RECLAMATION
Managing Water in the West

Investigating the Impact of River Regulation on Groundwater Supplies in the Western U.S.

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

December 2014

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Cover Photograph: Sprinkler irrigation in the Columbia Basin Project, WA. *Photograph by Dave Walsh.*

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Executive Summary

Regulated river systems have been impacting aquifer systems in the western United States since Reclamation first began delivering water for irrigation. Seepage from canals and on-farm infiltration has led to aquifer systems receiving larger quantities of recharge than would have occurred in the natural system. The more regular supply of recharge often results in a more sustainable system that is better able to support irrigation activities as well as provide ecosystem support through wetland and river flows.

Understanding the relationship between regulated river systems and underlying aquifer systems can inform the decision process for actions that may impact those relationships. This study looked at two regulated river systems that are associated with Reclamation projects, the Boise basin in Idaho and the Carson basin in Nevada. Both basins have integrated groundwater-surface water systems; however the relationships differ in each basin.

A generalized Systems Dynamics model was developed for this study to explore the impacts of changes to relationships between regulated river systems and local aquifers. The generalized model was populated with water budget data for both the Boise and Carson basins. Four scenarios were explored in each basin to understand potential impacts from infrastructure changes (lining canals, improving on-farm efficiencies, or changing reservoir storage volumes), water management changes (converting existing agricultural demands from surface water to groundwater), and climate change (annual hydrograph variability). For each scenario, the impact on the net flux to the aquifer and the ratio of recharge to discharge was reported.

All of these scenarios indicate that the manner in which the surface water system is regulated has a significant impact on the net flux of water to hydrologically connected aquifers, and hence the sustainability of these aquifers as water supplies. This impact is due to a combination of the physical infrastructure that was developed to regulate river systems (reservoirs and canals), the rules that were developed to manage both the infrastructure, and the current water use within the basin. The interconnection between all of the components of the water resource system is important to understand when making changes to the system (for example attempting to increase the water use efficiency within a basin).

As demonstrated in the analysis, increasing the efficiency of one or more components of the water resource system (e.g. canal lining or increased on-farm irrigation efficiency) within a basin may impact other components, and possibly result in decreasing the sustainability of the groundwater resource. This analysis also indicates that while Reclamation has no direct role in managing groundwater resources, the manner in which they develop and manage surface water infrastructure does significantly impact the fluxes of water into and out of a region's groundwater resources. The tool developed for this project could be useful in providing preliminary assessments for proposed changes in the management of water resources in Reclamation Project areas. It can be used to identify possible issues that could result in increased conflict of water resource use or non-sustainable water resource systems.

The results of the scenarios and the response exhibited by each basin demonstrated the usefulness of the System Dynamics model. The Systems Dynamics model could be used in the future to conduct preliminary evaluations of proposed system changes to more fully understand their impacts on overall water resource sustainability. Further analysis could be conducted to understand how the impacts to the groundwater system may impact overall system water supplies.

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Introduction

Throughout Reclamation's history, seepage from its canals, reservoirs, and irrigated lands have been actively recharging local aquifers. In some cases, this seepage has resulted in benefits being accrued by non-Reclamation water users through increased recharge to groundwater, wetlands, and drain return systems. In other cases this seepage has resulted in losses due to localized flooding, or water logging of soils that result in reduced crop yields.

With the growing concern of water availability in many of the western states, it is important to understand the extent of Reclamation's impact on both surface and groundwater supplies by answering the question, what are the impacts of river regulation on groundwater supplies in the western U.S. and are Reclamation projects supporting sustainable aquifers?

Changes made to Reclamation's operations and infrastructure can have impacts on groundwater supplies by increasing or decreasing recharge. Increasingly, Reclamation decision makers are being asked to include total system effects into the decision making process. Although the impacts to groundwater may not be the primary factor in the decision making process, understanding the relationship between Reclamation's projects and local aquifers can be a step toward ensuring that total system effects are included in the process.

Goal of Study

The intent of this study is to develop an approach for evaluating the relationship between regulated river systems and local aquifer systems. The first step of this project involved the development of a generalized Systems Dynamics model, representing a "generic", regulated, western river system. The SD model was used to evaluate the relationship between two basins with Reclamation Projects and the underlying aquifers: Boise basin, Idaho (Boise Project) and Carson basin, Nevada (Newlands Project).

Background

Western water systems have changed drastically since Reclamation began delivering water to irrigators and applying water in places where it previously was not applied. This changed not only the surface landscape, but also the subsurface, where irrigation transportation and application inefficiencies contributed to the development and enlargement of aquifer systems.

The history of the Boise project demonstrates this behavior well. The New York Canal, which was first constructed in the early 1900s, delivers water to about 148,000 acres. Seepage from the canal caused aquifer water levels to rise by as much as 100 feet in some locations and caused water logging of some of the lands closer to the Boise River. Drainage systems were constructed to remove the excess water and route it to the Boise River. In turn, many water users have come to rely on the shallow groundwater and drain water for irrigation and these return flows and high shallow aquifer levels also help to sustain flow in the Boise River throughout the year, providing ecological benefits.

Reclamation's core mission is to provide water and power to the western United States while protecting the environment. Understanding the relationships between regulated water systems and the aquifers that they support is paramount to ensuring that this mission can continue to be carried out into the future. The development of Reclamation projects has resulted in the formation of important groundwater supplies in some locations and the ability to maintain these supplies may play a key role in water supply sustainability going into the future.

Sustainable Groundwater Supplies

The classic definition that is often used to define the sustainable use of groundwater resources from a water-budget perspective is that termed the "safe yield" of the aquifer. This is defined in Bouwer (1978) as:

> *"… the rate at which groundwater can be withdrawn without causing a long-term decline of the water table or piezometric surface. Thus, the safe yield is equal to the average replenishment rate of the aquifer."*

Similar definitions are found in the commonly used groundwater and hydrogeology text books such as Todd (1959), Freeze and Cherry (1979), and Bear (1979). This definition would appear to provide an understandable and easily-implementable policy on the use of groundwater: *don't extract more water from an aquifer than its rate of recharge*. This definition is referred to as the "Water-Budget Myth" (Bredehoeft et al. 1982; Alley et al. 1999). A simple pre-development water-budget approach cannot be used to understand sustainable groundwater use for three primary reasons: (1) aquifers do not exist in the environment as completely isolated water resources; (2) climate variability (particularly in the Western United States) can result in highly variable patterns of groundwater recharge and extraction; and (3) estimates of the "natural recharge" of water to a groundwater system contain high degrees of uncertainty.

The behavior of groundwater systems is altered through the extraction of water to support human activities, and will typically change the rates at which water recharges to, and discharges from, an aquifer (Alley et al., 1999). Thus, the sustainable use of groundwater must be defined in a systems context, as opposed to a simple water-budget concept. The use of groundwater can also be significantly impacted by variations in climate on a yearly to decadal time scale (Alley, et al., 1999). Such impacts can result in situations where a groundwater-budget computed using average extraction and recharge rates can appear sustainable, when in reality groundwater tables can drop below points where feasible extraction of the resource can be maintained for long periods of time.

Finally, recharge to groundwater systems typically occurs over large spatial areas with very low water flux rates and high spatial and temporal variability. Because of this, recharge to groundwater systems can rarely be determined as an independent variable when developing an aquifer's water budget. Rather, it must be estimated as a dependent variable (the "unknown" term in the water balance equation) in the development of an aquifer's water budget and any errors associated with the other elements of the water budget then become embedded in the recharge estimates. These factors combined make it difficult to define the sustainable use of groundwater using a simple water-budget approach.

There have been a variety of studies that have proposed different approaches for defining sustainable groundwater use at a variety of scales. A thorough bibliography of the studies and papers that broadly address this subject was developed and published by the National Ground Water Association (2006). A brief summary of the studies that are more directly related to this project, and studies that have been published after 2006, are summarized below.

State Approaches to Establishing Sustainable Groundwater Use

Within the United States, individual states have supremacy over the administration and management of their groundwater resources, with all states having statutes that for the most part prohibit the "mining" of groundwater. The definition of "mined groundwater' varies somewhat from state to state, but in general all states require that groundwater extracted for use must be replaced by either natural or artificial recharge processes. There are a handful of states that allow for the use of "fossil groundwater" (see http://en.wikipedia.org/wiki/Fossil_water for complete definition) during periods of extreme shortage to meet municipal or industrial water demands. These fossil water resources are not considered replenishable through natural processes, and in essence are administered as non-renewable resources. Fossil water only constitutes a very small portion of water use (<< 1%) within the United States and its use is generally not considered in evaluating sustainable management of groundwater resources. A survey conducted by the National Ground Water Association (2009) found that of the 28 state water resources agencies that responded to the survey, 26 anticipated groundwater supply shortages at the state or local level within the next 20 years. All of the surveyed states have policies that either explicitly or implicitly require groundwater resources be used in a sustainable fashion. None the less, only three states have performed studies that analyze the conditions that affect sustainable groundwater use, and have developed guidelines, analysis tools, and support resources that direct water users on how to achieve this policy goal.

Within the State of Michigan, a report developed by Steinman (2007) developed criteria that can be used to assess the sustainable use of groundwater resources within the state. The report classified the factors affecting sustainable use into three separate sectors (the Environmental Sector, the Economic Sector, and the Social Sector) and quantitative or qualitative measures of sustainability were developed for each sector. Within the Environmental Sector, five measures were proposed, including groundwater contribution to stream baseflow (quantitative measure), groundwater withdrawals (quantitative measure), land use impacts (quantitative measure), groundwater contamination (quantitative measure), and groundwater-dependent natural communities (qualitative measure). Within the Economic Sector, three measures were proposed for use, including the cost of groundwater development and use (qualitative measure), efficiency of groundwater usage (quantitative measure), and water usage from alternative sources (quantitative measure). And finally within the Social Sector three measures were proposed for use, including public education (qualitative measure), conservation (qualitative measure), and restricted groundwater access (qualitative measure).

The State of Minnesota Department of Natural Resources developed a report on the models and tools that can be used to assess the sustainable use of groundwater resources (Minnesota DNR 2010). No specific quantitative criteria were identified in the report to assess sustainable groundwater usage; however, the report does propose a suite of factors that should be considered to determine the impact that changes in water resources management practices will have on the groundwater systems. These factors primarily address the physical processes governing the flux of water within a subsurface environment and rely heavily on field-collected data. The factors identified in the report were all quantitative and covered surface-groundwater interactions, physical behavior of the groundwater system, water use and management practices, and water quality conditions. The report also provides a description of both policy tools and quantitative analysis tools (models) that have been developed within the state that can be used to develop sustainable use policies for specific groundwater systems. The policy tools consisted primarily of legislative rules and laws addressing the use and quality of water within Minnesota, while the quantitative analysis tools identified by the report primarily reference hydrogeologic and aquifer Mapping/GIS resources that have been generated by the Minnesota DNR.

The Association of California Water Agencies (2011) developed a report addressing the sustainability of groundwater use across California. This report provided examples and case studies of sustainable groundwater management practices for heavily-utilized aquifers for a range of physical and socio-economic conditions across the state. The specific groundwater management plans varied significantly between the case studies, however all of the studies included two common elements: (1) the development of a management plan using an Integrated Water Resources Management (IWRM) approach; and (2) the identification of new, local-scale water resource management governance structures that must be developed in order to successfully implement the IWRM plans. The report also recommended five elements for inclusion in the development of management plans for sustainable groundwater use in the future: (1) Optimize conjunctive use of groundwater and surface water; (2) Integrate efforts addressing conservation and water use efficiency; (3) Develop and implement comprehensive data collection and analysis plans; (4) Address the ways in which changes in land use can impact water fluxes to surface and groundwater systems; and (5) Ensure that a robust public education and engagement plan is undertaken.

Sustainability of Groundwater Aquifers and Basins

As summarized by the National Ground Water Association (NGWA 2006) there are a number of studies and articles that have proposed approaches to understand the sustainable use of groundwater resources from an aquifer, or interconnected aquifers and surface water resources. The most comprehensive effort was undertaken by Vrba and Lipponen (2007), which attempted to identify a wide range of factors that should be used to assess the sustainability of groundwater resources across a range of hydro-geologic, climatologic, economic, political and social environments. This study also proposed a series of indicators that could be used to assess the sustainability of groundwater development for aquifers throughout the world. The sustainability assessment approach proposed by this study are comprehensive in nature and primarily addressed the physical characteristics of the groundwater resources that are considered to be developable, and the socio-economic characteristics of water use within the municipality, region or nation. The study proposes the use of ten categories of sustainability, all of which can be measured quantitatively:

1) Renewable groundwater resources per capita
2) Total groundwater abstraction/groundwater recharge
3) Total groundwater abstraction/exploitable groundwater resources
4) Groundwater as a percentage of total use of drinking water use
5) Groundwater depletion
6) Total exploitable, non-renewable groundwater resources and annual abstraction of non-renewable groundwater resources
7) Groundwater vulnerability
8) Groundwater quality
9) Groundwater usability with respect to treatment requirements
10) Dependence of agricultural population on groundwater

The study also provided an extensive discussion of the methodology that should be used to quantify the sustainability measures for each of these categories and case studies presented the use of these measures at several different management scales, including municipal (Seville, Spain), state/regional (State of Sao Paulo, Brazil), and national (Finland and South Africa). While comprehensive in many respects, this study did not propose degree of hydraulic connection between surface and groundwater resources as an important consideration in assessing the sustainable use of groundwater resources.

As noted above, the vast majority of studies and state policies addressing sustainable groundwater use recognize the importance of the interaction between surface water and groundwater resources in understanding the sustainability of water use from both sources. However, none of these studies have developed methodologies to directly address how the regulation of surface water resources affects the sustainability of hydraulically connected groundwater resource.

Modeling Approach

Predicting the ability of water supplies to meet water demands in arid and semi-arid regions of the western United States requires an understanding of characteristic processes and linkages of the watershed. Generally speaking, these processes can be categorized into three different elements and together can effectively characterize the flux of water in regulated river systems:

- Physical System – The natural hydrologic and hydrogeologic processes within the watershed;
- Water Resource Infrastructure – The infrastructure that has been developed to utilize water resources within the watershed; and
- Water Management Regime – The water resource management regime that has been developed based on the natural and developed infrastructure.

Figure 1 illustrates the interconnected nature of these watershed elements, where changes in the behavior of one element impact the behavior of the other elements. For example, if canals (part of the water infrastructure) are lined to reduce seepage, this will reduce recharge to shallow groundwater aquifers (part of the physical properties), and could also lead to a reduction in the amount of water diverted from surface streams, making more water available for diversions downstream of the canal outtakes (part of the water management processes).

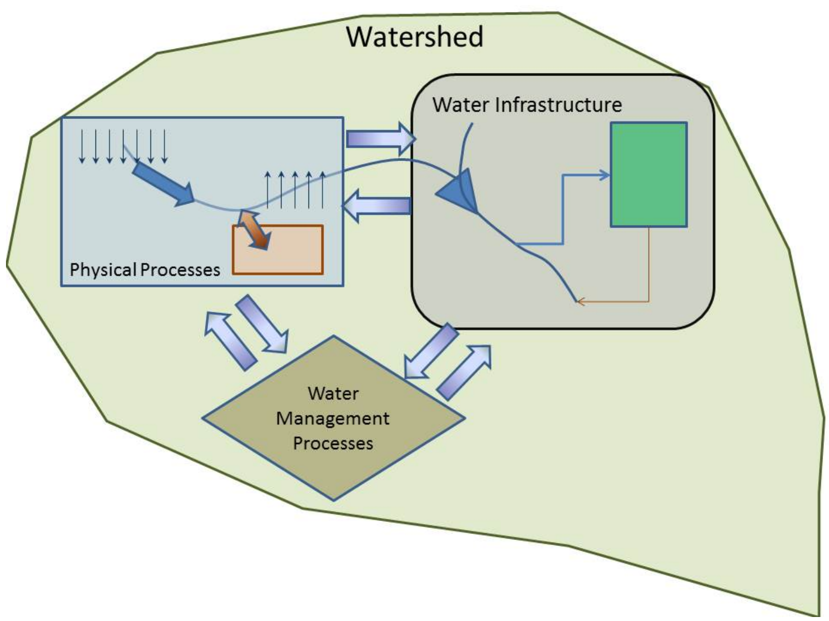

Figure 1. Watershed Elements and Processes.

Systems Dynamics Modeling

Systems Dynamics (SD) software was first introduced in the mid-80's and has since been gaining popularity amongst a variety of users. SD software is simple to use yet sophisticated enough to enable modeling of even the most complicated issues. SD software uses icon-based building elements to construct a conceptual representation of a system. Mathematical, logical and statistical relationships can then be applied to those elements and used to represent the behavior of each of these elements. The specific SD software used in this study is Stella® (ISEE systems - http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx).

A basic tenant of Systems Dynamics modeling is to develop simple modeling components that can be linked together to better understand the behavior of a complex system through the interaction of its objects. However, it is sometimes difficult to develop and understand a Systems Dynamics model by only using objects as the modeling components. Thus, it is useful to develop a modeling hierarchy that utilizes Objects, Elements, and Systems in describing a fully developed Systems Dynamics model.

There are four primary Objects within a Stella Systems Dynamics model (shown in Figure 2). These objects include:

- Stocks (boxes) – Stocks represent the accumulation of a variable, examples of which are volume, mass, energy, money, etc.
- Flows (pipes with valves) – Flows represent the flux of a variable between *Stocks*.
- Converters (circles) – Converters define the relationships between the objects that comprise the system.
- Connectors (red lines) – Connectors identify which objects in the system impact the behavior of other objects within the system.

Stock objects can serve as reservoirs that can accumulate, store and release flows, as well as serve as mere conduits, allowing flow to freely pass through. The behavior of flow objects can be governed by converter objects, the current state of stock objects, other flows objects, or a combination of all three.

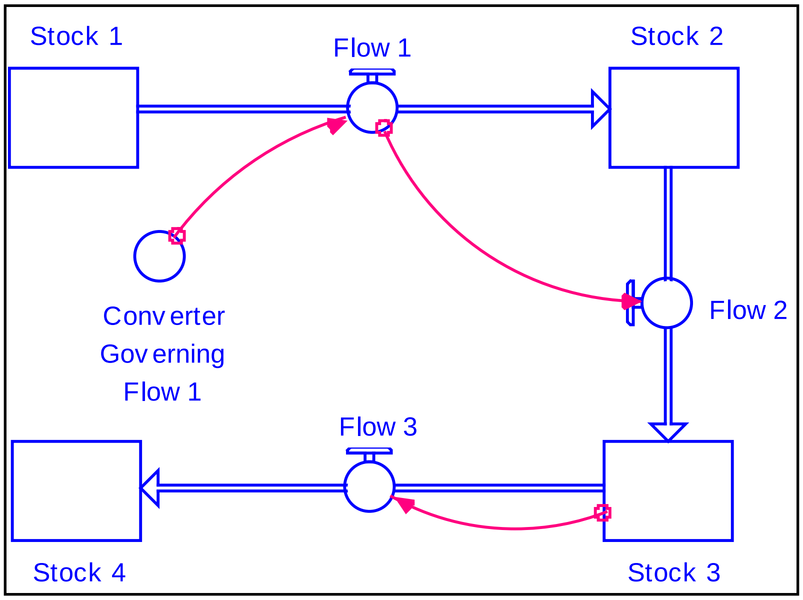

Figure 2. Example of Stella Components and Interactions.

A series of linked stock, flow and converter Objects can be formed into an Element, which can be used to represent the behavior of one or more processes. These processes can then be organized as Systems, representing the behavior of processes that are linked together. Finally, these systems can be linked together to form a full Systems Dynamics Model. Thus, the hierarchy of the modeling components are: the Model, which is comprised of linked Systems; Systems, which are comprised of linked Elements; and Elements, which are comprised of linked Objects.

