Performance Evaluation of the Bear River Canal Company (BRCC) to meet the irrigation demand of Box Elder County under different scenarios.

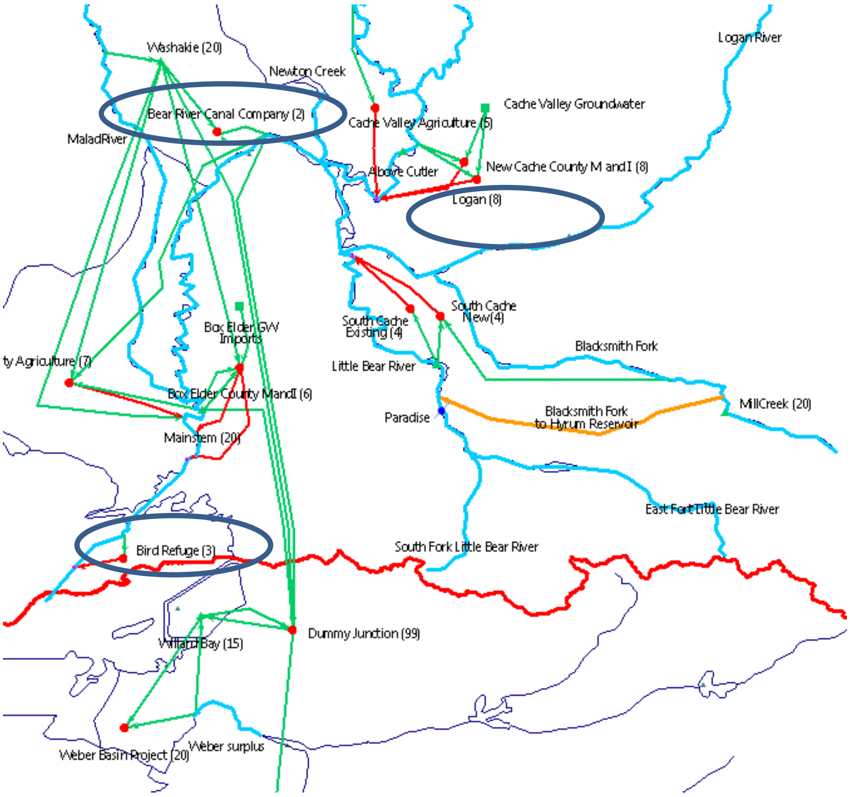

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Table of Content:

LIST OF TABLE

LIST OF FIGURE:

Acknowledgement:

We would like to thank Dr. David Rosenberg for providing a wonderful opportunity to work in WEAP (Water Evaluation and Planning) model and providing thoughtful insights regarding every aspect of the project. Sincere thanks goes to Mr. Charles Holmgren, President of BRCC for providing information and field data for this project. This project work provided us the baseline to understand the water management and planning in real case scenario (Bear River Canal Company) BRCC by the use of WEAP model. WEAP is a software that simulates the historical flows and demands for a number of demand sites and scenarios under the control of reservoir operation and thus, evaluates the performance of different stakeholders. This final report is the outcome of a group project on class CEE 6490. We had two members in our group namely Sal and Muhammad Rezaul. Both have contributed an equal effort for the project work regarding data collection, calculation, developing WEAP model and preparation of the final report.

Abstract:

Water demand is higher in the months of May to September (irrigation season) compared to the rest of the months in Box Elder County. From October to April, water is diverted mostly for animal live stocks and for some incidental irrigation. Currently BRCC is facing shortage of irrigation water in the months of July to September which is responsible for reduced crop yield in Box Elder County, Utah, USA. Most of the crop grows actively in the months of May to September. Shortage of irrigation water in active growth stage can have detrimental impact on the crop yield. This report develops alternative management scenarios (including structural and non-structural measures) to reduce the amount of irrigation water shortage and thereby improve the performance of BRCC. CropWat (8.0) has been used to calculate field irrigation requirement (FIR) and Water Evaluation and Planning (WEAP) model has been developed for the Lower Bear River watershed to simulate water deliveries under historical flow conditions and different scenarios. Structural alternative made maximum improvement of the performance of stakeholders compared to non-structural options.

