12-2011

Managing Water Shortages in the Weber Basin Using the Water Evaluation and Planning (WEAP) System

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MANAGING WATER SHORTAGES IN THE WEBER BASIN USING THE WATER

EVALUATION AND PLANNING (WEAP) SYSTEM

by

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

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

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UTAH STATE UNIVERSITY
Logan, Utah

2011

ABSTRACT

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An existing simulation model of the Weber Basin (GRES Model) was used as a basis for creating an equivalent model on the Water Evaluation and Planning (WEAP) system. The GRES Model was developed by the Utah Division of Water Resources (UDWR) and simulates the historical water allocation from 1950 to 2006. Using the GRES Model and additional information obtained from UDWR staff, two different WEAP models were created. The two models differed only in how water is transmitted to the service areas. End-of-month reservoir storage and other outputs from the GRES Model were compared to the two WEAP models. The two models turn out to be almost equal. The simplest version of the two WEAP models was selected and named the WEAP Weber Basin Model.

The WEAP Weber Basin Model is basically a historical simulation of water allocation in the Weber Basin and shows that the storage level in most reservoirs, except

Causey, does not reach the buffer zone. This result indicates the historical water security of the basin and also the security in the foreseable future.

The WEAP Weber Basin Model was also modified. Two scenarios consider demand growth (i) with, and (ii) without applying water conservation. These modifications were applied to one of the service areas which serves purely municipal and indusrial demands. The inflow to the system was populated by randomly reshuffling the historical flows. This is assuming that the historical flows will repeat in a random order in the future. Hence the inflows to the streams in 2006 were assigned the historical inflows of 1968 and so on.

The result from the WEAP Weber Basin Model without conservation (with growth) shows that most of the reservoirs, with the exception of Pinveview and Willard Reservoirs, do begin to draw from the buffer zone towards the end of the simulation period. Different storage carryover policies tested show that the reliability of the system decreases while its resilience increases when more and more of the water in the buffer zone is carried over between time steps.

Applying conservation seems to reduce the shortages created when different storage carryover policies were implemented compred to the model that did not apply conservation.

(75 pages)

PUBLIC ABSTRACT

Water is a scarce natural resource while the demand for water grows constantly. In Utah, most of the water resources have already been developed. In addition, Utah is prone to drought events and the effects of climate change may exacerbate the already dire situation. Hence, managing this scarce resource efficiently is very important in meeting the growing demand.

Reservoirs are used to store water which is subsequently released to meet demands. For management purposes, reservoirs have different zones such as flood control zone, conservation zone, buffer zone and inactive zone. Water is normally released from the conservation zone. The water in the buffer zone can be subjected to carryover depending on the reservoir operation policy adopted.

In this work, a software environment called WEAP is used to model the Weber River Basin. WEAP has a special parameter called the buffer coefficient which decides how much of the water in the buffer zone is to be allocated at any time step.

This study provides a tool which could be coupled with an optimization program to decide an optimum storage carryover in a system.

ACKNOWLEDGMENTS

This research was possible due to funding provided by the Utah Division of Water Resources and the Utah Water Research Lab. Therefore, my first thanks go to these organizations for the opportunity they created for me. Throughout the study, several employees of the Utah Division of Water Resources have provided crucial information including the precursor program (GRES Model) upon which this project is based. My special thanks go to Mr. Dave Cole of UDWR and Mr. Scot McGettigan also from UDWR. I would like to thank the Weber Basin Water Conservancy District (WBWCD) for their time in taking us on an actual tour of the field of study and in providing information relating to reservoir operations.

Finally, I would like to thank my adviser, Dr. David Rosenberg, for his guidance and both members of my committee, Dr. David Stevens and Dr. A.Bruce Bishop, for their mentoring and understanding.

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INTRODUCTION

The variablity of precipitation from year to year on the one hand and the increase in demand for water on the other make it necessary to anticipate shortages in any given year. There are a number of demand side measures such as conservation which could free up the available water in a system and decrease shortages. Alternatively we could also enhance the supply side and develop some of undeveloped water sources. We can also modify the operation of our reservoirs by introducing storage carryover particularly in response to drought events. Althought drought is difficult to predict, there are indicators such as Palmer Drought Severity Index-PDSI (Palmer, 1965) and Surface Water Supply Index-SWSI (Shafer and Dezman, 1982) which can detect and characterize drought conditions.

In a system where reservoirs are used to store water, we have the option of either meeting all demand at any given time or a protion of the available water could be carriedover into the future. "Release and carryover storage decisions should be made to maximize the sum of immediate use and carryover storage benefits" (Draper and Lund, 2004). However, in implementing storage carryover, the operating water rights law must be carefully considered.

In this study we develop a methodology that attempts to simulate different carryover storage policies at a selected basin while at the same time incurring shortages. The effects of the carryover policies will be studied by computing the reliability, resilience, and vulnerabilty of the system as defined in the Water Resource Systems Planning and Management (Loucks et al., 2005). Equations 1, 2, and 3 are the definition formulas for reliability, resilience, and vulnerability, respectively.

$$\text{Reliability to fully meet demand} = \frac{\text{Number of time periods of zero shortages}}{\text{Total time period}} \tag{1}$$

$$\text{Resilience} = \frac{\text{Number of times a satisfactory state follows an unsatisfactory state}}{\text{Number of an unsatisfactory value occurs}} \tag{2}$$

$$\text{Vulnerability} = \frac{\text{Sum of positive values of (target} - \text{delivery)}}{\text{Number of times an unstisfactory value occurs}} \tag{3}$$

Several softwares were considered to accomplish carryover simulation, such as the GRES Model (Cole, 2010a), RiverWare (Zagona et al., 2001) and WEAP (Stockholm Environmental Institute, 2007). The GRES Model is a FORTRAN based model developed by Utah Division of Water Resources to simulate the Weber River Basin. WEAP is a software environment whereby we can build individual basin models. Detailed descriptions for the GRES Model and WEAP are provided in the next sections.

RiverWare is a software environment which can be used to build and manage any basin. RiverWare is used in several applications in the US. It is used by the Tennessee Valley Authority to simulate and optimize more than 40 reservoirs. It is also used by the U.S. Bureau of Reclamation to manage the Colorado River. It is supported and maintained by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado at Boulder.

The Weber River Basin

The selected basin for the project is the Weber River Basin which is located in the north-central Utah and includes Davis, Weber, Morgan Counties, and a portion of Summit County. The river basin covers an area of about 2,460 square miles. The major tributaries of the river are Beaver Creek, Chalk Creek, Lost Creek, East Canyon Creek and the Ogden River. It has seven on-river reservoirs (Smith & Morehouse, Wanship, Echo, Lost Creek, Echo, Causey, Pineview) and one off-river reservoir (Willard) which supply the population centers and irrigated lands. Agriculture currently consumes about 69 percent of the developed supply while municipal and industrial uses consume the remaining 31 percent (Utah Division of Water Resources, 2009). There are some senior water right holders in the basin who use water for irrigation. Most of the water is however managed by Weber Basin Water Conservancey District (WBWCD). The total capacity of all the reservoirs is such that once full they can meet all current demands for about two years without additional inflow (worst case scenario) (Hogge, 2010, Personal Communication).

There are several reasons why the Weber River Basin was chosen for our project. First the Basin has an existing simulation model (GRES Model) which would be used as a basis to develop a comparable WEAP model of the Basin itself. Second, the Basin is one of the most well managed and documented basins in Utah and hence it was felt it would be more convenient for such a study.

The GRES Model

The Utah Division of Water Resources (UDWR) developed a model known as GRES that simulates the monthly historical (1950-2006) water allocation within the Weber River Basin (Cole, 2010a). The GRES model, written in FORTRAN, was developed mainly to evaluate the availability of storage space in the Willard Reservoir (Cole, 2010b, Personal Communication). Figure 1 shows the schematic of the Weber River Basin, which was the basis of the GRES Model. It consists of 20 service areas of which two (Service Area 1 and Service Area 7) had zero demand for the simulation period. A service area is simply a group of canals but there is little information as to how the grouping was made. There are seven on-river reservoirs and one off-river reservoir. The GRES Model allocates water based on priority (Table 1) and certain special rules that apply to the Basin. For example, Service Area 11 has a protected storage right of 28,800 acre-foot/year and 31,000 acre-foot/year in East Canyon and Echo Reservoirs, respectively (McGettigan, 2010, Personal Communication). Similarly, Service Area 13 and 14 have a protected storage of 44,000 acre-foot/year in Pineview Reservoir (McGettigan, 2010, Personal Communication). These protected storages described above represent users that have senior water right in the Basin.

As pointed out in the introduction, the objective of this project is to simulate different storage carryover policies and analyze their impacts. The GRES Model is not equipped with a capability to carryover storage (Cole, 2010b, Personal Communication). Hence, WEAP was considered as a potential option to test storage carryover policy. In fact, WEAP has a capability to carryover water storage in reservoirs.

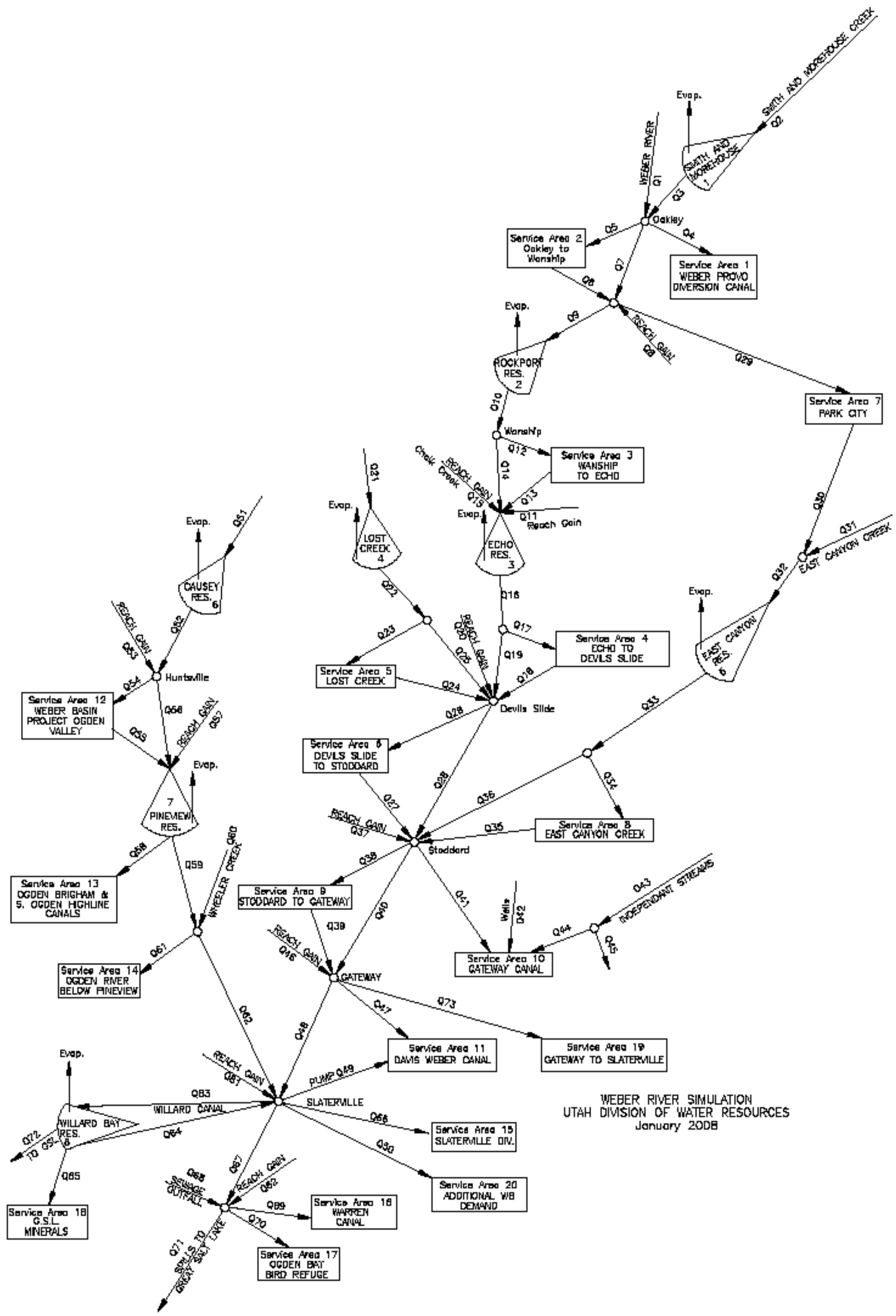


Figure 1. Weber River Basin flow diagram (developed and used for the GRES Model).

Table 1. Weber River Basin service areas (McGettigan, 2010, Personal Communication)

Priority	Service Area No.	Name	Order of Reservoirs Called
1	1	Weber Provo Diversion Canal	1
2	2	Oakley to Wanship	1
3	3	Wanship to Echo	2,1
4	4	Echo to Devils Slide	3,2
5	5	Lost Creek	4
6	6	Devils Slide to Stoddard	3,2
7	7	Park City	1
8	8	East Canyon Creek	5
9	9	Stoddard to Gateway	3,2
10	10	Gateway Canal	3,2,4,5
11	12	Weber Basin Project Ogden Valley	6
12	13	Ogden Brigham & S. Ogden Highline canals	7
13	14	Ogden River Below Pineview	7
14	11	Davis Weber Canal	8,7,3,5
15	19	Gateway to Slatterville	3,2,4,5
16	15	Slatterville Diversion	7,8,3,2,4,5
17	20	Additional Weber Basin Demand	8,7,3,2,4,5
18	16	Warren Canal	7,8,3,2,4,5
19	17	Ogden Bay Bird Refuge	8,7,3,2,4,5
20	18	G.S.L Minerals	8,3,2
21	21	Great Salt Lake	

The WEAP Model

WEAP, which stands for Water Evaluation and Planning System, is a software package for planning and managing water supply. WEAP operates on the basic principle of mass-balance and allocates water based on the priority specified for the system components such as the demand sites, reservoirs, environmental releases, etc. It is an initiative of Stockholm Environmental Institute (SEI) and was created in 1988. WEAP has been used in several water related projects/research through out the world. For example it was used on a research that focuses on developing decision support system (DSS) for three urban water utilities in the U.S. (Austin, Texas; Portland, Oregon; and Philadelphia, Pennsylvania) to facilitate long-term management of water supplies. In this reseach project WEAP will be used because of its capability to represent storage carryover.

As explained earlier, the GRES Model does not have an input parameter by which to control release and/or carryover storage. WEAP works by defining the buffer zone in each reservoir and a parameter called buffer coefficient, which specifies how much of the water in the buffer zone is to be released (Figure 2). WEAP allows us to create different scenarios of a model by using different buffer coefficient values and enables us to view the associated results such as shortages in the service areas.