The first step of this project involved the development of a generalized SD model, representing a "generic", regulated, western river system, which can be used as a surrogate to better understand the feedback mechanisms and responses between the water resource infrastructure, water management regimes, and hydrologic processes within a watershed. A conceptual depiction of such a system is provided in Figure 3, where the physical system is comprised of elements representing the inflow to the river system(s), properties governing the flow of water within the river system, properties governing the flux of water through the aquifer system(s), precipitation, evapotranspiration, and the properties governing the flux of water between surface and groundwater resources. Water resource infrastructure is comprised of reservoirs and other storage facilities, river outtakes and conveyance facilities, soil drainage and return flow facilities, irrigated agricultural facilities, and aquifer pumping facilities. Although not represented explicitly in the figure, the system operates under the constraints of the water management processes that consist of the water rights administration rules and reservoir operating rules.

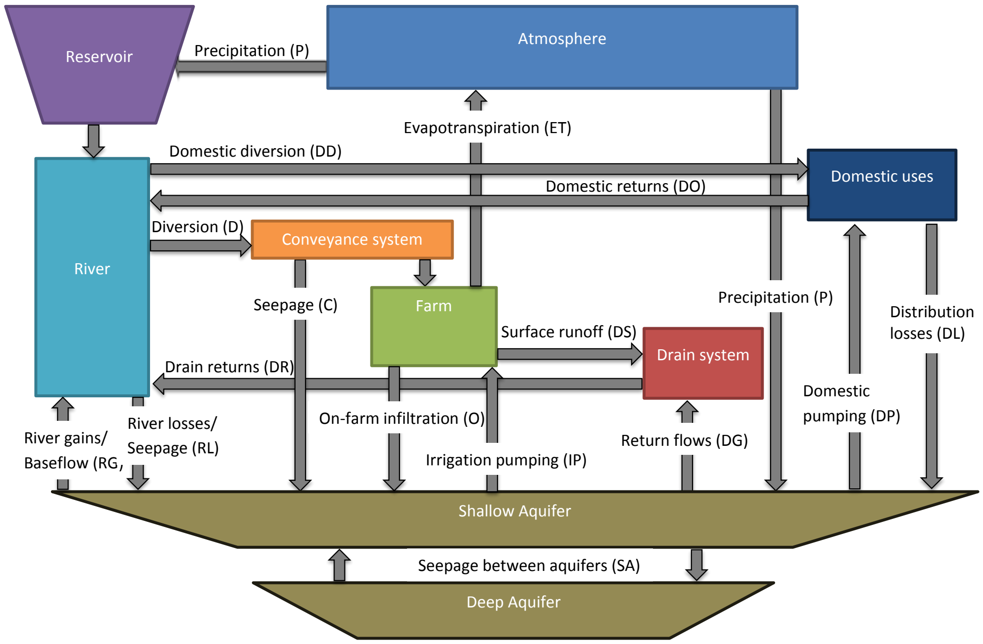

Figure 3. Conceptual representation of regulated river system.

Physical System

The SD model of the natural system consists of a network of elements representing the characteristic processes of a watershed. The natural system model shown in Figure 4 includes a representation of the upland watershed, multiple river segments, a shallow aquifer that is hydraulically connected to the river segments, and a deeper aquifer system that is hydraulically connected to the shallow aquifer system via a low permeability zone (aquitard). The following sections discuss these various model elements in more detail.

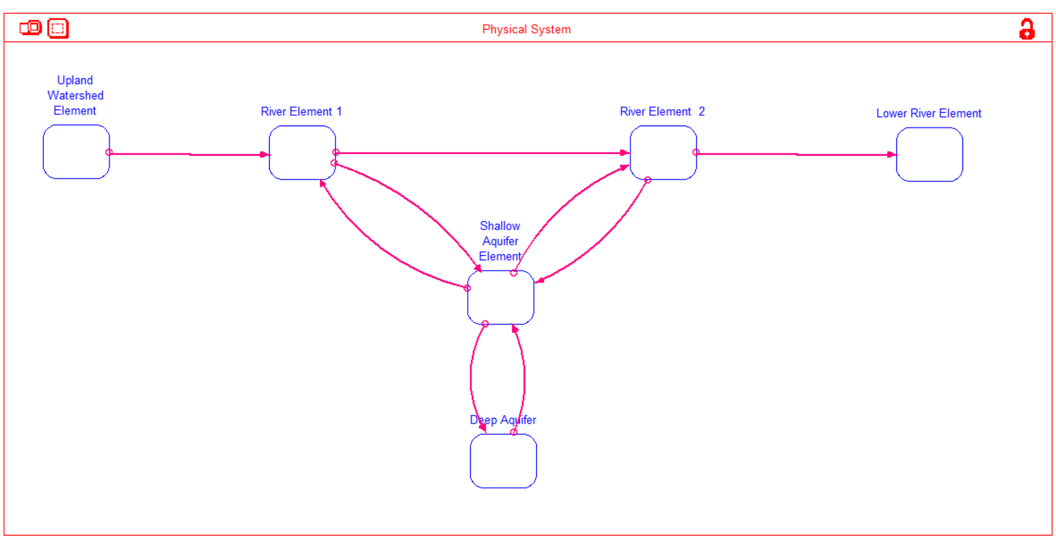

Figure 4. System Dynamics representation of the physical elements of a watershed.

Upper Watershed Element

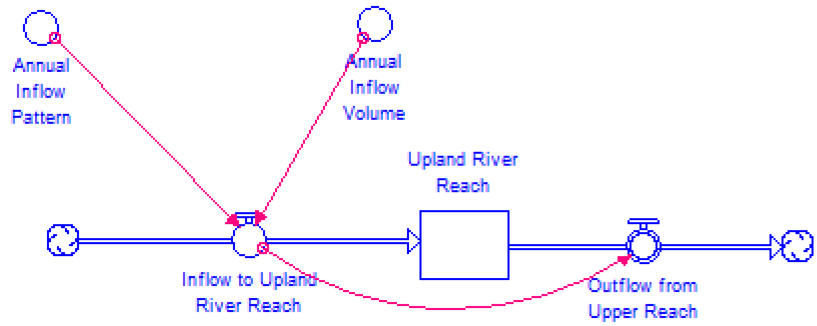

Figure 5. System Dynamics representation of the upper watershed element processes.

Figure 5 depicts the internal processes governing the behavior of the flow of water within the Upland Watershed Element from Figure 4. The "annual inflow pattern" object is used to define not only the pattern of inflow, but also its intra-annual statistical variability (or the variability of the inflow pattern within a single year). Similarly, the "annual inflow volume" object defines the annual volume flowing into the watershed and its inter-annual statistical variability (or the variability of the annual volume from year to year). This model assumes there is no loss of water in the Upland River Reach, thus the "Inflow from the Upland River Reach" object is set to always equal to the "Outflow from the Upper Reach" object.

River Element 1

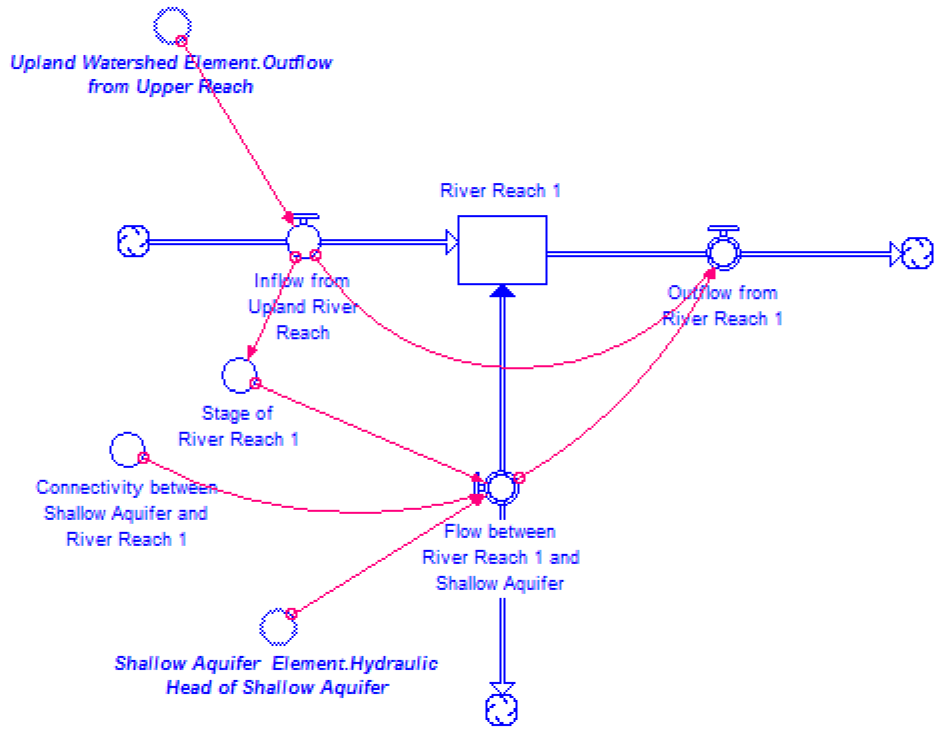

Figure 6. System Dynamics representation of River Element 1 processes.

The processes governing the behavior of the flow of water in River Element 1 are shown in Figure 6. The flux of water into and out of River Reach 1 is defined by the "Outflow from Upper Reach" (calculated in the Upland Watershed Element), the loss or gain of water from the hydraulically connected shallow aquifer, and the "Outflow from River Reach 1" object. The flux rate between River Reach 1 and the Shallow Aquifer is governed by the difference between the "River Stage" and the "Hydraulic Head of Shallow Aquifer" objects, and the parameters defining the hydraulic connectivity between River Reach 1 and the Shallow Aquifer (represented by "Connectivity between Shallow Aquifer and River Reach 1" object). For this study, the flux rate is computed as:

If $H_S > H_A$:

$$Q = LR * (1 - e^{\{(H_A - H_S)*P\}});$$

Else:

$$Q = LR * (1 - e^{\{(H_S - H_A)*P\}})$$

Where:

Q = the flux rate between the river reach and shallow aquifer (volume/time);

LR = Limiting flux rate between river reach and shallow aquifer (volume/time);
H_S = the river stage (Length);
H_A = the hydraulic head of the shallow aquifer (Length); and
P = a calibrated permeability factor between the river reach and the aquifer (1/length).

The “Outflow from River Reach 1” is then calculated as the sum of the “Inflow from Upland River Reach” plus the net gain (+) or loss (-) of water from the Shallow Aquifer (represented by the “Flow between River Reach 1 and Shallow Aquifer” object).

River Element 2

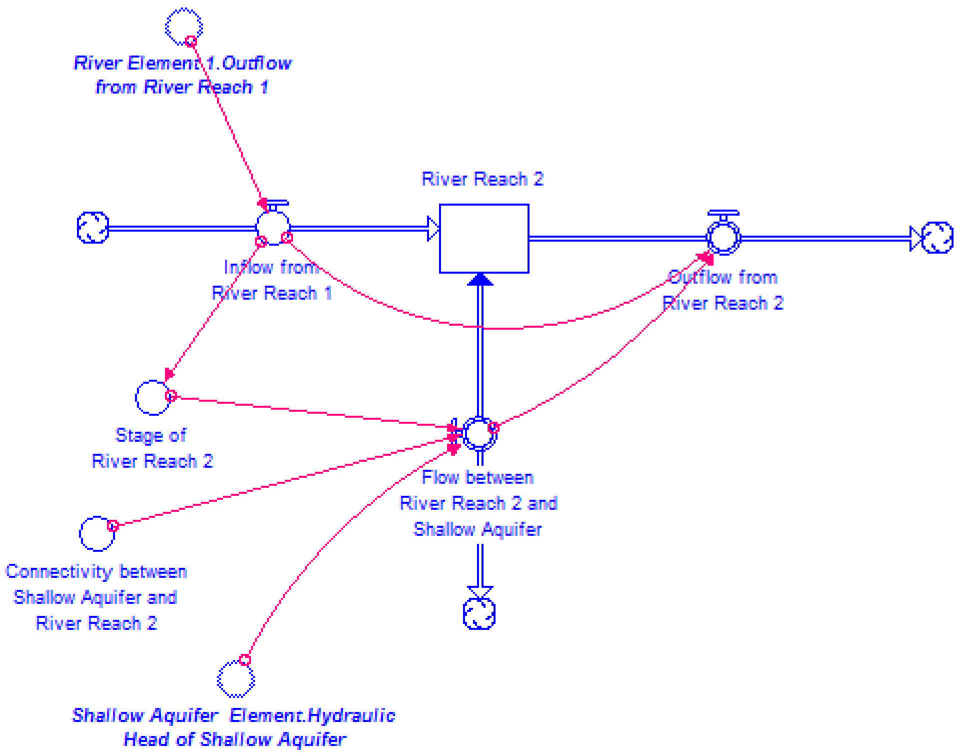

Figure 7. System Dynamics representation of River Element 2.

Figure 7 depicts the processes governing the behavior of the flow of water in River Element 2. The flux of water into and out of River Reach 2 includes the “Outflow from the River Reach 1” (calculated in River Element 1), the loss or gain of water from the hydraulically connected shallow aquifer, and the “Outflow from River Reach 2”. The flux rate between River Reach 2 and the Shallow Aquifer is calculated in the same manner as that described above for River Element 1. The “Outflow from River Reach 2” is then calculated as the sum of the “Inflow from River Element 1” plus the net gain (+) or loss (-) of water from the Shallow Aquifer.

Shallow Aquifer Element

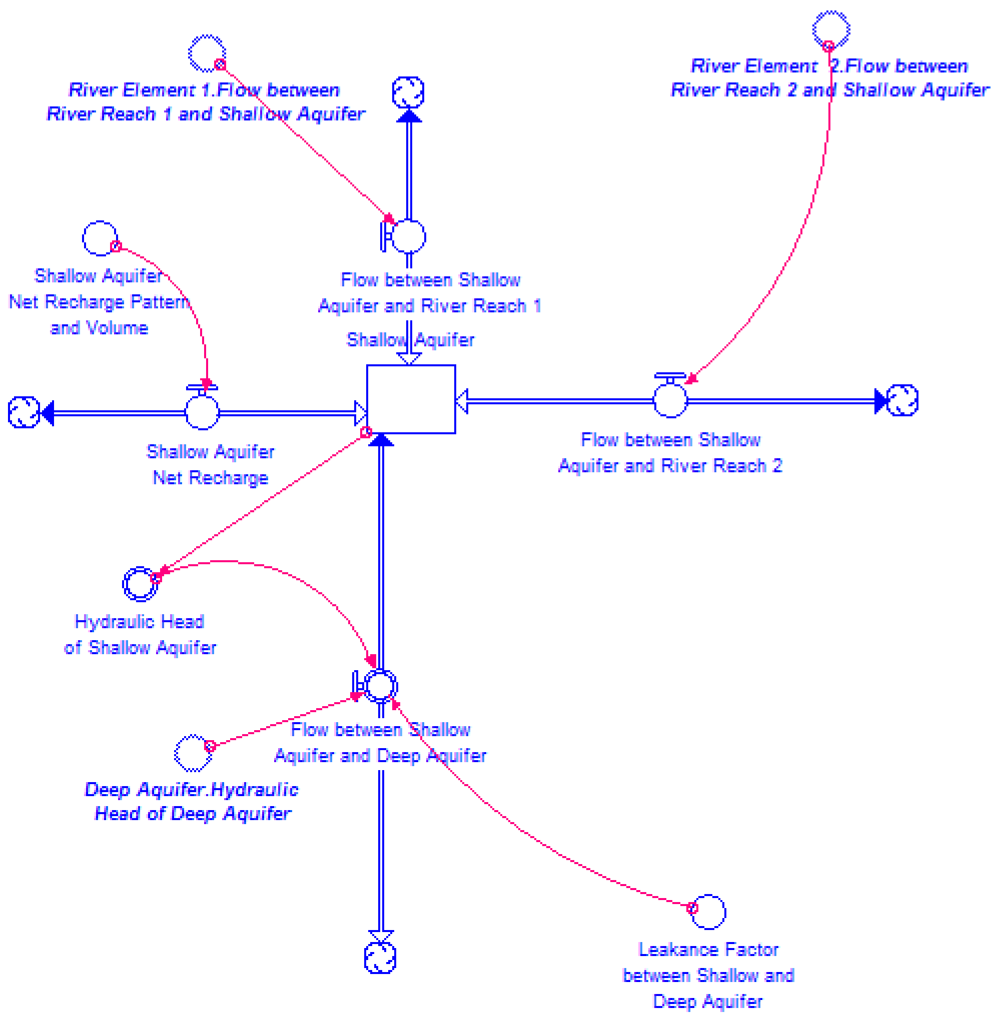

Figure 8. System Dynamics representation of Shallow Aquifer Element.

The processes governing the behavior of the flow of water in the Shallow Aquifer Element are shown in Figure 8. The flux of water into and out of the Shallow Aquifer includes the "Shallow Aquifer Net Recharge", the flux of water with the hydraulically connected River Reach 1 and River Reach 2, and the flux of water with the Deep Aquifer. The net recharge flowing to the Shallow Aquifer is defined as the difference between the natural recharge to the aquifer minus the natural outflow from the aquifer across the physical system boundaries, represented as the Net Shallow Aquifer Recharge Object in Figure 8. The net recharge flux can be defined as a time series, a yearly pattern, or a constant value. The flux of water between the river reaches and the Shallow Aquifer are calculated using the relationships described above for River Element 1 and River Element 2. The flux of water between the Deep Aquifer and Shallow Aquifer is calculated as:

$$Q_{SD} = (H_D - H_S) * p * A_S$$

Where:

Q_{SD} =the flux rate from the Shallow Aquifer to the Deep Aquifer (volume/time);
H_D = the hydraulic head of the Deep Aquifer (length);
H_S = the hydraulic head of the Shallow Aquifer (length);
p = the permeability of the aquitard (1/time); and
A_S = the effective surface area of water flux between the Shallow Acquifer and the Deep Aquifer (length^2).

Deep Aquifer Element

The processes governing the behavior of the flow of water in the Deep Aquifer Element are shown in Figure 9. The flux of water into and out of the Deep Aquifer includes the net natural recharge to the Deep Aquifer (represented by the “Deep Aquifer Net Recharge” object) and the flux of water between the Shallow Aquifer and Deep Aquifer. The net natural recharge to the Deep Aquifer is defined as the difference between the natural recharge to the aquifer minus the natural outflow from the aquifer across the physical system boundaries. This net recharge flux can be defined as a time series, a yearly pattern, or a constant value. The calculation of the flux of water between the Shallow Aquifer and the Deep Aquifer is defined in the Shallow Aquifer Element.

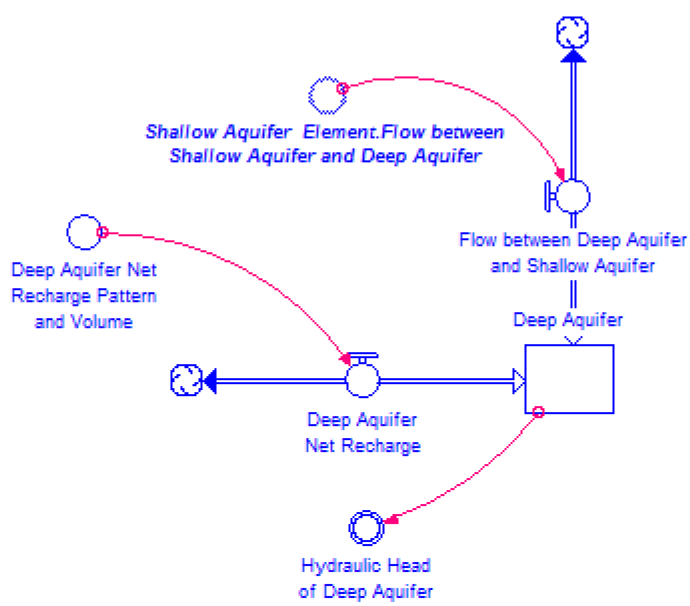

Figure 9. System Dynamics representation of Deep Aquifer Element.

