Figure 3.3, the black lines from the river reaches to the water user objects represent diversions and the red lines represent return flows. The 47 physical points of diversion were combined to 15 points of diversion in the model based on common lands and diversion location.

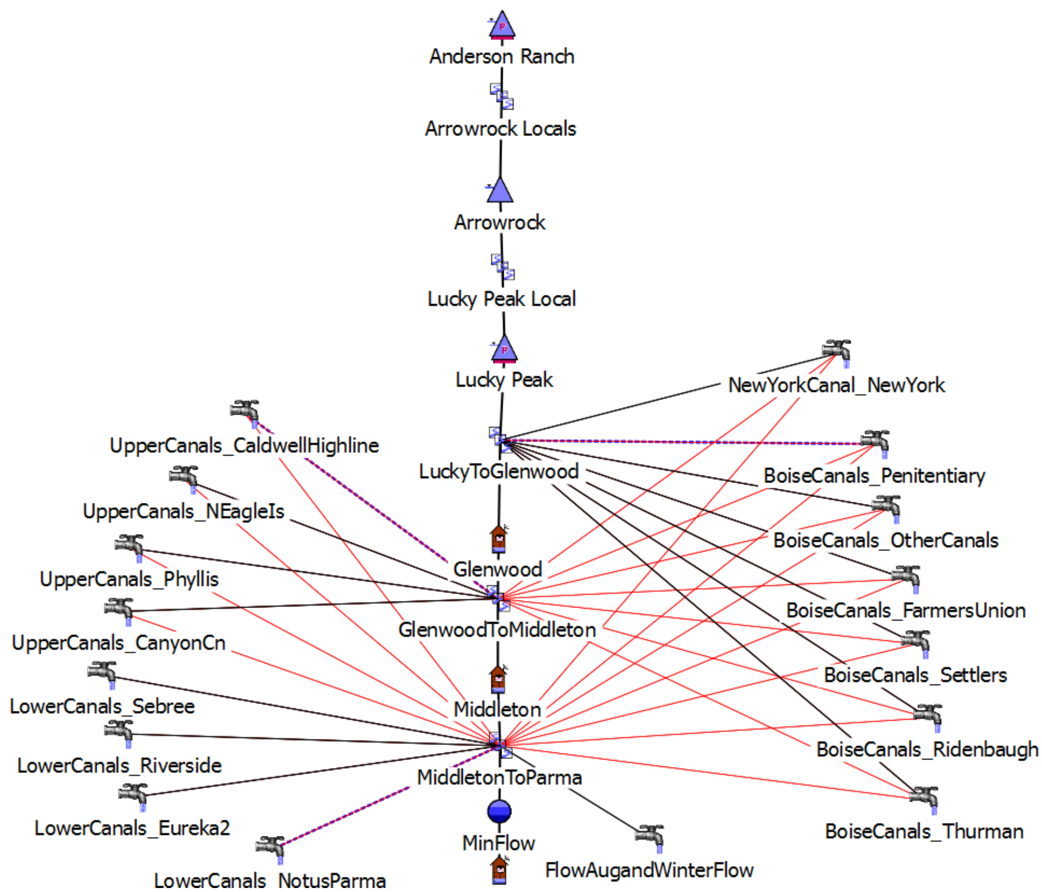

Figure 3. 4. Diagram of Boise River System simulation. Black and red lines represent diversions and return flows, respectively (Appendix A).

This study used a regulation model and an unregulation model developed by

Reclamation (Appendix A). The models have the same objects with differing input data, object methods, and operation rules. The unregulation model calculated local inflows to the reservoirs and reaches to represent natural flows in the basin. The unregulation model, which was adjusted for return flows, used measured data and a mass balance approach to calculate the local reach gains and losses. Those calculated local reach gains and losses are inputs to the regulation model. The regulation model distributes water based on water rights accounting and represents the current physical system following operation rules. The unregulation model calculated reach gains for the period 1929 through 2009. The regulation model used the unregulated gains and losses to simulate 28 years on a daily timestep. Further sources of methods and data for the development of the models are detailed in Appendix A.

Each of the 15 canal groups' diversions have multiple individual water rights with the individual water rights having assigned priority dates and request flow rates. To meet irrigation water requests, the model uses natural flow first then reservoir storage to supplement the natural flow. RiverWare uses the input priority to allocate water under the appropriated water right system such that the account with the oldest date gets water before more junior accounts. The model attempts to meet any irrigation diversion request exceeding the available natural flow by using the water user's available storage. Analysis of the model aggregated the 15 canal groups based on geography: New York Canal, Boise Canals, Upper Canals, and Lower Canals (Figure 3.4).

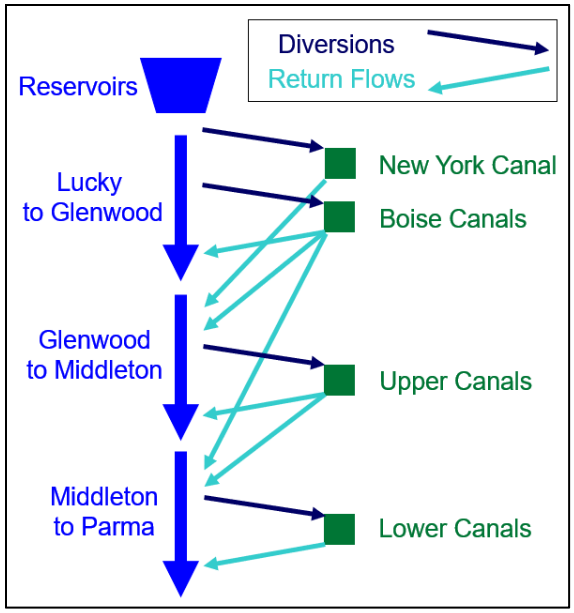

Figure 3. 5. Aggregated canal group diversions and return flow locations for model analysis (Appendix B).

The calculation for return flow was dependent on three types of inputs from groundwater analysis. The first input is the portion of diverted water that is not consumed by crops, which is assigned the Fractional Return Flow in RiverWare. The Fractional Return Flow was calculated in a previous Reclamation study of the groundwater water budget in the Boise River Basin for each diversion area (Reclamation, 2008). The Fractional Return Flow must be between 0 and 1. The second groundwater input is the fraction of the return flow that returns to a particular reach, which is the Return Flow Proportion parameter slot in RiverWare. There can be multiple Return Flow Proportions where return flows are spread over multiple river reaches and can return as groundwater or surface water. The Return Flow Proportion is assumed to return to the river via overland flow and the shallow aquifer (Reclamation, 2012). The total of all Return Flow Proportion for a water user adds up to 1. The third input is the response function, which is the rate at which water returns to the river from an irrigated area. Response functions are linear by their definition due to their governing equations (Johnson and Cosgrove, 1998). A time-dependent MODFLOW model was used to develop the response functions relating surface water and groundwater (Reclamation, 2012). Each irrigated area has a response function for any river reach to which it returns. The response function is an input for each RiverWare water user object in the Multi Return Lag Coeffs slot, which relates to the timing of return flows. The response function for each aggregated canal group diversion does not change over time and does not changed based on flow volume.

In mass balance terms, the return flow is a combination of canal spill, infiltration, field runoff, and deep percolation. The return flow to the river from each aggregated canal group is calculated in the simulation based on the groundwater information inputs and the operational rules (Appendix A). Appendix A provides a calculation example. The water user BoiseCanals_Penitentiary has a Fractional Return Flow of 0.1, which means that 10 percent of the water diverted returns to the river via overland flow or via the shallow aquifer. All the return flow for BoiseCanals_Penitentiary returns to the Boise River, with Return Flow Proportions of 33 percent returns for overland flow and 67 percent returns for the shallow aquifer. The Multi Return Lag Coeffs then controls when return flows return to the river. For BoiseCanals_Penitentiary, it takes about 60 days for all the water to return. The Boise River system has unique geographic and geologic characteristics such that return flows occur either as surface flow or shallow-aquifer (subsurface) flow. Once return flow returned to the river, it becomes natural flow.

Reclamation (Appendix B) scaled return flows to examine the sensitivity in the Boise Project to changes in return flow. Return flows were reduced by scaling return flows from 1.0 to 0.0 in 0.2 intervals. A scaling factor of 1.0 represented current conditions while a scaling factor of 0 represented no return flow. The return flow scaling of 0 is a boundary of the system more than a physical reality. Practically, it would be very difficult to have a system with absolutely no return flow (e.g. 100% water delivery and use efficiency). The Fractional Return Flow for each water user was multiplied by the scaling factor to reduce the return flows. Due to the model assumptions and capabilities, reductions in return flow from field and irrigation-district scale could not be separated.

The model was run separately for each of the six scaled return flows, with the scaled Fractional Return Flow values held constant throughout each model run and applied to each diversion. The constant scaling factor allowed for a sensitivity analysis on how a general reduction in return flow affects the system. Importantly, return flow volumes still varied over time since they were adjusted daily based on diversion flow rates and the groundwater and surface water routing function time lags.

The diversion requests were held constant for the six scenarios (Table 3.3). Reducing the return flow fraction effectively increased the consumptive use of water diverted by a canal. Increased consumptive use represents expanded irrigation acreage by an irrigation district, meeting irrigation requests that were shortages in prior seasons, increased cropping intensity, or increased crop water demand at the farm level.

Table 3. 3. Annual diversion and fractional return flow for the aggregated canal group and diversion area used in the model.

Aggregated Canal Group	Diversion Area	Annual Diversion (AF)	Fractional Return Flow
New York	New York	751,900	0.2
Boise Canals	Farmers Union	59,400	0.46
	Other Canals	17,400	0.4
	Penitentiary	1,700	0.1
	Ridenbaugh	155,200	0.54
	Settlers	42,500	0.41
	Thurman	7,600	0.7

Upper Canals	Phyllis	127,100	0.34
	North Eagle Island[1]	22,200	0.99
	Canyon County[1]	22,200	0.99
	Caldwell Highline	13,800	0.34
Lower Canals	Sebree	92,400	0.4
	Riverside	85,400	0.34
	NotusParma	54,800	0.56
	Eureka2[1]	22,200	0.99

[1]Return flow exceeds the irrigation diversion requests in these diversion areas. These areas capture other groundwater flows that are used and returned. That groundwater is not included in the model.

Uncertainty is inherent in modeling. First, this model is based on historical conditions for inputs such as land use, hydrology, and irrigation diversions. Changes such as urbanization and precipitation patterns could affect these inputs. Second, there is an assumed continuous connection of the return flow and the river. It is possible that reductions in aquifer recharge could cause the water table to drop below the river. This disconnection would mean that no return flow could reach the river and water could seep from the river to the aquifer. Third, the response functions were based on a model of a confined aquifer model in equilibrium, whereas the actual shallow aquifer system is unconfined and not static. Fourth, return flows in the model were scaled by the same fraction for all the different diversions. A more realistic scenario is that return flow would change throughout the system at different times depending on the priorities, funding, and resources of individual water users or irrigation districts.

The uncertainties affect the natural flow in the river, reservoir storage, and irrigation demand shortages. The model uses historical hydrology that may change into the future. Evaporation, Aquatic EvapoTranspiration, Surface Inflow, Field Runoff, and Spill were not directly modeled, but were represented in the interactions between Diverted Water, Delivery Water, and resulting return flow. The groundwater terms of

Subsurface Flow, Infiltration, and Deep Percolation have uncertainty due to how the data was represented.

Results

The percentage of the diversion request met by natural flow in the river declined for each aggregated canal group as the return flow scale stepped from current conditions to no return flow (Figure 3.5). As the return flow scaling factor was reduced, the irrigation diversion shortage and reservoir storage withdrawals increased.

The Lower Canals had the most changes in how the diversion request was met (Figure 3.5). From current conditions to no return flow, the use of natural flow to meet the irrigation request decreased more sharply than other canals. Lower Canals' percent of water from reservoir storage increased nearly five times from 6.9 to 34 percent, while shortages nearly tripled from 3.8 to 11 percent, from current conditions to no return flow. Lower Canals use more reservoir storage to help meet their irrigation request as the return flow decreases.

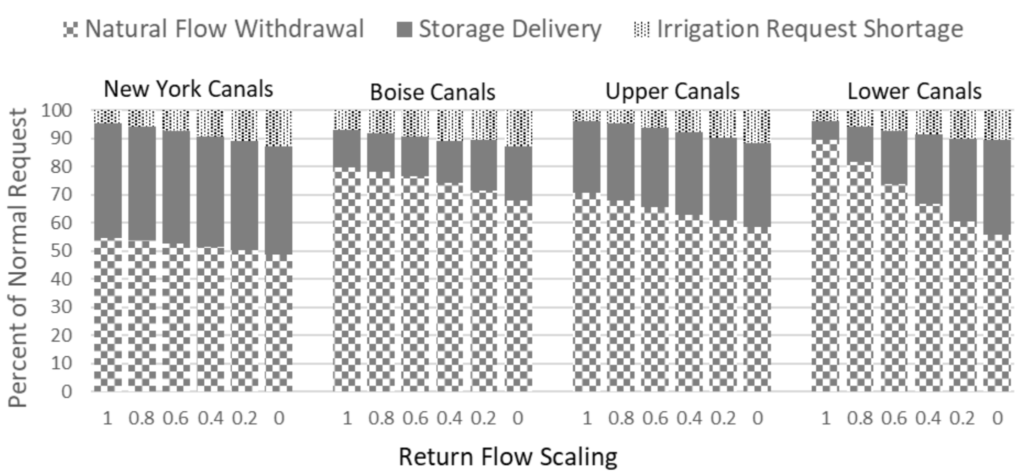

Figure 3. 6: 28-year average percentage of the normal annual diversion request satisfied by natural flow, reservoir storage releases, or shortage. Diversion groups are sorted left-to-right from higher to lower along the river, with numbers on the x-axis indicating the return flow scaling factor.

As the return flows are reduced, more water was released from reservoir storage to help meet irrigation demand and reservoir storage declines (Figure 3.6). System reservoir storage with each return fraction scaling follows a similar trend through the water year: increasing November to February due to minimum releases for stream flow maintenance, decreasing February and March for flood control drawdowns to prepare for the March to July runoff season, peaking in July, and reducing from July to October corresponding to irrigation season. When the return flow scale decreases, the system reservoir storage also decreases because irrigation requests must rely on increased reservoir releases.

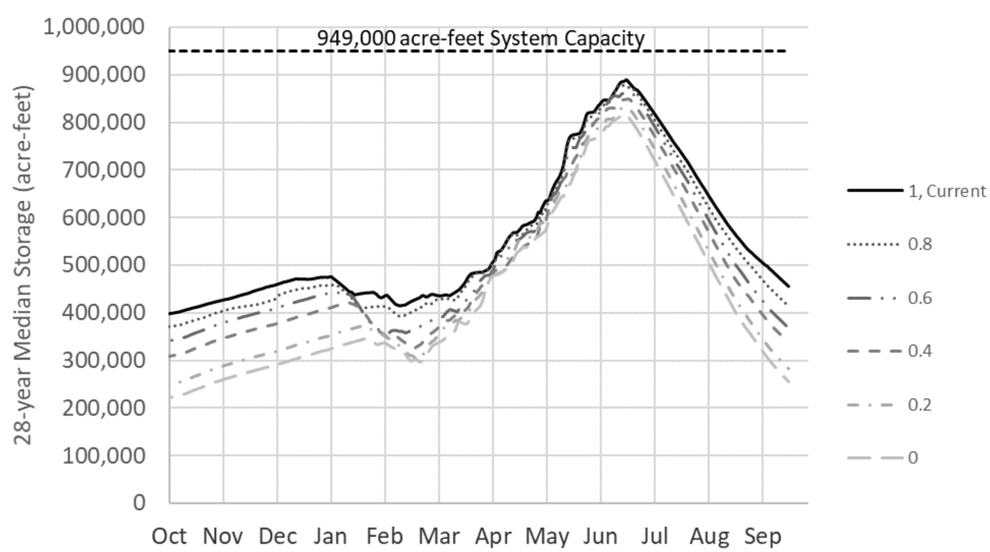

Figure 3. 7. The 28-year median daily combined Boise Project storage of all three reservoirs showing how storage changes due to return flow reductions.

Irrigation shortages are dependent on the type of water year in the basin (Figure 3.7). The total system shortages increase as the return flow scaling goes from 1.0 to 0. In the driest year of the simulation, the total system shortages range from 340 KAF with current return flow conditions (Figure 3.7, top) to 690 KAF with no return flow (Figure

3.7, bottom). For dry to moderate years, the shortages more than double from current conditions to no return flow. The percentage of years where the total shortage was less than 5 percent of the total irrigation demand (74 KAF) for current conditions and no return flows was 71 and 50 percent, respectively. As the return flow was reduced, shortages increased in all but the wettest years of the simulation.

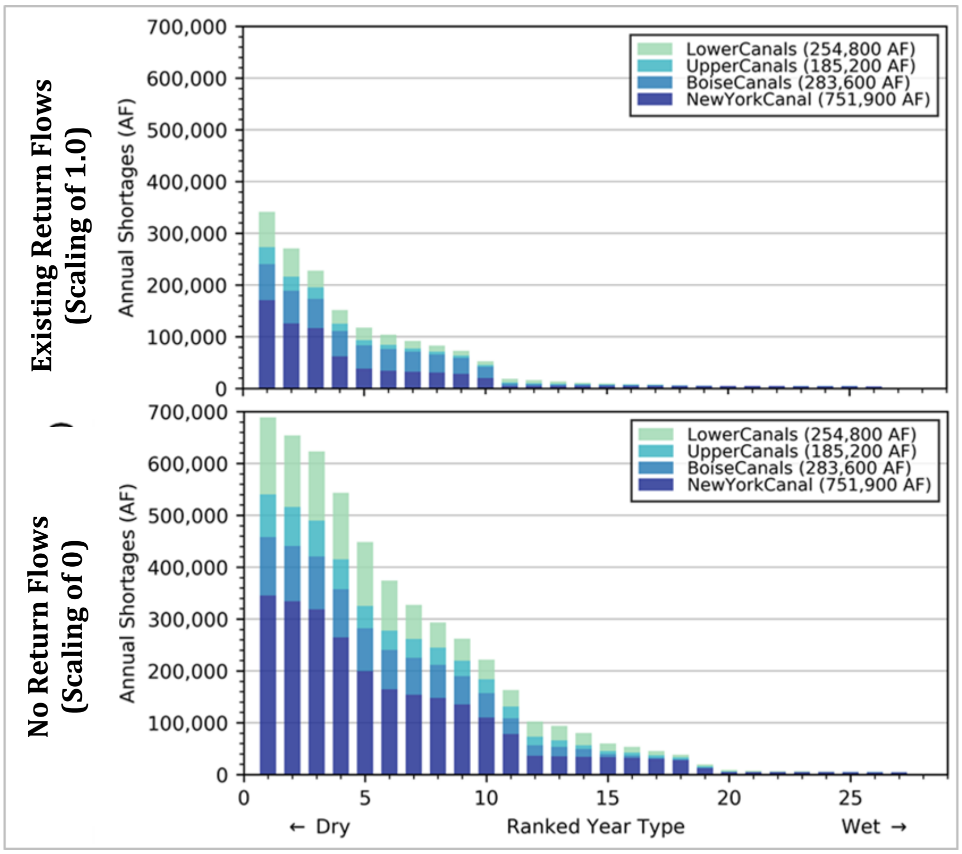

Figure 3. 8. Comparison of annual shortages from dry to wet years for scenarios for current conditions (top) and when the return flow was scaled to 0 (no return flow, bottom) (Appendix B).

The Boise River flow at the most down-stream gaging point, the Parma gage, decreased as the return flows decreased (Figure 3.8). The highest flows in the river occur during the spring for all return flow scaling fractions, which coincides with the routing of spring snowmelt through the system and flood control releases. Flows drop significantly after mid-June due when system flow augmentation for Biological Opinion requirements ceases and the system is no longer in flood control. Post-flow augmentation, the average flow during the height of irrigation season, from June 24th to September 30th, for the return flow scaling factors of 1.0, 0.8, 0.6, 0.4, 0.2, and 0.0 was 327, 227, 157, 102, 50.3, and 0 cfs, respectively.

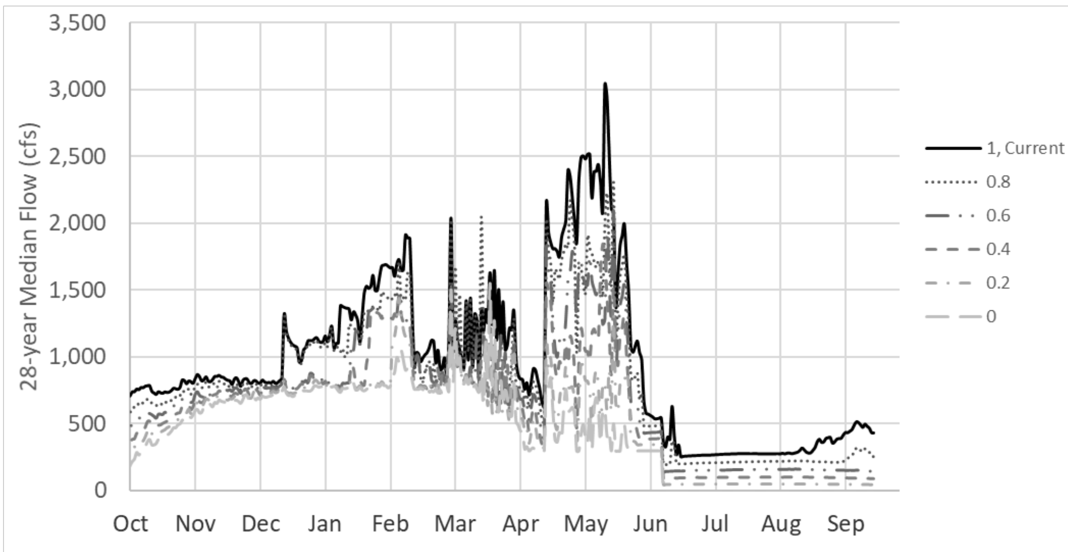

Figure 3. 9. The 28-year median daily flow rate at the Parma gage, which is the most downstream gage on the Boise River system, for each return flow scaling fraction scenario.

Discussion

The impacts of water conservation measures can extend beyond their immediate location of implementation. Reductions in the return flow were used to simulate water conservation measures within the Boise River Basin. When comparing current conditions to no return flow, the use of reservoir storage withdrawals increased as much as 388 percent, and irrigation shortages increased as much as 181 percent in the basin with the largest increases occurring during dry years. The percentage of irrigation diversion request met by natural flow reduced 20 percent and by reservoir storage increased 110 percent throughout the basin with no return flow. As more water conservation measures were incorporated via reducing return flows, irrigation delivery shortages increased for all irrigation areas. With no return flow, the irrigation delivery shortage increased by an average of 163 percent. Of the 949 KAF of system reservoir storage capacity, the amount of storage in the system reservoirs at the end of the water year ranged from 455 KAF with current conditions to 255 KAF for no return flow.

Any downstream water rights holders with natural flow senior rights limit natural flow available for other water users throughout the system. In the Boise River Basin, some downstream water users have senior water rights that get their full diversion request before other users. This caused the small decreases in natural flow being used by New York Canal even though it is the most upstream diversion area.

Due to their geographic location of being the most downstream, Lower Canals are the most dependent on return flows and most affected by decreased return flows. The Lower Canals relied more on storage and less on natural flow as return flows were reduced. Downstream users increased their reservoir storage withdrawals the most to attempt to meet irrigation demands, with a five-fold increase in the percent of the reservoir storage used to meet the irrigation delivery request. Reductions in return flow throughout the Boise River Basin had the most effect on downstream water users. In the Boise River system, water users farther downstream with a dependency on return flow had more irrigation demand shortages even with using reservoir storage. Reservoir storage cannot eliminate all irrigation demand shortages because there is not enough storage available.

The effect of reduced return flow is dependent on the type of water year. When simulating water conservation measures by reducing return flows, dry years have more irrigation shortages while wetter years have little or no change in irrigation shortage. In the driest year of the simulation, the total system shortage was 340 KAF with current conditions and 690 KAF with no return flow. The reduced return flows representing water conservation measure implementation did not reduce the irrigation shortage in drier years. Shortages increased for water users throughout the system in drier years because there is less reservoir storage available. Requests for reservoir storage water may decrease total reservoir storage and increase water shortages in drier and average years. Increased reservoir storage use may reduce carry-over, and the increased stored water use in one dry year may ultimately increase to shortages in the next.

The flow at the downstream end of the Boise Project is most affected by implementation of water conservation measures. As the scaling factor decreased and return flows decreased, the flow at the Parma gage decreased for all times of the year. Much of the water at the downstream end is provided by return flows, and as return flows decline, additional stored water may need to be released to maintain flow in downstream reaches.

Altering the return flows to simulate water conservation measures affects multiple mass balance terms within a river basin. Installing water conservation measures changes the amount of water for each mass balance term but the amount of water in the basin does not change. With no return flow, the interactions of mass balance are simplified as some terms are eliminated. The surface and subsurface inflows can be reduced or eliminated (return flow scaling factor of 0) by the simultaneous reduction or elimination of infiltration and spill terms.

This work builds on previous work that qualitatively identifies the concerns of implementing water conservation measures at local levels without considering basin-wide effects. Molden et al. (2001) recommended that systems with a natural recapture zone, of which Boise is, should leave canals unlined because the water that infiltrates from earthen canal channels returns to the river to be used by other canals. Simons et al. (2015) summarized the processes of water reuse in river basins but does not quantify how that reuse influences how storage, natural flow, and irrigation demands were met with return flow use. This study showed that when return flows are reduced or eliminated that water managers will require additional management strategies to balance natural flow, use of storage withdrawals, and shortages.

This study did have some limitations in addition to model uncertainty as described in the Methods section. It did not explicitly simulate how specific types and amounts of water conservation actions result in different fractional reductions in return flow. Modeling these relationships would require more specific information on specific conservation actions and simulating interactions with groundwater. Groundwater interactions between return flow, water table, and the river were not analyzed. As a case study, the Boise River Basin has unique characteristics (defined as natural recapture in Molden et al. (2001)). These results will not be the same for all basins, but the modeling methods and metrics described and presented are transferrable to other basins. Measurements of and calibration to runoff and spill mass balance terms could reduce uncertainty in supporting groundwater modeling in the modeling and methods.

The long-term effects of reduced groundwater recharge on groundwater dynamics should be explored when considering water conservation improvements. This work could include coupled surface and ground water modeling or in situ work such as tracking the water table with monitoring wells over time. The extended modeling would address uncertainty related to the response functions and return fractions. Reductions in aquifer recharge by reducing infiltration of diverted water or deep percolation could alter groundwater flow gradients, transit times, flow directions, and aquifer-river connectivity.

Further analysis regarding how system operations could be affected by water conservation measures should be conducted. In this study, the amount of water requested for diversion diverted was the same each year of the simulation. Investigating management alternatives when applying water conservation measures including increasing reservoir storage, conducting aquifer recharge, lengthening the irrigation season though storage use, or changing operations would increase understanding of what water managers should consider when deciding to implement water conservation measures. While this study simulated increased consumptive use with increased water conservation, further study should investigate the effects of other changes in consumptive use. As more water conservation projects take place, it is beneficial to consider impacts beyond short-term, hyper-localized affects.

Conclusions

Water conservation measures can allow water purveyors to increase field deliveries, extend their irrigation season, and increase the service area (to water land under its water right that is not currently irrigated or to expand serviced acreage if allowed under the water right) because more water is available to use. Water conservation such as irrigation method conversion (e.g., flood to drip irrigation) and canal lining may increase the amount of water available for consumptive use locally, but those changes can affect other users and basin efficiency in unintended and complex ways. The contribution of this study is to quantify the intensity of effects of water conservation at a basin-wide scale. This study proposes a method of how to use a simulation model to determine how water conservation measures affect irrigation demands shortages, system reservoir storage, and river flow at the end of the system.

The trend of these results (less flow at the bottom of the river, downstream users using reservoir storage to replace water previously supplied by return flows and thus changes in reservoir storage) was expected at the outset of the study based on a review of previous research and anecdotal evidence. Water purveyors and farmers have many reasons for installing water conservation measures. However, this study demonstrated how these changes can be quantified within a complex river basin with well-documented modeling efforts. We applied an existing model simulating real physical structures and operations to quantify the effects of reduced return flows that may be realized as water conservation measures are implemented.

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CHAPTER 4

EVALUATION OF STORING CONSERVED WATER TO INCREASE RIVER BASIN WATER MANAGEMENT FLEXIBILITY

Abstract

A river basin's reservoir storage, delivery requests, river flows, conservation actions, and return flows are all connected. The installation of water conservation measures typically leads to increased consumptive use because the conserved water is used to increase irrigation rather than returning or leaving the water in the stream. Allowing the storage of conserved water could increase river basin management flexibility to meet multiple demand, operation, and ecosystem needs. This study simulated altering water management practices to store conserved water by reducing return flows from irrigated agriculture. The simulation of reducing return flows indirectly represented the implementation of water conservation measures. The basin metrics of system storage, natural river flow, and irrigation shortages were quantified, after which an analysis was made of how those factors affect river basin management. A daily model of the Boise River Basin was run for 28 years with two types of irrigation diversion requests (full historic diversion request and reduced diversion request) and reduced return flow (stepped from current conditions to no return flow). Compared to current conditions, the full historic diversion represented an increase in consumptive use while reducing return flows and the reduced diversion request represented a constant consumptive use while reducing return flows. The reduced diversion request represented a reduction in demand equal to the amount of water retained by reducing return flows. The model allowed that conserved water to be stored in the reservoir system because less water was

released from the reservoirs for irrigation. Allowing for increased reservoir storage reduced shortages in dry years from current conditions due to increased carry-over. Reservoir storage was highest with a reduced diversion request and no return flow and lowest with a full diversion request and no return flow. Dry years had the largest range in total reservoir storage volume. Flood control, intra-district operations, inter-district operations, recreation, and ecosystems can be affected by the implementation of water conservation measures. Changing reservoir storage practices to store conserved water adds management flexibility in a river basin. The management of conserved water is critical to the ultimate impacts of water conservation measures. A range or combination of the irrigation diversion requests, and thus consumptive use, could be used by water managers to meet their objectives. Future work should consider the impacts of how changing return flows affects groundwater sources, irrigation demands altered by future demands and varying hydrologic conditions, and economic implications of those changes.

Subject Headings: water efficiency, water conservation, return flows, basin management, water management, consumptive use, irrigation efficiency

Introduction

Billions of dollars of public and private money have been spent on installing water conservation technologies in agriculture (Grafton et al., 2018). Water conservation measures typically occur at two levels: field (e.g., converting surface irrigation to sprinkler or drip irrigation, reduced tillage, and recycling tailwater) and delivery (e.g., canal operation automation and earthen canal lining and piping). Researchers and water management practitioners are becoming more interested in and concerned with water efficiency at watershed scales and how “saving” water in one location affects another area. Most of the technologies do not change the consumptive use of the water diverted but instead change the location or timing of the consumptive use such as meeting irrigation shortages, increased crop water demand, or increasing irrigated acreage.

Efficiency terms related to water use can be difficult to compare without further clarifying the spatial and temporal scale (Burt et al., 1997; Jensen, 2007; Grafton et al., 2018; Perry et al., 2009). Measures of irrigation efficiency usually only consider the field or delivery scale and ignore the impacts of return flows (Cai, 2003; Scott et al., 2014). Increases in field-scale irrigation efficiency often do not increase water supplies at basin scales (Willardson, 1985; Chen et al., 2018; Molden et al., 2001, Clemmens et al., 2008). For example, lining a canal, which could increase the efficiency at an irrigation district scale by reducing leakage from the canal to groundwater, may reduce aquifer recharge, increase groundwater depletion, and/or increase reservoir storage withdrawals for downstream users whose demands were previously met by the canal leakage return flow. Increases in classical efficiency may not lead to water savings on the basin scale but instead change flow paths, diversion points, and water use locations (Molden et al., 2001; Lankford, 2012; Scott et al., 2014). Basin-scale efficiency is affected by multiple factors, including local water use efficiency, return flows, and water reuse (Cai, 2003). The installation of water conservation measures at local levels with no change in basin-scale management could lead to increased irrigation shortages in some parts of the basin (Chapter 3). Irrigation efficiency and reservoir operation should be considered together to inform water management at the basin scale (Song et al., 2016; Karamouz and Araghinejad, 2008). To better represent how river basins operate, water rights and accounting should be included in analyzing the effects of water conservation (Grafton et al., 2018; Reclamation, 2002).

Downstream water users are more susceptible to changes in return flow (Scott et al., 2014; Willardson, 1985; Simons et al., 2015; Chapter 3). Within a basin, when an irrigation district lines their canals, other districts often do the same since they are no longer getting return flows and do not want to “lose” any water to seepage. Qureshi et al. (2010) found that local increases in efficiency at upstream locations in a basin may not increase basin efficiency if it reduces water available to downstream locations. Work conducted in Chapter 3 found that reduced return flows increased the demand for stored water and reduced the reliability of the water supply, resulting in increased shortages and that water users increased their use of storage to help meet irrigation requests.

Adaptability and flexibility in how conserved water can be stored and withdrawn later is needed to support the resiliency of water supplies. Irrigated agriculture needs to be adaptable to address issues such as wet and dry years, changing cultural practices, cropping changes due to grower preferences and market drivers, and changing values. One way that irrigated agriculture can adapt is increasing the amount of water stored in the reservoir or aquifer systems (Scott et al., 2014).

Water users and irrigation districts have interest in storing water from water conservation measures to use during drier times. Anecdotal evidence suggest that this is being done at the irrigation district level to “shore up supplies.” This additional flexibility is a common reason to justify funding for water conservation measures to reduce later shortages. In some systems, water users do not get their full allocation during drought due to a low water year. In some systems, irrigation districts may reduce diversions and retain their water rights by increasing storage in wet years to help meet demands in dry years

(Ender-Wada et al., 2009). The United States Bureau of Reclamation developed an Intentionally Created Surplus program to add management adaptability of the lower Colorado River as part of the Interim Guidelines for the Operation of Lake Powell and Lake Mead in 2007. The program encourages entities to take various conservation actions to augment reservoir storage in the lower Colorado River basin to allow for flexibility during drought periods (Reclamation, 2007).

Reservoir storage, water conservation effects, return flows water rights need to be examined together to better capture the interconnectedness within a basin. The physical components and management policies within a basin will influence these relationships. Storing conserved water from water conservation measures can affects mass balance terms throughout a basin differently (Figure 4.1). Water conservation measures would directly reduce canal spill and infiltration. This could be modeled by changing return flows for irrigation areas and quantifying how reservoir storage and river flows are affected. Most of the research on expanding the understanding of efficiency interdependency in a basin is qualitative (e.g., Willardson, 1985; Molden et al., 2001; Grafton et al, 2018) with a few quantitative studies beginning to emerge (Chapter 3; Chen et al., 2018). Quantification of how storing conserved water affects reservoir storage and meeting irrigation demands is needed to help water managers further understand how implementing water conservation will affect both local and basin operations. Changing reservoir storage accounts and withdrawal operations will affect irrigation shortages and river flow.

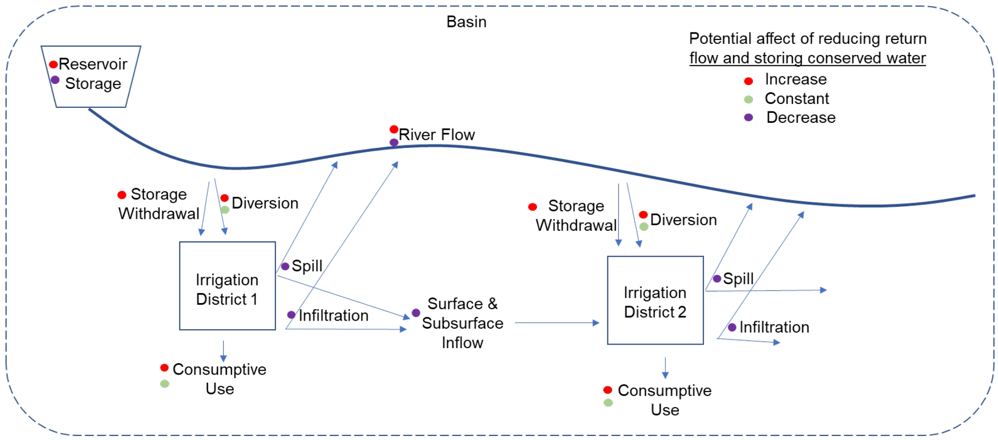

Figure 4. 1. Diagram of surface water interactions within a basin.

The objective of this study was to evaluate the effects of reducing irrigation return flows and storing that water for future use. The reduction of return flows simulated the implementation of water conservation measures. The historic irrigation diversion request was also reduced, and the difference of water in diversion was allowed to be stored. The first step was to quantify how changes in irrigation diversions and reservoir storage of water retained by water conservation measures affect system storage, natural river flow, and irrigation delivery in an existing river basin. Second, results were used to make recommendations for flood control, irrigation, recreation, and ecosystem management. This project builds on previous examination of return flows on river flow, reservoir storage, and irrigation shortages.

Methods

Boise River Basin Site Description

The Boise River Basin is located in southwest Idaho. The Boise River Basin consists of three reservoirs, one off-stream storage facility, approximately 1,170 miles of canals that deliver about 1.5 million acre-feet of water a year, and major water gages along the river (Figure 4.2). The reservoirs, with a total available storage of 949,000 acre-feet, are operated to provide irrigation water, flood control, recreation, and power generation to the Treasure Valley (Reclamation, 2014). Return flows from the diversions return to the river at various points along the river via a system of drains. The irrigation canals and farms currently have a wide variety of water conservation measures, such as canal lining or drip irrigation. A shallow aquifer underlying the Treasure Valley is recharged by precipitation, canal seepage, and deep percolation from irrigated fields with canal seepage being the largest single source (Urban, 2004).