Keywords: Crop yield, Reliability, Resiliency, and Vulnerability, Hydropower production, CropWat, WEAP model.

1. Introduction:

BRCC is facing problems including loss of irrigation water through seepage and inefficient flooding irrigation system, and shortage of supply in July through September, which are responsible for reduction in crop yield.

This report has developed four scenarios (structural and non-structural) for BRCC in order to minimize the shortage of irrigation water especially in the month of July to September: i) Base scenario ii) Field Irrigation Requirement (FIR) iii) Modified planting date and iv) Above cutler reservoir scenarios. FIR Calculated based on the crop periods for the irrigation season has been considered as the water demand of BRCC for $2^{nd,}$ 3^{rd}, and 4^{th} scenarios. Demand data provided by Utah Division of Water Resources (UDWR, 2011) for the months from October to April has been considered as BRCC demand in $2^{nd,}$ 3^{rd}, and 4^{th} scenarios. Four stakeholders (BRCC, Bird Refuge, Logan city, and PacifiCrop) have been taken in the current analysis.

Utah Division of Water Resources provides Fortran model (UDWR, 2011) for the Lower Bear River. The water demand calculated by UDWR may differ from actual field demand. This report attempts to determine the FIR and find the differences between UDWR demand and FIR for BRCC.

Thus finally, this report evaluates the performance metrics (Reliability, Resiliency, and Vulnerability) of stakeholders BRCC, Bird Refuge, Logan city, and Hydropower production for PacifiCorp in base scenario and compares these with other scenarios.

2. Background:

According to United States Department of Agriculture (USDA, 2015), agriculture is a major user of ground and surface water in the United States, accounting for approximately 80 percent of the Nation's consumptive water use and over 90 percent in many Western States.

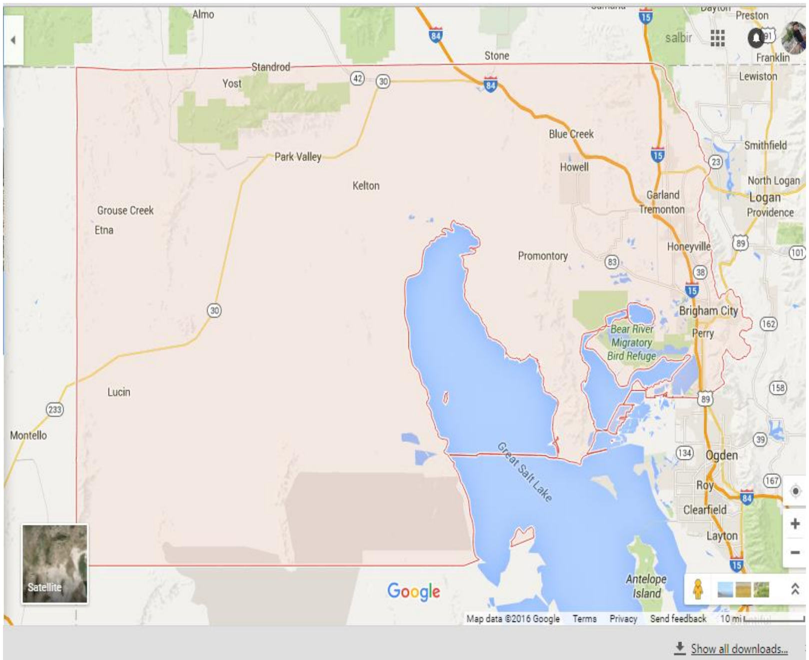

Figure 1: Map showing area under Box Elder County (red marked).