Lower River Element

Figure 10 depicts the processes governing the behavior of the flow of water in the Lower River Element. In this element the flux of water into Lower River Reach is determined by the

"Outflow from River Reach 2" (calculated in River Element 2), while the flux of water out of the Lower River Reach is dependent upon the "Downstream Flow" object, representing flow passing out of the physical system boundary.

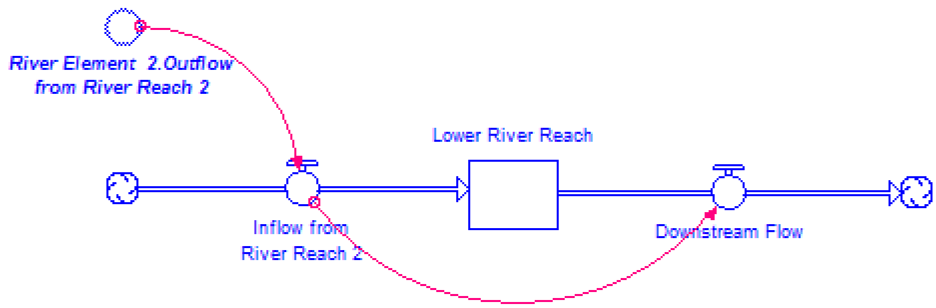

Figure 10. System Dynamics representation of Lower River Element.

Water Resource Infrastructure System

Figure 11 illustrates the configuration of the Water Resource Infrastructure System, which is comprised of several system dynamic modeling elements including the Storage Facilities element, the River Outtakes and Conveyance Structures element, the Irrigated Agriculture Facilities element, the Aquifer Pumpage Facilities element, and the Drainage and Return Flow Facilities element. The Irrigated Agriculture Facilities element is directly connected (in terms of water flow) to the River Outtakes and Conveyance Structures element, the Aquifer Pumpage Facilities element, and Drainage and Return Flow Facilities element. Note however, that no elements share a direct connection with the Storage Facilities element. Instead, the flow of water to and from this element occurs through model linkages to the elements of the Physical System and the Water Administration Systems, which will be discussed later in this Section.

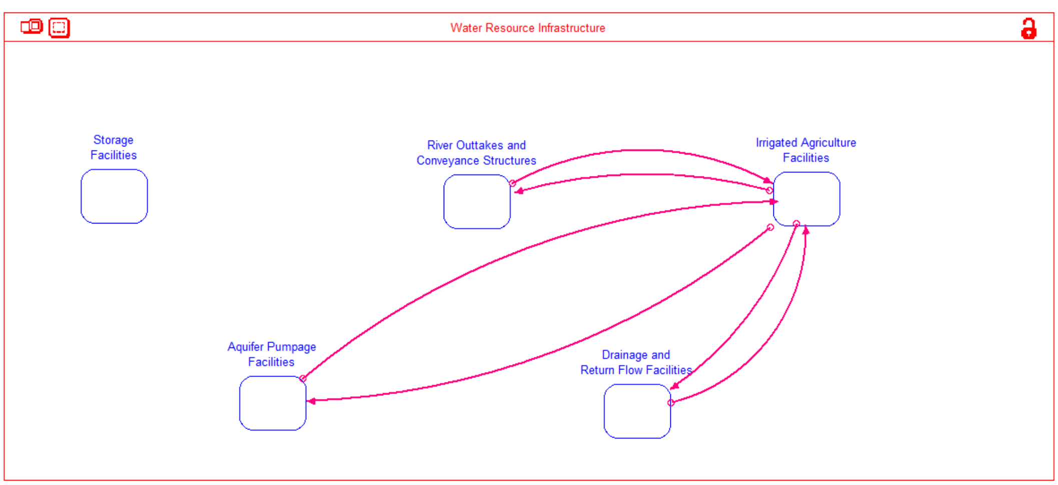

Figure 11. System Dynamics representation of the Water Resource Infrastructure Elements.

Storage Facilities Element

The processes that govern the behavior of the flow and storage of water in the Storage Facilities element are shown in Figure 12. Such an element may contain multiple water storage structures, but these structures are typically grouped into upstream and downstream water storage structures. The flux of water into each of the reservoir storage structures (here represented by the Upstream Reservoir Storage object) is simply the upstream inflow controlled by the Upstream Reservoir Inflow object. The outflow from each reservoir (or reservoir group) is determined by the volume of water stored within the reservoir(s), and the rules established for reservoir operation, discussed later in this report.

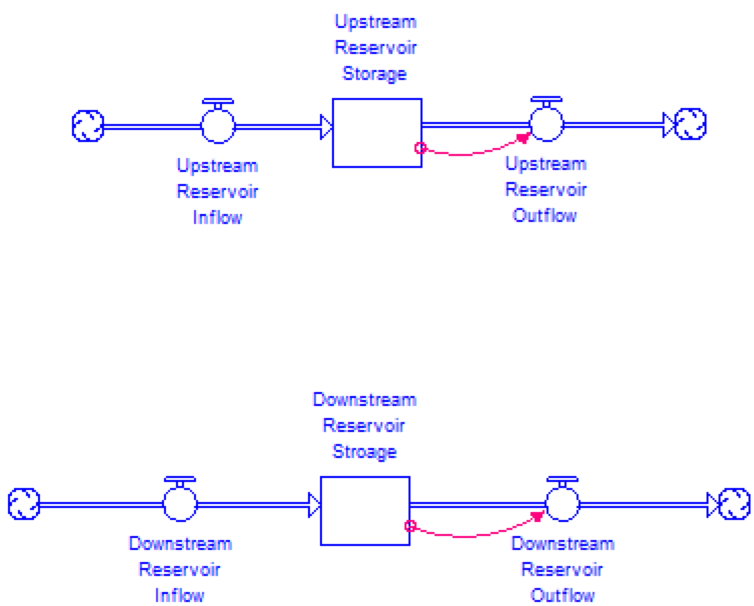

Figure 12. System Dynamics representation of the Water Resource Infrastructure Elements.

River Outtakes and Conveyance Structures Element

The processes that govern the behavior of water flow through the River Outtake and Conveyance Structures element are shown in Figure 13. The flux of water into this element occurs through the “Outtake from River Element 1” object, which is governed by the Crop Irrigation Demand object (tying back to, and defined within, the Irrigated Agriculture Facilities element). The flux of water out of the River Outtake and Conveyance Facilities element occurs via the Water Delivery to Irrigated Agriculture and the Canal Seepage Losses objects.

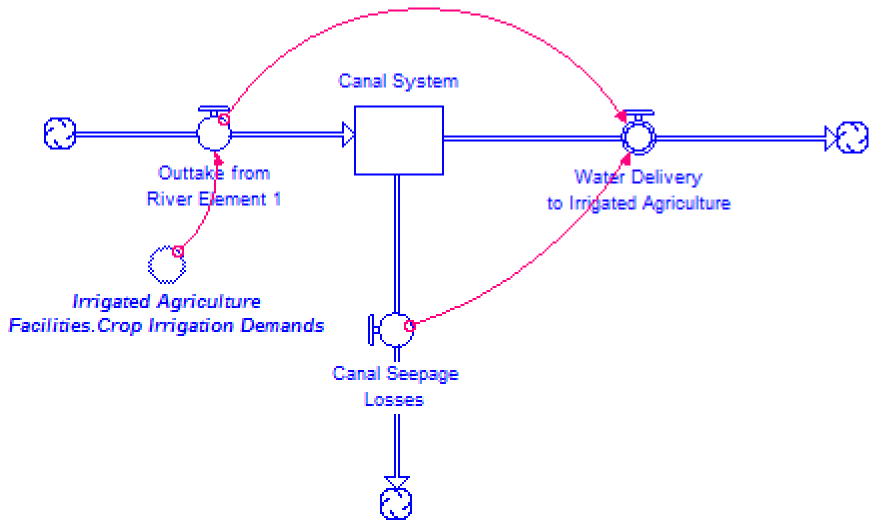

Figure 13. Systems Dynamics representation of the River Outtakes and Conveyance Structures element.

Irrigated Agriculture Facilities Element

The processes governing the behavior of the flow of water through the Irrigated Agriculture Facilities element are shown in Figure 14. The flux of water into this element occurs through three different objects, including Canal Deliveries, Drain Deliveries, and GW Use for Agriculture. The Canal Deliveries object is controlled by the irrigation demand for the crops being grown (represented by the Crop Irrigation Demands converter) and the Water Delivery to Irrigated Agriculture converter (calculated in the River Outtakes and Conveyance Structures element). The amount of water pumped from the Shallow Aquifer and Deep Aquifer is also governed by the irrigation demand as well as by the pumping rates calculated in the Aquifer Pumpage Facilities element (described in the next section). Irrigation demand also controls the Drain Deliveries, as does the Water Reuse for Agriculture calculated in the Drainage and Return Flow Facilities element.

The flux of water out of the Irrigated Agriculture Facilities element is defined by the consumptive use of water by the crops being grown, infiltration to the shallow aquifer, and return flows to the drains. Flow through the Consumptive Use object is a function of the Crop Evapotranspiration Demand Relationships and water from the Canal Deliveries, Drain Deliveries, and Groundwater Use for Agriculture objects. Meanwhile, the objects “Infiltration to Shallow Aquifer” and “Return Flow to Drainage System” are governed by the total amount of water used to irrigate crops (from groundwater, drain, and canal deliveries) and the efficiency of the irrigation systems being used, defined by the “Irrigation Efficiency Relationships” converter. The “Irrigation Efficiency Relationship” converter contains information on the percentage of water that is not consumptively used by the crops, and the fraction of this excess water that infiltrates to the shallow aquifer. To ensure a water balance is maintained for every time period in the simulation, the return flows to the drains are determined as the difference between all of the inflows to the Irrigated Agriculture Stock (Drain, Canals and Groundwater) minus the sum of the Consumptive Use and the Infiltration to Shallow Groundwater.

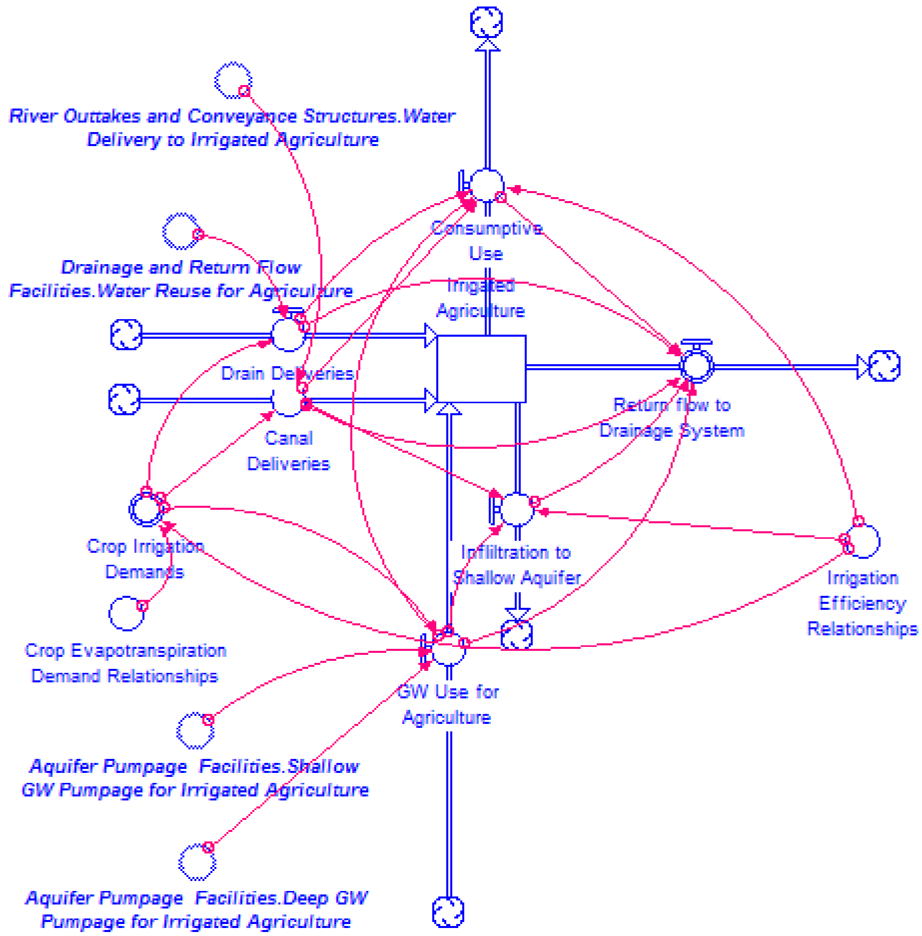

Figure 14. Systems dynamics representation of Irrigated Agriculture Facilities element.

Aquifer Pumpage Facilities Element

The processes governing the behavior of the flow of water through the Aquifer Pumpage Facilities element are shown in Figure 15. The flux of water into this element occurs through the pumping of water from the Shallow Aquifer, and the pumping of water from the Deep Aquifer, both of which are governed by the Crop Irrigation Demands calculated in the Irrigated Agriculture Facilities Element.

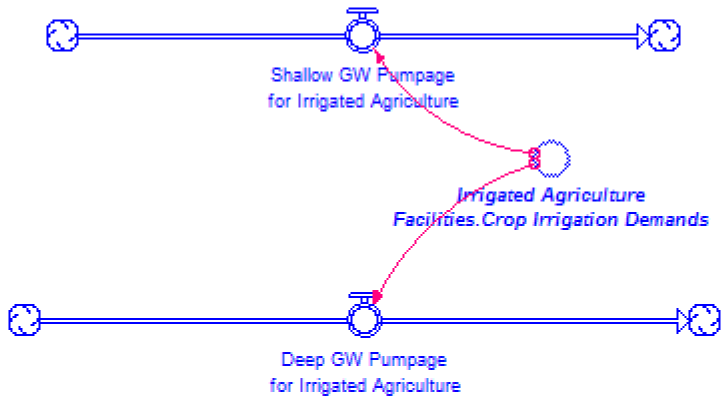

Figure 15. Systems Dynamics representation of Aquifer Pumpage Facilities element.

Drainage and Return Flow Facilities Element

The processes governing the behavior of the flow of water through the Drainage and Return Flow Facilities are shown in Figure 16. The flux of water into the Drainage and Return Flow Facilities occurs through the return flow from the irrigated agriculture facilities and any gains of water from the shallow groundwater aquifer. The flux of water out of this element occurs through the Water Reuse for Agriculture; and the Outflow to River Element 2 objects.

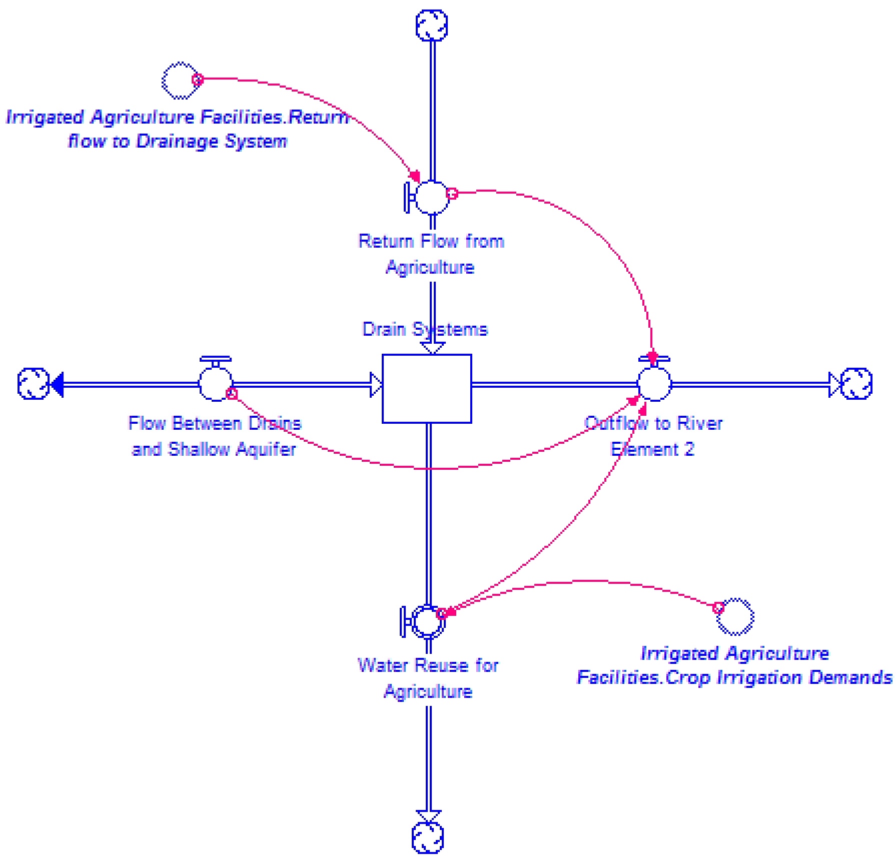

Figure 16. Systems Dynamics representation of the Drainage and Return Flow Facilities element.

Water Management System

The Water Management System within a watershed is comprised of two system dynamic modeling elements: Storage Facility Operating Rules and Water Rights Administration (Figure 17). There is no flow of water within, or between, these two elements. Rather these elements provide information that controls the flow of water between the Physical System and the Water Infrastructure System.

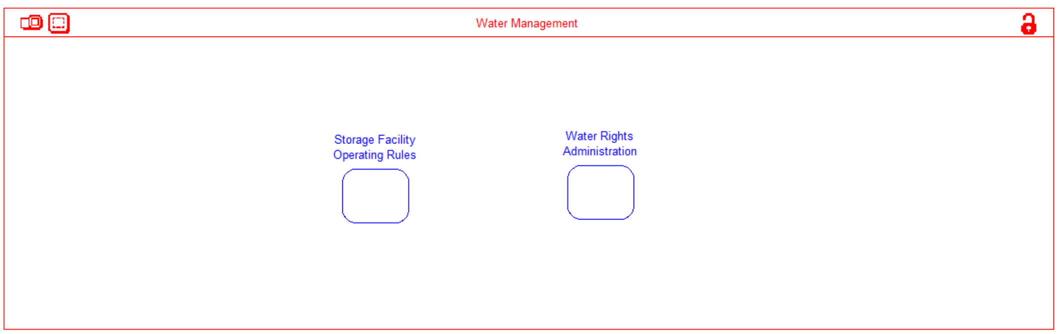

Figure 17. Systems Dynamics representation of the Water Management System elements.

Storage Operating Rules Element

The processes within the Storage Operating Rules element are shown in Figure 18. This element contains only two converters, each of which provide information on the rules that must be followed for the storage of water in reservoirs within a watershed. These operating rules typically entail the use of a range of maximum storage volumes (depending on the time of year) for flood management benefits (maintaining space in the reservoir to capture and regulate flood flows), but can also include more complex relationships that include additional information on measured and projected hydrologic conditions within a watershed.

Figure 18. Systems Dynamics representation of the Storage Operating Rules element.

Water Rights Administration Element

The processes that are included within the Water Rights Administration element are shown in Figure 19. This element contains only four converters that define the relationships between the amount of water extracted from the various elements of the Physical System (River Element 1, River Element 2, Shallow Aquifer Element and Deep Aquifer) through their associated elements in the Water Resource Infrastructure System (River Outtakes and Conveyance Structures, Aquifer Pumpage Facilities, and Drainage and Return Flow Facilities). These relationships can be as simple as providing a value for the total amount of water available for use by each of the Water Resource Infrastructure System elements, or can involve the use of more complex relationships utilizing additional information on the amount of water available within various elements of the Physical System. These relationships are unique to the watershed being analyzed and must be defined through developing mathematical, logical and statistical expressions.

Figure 19. Systems Dynamics representation of the Water Rights Administration element.

Integrated Physical, Infrastructure and Management System

In order for the systems to be integrated and function as a whole, linkages between the system elements must be developed. These linkages are critical in the development of a tool to understand how the various systems interact with one another. The first step in developing these linkages is to define how the elements of the Water Management System influence elements in the Water Resource Infrastructure System and the Physical System.