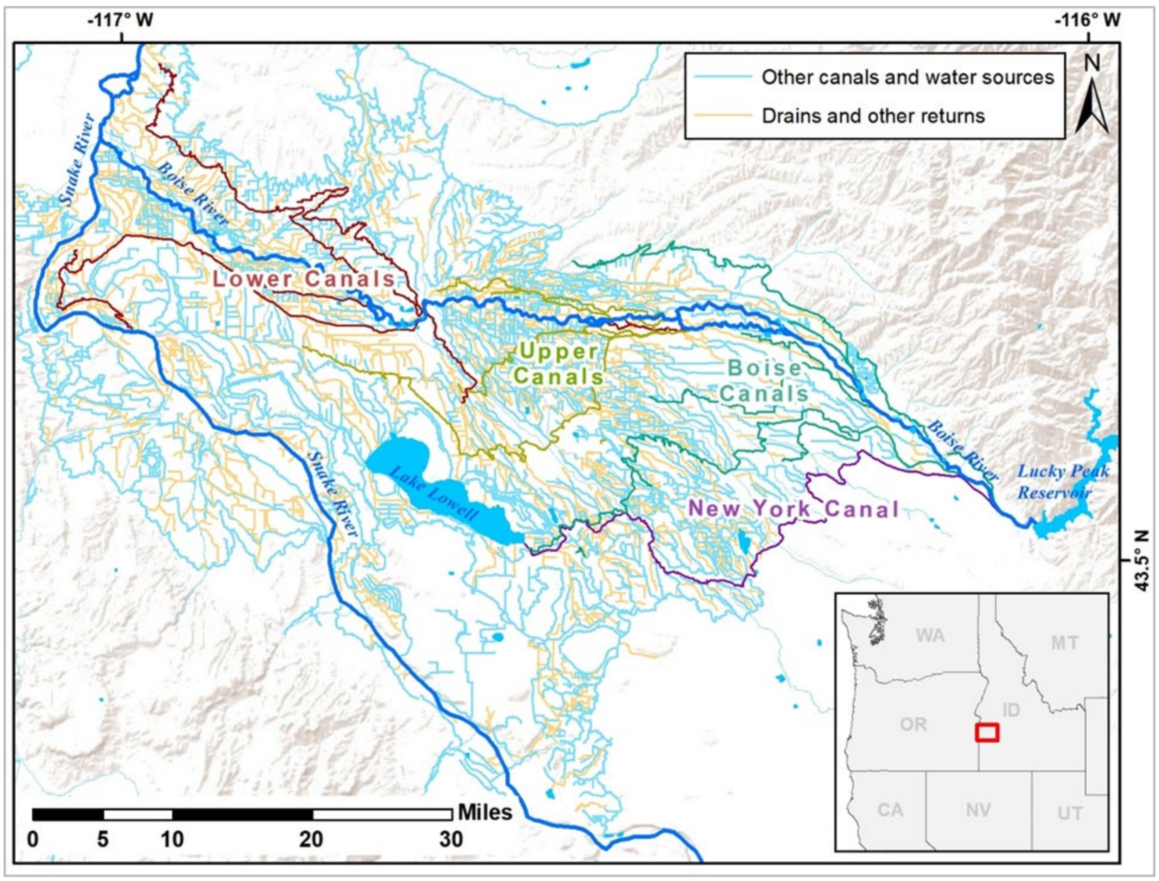

Figure 4. 2. Map of Boise River System with aggregated canal group: New York Canal (purple), Boise Canals (blue-green), Upper Canals (yellow-green), and Lower Canals (red).

Boise River Basin Modeling

The U.S. Bureau of Reclamation developed a RiverWare model of the Boise

River system to analyze the impacts of changes to the Boise Project (Appendix A). RiverWare (Zagona et al., 2001) is a river and reservoir simulation platform that uses a network of objects representing physical conditions and constraints along with a series of user-written rules to represent operation policies. Rule-based simulation helps track return flows (McMahon and Farmer, 2009).

The model distributes water through the system based on natural flow priorities via RiverWare's defined SolveWaterRights function and storage accounts following the prior appropriation doctrine. Each reservoir has a storage account for water users. The model uses water from a storage account to attempt to meet the irrigation diversion request if there is not enough natural flow available. Rental pool water, if available, is also distributed to a water user if natural flow and storage accounts cannot meet the irrigation request. Rental pool water was included in the storage delivery in the analysis.

The regulation model that was used represented the physical conditions and operational rules of the system. The regulation model was used to simulate 28 years on a daily timestep from 1981 - 2009. Using an accounting layer within the model allowed for the tracking of water requested, water received, amount of water received by a particular source (natural flow or storage), and amount of water available in or used from a reservoir storage account. Chapter 3 presented the uncertainties in the model.

Two sets of diversion requests for each irrigated diversion area were used in this study. First, the full historical diversion request was used as in Chapter 3. This meant that as the return flow fraction was reduced, the consumptive use for irrigation effectively increased. This increased consumptive use could represent increased irrigated acreage (which is often limited to acreages allowed under a water right), increased crop demand to produce higher yields of the same crop, or increased demand with crops planted requiring more water. The second set of diversion requests was reduced based on the reduction in return flow such that the consumption use was constant. The model then increased reservoir storage accounts by the reduction in diversion request if reservoir space was available. The increased storage would first go into water user storage accounts and then would be available for use through the rental pool. The model released water from the natural flow and reservoir storage to meet irrigation diversion requests. The reduced diversion request increases manager flexibility to use water conservation efforts to move what would have been return flows to storage in a reservoir (Scott et al., 2014). Irrigation shortage was defined as the difference between the diversion request and the amount of water delivered from either natural flow or storage.

Equation 1 was used to reduce the diversion request relative to the scaled return flow. Reducing diversion requests allowed the model to store conserved water (the reduction in return flow) instead of consumptively using that flow. Instead of releasing the water, the model added the water to the reservoir storage accounts. This scaling resulted in the same consumptive water use to grow crops (assuming water was available). The full diversion request and the return flow scale factor were inputs to the model. The reduced diversion request was calculated in the model in the rule set for each scale factor.

Equation 1:

$$Reduced\ Diversion\ Request = Full\ Diversion\ Request * \frac{1 - ReturnFlowProportion}{1 - Scale\ Factor * Return\ Flow\ Proportion}$$

Where

- Reduced Diversion Request is the diversion request when the full diversion request is reduced by the amount of return flow that has been prevented for a given scale factor
- Full Diversion Request was the historical diversion request, which is constant year-to-year in the model.
- Return Flow Proportion was the fraction of the diversion amount to a location that seeps, spills, runs off or is otherwise returned to the river. Each diversion has one or more return flow proportion. A diversion can have multiple return flow fractions, which must sum to 1. For example, in Figure 2 the New York Canal has a return flow fraction for Boise River at Glenwood and a return flow fraction for Boise River at Middleton.
- Scale Factor was an adjustment to the return flow fraction that reduces the return flow. The Scale Factor was 1.0, 0.8, 0.6, 0.4, 0.2, and 0.0, where 1.0 represented current historical return flow and 0.0 represented no return flow.

The return flow volume is the volume of diverted water that returns to the river system (Equation 2).

Equation 2:

$$Return\ Flow\ Volume = (Diversion\ Request - Shortage) * Return\ Flow\ Fraction * Scale\ Factor$$

A simple example of how the Reduced Diversion Request (Equation 1) and Return Flow Volume (Equation 2) equations are applied is below. Table 4.1 shows how the Full Diversion Request, Reduced Diversion Request, Consumptive Use, and Return Flow Volume are related assuming that there is no shortage.

- Given: Full Diversion Request of 10 cfs and Return Flow Fraction of 0.3.
- Assume: There is no shortage and the entire diversion request is diverted.
- 10 cfs is diverted, 7 cfs is consumptively used, while 3 cfs is returned to the river
- If the Return Flow Scale Factor is 0.8:

$$Reduced\ Diversion\ Request = \ 10\ cfs\ * \frac{1 - 0.3}{1 - 0.8 * 0.3} = \ 9.2\ cfs$$
$$Return\ Flow\ Volume = 9.2\ cfs * 0.3 * 0.8 = 2.2\ cfs$$

- Solve for the Reduced Diversion Request if Scale Factor is 0:

$$Reduced\ Diversion\ Request = \ 10\ cfs\ * \frac{1 - 0.3}{1 - 0.8 * 0} = 7.0\ cfs$$
$$Return\ Flow\ Volume = 7.0\ cfs * 0.3 * 0 = 0\ cfs$$

Table 4. 1. Simple calculations to demonstrate how return flow volumes and Reduced Diversion Request vary based on Scale Factor for a historical diversion request of 10 cfs and a Return Flow Fraction of 0.3 (assuming that there is no irrigation shortage).

Scale Factor	**Full Diversion Request (cfs)**			**Reduced Diversion Request (cfs)**		
	Diversion Request	Return Flow	Consumptive Use	Diversion Request	Return Flow	Consumptive Use
1.0	10	3.0	7.0	10	3.0	7.0
0.8	10	2.4	7.6	9.2	2.2	7.0
0.6	10	1.8	8.2	8.5	1.5	7.0
0.4	10	1.2	8.8	8.0	1.0	7.0
0.2	10	0.6	9.4	7.4	0.4	7.0
0.0	10	0	10	7.0	0.0	7.0

The return flows were reduced by scaling the return flow fraction for each of the 15 diversion areas. Due to the model assumptions and capabilities, reductions in return flow from field and irrigation-district scale could not be separated. The return flow of the irrigation distribution system (field irrigation and irrigation district) was reduced in the model. The return flow scaling of 0 represents no return flow from the irrigation distribution system. No return flow is a boundary of the system and is unlikely to be a physical reality but provides an estimate of the maximum potential effects.

The type of water year was analyzed to determine if the system responded differently in dry or wet years. The years of the simulation, 1981 to 2009, were ranked from wettest to driest based on the total storage in the three reservoirs. Dry years were classified as those that had 80 percent of other years having more total reservoir system storage. Conversely, wet years were defined as those that had 80 percent of other years having less total reservoir system storage.

There were twelve independent model runs: two irrigation diversion requests and six return flow scenarios. The model attempted to meet irrigation diversion requests by either natural flow or storage delivery, and any remaining irrigation diversion request was a shortage.

Results

Storing the conserved water reduced the shortages compared to the full diversion request and current conditions (Figure 4.3). Compared to current conditions, the amount of the diversion request supplied from natural flow declined with the full diversion request. The reduced diversion request had a higher percent of the diversion request met by storage than current conditions for all canal groups. The percentage of the diversion request met by reservoir storage for current conditions and the reduced diversion request with no return flow was similar at the most upstream canal group and diverges more progressing downstream.

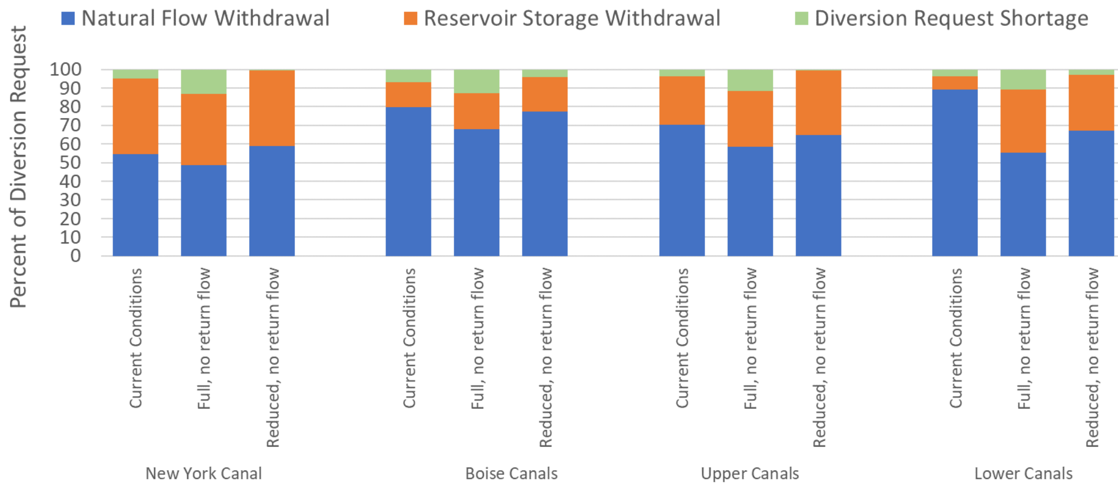

Figure 4. 3. The 28-year average percentage of the normal annual diversion request (y-axis) satisfied by natural flow, reservoir storage, or shortage (bar color) for full diversion request (Full) and reduced diversion request (Reduced). Diversion groups are sorted left-to-right from upstream to downstream canal diversion areas along the river.

The system reservoir storage affected by the scenarios, with more total storage with the reduced diversion request and less total storage with the full diversion request (Figure 4.4). As the return flows were reduced with the full diversion request, the 28-year median daily storage values decline due to irrigation withdrawals (Figure 4.4, purple lines). Conversely, as the diversion request was reduced, storage increased with declining return flows because less water needed to be diverted (Figure 4.4, green lines). These effects are more pronounced in summer, fall, and winter months. The 28-year median daily total system storage did not fill completely for any of the return flow scenarios.

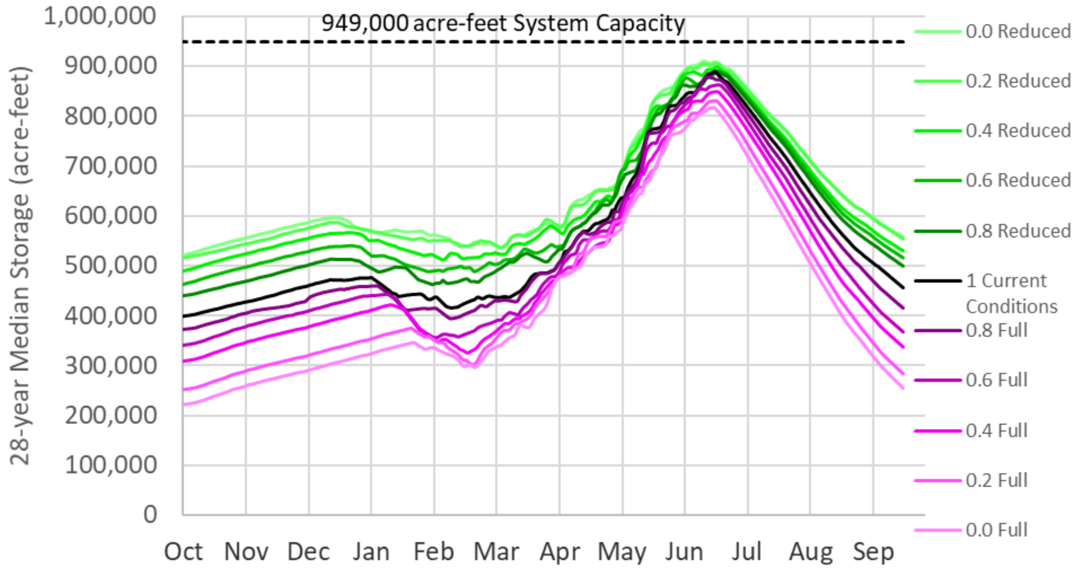

Figure 4. 4. The 28-year median daily combined Boise Project storage (all three reservoirs) for full and reduced diversion requests (Appendix B).

The finding of higher storage with a reduced diversion request and lower storage with a full diversion request was consistent for both dry and wet years (Figures 4.5). Wet years had less difference in system storage between both the return flow scenarios and the irrigation diversion scenarios than median years or dry years and essentially no difference in wet spring months (Figures 4.4 and 4.5). The percent difference for system storage among the scenarios for dry, median, and wet on August 1st was 107%, 24%, and 10%, respectively. In wet years, the peak total system storage was within 2 percent of the total system capacity for all return flow scenarios.

The date of peak storage was most affected in dry years. The dry year peak storage occurred the earliest on June 2 (no return flow and full diversion request) and the latest on June 15 (no return flow and reduced diversion request). Across all the scenarios, the peak storage among the return flow scenarios differed by 300 KAF, 95 KAF, and 10 KAF in dry, median, and wet years, respectively. Dry years exacerbated the effects of reducing the return flow with both full diversion requests.

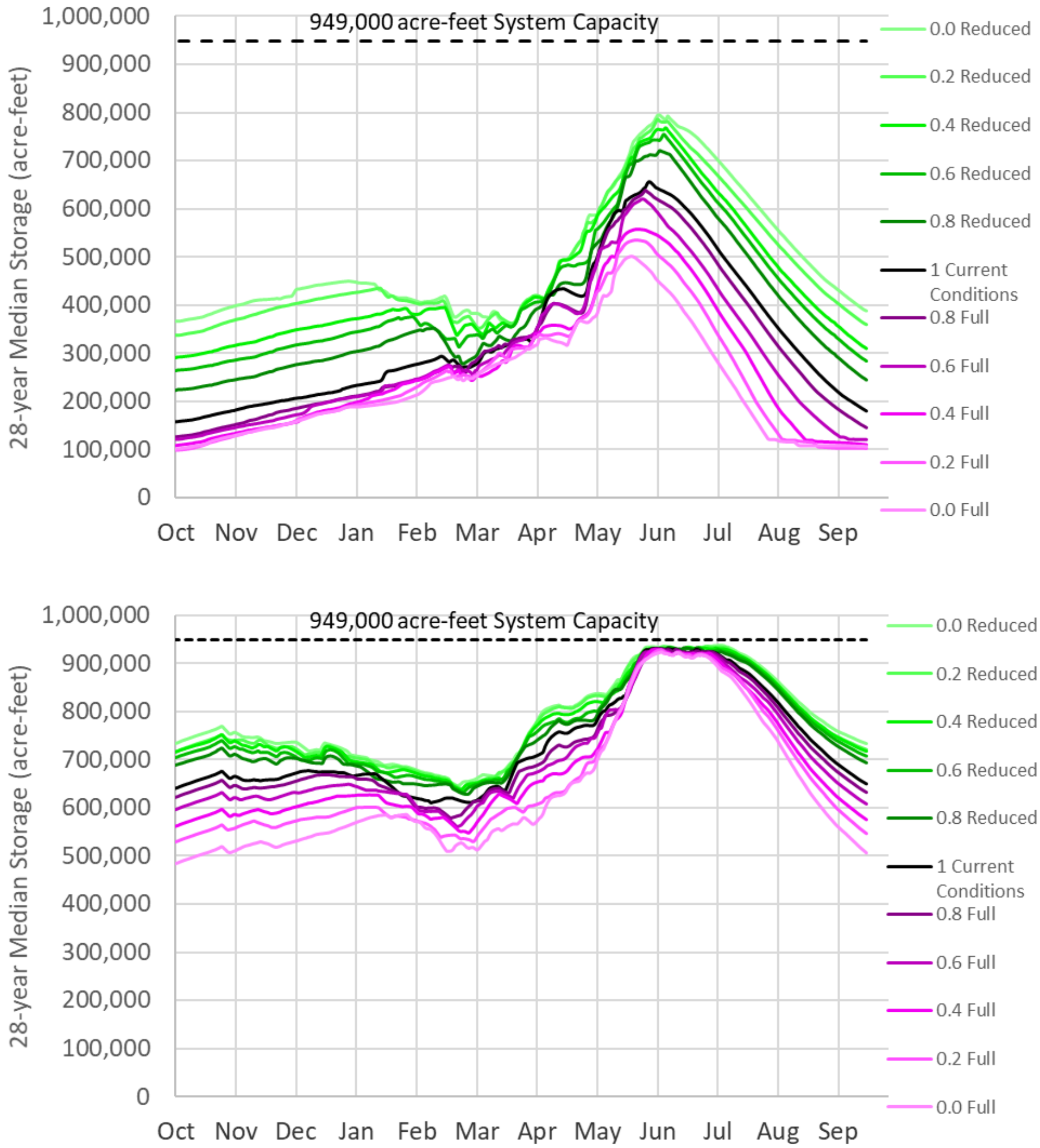

Figure 4. 5. The 28-year daily combined Boise Project storage (all three reservoirs) showing how storage changes due to return flow reductions in dry years (top) and wet years (bottom).

As the return flow was scaled 1.0 to 0.0, the shortages increased with the full diversion request and the shortages decreased with the reduced diversion request (Figure 4.6). Shortages were more pronounced in dry years than wet years. In the driest year of the simulation, the total system shortages for current conditions, no return flow and full diversion request, and no return flow with reduced diversion request are 340 KAF, 690

KAF, and 80 KAF, respectively, of the 1,476 KAF request. For dry to median years with full diversion request, the shortages more than doubled from current conditions to no return flow. The wettest years have no difference in shortages. The percentage of years where the total shortage was more than 5 percent of the total irrigation demand (74 KAF) for current conditions, full diversion request, and reduced diversion request was 71, 50, and 7 percent, respectively.

During the summer and fall, Boise River flows at the Parma gage for all return flow scenarios were less than flow with current return flow conditions because return flows were reduced (Figure 4.7). In spring, flows were higher for the reduced diversion request and lower for the full diversion request compared to current conditions. Storing the return flow had little effect on the summer and fall flows for all return flow scenarios. The spring flows were highest for the reduced diversion request and no return flow while the lowest flows were for the full diversion request and no return flow.

Discussion

The results of this study show that reducing return flows from irrigated areas can decrease irrigation shortages and increase reservoir storage if the saved water can be stored. Conserved water was simulated as a reduction in return flow. The reduced irrigation request represented constant consumptive use with the simulated implementation of water conservation measures. As the return flow was reduced, the percent of the irrigation request not met increased with the full diversion request and decreased with the reduced diversion request. When the irrigation request was reduced in proportion to the reduced return flow, shortages decreased as more water conservation measures were implemented. These shortages decreased because more reservoir storage was available to help meet irrigation diversion requests.

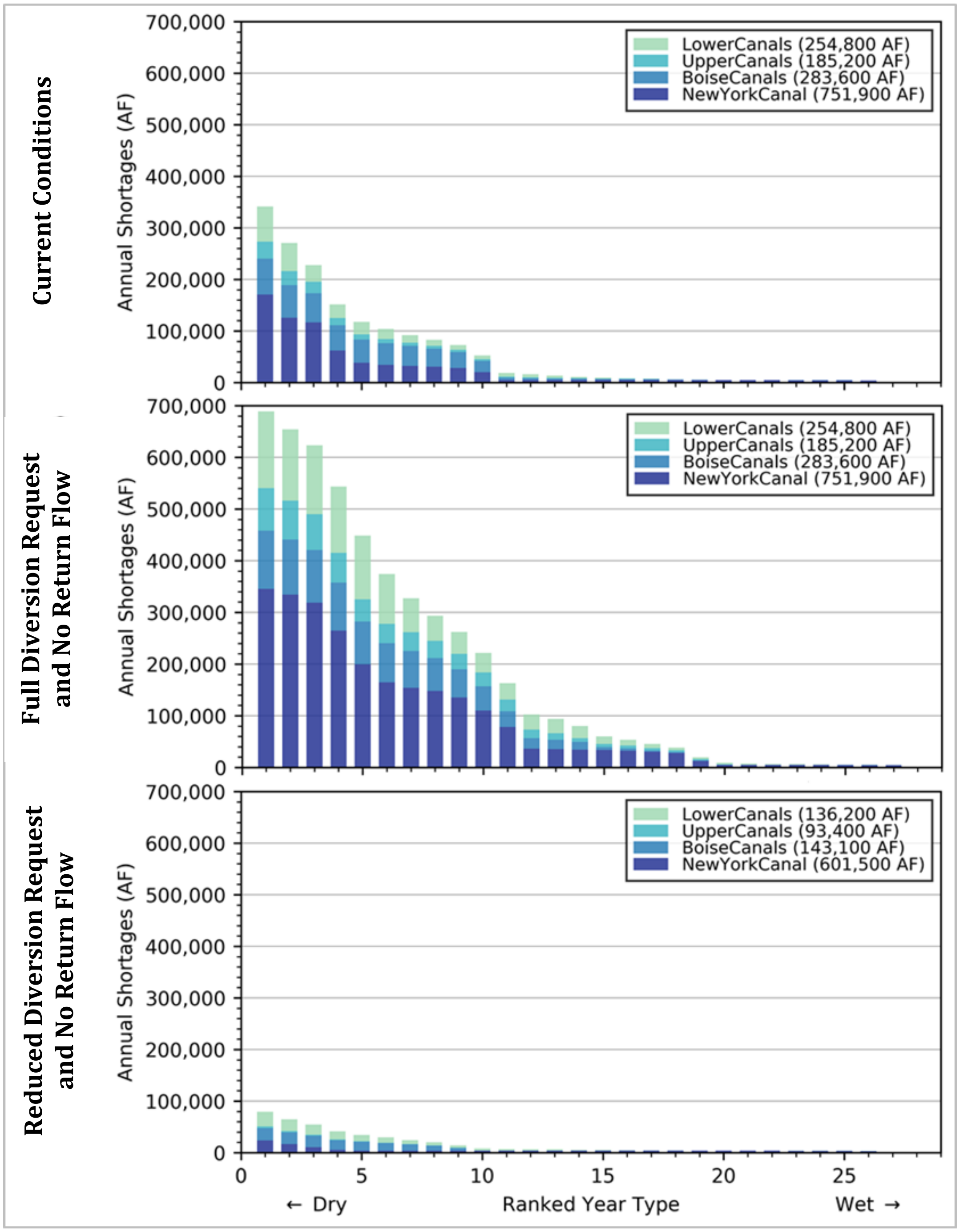

Figure 4. 6. Stacked annual shortages sorted from dry to wet years based on total annual shortages (i.e., combined bar height) with shortages for each diversion group discretized by color. The top plot shows shortage for current conditions (scaling factor of 1.0). The middle plot shows the estimated shortages with no return flow (scale factor of 0) and full diversion request. The bottom plot shows the estimated shortages with no return flow (scale factor of 0) and a reduced diversion request.

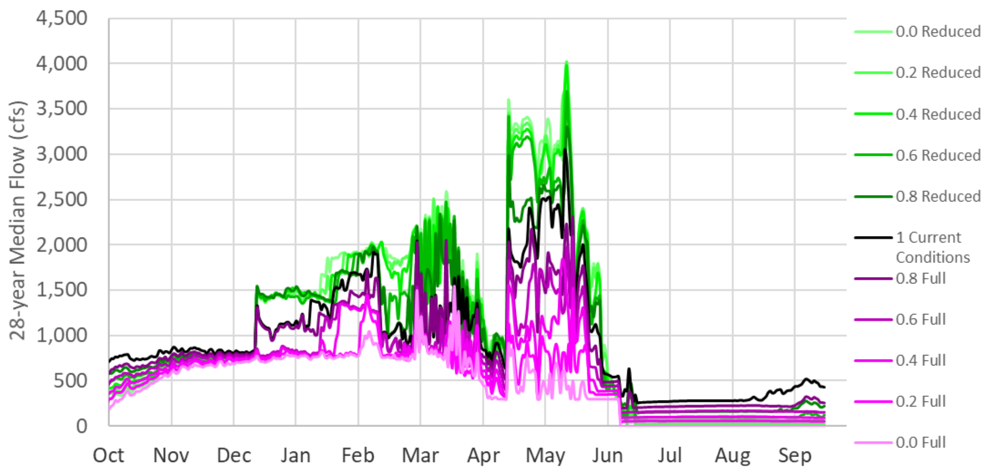

Figure 4. 7. The 28-year median daily Boise River flow at the end of the Project near Parma showing how flow changes due to return flow reductions.

The storage of conserved water had more of an effect on total system storage in dry years than median or wet years. The physical structure and operation of the project can amplify or minimize the effects of the difference in return flow. The total system storage capacity was not reached in median or dry years. This meant that there was a physical capacity limit to storing conserved water year-to-year in the Boise River system in the wet years. Decision makers may assume that they can always store conserved water. Storage of conserved water may not be possible during wet years because much of the water was released during the spring-time flood operations when there is more water in the reservoirs or drainage basin than the reservoirs can hold (and thus the excess must be released to the river). The reduced diversion request scenarios have more reservoir storage than current conditions or the full diversion request. That increased reservoir storage allows for more management flexibility in dry and median years as reservoir storage can be released to mitigate some irrigation shortages. Total system reservoir storage increased in wet years. Reducing return flows and diversion requests can increase management flexibility by having more water in the reservoir available to use without increasing system shortages. This could be critical to some basin in dry years.

Flow in the river is higher during winter and spring with reduced diversion request because the reservoirs have more storage from the previous water year. The Boise River is typically in flood operation season in late March, April, May, and early June. The increased storage means that there is more water that needs to be released for flood control during the winter and spring months.

Setting the model operation rules to store none or all the previous returned flow modeled the two extreme cases. Water managers may choose an alternative somewhere between these two scenarios. After installing water conservation measures, water managers could use of combination of storing conserved water and allowing increases in consumptive use to best meet priorities and demands.

The uncertainty of mass balance terms and model inputs propagate through the model to affect the outputs. Hydrology influenced how much water was available for natural flow and reservoir withdrawals. The amount, location, and timing of return flows impacts the natural flow available in the river, which influences how much reservoir storage a water user withdraws and the irrigation shortage.

Reducing return flows and changing the storage management of that water has many impacts throughout a basin for flood control, inter-district operations, intra-district operations, recreation, and ecosystems.

Flood Control. Increasing the amount of water stored in the reservoirs will raise the water levels. More water in the reservoir system can lead to more flood control releases. In this study, increased storage increased flood control operations because the reservoirs were already near capacity. Reservoirs released more water for flood control during median and wet years. Flood releases may occur earlier in the year or have a higher volume.

Inter-district Operations. There are many effects of water conservation measures between irrigation districts. Upstream districts do see some decrease the amount of the diversion request met by natural river flow when water users throughout the basin reduce their return flows. Some of the issues at the inter-district operations can be mitigated if the conserved water can be stored instead of districts having their full diversion amount after incorporating water conservation measures. When reducing return flows, downstream districts that depend on the return flow from canals further upstream will lose a water source. They will either depend more on stored water, install water conservation measures themselves, or reduce their demands (e.g., fallowing fields, planting crops with less water requirements, or have lower yields). Districts can be affecting neighboring districts with potentially little to no recourse. If upstream districts install water conservation measures, downstream districts will have to follow suit to add water conservation measures to retain spill or infiltrated water or withdraw more from storage. Systems may or may not have the infrastructure to convey water that previously moved through the drainage system. These effects could escalate issues in contentious basins.

Intra-district Operations. Irrigation districts often have multiple canals or laterals. The modelled results for upstream and downstream districts apply to canals and laterals within a district. The canals or laterals at higher elevations may supplement those at lower elevations with spill and infiltrated water. When water conservation measures are used on canals or laterals at a higher elevation, operations would need to change because the lower canal would have less water available. Shortages by diverting additional water to the lower canal may not be possible without the necessary water delivery infrastructure.

Recreation. Effects to recreation are varied. Increased storage could increase recreational opportunities during dry years in reservoirs during the summer months. Less river return flow would reduce flows in the river and could reduce summer recreation activities (for example, tubing, kayaking, and fishing are common on the Boise River).

Ecosystems. There are many ecosystem consequences of installing water conservation measures, both positive and negative. With increased reservoir storage if reservoir operations allowed, it may be possible to release cooler water from lower reservoir levels during hot summer months to benefit temperature-sensitive river species if the reservoir has the capacity to release water from deeper levels of the reservoir. Return flow can be cooler than river water and reducing return flow may make rivers warmer thus impacting the variety of species in the river. Increasing reservoir storage could increase the area available for aquatic habitat. Decreased river flow may increase water quality concerns based on concentration levels or conversely improve water quality in the river if the return flow water has quality issues (e.g., sediment, high levels of chemicals).

The Boise River Basin has some unique traits. Many systems do not have the ability to carry water from year-to-year based on infrastructure or operation capabilities and therefore may not see as much benefit from water conservation measures and storing the difference in return flows. The Boise River Basin has the additional capacity in the canals to handle the additional water to carry through the system modeled by reduced return flow and full diversion request. Canals already near capacity or with additional safety concerns may not be able to handle the additional water propagating through the system. The RiverWare rules for this model (as presented in Appendix A) were designed to replicate operations in the basin in a repeatable fashion. The rules and inputs into the model simulate the physical relationships in the basin. Changes to the rules or inputs such as return flow fraction could impact the results.

Many physical and management changes are needed to implement reducing diversion requests and storing conserved water (Table 4.2). Managers may also want the flexibility to use a portion and store the remaining conserved water instead of strictly one option or the other. Additional storage capacity in some systems may benefit in storing water in wet years that was released for flood control in this case study. A state engineer or river basin manager could support and promote storing conserved water: 1) provide the legal framework for the conversion of natural flow for reservoir storage rights, 2) provide the accounting to track water rights and volumes, and 3) allow users to convert their historical amount of water when they install water conservation measures. The third may be hard to enforce on all projects but could be enforced better when state or regional funding is used by the entity.

Table 4. 2. Summary of management strategies for storing conserved water in system reservoirs.

Issue	**Boise Basin**	**General Basin**	**Factors**
Motivations to store conserved water	Water users would participate in storing conserved water to help ensure that they will have more water during dry and water-short years.		If entities have storage and or natural flow rights

			Percentage that a basin is appropriated
Which water users benefit from storing conserved water in a reservoir?	Downstream users dependent on return flows from upstream users.	Downstream users dependent on return flows from upstream users. Junior water rights holders with storage rights.	River return flow location and timing
How stored water is distributed?	Stored water is distributed using the reservoir storage rules: an individual water user's storage is used to make up for shortages between the irrigation diversion request and available natural flow.	Stored conserved water could be distributed the same as other storage accounts. If a water user did not previously have storage, they would need accounts. Could track volume of water conserved.	Is carry-over reservoir storage allowed? Do water users already have storage accounts?
What are the effects on senior and junior water rights holders?	Storing conserved water would benefit all water rights holders in dry years. In dry years, there would be more benefit to junior water rights holders because they would have more storage to use in dry years when there is less natural flow available.		
What are the legal issues related to storing conserved water?	It is not currently legal to store a water user's natural flow right in reservoirs in the Boise Basin. This study shows that there are benefits to a management strategy that would require legal changes.	The basin would need to allow for conversion of natural flow rights to a right that could be stored in the system reservoirs. Accounting procedures would need the ability to track natural flow, reservoir storage and withdrawals, irrigation requests and deliveries, and	Natural flow rights and storage contracts in the basin

		adding to storage accounts for individual water rights.	
How geography affects outcomes	The Boise River system as a relatively quick return flow response for water to return from the irrigated areas to the Boise River.	Response functions, return flow fraction, if return flows return above other diversions or if they return at the end of the system	The geology and aquifer characteristics impact the location and timing of return flows. Systems with longer return times may require more data to support longer simulation times to investigate return flow effects.

This work can be expanded upon to further understand implementing water conservation measures. First, groundwater systems would likely be affected because underlying aquifers would lose a source of recharge. Simulating the dynamic responses of groundwater to changes in recharge was beyond the scope of the analysis. However, increases in the efficiency of water delivery and/or use, and corresponding reductions in aquifer recharge, could alter groundwater flow gradients, transit times, flow directions, and aquifer-river connectivity. Groundwater responses to changes in water conservation measures may be non-linear and vary for different irrigation systems. The long-term effects of reduced groundwater recharge on groundwater dynamics warrant further exploration when considering efficiency improvements. Second, it could be beneficial to separate the effects of specific efficiency improvement such as canal lining, irrigation method conversions, and canal operation automation. Third, intra-annual irrigation diversion request patterns were held constant for this analysis based on historical demand. Future studies could alter irrigation diversion requests to take changes such as future water demands and different hydrologic inflows for potential climate conditions into account. Fourth, there may be economic implications for those positively or negatively affected by water conservation measures including issues related to having access to more or less water, cost of water conservation measure installation, water markets, and mitigation for negative effects.

Conclusions

The interdependency of reservoir storage, natural flow, return flow, and water conservation effects needs to be examined together to better understand basin issues. This study evaluated the effects of changing reservoir storage practices related to reduced return flows on a river basin on system storage, natural river flow, and irrigation shortages and analyzed how those impacts affect river basin management. A RiverWare rule-based accounting model was applied to the Boise River Basin in a 28-year simulation case study. The return flow was scaled from current conditions to no return flow. Irrigation diversion requests were modeled for the full historic diversion request and for a reduced diversion request. The reduced diversion request was the full historic diversion minus the water that is no longer return flow under each return flow scaling factor.

When the return flow from the irrigation system was reduced, the reduced diversion request scenarios met irrigation requests better than the full diversion request or the current conditions. The extreme high and low reservoir storage occurred when there was no return flow: highest with reduced diversion request and lowest with the full diversion request. When comparing total reservoir storage volumes, dry years had a larger range followed by median and then wet years. The trend of higher storage with a reduced diversion request and lower storage with a full diversion request was consistent for both dry and wet years. The reduction of return flows and changes in irrigation diversions by storing conserved water has impacts to flood control, district operations, recreation, and ecosystems throughout the basin. The management of the water retained by water conservation measures is critical to the ultimate impacts of water conservation measures. Decisions made at field, irrigation district, and basin levels can impact all scales due to the interconnectedness of water resources. Managers should identify and understand these impacts when making physical, operational, and technological changes.

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CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary and Conclusions

This work advances support for water managers to improve water resources management through local and regional scales. The framework developed in this dissertation evaluate how local changes within a river basin impact water users and water managers throughout the basin. This dissertation was divided into two sections: development of a network analysis tool and two methods using simulation accounting-based modeling. The network analysis tool was applied to the Bear River system located in southeastern Idaho and northern Utah. The Boise River system, located in southwestern Idaho, was used as a case-study for modeling the effects of water conservation measures. The methodology and conclusions are relevant in watersheds with water supply and management concerns.

In Chapter 2, we presented a tool to quantify changes in water resources networks by removing a particular node within the network. The Ranking Automation for NetworKs (RANK) tool was developed that weights node connections based on flow capacity and direction and automates the process to quantify and rank nodes for three performance metrics: (1) stability: their roles do not depend on the existence of particular nodes, (2) topological significance: when removed or added to the network, these nodes cause other nodes to be unstable, and (3) redundancy: node pairs that have similar connections. The analysis removed a particular node and calculated the stability, topological significance, and redundancy of that node.