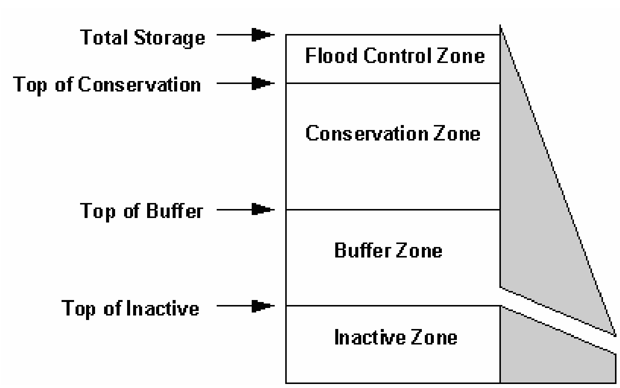


Figure 2. Definition of the operation parameters required by WEAP (SEI, 2007).

METHODOLOGY

The first step in working with WEAP is to create the schematic for the water supply system. This involves representing all the river systems, the reservoirs, the service areas, and other important components of the water supply system under consideration.

The second step is to input relevant data for each of the components of the system. Then the system can be ready to run. WEAP offers a number of interesting results for each component of the system. There are wide varieties of options of how to display the results.

WEAP Schematic for the Weber River Basin

The WEAP schematic for the Weber River Basin was based on the schematic used for the GRES Model (Figure 1). Since WEAP allows the of use shape files, a shape file representation of the Weber River Basin was acquired and used to trace the course of the various streams. A shape file for reservoirs locations was also used to represent the reservoirs in the Basin in their correct location. Service areas were represented based on their relative locations as shown in Figure 1.

Converting the GRES Model schematic to WEAP resulted in to two basic WEAP schematics models which differ by the way water is transmitted to demand sites. The first model is constructed by simply specifying the water demand priority of the various demand sites and hence is called as Demand Priority Model (DPM) (Figure 3). The second is built by using information on how each demand site in the basin gets water from the reservoirs and hence is called as Supply Preference Model (SPM) (Figure 4).

The components of the schematic are: the river, reach gains, reservoirs, wells, service areas, transmission links to service areas, return flow from service areas, and diversion. The naming of the components of the system has been preserved as was given in the original GRES Model schematic.

Figure 4 is the same as Figure 3 in all other aspects except that it specifies a demand site's order of call (supply preference) from the upstream reservoirs. Figure 3 and Figure 4 hence represent two models: DPM and SPM, respectively. Later on (under Model Selection) the two models will be compared to each other to see which one best approximates the GRES Model, which I am trying to reproduce in a WEAP environment.

Entering Data in the WEAP Environment

The rivers (streams)

Once the river was represented in the schematic, the monthly head flows were entered for each stream flow. In our case, the available data ranges from the year 1950 to 2006. The head flow data entered in WEAP are the values termed as Qx's in the GRES Model, which can be obtained from the model output. For example, for the Weber River, Qx-1 represents the head flow. Part of the Qx-1 values are shown in Table 2.

To enter this data in WEAP, we need to convert the table into a WEAP compatible format. One way to enter this data is to create a single column of year/month/value and save each head flow data as .csv file format. Thus we can use the ReadFromFile(filename) function in WEAP. Therefore, in the head flow data for the

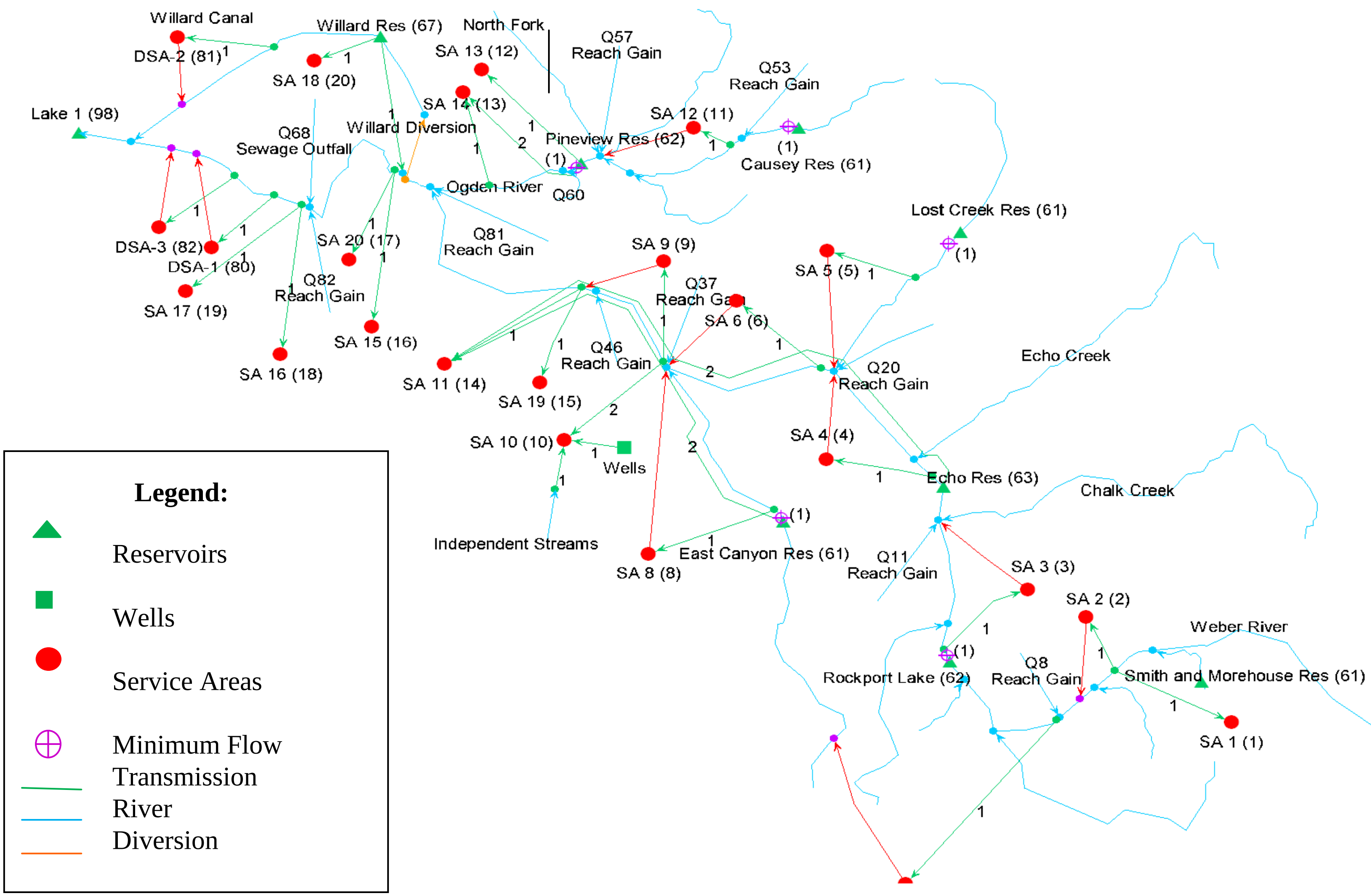


Figure 3. Demand Priority Model (DPM).

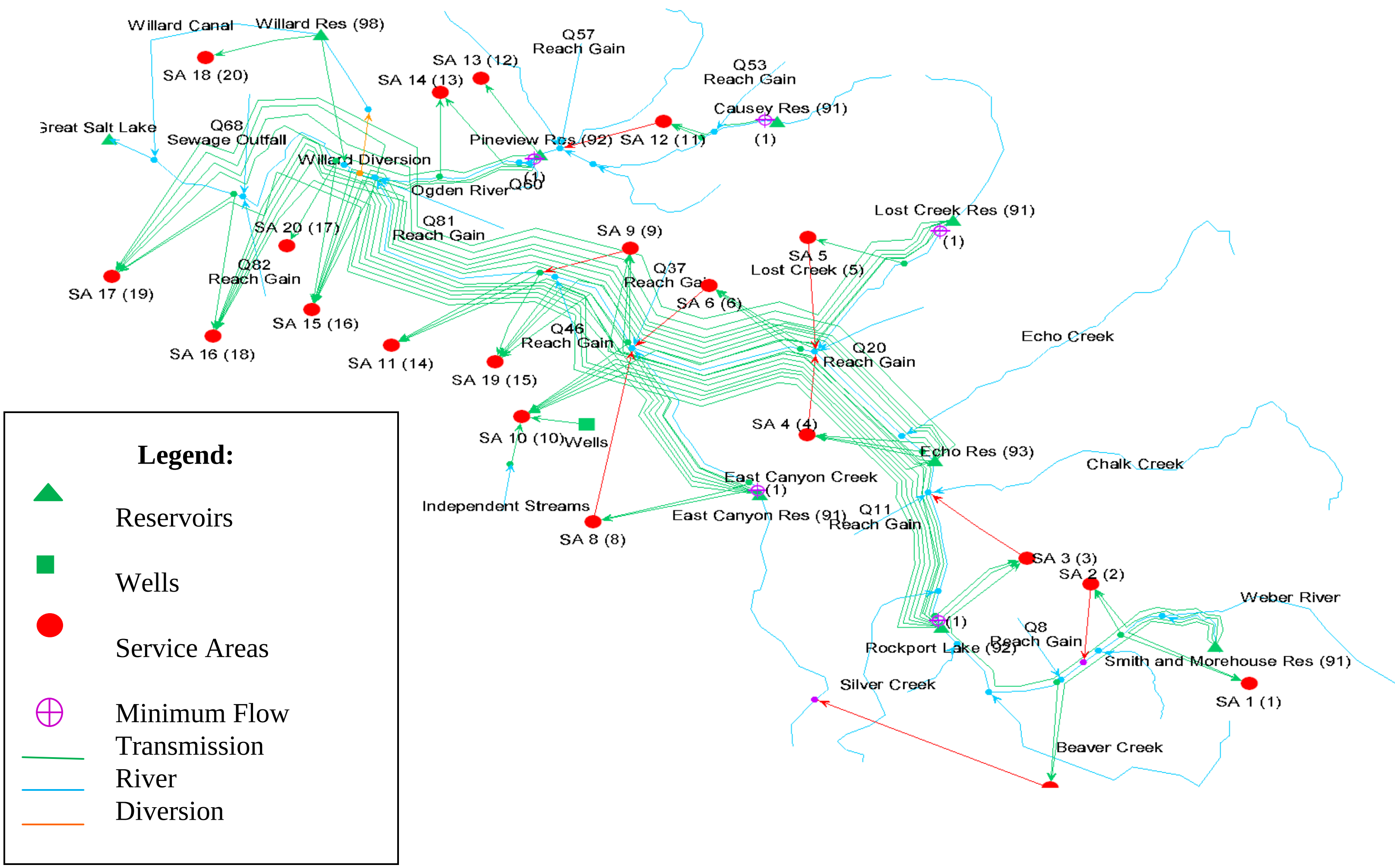


Figure 4. Supply Preference Model (SPM).

Table 2. Monthly head flow in acre-foot to the Weber River obtained from the GRES Model output

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1950	3,899	3,405	3,037	2,776	2,506	2,874	10,474	32,723	54,881	17,108	6,306	5,013
1951	3,913	3,893	3,565	3,232	3,034	3,206	9,811	31,207	40,863	13,192	6,723	4,068
1952	4,967	3,545	3,060	2,715	2,229	2,700	11,795	49,608	51,651	13,889	7,012	4,819
1953	4,091	2,943	2,391	2,479	2,206	2,937	6,071	13,086	46,059	9,821	5,872	3,083
1954	2,748	2,568	2,391	2,441	2,304	2,407	8,393	26,900	11,785	6,160	3,553	2,946
1955	2,496	2,350	2,158	2,166	1,943	1,925	4,089	28,897	23,571	6,428	4,377	3,068
1956	2,792	2,658	3,464	3,224	2,311	3,587	11,368	39,749	38,183	7,570	4,625	3,273
1957	2,946	2,553	1,917	2,012	2,101	2,526	4,297	21,079	55,678	18,373	6,518	4,256

Weber River, we select Enter Expression and write the above function as ReadFromFile(Qx-1.csv).

Reach gains

According to the GRES Model, reach gains are the sum total of return flows from the surrounding service areas and other small streams (Cole, 2010b, Personal Communication). As shown in the original GRES schematic, these flows are shown for some of the nodes. The same has been replicated on the WEAP system by drawing a river flowing to the location shown in the original GRES schematic (Figure 1) and data was entered for each location in the same way as was shown for the rivers.

The reservoirs

The two main data entered for reservoirs pertain to the physical and operation of the reservoirs.

Physical data. In WEAP, the physical data include storage capacity, initial storage, volume-elevation curve, net evaporation, loss to groundwater and observed volume. There is no available data on loss to groundwater. The end-of-month storage for each reservoir evaluated by the GRES model was assumed the observed volume. It will serve to compare the WEAP and GRES model outputs side by side. The physical data used for each reservoir in the Basin were obtained from the GRES model. All the physical data used for the WEAP models are in Appendices A, B, and C.

Operation data. The operation data include top of conservation, top of buffer , top of inactive and buffer coefficient. A pictorial definition of each of the parameters is given in Figure 2 (SEI, 2007). Table 3 provides some operation data for the reservoirs in the Basin (Hogge, 2010, Personal Communication).

Information in Table 3 was used to evaluate the operation parameters required by WEAP. The result is summarized in Table 4 below. The information obtained from the WBWCD does not provide these parameters explicitly. Therefore, some approximation and judgment has been used to arrive at the numbers filled in Table 4. Top of conservation has been taken as the full capacity of each reservoir. Ideally, a flood pool would have been subtracted from the full capacity to get the top of conservation as defined in Figure 2, however no information was provided in Table 3 on flood pool. Top of Buffer was evaluated by first calculating how much water is carried over each year, which was provided in Table 3. Top of buffer is the sum of the carried over storage and the dead pool. Top of inactive is the storage volume associated with the elevation of dead pool provided in Table 3.

Buffer coefficient is fraction of water in buffer zone available each month for release (must be between 0 and 1). There is no explicit information on this parameter. As a first approximation, a buffer coefficient value of 1 has been used for all the reservoirs in the WEAP models. A value of 1 for buffer coefficient means that water in the buffer zone is fully released to meet demand.

Table 3. Raw operation information for the reservoirs on the Weber River Basin (Hogge, 2010, Personal Communication)

Dam	**Spill level (Elevation)**	**Gross Storage (AF)**	**Conservation/Inactive/Dead Pool (Elevation)**	**Storage (AF) at top of Conservation/ Inactive/Dead Pool**	**Active Storage (AF)**	**Preferred Holdover (AF)**
Pineview	4900	110150	4818-Dead pool	< 1 AF	110150	50%+*
Causey	5692	7870	5607-Inactive Pool, 5601-Dead Pool	1000 AF	6870	30%+
Smith and Morehouse	7690	8350	7639.6-Inactive Pool, 7630-Dead Pool	750 AF	7600	40%+*
Wanship	6037	62120	5930-Dead Pool	1260 AF	60860	50%+
Echo	5560	73940	No Dead Pool	0 AF	73940	Weber Basin does not control holdover
Lost Creek	6005	22510	5812.3-Inactive Pool, 5842-Dead Pool	2500 AF	20010	60%+
East Canyon	5705	51200	5577-Conservation Pool (Inactive)	3090 AF	48110	60%+*
Willard Bay	4226	227189	4205-Dead Pool	25029 AF	202160	50%+

* Weber Basin only has rights to 60% active storage in Pineview, 42% active storage in East Canyon, and 86% active storage in Smith and Morehouse; therefore holdover is partially controlled by others.