Within the ISEE STELLA © System Dynamics modeling software, objects that are linked between different elements are graphically identified as either providing information to, or receiving information from another element. If an object is receiving information from an object residing within a different element, the object is shown in the graphical model development interface with a "fuzzy" outline, a label identifying the element that is providing the information, followed by the name of the object in italics. An example of this is shown in Figure 22, where the controller that defines the releases of water from the Upstream Reservoir is defined in the *Storage Facilities Operating Rules*, and named *Upstream Reservoir Operating Rules*. If an object is providing information to objects residing in a different modeling element, the object is shown in the graphical model development interface as having "bubbles" around the object. Examples of this are shown in Figures 20 and 21 below, where the Reservoir Operating Rule controllers and the Water Rights controllers now have "bubbles" around the controller circle, indicating that these controllers are connected to objects in other elements. Since an object could potentially provide information to objects in multiple elements, the names of the objects and elements that the information is provided to are not shown in the graphical interface.

Linkage of Storage Operating Rule Element to Other Elements

Figure 20 shows the Upstream Reservoir Operating Rules and Downstream Reservoir Operating Rules converters that govern the operation of the Upstream Reservoir Storage and Downstream Reservoir Storage objects within the Storage Facilities Element of the Water Resource Infrastructure System (Figure 22). The Storage Operating Rule Element has no other direct linkage to any other element within the watershed model, and is assumed to not be impacted by any changes in any other element within the watershed.

Figure 20. Representation of Storage Facilities Operating Rules element in relation to other watershed model elements.

Linkage of Water Rights Administration Element to Other Elements

Figure 21 shows the Surface Water Rights, Drain Water Rights, Shallow Groundwater Rights, and Deep Groundwater Rights converters that govern the operation of the River Outtakes and Conveyance Structures, Drainage and Return Flow Facilities, and Aquifer Pumpage Facilities elements (of the Water Resource Infrastructure System), respectively (see Figure 23, Figure 24, and Figure 25). The Water Rights Administration Element has no other direct linkage to any other element within the Watershed, and is assumed to not be impacted by any changes in any other element within the Watershed.

Figure 21. Representation of Water Rights Administration elements in relation to other watershed model elements.

Linkage of Storage Facilities Element to Other Elements

As shown in Figure 22, the flux of water into the Upstream Reservoir Storage object occurs through the “Outflow from Upper Reach” object in the Upland Watershed element, while the flux of water out of the Upstream Reservoir Storage object is governed by the amount of water stored in the reservoir and the Upstream Reservoir Operating Rules (defined in the Storage Facilities Operating Rules Element). Similarly, the flux of water into the Downstream Reservoir Storage object is the “Outflow from River Reach 1” (of River Element 1), with the flux of water out of the Downstream Reservoir Storage object governed by the amount of water stored in the reservoir and the Downstream Reservoir Operating Rules object (defined in the Storage Facilities Operating Rules Element). The flux of water out of the Upstream Reservoir governs the flux of water into River Reach 1 (River Element 1 of the Physical System, Figure 6), while flux of water out of the Downstream Reservoir object governs the flux of water into River Reach 2 (River Element 2 of the Physical System, Figure 7).

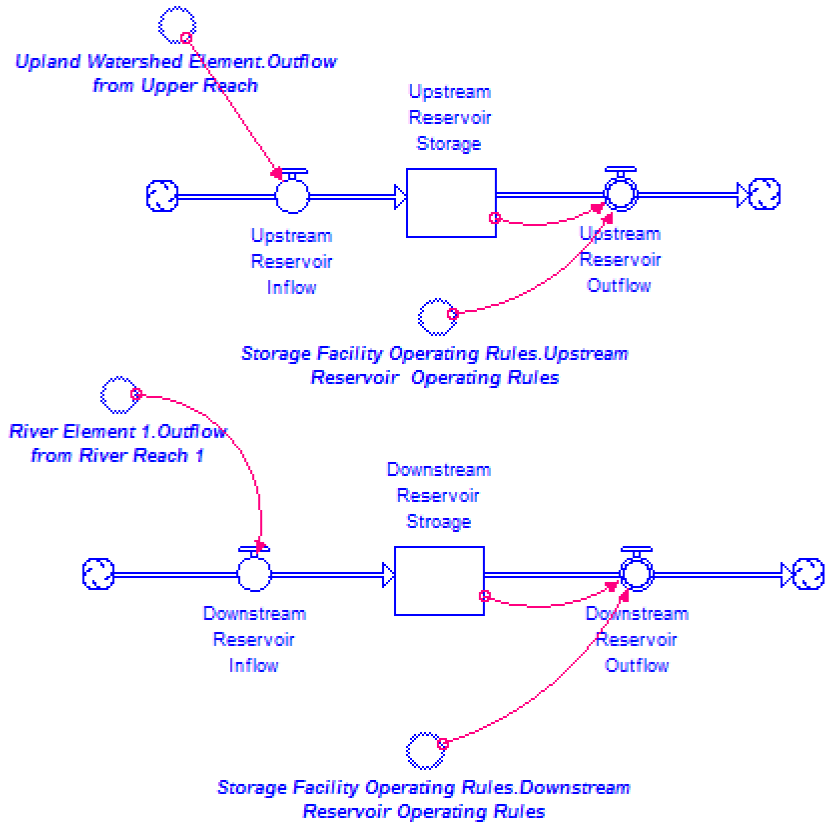

Figure 22. Representation of the Storage Facilities element in relation to other watershed model elements.

Linkage of Aquifer Pumpage Facilities Element to Other Elements

As shown in Figure 23, the pumping of shallow and deep groundwater are governed by the Crop Irrigation Demands (of the Irrigated Agriculture Facilities Element) and the Shallow Groundwater Rights and Deep Groundwater Rights (of the Water Rights Administration Element), respectively. The "Shallow Groundwater Pumpage for Irrigated Agriculture" object then represents a flux of water out of the Shallow Aquifer Element within the Physical System (Figure 8), and the "Deep Groundwater Pumpage for Irrigated Agriculture" object represents the flux of water out of the Deep Aquifer Element within the Physical System (Figure 9).

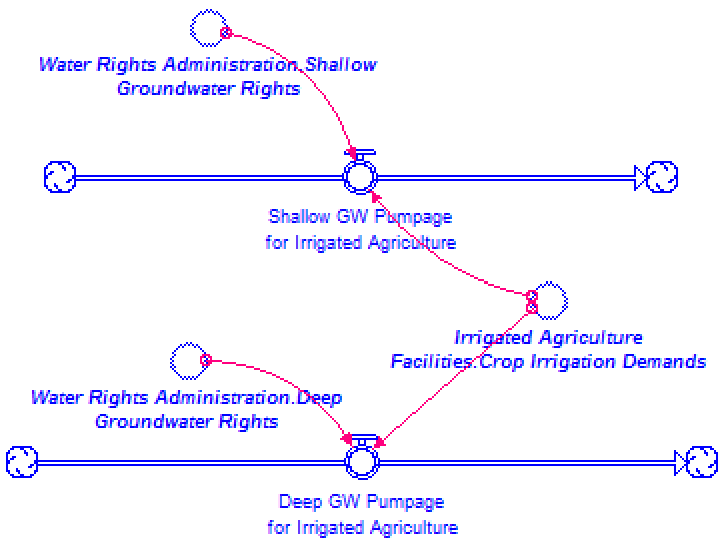

Figure 23. Representation of the Aquifer Pumpage Facilities element in relation to other watershed model elements.

Linkage of River Outtakes and Conveyance Structures Element to Other Elements

As shown in Figure 24, the flux of water into the Canal System object is governed by the Surface Water Rights of the Water Rights Administration Element, along with the Crop Irrigation Demands of the Irrigated Agriculture Facilities Element. The flux out of the Canal System object is represented by the delivery of water to irrigated agriculture and the seepage of water from the canal to the Shallow Aquifer Element of the Physical System. The flux rate between the canal system and the shallow aquifer is governed by the difference between the stage of water in the canals and the hydraulic head of the Shallow Aquifer, as well as the parameters defining the hydraulic connectivity between the canals and the Shallow Aquifer. The relationships used to determine the flux of water between River Element 1 and the Shallow Aquifer Element are also used here. The flux of water into the Canal System object also represents the flux of water out of River Element 1 of the Physical System (Figure 6).

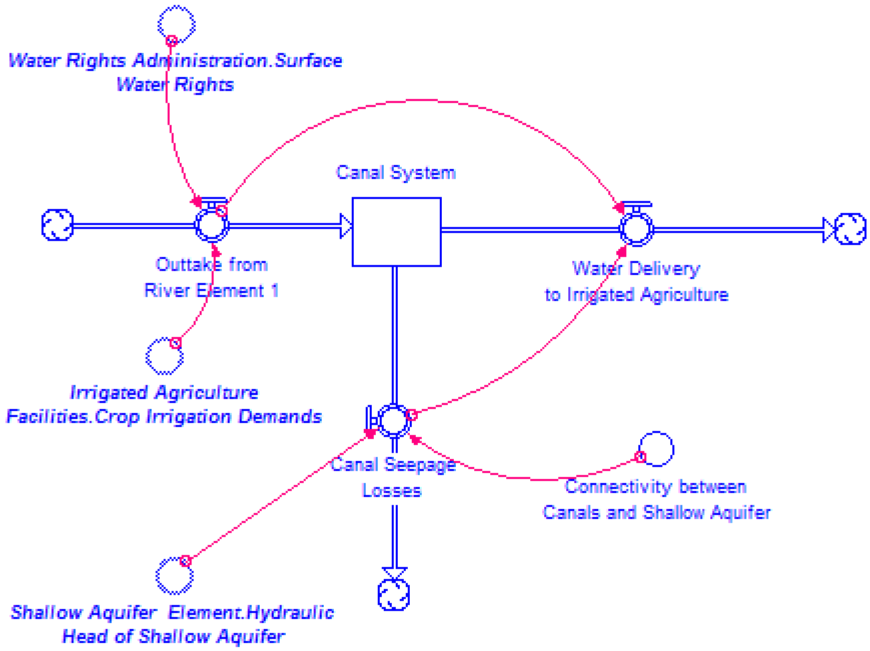

Figure 24. Representation of the "River Outtake and Conveyance Structures" element in relation to other watershed model elements.

Linkage of Drainage and Return Flow Facilities Element to Other Elements

As shown in Figure 25, the flux of water into the Drain Systems object is determined by the "Return Flow from Agriculture" object. The flux rate between the Drainage Systems object and the Shallow Aquifer (represented by the object "Flow between Drains and Shallow Aquifer") is governed by the difference between the stage of water in the drains and the hydraulic head of the Shallow Aquifer, and the parameters defining the hydraulic connectivity between the canals and the Shallow Aquifer. The relationships used to determine the flux of water between River Element 1 and the Shallow Aquifer Element are also used here. The flux of water out of the Drain Systems object occurs through the "Outflow to Lower River Element" object and the "Water Reuse for Agriculture" object (governed by the Drain Water Rights object of the Water Rights Administration Element), and is dependent upon the Crop Irrigation Demands object of the Irrigated Agriculture Facilities Element.

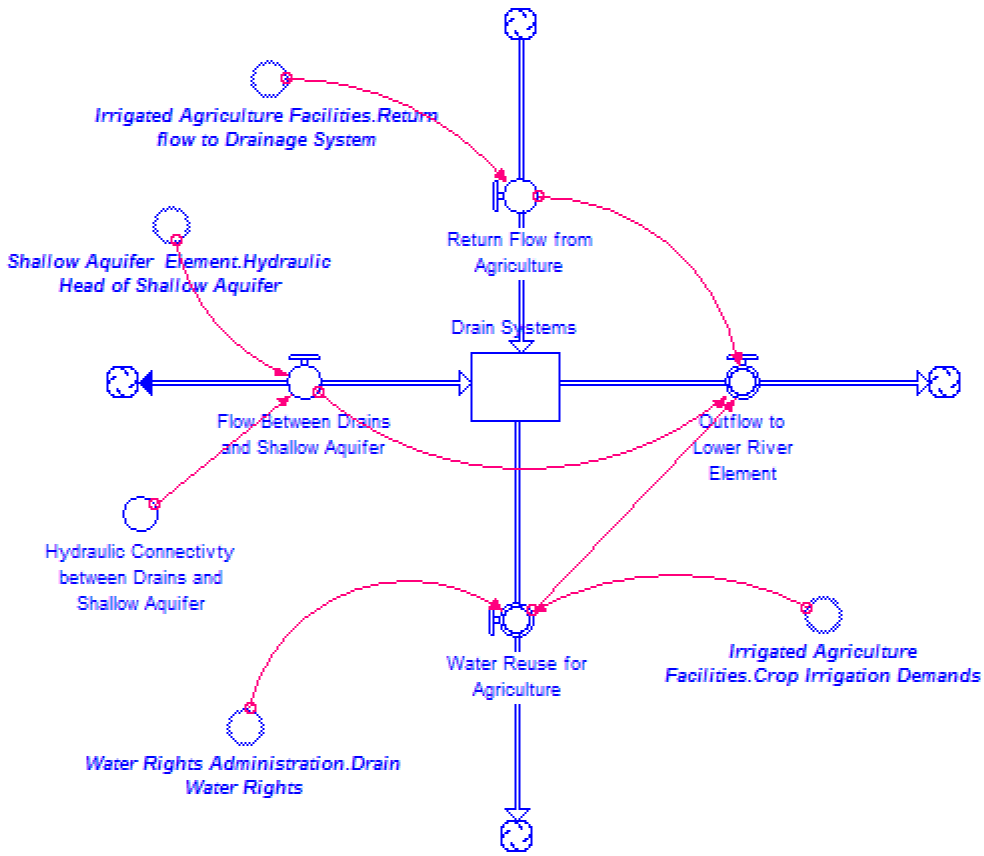

Figure 25. Representation of Drainage and Return Flow Facilities in relation to other watershed model elements.

Linkage of Irrigated Agriculture Facilities Element to Other Elements

As shown in Figure 26, all of the fluxes of water into and out of the Irrigated Agriculture Facilities Element have been discussed earlier in this section, with the only linkage to any of the Physical System elements or Water Management elements being the flux of excess irrigation water (Infiltration to Shallow Aquifer) to the Shallow Aquifer element of the Physical System (Figure 8).

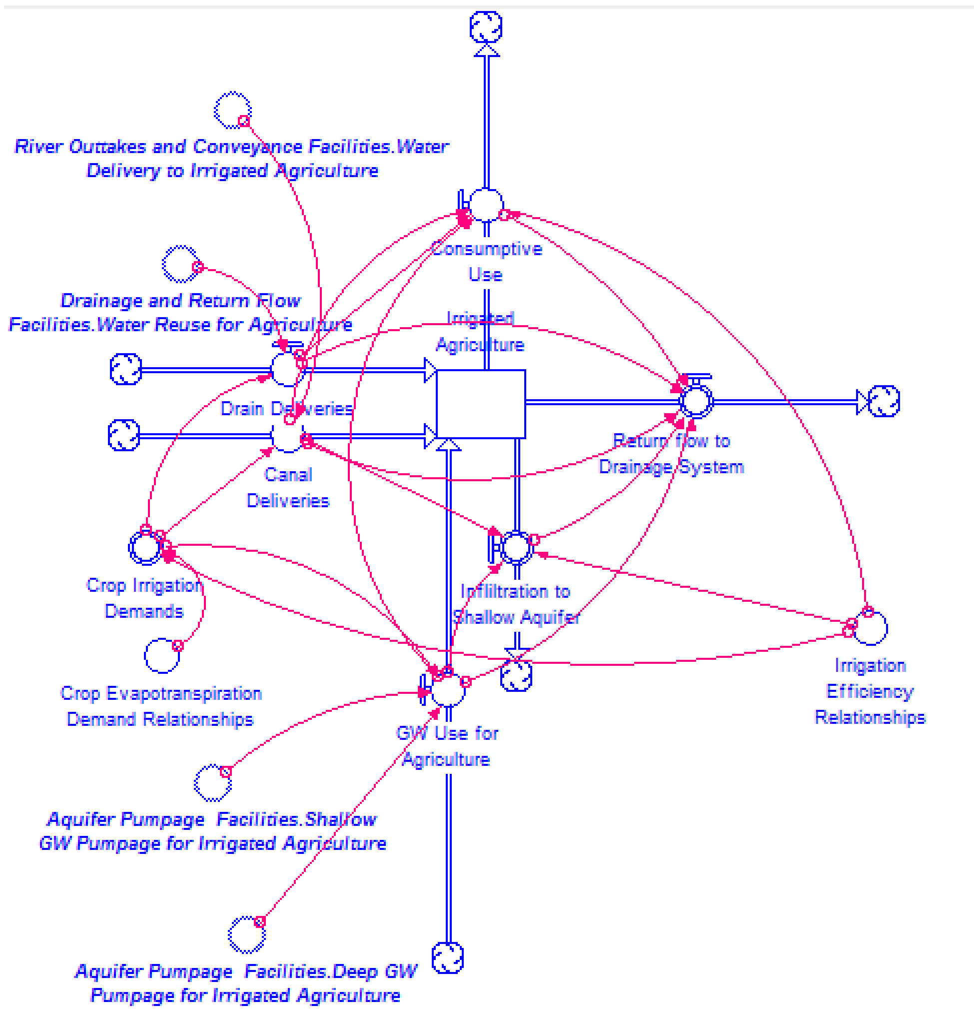

Figure 26. Representation of Irrigated Agriculture Facilities element in relation to other watershed model elements.

Linkage of Upland Watershed Element to Other Elements

As shown in Figure 27, all of the fluxes of water into and out of the Upland Watershed Element have been discussed earlier, with the only linkage to any of the Water Resource Infrastructure elements being the “Outflow from Upper Reach” to the Storage Facilities Element of the Water Resource Infrastructure System (Figure 22).

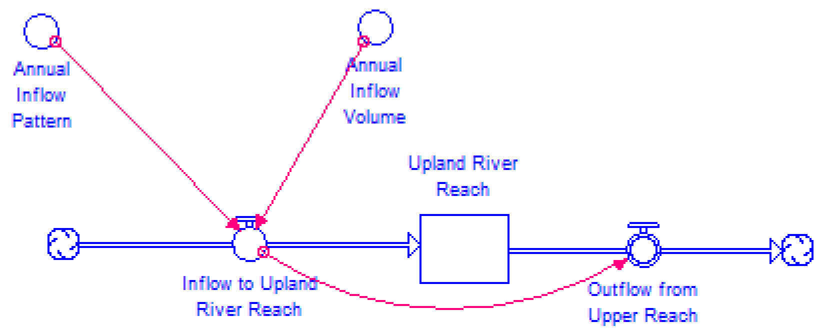

Figure 27. Representation of Upland Watershed element in relation to other watershed model elements.

Linkage of River Element 1 to Other Elements

As shown in Figure 28, the flux of water into River Reach 1 is determined by the "Outflow from Upper Reach" and the Upstream Reservoir Outflow (from the Storage Facilities Element of the Water Resource Infrastructure System) objects. The fluxes of water out of River Reach 1 are represented by the objects "Flow between River Reach 1 and the Shallow Aquifer", "Outflow from River Reach 1", and "Canal Outtake" (governed by the outtake of water defined in the "River Outtakes and Conveyance Structures" element of the Water Resource Infrastructure system.