In Chapter 3, we address the issue of how management changes at the field and irrigation district scales affect other water users in a river basin. Water conservation measures are applied at local (field or irrigation district) level while effects to the basin are often overlooked. This study developed a method to model and quantify the effects of water conservation measures on an existing river basin. Water conservation measures were simulated in the model by reducing the return flow from irrigated areas to the river in an existing simulation-based water accounting model of the Boise River Basin.

Chapter 4 built on the methods developed in Chapter 3 to understand how storing conserved water affects river basin water management decisions and operations. Flood control, intra-district operations, inter-district operations, recreation, and ecosystems can be affected by the implementation of water conservation measures. Managers should identify and understand these impacts when making physical, operational, and technological changes.

The analysis tool and methods presented in the dissertation describe novel approaches to analyzing watershed basins to improve water management. One finding throughout the work is the susceptibility of downstream users to physical and managerial changes in river basins. RANK analysis found that downstream nodes are more unstable while the return flow modeling similarly found that downstream users are more affected by decisions made by other water users within the basin. The frameworks presented in this dissertation can help water managers understand how decisions made at local levels can impact water users dependent on the same source of water within a river basin.

Management Findings and Recommendations

Findings and recommendations from the RANK tool include:

- Highly redundant, low topological significant nodes as candidate sources for water transfers,
- Building or expanding dams at reservoir sites with high topological significance,
- Removing existing or abandoning proposed dams at reservoir sites with low topological significance,
- Adopting conservation measures or developing alternative supplies at unstable service areas, and
- Monitoring flows and protecting environmental features at unstable and topologically significant nodes.

Findings and recommendations from the return flow simulation modeling include:

- Scaling return flows in a simulation model can be used to quantify how implementation of water conservation measures at local levels affect a river basin,
- Reducing return flows while maintaining historical diversion requests increases system irrigation shortages and reduces storage,
- Downstream water users depend on storage withdrawals to meet irrigation demands as return flows are reduced, and
- Water conservation measures will impact users differently depending the type of year and withdrawal location in the basin.

Findings and recommendations from the storing conserved water simulation modeling include:

- Storing conserved water in system reservoirs can dramatically reduce irrigation demand shortages in dry years with little to no benefit in wet years,

- Storing conserved water reduces the impacts of water conservation measures throughout the basin on downstream water users,
- Allowing the storage of the difference in return flows from current conditions adds flexibility and is critical to the ultimate impacts of water conservation measures, and
- Decisions made at field, irrigation district, and basin levels can impact all scales due to the interconnectedness of water resources.

Future Work

This dissertation presented a framework to support informed water management at a basin level. Potential future work to improve or build upon this framework and the results presented in this dissertation includes:

- Extend the RANK tool to incorporate changes in link weight throughout a water year.
- Couple the water conservation measurement simulation modeling with a corresponding groundwater model. Increases in the efficiency of water delivery and/or use, and corresponding reductions in aquifer recharge, could alter groundwater flow gradients, transit times, flow directions, and aquifer-river connectivity. Groundwater responses to changes in water conservation measures may be non-linear and vary for different irrigation systems. The long-term effects of reduced groundwater recharge on groundwater dynamics warrant further exploration when considering efficiency improvements.

- Extend the water conservation measurement simulation surface-water modeling to separate the effects of specific efficiency improvement such as canal lining, irrigation method conversions, and canal operation automation.
- Extend the water conservation measurement simulation accounting to include intra-annual irrigation diversion request variations. In the existing model, irrigation demand patterns were held constant based on historical demand. Future studies could alter irrigation diversion requests to take changes such as future water demands and different hydrologic inflows for potential climate conditions into account.
- Add analysis of game theory and the economic implications for those positively or negatively affected by water conservation measures including issues related to having access to more or less water, cost of water conservation measure installation, water markets, and mitigation for negative effects.

Water management for sustainable use of resources involves understanding how changes in one area affect water users throughout a river basin dependent on the same resources. The framework presented in this dissertation can be applied to understand the hydrologic and the management relationships within a river basin. Application of the tool and methods in more river basins can help water managers make more informed decisions to support sustainable water use.

APPENDICES

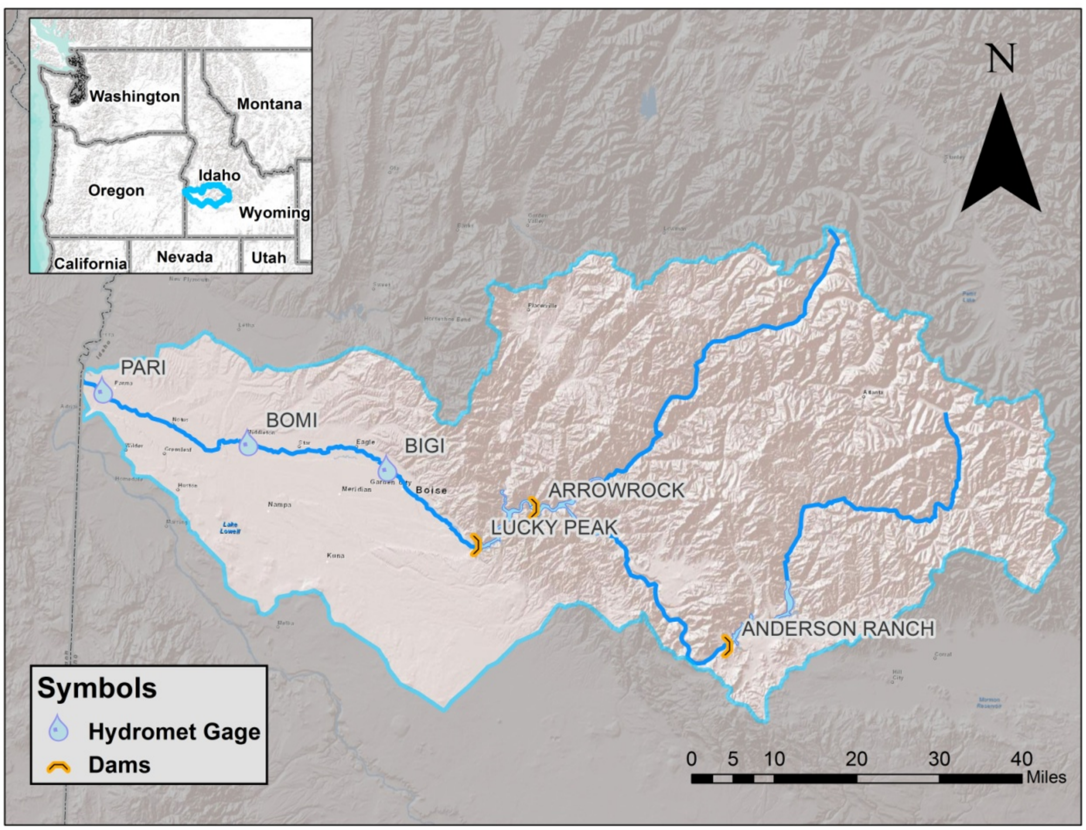
Appendix A. Bureau of Reclamation: Development of a Daily Water Distribution Model of the Boise River, Idaho, using RiverWare.

Appendix A documents the Boise River Basin RiverWare model that was used as the baseline model for Chapters 2 and 3. It is included as an appendix as the model documentation not easily accessible to someone trying to understand the underlying model and work to this dissertation's analysis. This document is set to be published on a public Bureau of Reclamation modeling repository in 2021.

The information being offered herein represents the opinion of the author(s). It has not been formally disseminated by the Bureau of Reclamation. It does not represent and should not be construed to represent Reclamation's determination or policy.

RECLAMATION
Managing Water in the West

Development of a Daily Water Distribution Model of the Boise River, Idaho, using RiverWare



U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Region
Boise, Idaho

July 2013

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

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

Development of a Daily Water Distribution Model of the Boise River, Idaho, using RiverWare

prepared by

River and Reservoir Operations
Jennifer Johnson, Hydraulic Engineer, P.E.

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Region
Boise, Idaho

July 2013

Acknowledgments

Sponsors:

- Snake River Area Office, Bureau of Reclamation, Pacific Northwest Regions
- Research and Development Office, Bureau of Reclamation, Denver

Agencies' Comments and Contributions From:

- Bureau of Reclamation, Pacific Northwest Region: Patrick McGrane, Mary Mellema, Toni Turner, Bob Lounsbury, Jama Hamel
- Idaho Water Resources Research Institute – University of Idaho: RD Schmidt
- Idaho Department of Water Resources – Liz Cresto

Contents

Page

Tables

Figures

Executive Summary

A daily simulation model of the Boise River System was developed using RiverWare, a river system simulation tool developed by CADWES at the University of Colorado. The model was developed for multiple purposes, including evaluating potential impacts from climate change. It was funded by the Snake River Area Office.

A regulation model was developed using RiverWare's accounting module, which distributes flow according to water right legal constraints. It simulates reservoir operating procedures, minimum flow requirements, and natural flow and storage water ownership information. It also includes a simplified rental pool operation.

RiverWare rules were adjusted to calibrate the model to historical system reservoir storage contents, outflows from the reservoirs, and flows at three downstream gages, Boise River at Glenwood (BIGI), Boise River at Middleton (BOMI), and Boise River at Parma (PARI). The historical period was October 1 1981 through September 30, 2009.

The model was used to simulate the impacts of climate change on the Boise River System. Six 120 year transient CMIP3 climate change projections were run through the regulation model. The six projections were generally drier than the 30 year calibration period in the Boise River watershed, and therefore the results indicated that under five of the six projected futures, the reservoirs would fill less often and less water would be delivered for irrigation. In addition, the timing of the peak runoff tended to shift one to two months earlier than historical runoff and the potential for flow values at Glenwood Bridge exceeding flood state, 7000 cubic feet per second, for more than five days increased.

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1 Introduction

1.1 Purpose

The purpose of this report is to describe the development of a daily RiverWare model of the Boise River and to document the data sources that were used in the model. The report also describes the methods used to simulate the impacts of climate change on the system.

The daily RiverWare model of the Boise River System, Idaho, was developed as part of a Reclamation Science and Technology research project. The research project developed a method to combine hydrologic and economic models in an effort to quantify changes to a hydrologic system in terms of dollars. The test region for this research effort was the Treasure Valley.

The model development was funded by the Snake River Area Office so that it could be developed to meet future planning study needs. Potential studies may include investigating the impacts of changing water supply due to climate change, changes in demands (water use requirements), or changes in minimum flow requirements. It may also be used to simulate changes in operations and the impact of such changes on the system.

1.2 Scope

This report describes the development of the RiverWare model and the application of climate change projections using the model. The Science and Technology research project work will be described in another report that is scheduled to be released in June 2013 by the Idaho Water Resources Research Institute.

The daily RiverWare modeling of the Boise River System simulates the Boise River starting above Anderson Ranch Reservoir down to the confluence with the Snake River near Parma, Idaho (Figure 1-1).

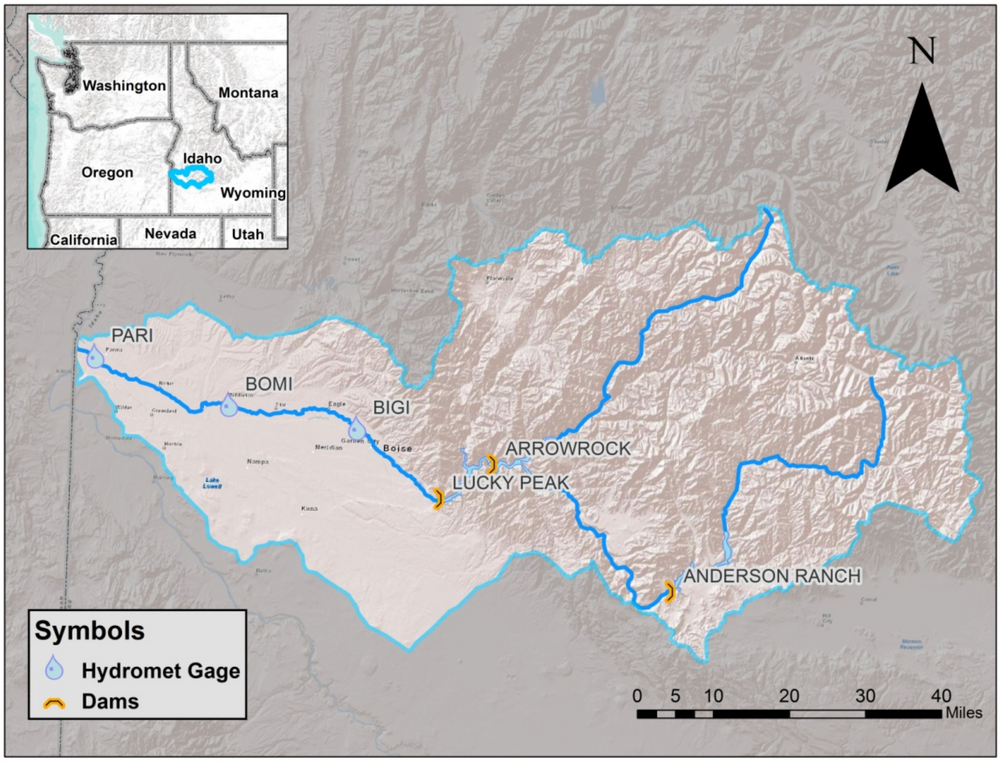

Figure 1-1: Map of Boise River System.

Two model networks were developed for this study, an unregulation model network and a regulation model network. The unregulation model simulates the period of record from 1929 through 2009 and is used to develop unregulated flows (reach gains and losses) that are used in the regulation model. The regulation model simulates the period of record from 1981 through 2009. Both models were developed using a daily time step.

1.3 Data Sources

Data for the RiverWare model came from many different sources and were adjusted to meet the needs of the model.

Physical characteristics of the system were extracted from the U.S. Army Corps of Engineers water control manual for the Boise River and from sedimentation surveys conducted by Reclamation (USACE, 1985, Reclamation 1997; Reclamation 1998). This includes reservoir size and capacity, outlet capacity, and spillway capacity. The water control manual also provided information about flood control operating rules, general irrigation release information, and other information about system operations. Operation information was supplemented with knowledge provided by Reclamation real-time dam operators.

Daily historical stream flow data, reservoir contents, and reservoir outflow were collected from the Hydromet data system, where available (Reclamation, 2012b). In many cases, daily data were not available for the entire period of record, so data were generated to fill in gaps. The generated data were developed using a method developed by the University of Idaho that disaggregates monthly data using a nearby gaging station with daily data as a surrogate for the pattern while maintaining the monthly volume (Reclamation, 2012b; Acharya and Ryu, 2013).

Daily historical diversion data were collected from Idaho Department of Water Resources (IDWR) records, where available (IDWR, 2011). As with the stream flow data, daily data were not available for the entire period of record, so data were generated to fill in gaps. The missing data was generated using a technique developed by Reclamation called Estimate Daily From Monthly, that estimates missing daily data using the available record for that diversion (Reclamation, 2012d). This method is available in Reclamation's Pisces data processing tool (Reclamation, 2012c).

Details about the interaction of surface water and groundwater interaction came from a water budget developed by Reclamation and IDWR (USBR and IDWR, 2008). Response functions were developed using a time-dependant MODFLOW model of the Treasure Valley (Reclamation, 2012a).

Natural flow water rights data were supplied by IDWR (IDWR, 2011). Storage water rights data were collected from Reclamation records.

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2 System Description

2.1 Reservoirs

The Boise River System includes three on channel reservoirs, Anderson Ranch, Arrowrock, and Lucky Peak. The reservoirs are operated together for flood control and to provide storage water for irrigation in the Treasure Valley. All three reservoirs are hydropower generating facilities, but Anderson Ranch is the only Federal power producer. Although hydropower can be modeled using RiverWare, it was not in this study, therefore hydropower generation capability is not discussed here. Boise Diversion Dam is a small hydropower facility at the diversion structure for the New York Canal. The diversion to the New York Canal is modeled, but the hydropower generation is not.

There is a fourth reservoir in the system, Lake Lowell. Lake Lowell is an off channel storage facility that is used to store additional water for irrigation. Lake Lowell is not directly modeled in the Treasure Valley RiverWare model and therefore is not included in this discussion.

2.1.1 Anderson Ranch

Anderson Ranch Dam is on the South Fork of the Boise River and is the furthest upstream reservoir in the system. It is composed of rolled earth and rockfill and began storing water in December 1945. Figure 2-1 shows an illustration of the storage capacity of Anderson Ranch Reservoir, where dead and inactive storage is 61,868 acre-feet, active storage is 413,074 acre-feet, and surcharge is 10,502 acre-feet (Reclamation, 1998).

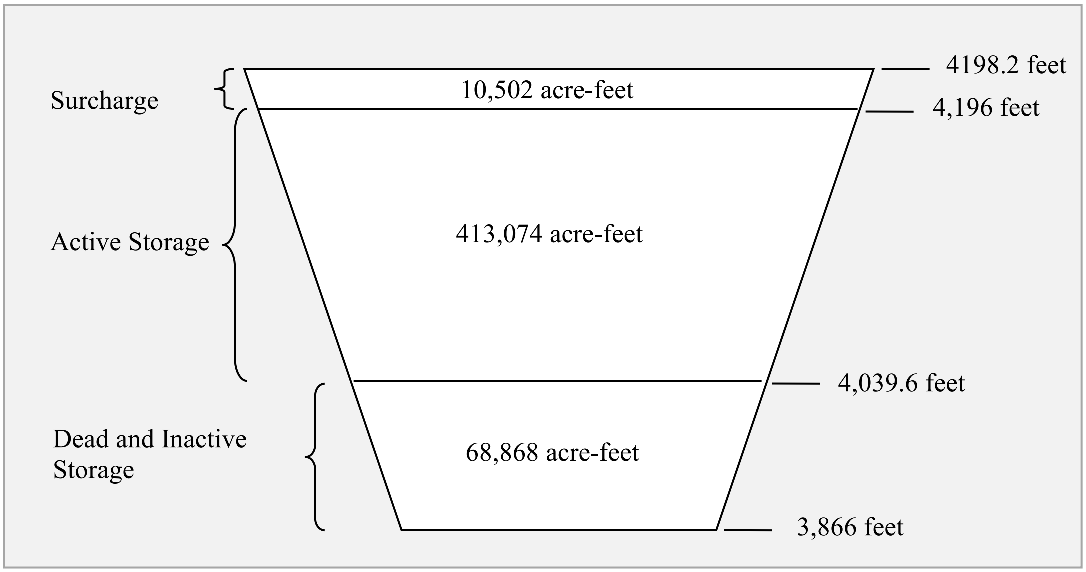

Figure 2-1: Illustration of Anderson Ranch storage capacity levels (not to scale).

Maximum discharge at full pool through controlled outlet works is 10,000 cfs with spillway capacity of 20,000 cfs.

2.1.2 Arrowrock

Arrowrock Dam is between Anderson Ranch and Lucky Peak on the Boise River. It was the first reservoir on the system and began storing water in 1915. It has a concrete arch design. Figure 2-2 shows an illustration of Arrowrock's storage capacities, where active storage is 272,224 acre-feet and surcharge is 11,630 acre-feet (Reclamation, 1997).

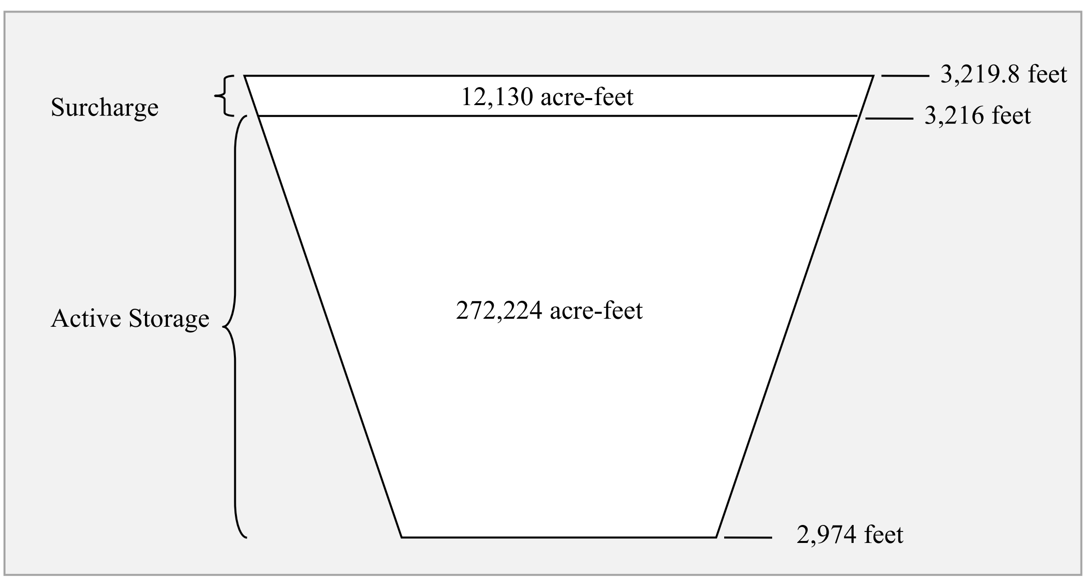

Figure 2-2: Illustration of Arrowrock storage capacities (not to scale).

Maximum discharge at full pool through controlled outlet works is 10,230 cfs with spillway capacity of 40,000 cfs.

2.1.3 Lucky Peak

Lucky Peak Dam is the lowest reservoir in the system. It began storing water in 1954 and is composed of rolled earth and gravel fill. Figure 2-3 shows an illustration of the storage capacity in Lucky Peak Reservoir, where inactive storage is 28,767 acre-feet, active storage is 264,371 acre-feet, and surcharge is 13,905 acre-feet (USACE, 1985).

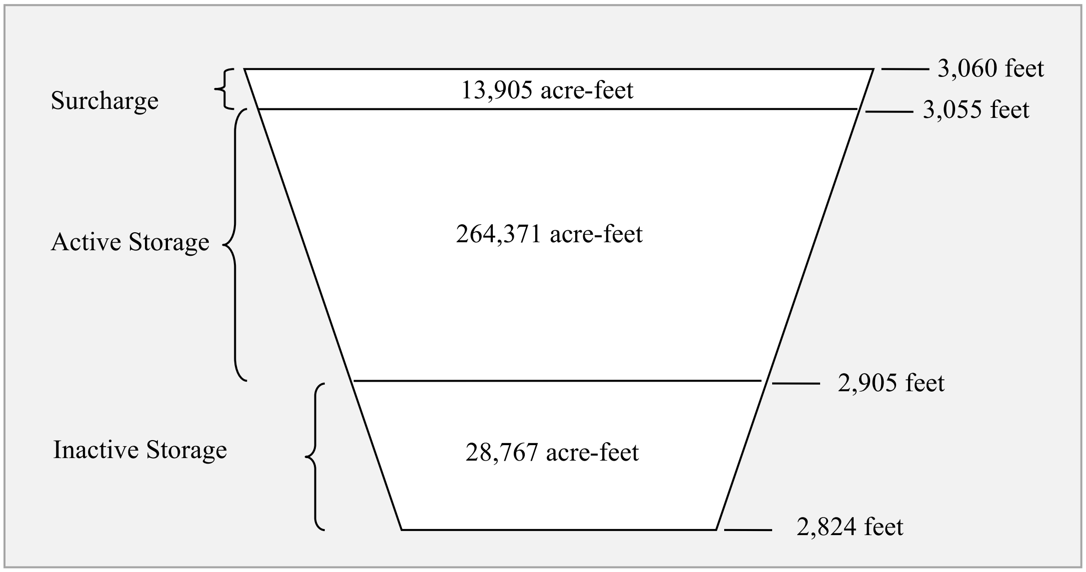

Figure 2-3: Illustration of Lucky Peak storage capacities (not to scale).

Maximum discharge at full pool through controlled outlet works is 30,500 cfs and with spillway capacity of 93,300 cfs.

2.2 River Reaches

For this modeling study, the Boise River is divided into three reaches below Lucky Peak Reservoir. The reaches correspond with Hydromet gages and include Lucky Peak to Glenwood Bridge (BIGI), BIGI to Middleton (BOMI), and BOMI to Parma (PARI). Each reach contains surface gains from small streams, subsurface gains from groundwater return flows, irrigation diversions, and losses to groundwater.

2.3 Diversions

Water is diverted from the Boise River largely for agricultural uses, and to a lesser extent, municipal, and industrial uses. The water is transported to its areas of use via an extensive network of canals (Figure 2-4) that cover approximately 1,170 miles (major canals only) (IDWR, 2004). For the purposes of this study, 47 points of diversion (PODs) are aggregated into 15 PODs. Table 2-1 shows the diversions that are aggregated and the name of the aggregated diversion.

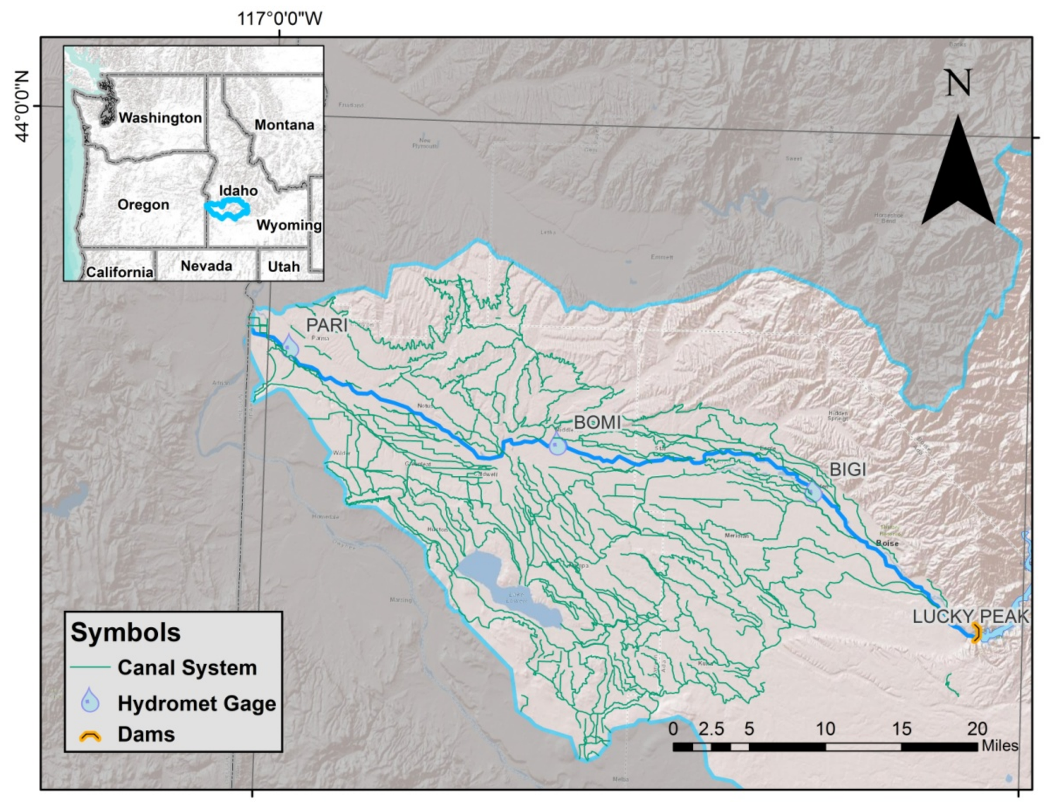

Figure 2-4: Map of canal system in the Treasure Valley.

Table 2-1: Table of IDWR diversion number, physical diversion names, and the associated Water User object.

IDWR Div. No.	Physical Diversion	Water User Object	IDWR Div. No	Physical Diversion	Water User Object
13202995	PenitentiaryCanal	Penitentiary	**13208738**	BarberPumps	NEagleIsland
13203000	NewYorkCanal	NewYork	**13208740**	SevenSuckersCanal	NEagleIsland
13203527	SurpriseValley/Micron	OtherCanals	**13209480**	PhyllisCanal	Phyllis
13203760	RidenbaughCanal	Ridenbaugh	**13209630**	LittlePioneerCanal	NEagleIsland
13204005	BubbCanal	OtherCanals	**13209990**	CanyonCountyCanal	CanyonCn
13204015	Herrick	OtherCanals	**13210005**	CaldwellHighlineCanal	CaldwellHighline
13204020	Meeves	OtherCanals	**13210984**	RiversideCanal	Riverside
13204060	RossiMillCanal	OtherCanals	**13210992**	SebreeCanal	Sebree
13204190	BoiseCityCanal	OtherCanals	**13210995**	CampbellCanal	Sebree
13204200	UnitedWater	OtherCanals	**13210994**	SiebenbergCanal	Sebree
13205515	SettlersCanal	Settlers	**13211001**	ShipleyPumps	Sebree
13205517	FairviewAcres	Settlers	**13211003**	WagnerPumps	Sebree
13205613	BoiseCityParks	OtherCanals	**13211603**	SimplotPumps	Sebree
13205622	ThurmanMillCanal	Thurman	**13211725**	Eureka#2	Eureka2
13205640	FarmersUnionCanal	FarmersUnion	**13211735**	UpperCenterPointCanal	Eureka2
13205641	BoiseValley	FarmersUnion	**13211745**	McManusandTeaterCanal	Eureka2
13206090	NewDryCreekCanal	NEagleIsland	**13211825**	LowerCenterPoint	Eureka2
13206205	LempCanal	NEagleIsland	**13212548**	BowmanAndSwisher	NotusParma
13206220	WarmSpringsCanal	NEagleIsland	**13212645**	BaxterCanal	NotusParma
13206260	Graham-GilbertCanal	NEagleIsland	**13212832**	AndrewsCanal	NotusParma
13206265	Ballentyne Canal	NEagleIsland	**13212896**	MammonPumps	NotusParma
13206270	Conway-HammingCanal	NEagleIsland	**13212938**	HaasCanal	NotusParma
13206290	ThomasAikenCanal	NEagleIsland	**13212954**	ParmaCanal	NotusParma
13206292	Mace-CatlinCanal	NEagleIsland	**13212966**	IslandHighlineCanal	NotusParma
13206295	Mace-MaceCanal	NEagleIsland	**13212992**	CrawforthPumps	NotusParma
13208450	Hart-DavisCanal	NEagleIsland	**13212994**	McconnelIslandCanal	NotusParma
13208710	MiddletonCanal	NEagleIsland			

2.4 Groundwater

There is substantial interaction between groundwater and surface water in the Treasure Valley. Incidental seepage from the canal system and water applied to farmland that is not consumptively used by crops recharges the shallow aquifer. When the irrigation system was first developed, this recharge increased the elevation of the shallow aquifer to an elevation where water began appearing on the surface. Drains were dug and natural creeks were enlarged to route this water back to the river and prevent flooding on the surface. In an average year, the same amount of water that enters the shallow aquifer as recharge leaves the aquifers via creeks and drains, so the system is assumed to be in equilibrium on an annual basis (Urban and Petrich; 2004;Reclamation, 2008a).

These local groundwater interactions are simulated using response functions in the RiverWare model. In general, response functions are generated using a groundwater model (Reclamation, 2012a) and represent the length of time that it takes for one unit of water to return to the river from a particular application location. For the purposes of this study, response functions were generated using a MODFLOW model of the Treasure Valley. A response function was generated for each point of diversion associated irrigated area and for each river reach below Lucky Peak, Lucky Peak to Glenwood, Glenwood to Middleton, and Middleton to Parma. Figure 2-5 shows the irrigated areas that were used to generate the response functions. The MODFLOW model uses monthly time steps, so the output were interpolated to a daily time step for the RiverWare model.

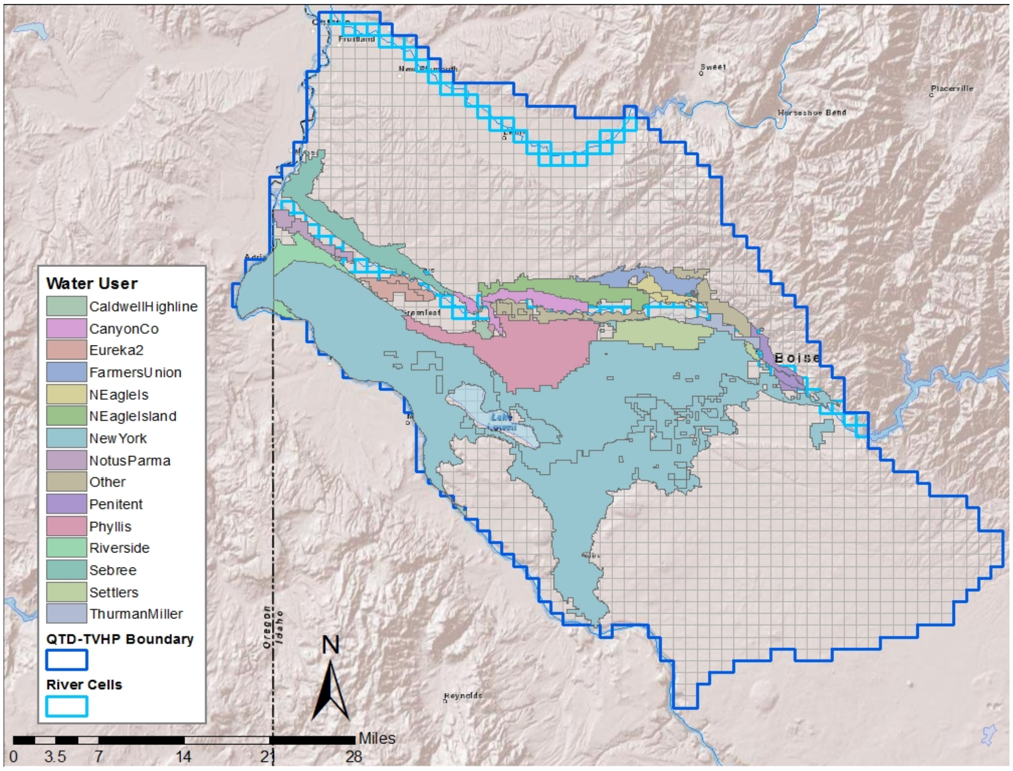

Figure 2-5: Areas, serviced by Water User objects, used to generate response functions using the Reclamation model of the Treasure Valley aquifer system (Reclamation, 2012a).

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3 Water Rights

A water right is the authorization to use water at a prescribed location and in a prescribed manner, not to own the water itself. Surface water is distributed in the Treasure Valley using natural flow rights and storage rights.

3.1 Natural Flow

Natural flow is distributed in the Treasure Valley using prior appropriation, where the most senior right to divert water is given to the person who diverted the water at the earliest date or first in time. There are 378 natural flow rights in the Treasure Valley system, which include the natural flow right to divert water directly from a river channel or to store water in the three reservoirs (listed in Appendix A). The earliest water right date in the system is June 1, 1864.

Arrowrock is the first reservoir in priority to store natural flow with a date of January 13, 1911. It can only store water at 8000 cfs until it fills to 272,200 acre-feet, and is the only reservoir with a limit on the rate that it can store water. Anderson Ranch is next in priority with a date of December 9, 1940 and has a right to store water until it fills to 413,000 acre-feet. Lucky Peak is last in priority with a date of April 23, 1963 and can also store water until it fills to 264,400 acre-feet.

3.2 Storage

Some water users have space allocated in the reservoirs and are allowed to call upon water stored in that space when needed. The storage volumes and the associated water users are listed in Appendix B.

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4 RiverWare Model Development

Two RiverWare models were developed for this study: an unregulation model and a regulation model. The unregulation model is used to calculate local inflows to the reservoirs and reaches (also called gains). The calculated gains are then used as input to the regulation model, which distributes water based on water rights.

Both models use the same objects, but the input data, object methods, and rules vary. Figure 4-1 shows the object layout for both models. Table 4-1 shows a table of the objects with objet type and name.

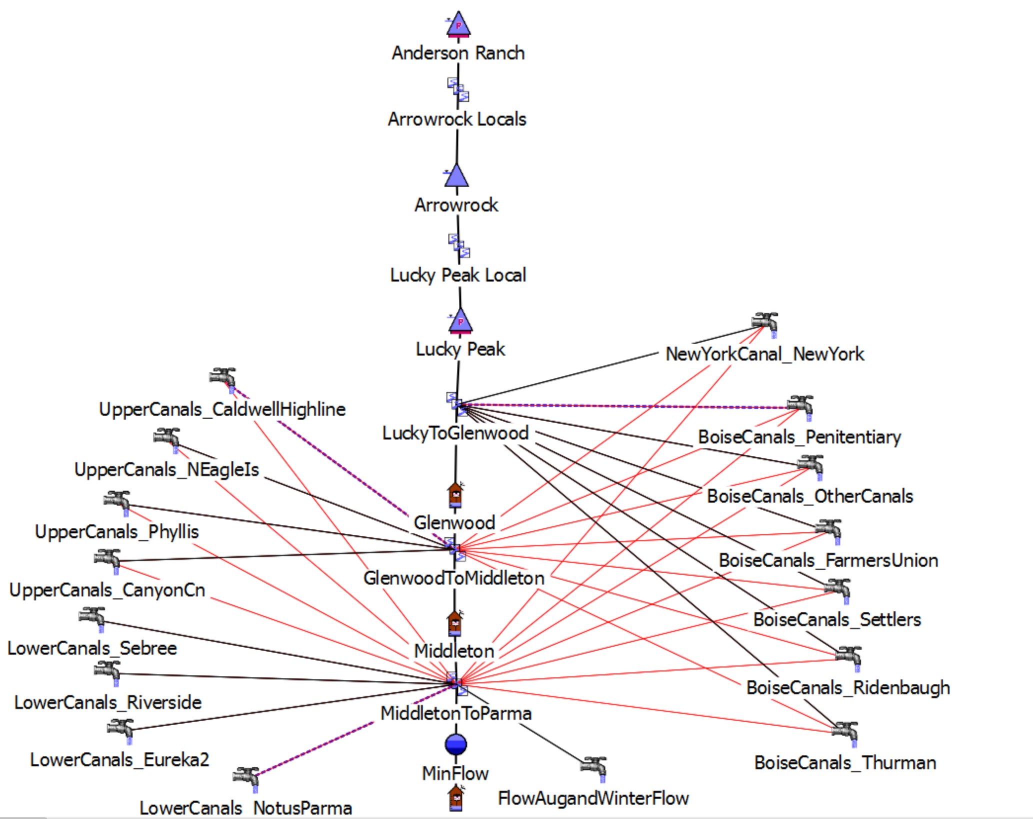

Figure 4-1: Boise River System RiverWare network.