Table 4. Consolidated operation information for the reservoirs in the Basin (used in WEAP Models)

Dam	**Top of Conservation, AF**	**Top of Buffer , AF**	**Top of Inactive, AF**	**Buffer coefficient**
Pineview	110,150	33,046	1	1
Causey	7,870	2,868.6	807.6	1
Smith and Morehouse	8,350	2,920.122	306.122	1
Wanship	62,120	31,690	1,260	1
Echo	73,940	Not Buffer	0	1
Lost Creek	22,510	12,019.6	13.6	1
East Canyon	51,200	15,244.72	3,121	1
Willard Bay	215,120	117,930	16,850	1

In WEAP, the other data that could be entered are related to hydropower, water quality, cost and priority. There are no available data on the first three. The filling priority for the reservoirs is not obvious and will be explored further later in this section.

Wells

The wells in this system are connected to Service Area 10 or Gateway Canal. Looking into the GRES schematic, the flow from wells is Q42. According to the GRES Model, the monthly and annual flow throughout the simulation period (1950-2006) has been constant. The basic data required for wells are storage capacity of the aquifer, initial storage in the aquifer and maximum withdrawal. Arbitrarily large figures were entered for the first two parameters because doing so ensures that a specified maximum withdrawal can flow out of the wells to Service Area 10. For maximum withdrawal, the monthly flow values used by GRES Model (Q42) were entered using WEAP's Monthly Time-Series Wizard.

Service areas

According to the schematic prepared for the GRES Model, there are 20 service areas. Each service area has its own aggregated demand on a monthly basis for the entire simulation period. The service areas used in the GRES Model represent canals and diversions in the Basin (Cole, 2010b, Personal Communication). Although WEAP allows disaggregated demands, it was not possible to find any documentation on these service areas to answer questions such as how demands were aggregated for each service area, and what the areal coverage for each service area is. Cole was not able to offer any further help perhaps due to the length of time elapsed since the GRES Model was developed. Hence, the WEAP models may not be used to accurately simulate demand growth scenarios. The service areas used in the GRES Model, their priority (known as the demand priority in WEAP terminology) and order of reservoirs called (in WEAP terminology, know as supply preference) are listed in Table 1.

The same aggregated monthly demand for each service area has been used for the WEAP model. As with the head flow to rivers/streams, the demand data were organized in a WEAP readable format (see "The river" section). Since the GRES model outputs zero return flows for all the service areas, in WEAP 100 percent consumption was assumed (and used as an input) in the WEAP Models. This input will have a similar effect on the WEAP Models- no return flows.

Transmission links

Each service area must be connected to a source. In WEAP this can be done, in the schematic mode, by drawing a "Transmission link" element from the source to a service area. For the DPM the transmission links were constructed based on the schematic used by GRES Model as explained in the "WEAP schematic for Weber River Basin" section.

In WEAP, we could specify the maximum flow volume, maximum flow percent of demand, and supply preference. None of these parameters has been specified due to lack of information. There is, however, information on supply preference (Table 1) for each demand site. In Table 1 we see that each demand site has a number of reservoirs arranged in order of priority from which it can call as has been represented in Figure 4. This is the basis for the SPM.

Return flow

Following the strategy used in the GRES model, 100 percent consumption was applied to each service area in all the WEAP Models. As a result, no water flows through the return flow links in the WEAP Models. However, the actual return flow from service areas has been accounted for and is included in the reach gains as explained in "Reach gains" section.

Diversion

In WEAP, transmission links and diversions are represented differently. There are several diversions in the Weber Basin. Most of them take water to a service area and have already been treated as transmission links. There is one special diversion at Slaterville (Willard Canal, with a capacity of 1000 cfs) that diverts water from the Weber and Ogden River to the Willard Reservoir and at times carries water from the reservoir to the same point of diversion. This is possible because the canal has approximately a zero slope and pumps are used to boost the water flow in both directions. Normally water is released to meet demands both downstream of Slaterville and demands around the Willard Bay but when it comes to spilling any extra flow, water can be spilled through the river (Weber and Ogden River or Q67 as per Figure 1) up to 740 cfs and the rest (if any) is sent up to 1000 cfs through Willard Canal and ultimately spilled through the Willard spillway. If there is still more water to spill while the Willard Canal is running at full capacity, more water continues to flow down the river that is at a flow rate greater than 740 cfs. Hence in times of excess flow at Slaterville (after meeting all demands including those of filling the Willard Bay), flow towards Willard Canal (up to 1000 cfs) is triggered when the flow in the river reaches 740 cfs (Figure 5). However, both flows end up in the Great Salt Lake (GSL).

In WEAP it was possible to represent the Willard Diversion along with its maximum capacity. It was then connected to dummy river named as Willard Canal in WEAP models. Willard Canal flows to Willard Bay and continues down to meet the

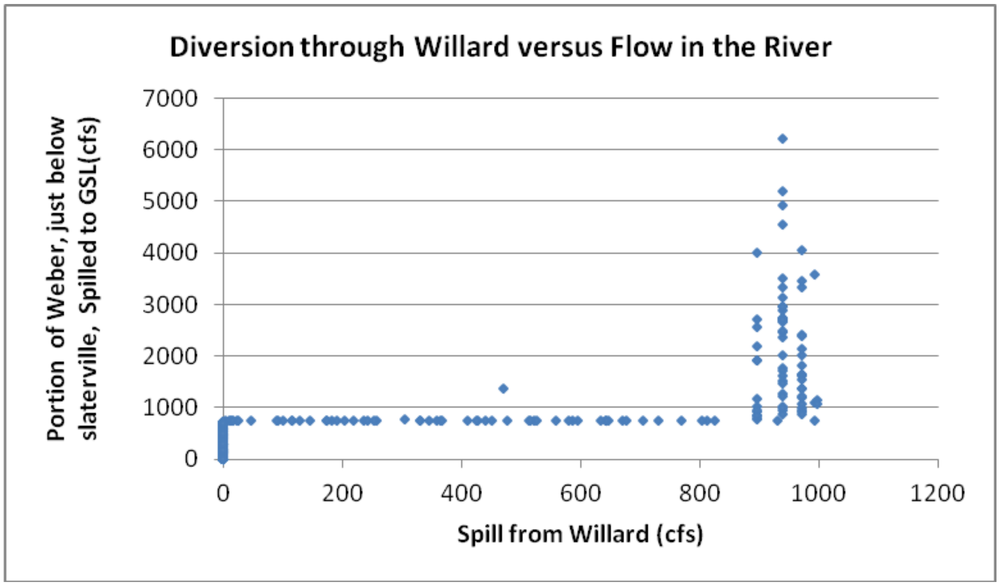


Figure 5. Relationship between water spilled via the Willard spillway and surplus flow at the Weber River.

Weber River and ultimately flows to Great Salt Lake (GSL). WEAP does not have an obvious way of representing the flood routing trigger of 740 cfs, which has been described in the above paragraph. Initially, the results from WEAP Models showed that WEAP was not sending water past the Willard Bay and this has to do with the way WEAP works that is water flows to meet demands based on specified priorities. Adding three dummy service areas (DSAs) in the DPM (Figure 6) which consume none of the water that enters them resolved this problem. DSA-1 has a priority of 80, which is lower than filling the Willard Bay. Therefore, once the Willard Bay is filled, water up to 740 cfs (the flood threshold below Slaterville Diversion described above) should continue to flow down the Weber River. If there is more water then it will have to flow to DSA-2, which has a priority of 81. However, since the Willard Canal's maximum capacity is 1000 cfs, any extra water will have to flow back to the Weber River and reach DSA-3 which has a priority of 82.

Monthly minimum releases

Most of the reservoirs have minimum monthly releases for environmental purposes (Table 5). The data was extracted from the GRES Model. In WEAP, monthly minimum release is represented by placing a flow requirement element immediately below the relevant reservoir. Then data is entered using WEAP's Monthly Time-Series Wizard. Since it is obvious that monthly minimum releases must have top priority, in WEAP a priority of 1(highest) was assigned to all monthly minimum releases.

Reservoir filling priority

Filling a reservoir is in a way water demand in its own right with specified priority. In a system such as the Weber River Basin where there are multiple reservoirs, it is important to specify how the reservoirs should be filled. Reservoir filling priority was not readily available from the GRES Model. However, Cole (2010b) has indicated that reservoirs are filled in downstream order starting at the highest in the watershed. It was also obvious that in the case of the Weber River Basin, reservoirs have lower priority than all other demands in the Basin. Since not all of them are in series, it was necessary to iteratively calibrate the model while checking the results if they make sense compared to the GRES Model output. In WEAP the highest priority is assigned 1 while the lowest is assigned 99. It was found that Smith and Morehouse, Lost Creek, East Canyon and Causey must have equal filling priority since they are located at the start of their respective streams. In the WEAP Models, I arbitrarily assigned a priority of 61 to each and worked downstream from each reservoir. Hence, Rockport was 62 while Echo was 63 in filling priority. Pineview was assigned a priority of 62 since it is located downstream of Causey with a priority of 61. Willard is assigned relatively lowest filling

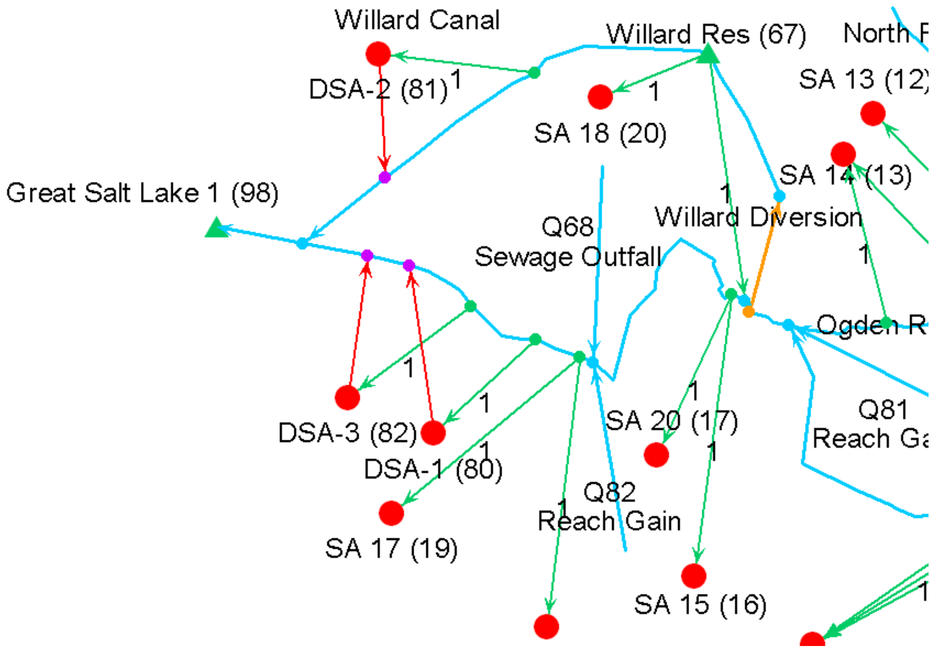


Figure 6. Representing Willard Diversion by adding dummy service areas (DSAs).

Table 5. Monthly minimum releases for Weber River Basin reservoirs

Reservoir	Monthly Minimum Releases (Acre-foot)											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Smith & More house	0	0	0	0	0	0	0	0	0	0	0	0
Rockport	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
Echo	0	0	0	0	0	0	0	0	0	0	0	0
Lost Creek	300	300	300	300	300	300	300	300	300	300	300	300
East Canyon	300	300	300	300	300	300	300	300	300	300	300	300
Causey	600	600	600	600	600	600	600	600	600	600	600	600
Pineview	600	600	600	600	600	600	600	600	600	600	600	600
Willard	0	0	0	0	0	0	0	0	0	0	0	0

priority of 67 compared to the upstream reservoirs in the system. Finally, GSL where all excess flow ends must also have filling priority specified although it does not directly affect the system. Therefore, its filling priority must be lower than that of the Willard. In this case it is 98. It must be noted that any number can be used for specifying priority as long as the relative priority throughout the system is respected. All demand priorities in the Weber Basin are summarized in Table 6.

Running and Viewing Results

Once a model is run in WEAP, several results can be viewed. For a given service area we can view how much water was supplied from each source it is connected to, unmet demand, coverage, reliability etc. Similarly, for each reservoir we can view its simulated storage volume, storage elevation, inflows and outflows, evaporation etc. We can also view the flows at any section of a given river. We can select a number of other formats to view such as annual total versus monthly average or for a specific month of a specific year and so on. A sample of one of the reservoir result is shown in Figure 7.

Model Verification

The next important step is to compare the WEAP and GRES Model results. The system contains reservoirs, streams, service areas, and a diversion. Hence, the outputs

Table 6. Summary of overall system water demand priorities

Priority	Weber Basin system component
1	All minimum releases from reservoirs
1-21	Service Areas 1-21 (Table 5)
61	Reservoirs: Smith & Morehouse, Lost Creek, East Canyon, Causey
62	Reservoirs: Rockport, Pineview
67	Reservoir: Willard
80	Dummy Service Area 1
81	Dummy Service Area 2
82	Dummy Service Area 3
98	Great Salt Lake

associated with these system components will be selected to make the comparison. These are end of month storages in reservoirs, monthly releases from reservoirs, flow in the Willard Diversion, spills to GSL, and unmet demands.