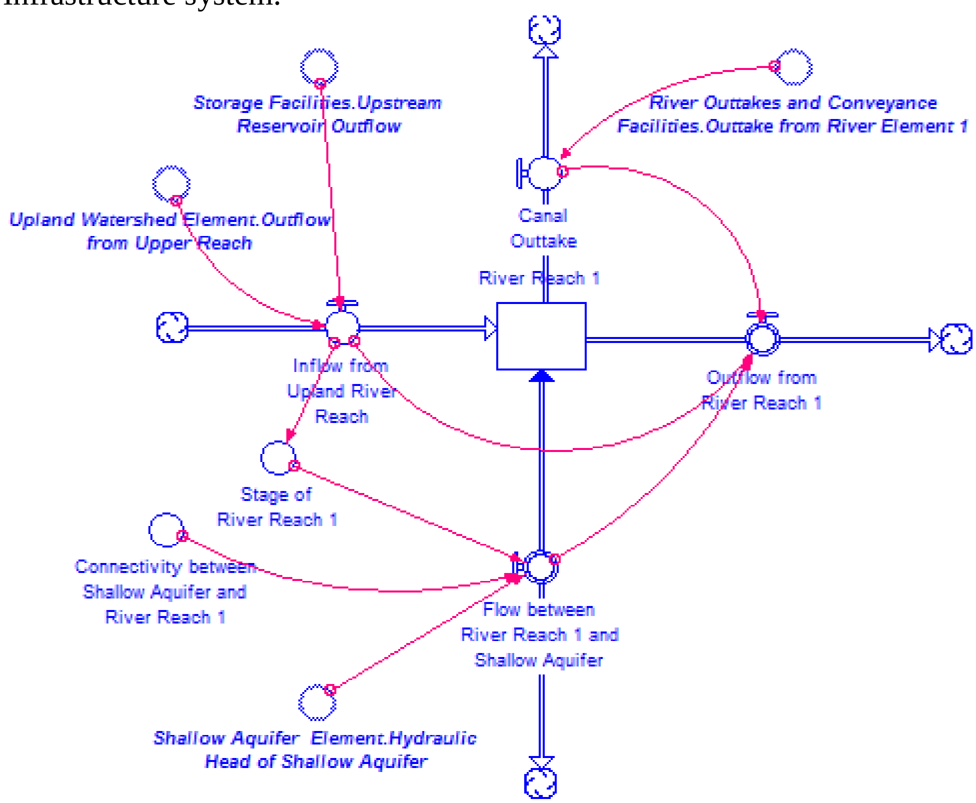

Figure 28. Representation of River Element 1 in relation to other watershed model elements.

Linkage of River Element 2 to Other Elements

As shown in Figure 29, the flux of water into River Reach 2 occurs through the objects “Inflow from River Reach 1” and Downstream Reservoir Outflow (calculated in the Storage Facilities element of the Water Resource Infrastructure system). The fluxes of water out of River Reach 2 are represented by the objects “Flow between River Reach 2 and the Shallow Aquifer” and “Outflow from River Reach 2.”

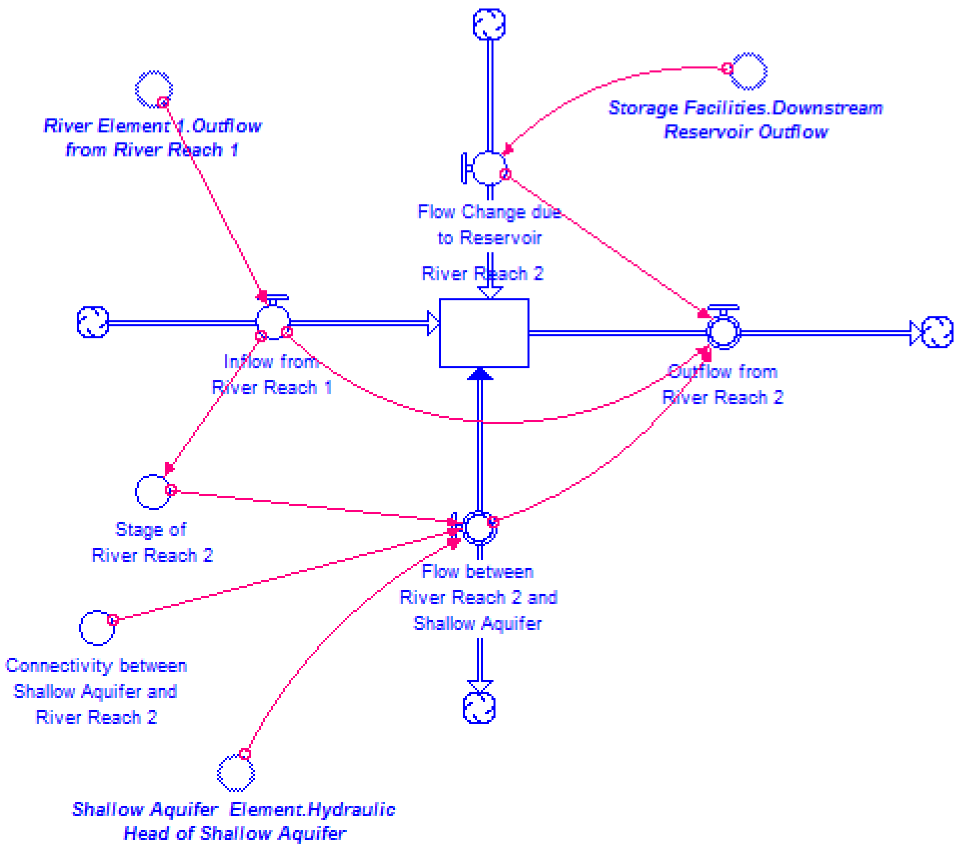

Figure 29. Representation of River Element 2 in relation to other watershed model elements.

Linkage of Shallow Aquifer Element to Other Elements

As shown in Figure 30, the flux of water into the Shallow Aquifer is represented by the objects “Shallow Aquifer Net Recharge”, “Flow between Shallow Aquifer and River Reach 1”, “Flow between Shallow Aquifer and River Reach 2”, “Flow between the Shallow Aquifer and Deep Aquifer”, “Canal Seepage”, and “Recharge from Excess Irrigation”. The last two fluxes listed are related to the Water Resource Infrastructure system. The “Recharge from Excess Irrigation” object is governed by the “Infiltration to Shallow Aquifer” (part of the Irrigated Agriculture Facilities element) and the “Canal Seepage” object is governed by the “Canal Seepage Losses” object (calculated within the River Outtakes and Conveyance Structures element). Since canals are typically located at higher elevations in the landscape, as compared to streams, drains and the shallow groundwater table, the canal seepage is modeled as a one-way flux from the canals to the shallow groundwater system. Finally, "Pumpage for Agriculture" represents an additional flux of water out of the Shallow Aquifer and is governed by the "Shallow GW Pumpage for Irrigated Agriculture" object (defined within the Aquifer Pumpage Facilities Element of the Water Resource Infrastructure system).

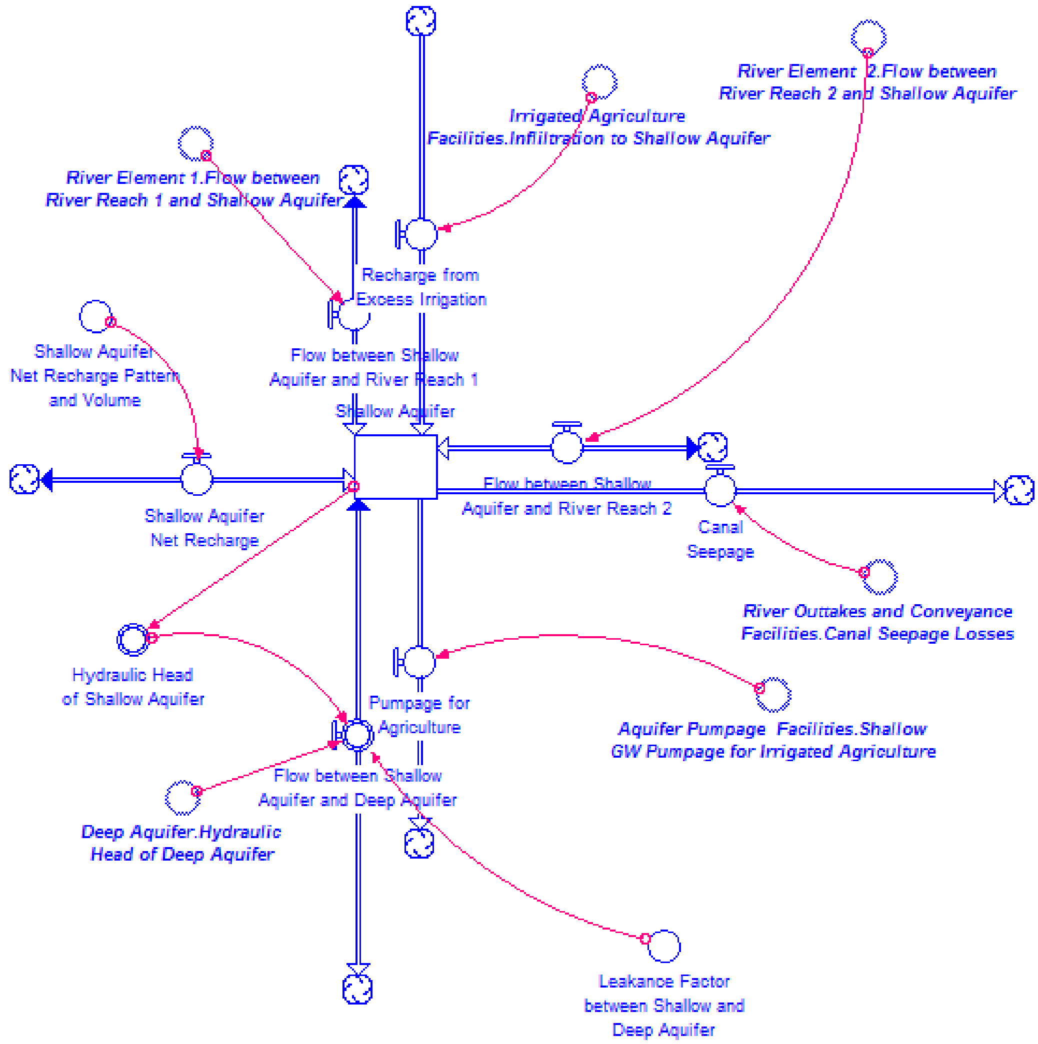

Figure 30. Representation of Shallow Aquifer Element in relation to other watershed model elements.

Linkage of Deep Aquifer Element to Other Elements

As shown in Figure 31, the flux of water into the Deep Aquifer is dependent upon the objects "Deep Aquifer Net Recharge" object and "Flow between Deep Aquifer and Shallow Aquifer". Meanwhile, the flux of water out of the Deep Aquifer is represented by the "Agricultural Use from Deep Aquifer" object, which is governed by the amount of groundwater pumpage from the Deep Aquifer for agricultural irrigation (defined in the Aquifer Pumpage Facilities element of the Water Resource Infrastructure system).

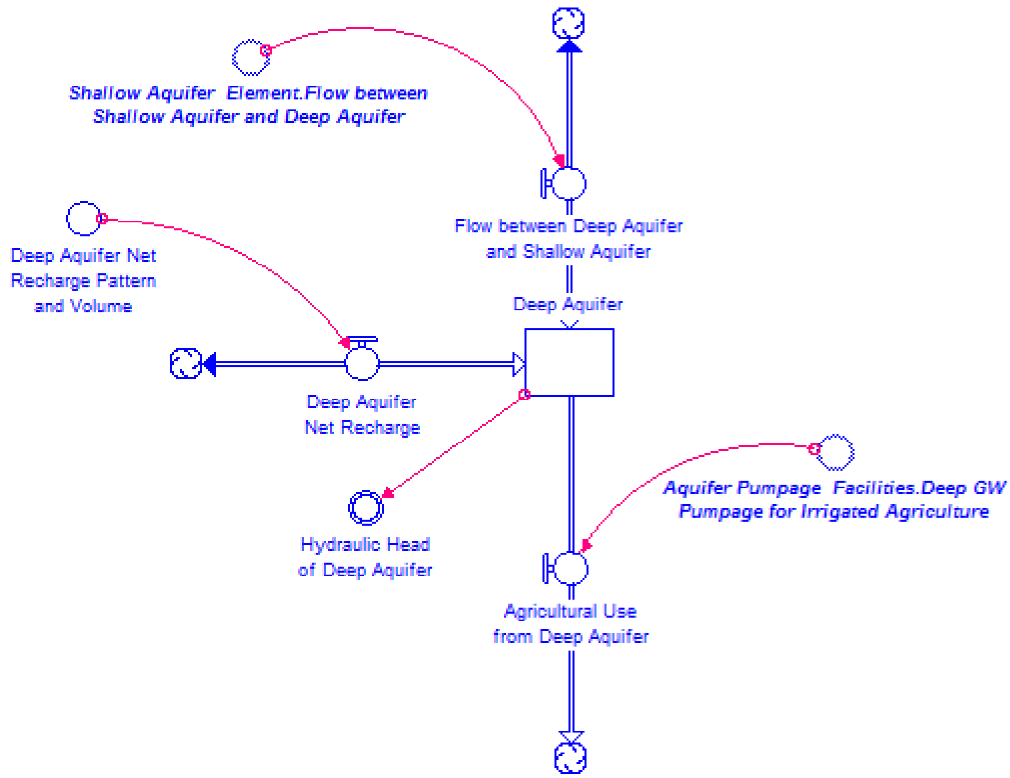

Figure 31. Representation of Deep Aquifer Element in relation to other watershed model elements.

Linkage of Lower River Element to Other Elements

As shown in Figure 32, the flux of water into the Lower River Reach is dependent upon the objects “Outflow from River Reach 2” and “Outflow to the Lower River Element”, the latter of which is part of the “Drainage and Return Flow Facilities” element of the Water Resource Infrastructure System. The flux of water out of the Lower River Reach is defined by the Downstream Flow object that exits at the lower end of the watershed model.

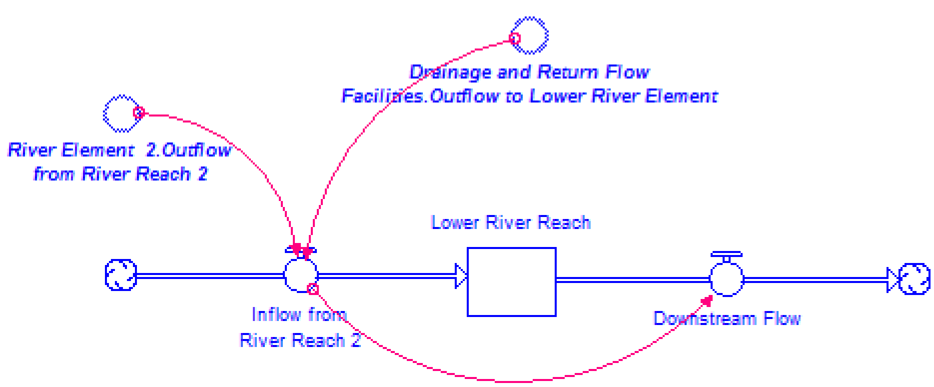

Figure 32. Representation of Lower River Element in relation to other watershed model elements.

Linkage Between all Elements of the Physical, Water Resource Infrastructure and Water Management Systems

Finally, the overall linkage between the elements of the Physical System, the Water Resource Infrastructure System, and the Water Management System within a watershed can be seen in the Figure 33. This figure illustrates the way the interactions between the elements of the Water Resource Infrastructure System occur indirectly, through linkages with elements of the Physical System. In addition, all of the elements in the Water Resource Infrastructure System are controlled by elements of the Water Management System, with the exception of the Irrigated Agriculture Facilities element. Notably, the Shallow Aquifer Element (within the Physical System) and the Irrigated Agriculture Facilities element (within the Water Resource Infrastructure System) have the largest number of linkages to other elements in the watershed model. This indicates that the behavior of each of these elements not only has the most significant impacts on other elements within the watershed, but also the most sensitivity to changes in the other elements within the watershed.

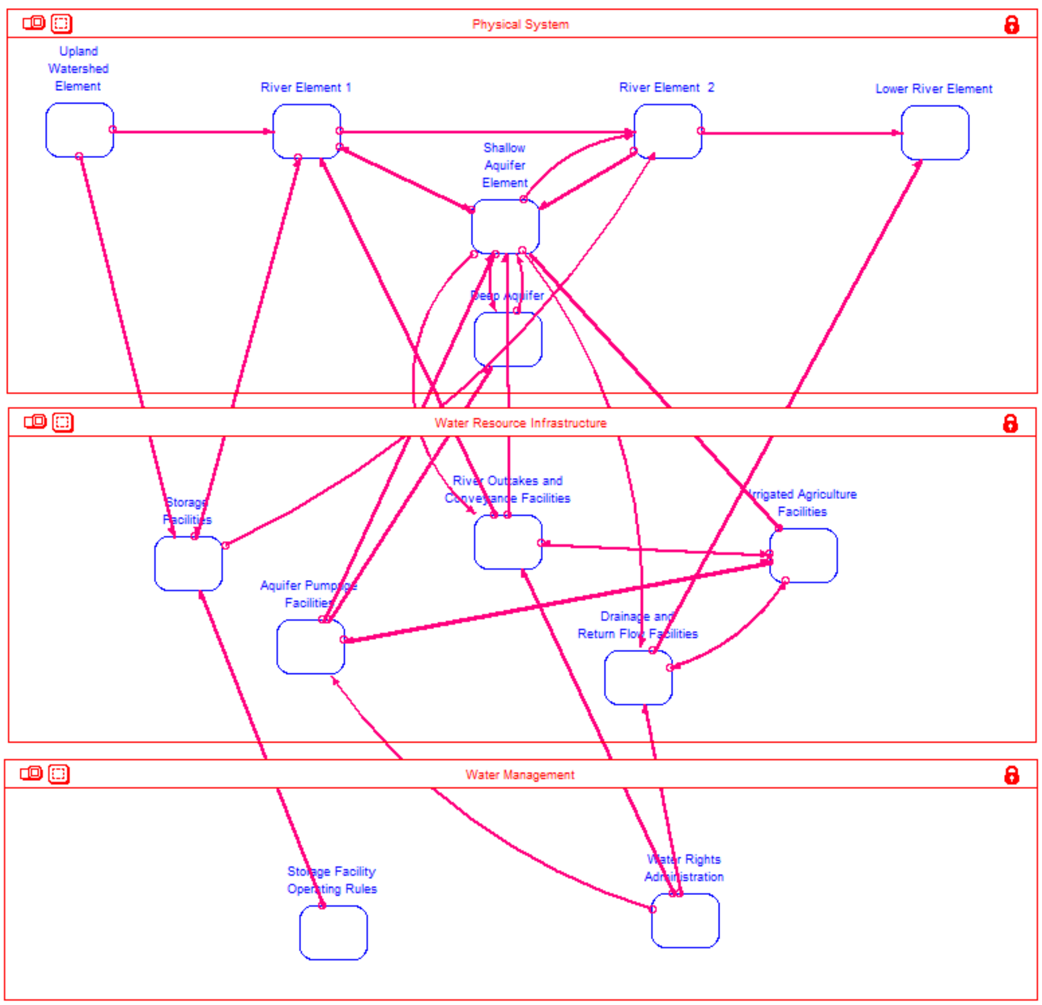

Figure 33. Systems Dynamics Representation of all elements within the watershed model.

Basin Case Studies

In order to illustrate applications of the System Dynamics model, two basin case studies were developed. Two basins were selected for their association with Reclamation projects and their differing water budget characteristics: the Boise River Basin (Boise Project) and the Carson River Basin (Newlands Project). For both basins, available data for water budget components were used to develop the base conditions for the systems model. Selected parameters within the base model were then systematically adjusted in order to observe the impacts that could result from water budget changes.

Boise Basin

The Boise River Basin is home to the Boise River and is located within the Treasure Valley in Southwest Idaho (Figure 34). The basin drains 4,020 square miles and covers elevations ranging from 2,185 feet to 10,174 feet above mean sea level. The climate in the Treasure Valley is semi-arid and typical of high dessert climates (NOAA 2014a). Precipitation ranges from 8 to 14 inches per year and averages just over 11 inches per year at the Boise Airport (NOAA 2014b). July is typically the hottest month of the year, with average temperatures ranging between 60 to 90 degrees Fahrenheit. December is typically the coldest month, with average temperatures ranging from 24 to 38 degrees (NOAA 2014b).