Table 4-1: Table of RiverWare object types and names used in models.

Object Type	Object Name
Reservoirs	
Level Power Reservoir	Anderson Ranch
Level Power Reservoir	Lucky Peak
Storage Reservoir Object	Arrowrock
Reaches	
Aggregate Reach	Arrowrock Locals
Aggregate Reach	Lucky Peak Local
Aggregate Reach	LuckyToGlenwood
Aggregate Reach	GlenwoodToMiddleton
Aggregate Reach	MiddletonToParma
Diversion	
Water User	NewYorkCanal_NewYork
Water User	BoiseCanals_Penitentiary
Water User	BoiseCanals_OtherCanals
Water User	BoiseCanals_FarmersUnion
Water User	BoiseCanals_Settlers
Water User	BoiseCanals_Ridenbaugh
Water User	BoiseCanals_Thurman
Water User	UpperCanals_CanyonCn
Water User	UpperCanals_NEagleIs
Water User	UpperCanals_CaldwellHighline
Water User	UpperCanals_Phyllis
Water User	LowerCanals_Eureka2
Water User	LowerCanals_NotusParma
Water User	LowerCanals_Riverside
Water User	LowerCanals_Sebree
River Gage	
Stream Gage	Glenwood
Stream Gage	Middleton
Stream Gage	Parma

4.1.1 Reservoirs

The Reservoir Objects are designed to calculate the behavior of the three reservoirs in the Boise System, Anderson Ranch, Arrowrock, and Lucky Peak. For the unregulation and regulation models, the physical properties of the reservoirs do not change, including the storage capacities as shown in Chapter 4, regulated and unregulated spill capacities, and power generation capacities, if applicable.

The reservoir objects are solved to determine the volume of storage given a particular inflow and outflow. Inflow is specified on the Anderson Ranch object in the Hydrologic Inflow slot and in the Local Inflow slot on the Arrowrock

Locals and Lucky Peak Locals aggregated reach objects upstream of their respective reservoirs. Outflow is specified using rules that account for reservoir releases for flood control, irrigation demand, and minimum stream flows. Figure 4-2 shows the reservoir object and the aggregated reach objects that separate them. The blue boxes indicate input, the red indicates where rules are applied, and the green indicate where RiverWare solves for the result.

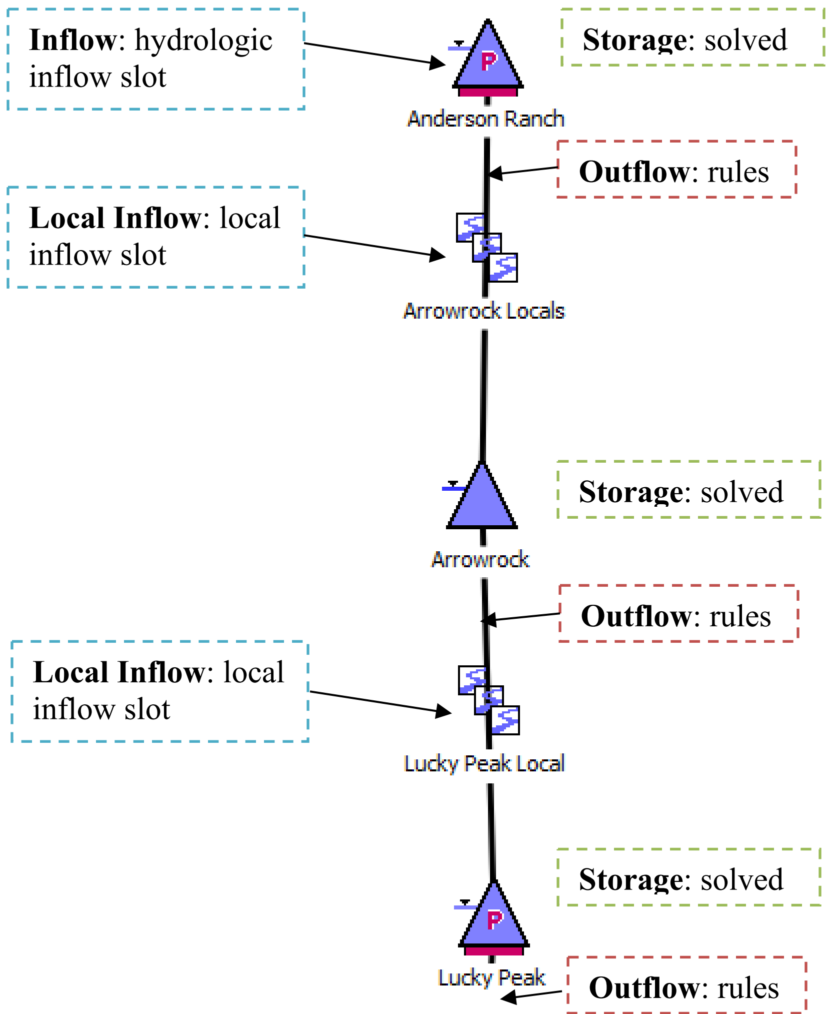

Figure 4-2: Diagram of RiverWare reservoir and aggregated reach objects.

Although hydropower is generated at all three reservoirs, this model does not simulate generation. However, it can be easily added for future studies.

4.1.2 Water Users

Water Users represent the aggregated diversion groups shown in Table 2-1. The Water User objects divert water from a reach in the river. They calculate the quantity of water that is consumptively used and the quantity that is returned to various reaches in the stream via return flows. In the calibration model, the volume of water diverted is based on the historical diversion rate, which can be found in the Diversions data object (refer to section 4.3 for how this data was compiled). The data is assigned to the *Diversion Requested* slot on each Water User object with a rule.

Figure 4-3 illustrates the calculation that is used by RiverWare to calculate return flows to the river. A portion of the water that is diverted is consumptively used by crops. The remaining fraction is assumed to return to the river via overland flow and the shallow aquifer, which is called Total Return Flow for the purpose of this discussion. The Total Return Flow was determined using a groundwater water budget (Reclamation, 2008a) and is assigned to the *Period Fraction, p,* slot on the water user object. Water applied to irrigated acres returns to different reaches on the river. The faction of the Total Return Flow that returns to each reach of the river was determined using a groundwater model (Reclamation, 2012) and is assigned to the *Return Flow Proportion* table on the water user object. The fractions in the *Return Flow Proportion, x,* add up to one. The function that describes the rate that a unit of water returns to the river, called a response function, was also determined using a groundwater model (Reclamation, 2012) and is assigned to the *Multi Return Lag Coeffs* table on the Water User object.

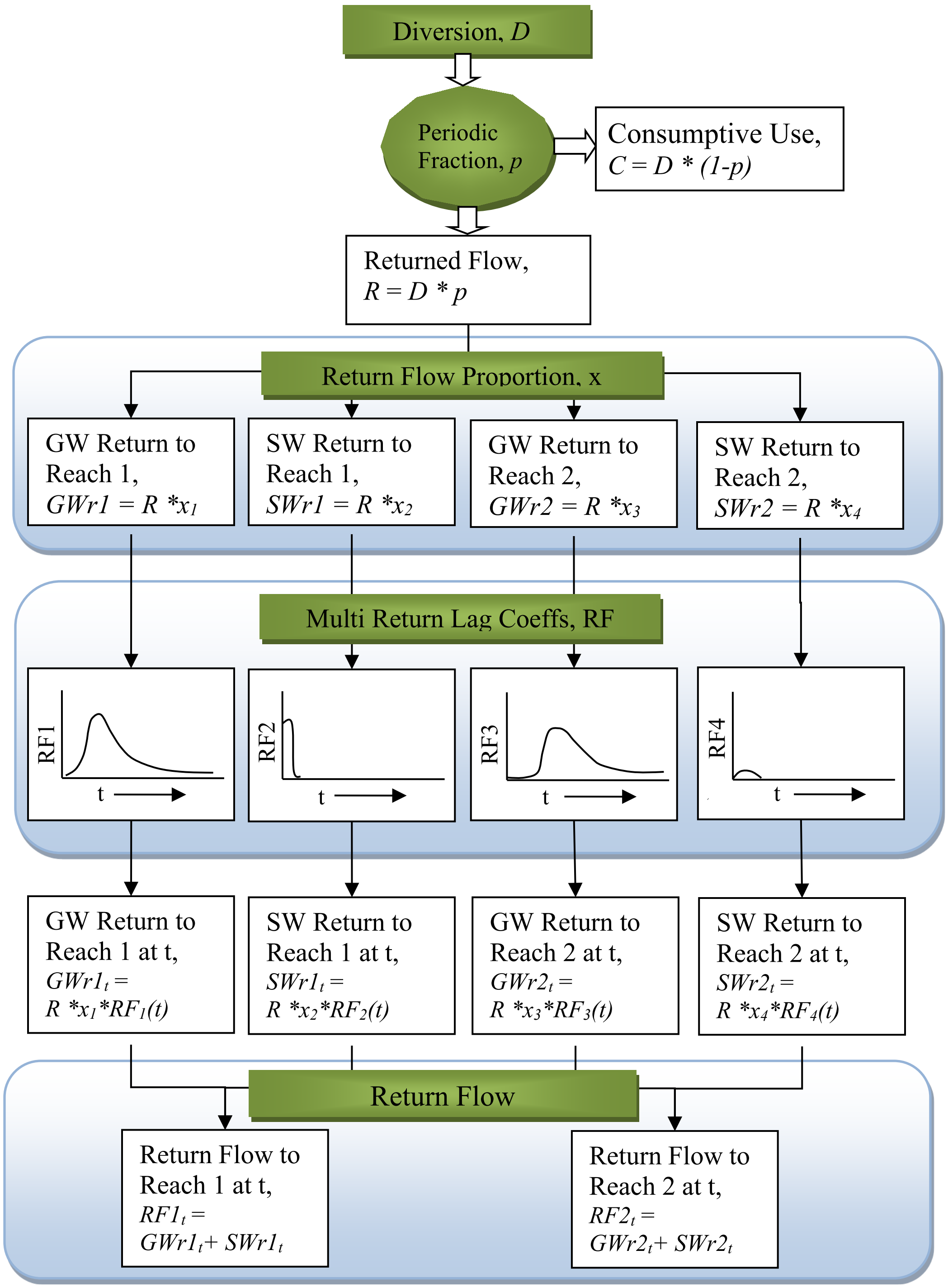

Figure 4-3: Illustration of the return flow calculation.

As an example, the water user BoiseCanals_Penitentiary has a periodic fraction of 0.1, which means that ten percent of the water diverted for the Penitentiary Water User group returns to the river via overland flow or via the shallow aquifer. The return flow from this user group returns only to the LuckyToGlenwood reach of the Boise River. Of the ten percent of diverted water that returns, 33 percent returns via overland flow and 67 percent returns via the shallow aquifer. Figure 4-4 shows the lag factors used to return water to the Lucky to Glenwood and Glenwood to Middleton reaches. Note that in this case, it takes about 60 days for all of the water to return.

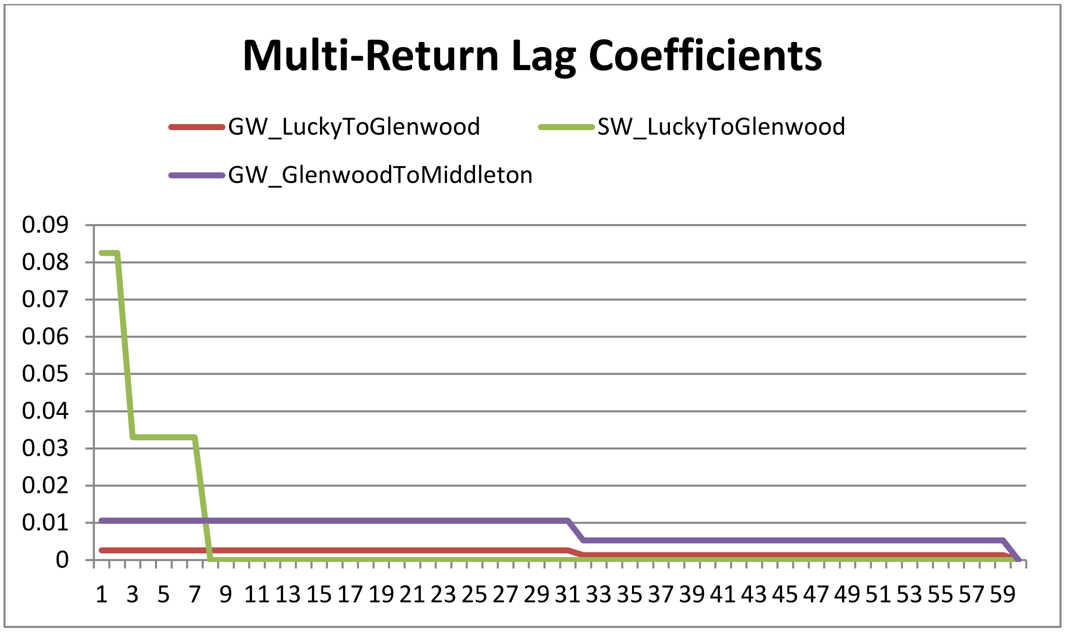

Figure 4-4: Multi-return lag coefficients for water applied to lands associated with the Penitentiary Water User object.

4.1.3 Aggregated Reaches

Aggregated Reaches represent combined stream reaches between gaged locations. Table 4-2 shows the individual reaches in each aggregated reach. Note that there is a reach for each diversion location. This is for modeling purposes only because RiverWare needs to connect a water user to an individual reach. The reach called gain is where the gains or losses calculated in the unregulation model are input.

Table 4-2: List of Aggregated Reach objects and associated individual reaches.

Aggregated Reach Object	Reach
ArrowRock Locals	Gain
Lucky Peak Locals	Gain
LuckyToGlenwood	Gain
	DiversionDam_NewYork
	BoiseCanals_Penitentiary
	BoiseCanals_Ridenbaugh
	BoiseCanals_OtherCanals
	BoiseCanals_Settlers
	BoiseCanals_Thurman
	BoiseCanals_FarmersUnion
	gwReturn
	swReturn
GlenwoodToMiddleton	Gain
	gwReturn
	swReturn
	UpperCanals_NEagleIs
	UpperCanals_Phyllis
	UpperCanals_CanyonCn
	UpperCanals_CaldwellHighline
	sw2
	gw2
MiddletonToParma	Gain
	gwReturn
	swReturn
	LowerCanals_Sebree
	LowerCanals_Riverside
	LowerCanals_Eureka2
	LowerCanals_NotusParma
	FlowAugandWinterFlow
	gw2
	sw2

The reaches called gwReturn, swReturn, gw2, and sw2 are locations where return flows enter the river. LuckyToGlenwood only has gwReturn and swReturn reaches at the bottom of the system because it is assumed that all return flows to this reach will return below where the diversions leave the river, so the return flows are not available for diversion in this reach. GlenwoodToMiddleton and MiddletonToParma have gwReturn and swReturn reaches at the top of the reach and gw2 and sw2 and the bottom of the reach. Return flows are assigned to the appropriate reach to simulate whether or not they are available for diversion in that reach. Table 4-3 shows the Water User groups and the reaches that receive their return flows.

Table 4-3: Table of Water User groups and their associated return flow reaches.

Water User Group	Return Reach
NewYorkCanal	GlenwoodToMiddleton:gwReturn
	GlenwoodToMiddleton:swReturn
	MiddletonToParma:gwReturn
	MiddletonToParma:swReturn
BoiseCanals	LuckyToGlenwood:gwReturn
	LuckyToGlenwood:swReturn
	GlenwoodToMiddleton:gwReturn
	GlenwoodToMiddleton:swReturn
	MiddletonToParma:gwReturn
	MiddletonToParma:swReturn
UpperCanals	GlenwoodToMiddleton:sw2
	GlenwoodToMiddleton:gw2
	MiddletonToParma:gwReturn
	MiddletonToParma:swReturn
LowerCanals	MiddletonToParma:gw2
	MiddletonToParma:sw2

4.1.4 Stream Gages

Stream Gages are locations in the model that flow passes through. The flow that passes through the stream gages is compared to historical observed flow during the calibration process.

4.2 Unregulation Model

The unregulation model was developed to generate reach gains and losses for use the regulation model. Gains and losses are flows that are added to or subtracted from an individual reach that are not accounted for with other input data.

For a stream reach, they are calculated by the following equation:

$$G_{Down} - G_{Up} + div - stream \pm gw = gain\ or\ loss$$

where, G_{up} is the flow at the upstream gage, G_{down} is the flow at the downstream gage, div is the sum of all diversions in the reach, stream is the sum of all known stream flow that will be defined as separate inflows to the reach, and gw is local groundwater influence. If any of these values are not used to calculate the gain or loss, the influence from that parameter will be imbedded in the gain or loss value.

If there is a reservoir in the reach, the following equation is used:

$$\Delta storage - G_{Up} + div - stream \pm gw = gain/loss$$

where Δstorage is the change in reservoir storage.

Table 4-4 shows the objects and slots where data was input to calculate the gains and losses.

Table 4-4: Table of input slots for unregulation model.

Object Type	Slot	Gain/loss parameter
Level Power Reservoir	Storage	Δstorage
	Outflow	g_{up}
Storage Reservoir	Storage	Δstorage
	Outflow	g_{up}
Water User	Diversion	div
	Lag Coefficients	gw
Aggregate Reach	Outflow	g_{up}, g_{down}

Gains and losses are calculated using the calcLocalInflow method on the Local Inflow Slot on the Gain segment of the following objects: Arrowrock Locals, Lucky Peak Local, LuckyToGlenwood, GlenwoodToMiddleton, and MiddletonToParma. They are also calculated on the Inflow slot on the Anderson Ranch Reservoir Object.

Figure 4-5 through Figure 4-10 shows the daily gains and losses calculated using the unregulation model. The figures show that the gains and losses contain a large amount of variability, which is likely due to daily gage fluctuations or erroneous measurements. An example of this large variability is the October 2000 data point in Figure 4-5, which is likely due to an inconsistent data point in one of the datasets used to calculate the gain. The RiverWare rules were written in such a way to handle large variability.

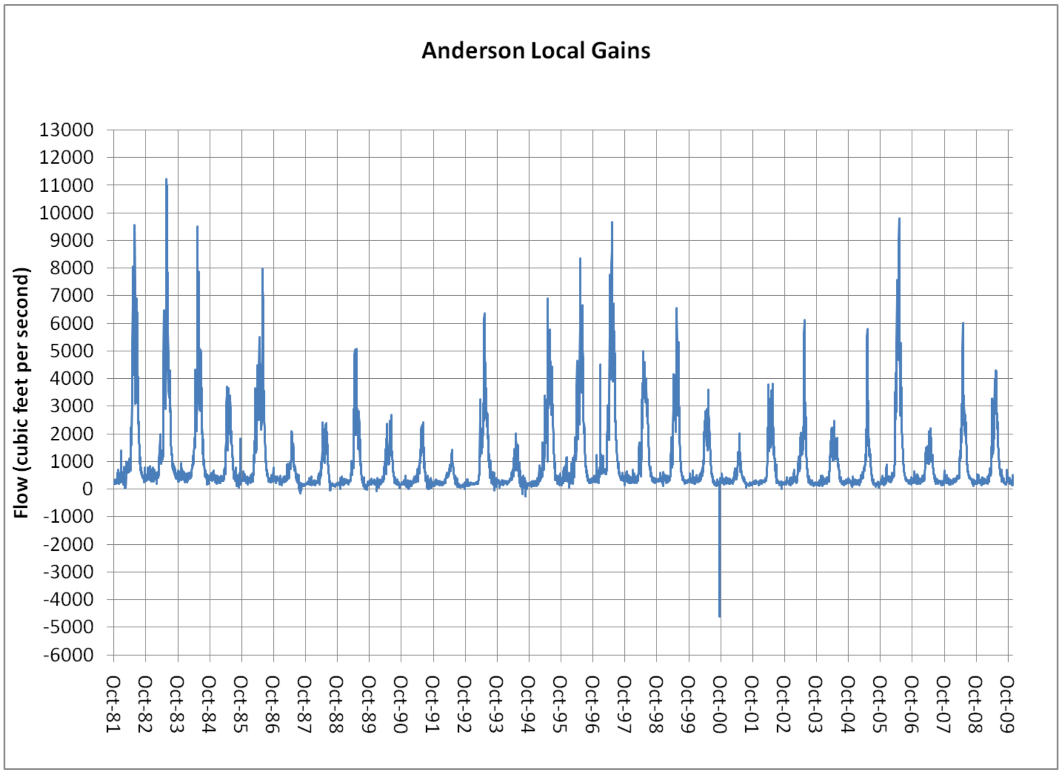

Figure 4-5: Anderson Ranch local gains.

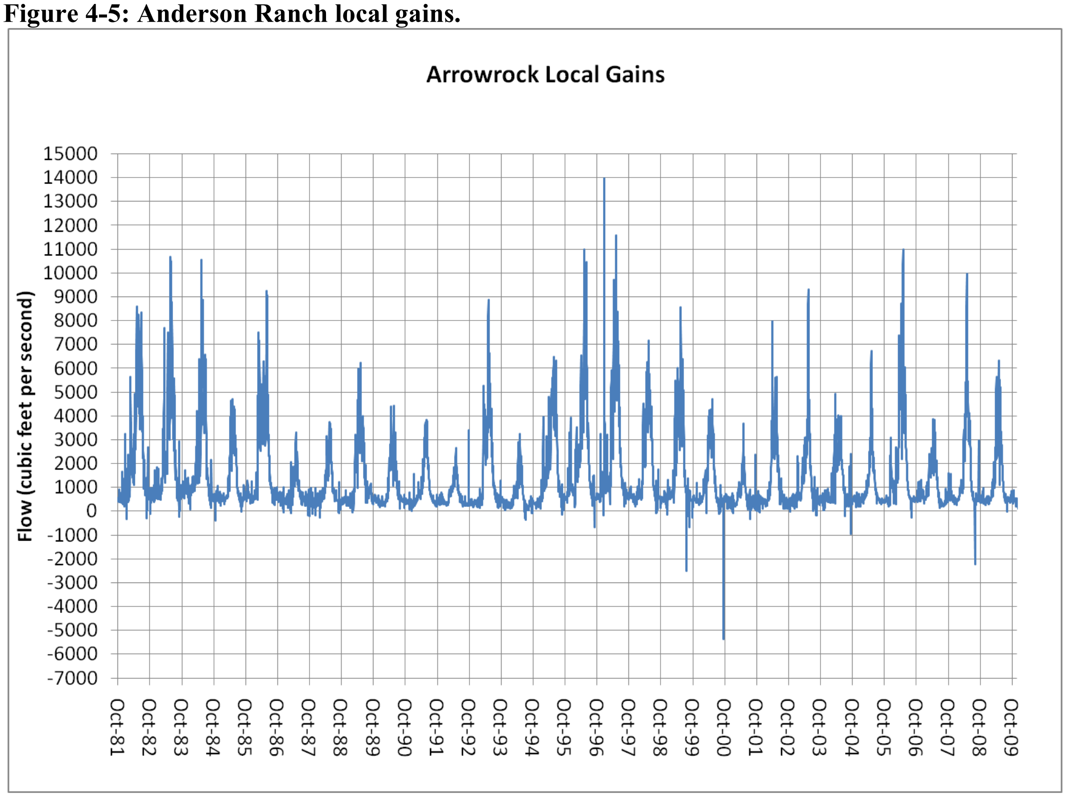

Figure 4-6: Arrowrock local gains.

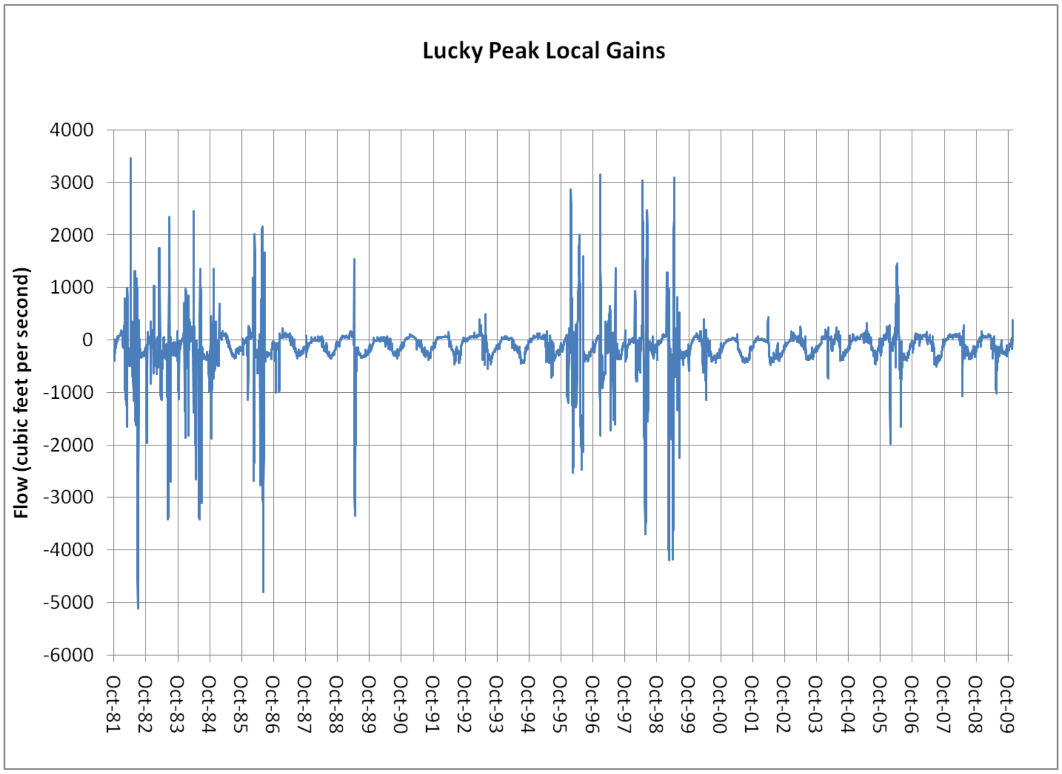

Figure 4-7: Lucky Peak local gains.

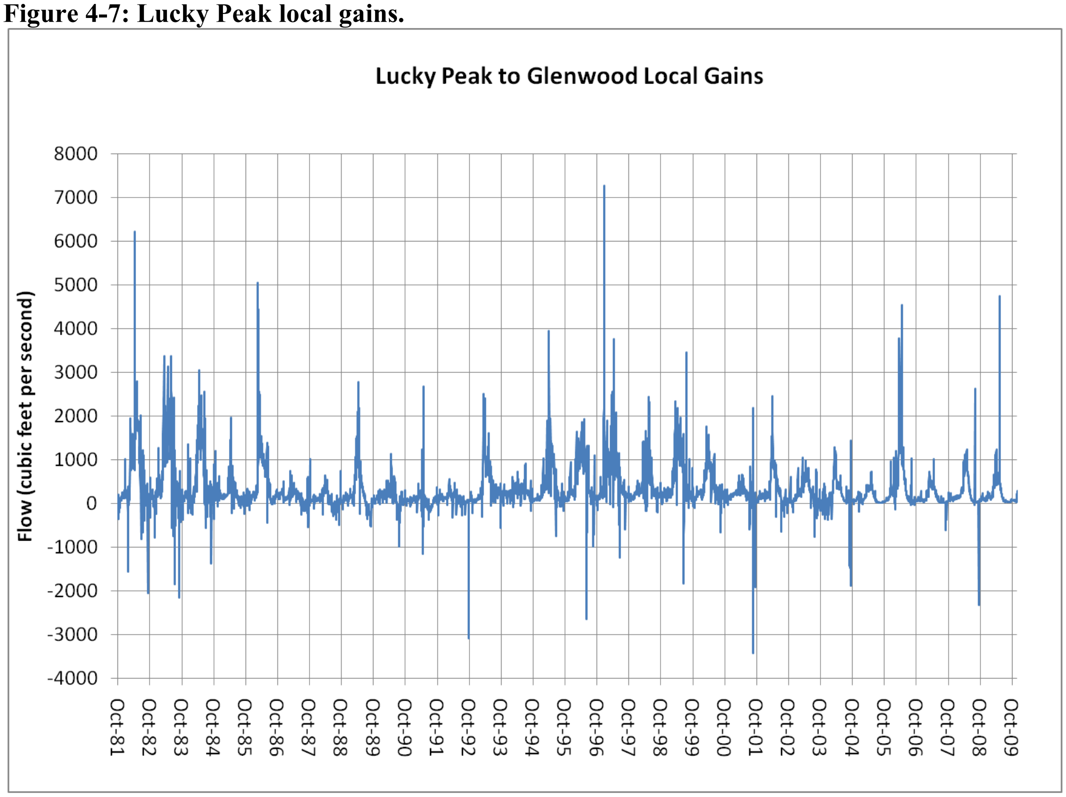

Figure 4-8: Local gains from Lucky Peak to Glenwood.

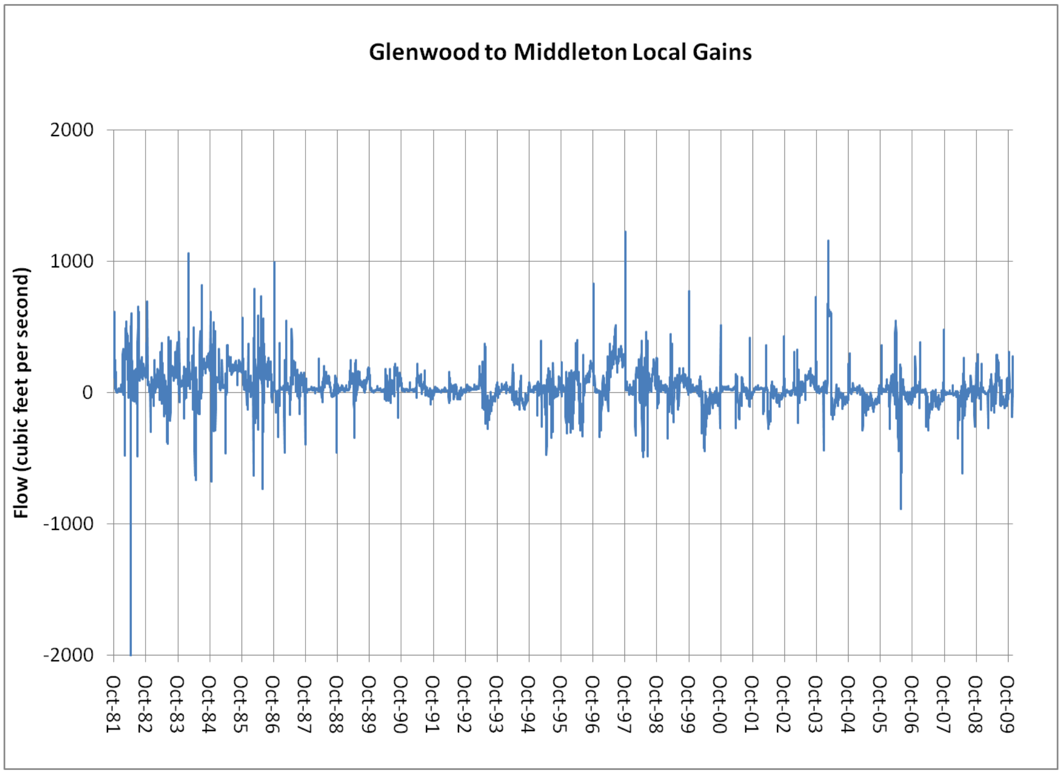

Figure 4-9: Local gains from Glenwood to Middleton.

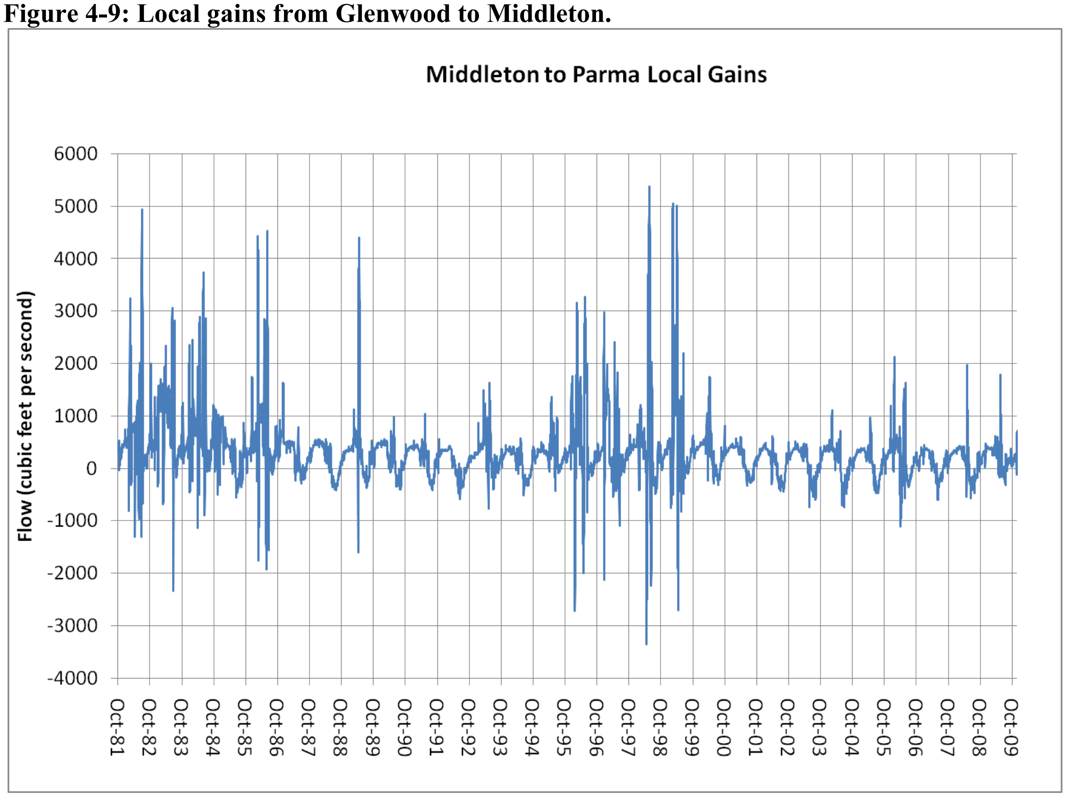

Figure 4-10: Local gains from Middleton to Parma.

4.3 Regulation Model

The regulation model simulates flow through the physical system using priority water rights flow distribution. The regulation model uses the same objects and physical behaviors as the unregulation model, such as return flows.

During development, the model was run for a 28 year simulation period from October 1, 1981 to September 30, 2009. Reservoir storage contents and flow at the three river gages was compared to historical observed data. Although this comparison was made, it was recognized that simulated reservoir contents and flow at the river gages may not fully match observed historical data since actual operations do not always follow a set logical pattern that is necessary for the model to run.

Three types of accounts were used in the regulation model, storage, diversion, and pass-through. The terminology used to describe the type of account is based on the RiverWare names for the accounts, not the legal name of the type of accounts. Storage accounts reside on reservoir objects and represent stored water in a reservoir. Diversion accounts reside on water user objects and are used to account for water that is diverted to natural flow and storage water users. Pass-through accounts are used to move water downstream and account for ownership on each object.

The regulation model is not designed to exactly replicate the official accounting that takes place in the basin, which is the responsibility of IDWR. Rather, it is used as a method for simulating the system to ensure that water is moved through the system based on ownership, not just physical availability. For this reason, generalizations are made when assigning the initial request of the diversion accounts which may not exactly represent the historical initial request or diversion of an individual account.

4.3.1 Storage accounts

Each reservoir object has a corresponding storage account, Anderson Ranch has ANDactiveAccrual, Arrowrock has ARK1, and Lucky Peak has LUC. Each a storage account is assigned the priority water right that belongs to the reservoir. The model distributes natural flow using the SolveWaterRights function and the priority water right dates. The model fills the reservoir accounts (and the physical reservoir objects) when the SolveWaterRights function is called, in priority according to the priority water right date.

4.3.2 Diversion accounts

Each water user object represents a canal or group of canals that may own numerous water rights. Both natural flow rights and storage contracts are represented on a water user object using diversion accounts and they are represented as separate accounts. The diversion accounts that receive natural flow are named with the name of the owner and the date of the water right. For example, the right owned by Penitentiary with a June 1, 1870 priority date is named “Penitentiary_1Jun1870”. The diversion accounts that receive stored water are named with the name of the water user object and the reservoir in which the storage contract exists. For example, the diversion account on Ridenbaugh that receives Arrowrock stored water named “RidenbaughStoredARK”.

There are 287 diversion accounts, 241 represent natural flow rights and 46 represent storage rights. The water user object, the account type, and the account name can be found in Appendix A for natural flow rights and Appendix B for stored water rights. If the account receives natural flow, the maximum diversion rate (cfs) is displayed. If the account receives stored water, the maximum accrual (acre-feet) is displayed.

4.3.3 Simulation

During each timestep of the simulation, the model sets the initial request of all of the accounts that receive natural flow on both reservoirs and water user objects. Then the model releases water for flood control, if necessary, since water released for flood control is assumed to be available for natural flow distribution. After the flood control releases, water is moved between reservoirs to maintain elevations for various purposes within each reservoir. The SolveWaterRights function is called to distribute natural flow to the natural flow diversion accounts. If a Water User object has a shortage (does not receive all of the water it asked for in the initial request stage) after the natural flow distribution and has rights to stored water, it can request storage water from the reservoirs. If the Water User object still has a shortage and water is available in the reservoirs, the Water User may request rental water. Once all of the reservoir releases have been made for natural flow, storage, rental, and to meet minimum flows, the model sums the outflows for all of the accounts on the reservoir and assigns the sum of the outflows to the outflow on the physical object. The same is done on the diversion accounts for the diversion amount on the Water User objects. RiverWare solves the physical objects and the timestep is over.