The Bear River covers an area of about 7,600 square miles in Utah, Idaho and Wyoming. Box Elder County is located in the northwest corner of Utah and is bordered by the states of Idaho and Nevada. The eastern part of the county is where the majority of the population is located and where the bulk of the irrigated farmland lies. BRCC servers about 66,000 acres (60%) out of 110,000 acres of irrigated land in Box Elder County (Holmgren et al., 2012). The remaining 40% of irrigated land is covered by Pine View Reservoir and Deep wells.

Box Elder County (see figure 1) lies in one of the primary agricultural production regions in the state. The majority of the irrigated and dry land farming is done in the eastern half of the county. Irrigated land consists mostly of wheat, corn, alfalfa, pasture, barley and onions. The command areas under corn increased primarily due to better prices and yields whereas that under barley and onion have notably decreased in recent years. The soil type in Box Elder County is clay.

Water demand is higher in irrigation season compared to the rest of the months of a year in Box Elder County. From October to April, water is diverted mostly for animal live stocks and for some incidental irrigation.

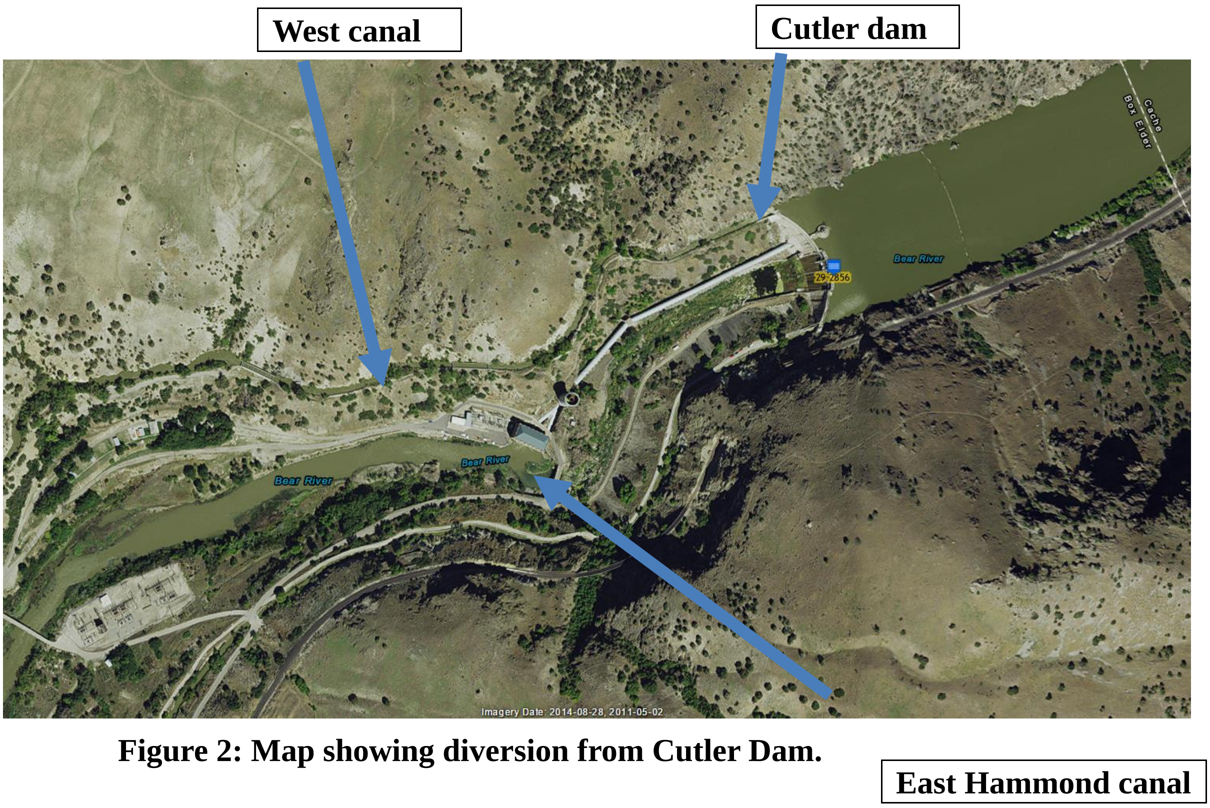

Figure 2: Map showing diversion from Cutler Dam.