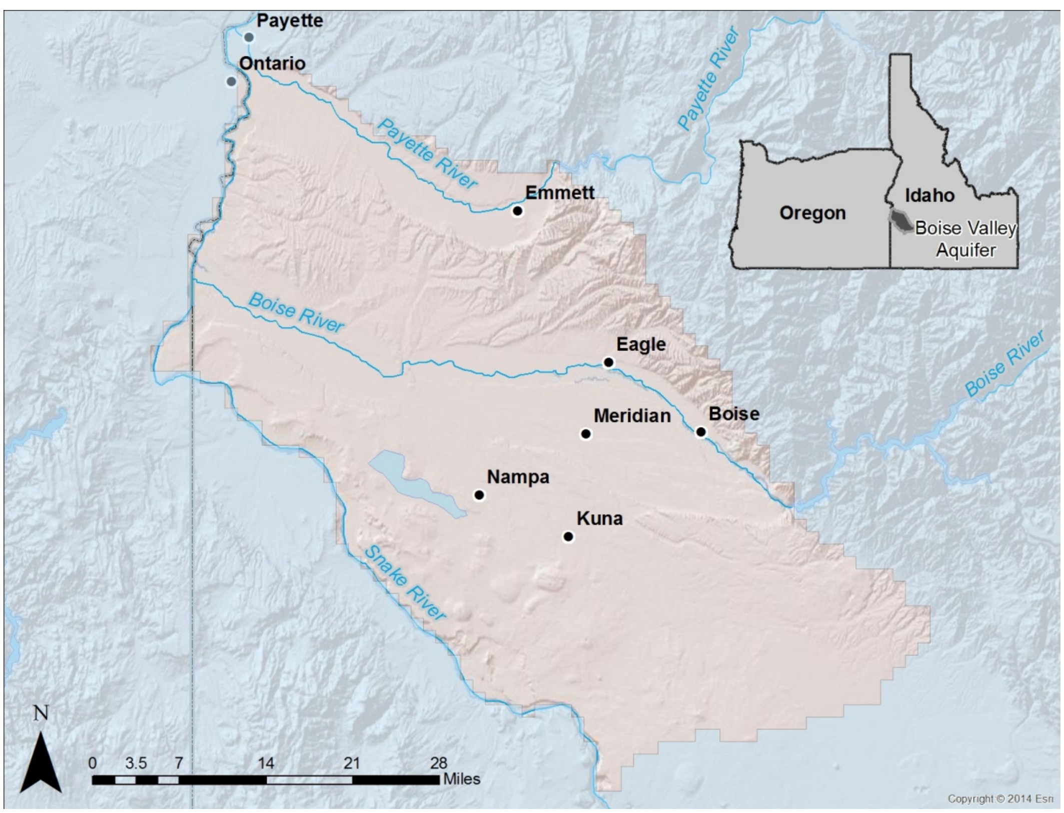

Figure 34. Extent of Boise Valley aquifer.

The Boise Project consists of four storage facilities (Anderson Ranch, Arrowrock, Lucky Peak, and Lake Lowell) that together store 1,109,069 acre-feet of water annually (Reclamation 1997; Reclamation 1998; USACE 1985; Reclamation 1994). Approximately 1,170 miles of major canals deliver about 1.5 million acre-feet of surface water to 252,000 irrigated acres, producing a range of crops including sweet corn seed, grain, alfalfa hay, pasture, sugar beets, corn, potatoes, onions, apples, and alfalfa seed (Urban 2004; Petrich and Urban 2004; USBR 2014b). Approximately 4,050 acre-feet of surface water are used for domestic and industrial purposes.

The Boise Project overlays the Treasure Valley Aquifer in the lower valley. The aquifer is comprised of a series of sedimentary aquifers interbedded with low permeability layers that confine and semi-confine the aquifer layers (Petrich and Urban 2004). The shallow aquifers are recharged from canal losses, on-farm infiltration, and precipitation. The deeper aquifer layers are recharged in the eastern portion of the valley and are estimated to have residence times greater than 20,000 years (Hutchings and Petrich 2002). Approximately 55,000 acre-feet of water annually is pumped from the aquifer for irrigation. Another 119,000 acre-feet annually is pumped for domestic and industrial purposes. A groundwater budget for an average water year is shown in Table 1 and is based on data for the year 2000 in Urban (2004).

Table 1. Water budget for average water year in Boise Valley.

Water Budget Parameter	AF/yr
Recharge	
Canal Seepage	512,500
Shallow recharge	91,500
Underflow (Deep recharge)	4,300
On-farm	404,400
Sum	1,012,700
Discharge	
Shallow Pumping	-66,000
Deep Pumping	-109,000
Discharge to Rivers and Drains	-804,600
	-979,600
Net Recharge(+)/Discharge(-)	33,100

Systems Dynamics Model Input

Water budget data for the Boise basin was obtained from multiple sources. The year 2000 was selected as being representative of an average water year and for its completeness in terms of data availability for all required input values. Table 2 shows the water budget parameters, the base condition values, and the data source. The calibration parameters were adjusted so that the model output matched the water budget values shown in Table 2. Only the three on-channel reservoirs were included in the reservoir storage capacity for a total of approximately 950,000 acre-feet. Recharge from Lake Lowell to the shallow aquifer was accounted for in the monthly shallow groundwater recharge rate.

Table 2. System model input parameters, values, and data source for the Boise basin.

Water Budget Parameter	Value	Source
Annual Water Supply (AF/yr)	1,647,000	(Reclamation 2013)
Monthly Deep GW Recharge Rate (AF/mo)	400	(Urban 2004)
Monthly Shallow GW Recharge Rate (AF/mo)	7,630	(Urban 2004)
Stream-GW Permeability Factor	0.10	Calibrated
Monthly Limiting Loss Rate for Stream	20,000	Calibrated
Shallow-Deep GW Linkage	0.09	Calibrated
Ag SW Demand (AF/yr)	1,520,000	(Urban 2004)
M&I SW Demand (AF/yr)	5,000	(IDWR 2014)
Instream Flow Demands (AF/mo)	0	Set to zero to simplify scenario
Ag Shallow GW Demands (AF/yr)	55,600	(Urban 2004)
Ag Deep GW Demands (AF/yr)	0	Assumed to be zero due to pumping costs.
M&I Shallow GW Demands (AF/yr)	10,000	(Urban 2004)
M&I Deep GW Demands (AF/yr)	109,000	(Urban 2004)
Drain Water Demand (AF/yr)	0	Assumed to be zero
Ag Return Flow Fraction	0.53	Calibrated
Portion of Ag Return Flow to Shallow GW	0.80	Calibrated
M&I Return Flow Fraction	0.20	Calibrated
Portion of M&I Return Flow to Shallow GW	0.80	Calibrated
Volume of Reservoir Storage (AF/yr)	949,700	(Reclamation 2014a)
Volume of Flood Storage in Reservoir (AF/yr)	0	Set to zero to simplify scenario
Canal Seepage Factor to Shallow GW	0.35	Calibrated
Limiting Seepage Rate for Canal (AF/yr)	85,000	Calibrated
M&I System Leakage Factor	0	Set to zero to simplify scenario
Drainage Seepage Factor to/from Shallow Aquifer	1.00	Calibrated
Limiting Seepage Rate for Drains (AF/yr)	75,000	Calibrated

Acronyms: GW – Groundwater; SW – Surface Water; Ag – agricultural; M&I – Municipal and Industrial; AF – acre-feet; mo – month; yr – year.

The model was calibrated through a comparison of four model output parameters to the water budget parameters shown in Table 1. These parameters include canal seepage, discharge to rivers and drains, on-farm infiltration, and the net recharge/discharge to the aquifer system. Table 3 shows the water budget values, the SD model output, and the percent difference between the two. This base case is considered to be well calibrated with a percent difference of less than ten percent for each parameter.

Table 3. Calibration results of SD modeling for Boise base case.

Parameter	Water Budget (AF/yr)	SD Output (AF/yr)	Percent Difference
Canal Seepage	512,500	514,165	0%
Discharge to Rivers and Drains	-804,600	-793,845-	1%
On-farm Infiltration	404,400	404,827	0%
Net Recharge/Discharge	33,100	34,772	5%

Carson Basin

The Carson basin is located in west-central Nevada and receives water from Lake Tahoe, the Truckee River and the Carson River. The drainage area is nearly 3,400 square miles (Reclamation 2014b). The elevations in the project area range from 3,870 to 8,800 feet (Maurer et al 2004). Over the period of record, average precipitation was 10 inches per year (DRI 2014). The hottest month is typically July, with average temperatures ranging between 50 to 89 degrees, and the coldest months are December and January with temperatures ranging between 21 to 45 degrees (DRI 2014).

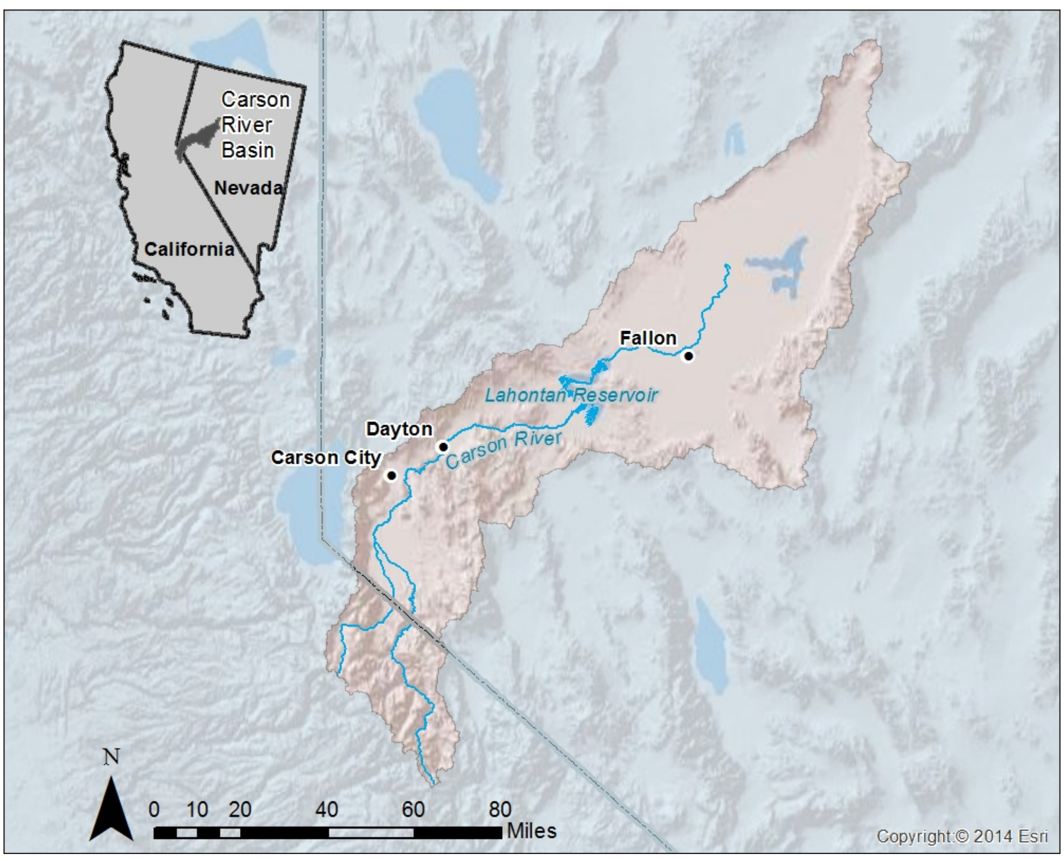

Figure 35. Carson River Basin.

The Newlands Project consists of two major storage facilities, Lake Tahoe and Lahontan, which together store 1,027,500 acre-feet of water; however, only Lahontan is included in the water budget calculations. The project area includes 68.5 miles of major canals, more than 300 miles of laterals, and almost 350 miles of drains (Reclamation 2014b). Approximately 67,000 acres are irrigated annually and primarily produce alfalfa and other pasture crops (Reclamation 1996).

The project overlays an aquifer system that contains four major aquifer units: three sedimentary aquifers and one basalt aquifer (Glancy 1986; Maurer and Berger 2006). Over 5,000 domestic wells are completed in the shallow sedimentary aquifer layers are estimated to pump 6,200 acre-feet annually (Maurer et al. 1996). The cities of Fallon and US Naval Air Station near Fallon pumps groundwater from the deeper basalt aquifer and it is estimated that 3,000 acre-feet is pumped annually. Little, if any, irrigation water is pumped from the aquifer. Many studies have shown that the shallow aquifer is recharged during the irrigation season anywhere from 50,000 to 100,000 acre-feet per year (summarized in Lico 1992).

A water budget for the aquifer below the Carson River Basin is shown in Table 4. Although there is essentially no shallow recharge and underflow, the values are shown in the table for consistency with the Boise Project.

Table 4. Water budget for average water year in Carson River Basin.

Water Budget Parameter	AF/yr
Recharge	
Canal Seepage	100,000
Shallow recharge	0
Underflow (Deep recharge)	0
On-farm	4,200
Sum	104,200
Discharge	
Shallow Pumping	-59,000
Deep Pumping	-5,000
Discharge to Rivers and Drains	-36,000
	-100,000
Net Recharge(+)/Discharge(-)	4,200

Systems Dynamics Model Input

The water budget data for the Carson River Basin was mostly obtained from a USGS report published in 1996. The values represent average conditions based on observed, calculated, and anecdotal information. Table 5 shows the water budget parameters, the base condition values, and the source of the values.

Table 5. System model input parameters, values, and data source for the Carson River Basin.

Water Budget Parameter	Value	Source
Annual Water Supply (AF/yr)	850,000	(Maurer et al. 1996)
Monthly Deep GWRecharge Rate (AF/mo)	0	(Maurer et al. 1996)
Monthly Shallow GW Recharge Rate (AF/mo)	0	(Maurer et al. 1996)
Stream-GW Permeability Factor	0	(Maurer et al. 1996)
Monthly Limiting Loss Rate for Stream	0	(Maurer et al. 1996)
Shallow-Deep GW Linkage	0.07	Calibrated
Ag SW Demand (AF/yr)	270,000	(Maurer et al. 1996)
M&I SW Demand (AF/yr)	0	(Maurer et al. 1996)
Instream Flow Demands (AF/mo)	0	Set to zero to simplify scenario
Ag Shallow GW Demands (AF/yr)	50,000	(Maurer et al. 1996)
Ag Deep GW Demands (AF/yr)	0	(Maurer et al. 1996)
M&I Shallow GW Demands (AF/yr)	9,000	(Maurer et al. 1996)
M&I Deep GW Demands (AF/yr)	5,000	(Maurer et al. 1996)
Drain Water Demand (AF/yr)	0	Assumed to be zero
Ag Return Flow Fraction	0.19	Calibrated
Portion of Ag Return Flow to Shallow GW	0.10	Calibrated
M&I Return Flow Fraction	0.30	Calibrated
Portion of M&I Return Flow to Shallow GW	1.00	Calibrated
Volume of Reservoir Storage (AF/yr)	295,500	(Reclamation 2014b)
Volume of Flood Storage in Reservoir (AF/yr)	0	Set to zero to simplify scenario
Canal Seepage Factor to Shallow GW	0.37	Calibrated
Limiting Seepage Rate for Canal (AF/yr)	15,000	Calibrated
M&I System Leakage Factor	0	Set to zero to simplify scenario
Drainage Seepage Factor to/from Shallow Aquifer	0.47	Calibrated
Limiting Seepage Rate for Drains (AF/yr)	28,000	Calibrated

Acronyms: GW – Groundwater; SW – Surface Water; Ag – agricultural; M&I – Municipal and Industrial; AF – acre-feet; mo – month; yr – year.

As in the Boise base case model, the model was calibrated by comparing four of the model output parameters to the corresponding water budget values shown in Table 5, including: canal seepage, discharge to rivers and drains, on-farm infiltration, and the net recharge/discharge to the aquifer system. Table 6 shows the water budget values, the SD model output, and the percent difference between the two. This base case is considered to be well calibrated, with a percent difference of less than ten percent for each parameter.

Table 6. Calibration results of SD modeling for Carson River Basin base case.

Parameter	Water Budget (AF/yr)	SD Output (AF/yr)	Percent Difference
Canal Seepage	100,000	99,555	0%
Discharge to Rivers and Drains	-36,000	-35,580	1%
On-farm Infiltration	4,200	4,163	1%
Net Recharge/Discharge	4,200	4,425	5%

Scenarios

Using the parameters in Table 2 and Table 5, baseline models were developed for each basin. Four scenarios were then simulated for each basin, where one or two parameters were incrementally adjusted to observe their influence on recharge. These scenarios represent changes that could be made to the water resources infrastructure, water management practices, or caused by climate change within each of these basins.

1. Canal Seepage and On-Farm Infiltration – Canal seepage and on-farm infiltration rates were incrementally reduced in separate scenarios (infrastructure change).

2. Agricultural Demands – Agricultural demands were incrementally shifted from surface water to groundwater, without increasing or decreasing the total demand (water management change).

3. Reservoir Storage – Total reservoir storage was incrementally increased and decreased (infrastructure change).

4. Annual Hydrograph – The ratio of the peak flow to average annual flow was incrementally adjusted (climate change).

Simulation Results and Discussion

The results of the four scenarios were reported by graphing the influence that each one had on (1) the change in the net flux of water to the aquifer and (2) the change in the ratio of total recharge to total discharge for the aquifer. The first metric was designed to show how the scenarios directly impact sustainability of the aquifer system (a negative net flux would indicate reduction in aquifer recharge) and the second was designed to show how the scenarios impact the traditional definition of groundwater sustainability (the ratio of recharge to discharge should be larger than 1 in a sustainable system).

Scenario 1: Canal and On-farm Seepage

For Scenario 1, simulations were performed by incrementally reducing canal seepage from a base case of zero percent (current level of canal lining and seepage) to a maximum reduction of 100 percent (completely lined or piped, and sealed). Figure 36 shows the impact on the change in net flux to the aquifer system from the relative reduction in canal seepage for both basins. The reduction in canal seepage is calculated using equation (1):

$$\text{Reduction in canal seepage} = \frac{(\text{Base case canal seepage} - \text{Modeled canal seepage})}{\text{Base case canal seepage}} \quad (1)$$

The relative change in net flux to the aquifer is calculated using equation (2):

$$\text{Relative change in net flux} = \frac{\text{Modeled net flux} - \text{Base case net flux}}{\text{Base case net flux}} \quad (2)$$

As expected, reducing canal seepage reduces the amount of recharge to the aquifer. Since the aquifer system in the Boise basin receives recharge from multiple sources, total recharge is only reduced by 60 percent if the canal seepage is reduced to zero. However, canal seepage comprises a much larger portion of the recharge to the Carson basin, so reducing canal seepage by 45 percent reduces recharge to the shallow aquifer by 100 percent.