GRES Model versus Demand Priority Model (DPM)

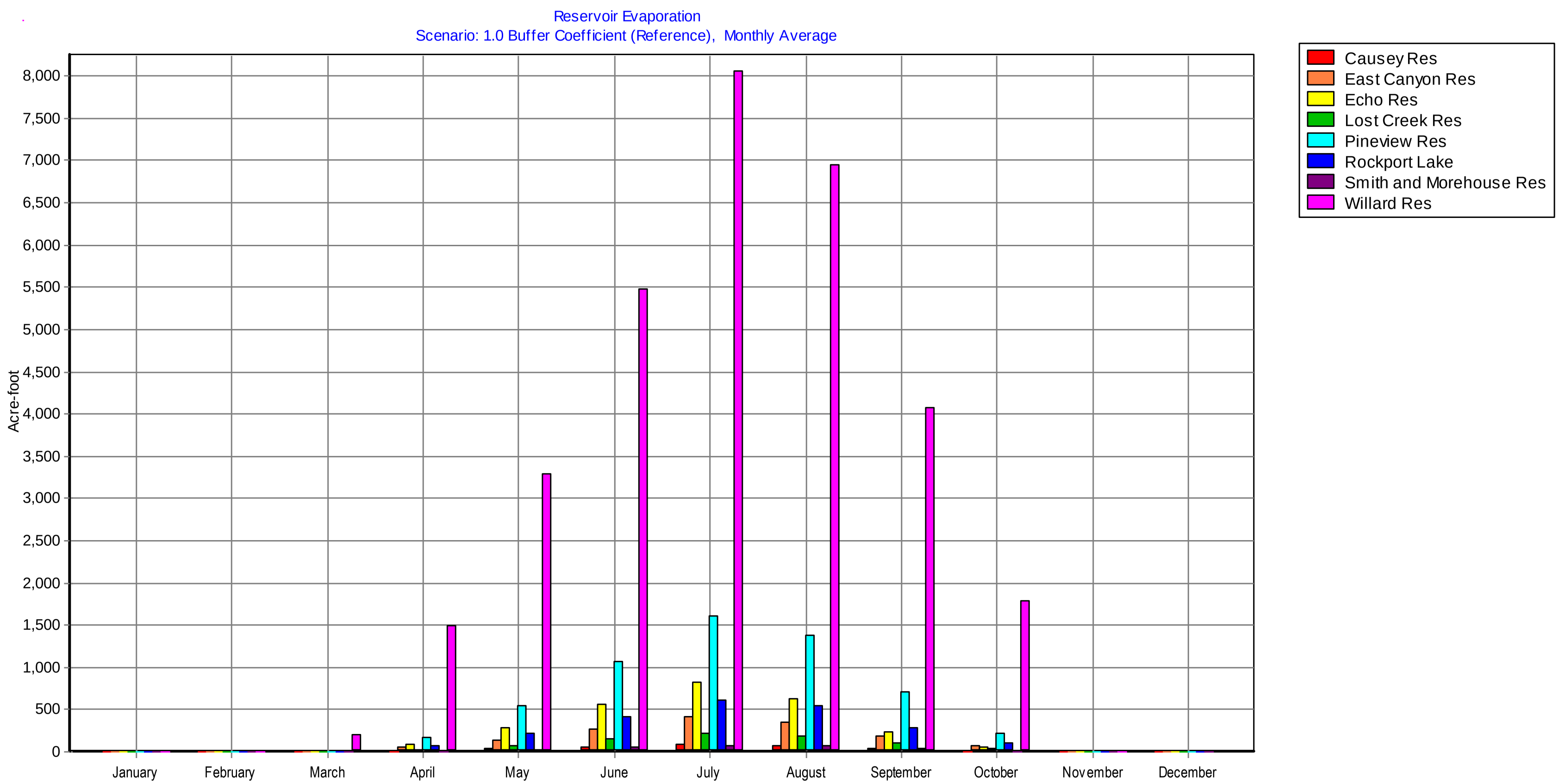
One of the main results that was used to compare outputs was the end of month storage of reservoirs. In WEAP, we can enter observed end of month storages as an input. In this case, the result from the GRES Model was entered as an observed storage for each reservoir. Hence, once the model is run, we can make the two time series in one chart. Figure 8 shows where the DPM performs well while Figure 9 is a sample where DPM fails to reproduce the GRES Model.

A noticeable disparity between the two models occurred at three reservoirs (Echo, East Canyon, and Pineview) for which there are protected storages for some service areas. There is no direct way of representing protected storages in WEAP. All service areas are normally served based on the priority assigned to them.

GRES Model versus Supply Preference Model (SPM)

A Similar approach was used to compare SPM with the GRES Model. Figure 10 compares end-of-month storage at Willard from both GRES and SPM.

It was found that the SPM results do not actually differ from the DPM results despite their difference in approach hence comparing GRES Model to SPM is similar to comparing GRES Model to DPM as described in the preceding section. This result was confirmed by looking at the SPM results that show that no water flows through the transmission links that have lower preference. Since all the service areas must draw water from the river first then call from the reservoirs, in WEAP this translates that water flows



Fifure 7. Monthly average reservoir evaporation (for the DPM).

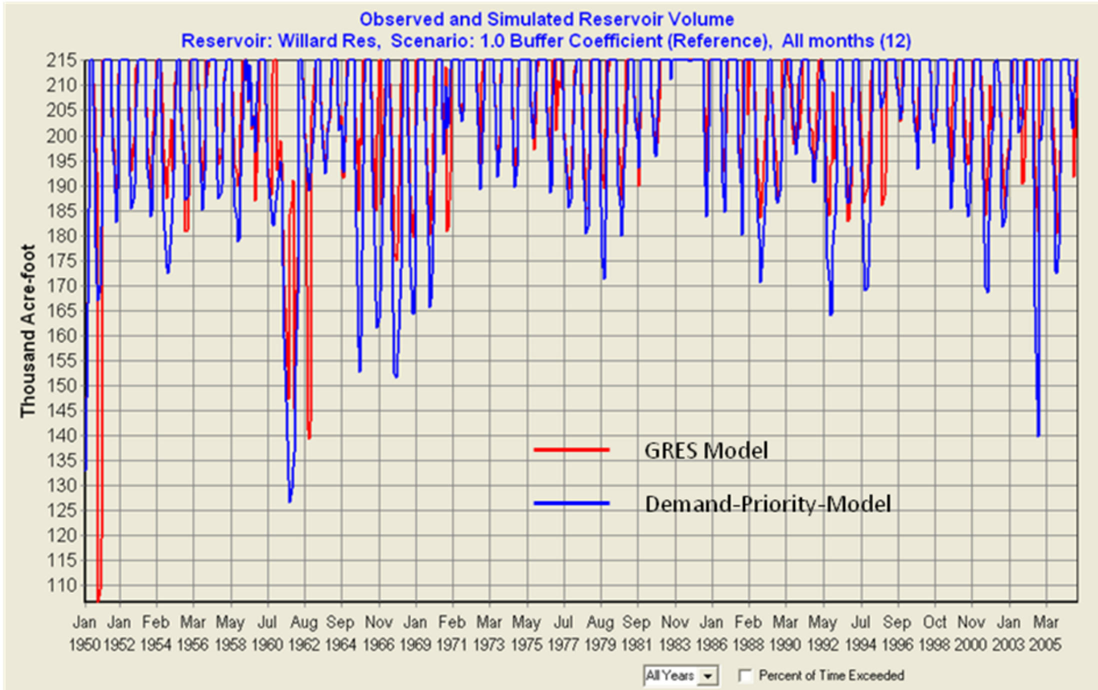


Figure 8. End-of-month storage at Willard (GRES Model vs. DPM).

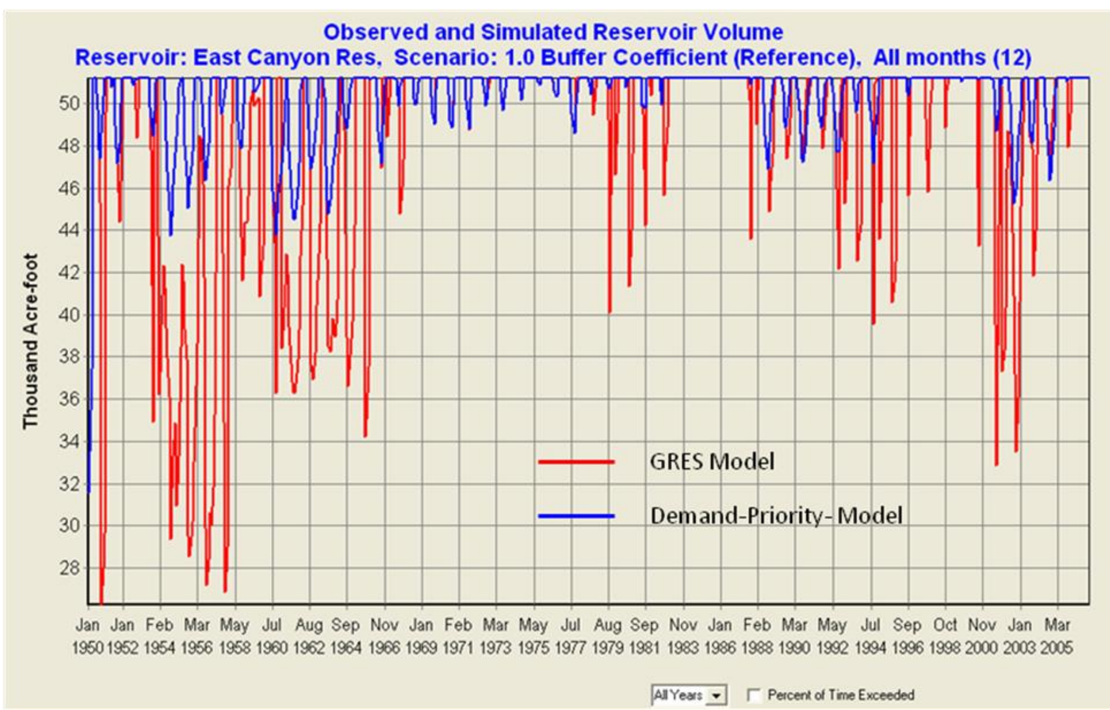


Figure 9. End-of-month storage at East Canyon (GRES Model vs. DPM).

through the link that is connected to the river. Figure 11 shows that the end-of-month storage results at East Canyon reservoir for both DPM and SPM are identical.

Model Selection

The comparison of the two WEAP Models against the GRES model described above show that both DPM and SPM perform well against the GRES model on most the performance criteria listed in "Model Verification" section. On the other hand, both perform poorly on certain performance criteria such as end of month storages at Echo, East Canyon and Pineview reservoirs. The results from SPM and DPM (Figures 3 and 4, respectively) are identical despite the fact that the SPM has additional transmission links.

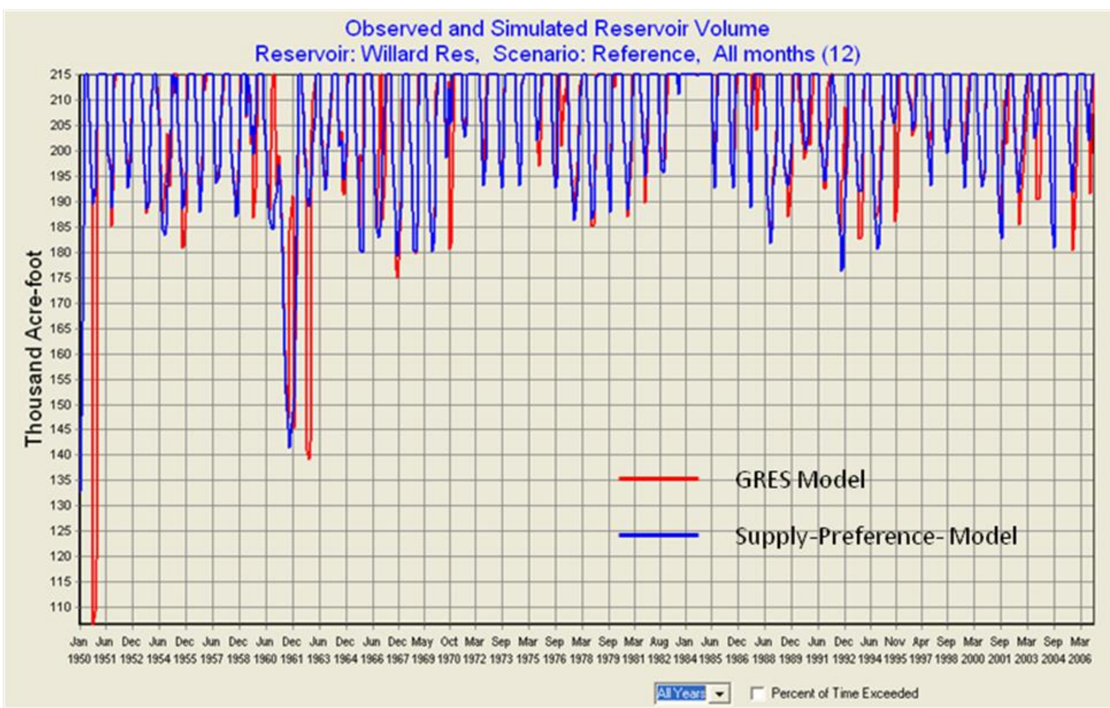


Figure 10. End-of-month storage at Willard (GRES Model vs. SPM).

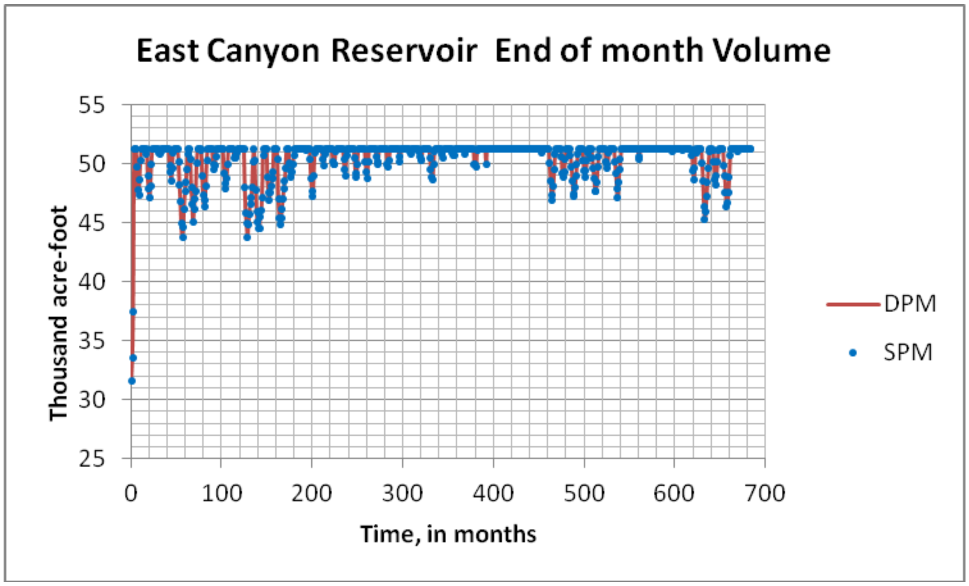


Figure 11. End-of-month storage at East Canyon (DPM vs. SPM).

Therefore, DPM which is a much simpler version compared to the SPM will be adopted as a working model to represent the GRES Model and it will be referred to as simply WEAP Weber Basin (WEAP WB) Model.

However, WEAP WB Model shows some serious discrepancies compared to the GRES Model results, which need improvement. The problem areas are end of month storage at some reservoirs (Echo, East Canyon and Pineview), release from Willard Bay and flow through the Willard Diversion.