4.3.3.1 Initial Request

During simulation, the Water User diversion accounts requests an amount of water that it would like to divert. For the calibration model, this quantity of water is based on the historical diversion for that Water User. Initial request for each natural flow diversion account is calculated using the following equation,

$$IR = HD * \left(\frac{DR_i}{\sum_{Water\ User} DR}\right)$$

where, the historical diversion, HD, is the historical diversion rate for the Water User at a timestep, the diversion rate, DR, is the maximum allowable diversion rate for the water right account, and the sum of the diversion rate is the sum of all of the maximum allowable diversion rates for all of the accounts on the Water User. The initial request is limited to the maximum allowable diversion rate of the account. If the system is considered to be in flood control, meaning that the reservoirs are within 10,000 acre-feet of the rule curve target, the maximum allowable diversion rate is increased to an arbitrarily large number, since water users are allowed to divert as much as needed during flood control. As stated previously, the regulation model is not designed to exactly replicate historical diversions on each account. This method generalizes the individual account request and will be used for all scenarios.

4.3.3.2 Shortage

Shortage is defined as the difference between the historical diversion and the sum of the diversions for all of the natural flow diversion accounts on the Water User object. This definition of shortage is used to determine the quantity of stored or rental water should be released for that Water User object.

4.3.3.3 Natural Flow Distribution

Natural flow is distributed using the allocatableFlow pass-through accounts and the *SolveWaterRights* function. The solve water rights function sorts the natural flow rights in order of priority date and distributes water based on the Initial Request of each account.

4.3.3.4 Storage Water Distribution

Storage water is distributed through the Stored pass-through accounts to meet the shortage on a Water User. If the Water User has storage water ownership and water is available in the Reservoir storage account for that user, storage water is released from the Reservoir storage account and delivered to the Water User storage diversion account.

4.3.3.5 Rental Water Distribution

Rental water behaves similarly to storage water. It is also distributed through the Stored pass-through accounts. All Water User accounts have rental accounts. If the Water User does not receive its initial request through natural flow or stored water, it is assumed to have received rental water. To prevent the reservoirs from releasing too much water in water short years, the system checks to make sure there is enough water in the reservoirs to distribute rental water. This check becomes important in modeled scenarios where actual diversions are not known.

4.3.3.6 NegGains

The NegGains pass-through accounts are set up to receive negative gains that might flow into a reach. Negative gains are the result of losses from a particular reach in the river during a given timestep and must be accounted for. The SolveWaterRights function will not solve if there is a negative number in the AllocatableFlow pass-through accounts, so the NegGains pass-through accounts were added as a place holder for the negative gain values.

4.3.4 Initialization Rules

Initialization rules are only used during the initialization step of the model run period. In this model, they are used to set starting conditions and values that do not change during the run period. This section provides brief descriptions of each rule and its functionality.

4.3.4.1 SetInitialAccrual
Each account on the Water User objects calculates an accrual as it diverts water. For the accrual to calculate, an initial value is required at the initialization timestep (run start date minus one day). This rule sets the initial accrual value for each account on each Water User object.

4.3.4.2 SetReservoirs
The Reservoirs Objects and storage accounts require an initial storage value to calculate storage. This storage accounts also require and initial accrual value to calculate storage and accrual. This rule sets the initial values at the initialization timestep.

4.3.4.3 SetGainLoss
The reservoir accounts have a slot called gain/loss, where the user can set known gains or losses to the reservoir. An example of a loss might be evaporation. This value must be set for the account to solve, so this rule sets the gain/loss value at each timestep to 0.

4.3.4.4 SetPreroutedReturnFlows
Return flows are calculated using lag factors, so to ensure that the proper return flow value is used on the first timestep, pre-routed return flows are input into the model. They are required for the number of lag time steps. In this model, there are 365 lag timesteps, so 365 pre-routed return flow values are required. The values are set using this rule.

4.3.4.5 SetLocals
The local inflows are set on the objects for all of the timesteps.

4.3.5 Rules
The regulation model solves using 26 rules and many functions. In general, the rules initialize the model by setting all of populating the required data slots. The rules execute the steps described in the simulation section. This section provides a brief description of each rule and its functionality. The rules are not necessarily in the listed order in the simulations.

4.3.5.1 allocatableFlow_LocalInflow
The slot inflows on the allocatable flow pass through accounts are set where local inflows enter the allocatable flow line.

4.3.5.2 SetResOutflow and WU DIVReq1
The starting condition for all of the Reservoir Objects is set by setting the initial outflow value on each Reservoir Object. The initial outflow is a sum of all of the accounts on the reservoir object at the current time step.

This rule also sets the starting condition for all of the Water User objects by setting the diversion requested value on each Water User object. The diversion requested is a sum of all of the accounts on the Water User object at the current time step.

4.3.5.3 SetMaxRequest
The maximum request on each natural flow account is set equal to the legal allowable diversion rate, or, if the system is considered to be in flood control, the maximum request is set to some large number to allow the Water User to divert their total request.

4.3.5.4 InitialRequestHistorical
The initial requests for all of the diversion accounts on each Water User object are set according to the function described in section 4.3.3.1. This rule is used in the calibration model run to set the diversions to historical values.

4.3.5.5 InitialRequestReservoirs
This rule sets the initial requests for the storage accounts on the Reservoirs. The storage accounts on Anderson Ranch and Lucky Peak set their initial request based on the Fill Conservation Pool method. The water right for the storage account on Arrowrock is limited to 8000 cfs, so the initial request is set at 8000 cfs. The initial request is decreased as the reservoir is close to full, so as to not fill the reservoir beyond its capacity.

4.3.5.6 ANDFloodNew
Flood control outflows are set from the storage account on Anderson Ranch reservoir, AND. Anderson Ranch flood control season is from November 20 through July 15.

The three reservoirs use a system rule curve that dictates the amount of required space in the reservoirs at a particular time of the year and given the forecast at that date. Another similar curve dictates the percentage of space is required in each reservoir. Outflows are set to ensure the space requirement is met, while making sure the reservoir does not release more water than is physically possible.

4.3.5.7 ARKFloodNew
Flood control outflows are set from the storage account on Arrowrock, ARK1. Arrowrock flood control season starts in December and ends on July 15. Arrowrock flood control releases follow the same rule curves discussed in the previous section.

4.3.5.8 LUCFloodNew
Flood control outflows are set from the storage accounts on Lucky Peak, LUC. Lucky Peak flood control season is from November 20 through July 15. Lucky Peak flood control releases follow the same rule curves as described in section 4.3.5.6.

4.3.5.9 DownstreamNegGains
Water is released from the Lucky Peak storage account LUC to make up for any negative flows in the pass-though accounts downstream of Lucky Peak. If LUC does not have enough water, the rule checks for available water in ARK or AND to release.

4.3.5.10 AND2LUC
Water is released from Anderson during the summer to maintain minimum flows below the dam and to maintain volumes in Arrowrock that are needed for habitat. Arrowrock storage should not be drawn down below 33,600 acre-feet and it should be at 50,000 acre-feet by September 30 to maintain bull trout habitat.

4.3.5.11 ARK2LUC
This rule releases water from Arrowrock to Lucky Peak to maintain recreation reservoir elevations throughout the summer months.

4.3.5.12 ReturnFlows
The return flows from the physical objects are set on the accounts using this rule. Return flows are calculated at each timestep when the diversions are set on the Water User object. They do not automatically transfer to the accounting layer, so this rule is used to do that. The return flows in the current timestep on the accounting layer are from the previous timestep since the current timestep's return flows have not yet been calculated. Since the timesteps are only one day long, this inaccuracy is considered acceptable.

4.3.5.13 allocateFlow1
SolveWaterRights function is called to distribute the natural flow based on availability, priority date, and initial request of each account.

4.3.5.14 SetTotalStorageOut
After the natural flow is distributed, the shortage on each Water User with a storage account is summed and released from LUC into the Stored water distribution line.

4.3.5.15 NewStoredSupplies
The supply to each storage account is set with either the Water User shortage or 0 cfs. If a Water User contains multiple storage accounts, the shortage is divided evenly among the accounts and the supplies are set accordingly.

4.3.5.16 Rental
This rule calculates the quantity of rental water to release from the reservoirs. The quantity of rental water is calculated on the Water User objects and is the shortage on each object after each object receives natural flow and storage water (or just natural flow if the Water User does not have any storage accounts). The rental water is released into the Stored water distribution line.

4.3.5.17 Rental Supplies
Supplies to each rental account are set to the Water User shortage or 0 cfs.

4.3.5.18 FlowAug

This rule is used to meet the Flow Augmentation requirements on the Boise River System, which is 40,932 acre-feet of stored water released to flow out of basin to augment flows for fish downstream. Flow Augmentation water is released between April 15 and June 15. This rule sets the release from the reservoirs into the Stored water distribution line if flows at the Glenwood gage are below 6,500 cfs and sets the diversion on the FlowAug account on the FlowAugandWinterFlow Water User object. The water user object returns all of the water in the next timestep and is just used to keep track of the volume of water released for Flow Augmentation each year.

4.3.5.19 CheckMins

Minimum flows are checked downstream of Anderson Ranch reservoir and at the Glenwood gage. If the flows in the stream do not meet minimum flow requirements after all of the previous rules set the releases, additional water is released from Anderson Ranch or Lucky Peak to meet the minimum flow requirement at these two locations.

4.3.5.20 Glenwood

Flood stage requirements at the Glenwood gage are checked. If the flow past the gage is higher than flood stage, 6,500 cfs, an attempt is made to reduce the outflows from Lucky Peak. This reduction is done in a stepwise fashion, first trying to reduce the flows to 6,500 cfs, then 8,500 cfs, then 12,500 cfs.

4.3.5.21 SetResOutflow and WU DivReq

Outflow on the Reservoir objects are set with the sum of the account Outflows on that object. It also sets the Diversion Requested with the account Diversions on each Water User object. After these values are set, the RiverWare controller can solve the physical system and the timestep ends.

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5 Calibration

The Boise System regulation model was calibrated by adjusting rules to match historical reservoir contents and outflows, streamflow at the gages, and grouped diversions represented on the Water User objects. Although every attempt is made to match the historical values, it is recognized that reservoirs are operated by humans, and not every action is repeatable using logical statements. Therefore, there are some areas where the calibrated model values do not match historical values.

5.1 Reservoirs

Figure 5-1 through Figure 5-4 show the end of month reservoir contents for Anderson Ranch, Arrowrock, Lucky Peak, and the sum of all three, respectively. Although each reservoir has its own set of operational rules, adjustments between the reservoirs do not always follow a repeatable set of rules. Therefore, it is most useful to compare the total modeled system storage to historical system storage when trying to determine the goodness of fit. System storage is the sum of the storage in all three reservoirs.

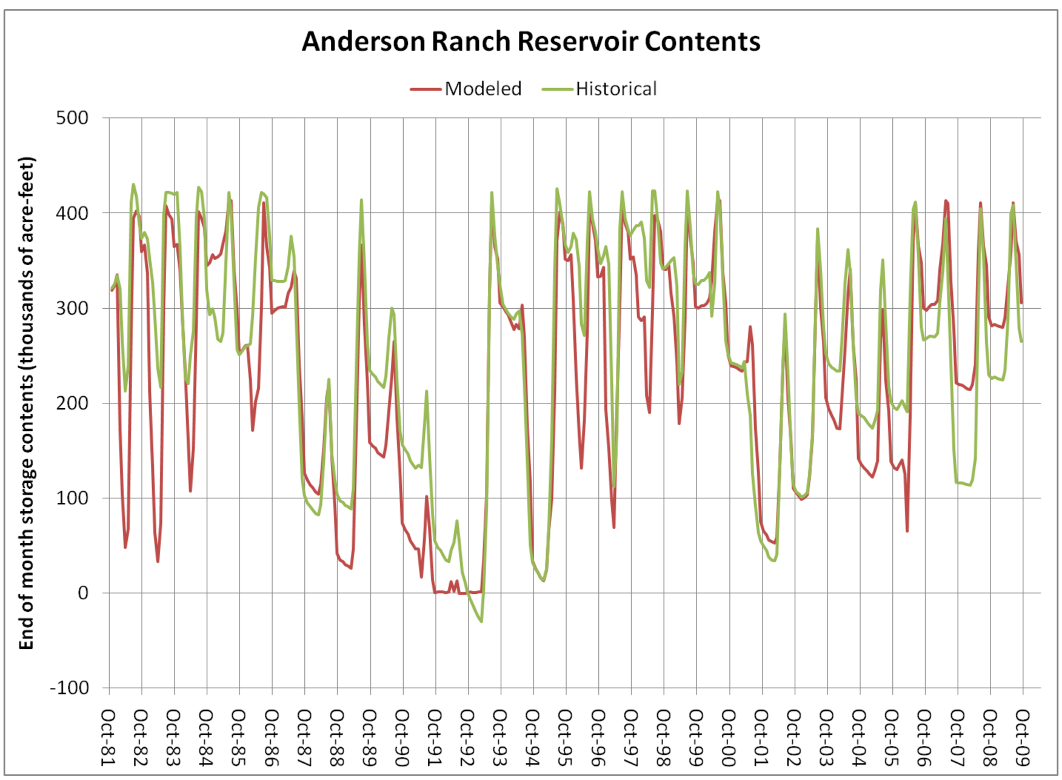

Figure 5-1: Plot of modeled and historical end of month reservoir contents at Anderson Ranch.

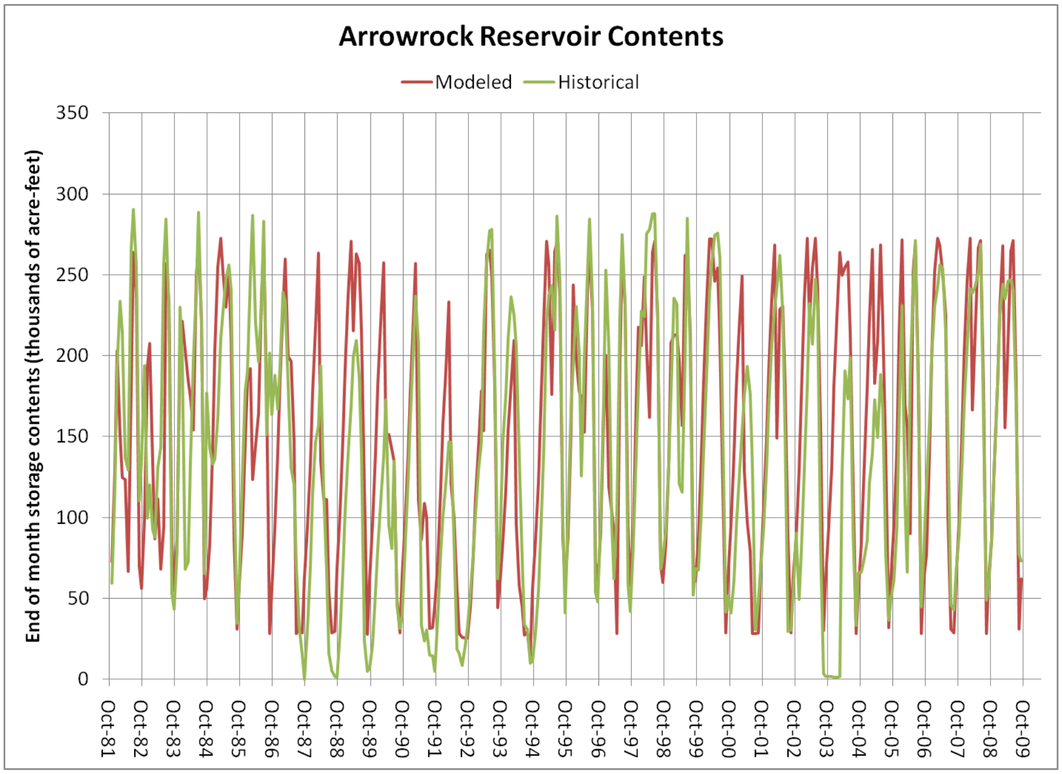

Figure 5-2: Plot of modeled and historical end of month reservoir contents at Arrowrock.

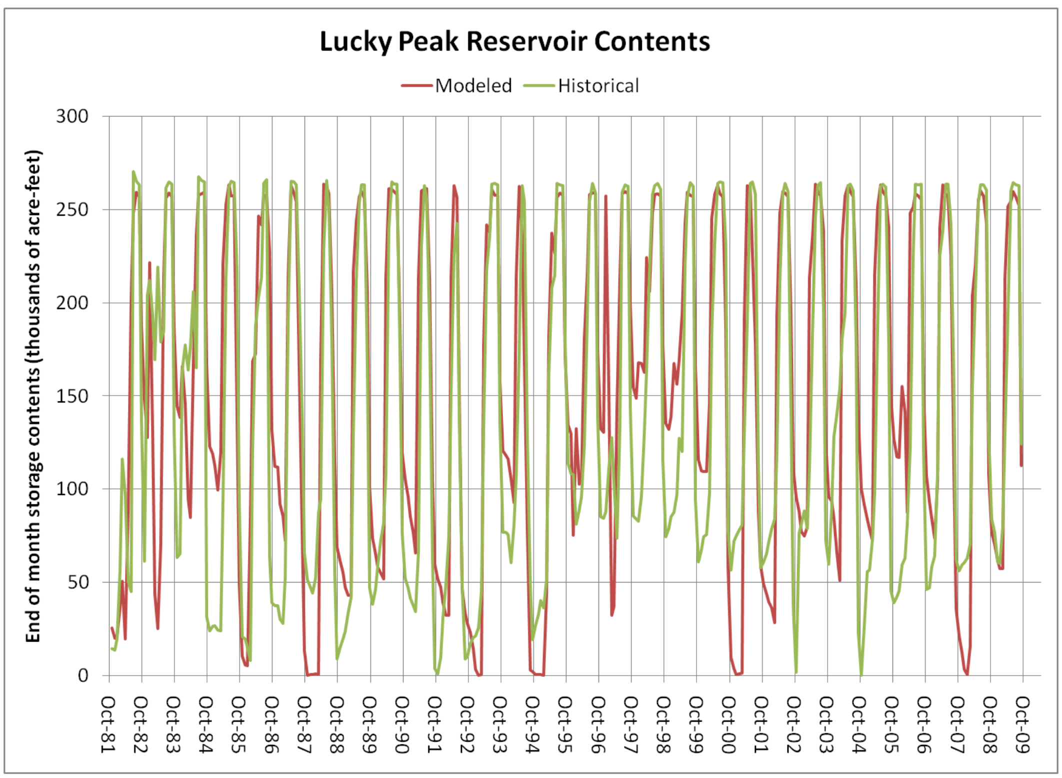

Figure 5-3: Plot of modeled and historical end of month reservoir contents at Lucky Peak.

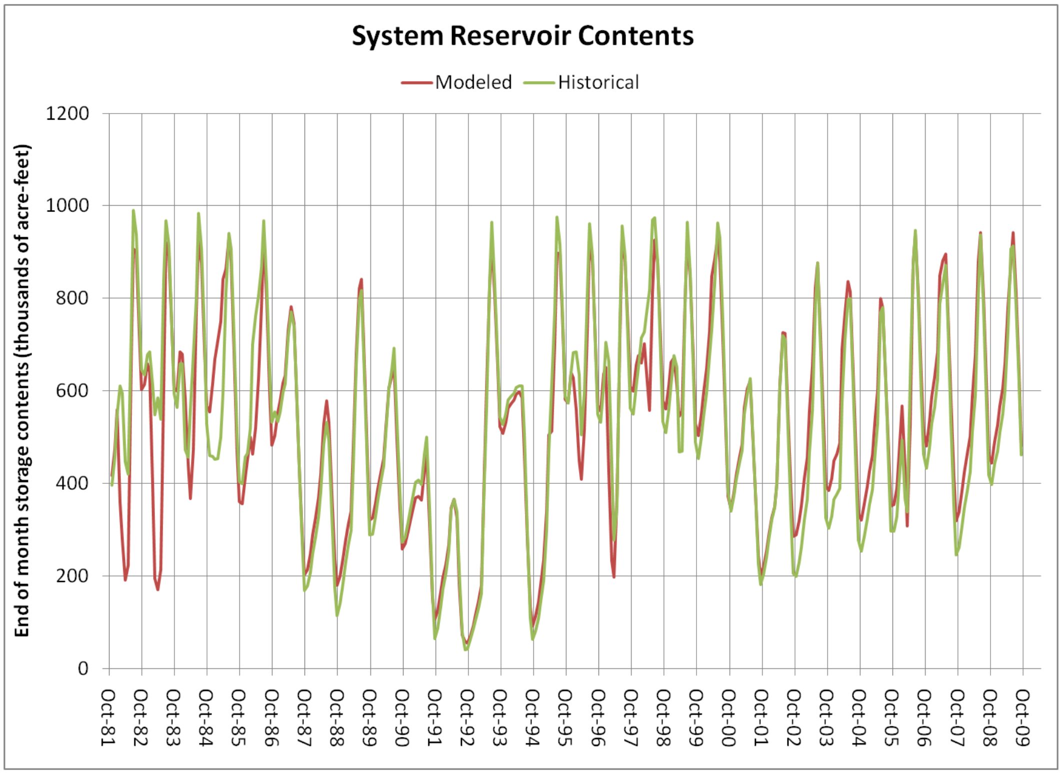

Figure 5-4: Plot of modeled and historical end of month reservoir contents for the system.

Figure 5-5 shows a plot of modeled versus historical system end of month contents. Comparing the modeled and historical end of month contents for all three reservoirs gives a coefficient of determination value (r^2) of 0.87. For reference, a perfect match between modeled and historical reservoir contents would produce an r^2 value of 1.0, and the values would line up in a one-to-one line.

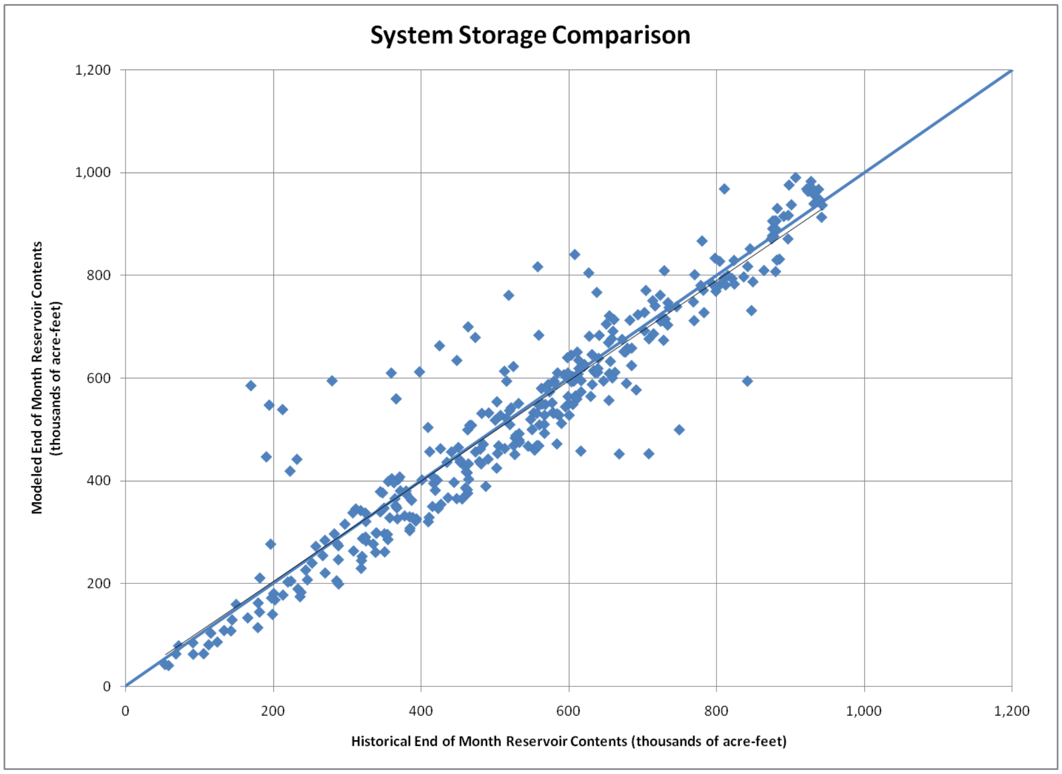

Figure 5-5: Modeled versus historical system end of month contents.

Figure 5-6 through Figure 5-8 show observed historical and modeled reservoir outflow. In general, the modeled outflow from the three reservoirs matched historical.

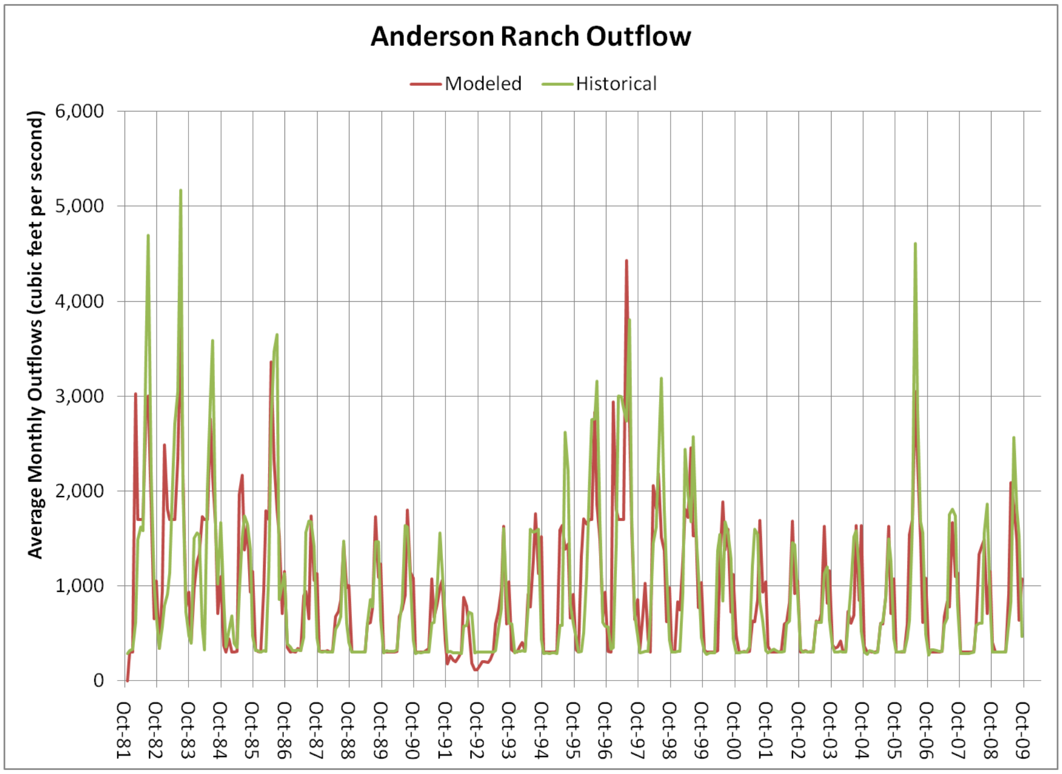

Figure 5-6: Modeled and historical outflow from Anderson Ranch.

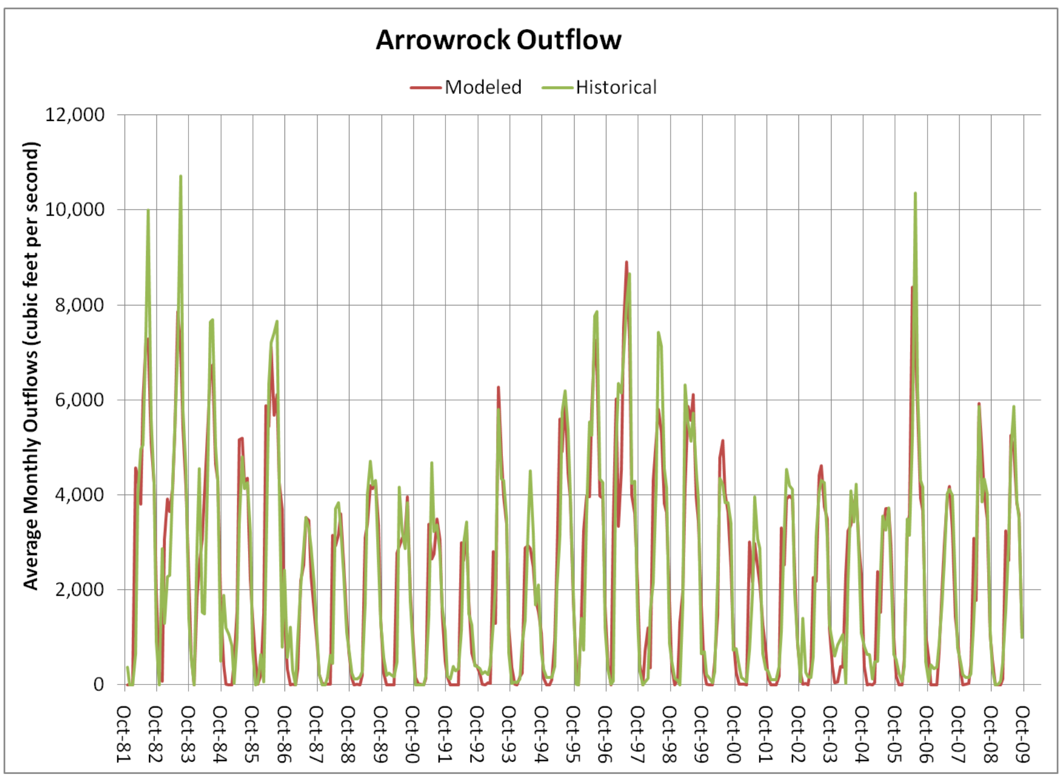

Figure 5-7: Modeled and historical outflow from Arrowrock.

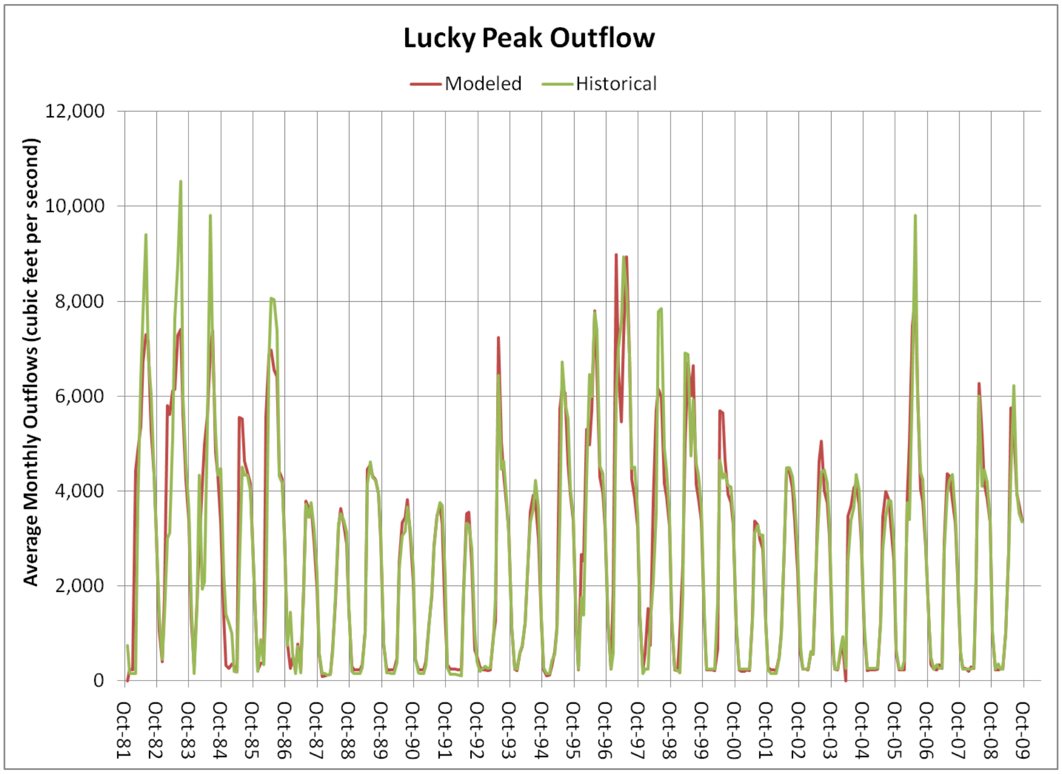

Figure 5-8: Model and historical outflow from Lucky Peak.

5.2 Gages

Figure 5-9 through Figure 5-11 show the modeled and historical flow at the Glenwood gage (BIGI), the Middleton gage (BOMI), and the Parma gage (PARI). In general, the modeled flow at the gages matches the historical flow measured at the gage.

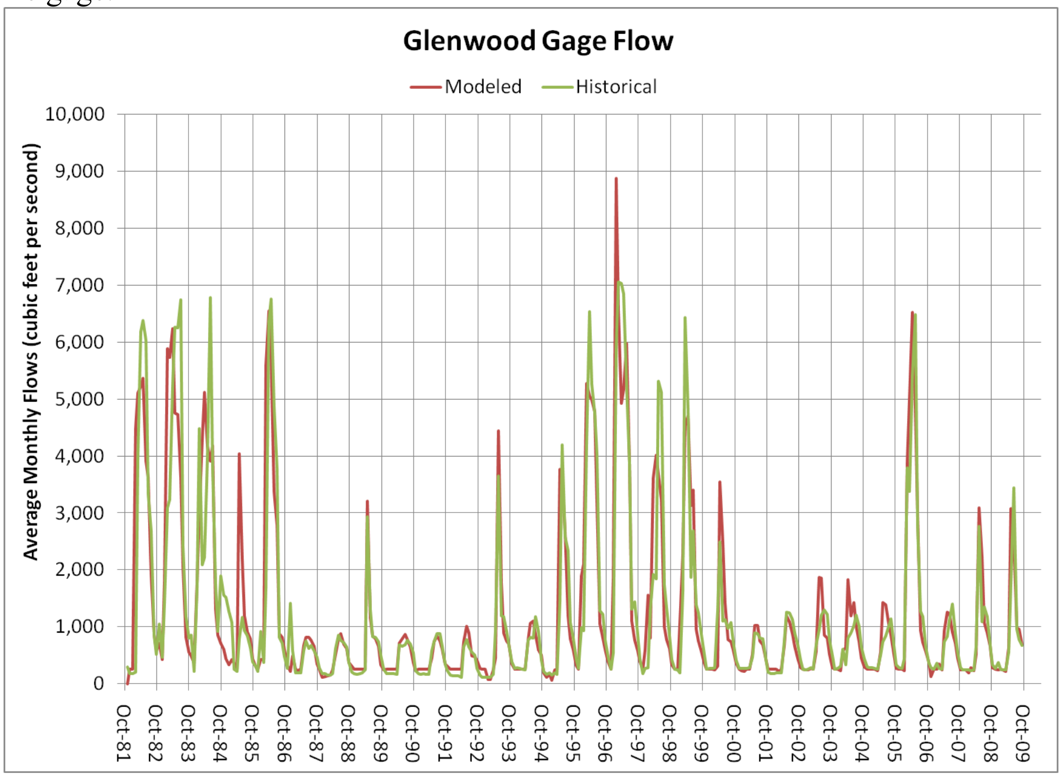

Figure 5-9: Modeled and historical flow at the Glenwood gage (BIGI).

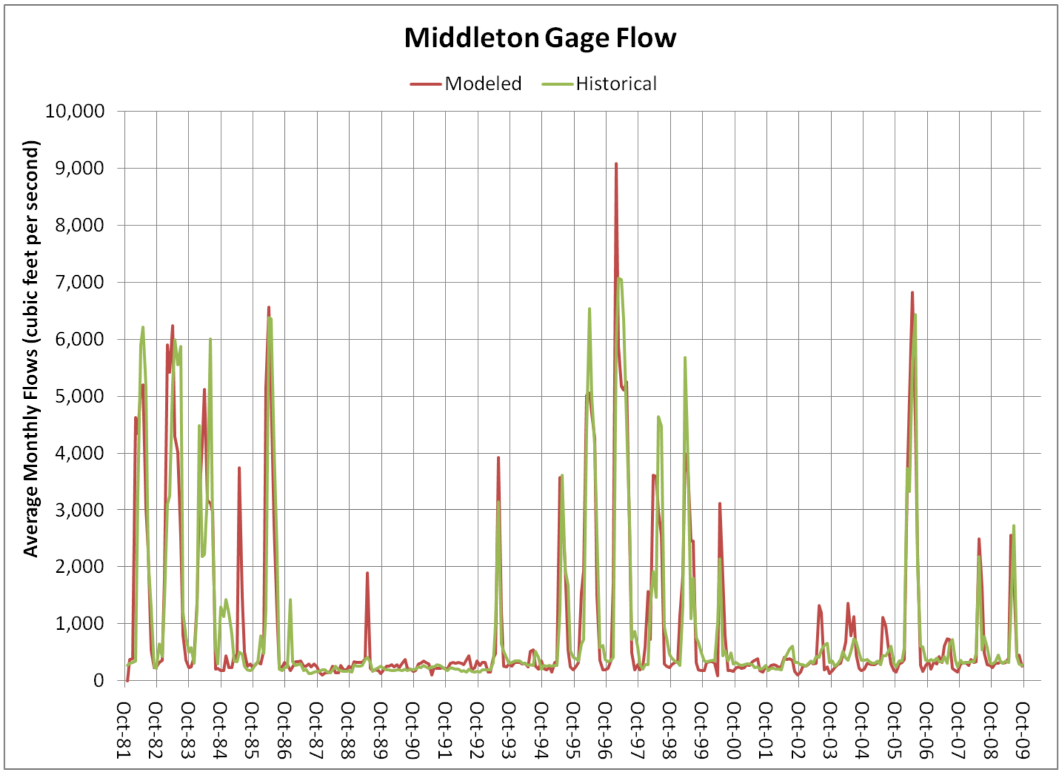

Figure 5-10: Modeled and historical flow at the Middleton gage (BOMI).