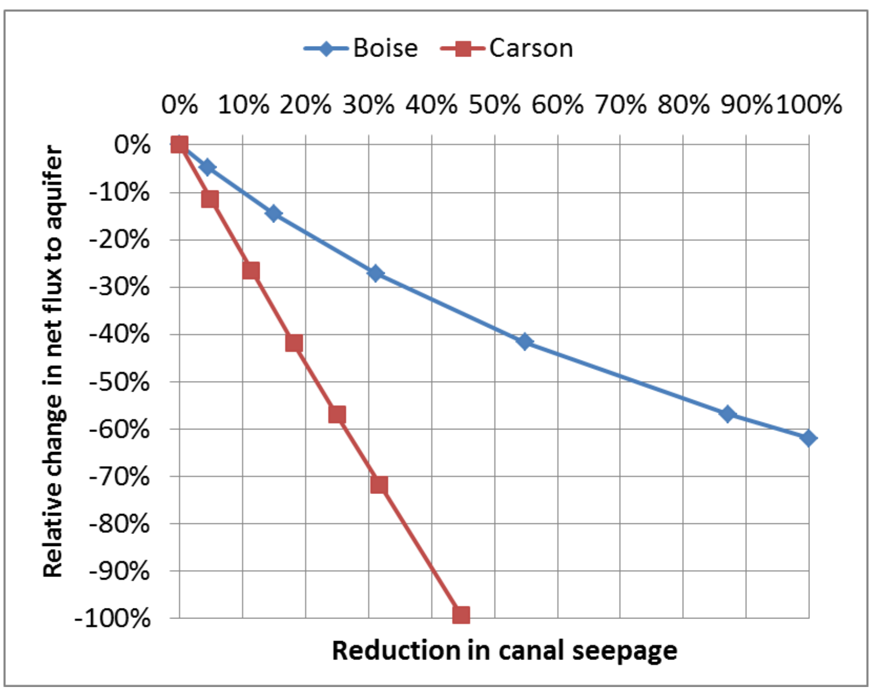

Figure 36. Relative change in net flux aquifier system versus reduction in canal seepage on the y-axis a negative value indicates a reduction in net flux to the aquifer.

The difference in response between the Boise and Carson basins is partially illustrated by the charts in Figure 37. Canal seepage is approximately 40 percent of the average annual seepage in the Boise basin, so although the amount of canal seepage is reduced to zero, the other sources of recharge continue to support the aquifer. In the Carson basin, approximately 96 percent of the recharge is from canal seepage, so reducing the canal seepage to zero results in reducing total recharge to approximately zero. Therefore, the Carson basin is impacted substantially more than the Boise basin even when canal seepage is reduced by relatively small amounts.

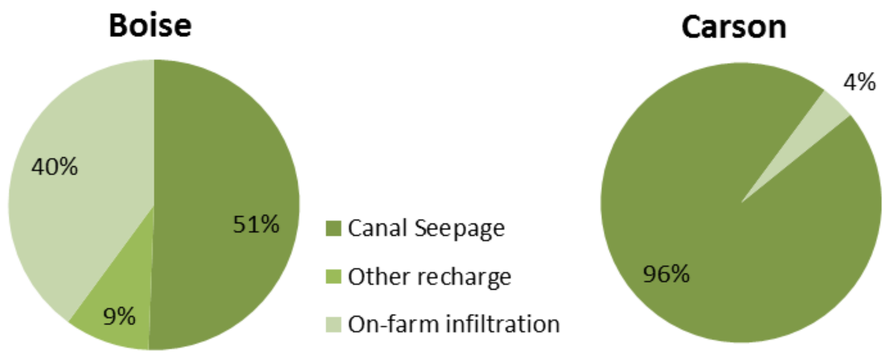

Figure 37. Relative sources of recharge for the Boise and Carson basins.

Figure 38 shows the impact on the recharge to discharge ratio resulting from relative reduction in canal seepage for both basins. Recharge is the sum of canal recharge, on-farm infiltration, and shallow and deep base recharge. Discharge is the sum of all pumping and discharge to river and drains. Equation (3) describes how the ratio between recharge and discharge is calculated:

$$Ratio\ of\ recharge\ to\ discharge = \frac{canal\ recharge + onfarm\ infiltration + shallow\ and\ deep\ base\ recharge}{all\ pumping + discharge\ to\ rivers\ and\ drains} \quad (3)$$

In general, as recharge decreases, the phreatic surface in the aquifer also decreases, which has the effect of reducing the amount of discharge to drains and rivers.

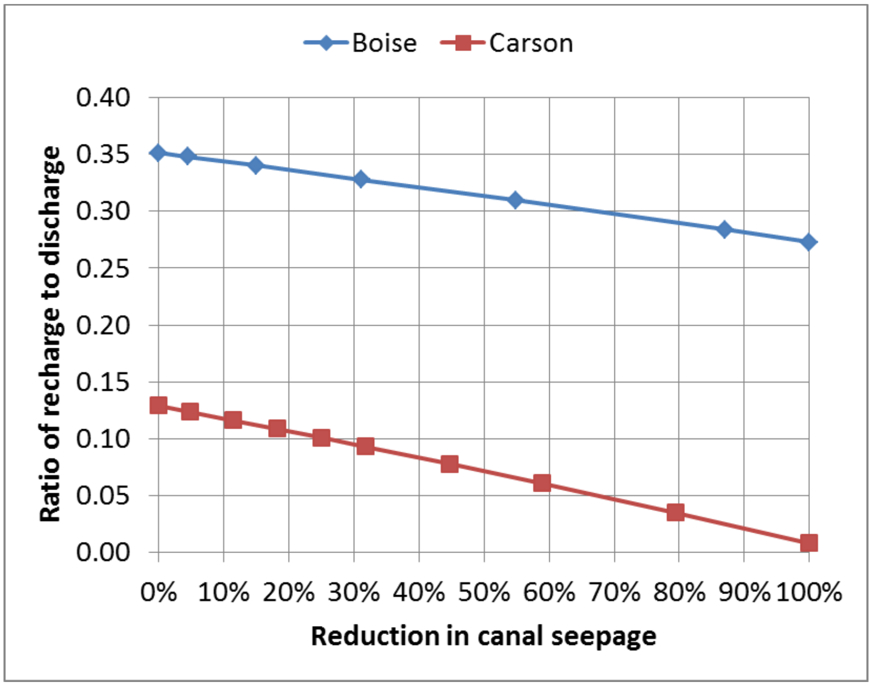

Figure 38. Relative sources of discharge for the Boise and Carson basins.

Figure 39 helps to explain the results seen in Figure 38. The ratio of recharge to discharge decreases as recharge decreases in the Boise valley, but not as fast as the ratio decreases for the Carson basin. This is because as recharge decreases, so does the amount of discharge to rivers and drains. The component of discharge to rivers and drains is larger for the Boise basin, so the ratio decreases at a slower rate than in the Carson basin.

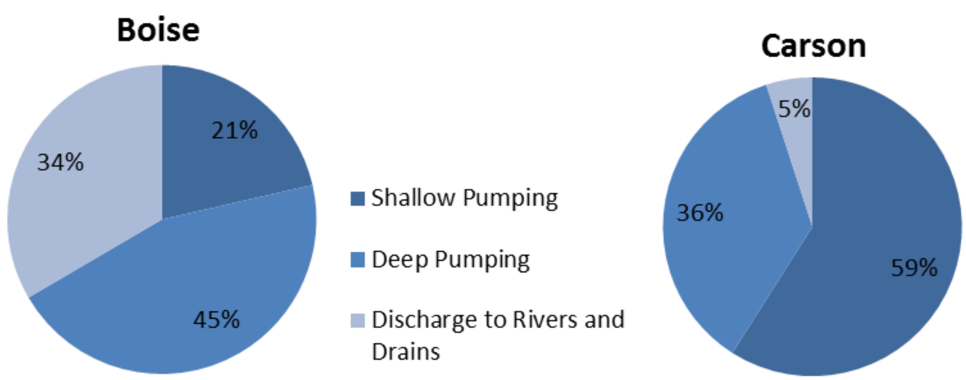

Figure 39. Relative sources of discharge for the Boise and Carson basins.

The reduction in on-farm infiltration had a similar result to the reduction in canal seepage since the total contribution from each feature is so similar in the baseline model (Figure 40). The values in Figure 40 were calculated using equations (1) and (2). On-farm infiltration can be reduced by improving the efficiency in which water is applied to irrigated lands, for example, converting flood irrigation to sprinkler or micro-drip application. In this case, the response in the Carson River Basin is much smaller than the response in the Boise River Basin because the relative contribution of recharge from on-farm infiltration is much smaller than in the Boise basin (Figure 37).

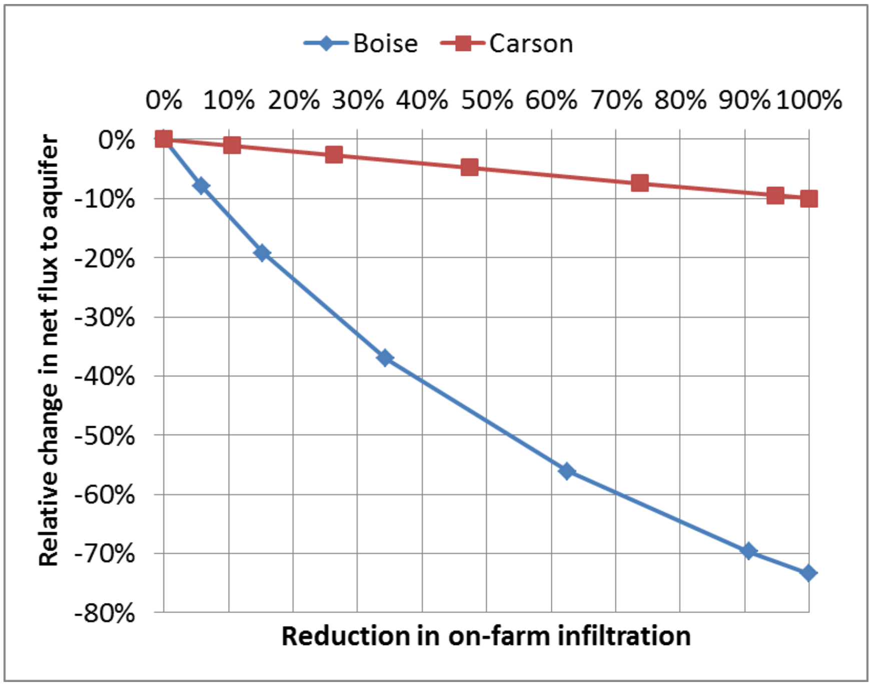

Figure 40. Change in net flux to the aquifer system versus reduction in on-farm infiltration; on the y-axis, a negative value indicates a reduction in net flux.

The Boise basin shows a similar result to the canal seepage scenario where the ratio of recharge to discharge decreases as on-farm infiltration is reduced (Figure 41). The values in Figure 41 were calculated using equations (1) and (3). Unlike the results for canal seepage however, the Carson basin shows almost no change to the ratio of recharge to discharge. This is because on-farm infiltration is a very small part of total recharge in the basin (Figure 37), indicating that the farming practices are already extremely efficient in the basin.

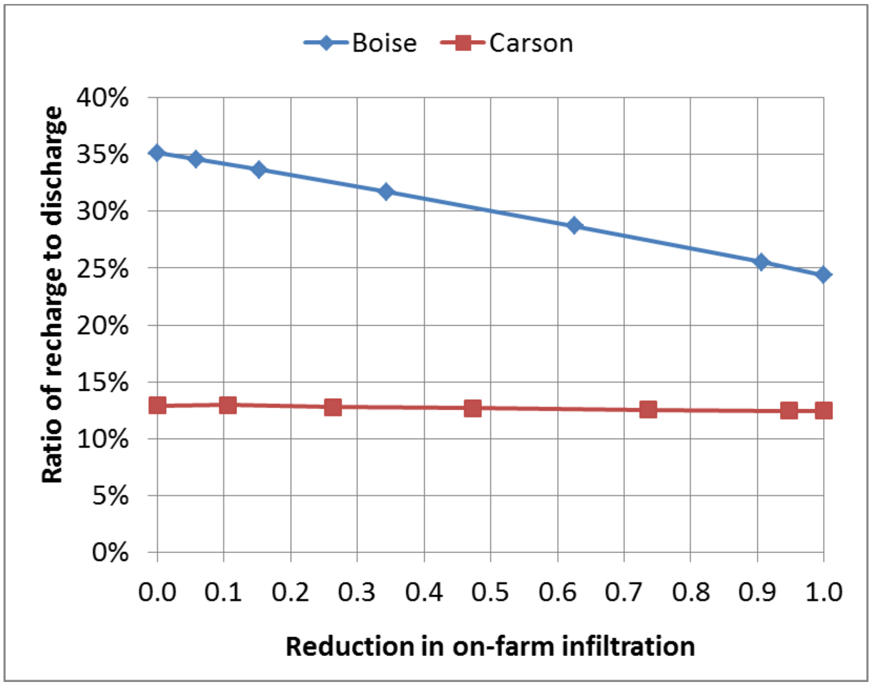

Figure 41. Ratio of recharge to discharge versus reduction in on-farm infiltration.

Scenario 2: Agricultural Demands

For Scenario 2, simulations were performed by varying the amount of water demand for irrigation being met from surface and groundwater sources. Figure 42 and Figure 43 show the results of converting some of the existing agricultural demand that is supplied by surface water to groundwater. The total amount of agricultural demand is not increased for this scenario, but simply a portion of water supplied by surface water is converted to water pumped from the aquifer.

Figure 42 shows the reduction in net flux to the aquifer that results from changing the source of the agricultural water from surface to groundwater. The ratio of agricultural water that comes from groundwater versus total agricultural demands was calculated using equation (4):

$$Ratio\ of\ ag\ demands\ from\ groundwater\ to\ total = \frac{Agricultural\ shallow\ GW\ demand + Agricultural\ deep\ GW\ demands}{Agricultural\ shallow\ GW\ demand + Agricultural\ deep\ GW\ demands + Agricultural\ SW\ Demands} \quad (4)$$

The relative change in net flux to the aquifer is calculated using equation (2). Note that the plots approach negative 100 percent. This is because the relative change in net flux to the aquifer is calculated based on the baseline value, which is positive for both basins. When the net flux becomes negative, this value can calculate to greater than 100 percent. The 100 percent line indicates the ratio of agricultural water that comes from groundwater to total agricultural demand has caused the aquifer to change from being recharged to being depleted.

The ratio of agricultural water that comes from the aquifer is about three percent in the Boise basin and about 15 percent in the Carson basin. In the Boise basin, the ratio of groundwater to total agricultural water needs can be increased to 60 percent before the aquifer system begins to be depleted. In the Carson basin, the ratio can only be increased to about 25 percent before the system starts to become depleted.

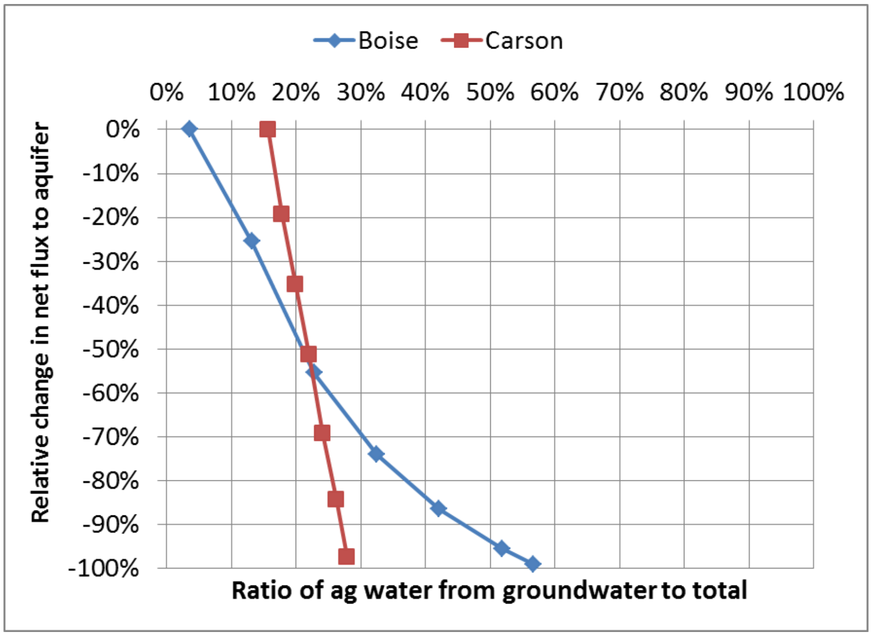

Figure 42. Relative change in net flux to aquifer versus ratio of agricultural water from groundwater to total; on the y-axis, a negative value indicates a reduction in net flux to the aquifer.

Figure 43 shows how the ratio of recharge to discharge is impacted by converting a portion of the surface agricultural demands to groundwater pumping. The values in Figure 43 are calculated using equations (2) and (4). The ratio of recharge to discharge is impacted in the Boise basin to a much larger extent than in the Carson basin. The main reason for this has to do with the amount of water that is supporting recharge from surface water deliveries relative to the amount of water being pumped. The pumping for agricultural use in the Boise basin makes up only about 5 percent of the total amount of water needed for agricultural purposes. Since there is a substantial amount of recharge originating from the delivery and application of water, the system can support a larger amount of conversion to groundwater. The system begins to deplete when there are not enough surface water deliveries and applications to support the increase in pumping. Whereas in the Carson basin, the amount of groundwater pumped is around 15 percent of total agricultural needs. Since the main source of recharge in the basin is from canal seepage, there is less flexibility in the system and the amount of water pumped begins to exceed the rate recharge much more quickly.

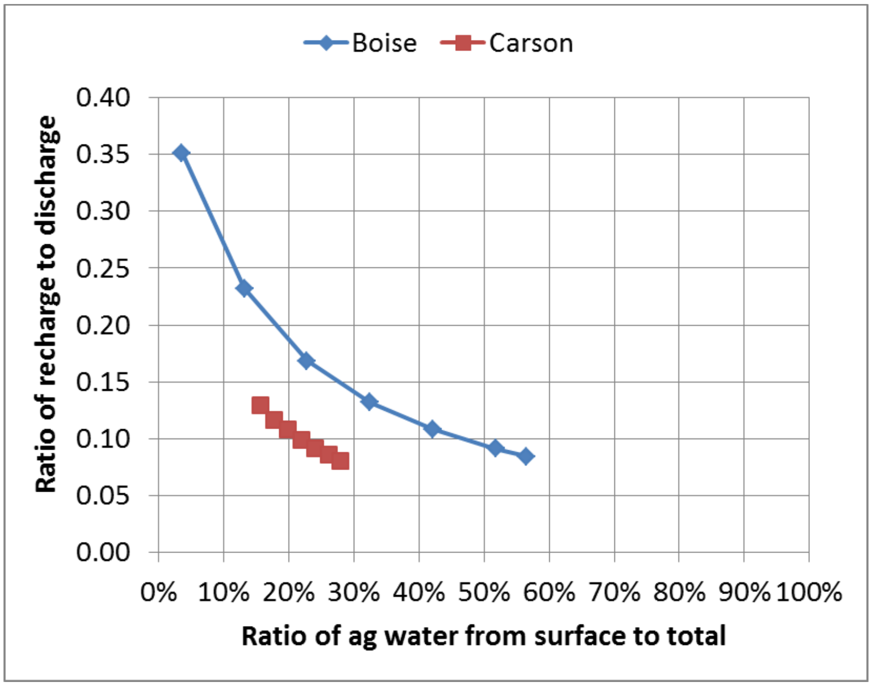

Figure 43. Ratio of recharge to discharge versus ratio of agricultural water from surface to total.

Scenario 3: Reservoir Storage

Figure 44 shows the impact to aquifer storage due to increasing or decreasing total reservoir storage. The percent change in reservoir storage was calculated using equation (5):

$$\text{Change in reservoir storage} = \frac{\text{Modeled reservoir storage}}{\text{Base reservoir storage}} \qquad (5)$$

The relative change in net flux to the aquifer was calculated using equation (2). Increasing reservoir storage in the Boise basin by up to 30 percent has the impact of increasing aquifer storage by almost 20 percent. Conversely, decreasing storage by up to 30 percent has the impact of decreasing aquifer storage by 20 percent. This is because additional storage allows surface water demands to be met more frequently, which increases the amount of water that is delivered and applied to lands, thus increasing the amount of recharge. Decreasing storage has the opposite effect.

The results from the Carson basin show that any increase or decrease in storage would have zero impact on the change in aquifer storage. This is because the amount of inflow in the basin ensures that the reservoir fills every year, and the amount of demand on the system does not exceed the amount of water that can be supported by the reservoir. Given this, increasing the storage will not improve deliveries. Deliveries begin to decrease if the amount of storage is reduced down to 50,000 acre-feet or about 17 percent of the current volume.