Creating and Exploring Scenarios

We now turn to implementing storage carryover policies and analyzing their impacts. In WEAP storage carryover is implemented by defining a buffer zone and specifying a buffer coefficient (a value that represents how much water from the buffer zone should be carried over/released between time steps) for each reservoir. Different storage carryover policies have been tested on three versions of the WEAP WB

Table 7. Buffer coefficients tested in the WEAP Models

Buffer coefficient (unit less)	1.0	0.8	0.6	0.4	0.2	0.0
Storage Carryover (percent of the buffer zone volume.)	0.0	20	40	60	80	100

Model, namely: the WEAP WB Model (the historical scenario), WEAP WB without conservation (with growth), and WEAP WB with conservation (with growth) (Table 7). In each case, the shortages incurred are analyzed.

<u>WEAP WB Model (the historical scenario)</u>

The WEAP WB Model replicates several of the GRES Model outputs and may be taken as an approximation of the GRES Model. The buffer coefficient used for WEAP WB Model for all the reservoirs was 1.0. This was obtained during the calibration process, that is, by using different buffer coefficient values and comparing the end of month storage results from the WEAP WB with those of the GRES Model. It was also evident from the outset that the GRES Model does not use the concept of storage carryover hence, the historical buffer coefficient has to be 1 for all reservoirs.

In the WEAP WB Model, different sub-scenarios were created by using different values of storage carryover. For example, a sub-scenario with a buffer coefficient of 0.8 (20% storage carryover) uses all other inputs of the WEAP WB model with the exception that all the reservoirs have a buffer coefficient of 0.8. Therefore, if we assume that a buffer coefficient of 1 for all reservoirs is the base case scenario, five other scenarios were created.

<u>WEAP WB Model without conservation (with growth)</u>

WEAP WB Model without conservation (with growth) represents a projected scenario where population growth in the Basin is considered but no conservation. In a general sense demand for water can be categorized into municipal and industrial (M&I) and agricultural. In the Weber Basin, the water demand in the former category is expected to rise over the future. On the other hand the demand for agricultural water will decline (Utah Division of Water Resources, 2009). The GRES Model which was used as a basis for the WEAP WB Model uses 20 service areas. It is not clear how the authors were able to populate the demands for those service areas and which category (M&I or agricultural or a mixture of both) each service area falls under. However, the demand at Gateway Canal (Service Area 10) is purely M &I demand as was confirmed during a field visit to the Basin. As of 2005, M&I water for the Basin was 206,300 acree-foot and it is projected to 320,900 acre-foot as of 2060 (Utah Division of Water Resources, 2009). The same document also shows that the 2000 Weber River Basin population would more than double by 2060. Hence these information were used to create a new demand file for the Gateway Canal. The new demand file created assumes a doubleing of the 2006 demand at the Gateway Canal by 2062. For the intermidiate values a linear interpolation was used (Figure 12). All other input files (except inflow files) used in WEAP WB Model were used by changing the dates only. That is, 1950 was converted to 2006 while 2006 was switched to 2062.

It was decided to randomly sample (without replacement) from the historical inflow data to populate the inflow data from 2006 to 2062. Hence new inflow files were generated by the method just described and used in this scenario.

As the Weber River Basin grows, water shortages are expected. Storage carryover may be used to spread the shortages more evenly. Hence different buffer coefficients

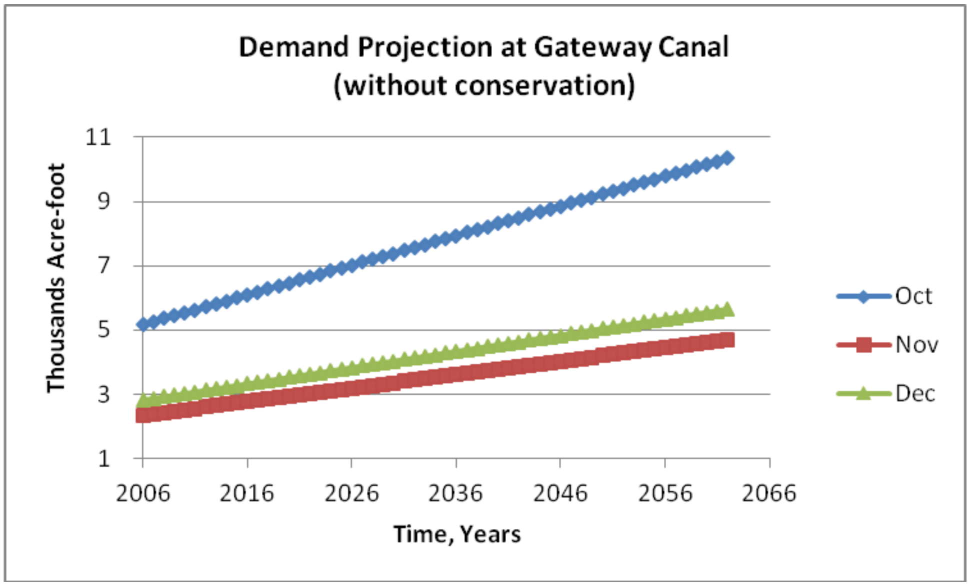


Figure 12. Demand projection at Gateway Canal for three months (without conservation).

representing various storage carryover policies were tested to anyze their impacts on shortages in the Weber River Basin.

WEAP WB Model with conservation (with growth)

WEAP WB Model with conservation (with growth) takes into account conservation measures projected into the future in addition to population growth.

In Utah, there is wide attention to the application of conservation to save water. Water conservation will play an important role in satisfying future water needs in the Weber River Basin by reducing future water demands as well as the costs associated with additional water development (Utah Division of Water Resources, 2009). The state's goal is to reduce the 2000 per capita water demand by at least 25 percent before 2050 (Utah Division of Water Resources, 2009). For this project, it will be assumed that the 2006 per capita water demand at the Gateway Canal will be reduced by 25 percent by the year 2062. This assumption is in line with the state's goal but it also fits the span of the WEAP WB Model (with growth).

In WEAP, this scenario was implementated by assuming a water consumption rate of 295 gallons per day in 2006 and reducing it to a level of 221 gallons per day by 2062. This was combined with the popluation growth projection discussed in the preceding section. Annual water consuption was then calculated and distributed across the months of the year by using factors which have been adopted from the GRES Model (Table 8).

Table 8. Water demand calculations at Gateway Canal (with and without conservation and population growth)

Year	Population	Without Conservation		With Conservation	
		Per Capita Use (gal/cap/d)	Annual Use (Ac-ft/yr)	Per Capita Use (gal/cap/d)	Annual Use (Ac-ft/yr)
2006	284,467	295	94,000	295	94,000
2010	304,786	295	100,714	290	98,916
2015	330,185	295	109,107	283	104,723
2020	355,584	295	117,500	277	110,156
2025	380,983	295	125,893	270	115,214
2030	406,382	295	134,286	263	119,898
2035	431,780	295	142,679	257	124,207
2040	457,179	295	151,071	250	128,141
2045	482,578	295	159,464	244	131,700
2050	507,977	295	167,857	237	134,885
2055	533,376	295	176,250	230	137,695
2060	558,775	295	184,643	224	140,131
2061	563,854	295	186,321	223	140,573
2062	568,934	295	188,000	221	141,000

RESULTS

WEAP WB Model (Historical Scenario)

Historically the Weber River Basin has not been using storage carryover. However, it can be informative to look back and see how the system would have responded to storage carryover.

Shortages

WEAP WB Model successfully replicates the GRES Model when it comes to the shortages created in the Weber River Basin. In both models, Service Area 12 experiences shortages. Using different values of buffer coefficient creates different levels of shortages at the same service area (Figure 13).

System performance

The reliability, resilience, and vulnerability of the system (Weber River Basin) corresponding to each storage carryover policy as represented by a buffer coefficient are given in Figure 14. The system's vulnerability decreases as more storage volume is carried over. On the other hand, the system's resilience increases with carryover storage up to about 50 percent carryover storage. At larger carryover storage volumes, resilience decreases. The system's reliability falls gradually as percentage of storage carryover increases.

End-of-month storages at reservoirs

The end-of-month storages at most reservoirs show that, most do not reach their buffer zone. The Echo reservoir is an exception because it does not have a buffer zone. This explains why there were not many shortages in the Basin. The only reservoir that

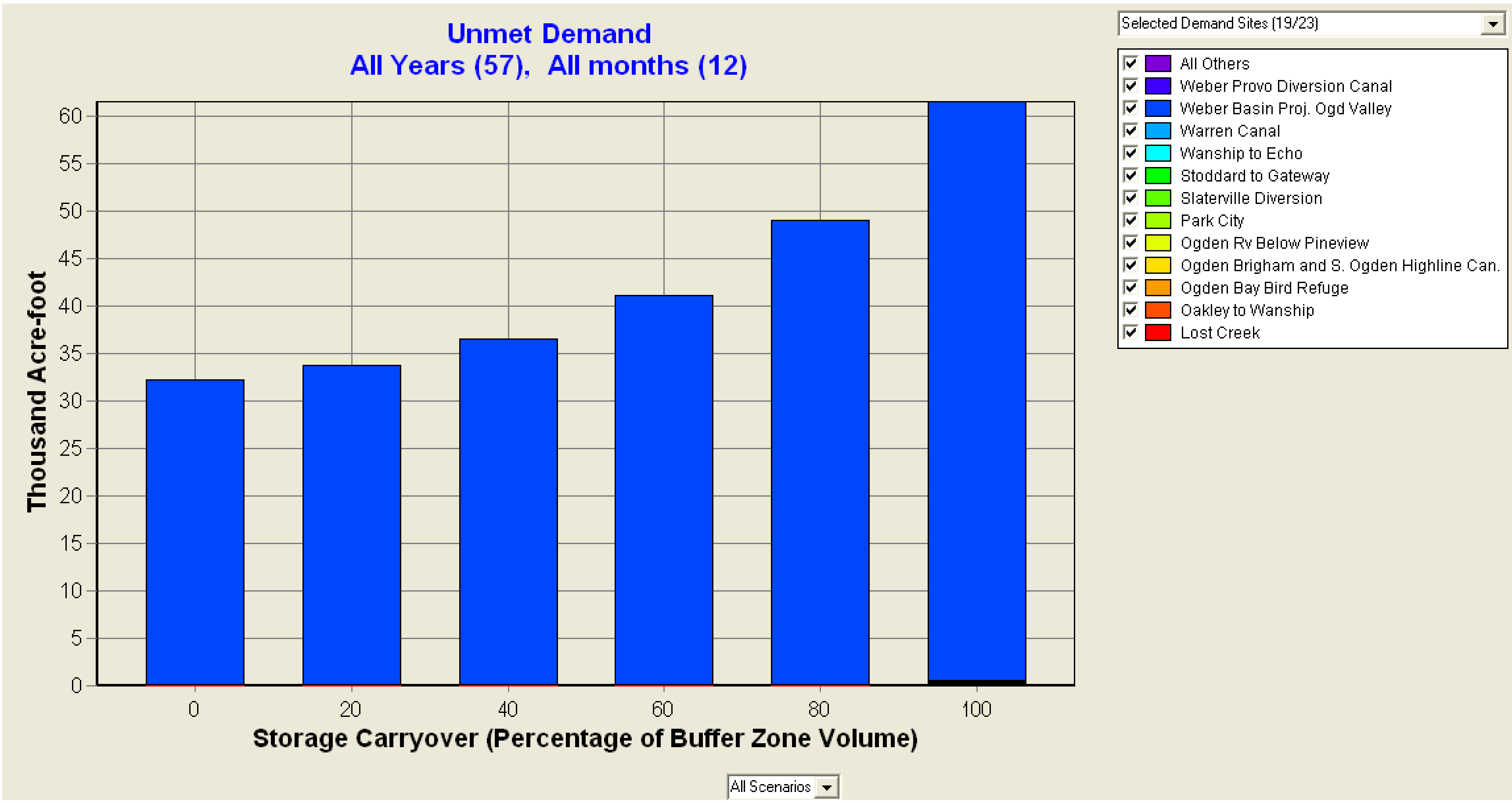


Figure 13. Total shortages versus buffer coefficient.

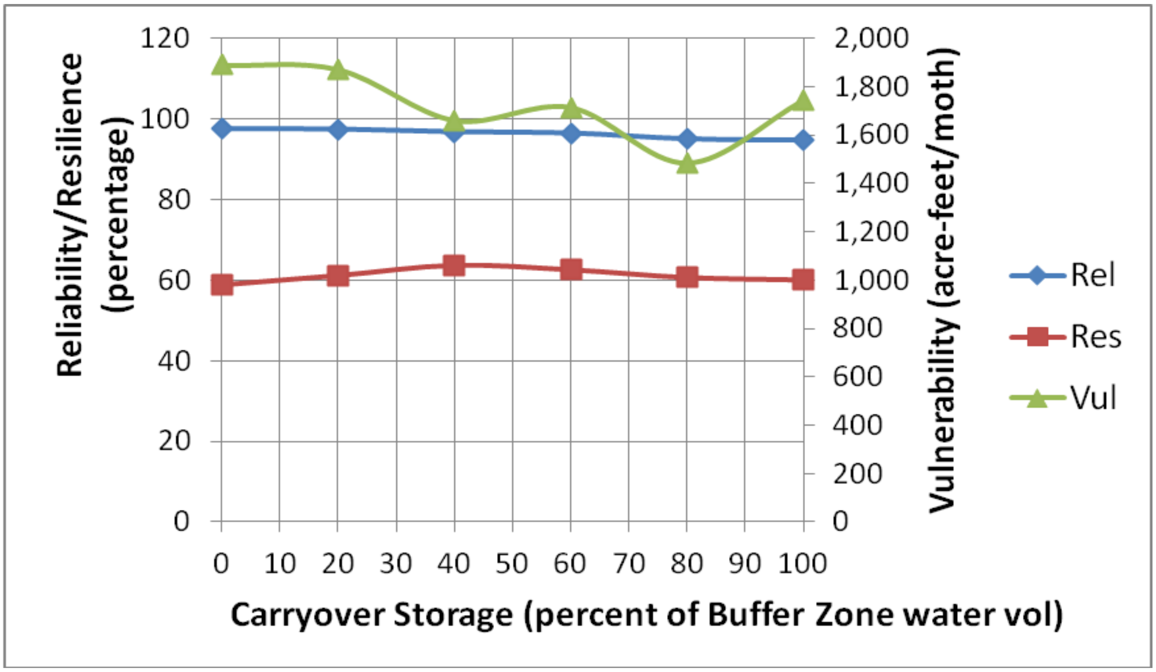


Figure 14. Reliability, resilience, and vulnerability (historical scenario).

reaches its buffer zone when operated under a buffer coefficient of 1.0 is the Causey Reservoir (see Figure 15). The top of the buffer zone has also been indicated by a dotted line.

WEAP WB Model without Conservation (with growth)

The following results show how the system would respond to various storage carryover policies.