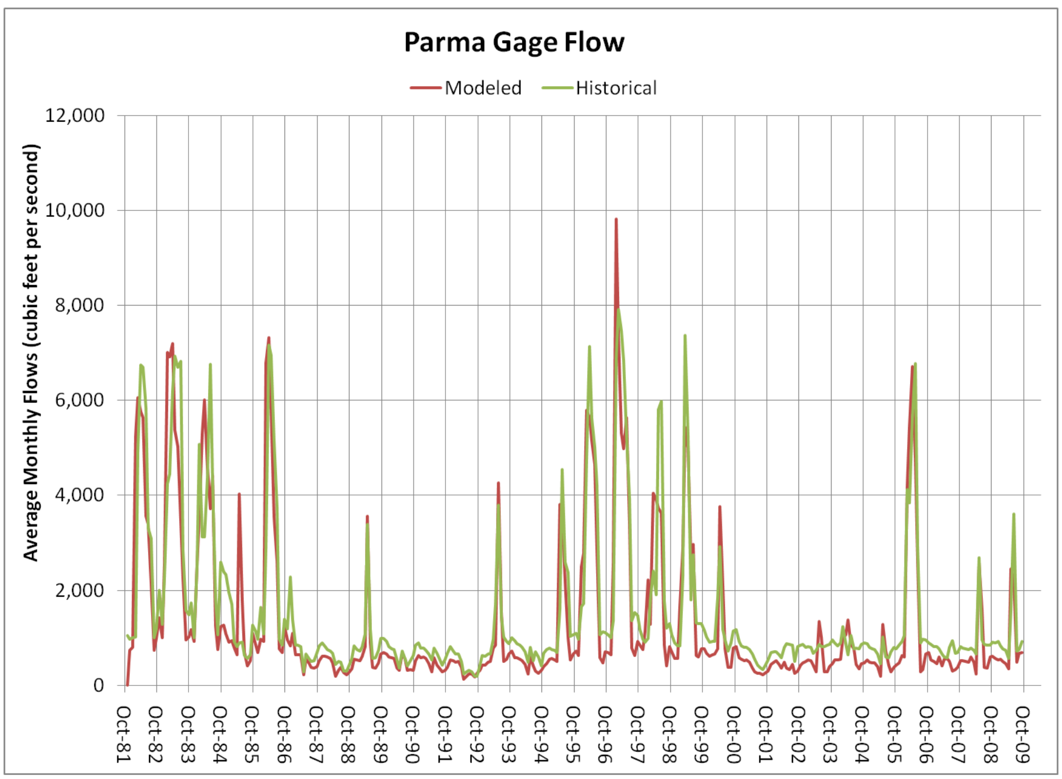

Figure 5-11: Modeled and historical flow at the Parma gage (PARI).

5.3 Diversions

Figure 5-12 shows the total annual historical and modeled diversion. The years where the historical diversion was not met by the model corresponds to years where the storage contents were low.

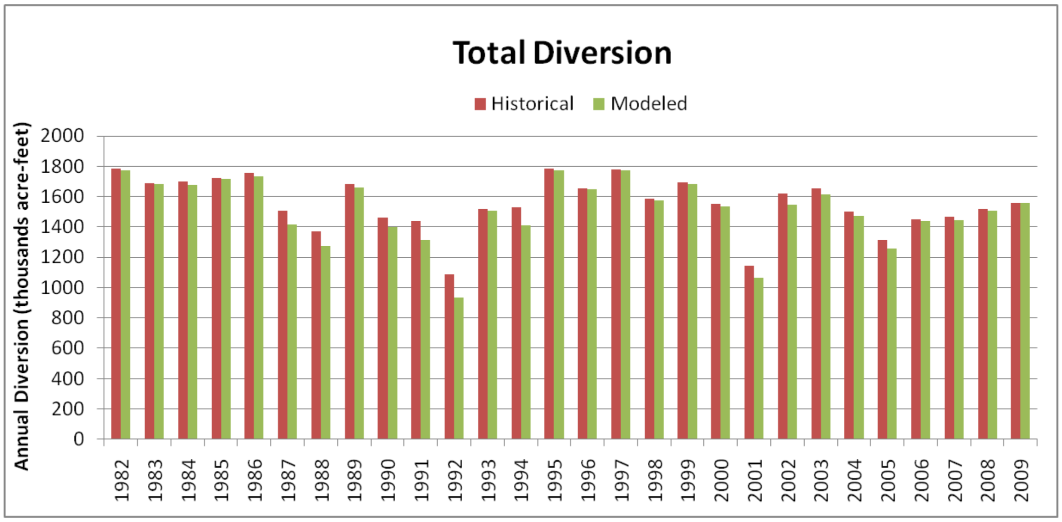

Figure 5-12: Historical and modeled total annual diversion (acre-feet).

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6 Future Climate Flow Modeling

The impacts of future climate flows on the Boise River System were simulated using the calibrated RiverWare model. This section will describe the preparation of the climate flows for use in the RiverWare model and their simulated impacts on the system.

6.1 Selection of Future Projections

The climate change investigation for this study consisted of running climate flow projections through the calibrated Boise River System RiverWare model. The flow projections were obtained from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (CMIP3 archive) website hosted by the Lawrence Livermore National Laboratory (LLNL). The bias corrected and downscaled hydrology projections available on the website are the result of work by the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Couple Modeling (WGCM). Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

Six Transient projections were selected for analysis in this study because of their time-evolving nature reflecting the gradual influence of global warming on more regional weather conditions. Transient projections do not retain the timing of historical observations (e.g., droughts) or other patterns (duration or frequency aspects of climatic changes on a monthly or larger time scale) that have been experienced so they cannot be directly compared to the observed historical record Where comparisons are provided, it is more to indicate the relative differences between the datasets, not specifically quantifiable differences. They depict a potential drift in system performance over time that might be useful for adaptation planning. To portray future climate, several Transient projections were viewed as an ensemble to show an evolving envelop of climate variability over time. The selection of six (as opposed to more) can somewhat limit the characterization of climate envelop as it varies through time, but this effort is intended to provide an understanding of potential climate change and potential impacts of that change on flows in the Boise River system.

These same six projections (i.e., projections are comprised of a Global Climate Model or GCM, an emission scenario, and climate characterization type like wetter or drier than historical conditions) were also used in the recently completed RMJOC Climate Change Study (Reclamation 2011). The primary difference is that the Transient projections in the RMJOC Climate Change Study were downscaled using the 1/16th degree grid while the projections from the LLNL site were downscaled to the 1/8th degree grid. General trends between the two datasets should not be affected, but the differences were not quantified in this effort. They represent six distinct changes in total precipitation and average temperature conditions based on a simulated historical timeframe of 1950 to 1999 and are spatially averaged over the entire Columbia River Basin (Reclamation, 2010). The climate conditions will vary from sub-basin to sub-basin within the Columbia River Basin. It should also be noted that as the scale of interest decreases, the accuracy of the results do as well. In the pages that follow, ensembles, as generally are shown when providing results of Transient projections, are reported. In addition, the projections have been shown individually, which allows understanding of potential impacts of climate change on flow that may be outside the range of the historical patterns.

6.2 Flows

In general, GCMs generate a number of variables (e.g., temperature, precipitation, etc) that are used as input to hydrologic models that in turn generate flow at specified locations. In this case, the flow projections were developed from the Variable Capacity Infiltration (VIC), which was developed by the University of Washington. Of the 112 projections that are available at 1/8th degree resolution, the six Transient projections that were selected for this study are shown in Table 6-1 (adapted from Reclamation, 2010). Each of the 112 projections is considered to represent an equally likely climate future (Reclamation, 2010; Reclamation, 2011).

Table 6-1: Six Transient projections used in this study (adapted from Reclamation 2010).

Climate Projections			
Number	**Climate Model**	**Emission Scenario**	**Study Name**
1	ccsm3	B1	ccsm
2	cgcm3.1 t47	B1	cgcm
3	echo g	B1	echo
4	hadcm	B1	hadcm
5	echam5	A1b	echam
6	pcm1	A1b	pcm

For reference as to how the climate conditions impact the climate projections in the Boise River sub-basin, Figure 6-1 though Figure 6-6 show the annual total precipitation and annual average temperature values that were used to generate the flows for each projection. Figure 6-1 shows the annual total precipitation for all six climate projections with a black line indicating the ensemble median of the projections. The trend-line is the trend of the ensemble median and it indicates that, in general, precipitation used in this study increases over time. The ensemble results in precipitation changes are similar to those reported in the RMJOC Climate Change Study over the entire basin.

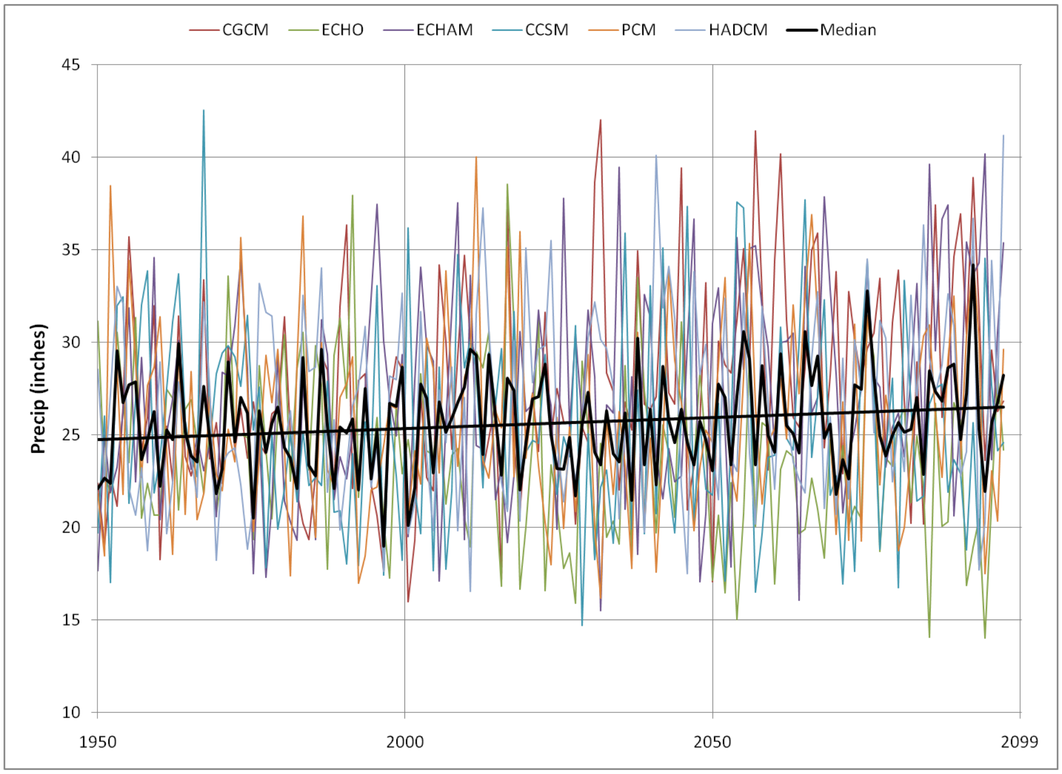

Figure 6-1: Annual total precipitation for the six climate projections used in this study. The black line indicates the ensemble median of the annual total precipitation. The trend-line is the trend of the ensemble median.

Figure 6-2 shows the annual total precipitation for the six projections individually along with the annual total precipitation for the ensemble. The trendline shows the trend for the individual projections. Projections CCSM and PCM show little change in precipitation over the run period. Projections CGCM, ECHAM, and HADCM show an increasing trend in precipitation over the run period and projection ECHO shows a decrease.

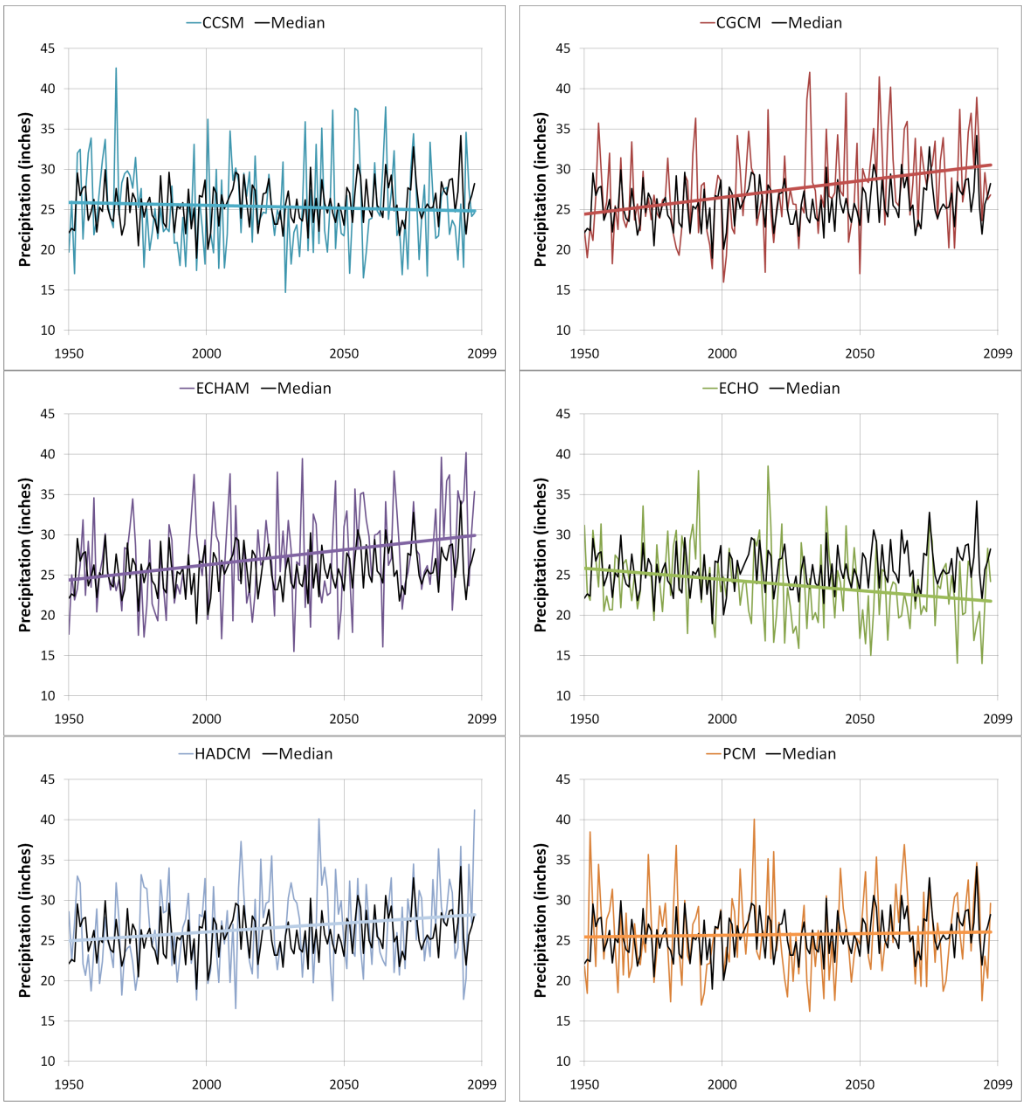

Figure 6-2: Annual total precipitation for the six individual climate projections. The trend-lines are the trend for the individual climate projection. The solid black lines show the ensemble median of the six projections.

Figure 6-3 shows the average annual minimum temperature for the six projections and Figure 6-4 shows the average annual minimum temperature for the six individual projections. In all GCMs, temperature is shown to increase in the future. These results reflect those trends.

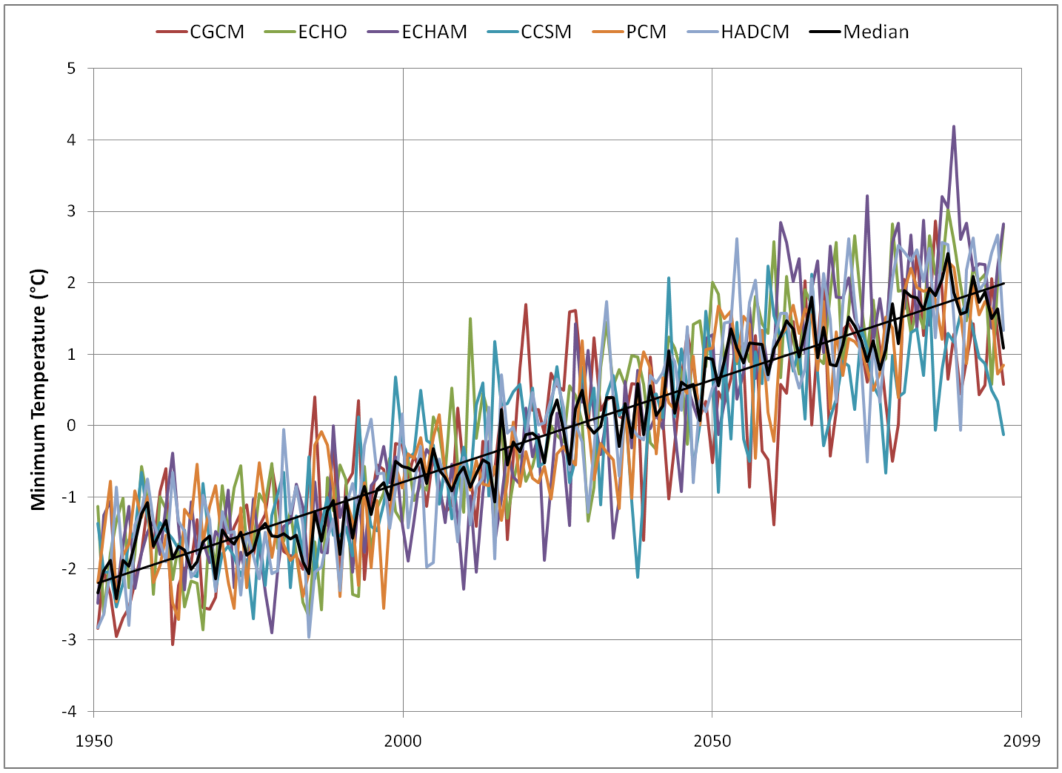

Figure 6-3: Average annual minimum temperature for the six climate projections used in this study. The black line indicates the ensemble median. The trend-line is of the ensemble median of the six multi-model projections.

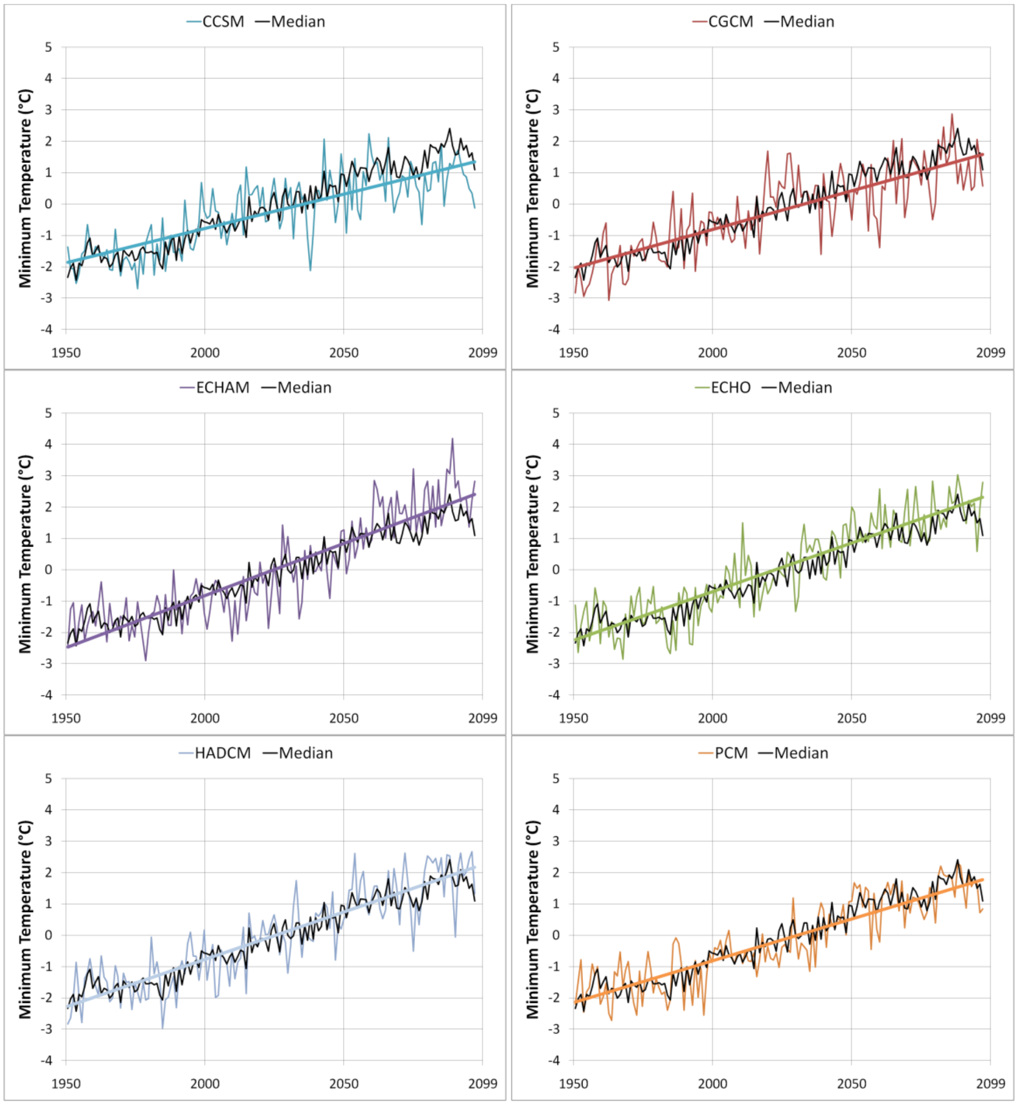

Figure 6-4: Average annual minimum temperature for the six individual climate projections. The trend-lines are the trend for the individual climate projection. The solid black line is the ensemble median of the six projections.

Figure 6-5 shows the average annual maximum temperature for the ensemble of the six projections and Figure 6-6 shows the average annual maximum temperature for the six individual projections.

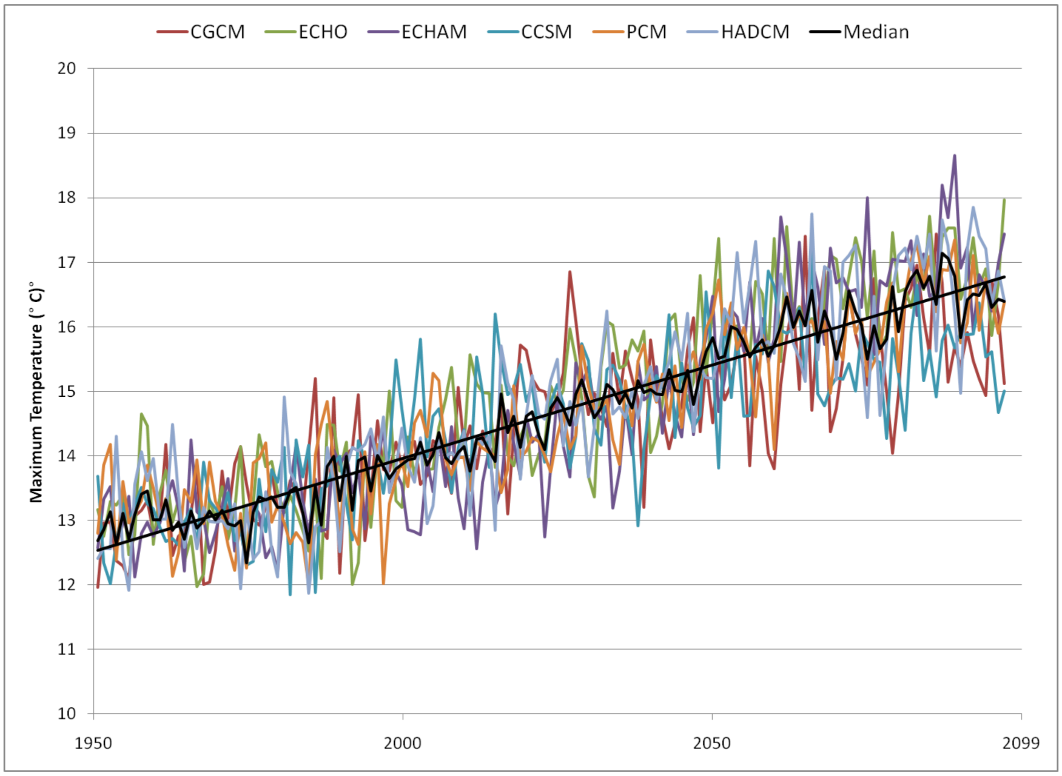

Figure 6-5: Average annual maximum temperature for the six climate projections used in this study. The black line indicates the ensemble median for all six projections. The trend-line is the trend of the ensemble median.

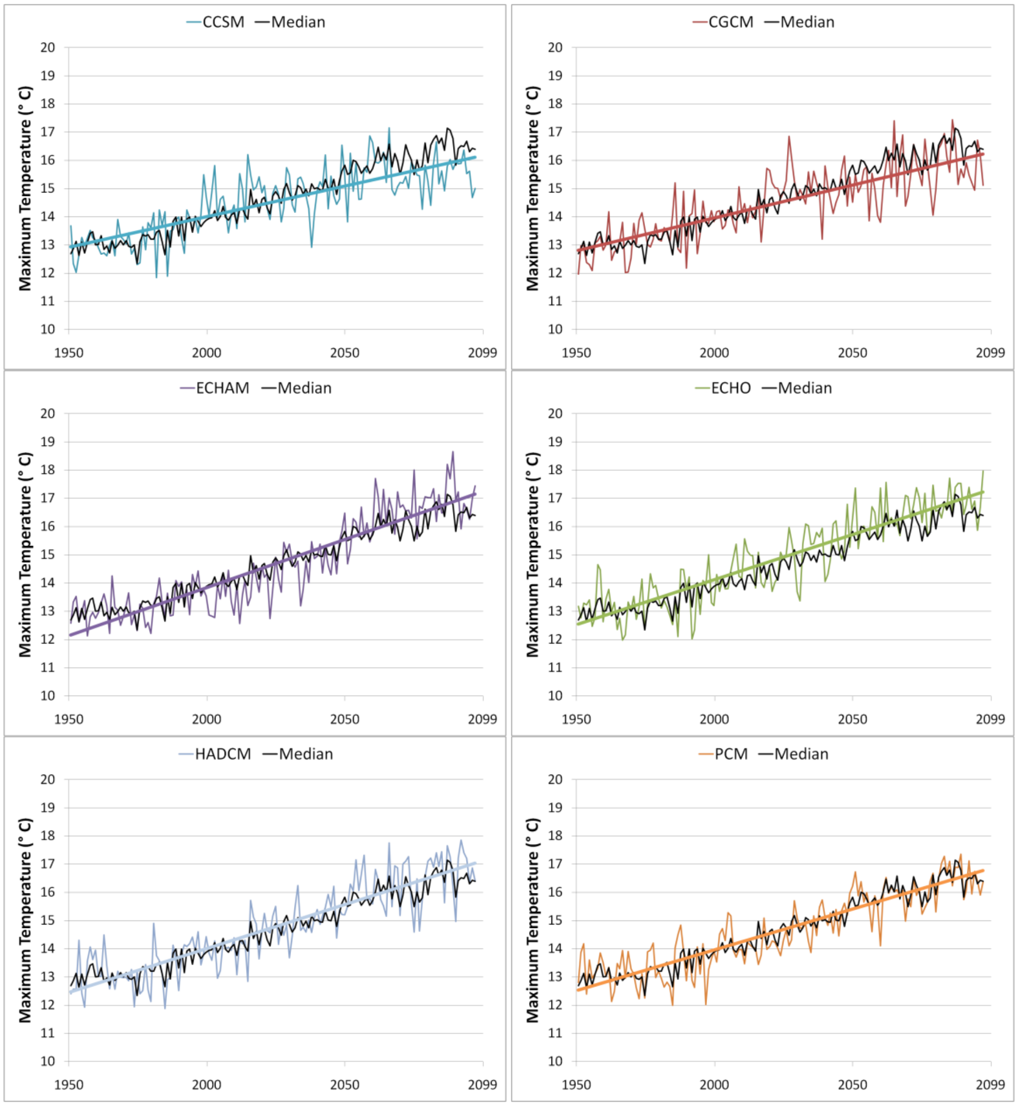

Figure 6-6: Average annual maximum temperature for the six individual climate projections. The trend-lines are the trend for the individual climate projection. The solid black line is the ensemble median of the six projections.

Flows for each of the 112 projections are available at routed locations throughout the Pacific Northwest. The routed locations selected for the flow on the Boise River corresponded to six gage locations on the Boise River; Anderson Ranch Dam, Arrowrock Dam, Lucky Peak Reservoir, Glenwood Bridge, Middleton Road, and Parma. These locations were selected using the experimental tributary area selection tool, where the user selects a point on the river and the cells contributing to the tributary's drainage area are automatically highlighted (shown by the green highlighted area on the map in Figure 6-7). The drainage area is limited by the 1/8th degree grid cell resolution and therefore has the potential to overestimate or underestimate the drainage size and ultimately the flow volume (WCRP, 2012). The area and thus flow were adjusted to reflect the actual drainage area post-download.

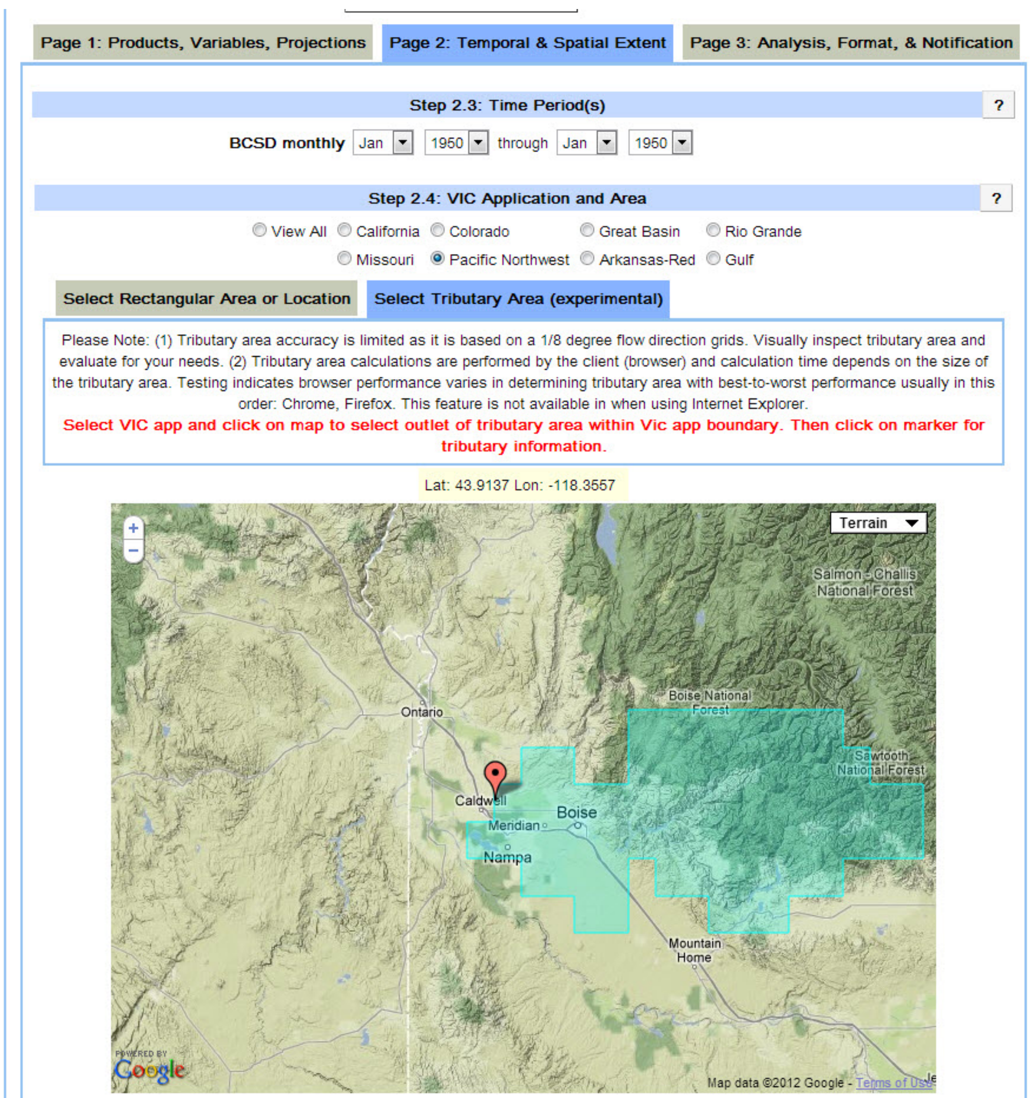

Figure 6-7: Screenshot of the experimental tributary area selection tool available on the WCRP webpage (WCRP, 2012). The highlighted green area shows the tributary area selected for the Middleton gage. The dates shown are not representative of the data used in this study.

The projected flows at each gage location are the total unregulated inflows to that gage and are the cumulative of the inflow from any upstream gages. Figure 6-8 shows a 10-year moving average of the total inflows and for each climate projection above Lucky Peak Reservoir on the Boise River System. Note that in general the two bounding projections (CGCM and ECHO) do not diverge from the remaining projections until the 2020s, but the 10-year moving average of the ensemble is generally stable over the 21st century. Also note that five of the six projections are generally within a couple of hundred cfs from the median. The outlier, CGCM, is significantly higher (more than 800 cfs at times) than the median. This is consistent with the results in the RMJOC Climate Change Study (Reclamation 2010).

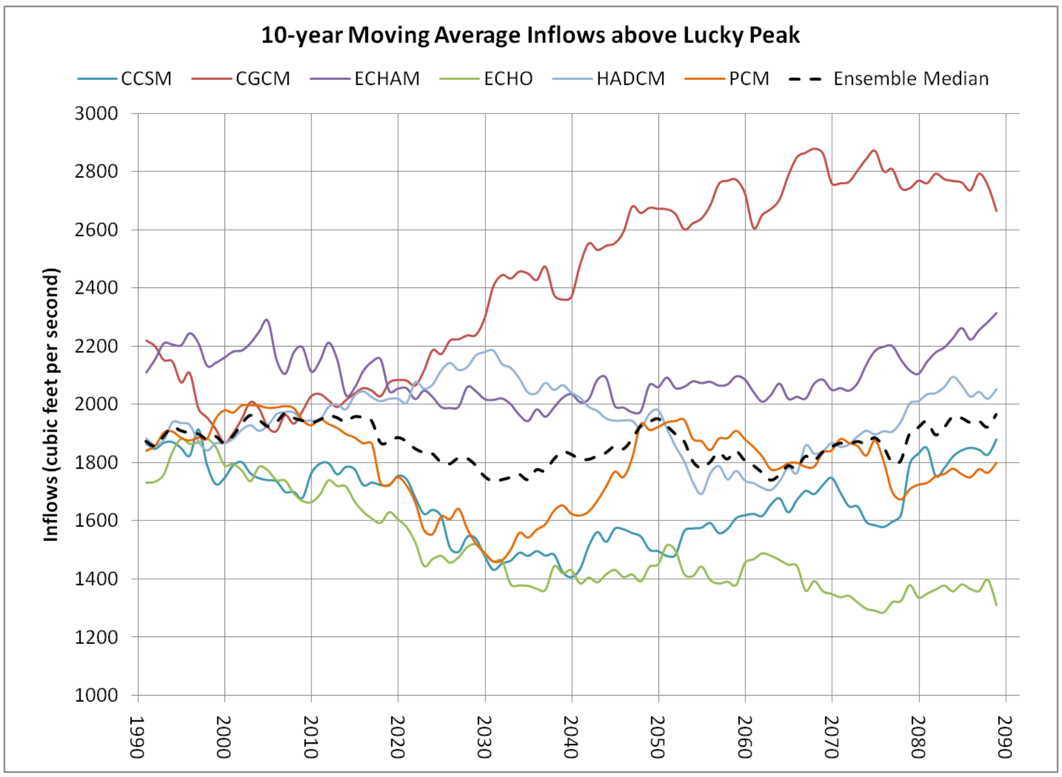

Figure 6-8: Ten-year moving average of unregulated total inflows (dashed line) and each climate projection (solid colored lines) above Lucky Peak Reservoir on the Boise River System .

Figure 6-9 shows an exceedance plot of the total inflows above Lucky Peak for each projection along with the 30-year modeled historical period. Note that for the most part, none of the projections exceed the modeled historical inflows above Lucky Peak during the 30-year historical window. So, although the six projections chosen for this study reflect an increase in precipitation over the 150-year window when compared to each other, together they represent a decrease in total inflows when compared to the observed historical period of record from 1981 to 2009. This is reflective of the general pattern shown in Figure 6-8 in which each projection's divergence away from the median generally does not occur until after the 2020s.

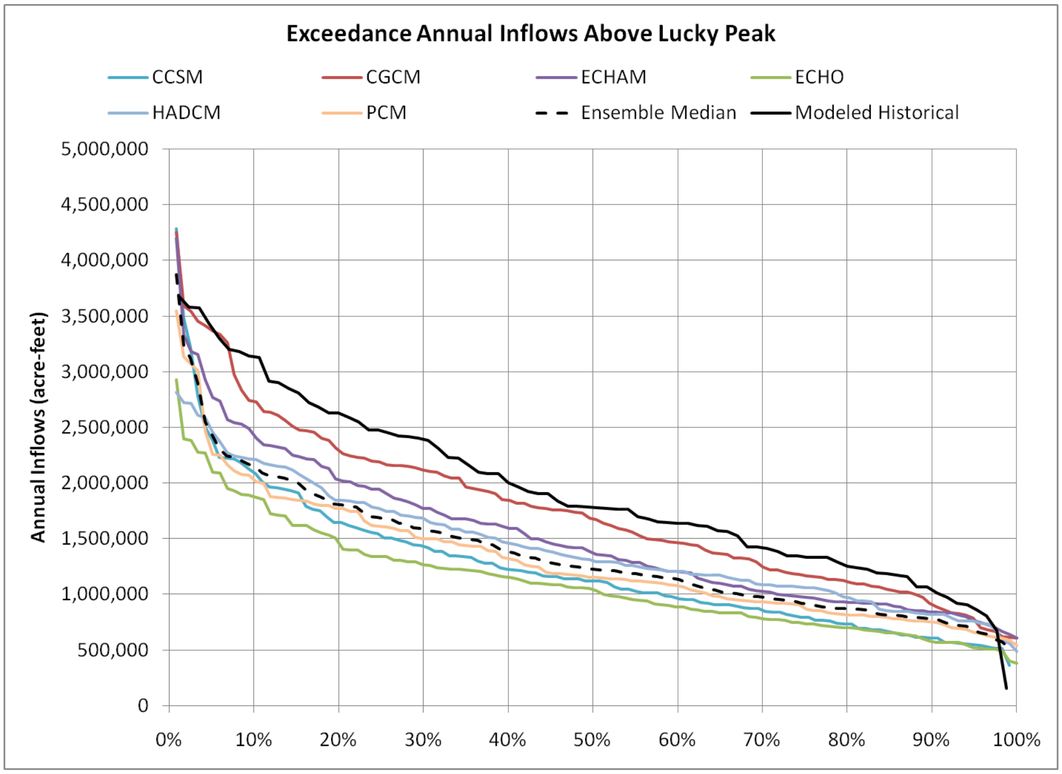

Figure 6-9: Exceedance of annual inflows above Lucky Peak for each Transient projection, including historical inflows from 1981 through 2009.