The most senior (highest priority-2) water rights holder in the Bear River basin is the BRCC which diverts irrigation water from the Cutler Reservoir (figure 2) through two canal (East Hammond and West Canals) systems. 90% of the canal under BRCC is unlined. The total length of both canals is 120 miles. The total water rights for BRCC is 900 cfs (Utah Division of Water Rights, 2016) in irrigation season and 150 cfs for the rest of the year. The water rights for East Hammond and West Canlas are 160 and 740 cfs, respectively during irrigation season. The most senior water right for BRCC is 29-2856 which accounts for 333 cfs. There are several other water rights of BRCC namely 29-2857, 29-2858, and 29-3321.

3. Current problem(s):

BRCC faces some problems as stated below:

(i) Significant loss of irrigation water due to seepage through the unlined canal system.

(ii) Irrigation water is applied to the fields by flooding method which results in loss of irrigation water.

(iii) There is shortage of irrigation water supply in the months of July to September which reduces crop yield.

4. Objectives of the Study:

This study aims to reduce the BRCC irrigation demand in shortage period (July to September) and thus, increase the performance of BRCC. The specific objectives of this report are as follows:

(i) Evaluation of the performance of BRCC to meet the irrigation demand (calculated by Utah Division of Water Resources) of Box Elder County.

(ii) Development of scenarios to improve the performance of BRCC to meet the irrigation demand.

(iii) Comparison of performance of four stakeholders in the Bear River Basin under different scenarios.

5. Results of Institutional Analysis:

We performed Institutional analysis for Irrigation in Box Elder County to assess the capacity and role of different organizations and stakeholders. Major stake holders and their role in Irrigation management of Box Elder are presented in Table 1.

Table 1: Major Stakeholders and their role in Irrigation of Box Elder.

Stakeholders	Role in Irrigation management of Box Elder
Bear River Commission	To remove the causes of present and future controversy over the distribution and use of the waters of the Bear River; to provide for efficient use of water for multiple purposes; to permit additional development of the water resources of Bear River; and to accomplish an equitable apportionment of the waters of the Bear River among the compacting States.
Bear River Canal Company	BRCC negotiates with other water users on the Bear River as to using the best management practices to conserve water from Bear Lake primarily, and administer water through the canal system.

Ditch Companies	To divert water from the canal system, make assessments for maintenance and negotiate "trading" water from one neighbor to another.
Utah State University (USU)	Researches aiming to increase irrigation efficiencies, estimation of water demand, optimization of water resources.
Utah Division of Water Rights	Administration of the appropriation and distribution of the State water resources, and maintaining public record for information pertaining to water rights.

SWOT analysis is a structured planning method used to evaluate the Strengths, Weakness, Opportunities and Threats (SWOT) involved in a project. In our project SWOT analysis is performed for BRCC to identify the different factors that might affect irrigation services. The results of the analysis are as follows:

Strengths: 1) Maintenance of canal network as per requirement, 2) Negotiation with other stakeholders, 3) Communication with users.

Weakness: 1) High summer demands. 2) Seepage losses. 3) Less efficient method of irrigation. 4) High labor cost.

Opportunities: 1) Collaborations with organizations such as USU and other government departments.

Threats: 1) Natural disaster to water infrastructures. 2) Climate change.

6. Field data for BRCC:

6.1 Command Area for different crops:

BRCC supplies irrigation water for 66000 acres of agricultural land in Box Elder. The command areas under different crops are stated in Table 2:

Table 2: Command areas under different crops.