Shortages

When a growth scenario at Gateway Canal is implemented, many service areas experience shortages in addition to Service Area 12, which has already experienced shortage in the historical simulation. The total shortages created in the Basin when using different storage carryover are noted and plotted in Figure 16. The biggest shortages occur at David Weber Canal, the Gateway Canal and the Weber Basin Project Ogden

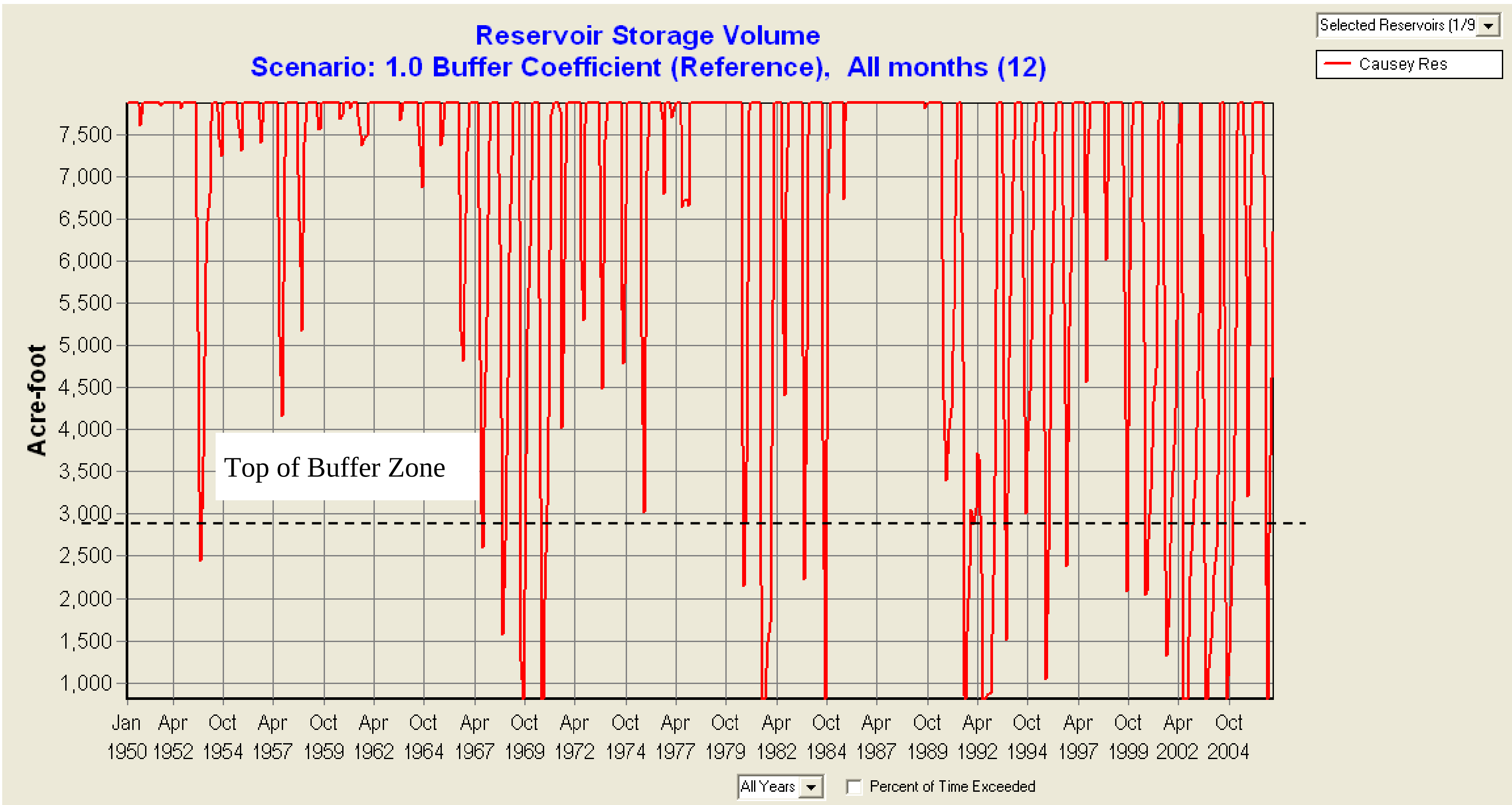


Figure 15. Draw down of Causey Reservoir to its buffer zone.

Valley. The main driver for the shortages is population growth. However, the fact that some service areas experience greater shortages compared to others has to do with the availability of water upstream of each service area. Hence, service areas situated higher in the Basin and with relatively bigger demands are likely to experience shortages. On the other hand, service areas situated at the bottom of the Basin are less likely to experience shortages since there is a huge water reserve at Willard Bay. In this Basin service areas that have lower priority happen to be situated at the bottom of the Basin. Hence, lower priority is counteracted with increased water availability at the bottom of the Basin.

System performance

The reliability, resilience, and vulnerability of the system (Weber River Basin) corresponding to each storage carryover policy as represented by a buffer coefficient are summarized in Figure 17. The result show that reliability declines linearly as carryover storage increases. Vulnerability and resiliency do not follow any consistent pattern. The system's vulnerability falls initially as carryover storage increases and increases beyond a carryover storage of 40 percent. The system's resilience peaks at around 60 percent of carryover storage.

End-of-month storages

As would be expected, the reservoirs do draw from their buffer zone when a growth scenario is considered. The artificially generated inflow seems to have a period of low flow around the 2030s which can be deduced by looking into end-of-month storage for all reservoirs which show sag in that period (Figure 18). These low flows show that in the long run and particularly when drought strikes, the system's water is likely to be stressed and carryover storage may play important role in managing the scarce water resource.

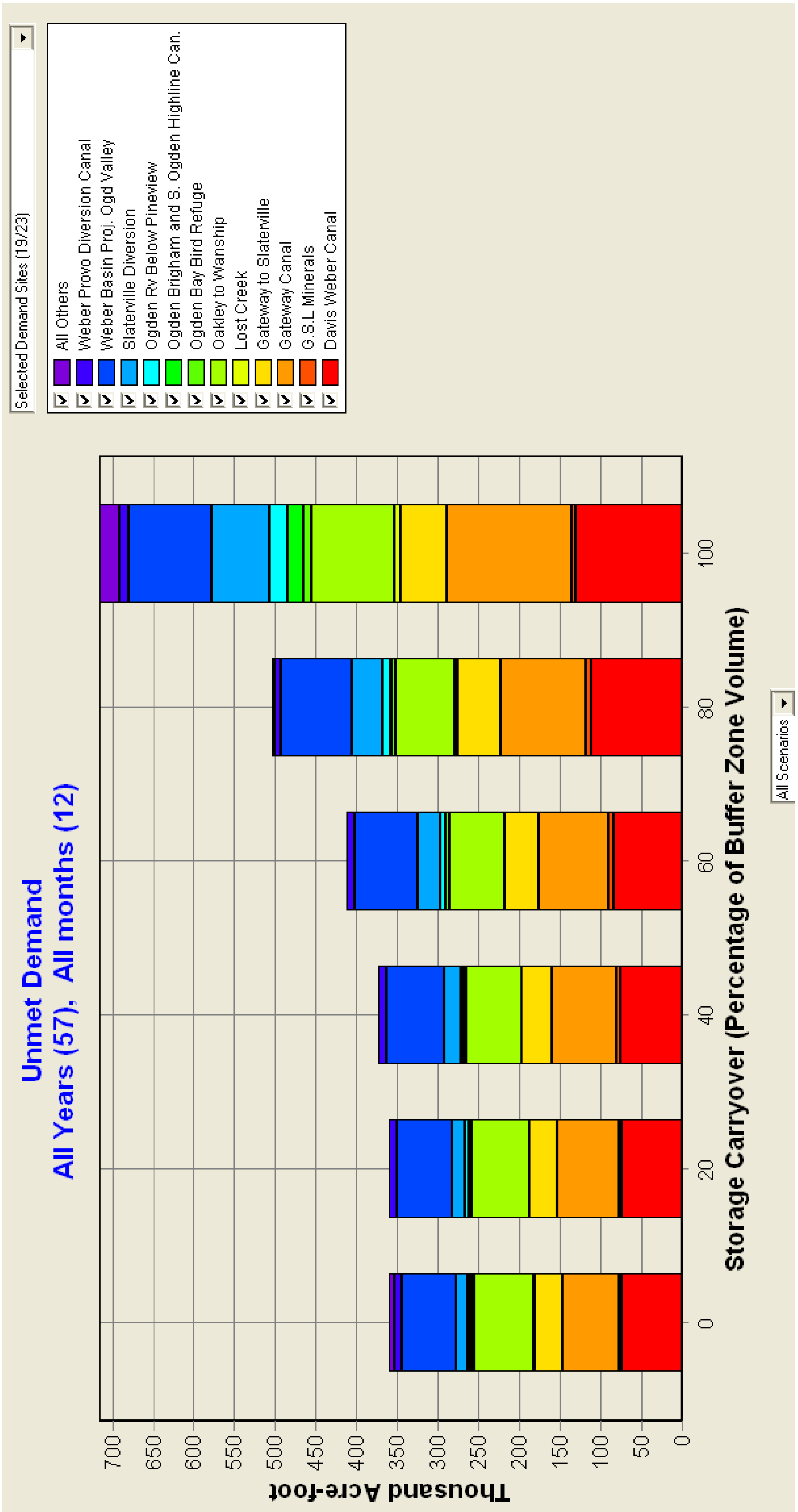


Figure 16. Total shortage versus buffer coefficient (WEAP WB Model without Conservation).

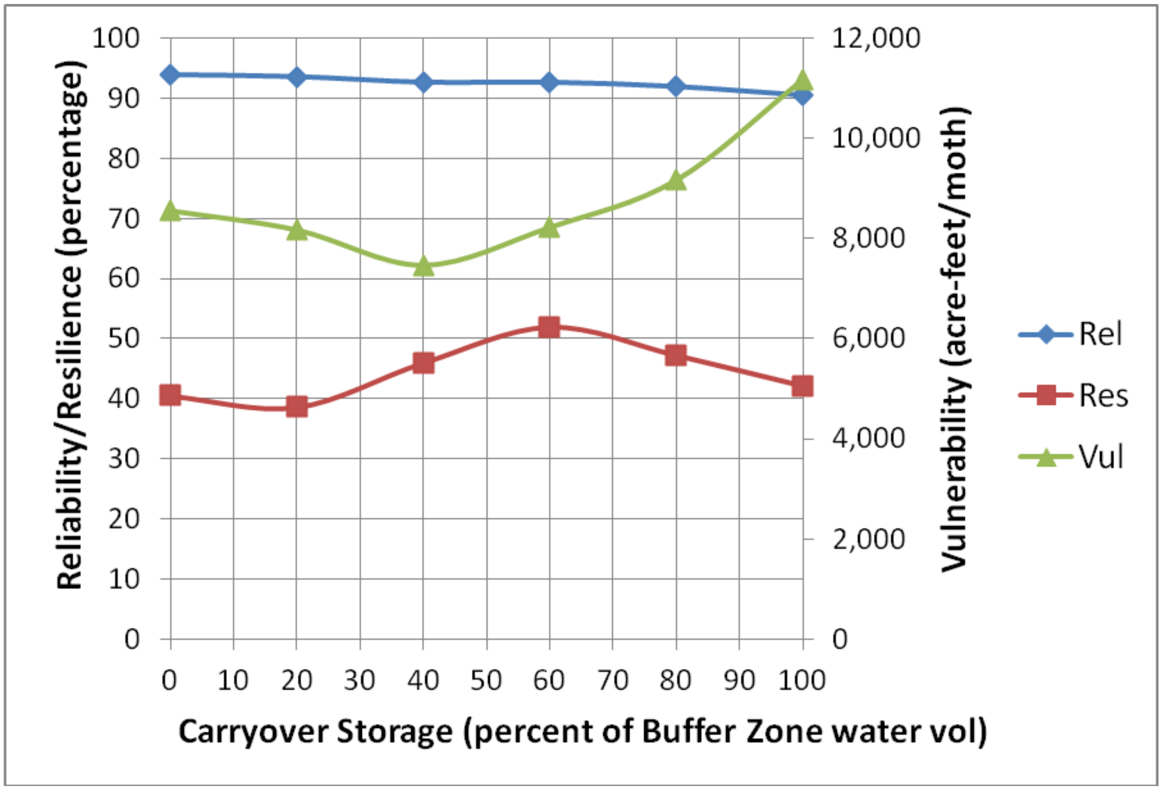


Figure 17. Reliability, resilience, and vulnerability.

<u>WEAP WB Model with Conservation (with growth)</u>

The results for this scenario are similar to the results described for the WEAP WB Model without conservation. The major distinction lies in the availability of more water because of conservation under this scenario. Hence, this scenario has fewer shortages and an overall better system performance.

<u>Shortages</u>

The system's response, in terms of shortages, to various storage carryover policies is shown in Figure 19. As with the scenario without conservation, the same service areas experience major shortages. However, the total shortages for each carryover storage for this scenario are smaller compared to the preceding scenario. For example, when all the

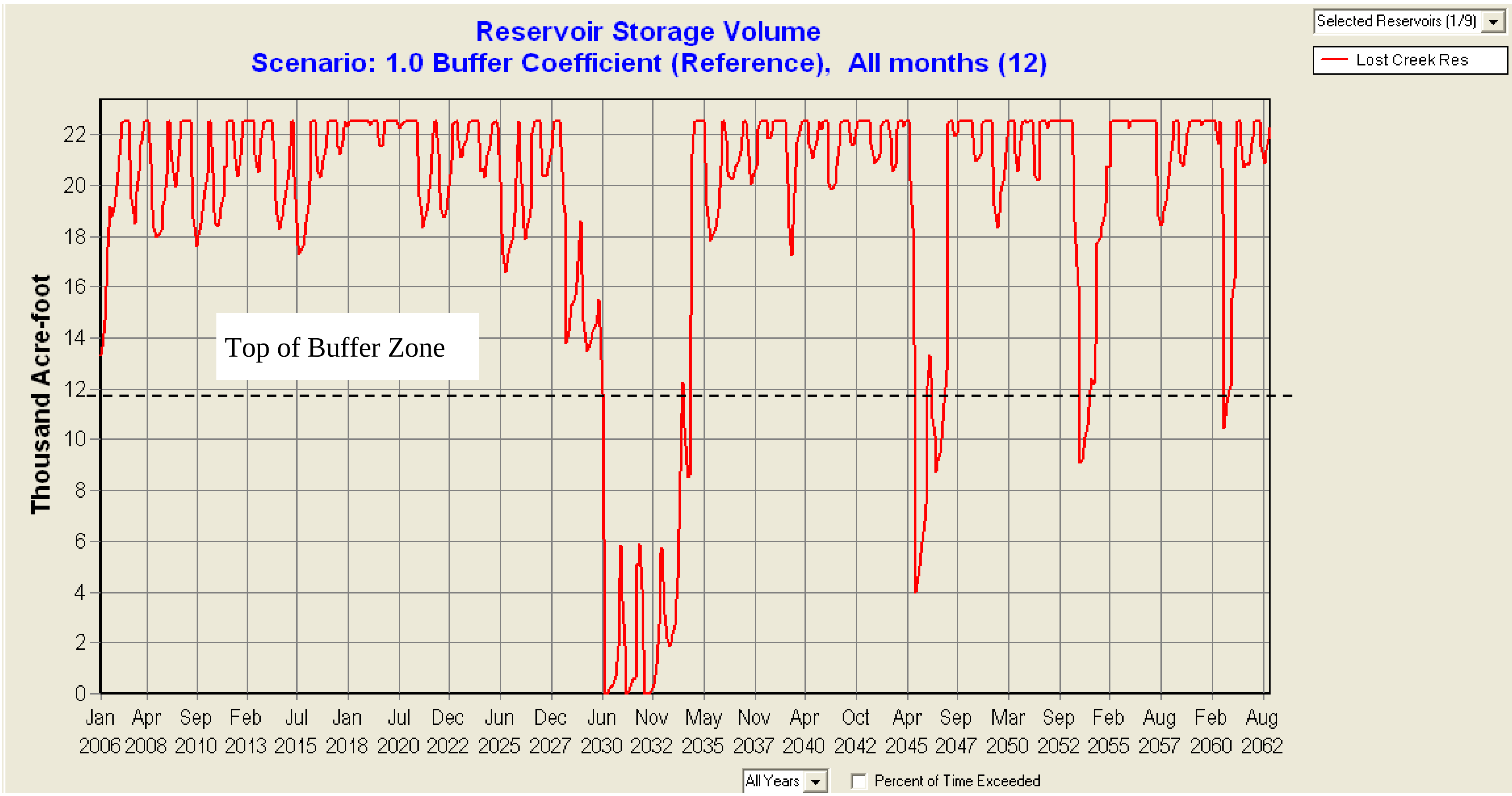


Figure 18. Draw down of the Lost Creek Reservoir to its buffer zone (WEAP WB Model-with growth).

water in the buffer zone is carried over, the total basin wide shortage is less than 600 thousand acre-foot compared to a shortage of above 700 thousand acre-foot for the scenario without conservation. Obviously, these differences arise due to the saved water because of conservation measures.