Figure 6-10 shows the ensemble median of the six projections of the inflows above Lucky Peak reservoir for the 1990s and three future decades, 2020s, 2050s, and 2070s. The historical inflows for the 1990s are also shown. The plot shows that the timing of the peak runoff shifts earlier for each future decade and, as in Figure 6-9, the total projected flows are less than historical flows. In addition, the runoff volume decreases for each decade from June through August. This portrayal provides a range of potential climate variability.

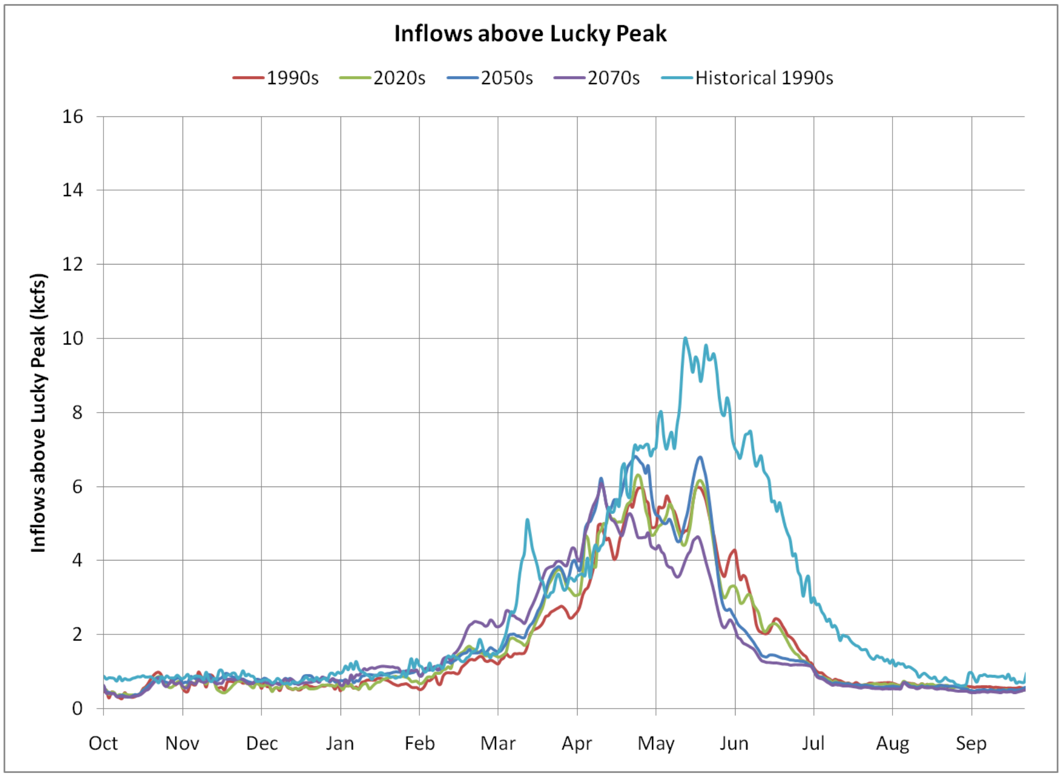

Figure 6-10: Summary hydrographs for 1990s, 2020s, 2050s, and 2070s ensemble median of six climate projections and historical 1990s.

6.2.1 Monthly to Daily Disaggregation

The data that are available on the LLNL website is in a monthly time step and the Boise River System RiverWare model is in a daily time step, so the monthly climate flow data needed to be disaggregated to a daily time step for use in the RiverWare model. A method developed by the University of Idaho and available in Reclamation's Pisces time series tool was used to disaggregate the monthly data to a daily time step (Archarya and Ryu, 2013; Reclamation, 2012c).

The University of Idaho method requires a daily dataset with a corresponding monthly dataset at the source gage and the monthly dataset to be disaggregated at the target gage. In general, the method follows the following steps to disaggregate the target gage monthly dataset:

1. For the month that is being disaggregated, the three month window for the month and the two on either side are summed for the target gage and compared to the same three month window for the source monthly dataset using a root mean squared error (RMSE). For example, if month being disaggregated is April, the flow volume for March, April, and May will be summed and compared to the flow volume for March, April, and May for each year in the source dataset. The three month window from the source gage with the smallest RMSE when compared to the three month window from the target gage is selected.
2. For each day in the selected source month, an index is calculated that is the source daily value divided by the source monthly value.
3. For each day in the target month, the index value is multiplied by the target monthly value.
4. A cubic spline smoothing algorithm is applied to smooth the inherent jumps that occur at the end of one month to the beginning of the next.

(Archarya and Ryu, 2013)

For this study, the target datasets were the monthly projected datasets for each gage location from 1981 through 2098. The local inflow to Anderson Ranch reservoir from 1981 through 2010 was used as the source daily and monthly dataset for all six gage locations because it was considered a representative dataset for the daily flow pattern that occurs in the basin. Had the basin been larger, multiple daily source gages would have been used.

Since the gage data was unregulated flow, the gains between each gage location were calculated simply by subtracting the upstream gage from the downstream gage.

6.3 Output

The six climate change projections were run through the RiverWare Boise River System regulation model using the operational rules developed during the calibration period. The simulation period for each projection was 1980 through 2098 at a daily timestep. Local gains were updated with flows from each projection for each simulation. For each water user, daily demands were calculated by taking the daily average from 2000 through 2010. The same annual demand pattern was used for each year of the simulation period for each climate projection.

Figure 6-11 shows the exceedance probability of the maximum reservoir contents for the six climate projections. The exceedance probabilities for the six climate projections are based on the 1981 through 2098 simulation period and the modeled historical exceedance probabilities are based on the 1981 through 2009 simulation period.

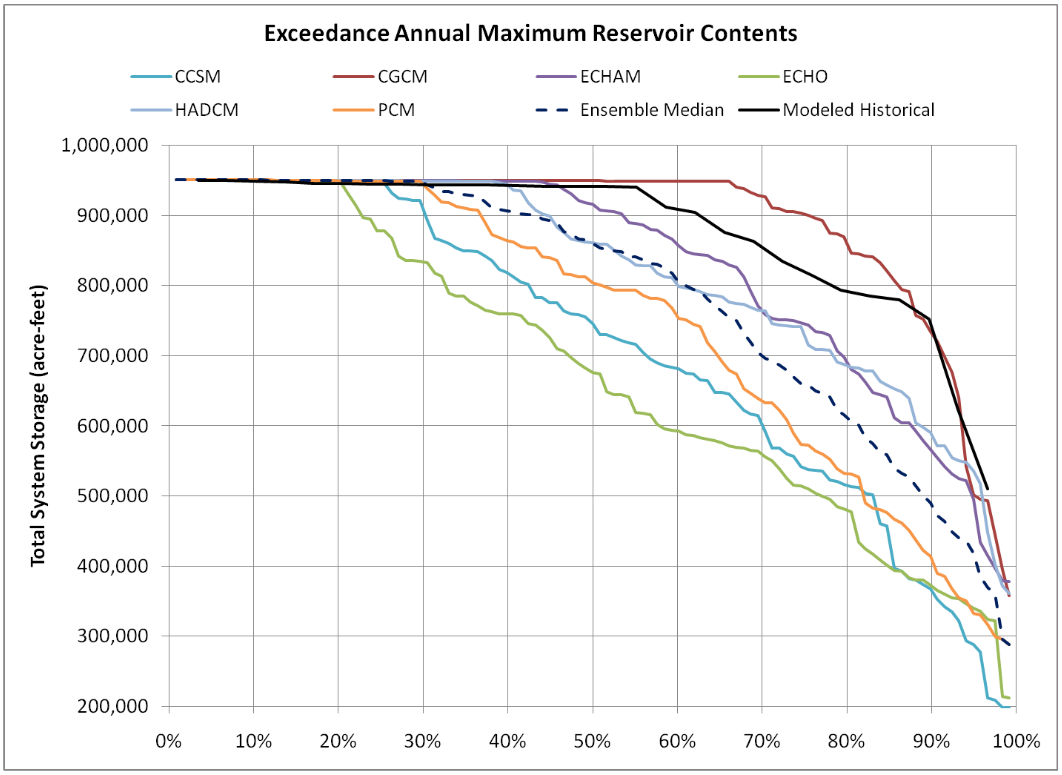

Figure 6-11: Exceedance of annual maximum reservoir contents for each climate projection.

The CGCM projection shows an approximately 10 percent higher probability of filling the system than the modeled historical system. The remaining projections show a lower probability of filling the system than the modeled historical system, with the ECHO projection having the lowest probability of fill. This is to be expected given that ECHO is the projection that has the greatest decrease in precipitation over time (Figure 6-8).

Figure 6-12 shows summary hydrographs for total system storage for select future ten year periods. The projections are shown as an ensemble, which represents the median of the six projections. When the future decadal ensembles are compared to the simulated historical period, this plot indicates that the reservoirs fill earlier for each decade represented and except for the 2020s, fill less often. There also appears to be a shift in the peak timing of maximum system storage from July to June.

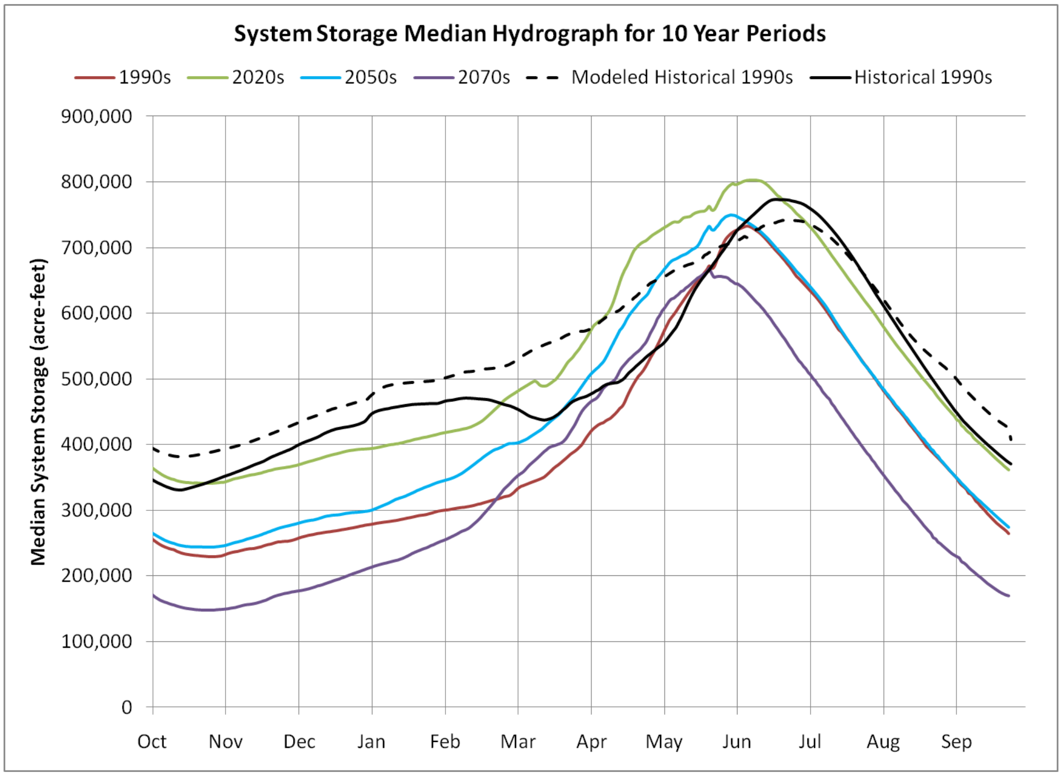

Figure 6-12: Ensemble summary hydrographs for the observed historical, simulated historical, climate change projection for the 1990s and three future decades, 2020s, 2050s, and 2070s.

Figure 6-13 shows the exceedance of sum of annual diversions. For all years and for each projection, the total diversion requested is 1,470,000 acre-feet.

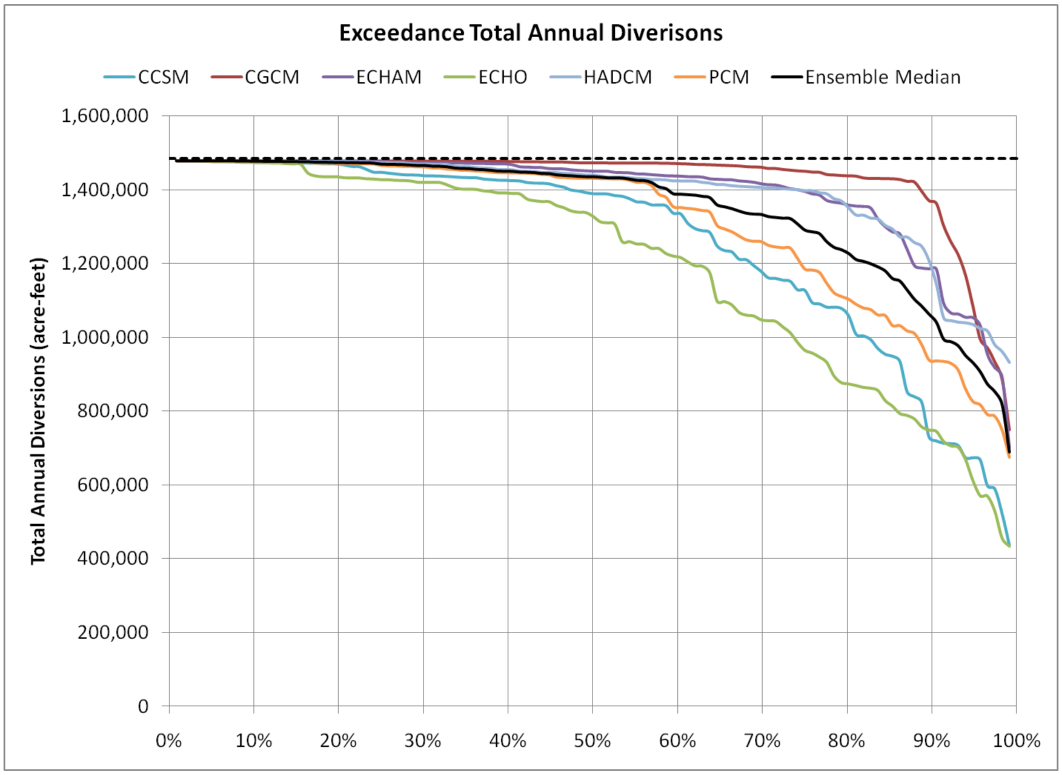

Figure 6-13: Exceedance of total annual diversions for each climate projection and the ensemble median of the projections (total annual diversion requested is dashed line).

As with the probability of filling the reservoir system, the projection with the highest probability of meeting demands is the CGCM projection and the projection with the lowest probability of the meeting demands is the ECHO projection. In this dry projection, 1.2 million acre-feet demand is met only 60 percent of the time. This could have significant impacts on future irrigation requirements if a drier climate future occurs.

Table 6-2 shows the number of years for each climate projection that flows at the Glenwood gage exceed 7000 cfs for more than five days per year. The criterion of more than 5 days per year was selected because reservoir operators would likely be able to manage operations to attenuate the impacts of the peak flood if it occurred for a duration less than five days. During the 30 year historical period, the criterion was met 4 times. The projection with the greatest number of years exceeding 7000 cfs is CGCM and the projection with the least is ECHO.

Table 6-2: Number of years that flows exceed 7000 cfs at the Glenwood gage for more than 5 days per year.

Climate Projection	No. of Years Exceeding 7000 cfs at Glenwood for more than 5 days
CCSM	22
CGCM	54
ECHAM	40
ECHO	15
HADCM	29
PCM	23

This pattern of increasing flow above flood stage on the Boise River was also reported in the Boise River Storage Study (Reclamation, 2008a). The Boise River Storage Study showed that due to climate change, it is possible that flow on the Boise River could remain above flood stage for most of the spring. For more information on the results of the Boise River Storage Study, please refer to that work.

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7 References

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8 Appendix A: Natural Flow Water Rights

Water User	Account Name	Priority Date	Maximum Diversion Rate (cfs)
CaldwellHighline	CALDWELL HIGHLINE_10/29/1880	10/29/1880	27.6
CaldwellHighline	CALDWELL HIGHLINE_4/1/1904	4/1/1904	56.34
CaldwellHighline	CALDWELL HIGHLINE_4/1/1905	4/1/1905	306.56
CaldwellHighline	CALDWELL HIGHLINE_4/1/1908	4/1/1908	54.5
CaldwellHighline	CALDWELL HIGHLINE_5/1/1866	5/1/1866	21.715
CaldwellHighline	CALDWELL HIGHLINE_6/1/1869	6/1/1869	36.2
CaldwellHighline	CALDWELL HIGHLINE_6/1/1884	6/1/1884	53.1
CaldwellHighline	CALDWELL HIGHLINE_7/3/1866	7/3/1866	15.4
CaldwellHighline	CALDWELL HIGHLINE_9/1/1890	9/1/1890	200
CanyonCo	CANYON COUNTY _10/12/1999	10/12/1999	5
CanyonCo	CANYON COUNTY_6/1/1866	6/1/1866	2.6
CanyonCo	CANYON COUNTY_6/1/1867	6/1/1867	76.77
CanyonCo	CANYON COUNTY_6/1/1869	6/1/1869	1
CanyonCo	CANYON COUNTY_7/13/1923	7/13/1923	12.68
Eureka2	EUREKA #2_10/1/1887	10/1/1887	28.6
Eureka2	EUREKA #2_11/9/1883	11/9/1883	18.3
Eureka2	EUREKA #2_5/11/1950	5/11/1950	46
Eureka2	EUREKA #2_6/1/1865	6/1/1865	1.4
Eureka2	EUREKA #2_6/1/1883	6/1/1883	1.7
Eureka2	EUREKA #2_7/20/1959	7/20/1959	24
Eureka2	MCMANUS AND TEATER_3/27/1981	3/27/1981	3
Eureka2	UPPER CENTER POINT_10/1/1887	10/1/1887	3
Eureka2	UPPER CENTER POINT_11/9/1883	11/9/1883	0.5
Eureka2	UPPER CENTER POINT_3/15/1954	3/15/1954	10
Eureka2	UPPER CENTER POINT_6/1/1865	6/1/1865	11.32
FarmersUnion	BOISE VALLEY_6/1/1865	6/1/1865	49.51
FarmersUnion	BOISE VALLEY_7/13/1923	7/13/1923	10.03
FarmersUnion	BOISE VALLEY_7/19/1921	7/19/1921	1.2
FarmersUnion	FARMERS UNION_5/20/1926	5/20/1926	1.8
FarmersUnion	FARMERS UNION_6/1/1864	6/1/1864	14.905
FarmersUnion	FARMERS UNION_6/1/1866	6/1/1866	2.17
FarmersUnion	FARMERS UNION_6/1/1871	6/1/1871	0.34
FarmersUnion	FARMERS UNION_6/1/1877	6/1/1877	3.12
FarmersUnion	FARMERS UNION_7/13/1923	7/13/1923	20.99
FarmersUnion	FARMERS UNION_7/2/1894	7/2/1894	164.46
NampaMeridian	GREEN RANCH_5/1/1878	5/1/1878	169.6
NampaMeridian	GREEN RANCH_6/1/1864	6/1/1864	0.2
NampaMeridian	GREEN RANCH_6/1/1877	6/1/1877	0.4
NampaMeridian	GREEN RANCH_8/20/1888	8/20/1888	361.94

NEagleIsland	BALLENTYNE_4/1/1878	4/1/1878	3
NEagleIsland	BALLENTYNE_5/1/1883	5/1/1883	0.756
NEagleIsland	BALLENTYNE_5/1/1893	5/1/1893	0.135
NEagleIsland	BALLENTYNE_5/1/1906	5/1/1906	0.392
NEagleIsland	BALLENTYNE_6/1/1877	6/1/1877	0.06
NEagleIsland	BALLENTYNE_6/1/1888	6/1/1888	9.67
NEagleIsland	BALLENTYNE_6/1/1891	6/1/1891	0.8
NEagleIsland	BALLENTYNE_7/13/1923	7/13/1923	3.04
NEagleIsland	CONWAY-HAMMING_6/1/1870	6/1/1870	2.6
NEagleIsland	CONWAY-HAMMING_6/1/1877	6/1/1877	0.66
NEagleIsland	CONWAY-HAMMING_6/1/1891	6/1/1891	1.6
NEagleIsland	GRAHAM-GILBERT_6/1/1865	6/1/1865	3.6
NEagleIsland	HART-DAVIS_6/1/1864	6/1/1864	3.3
NEagleIsland	HART-DAVIS_6/1/1872	6/1/1872	6.66
NEagleIsland	LEMP_3/1/1865	3/1/1865	6
NEagleIsland	LITTLE PIONEER_6/1/1866	6/1/1866	0.98
NEagleIsland	LITTLE PIONEER_6/1/1870	6/1/1870	25.02
NEagleIsland	LITTLE PIONEER_7/13/1923	7/13/1923	4.46
NEagleIsland	MACE-CATLIN_6/1/1864	6/1/1864	2.69
NEagleIsland	MACE-CATLIN_6/1/1871	6/1/1871	7.79
NEagleIsland	MACE-CATLIN_6/14/1912	6/14/1912	0.44
NEagleIsland	MACE-CATLIN_7/21/1980	7/21/1980	0.72
NEagleIsland	MACE-MACE_5/1/1909	5/1/1909	1.6
NEagleIsland	MACE-MACE_6/1/1889	6/1/1889	0.8
NEagleIsland	MIDDLETON_4/15/1893	4/15/1893	1.6
NEagleIsland	MIDDLETON_5/1/1866	5/1/1866	0.4
NEagleIsland	MIDDLETON_6/1/1864	6/1/1864	11.88
NEagleIsland	MIDDLETON_6/1/1866	6/1/1866	2.9
NEagleIsland	MIDDLETON_6/1/1867	6/1/1867	0.41
NEagleIsland	MIDDLETON_6/1/1868	6/1/1868	0.79
NEagleIsland	MIDDLETON_6/1/1891	6/1/1891	16.44
NEagleIsland	MIDDLETON_7/13/1923	7/13/1923	35
NEagleIsland	NEW DRY CREEK_3/19/1986	3/19/1986	5.29
NEagleIsland	NEW DRY CREEK_4/1/1880	4/1/1880	0.44
NEagleIsland	NEW DRY CREEK_4/1/1897	4/1/1897	0.54
NEagleIsland	NEW DRY CREEK_5/1/1866	5/1/1866	0.54
NEagleIsland	NEW DRY CREEK_5/1/1883	5/1/1883	0.68
NEagleIsland	NEW DRY CREEK_5/1/1893	5/1/1893	0.69
NEagleIsland	NEW DRY CREEK_6/1/1864	6/1/1864	0.4
NEagleIsland	NEW DRY CREEK_6/1/1871	6/1/1871	1.01
NEagleIsland	NEW DRY CREEK_6/1/1879	6/1/1879	31.32
NEagleIsland	NEW DRY CREEK_6/1/1880	6/1/1880	1.816
NEagleIsland	NEW DRY CREEK_6/1/1886	6/1/1886	15.22
NEagleIsland	NEW DRY CREEK_6/1/1888	6/1/1888	8.95
NEagleIsland	NEW DRY CREEK_6/1/1891	6/1/1891	0.48
NEagleIsland	NEW DRY CREEK_7/13/1923	7/13/1923	9.47
NEagleIsland	THOMAS AIKEN_6/1/1877	6/1/1877	0.52
NEagleIsland	WARM SPRINGS_6/1/1876	6/1/1876	2.3
NEagleIsland	WARM SPRINGS_6/1/1882	6/1/1882	5.1
NEagleIsland	WARM SPRINGS_6/1/1889	6/1/1889	0.4

NEagleIsland	WOODS_3/19/1986	3/19/1986	5.29
NewYork	NEW YORK_10/1/1887	10/1/1887	1.2
NewYork	NEW YORK_3/23/1900	3/23/1900	277.96
NewYork	NEW YORK_4/1/1909	4/1/1909	292.5
NewYork	NEW YORK_5/1/1866	5/1/1866	13.85
NewYork	NEW YORK_6/1/1869	6/1/1869	0.34
NewYork	NEW YORK_6/16/1909	6/16/1909	634
NewYork	NEW YORK_8/18/1924	8/18/1924	300
NewYork	NEW YORK_8/20/1888	8/20/1888	8.9
NewYork	NEW YORK_9/1/1864	9/1/1864	20
NotusParma	ANDREWS_12/28/2005	12/28/2005	20
NotusParma	ANDREWS_12/8/2004	12/8/2004	20.5
NotusParma	ANDREWS_6/1/1864	6/1/1864	2.376
NotusParma	ANDREWS_6/1/1865	6/1/1865	9.8
NotusParma	ANDREWS_6/1/1869	6/1/1869	11.4
NotusParma	ANDREWS_6/1/1870	6/1/1870	1.3
NotusParma	ANDREWS_6/1/1874	6/1/1874	2.2
NotusParma	ANDREWS_6/1/1888	6/1/1888	0.9
NotusParma	ANDREWS_6/1/1891	6/1/1891	3.5
NotusParma	BAXTER _2/15/1929	2/15/1929	2.4
NotusParma	BAXTER _3/1/1880	3/1/1880	3.2
NotusParma	BAXTER _6/1/1865	6/1/1865	1.91
NotusParma	BAXTER _8/24/1929	8/24/1929	2.9
NotusParma	BOWMAN AND SWISHER_10/1/1887	10/1/1887	0.7
NotusParma	BOWMAN AND SWISHER_11/9/1883	11/9/1883	0.2
NotusParma	BOWMAN AND SWISHER_2/15/1929	2/15/1929	7.4
NotusParma	BOWMAN AND SWISHER_6/1/1865	6/1/1865	7.37
NotusParma	CRAWFORTH_5/1/1889	5/1/1889	0.52
NotusParma	HAAS_6/1/1868	6/1/1868	8.54
NotusParma	HAAS_6/1/1878	6/1/1878	8.8
NotusParma	ISLAND HIGHLINE_4/1/1879	4/1/1879	3
NotusParma	ISLAND HIGHLINE_4/1/1910	4/1/1910	7
NotusParma	ISLAND HIGHLINE_4/1/1915	4/1/1915	10
Eureka2	LOWER CENTER POINT_11/9/1883	11/9/1883	2.7
Eureka2	LOWER CENTER POINT_4/1/1966	4/1/1966	21.2
Eureka2	LOWER CENTER POINT_6/1/1865	6/1/1865	6.1
Eureka2	LOWER CENTER POINT_6/1/1868	6/1/1868	3.2
Eureka2	LOWER CENTER POINT_6/1/1869	6/1/1869	3.6
Eureka2	LOWER CENTER POINT_6/1/1879	6/1/1879	4
NotusParma	MAMMON_2/21/1967	2/21/1967	0.56
NotusParma	PARMA_3/15/1943	3/15/1943	0.75
NotusParma	PARMA_5/1/1889	5/1/1889	0.8
NotusParma	PARMA_6/1/1878	6/1/1878	4.32
NotusParma	PARMA_6/1/1880	6/1/1880	1.18
NotusParma	PARMA_6/1/1881	6/1/1881	3.7
NotusParma	PARMA_6/1/1894	6/1/1894	1.41
Other	BOISE CITY CANAL_6/1/1866	6/1/1866	36.37
Other	BOISE CITY CANAL_7/13/1923	7/13/1923	0.03
Other	BUBB CANAL_3/1/1889	3/1/1889	0.84
Other	BUBB CANAL_4/1/1865	4/1/1865	2.3

Other	BUBB CANAL_4/1/1870	4/1/1870	1
Other	BUBB CANAL_5/1/1889	5/1/1889	2.22
Other	BUBB CANAL_9/13/1927	9/13/1927	2.25
Other	CAPITOL VIEW_2/17/1929	2/17/1929	0.91
Other	CAPITOL VIEW_6/1/1864	6/1/1864	7
Other	CITY OF BOISE (Williams Park)_4/30/1965	4/30/1965	2.67
Other	DISCOVERY PARK_12942	6/7/1935	0.1
Other	EUREKA #1_6/1/1865	6/1/1865	33.32
Settlers	FAIRVIEW ACRES_6/1/1886	6/1/1886	13.4
Settlers	FAIRVIEW ACRES_6/1/1891	6/1/1891	0.54
Other	HERRICK_5/1/1889	5/1/1889	0.18
Other	PIONEER DIXIE_10/1/1887	10/1/1887	2.2
Other	PIONEER DIXIE_6/1/1869	6/1/1869	35.1
Other	PIONEER DIXIE_6/1/1883	6/1/1883	2.3
Other	PIONEER DIXIE_7/9/1914	7/9/1914	20.9
Other	RIVER RUN_6/4/1980	6/4/1980	20
Other	SANDY PT PARK_20454	########	0.27
Other	SHAKESPEARE_12/2/1999	12/2/1999	0.11
Other	SHAKESPEARE_6/1/1865	6/1/1865	0.31
Other	SURPRIS VY/MICRN_5/1/1866	5/1/1866	2.82
Other	SURPRIS VY/MICRN_5/1/1878	5/1/1878	169.6
Other	SURPRIS VY/MICRN_6/1/1864	6/1/1864	0.2
Other	SURPRIS VY/MICRN_6/1/1865	6/1/1865	3.97
Other	SURPRIS VY/MICRN_6/1/1877	6/1/1877	0.4
Other	SURPRIS VY/MICRN_8/20/1888	8/20/1888	361.94
Other	UNITED WATER COLUMBIA WTP_11/16/2001	11/16/2001	20
Other	UNITED WATER COLUMBIA WTP_12/31/1963	12/31/1963	35.21
Other	UNITED WATER MARSDEN WTP_11/16/2001	11/16/2001	20
Other	UNITED WATER MARSDEN WTP_12/31/1963	12/31/1963	35.21
Other	UNITED WATER MARSDEN WTP_5/1/1889	5/1/1889	4.23
Other	UNITED WATER MARSDEN WTP_6/1/1865	6/1/1865	0.79
Other	UNITED WATER MARSDEN WTP_6/1/1868	6/1/1868	0.81
Other	UNITED WATER MARSDEN WTP_9/8/1993	9/8/1993	24.8
Other	WARM SPRINGS_8/13/1925	8/13/1925	2.55
Penitentiary	PENITENTIARY CANAL_6/1/1870	6/1/1870	2.24
NEagleIsland	BARBER_6/1/1882	6/1/1882	0.78
Phyllis	PHYLLIS_4/1/1904	4/1/1904	56.34
Phyllis	PHYLLIS_4/1/1905	4/1/1905	306.56
Phyllis	PHYLLIS_4/1/1908	4/1/1908	54.5
Phyllis	PHYLLIS_4/1/1961	4/1/1961	0.1
Phyllis	PHYLLIS_5/1/1866	5/1/1866	21.715
Phyllis	PHYLLIS_6/1/1884	6/1/1884	53.1
Phyllis	PHYLLIS_9/1/1890	9/1/1890	200
NEagleIsland	SEVEN SUCKERS_1/26/1971	1/26/1971	0.5
NEagleIsland	SEVEN SUCKERS_10/2/1915	10/2/1915	0.58
NEagleIsland	SEVEN SUCKERS_6/1/1864	6/1/1864	0.168
NEagleIsland	SEVEN SUCKERS_6/1/1871	6/1/1871	0.072

NEagleIsland	SEVEN SUCKERS_6/1/1872	6/1/1872	0.66
Ridenbaugh	RIDENBAUGH_4/1/1865	4/1/1865	0.8
Ridenbaugh	RIDENBAUGH_4/1/1870	4/1/1870	0.404
Ridenbaugh	RIDENBAUGH_5/1/1878	5/1/1878	169.6
Ridenbaugh	RIDENBAUGH_6/1/1864	6/1/1864	0.2
Ridenbaugh	RIDENBAUGH_6/1/1877	6/1/1877	0.564
Ridenbaugh	RIDENBAUGH_8/20/1888	8/20/1888	361.94
Ridenbaugh	RIDENBAUGH_9/13/1927	9/13/1927	3.7
Riverside	RIVERSIDE_1/23/1887	1/23/1887	4
Riverside	RIVERSIDE_10/1/1899	10/1/1899	20
Riverside	RIVERSIDE_4/1/1910	4/1/1910	63.78
Riverside	RIVERSIDE_4/15/1882	4/15/1882	3.674
Riverside	RIVERSIDE_4/4/1914	4/4/1914	17.7
Riverside	RIVERSIDE_5/1/1883	5/1/1883	1.5
Riverside	RIVERSIDE_5/1/1893	5/1/1893	80
Riverside	RIVERSIDE_6/1/1883	6/1/1883	8
Riverside	RIVERSIDE_6/1/1884	6/1/1884	20
Riverside	RIVERSIDE_6/1/1901	6/1/1901	70
Sebree	CAMPBELL_10/1/1887	10/1/1887	12.1
Sebree	CAMPBELL_10/25/1901	10/25/1901	5.54
Sebree	CAMPBELL_2/19/1980	2/19/1980	0.5
Sebree	CAMPBELL_5/17/1900	5/17/1900	10
Sebree	CAMPBELL_6/1/1865	6/1/1865	0.5
Sebree	SEBREE_4/1/1905	4/1/1905	154.449
Sebree	SEBREE_6/1/1865	6/1/1865	0.64
Sebree	SEBREE_6/1/1875	6/1/1875	10
Sebree	SEBREE_6/1/1883	6/1/1883	20
Sebree	SEBREE_7/1/1888	7/1/1888	50
Sebree	SEBREE_7/1/1896	7/1/1896	83.5
Sebree	SHIPLEY PUMP_3/15/1965	3/15/1965	0.22
Sebree	SIEBENBERG_6/1/1865	6/1/1865	12.28
Sebree	WAGNER PUMP_3/1/1952	3/1/1952	0.114
Settlers	SETTLERS_10/12/1884	10/12/1884	0.2
Settlers	SETTLERS_10/13/1884	10/13/1884	0.06
Settlers	SETTLERS_10/17/1884	10/17/1884	98.38
Settlers	SETTLERS_4/1/1883	4/1/1883	1
Settlers	SETTLERS_5/1/1866	5/1/1866	7.345
Settlers	SETTLERS_5/1/1878	5/1/1878	0.4
Settlers	SETTLERS_6/1/1864	6/1/1864	0.62
Settlers	SETTLERS_6/1/1868	6/1/1868	1.508
Settlers	SETTLERS_6/1/1877	6/1/1877	0.35
Settlers	SETTLERS_6/1/1882	6/1/1882	1.12
Settlers	SETTLERS_6/1/1891	6/1/1891	73.31
ThurmanMiller	THURMAN MILL_10/20/1880	10/20/1880	0.9
ThurmanMiller	THURMAN MILL_6/1/1864	6/1/1864	3.3
ThurmanMiller	THURMAN MILL_6/1/1865	6/1/1865	1.86
ThurmanMiller	THURMAN MILL_6/1/1868	6/1/1868	15.48
ThurmanMiller	THURMAN MILL_6/1/1869	6/1/1869	1.6
ThurmanMiller	THURMAN MILL_6/1/1872	6/1/1872	2.1
ThurmanMiller	THURMAN MILL_6/1/1876	6/1/1876	2.74

ThurmanMiller	THURMAN MILL_6/1/1880	6/1/1880	2.4
ThurmanMiller	THURMAN MILL_6/1/1882	6/1/1882	11.06
ThurmanMiller	THURMAN MILL_6/1/1883	6/1/1883	0.9
ThurmanMiller	THURMAN MILL_6/1/1889	6/1/1889	0.4
ThurmanMiller	THURMAN MILL_7/1/1895	7/1/1895	0.66
ThurmanMiller	THURMAN MILL_8/13/1925	8/13/1925	11.42

9 Appendix B: Storage Accounts

	Spaceholders	AndersonRanch	Arrowrock	LuckyPeak	Sum
NewYork	BigBend	3797	2533		6330
NewYork	Boise-Kuna	109538	71386		180924
CanyonCn	CanyonCountyCanal			6000	6000
Eureka2	Eureka#2			2800	2800
FarmersUnion	BoiseValley	939		2500	3439
FarmersUnion	CapitolView	449		300	749
FarmersUnion	FarmersUnionCanal	5593	2779	10000	18372
NewYork	NampaMeridian	90758	58201		148959
NEagleIs	Ballentyne Canal	367		1300	1667
NEagleIs	EagleIsland			1718	1718
NEagleIs	MiddletonCanal			6380	6380
NEagleIs	MiddleMillDitch			4620	4620
NEagleIs	NewDryCreekCanal	1266		3000	4266
NewYork	NewYorkID	40051	26014		66065
BoiseOther	BoiseCityCanal			1000	1000
BoiseOther	FairviewAcres			1500	1500
BoiseOther	NewUnionDitch			1400	1400
BoiseOther	SouthBoiseMutual	531		500	1031
BoiseOther	SouthBoiseWater			700	700
BoiseOther	SurpriseValley/Micron	3000			3000
BoiseOther	UnitedWater	1000			1000
Phyllis	PioneerDitch	2123		500	2623
Phyllis	PioneerID	24986	20326	16000	61312
Ridenbaugh	RidenbaughCanal		3794		3794
Sebree	FarmersCoop		1146		1146
Settlers	SettlersCanal	5675	2668	10000	18343
Thurman	ThurmanMillCanal			800	800
NewYork	WilderID	122195	83187		205382
	BoiseProjectBOC				
	USForestService		190		190
	TrinitySprings	800			800
	ReaquiredFlowAug			40932	40932
	Uncontracted	6			6
	UncontractedStreamflowMaint			152420	152420
Total		413074	272224	264370	949668

Appendix B. Bureau of Reclamation: Boise Project Sensitivity to Efficiency-related Return Flow Reductions.