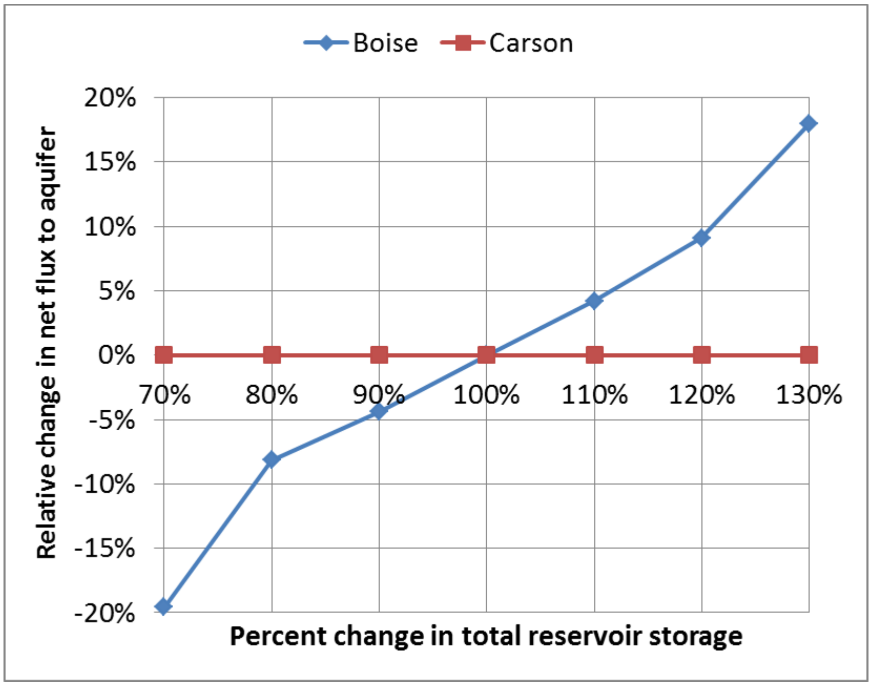

Figure 44. Change in aquifer storage versus change in total reservoir storage.

Figure 45 shows the ratio of recharge to discharge which results from changing the amount of reservoir storage. The values in Figure 45 were calculated using equations (5) and (3). Although the amount of aquifer storage increases with an increase in storage in the Boise project, there is also an increase in drain and river returns due to the rise in groundwater elevations. As a result, the ratio of recharge to discharge does not change substantially. As in the previous plot, the ratio of recharge to discharge does not change at all in the Carson basin as a result of changing reservoir storage since reservoir storage does not appear to impact aquifer storage in this basin, unless storage is reduced drastically.

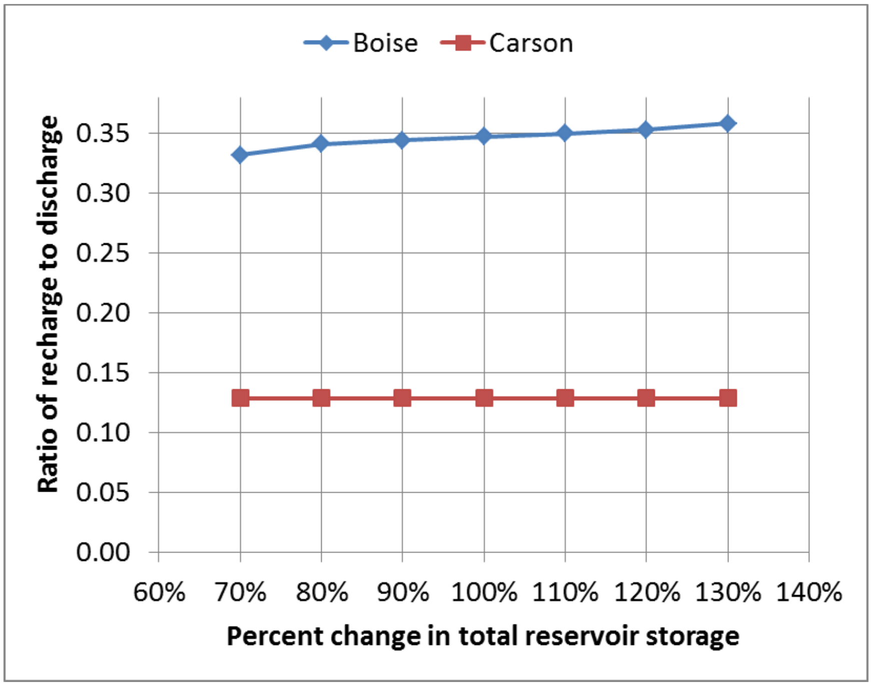

Figure 45. Ratio of recharge to discharge versus change in total reservoir storage.

Scenario 4: Adjustments to Annual Hydrograph

Scenario 4 was designed to demonstrate the impacts of possible changes to the hydrograph that may result from climate change. Some climate change projections indicate that peak flows will increase relative to the mean annual flow and others indicate peak flow will decrease. To illustrate this behavior, the ratio of peak flow to average flow was increased by up to 40 percent and decreased by up to 60 percent, with no changes made to the timing (months) with which the peak flows occur. Increasing peak flow by 40 percent causes the flow to increase in the late spring and early summer months, with flow decreasing during the rest of the year. Meanwhile, decreasing peak flow by 60 percent essentially reduces the hydrograph to a flat line, with equal flow rates for each month. These changes are likely extreme, but the large changes are used to demonstrate the potential impact of climate change on groundwater recharge. The hydrograph describes the inflow into the reservoir system, so the results of this scenario are impacted by the ability of the reservoir to store water based on existing flood rule curves.

Figure 46 shows the relative change in net flux to the aquifer. In the Boise basin, as the ratio of peak flow to annual average flow increases, so does recharge to the aquifer. This may be a counter-intuitive result, because one might suspect that there would be more opportunities for recharge if there were a more constant flow of water in the river creating a more constant head to contribute to recharge. This would be the expected result if the model was simulating a system without a reservoir to modify the annual hydrograph.

In the Boise model, however, the reservoir system is operated in accordance with a flood rule curve that requires the reservoirs to remain unfilled during the early part of the year (January, February, March and April) to allow for reduction of peak flood flows when snow melt occurs.

When there are higher peak flows entering the reservoir during the months of May, June and July (which would be the case for an increased ratio of peak to average flows), the reservoir will have the opportunity to capture more water, as the flood rule curve allows for more water storage during these months. This stored water can then be released at a higher rate for the remainder of the irrigation season. On the other hand, when there is a flatter hydrograph entering the reservoir (which is the case for a decreased ratio of peak to average flows), the rule curves would prevent the reservoir from filling during the months of March and April, when these higher flows occur, resulting in less water being captured by the reservoirs, and water being released at a lower rate during the irrigation season.

This analysis suggests that once the operating rules for a reservoir have been established, changes that increase the ratio of the peak to average flow of the hydrograph will result in more water being available to be released by the reservoir during the irrigation season, resulting in increased groundwater recharge. Conversely, changes that decrease the ratio of the peak to average flow of the hydrograph will result in less water being available to be released during the irrigation season, resulting in decreased groundwater recharge. As in the change in storage results, the Carson basin is unaffected by this change in operation.

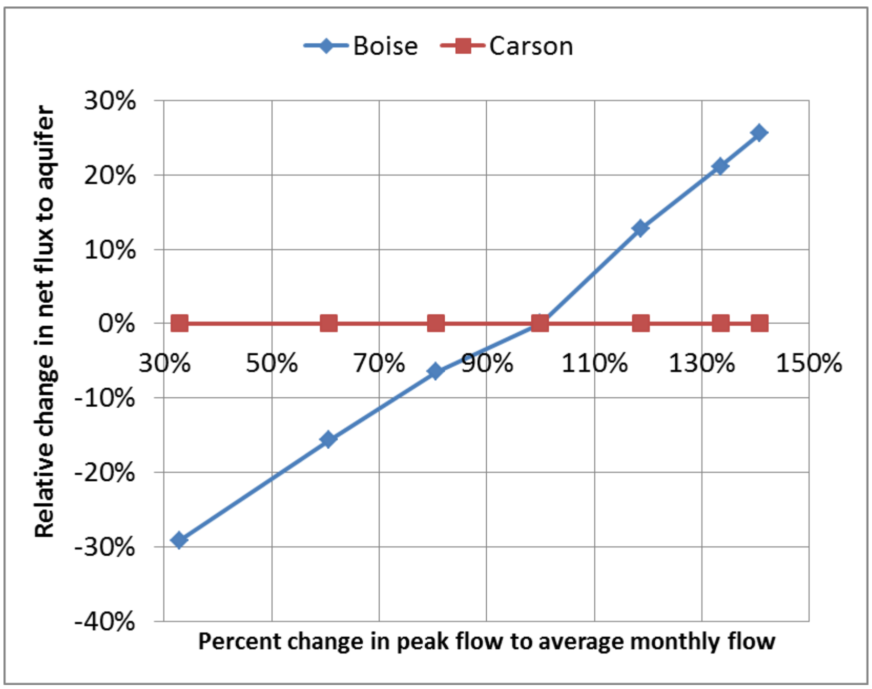

Figure 46. Relative change in net flux to the aquifer versus the percent change in peak flow to average monthly flow.

Figure 47 shows the ratio of recharge to discharge as a result of changing the ratio of peak flow to average monthly flow. The ratio of recharge to discharge increases as the ratio of peak flow to average monthly flow increases, following the logic described above.

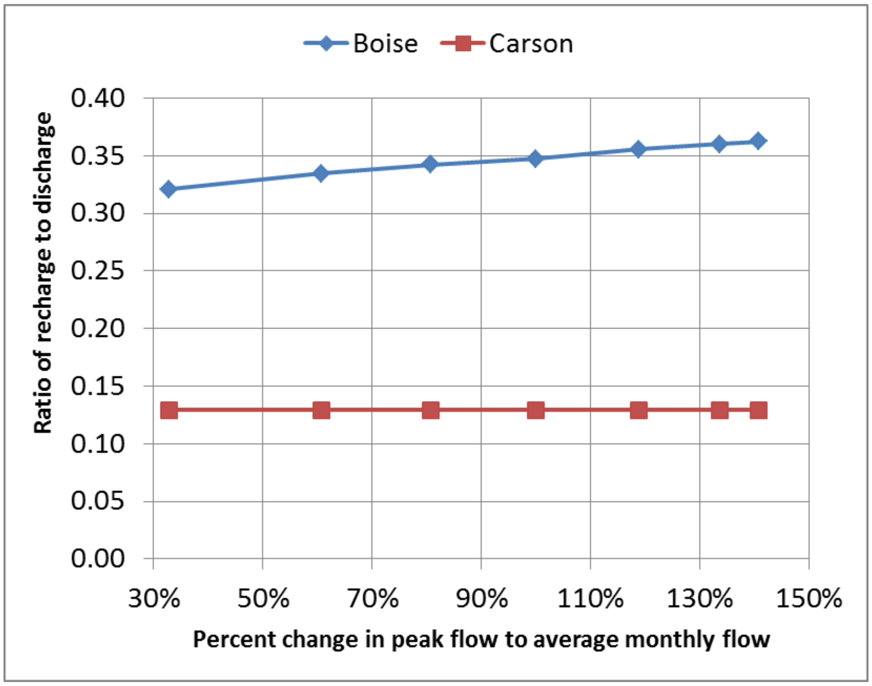

Figure 47. Ratio of recharge to discharge versus percent change in peak flow to average monthly flow.

Summary and Conclusions

Regulated river systems have an impact on local aquifers and changes that may result from infrastructure, water management, climate changes have an impact on those combined systems. A generalized Systems Dynamics model of a regulated river system and associated local aquifer system was developed for this study to provide a framework to explore how specific basins may respond to change. The Systems Dynamics model was used to evaluate the possible impacts in two basins, the Boise basin in Idaho and the Carson basin in Nevada.

Water budgets representing an average water year were used to establish base case models for both basins. Available data was used to populate the systems model and unavailable parameters were calibrated so that the model output matched water budget parameters including canal seepage, discharge to rivers and drains, on-farm infiltration, and net recharge or discharge.

In the Boise basin, average annual recharge is made-up of about 50 percent canal seepage, 40 percent on-farm-infiltration, and 10 percent from other sources. Average annual discharge is almost equal to recharge and is made-up of about 55 percent pumping from shallow and deep aquifers and 45 percent returns to rivers and drains. In the Carson basin, average annual recharge is made-up of 96 percent canal seepage and 4 percent on-farm infiltration. Average annual discharge is made-up of 95 percent pumping from shallow and deep aquifers and 5 percent returns to rivers and drains. Like the Boise basin, recharge and discharge are approximately equal in an average year.

Four scenarios were explored for this study:

1. Canal Seepage and On-Farm Infiltration – Canal seepage and on-farm infiltration rates were incrementally reduced in separate scenarios (infrastructure change).

2. Agricultural Demands – Agricultural demands were incrementally shifted from surface water to groundwater, without increasing or decreasing the total demand (water management change).

3. Reservoir Storage – Total reservoir storage was incrementally increased and decreased (infrastructure change).

4. Annual Hydrograph – The ratio of the peak flow to average annual flow was incrementally adjusted (climate change).

For each scenario, the change in net flux to the aquifer from the base case was reported along with the change in the ratio of recharge to discharge. Both of these metrics can be interpreted as indicators of aquifer sustainability because a decrease in net flux to the aquifer indicates a decrease in groundwater supplies overall, while a decrease in the ratio of recharge to discharge indicates an increase in aquifer depletion. In all of the scenarios, the existing relationship of the surface system to the groundwater systems was an important factor in the response of each system to various changes.

The first scenario explored the impacts of lining canals or improving on-farm efficiencies in both the Boise and Carson basins. Reducing seepage from canals or on-farm infiltration in the Boise basin reduced recharge, but since there was a large amount of recharge from both canal seepage and on-farm infiltration, reducing one or the other caused the net flux to the aquifer to still be positive. However, in the Carson basin, most of the recharge comes from canal seepage, so reducing canal seepage reduced the net flux to the aquifer completely. The net flux was not substantially impacted by reducing on-farm infiltration since it was a much smaller source of recharge. In both cases, reducing recharge from canal seepage caused a visible reduction in overall recharge, thus reducing aquifer levels and returns to rivers and drains. The same was true in the Boise basin for on-farm infiltration.

The second scenario looked at the impact of converting existing agricultural water supplies from surface water sources to groundwater sources. In both basins, this scenario caused a rapid decrease in the net flux of water to the aquifer and resulted in aquifer depletion before the entire surface supplied demands could be converted to groundwater. The overall demand on water did not increase, yet moving the source of the water to meet the demands from surface to groundwater caused a rapid decrease in the flux to aquifers. In the Carson basin, converting only 10 percent of the demands to groundwater resulted in a net negative flux of water to the aquifer, indicating a reduction in aquifer recharge. Since less water is currently being pumped in the Boise basin, 50 percent of the demands were able to be converted before the net flux of water to the aquifer became negative.

The third scenario explored the impact of increasing or decreasing the amount of reservoir storage in each basin. In the Boise basin, increasing the amount of reservoir storage allowed the surface water demands to be satisfied more frequently, which increased the amount of water in the canals and water being applied to lands, resulting in more recharge from both sources. Decreasing the amount of storage had the opposite effect, resulting in decreased recharge. The Carson basin was not at all impacted by up to a 30 percent change in reservoir storage in either direction. If reservoir storage was decreased to 18 percent of current volumes, net flux to the aquifers began to decrease slightly. This indicates that the reservoir system for the Carson basin is sized appropriately because it can supply enough water to satisfy demands in all years, resulting in very little change in canal flows from one year to the next, which in turn results in a near constant yearly rate of recharge to the aquifer.

In the fourth scenario, the annual inflow hydrograph was adjusted in order to demonstrate the possible influence of climate change on the system. The ratio of peak flow to average annual flow was increased and decreased, possibly to the extreme, going from high peak in the spring and essentially no flow the rest of the year to that of a flat hydrograph. In the Boise basin, the scenarios with the higher peak to average flow ratio resulted in larger amounts of water being available for recharge, because the reservoir operation rules allowed the reservoir to fill more often which in turn allowed for irrigation demands to be met more often. Conversely, the scenarios with the lower peak to average flow ratio resulted in the reservoirs filling less often, thus the irrigation demands were met less frequently. As seen in the previous scenarios, the more often irrigation demands can be met, given current conveyance and on-farm efficiencies, the more recharge will occur. It should be pointed out that these scenarios were based on a single flood rule curve that may be adjusted if climate change predictions become reality, which could impact the results. As in the third scenario, the Carson basin was not impacted by the changing hydrographs.

All of these scenarios indicate that the manner in which the surface water system is regulated has a significant impact on the net flux of water to hydrologically connected aquifers, and hence the sustainability of these aquifers as water supplies. This impact is due to a combination of the physical infrastructure that was developed to regulate river systems (reservoirs and canals), the rules that were developed to manage both the infrastructure, and the current water use within the basin. The interconnection between all of the components of the water resource system is important to understand when making changes to the system (for example attempting to increase the water use efficiency within a basin).

As demonstrated in the analysis above, increasing the efficiency of one or more components of the water resource system (e.g. canal lining or increased on-farm irrigation efficiency) within a basin may impact other components, and possibly result in impacting the sustainability of the groundwater resource. This analysis also indicates that while Reclamation has no direct role in managing groundwater resources, the manner in which they develop and manage surface water infrastructure does significantly impact the fluxes of water into and out of a region's groundwater resources. In order to increase the likelihood of maintaining sustainable water resources and minimize the chance of conflicts over water, Reclamation should consider the impacts to water resources that it does not directly manage, especially groundwater, when developing plans and strategies. The tool developed for this project could be useful in providing preliminary assessments for proposed changes in the management of water resources in Reclamation Project areas. It can be used to identify possible issues that could result in increased conflict of water resource use or non-sustainable water resource systems.

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Appendix A
Review Statement

Investigating the impact of river regulation on groundwater supplies in the western US
Report#: 2014.2892

1. Scientific and technical merit
The project aims to investigate the impact of regulated water systems on groundwater supplies in two water basins in the western US. The Boise basin and Carson basin are selected to improve understanding relational dynamics between regulated river systems and aquifer system mainly providing irrigation water downstream. Surface water and groundwater interaction is one of the critical water issues to address the sustainability of water systems in the urban-rural interface, such as Boise and Carson system. Yet, no study has developed methodologies to directly address how the regulation of surface water resources can affect the sustainability of hydraulically connected groundwater resources. Overall this report is well organized and current challenges of water managers facing climate change, surface water and groundwater interactions, and regulatory constraints are clearly addressed. Scientific and technical approaches suggested by this report are acceptable. This research will be a valuable addition to build our cases toward sustainable water resources management in the west.

2. Importance and Applicability
With regards to the sustainability of groundwater resources, the investigators have well addressed the key water management issues, including climate change, storage augmentation, and demand projection, to provide useful insights for long-term planning and impact mitigation in a changing water management environment in the west. A system dynamics modeling approach using STELLA is a good choice in the sense that contemporary water issues, such as climate change requires shared vision planning to evaluate system performance in human dimension. Since the model is developed as “a generalized system dynamics model”, it’s broad applications to other basins beyond western watersheds are highly expected.

3. Comments for Future Work
The research lays out several water management scenarios, such as canal lining and on-farm efficiency improvement to evaluate how the altered water management can affect the aquifer sustainability. If a series of matrix indicating safe yield for system-wide sustainability analysis can be developed in the future, it would be helpful to evaluate holistic system performance. System reliability, resiliency, vulnerability, and/or a new sustainability index, for example, would be useful information to evaluate water supply system, while few matrices representing population growth and urbanization would be another avenue to drive research agenda toward the sustainability in the natural and built environment in the west. Additionally, if the investigators are able to elaborate generic processes to promote interactions with stakeholders (e.g., surface/groundwater irrigators) and to provide a framework to communicate with them through a user interface would be more valuable. Surely, collaborations with academia will be critical to get these aspects of research done.