System performance and end-of-month storages

The results for the system performance (resilience, reliability and vulnerability) and the end-of-month storages (for the reservoirs) are also similar to the results presented in the above section and are not presented. In general, due to the conservation measures, this model incurs fewer shortages in the system compared to the comparable model that does not apply conservation and better system performance.

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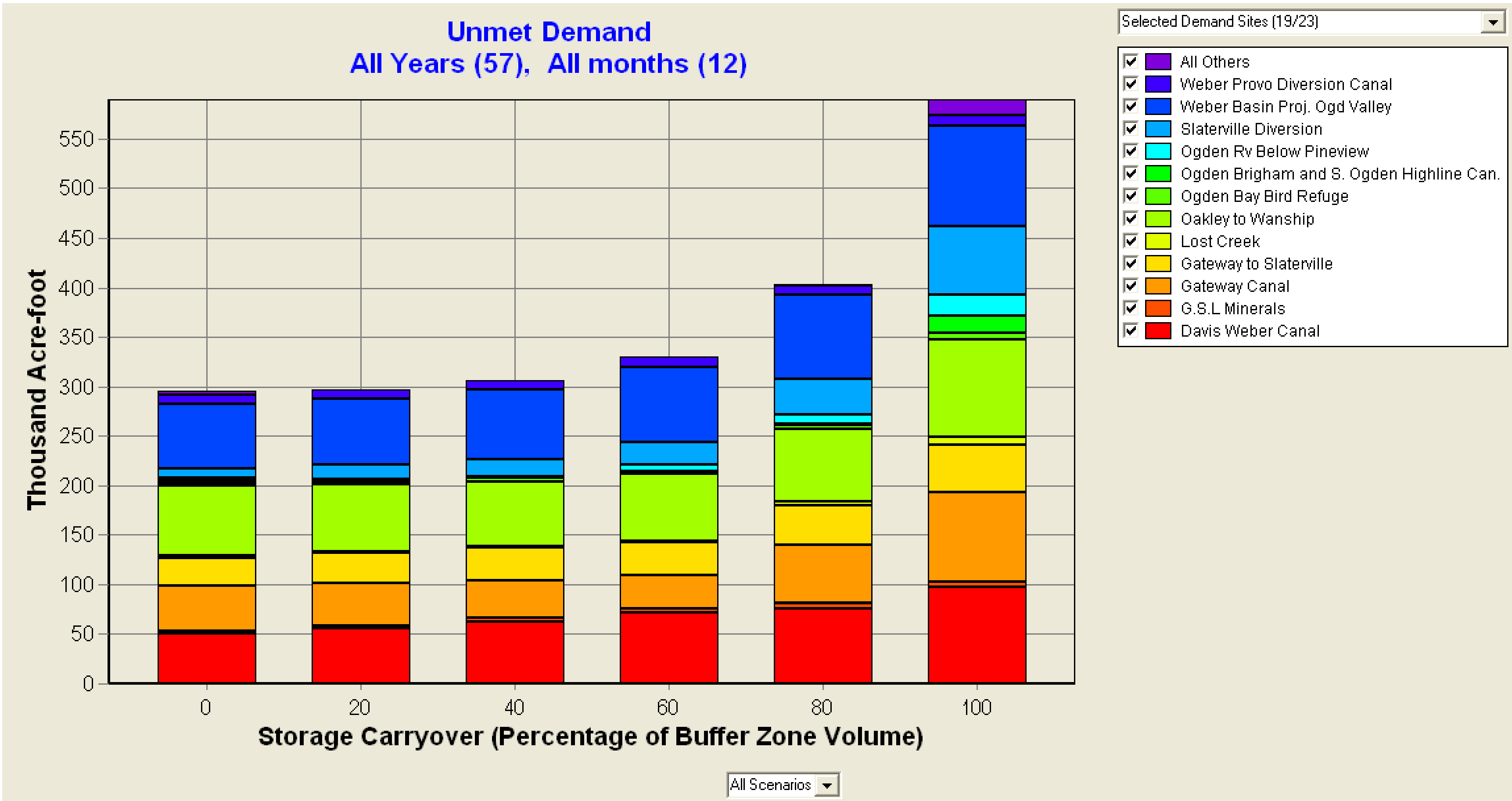

Figure 19. Total shortages versus buffer coefficient (WEAP WB Model-with growth).

DISCUSSION

We know that the mangers of the Weber River Basin have not been using storage carryover in the past. The WEAP WB Model (the historical model) shows that most reservoirs do not reach their buffer level except for Causey Reservoir. Hence, the Weber River Basin had sufficient water to meet past demands. However, shortages could arise in the future with population growth.

Using different storage carryover policies meant that different shortage levels are incurred in the system. If a reservoir is operated near its buffer zone, then shortages are likely to occur as was the case with Causey Reservoir and Service Area 12, which is located immediately downstream from the reservoir. The results show that the more storage is carried over from one month to the next the more shortages occur.

In WEAP WB Model (with growth) it was shown that all of the reservoirs in the Basin do reach their buffer zone around 2030s. Several service areas particularly those that are situated upstream in the Basin and have relatively large demand, seem to experience more shortages because they have fewer reservoirs to draw from. Service areas at the bottom of the Basin are less likely to experience shortages since there are more reservoirs they can draw from but also because there is water reserve at the Willard Reservoir.

In the WEAP WB Model (with growth) that incorporates conservation measures, results similar to the WEAP WB Model without conservation discussed above were observed with one major difference. The impact (total shortages) of the various storage carryover policies on the system was lesser compared to the model with no conservation.

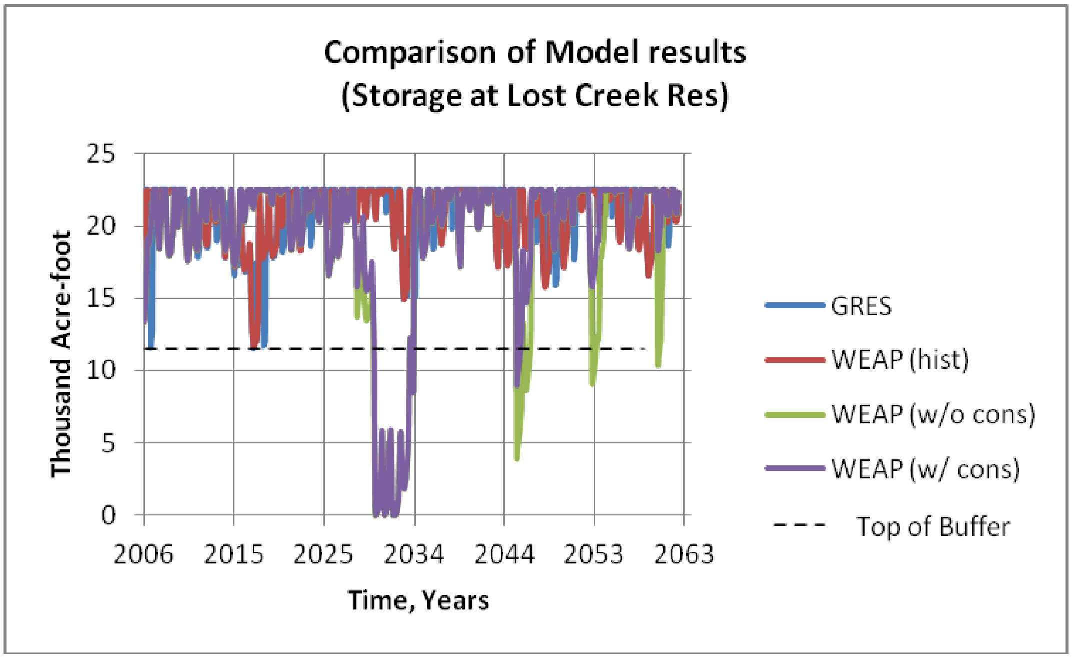

Figure 20. Comparison of results across all simulated models for storage at Lost Creek Reservoir.

Figure 20 shows how the historical storage at Lost Creek Reservoir compares to two growth scenarios: with and without conservation. The horizontal dotted line shows the location of the top of buffer zone for the Lost Creek Reservoir. This shows that historically the reservoir had met demands without encroaching the buffer zone of the reservoir; however, it will start to draw from the buffer zone as population grows. It also indicates that there is less draw down from the buffer zone of the reservoir when conservation measures are adopted.

In general, carrying over storage between time steps decreases the reliability of the system while increasing its resilience. In all the WEAP WB Models, the historical and the two scenarios with growth, considered above, vulnerability does not show any consistent results. However, it does seem that it decreases in certain storage carryover polices. The system performance plots show that there is a trade off involved between the three performance criteria considered in this project.

The merit of storage carryover comes when one anticipates drought conditions, which are as yet difficult to predict. This project has shown how to represent storage carryover in the Weber Basin using WEAP. Most of the data and logic on the GRES Model have successfully been transferred to the WEAP WB Model. However, there were some rules of the Basin that could not be represented in the WEAP WB Model.

One of the main problems that was not successfully represented in the WEAP WB Model has to do with protected storages. For example, the Davis Weber Canal (one of the service areas in the system) has protected storages of 28,800 and 31,000 acre-foot in East Canyon and Echo Reservoir respectively. However, the service area must draw water from the river first and if its demand is not fully met then it could call from its protected storages. In all the WEAP WB Models, these sources (East Canyon and Echo Reservoirs) are represented by drawing three transmission links to the service area: one from the river and two from the reservoirs. The link connected to the river takes a supply preference of 1 (highest) while the other links take a supply preference of 2. The results show that no water is flowing through the links with lower supply preference. If there is any water in the reservoirs, the link with highest preference can still convey it and there is no need for the WEAP model to use the other two links with lower supply preference. This issue remains unresolved.

CONCLUSION

WEAP can successfully be used to represent water basins such as the Weber River Basin. It is flexible and allows to enter available data in different formats. One of its main powers is its ability to view different useful results such shortages in sevice areas, end-of-month storage, and evaporation at a given reservoir. The other merit which WEAP has is that it enables simulating different storage carryover policies by specifiying the corresponding buffer coefficients.

Initially two competing WEAP Models were considered. The two models were named as Demand Priority Model (DPM) and Supply Preference Model (SPM). The two models differ in the approach used to transfer water from the sources to the service areas. However, it was shown the two turn out to be identical and the DPM which was the simplest WEAP representation of the GRES Model was adopted as the WEAP WB Model. Most of the GRES Model logic and data were successfully transferred to the WEAP WB Model and hence most of the corresponding results from these two models are comparable. However, there was one particular area, namely, protected storage which was not successfully represented in WEAP. This problem probably is the cause for some observed discrepancies between the GRES Model and the WEAP WB Model. Nonetheless, it is believed that the WEAP WB Model provides a working representation of the GRES Model and hence was used to create two other future scenarios with the purpose of testing various storage carryover policies and analyzing their impacts.

The WEAP WB Model (the historical scenario) show that the historical status of the Weber River Basin seems very satisfactory in terms of water quantity with few and negligible shortages in one service area (Weber Basin Project, Ogden Valley). Weber

Basin Project, Ogden Valley is located downstream of the smallest reservoir in the Basin which is why it is vulnerable to shortages. All other service areas have had no shortages. Experimenting with storage carryover policies on the historical scenario show that there is no or little impact due to the fact that most of the reservoirs did not reach their buffer zone.

The WEAP WB Model without conservation (with growth) shows that with the current infrastructure in the Basin, the Basin is likely to experience shortages in several service areas.

The WEAP WB Model with conservation (with growth) shows similar results to WEAP WB Model without conservation except in this case the shortages are smaller because of the increased availability of water due to conservation measures.

In general, carrying over storage between time steps decreases the reliability of the system while increasing its resilience. In all the WEAP WB Models, the historical and the two scenarios with growth, considered above, vulnerability does not show any consistent results. However, it does seem that it decreases in certain storage carryover polices. The system performance plots show that there is a trade off involved between the three performance criteria considered in this project.

The merit of storage carryover comes when one anticipates drought conditions, which are as yet difficult to predict. However, in the presence of a drought optimization model, the relationship between shortages and different storage carryover policies can be used as some sort of input into such a model.

The relationship obtained between different storage carryover policies and total shortages incurred may be used in a drought optimization model to arrive at a storage carryover for the Weber Basin. Although there does not seem to be a definite relaltionship between storage carryover policies and the various system performance criteria, the trade-off for carryover storage between time steps may be found in the increased system resiliency. In the context of WEAP simulations, it may be dificult to determine a storage carryover policy since future water supply and demand are uncertain.