Appendix B documents the initial modeling of the return flow analysis in Chapters 2 and 3 using Boise River Basin RiverWare model. It is included as an appendix as the documentation not easily accessible to someone trying to understand the underlying model and work to this dissertation's analysis. This document is set to be published on a public Bureau of Reclamation modeling repository in 2021.

The information being offered herein represents the opinion of the author(s). It has not been formally disseminated by the Bureau of Reclamation. It does not represent and should not be construed to represent Reclamation's determination or policy.

RECLAMATION
Managing Water in the West

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Technical Memorandum

Boise Project Sensitivity to Efficiency-related Return Flow Reductions

Boise Project, Idaho

Pacific Northwest Region

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Regional Office
Water Management – Modeling Team

August 2019

Mission of the U.S. Department of the Interior

Protecting America's Great Outdoors and Powering Our Future

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.

Mission of the Bureau of Reclamation

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.

Table of Contents

List of Figures

1 Introduction

Each year, the Bureau of Reclamation delivers around 10 trillion gallons water to 31 million people, including irrigation water to approximately 10 million acres throughout the Western US (Reclamation, 2019). Reclamation manages approximately 8,100 miles of irrigation canals and provides water to many more. Water is delivered through many different types of conveyance systems that can vary widely in their levels of efficiency. Efficiency improvements offer the opportunity to reduce water consumption but may also affect those who have come to rely on inefficiencies to return water for further use (Reclamation, 2014; Grafton et al., 2018).

1.1 Background

Increased efficiencies in water delivery and use, whether through canal lining, piping, or changes in on-farm irrigation practices (e.g. drip irrigation), may reduce groundwater recharge and return flows (Reclamation, 2014; Grafton et al., 2018). Additional water may need to be released from reservoir storage to offset reduced return flows and continue to meet the needs of downstream water users and maintain in-stream flow targets. In turn, reductions in storage may reduce how much water is carried over from one year to the next, reducing system resilience, and causing increased shortages in drier years when more carry-over would have helped alleviate shortages. Increased system efficiencies have the potential to affect natural flow availability and storage.

The effect of increasing efficiencies and reducing return flows on a system depends, in part, on what is done with the water that is retained by these efficiencies (i.e. efficiency-water). For example, if water users continue to divert their full historical volume, despite saving water via improved efficiencies, then additional reservoir releases may be necessary to provide water for downstream users that were normally supplied by return flows. These supplemental reservoir releases could deplete storage and exacerbate shortages in drier years. However, if the efficiency-water is retained in storage and released to fill diversion requests, it could help improve system reliability (i.e. reduce shortages in drier years). Efficiency-related reductions in return flows and increases in demand from reservoirs need to be evaluated in conjunction with changes in water use behavior to better understand how increasing efficiencies might affect system reliability.

1.2 Goals of the Study

This study explores 1) how reductions in return flows affect demand for stored water and water shortages, and 2) how saving efficiency-water (i.e. water retained by efficiency improvements) in reservoirs, rather than using it as normal, can increase storage and reduce shortages.

2 System Hydrology

Snowmelt and rain in the mountains of central Idaho generates runoff that flows unregulated into three reservoirs: Anderson Ranch, Arrowrock, and Lucky Peak. Anderson Ranch is located farthest upstream and stores approximately 413,000 acre-feet of water. Anderson Ranch Reservoir releases water into the South Fork Boise River, which flows into Arrowrock Reservoir. The North and Middle forks of the Boise River also flow into Arrowrock Reservoir. Arrowrock Reservoir can store approximately 272,000 acre-feet of water. Arrowrock releases water directly into Lucky Peak reservoir, which also receives inflows from unregulated tributaries. Lucky Peak can store approximately 264,000 acre-feet of water, and release water into the Boise River. The Boise River flows through the Western Snake River Plain, supplying water to municipalities and agricultural lands and interacting with local aquifers before converging with the Snake River. The three reservoirs are operated together for irrigation supply, flood control, wildlife, recreation, power generation, and in-stream flow objectives.

Below the reservoirs, along the Boise River, an extensive network of diversion canals has been developed to provide approximately 1.5 million acre-feet of water annually to agricultural lands (Reclamation, 2014). The first, largest, and highest elevation diversion is the New York Canal, which can divert a large portion of the Boise River flow to water users. The relatively high elevation of the New York Canal allows it to deliver gravity-driven flow to smaller canals and laterals, storage reservoirs, and farms. Numerous smaller canals also divert water from the Boise River.

The canal networks are lined and permeable to varying degrees; seepage from the canals and their reservoirs is an important source of groundwater recharge. Additionally, a portion of the water applied to fields infiltrates into the ground to recharge groundwater or runs-off into return drainages. Groundwater recharge elevates the water table; a network of drains was excavated to lower the water table and prevent seepage-related flooding. The drains flow back into the Boise River. Groundwater may also flow through the subsurface to the Boise River. Reservoir operations rely on return flows to help meet the diversion requests of downstream canals and water users, allowing more water to be retained in storage. Reduced return flows due to increased efficiency of water delivery (e.g. reduced canal seepage) and on-farm application (e.g. drip irrigation) may change how the reservoirs need to be operated.

3 Sensitivity Analysis Methodology

A sensitivity analysis was performed using a previously developed RiverWare model for the Boise Project (Reclamation, 2013). This sensitivity analysis assessed how system operations (e.g. water storage, water delivery, and in-stream flows) might be affected by increases in the efficiencies of irrigation delivery and use. Specifically, this analysis adjusted return flows, which are the quantities of water in canals and applied on fields that are returned to the Boise River through surface (e.g. runoff from fields and drains) and groundwater flow. Return flows serve as an important water source for downstream diversions. Adjusting return flows facilitated simulating the combined net effects of progressive canal lining and water application efficiency improvements (e.g. switching from flood irrigation to sprinklers or drip lines). Additionally, the analysis assessed how water storage and delivery were altered by changing whether the water saved by irrigation efficiency improvements (i.e. efficiency-water) was either used or stored. Efficiencies of water delivery and use for all diversions were incrementally increased in individual independent model runs and repeated for two scenarios where water users either effectively 1) continue to divert their full historical water right volume, with efficiency water consumptively used, or 2) retain the efficiency-water in storage by reducing their diversion request by the amount of water saved from seepage, such that the total consumptive use remains constant. Six return flow scaling scenarios are conducted for each of the two water use scenarios, for a total of twelve individual model runs. Each model run spans twenty-eight years at daily timesteps using historical reservoir and river inflows, modern diversion demands, and previously established groundwater response functions. The hydrologic network includes reservoirs, dams, rivers, canals, water users, and return drains. Each model run is evaluated by quantifying changes in storage, natural flow diversions, storage releases, and shortages.

3.1 Model description

The RiverWare model simulates the Boise Project using a series of interconnected nodes, which route, store, and use water based on rules and node characteristics. Each node represents a hydrologic feature, including nodes effectively representing:

- historical water inflows, stream networks, and flow routing
- reservoirs, lakes, dams, outlet works, spillways, and flood control and storage operations
- canal networks, diversion flow capacities, and modern diversion patterns
- water use for growing crops (i.e. consumption via evapotranspiration)
- fractional return flow from canal seepage, on-farm runoff and infiltration, and surface and groundwater flow

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- downstream irrigation diversions that currently use return flows to help meet water needs

Downstream from the diversion for the New York Canal, the model includes fifteen more diversions, representing forty-seven aggregated individual points of diversion (see Reclamation, 2013). Each aggregated diversion is represented as a node with one or more return flows to different reaches. In this analysis, the resulting diversions and shortages for the fifteen canals are further grouped geographically into three diversion groups, which are, from upstream to downstream, the Boise Canals, the Upper Canals, and the Lower Canals (Figure 1). Return flows from the diversions return to the river at various points along the river. Downstream diversions increasingly use return flows to help meet their diversion needs.

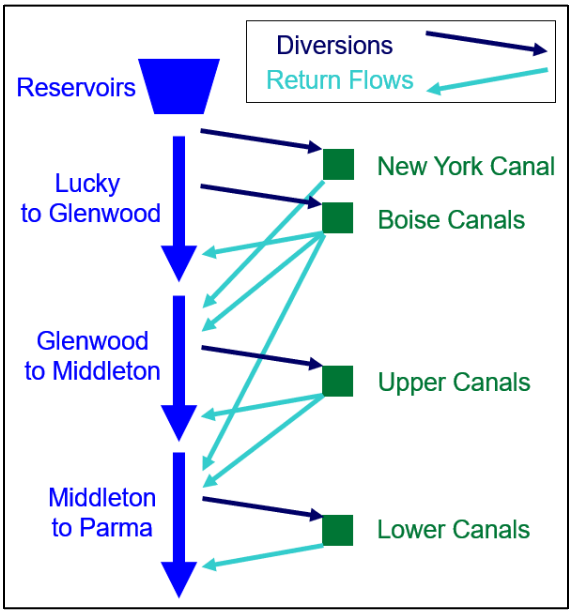

Figure 1: Organization of the Boise Project.

The return flows for each of the sixteen total diversions are calculated as a fraction of the water diverted. Flow is returned using a response function that effectively delays and distributes return flows over time. This calculation is described in detail in prior model documentation (Reclamation, 2013). Return flow fractions, return flow partitioning to different reaches, and distributions of return over time were estimated individually for each diversion during prior model development by analyzing the groundwater budget (Reclamation and IDWR, 2008).

Each diversion is represented using an accounting system with individual water rights volumes and priorities. RiverWare uses algorithms to distribute the water available each day according to the natural flow date priorities and reservoir storage specified by water rights. This allows downstream diversion accounts with more senior water rights to claim water before upstream diversion accounts with more junior priority. The water accounting includes rights for both diverting natural flow and storing and delivering water.

3.2 Model assumptions

This sensitivity analysis operated on the assumption that the base model accurately reflected current operations of the Boise Project. The analysis was performed by adjusting specific parameters that control how much water returns from diversions and whether the water saved through efficiency improvements was stored or still diverted and consumptively used. The RiverWare model has built-in assumptions that could affect the analysis, including:

- Return flow reductions reflect the net effect on return flows of efficiency improvements for both diversions and on-farm water applications. Specific net return flow reductions might result from a range of efficiency improvement scenarios. If the water retained by efficiency improvements continued to be diverted and used by the water rights holder for irrigation, a fraction applied to fields might still infiltrate and return, but this fraction would depend on the efficiency of the water user. For example, a 20% reduction in canal seepage might only correspond with a 10% return flow reduction if half of the efficiency-water still infiltrated after being applied to fields. In this sense, a 100% reduction in return flows would not occur unless both canal and on-farm efficiencies were 100%.
    - The objective of the study was to assess how net return flow reductions affect system operations and water management. As such, it was not necessary to simulate how specific efficiency improvements, such as canal lining or on-farm changes, might affect return flows. Rather, to constrain the effects of return flow reductions on water management, the return flows were simply scaled to reflect the net change in the fraction of water returned.
- Groundwater may respond non-linearly to reduced recharge from increases in the efficiency of water delivery and use. For example, reductions in recharge could alter groundwater gradients, flow directions, and river-aquifer connectivity, with specific river reaches changing from gaining water from groundwater return flows to losing it to seepage or becoming disconnected completely.
    - This complexity was avoided by simply scaling the resulting return flows, and not simulating the processes that produce those return flows. It was assumed that the response functions that control the timing of return flow delivery to the river would not change with the volume. Water that infiltrates into the ground might be expected to take longer to travel through the ground and exfiltrate as return flows to the river if reductions in recharge reduced groundwater gradients. Although interactions between canal seepage, on-farm infiltration, groundwater responses, and exfiltration warrant further study, modeling these dynamics were beyond the scope of this sensitivity analysis.
- Intra-annual diversion request patterns were held constant for all diversions in all years using average historical demand patterns scaled up to account for expected increases in evapotranspiration. While scaling the diversions simulates future water demands, simulating different hydrologic inflows for potential climate conditions was beyond the scope of this study.

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3.3 Reducing return flows

The effects of increasing the efficiency of water delivery and use were simulated by incrementally reducing, across multiple individual model runs, the fraction of water each diversion returns to the Boise River and assessing changes in water storage and shortages. Parsing out the individual effects of increased water delivery efficiency (e.g. canal lining and piping) versus on-farm use efficiencies (e.g. sprinklers, drip, etc.) exceeded the model complexity and was beyond the scope of this work. The combined effects of the two efficiencies are represented by a single 'FractionalReturnFlow' variable for each water diversion that dictates how much of the water in the diversion leaks or runs off and is returned to the river via surface or groundwater flow paths. A 'ScalingFactor' was iteratively set for individual copies of the model using values of 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0. When each model run begins, previous return flow fractions estimated for each diversion are multiplied by the model's 'ScalingFactor' to set the 'FractionalReturnFlow' for each diversion. This effectively scales previously estimated return flow volumes on a diversion-by-diversion basis and distributes them over time following previously estimated response functions for each diversion. It is assumed that the changes in groundwater recharge would not alter the response functions (i.e. return flow timing).

In the first set of models, in which return flows are reduced but the efficiency-water is still diverted and used, diversion requests were held constant, which means that as return flows were reduced, the amount of water consumed to grow crops (i.e. lost as evapotranspiration to the atmosphere) essentially increased.

3.4 Reducing diversions and storing efficiency-water

The analysis was repeated for each return flow scaling scenario (i.e. 'ScalingFactor') while also reducing diversion requests in proportion to return flow reductions. Reducing diversion requests effectively saves efficiency-water (i.e. the water retained by efficiency improvements) in storage, instead of it being consumed to grow crops (i.e. lost to the atmosphere). This coupled scaling resulted in a constant amount of water delivered and consumed to grow crops (assuming water is available), while the efficiency-water that would have become return flow is instead stored in the reservoir. To determine new diversion requests, water consumption for crops was held constant by setting its equations for the two scenarios equal and solving:

$$\begin{aligned} &ScaledDiversionRequest * (1 - ScaledReturnFlowFraction) \\ &= UnscaledDiversionRequest * (1 - UnscaledReturnFlowFraction) \end{aligned}$$

$$ScaledDiversionRequest = UnscaledDiversionRequest * \frac{1 - OldReturnFlowFraction}{1 - NewScaledPeriodicFraction}$$

4 Results

The model was run independently for each of the six return flow scaling scenarios for both scenarios for using or storing efficiency-water. The first scenario holds the diversion requests constant, with the efficiency-water still being diverted and consumptively used. The second scenario reduces the diversion requests in proportion to return flow reductions, such that the amount consumptively used remains constant, and the efficiency-water is retained in the reservoir.

If the efficiency-water continues to be diverted and consumptively used (i.e. diversion requests are held constant), additional water must be released from storage to meet diversion requests downstream that could normally be met in part by return flows. As the return flows are reduced, if the efficiency water is used the 28-year median daily storage values decline more rapidly in the summer (Jul.-Sep.) due to irrigation withdrawals (Figure 2, green lines). Conversely, if the efficiency water is saved in the reservoirs, storage is depleted less rapidly in the summer because less water needs to be diverted (Figure 2, blue lines).

If the efficiency-water is used, as return flows are reduced and diversions are not changed, the diversion requests supplied from natural flow decline for all four canal groupings (Figure 3; top). For the three upstream canal groups, the water supplied from storage remains relatively constant, while shortages increase in proportion to declines in natural flow. For the Lower Canals as return flows are reduced, the natural flow deliveries decline more, decreasing by around one third of the total annual demand. The total demand met by storage releases increases more than five-fold, but cannot fully fulfill demand, and shortages also more than double.

If the efficiency-water is saved, and diversions are reduced in proportion to return flow reductions, the total water requests decline relative to the normal request (Figure 3; bottom). The amount of diversion water supplied by natural flow to the lower three canal groups declines more rapidly as return flows are reduced, both because less water is diverted and a smaller fraction of that water returns (Figure 3; bottom). The amount of water supplied from storage declines slightly for the upper three reaches and increases slightly for the Lower Canals. Shortages decline for all canal groups.

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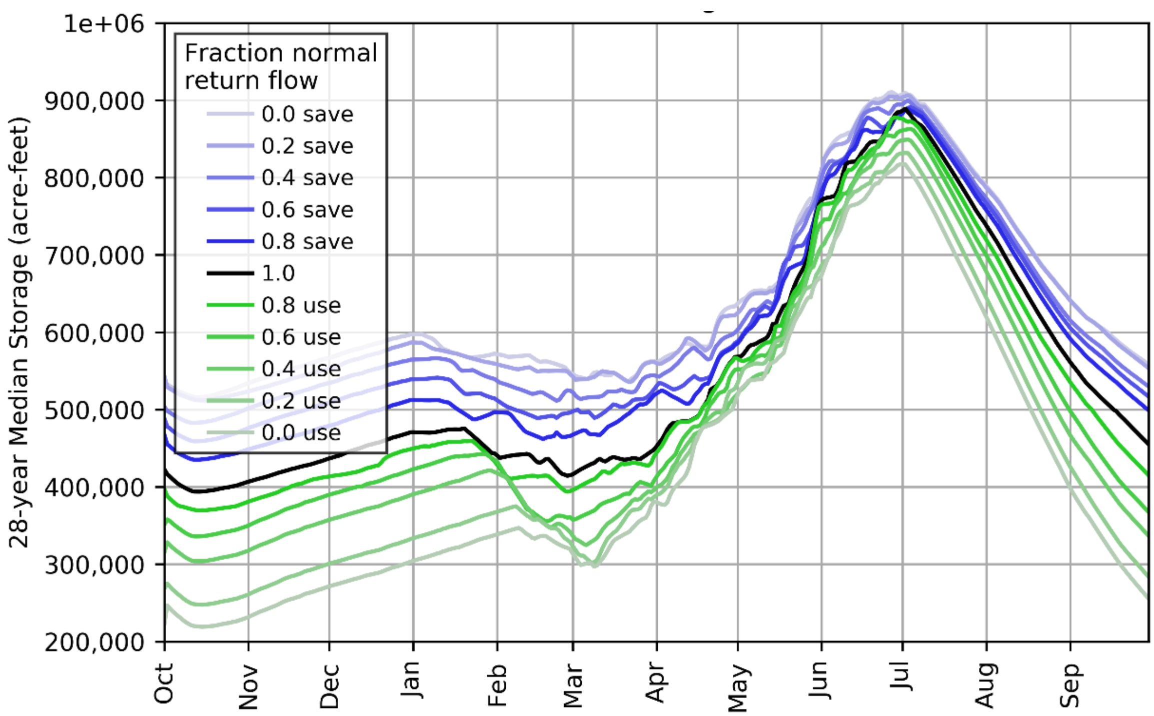

Figure 2: 28-year median daily combined Boise Project storage (all three reservoirs) showing how storage changes in proportion to efficiency improvements and return flow reductions, and how the direction of change from the current conditions (black line) depends on whether efficiency water is used (green) or saved (blue).

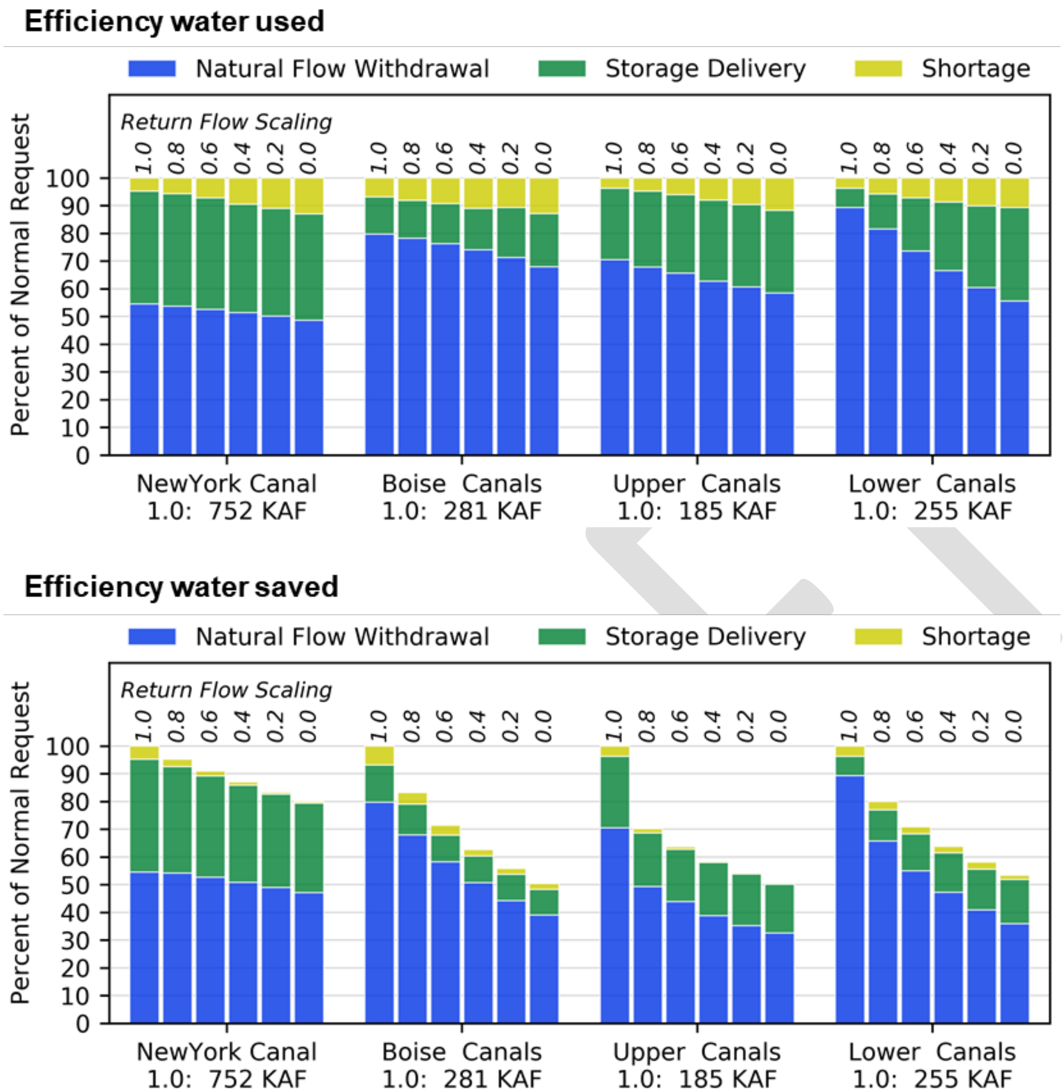

Figure 3: 28-year average percentage of the normal (1.0 scaling) annual diversion request satisfied by natural flow, storage releases, or shorted for the 'use' (top) and 'save' (bottom) scenarios. Diversion groups are sorted left-to-right from higher to lower along the river, with numbers below indicating the normal (1.0 scaling) annual diversion request.

Comparing interannual variations of how much of the annual diversion requests are met by natural flow diversions and storage releases, and how much they are shorted, highlights water-year dependent shortage dynamics. When the efficiency-water is used rather than saved, shortages increase as the return flows are reduced (Figure 4, top; red lines increase from return flow scaling scenario 1.0 to 0.0). This is because natural flow diversions decline and the increased storage releases cannot be sustained to meet the elevated demand (e.g. 1994; Figure 4, top).

In contrast, when the efficiency-water is saved, and return flows are reduced, diversion shortages decrease (Figure 4, bottom plot; red lines decline from return flow scaling scenario 1.0 to 0.0). Although reducing the return flows reduces the amount of water supplied from natural flows (Figure 3), the total diversion requests also decline because not as much water is required, so the proportion provided from natural flows changes less. More storage water is also available to meet remaining diversion requests and reduce shortages (Figure 2).

System sensitivity to reduced return flows and efficiency-water use depends on the type of water year. Shortages roughly double in drier years if efficiency-water is still used (Figure 5, top vs. middle plot), and more than double for moderate to dry years, but still do not occur in wetter years. Conversely, shortages decline from the baseline in all years if the efficiency-water is saved in the reservoir (Figure 5, top vs. bottom), due to both reduced requests and increased storage.

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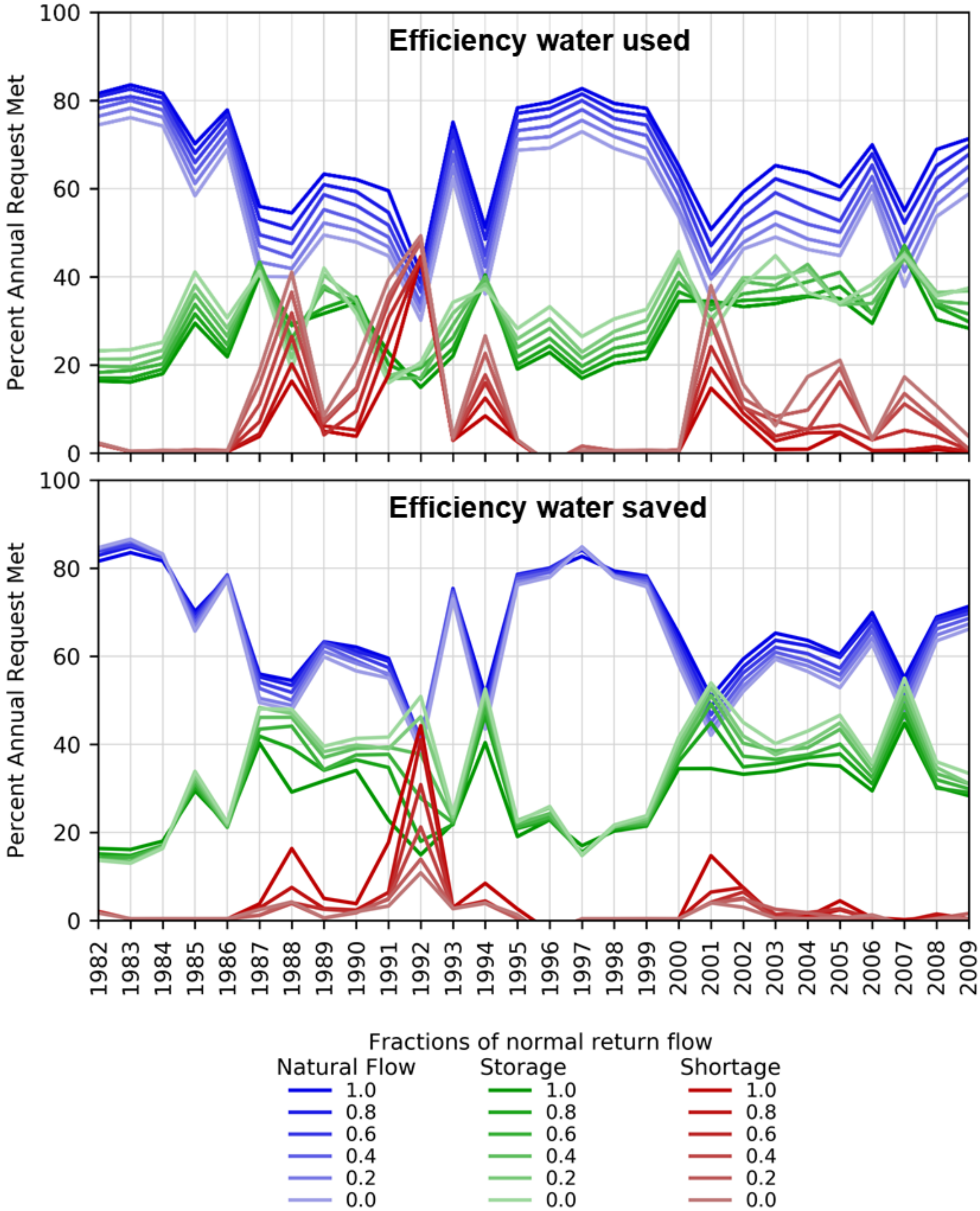

Figure 4: Plots showing the percentages of the annual requests delivered from natural flows and storage releases, or shorted, for each year and each return flow scaling (0.0 to 1.0). The top plot shows the deliveries if the water gained from efficiency improvements continues to be diverted and used (e.g. higher yield crops). The bottom plot shows the deliveries if the water gained from efficiency improvements were saved in reservoir storage instead of being used.

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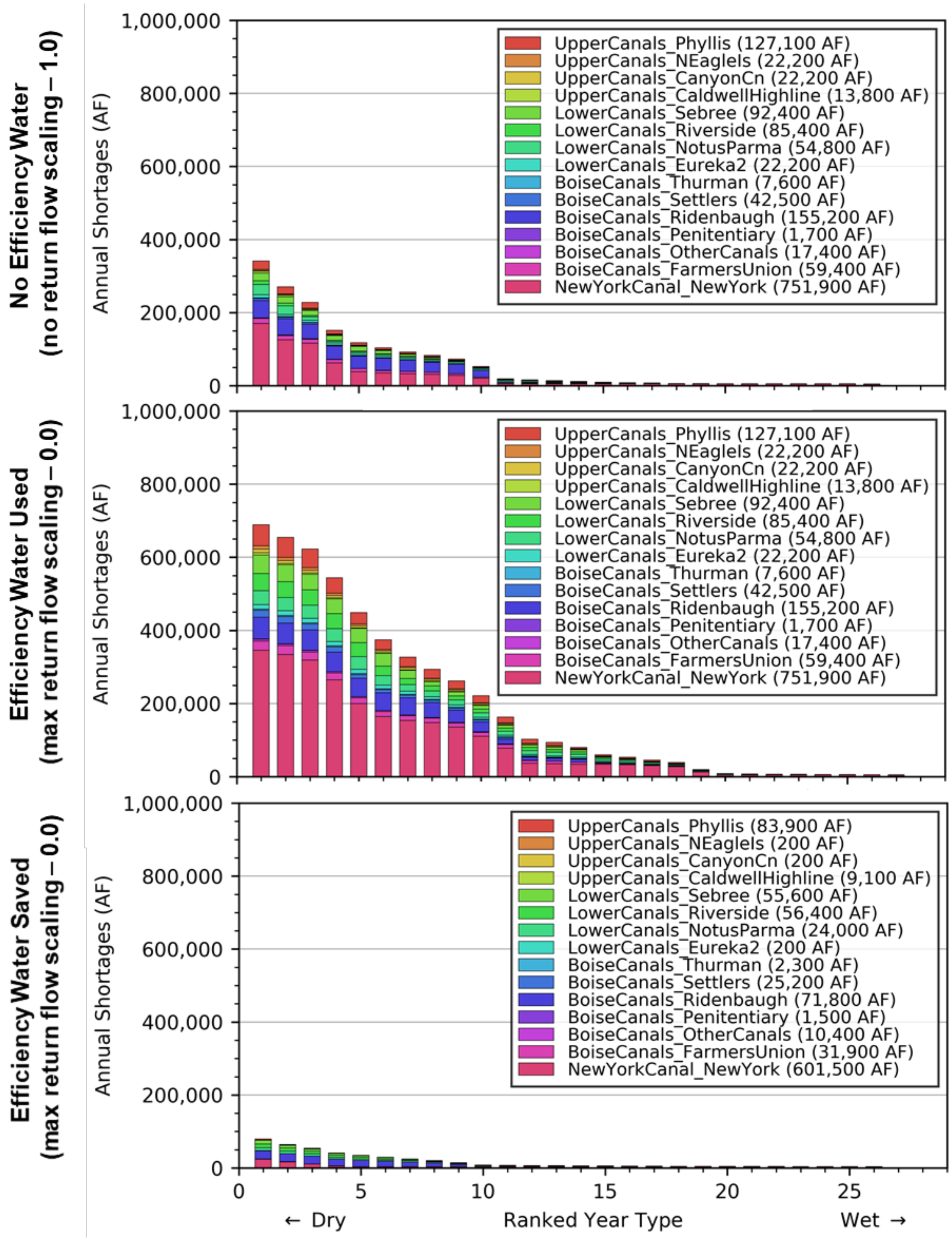

Figure 5: Comparison of annual shortages from dry to wet years for scenarios with (top) and without (middle and bottom) return flow reductions due to increases in water delivery and use efficiency. The bottom two graphs compare shortages for scenarios where the efficiency water is used (middle) or saved (bottom).

5 Conclusions

Return flow reductions related to increases in the efficiency of water delivery and/or use have the potential to affect how much water can be provided from natural flows and increase dependence on reservoir storage to meet diversion requests. If water rights holders continue to divert their regular volume of water despite efficiency improvements, then requests for water from storage may decrease reservoir storage and increase water shortages in drier and average years. However, if the efficiency-water is saved and stored in the reservoir, shortages in drier years may be reduced from the baseline scenario, despite increased diversion requests for stored water. This work emphasizes the importance of planning how efficiency-water will be used when considering efficiency improvements and including the potential negative effects to downstream diversions, in-stream flows, and/or reservoir storage demand in cost-benefit analyses.

Importantly, the scenarios only examined the effects of reducing return flows with and without proportional reductions in diversion requests (e.g. saving vs. using efficiency water). From a mass balance perspective, if efficiency improvements allow more water to be retained in storage or used consumptively to grow crops, groundwater recharge will be reduced. Simulating the dynamic responses of groundwater to changes in recharge was beyond the scope of the analysis. However, increases in the efficiency of water delivery and/or use, and corresponding reductions in aquifer recharge, could alter groundwater flow gradients, transit times, flow directions, and aquifer-river connectivity. The long-term effects of reduced groundwater recharge on groundwater dynamics warrant further exploration when considering efficiency improvements.

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Department of Civil and Environmental Engineering, Utah State University &
Columbia – Pacific Northwest Region, U. S. Bureau of Reclamation

EDUCATION

PhD	Civil and Environmental Engineering, Utah State University, Logan, Utah	August 2021
ME	Agricultural and Biological Engineering, University of Florida, Gainesville, Florida	August 2010
BS	BioResource and Agricultural Engineering, California Polytechnic State University, San Luis Obispo, California	June 2008

PROFESSIONAL ROLES

1. November 2016 – Present. **Regional Water Conservation Program Specialist,** Columbia – Pacific Northwest Region, U. S. Bureau of Reclamation, Boise, Idaho.
2. May 2015 – November 2016. **Hydrologic Engineer,** Columbia – Pacific Northwest Region, U. S. Bureau of Reclamation, Boise, Idaho.
3. May 2013 – October 2013. **Agricultural Engineer,** Agri Industries, Inc., Miles City, Montana.
4. August 2010 – Present. **Doctoral Candidate**, Department of Civil and Environmental Engineering, Utah State University, Logan, Utah.

PROFESSIONAL EXPERIENCE

Regional Water Conservation Program Specialist, U. S. Bureau of Reclamation

- Serve as Program Manager for Region's Water Conservation Program
- Formulate, develop, and manage $1.5M budget for Water Conservation Field Services
- Coordinate 18 WaterSMART and Water Conservation Field Services staff supporting program activities in Regional, Area, and Field Services
- Manage an average of 65 active grants in the Columbia-Pacific Northwest Region
- Serve as the Grants Officer Technical Representative on 16 grants to evaluate scope, budget, and recipient activities during each grant's lifecycle

Hydrologic Engineer, River and Reservoir Operations group, U. S. Bureau of Reclamation

- Develop surface water models to support decision maker analysis (RiverWare, ModSim)
- Conduct simulation model runs based on Global Climate Model data
- Analyze storage capability of reservoirs to help meet Biological Opinion flows
- Draft and review technical memorandums for hydrologic and climate change studies

Agricultural Engineer, Agri Industries, Inc.

- Design and cost estimate pumping, pipeline, and irrigation systems for area farmers
- Draft state and federal permits for environmental and water rights applications (e.g., storm water prevention, reserved water rights, USACE 404 permitting)

Doctoral Candidate, Civil and Environmental Engineering, Utah State University

- Develop system analysis tools with Excel VBA and RiverWare to increase understanding of water management decision on a basin scale
- Remote Sensing Laboratory research assistant fall 2010

PROFESSIONAL AFFILIATIONS

- American Society of Agricultural and Biological Engineers, Member (2005 - present)
- American Society of Civil Engineers, Member (2012 - present)
- United States Committee on Irrigation and Drainage, Member (2005 - present)

RECENT PROFESSIONAL DEVELOPMENT

- Registered Agricultural Engineer, Idaho
- Bureau of Reclamation: Cost Estimating School (May 2019)
- Bureau of Reclamation: Concrete and Concrete Repair School (April 2018)
- International Institute for Learning, Inc: Project Management Training Modules – Introduction, Risk Analysis, and Facilitation (June and Sept. 2017)
- Groundwater Vistas: Intro to Groundwater Modeling and PEST Calibration (Sept. 2015)
- RiverWare Training: Introduction, Rule-based Simulation, and Accounting (2015)

HONORS AND AWARDS

- STAR Award 2018 for grant coordination, Columbia – Pacific Northwest Region, USBR
- Aspiring Leaders Class of 2017, Columbia – Pacific Northwest Region, USBR
- STAR Award 2017 for expanding a regional leadership program, Columbia – Pacific Northwest Region, USBR
- Outstanding Collegiate Member Award 2015, Society of Women Engineers
- Outstanding Graduating Senior for Service to the Community 2008, College of Agriculture, California Polytechnic State University, San Luis Obispo
- Outstanding Women Engineer 2008, Society of Women Engineers, California Polytechnic State University, San Luis Obispo
- Student of the Year 2006, American Society of Agricultural and Biological Engineering

PEER-REVIEWED JOURNAL PUBLICATIONS

Meeks, L. and Rosenberg, D.E. 2017. High Influence: Identifying and Ranking Stability, Topological Significance, and Redundancies in Water Resource Networks. Journal of Water Resources Planning and Management, 143(6).

Meeks, L. Dukes, M.D., Migliaccio, K.W., Cardenas-Lailhacar, B. 2012. Expanding-Disk Rain Sensor Dry-Out and Potential Irrigation Savings. Journal of Irrigation and Drainage, 138(11): 972-977.

Meeks, L. Dukes, M.D., Migliaccio, K.W., Cardenas-Lailhacar, B. 2012. Long Term Expanding-Disk Rain Sensor Accuracy. Journal of Irrigation and Drainage, 138(1): 16-20.