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APPENDICES

Appendix-A

Storage capacity and initial storage

Table A 1. Storage capacity and initial storage for the reservoirs on Weber River Basin

Reservoir	Storage Capacity (Thousand AF)	Initial Storage (Thousand AF)
Smith and More house	8.35	4
Wanship (Rockport)	62.120	32
Echo	73.94	37
Lost Creek	22.51	11
East Canyon	51.2	25
Causey	7.87	3.9
Pineview	110.15	60
Willard	215.1	110

Appendix-B

Volume-elevation curve

Smith and Morehouse Reservoir

Table B 1. Elevation, area, and capacity information for Smith and Morehouse Reservoir

Elevation, ft	Area, Acre	Capacity, Acre Feet
7620	0	0
7639.6	85	600
7650	129	1700
7660	152	3400
7670	171	5300
7680	188	7000
7690	203	8350
7700	220	9600

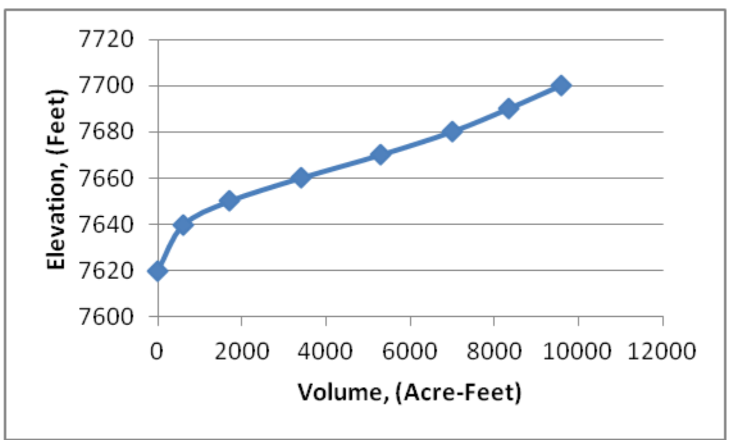

Figure B 1. Volume-elevation curve for Smith and Morehouse Reservoir.

Wanship (Rockport) Reservoir

Table B 2. Elevation, area, and capacity information for Wanship (Rockport) Reservoir

Elevation, ft	Area, Acre	Capacity, Acre Feet
5930	121	1260
5940	192	2840
5950	265	5100
5960	358	8280
5970	446	12290
5980	528	17160
5990	608	22830
6000	708	29410
6010	795	36920
6020	897	45390
6030	1000	54860
6040	1107	65400

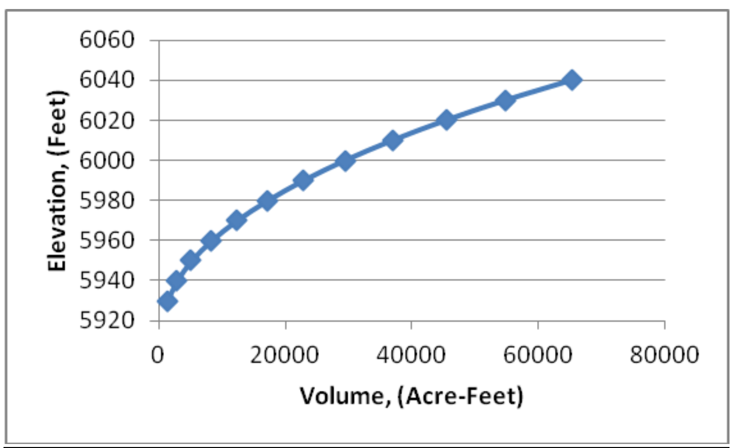

Figure B 2. Volume-elevation curve for Wanship (Rockport) Reservoir.

<u>Echo Reservoir</u>

Table B 3. Elevation, area, and capacity information for Echo Reservoir

Elevation, ft	Area, Acre	Capacity, Acre Feet
5450	0	0
5460	50	153
5470	125	894
5480	270	3060
5490	425	6730
5500	580	11830
5510	720	18480
5520	865	26620
5530	1010	36100
5540	1155	47200
5550	1305	59880
5560	1455	73940

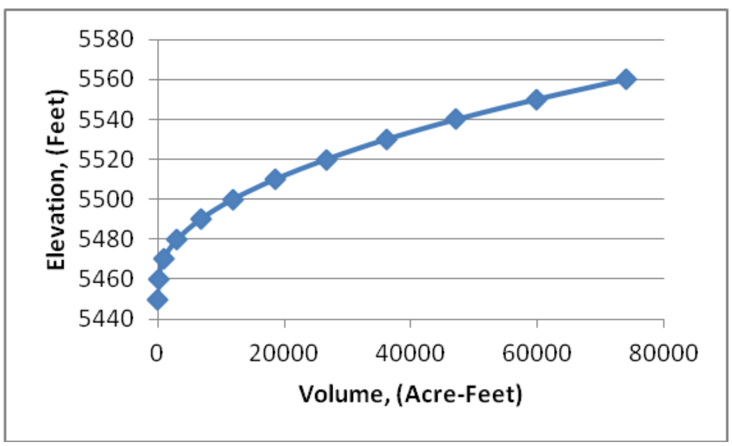

Figure B 3. Volume-elevation curve for Echo Reservoir.

<u>Lost Creek Reservoir</u>

Table B 4. Elevation, area, and capacity information for Lost Creek Reservoir

Elevation, ft	Area, Acre	Capacity, Acre Feet
5837	1	1
5840	2	5
5850	7	48
5860	13	146
5870	21	320
5880	32	586
5890	47	976
5900	66	1530
5910	89	2290
5920	110	3290
5930	130	4490
5940	154	5910
5950	178	7550
5960	211	9490
5970	242	11760
5980	280	14410
5990	316	17390
6000	351	20720
6010	390	24390
6020	427	28490

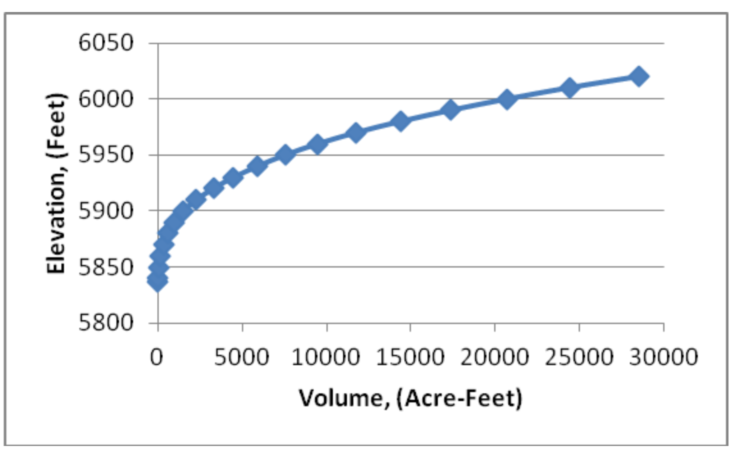

Figure B 4. Volume-elevation curve for Lost Creek Reservoir.

East Canyon Reservoir

Table B 5. Elevation, area, and capacity information for East Canyon Reservoir

Elevation, ft	Area, Acre	Capacity, Acre Feet
5523	1	1
5530	7	23
5540	28	187
5550	55	605
5560	82	1290
5570	110	2260
5580	134	3490
5590	165	4980
5600	205	6820
5610	239	9040
5620	278	11620
5630	319	14600
5640	356	17980
5650	399	21750
5660	444	25960
5670	493	30640
5680	544	35820
5690	602	41560
5700	656	47850
5710	715	54700
5720	781	62170

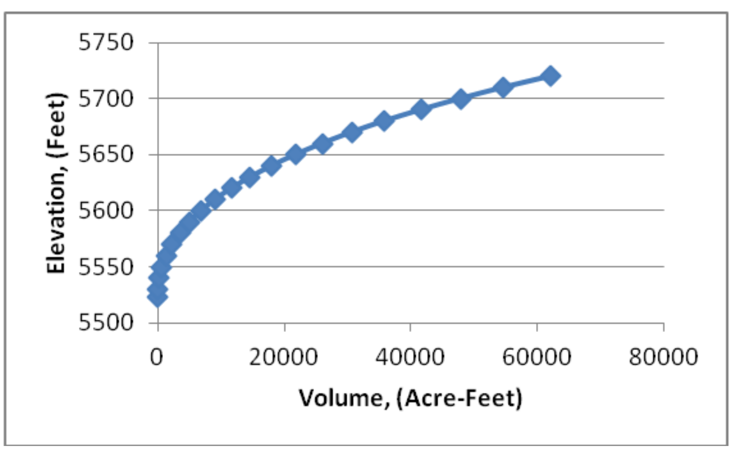

Figure B 5. Volume-elevation curve for East Canyon Reservoir.

Causey Reservoir

Table B 6. Elevation, area, and capacity information for Causey Reservoir

Elevation, ft	Area, Acre	Capacity, Acre Feet
5514	0	0
5520	0	2
5530	1	7
5540	1	16
5550	3	39
5560	7	93
5570	11	183
5580	17	320
5590	22	512
5600	31	774
5610	36	1110
5620	48	1530
5630	52	2030
5640	70	2640
5650	76	3370
5660	94	4220
5670	105	5210
5680	121	6340
5690	130	7600
5692	136	7870
5700	149	9010
5710	161	10560

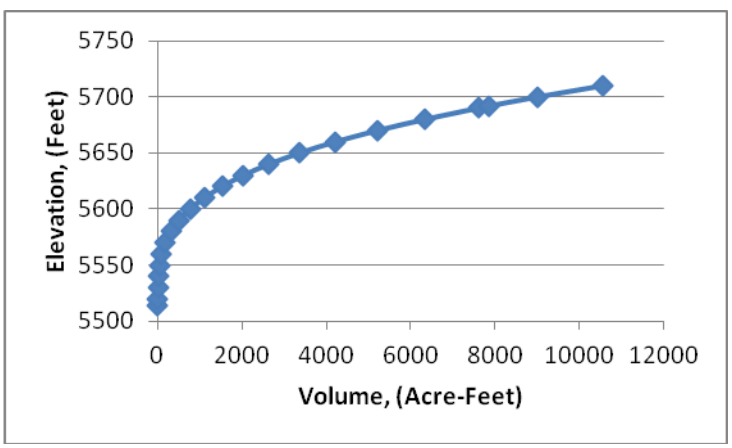

Figure B 6. Volume-elevation curve for Causey Reservoir.

Pineview Reservoir

Table B 7. Elevation, area, and capacity information for Pineview Reservoir

Elevation, ft	Area, Acre	Capacity, Acre Feet
4818	0	0
4820	13	13
4830	326	1380
4840	630	6150
4850	970	14060
4860	1329	25480
4870	1710	40680
4880	2092	59670
4890	2538	82820
4900	2874	110150

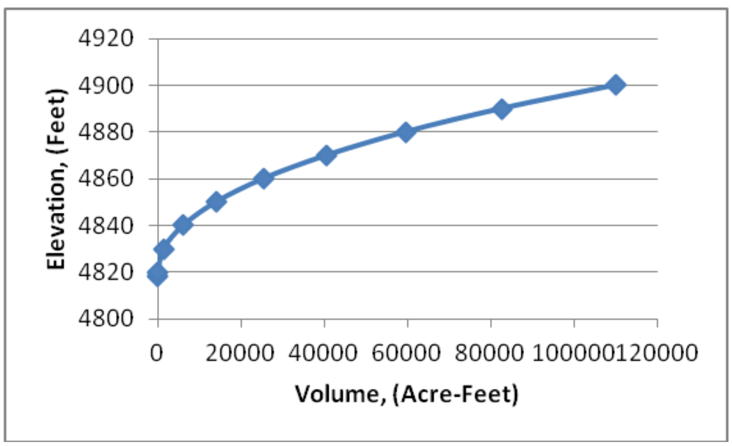

Figure B 7. Volume-elevation curve for Pineview Reservoir.

Willard Bay

Table B 8. Elevation, area, and capacity information for Willard Reservoir

Elevation, ft	Area, Acre	Capacity, Acre Feet
4200	261	6
4201	1060	610
4202	2210	2200
4203	4200	5440
4204	6080	10590
4205	6540	16850
4206	8000	23990
4207	8490	32250
4208	8830	40910
4209	9080	49870
4210	9270	59050
4211	9390	68380
4212	9490	77820
4213	9580	87360
4214	9660	96980
4215	9720	106670
4216	9760	116410
4217	9790	126180
4218	9810	135990
4219	9840	145810
4220	9860	155660
4221	9880	165530
4222	9900	175420
4223	9920	185330
4224	9930	195250
4225	9940	205180
4226	9950	215120

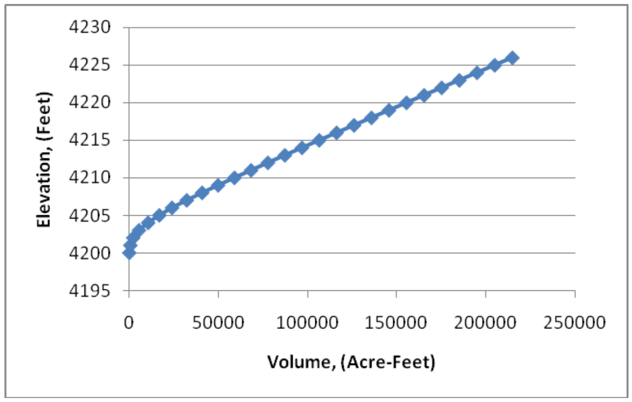

Figure B 8. Volume-elevation curve for Willard Reservoir.

Appendix-C

Monthly net evaporation

Smith and Morehouse Reservoir

Table C 1. Monthly evaporation at Smith and Morehouse Reservoir

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evaporation, ft	0	0	0	0	0.14	0.32	0.48	0.42	0.2	0.04	0	0

Wanship (Rockport) Reservoir

Table C 2. Monthly evaporation at Wanship Reservoir

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evaporation, ft	0	0	0	0.06	0.2	0.39	0.58	0.51	0.27	0.09	0	0

Echo Reservoir

Table C 3. Monthly evaporation at Echo Reservoir

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evaporation, ft	0	0	0	0.06	0.2	0.39	0.59	0.51	0.27	0.09	0	0

Lost Creek Reservoir

Table C 4. Monthly evaporation at Lost Creek Reservoir

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evaporation, ft	0	0	0	0.06	0.2	0.39	0.59	0.51	0.27	0.09	0	0

East Canyon Reservoir

Table C 5. Monthly evaporation at East Canyon Reservoir

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evaporation, ft	0	0	0	0.06	0.2	0.39	0.59	0.51	0.27	0.09	0	0

Causey Reservoir

Table C 6. Monthly evaporation at Causey Reservoir

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evaporation, ft	0	0	0	0.06	0.2	0.39	0.59	0.51	0.27	0.09	0	0

Pineview Reservoir

Table C 7. Monthly evaporation at Pineview Reservoir

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evaporation, ft	0	0	0	0.06	0.2	0.39	0.59	0.51	0.27	0.09	0	0

Willard Reservoir

Table C 8. Monthly evaporation at Willard Reservoir

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evaporation, ft	0	0	0.02	0.15	0.33	0.55	0.81	0.7	0.41	0.18	0	0