Sl. No.	Crop	Command Area (acre)	Percent of Total
1	Wheat	16500	25%
2	Barley	1980	3%
3	Alfalfa	19800	30%
4	Corn	19800	30%
5	Pasture	3960	6%
6	Onion	3960	6%
	Total:	66000	100%

6.2 Planting date for different crops:

Crop period (see Table 3) for different crops have been obtained from field office. It is obvious that the demand is high in the months of May to September which leaves some crops in stress.

Table 3: Crop period for different crops.

Types of crops	Existing Crop period (day/month)	Growth period (days)
Wheat	07/05 – 05/07	60
Alfalfa	01/05 – 30/09	153
Corn	10/04 – 26/09	170
Pasture	01/05 – 30/09	153
Barley	01/07 – 07/09	68
Onion	22/05 – 21/08.	92

6.3 Canal infrastructure data:

Canal infrastructures vary widely as the canal near the head of the system is 20 feet wide at the bottom and 35 to 40 feet at the top. The water depths vary from 3 to 5 feet. At the canal ends the canals are 4 feet wide at the bottom and 6 feet wide at the top and have only a depth of 2 feet.

7 Methodology:

7.1 Introduction:

CROPWAT 8.0 (FAO, 2015) for Windows has been used to calculate crop water requirements and irrigation requirements based on soil, climate and crop data. CropWat-8.0 is a computer program that uses the Penman-Monteith equation for calculating reference crop evapotranspiration (ET0). The procedures used in CROPWAT 8.0 are based on the two FAO publications of the Irrigation and Drainage Series, namely, No. 56 "Crop Evapotranspiration - Guidelines for computing crop water requirements" (Allen et al., 1998) and No. 33 titled "Yield response to water" (Doorenbos et al., 1979).

7.2 Estimation of Evapotranspiration for different crops:

The FAO Penman-Monteith equation (Allen et al., 1998) used for estimating ET_0 is as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(\frac{900}{T+273})u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \dots\dots\dots\dots\dots\dots\dots\dots..(i)$$

Where,

ET_o reference evapotranspiration [mm day^{-1}],
R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],
G soil heat flux density [MJ m^{-2} day^{-1}],
T mean daily air temperature at 2 m height [°C],
u_2 wind speed at 2 m height [m/s],
e_s saturation vapour pressure [kPa],
ea actual vapour pressure [kPa],
e_s-e_a saturation vapour pressure deficit [kPa],
Δ slope of vapour pressure curve [kPa /°C],
γ psychrometric constant [kPa/°C].

The evapotranspiration for each crop (ET_c) is found by multiplying the reference crop evapotranspiration by the respective crop co-efficient, K_c:

$$ET_c = ET_0 * K_c \dots\dots\dots\dots\dots\dots(ii)$$

Where

ET_c is the evapotranspiration of a crop [mm/day],
K_c is the crop co-efficient.

7.3 Input Data for CropWat-8.0:

The following are the input data for CropWat:

7.3.1 Location of Station:

- Latitude
- Longitude
- Altitude.

7.3.2 Monthly average weather data:

- Temperature (Max and Min) in degree centigrade
- Relative Humidity (%)
- Sunshine (hours)
- Wind speed (km/day).

7.3.3 Monthly average rainfall data in mm.

7.3.4 Crop data:

- Planting date
- Number of days in different growth stages
- Crop coefficient (K_c) values in different growth stages
- Root depth

- Critical depletion fraction in different growth stages
- Yield response factor in different growth stages.

7.3.5 Soil data:

- Total available soil moisture (Field Capacity – Wilting Point)
- Maximum rain infiltration rate (mm/day)
- Maximum root depth (cm)
- Initial soil moisture depletion (%).

7.4 Preparation of Data for CropWat:

7.4.1 Weather parameters:

Temperature (maximum and minimum), relative humidity, wind speed data for five weather stations in Box Elder County has been collected for up to eight years from Weather Underground (WU, 2016). Monthly average values (Table A1 in *Appendix A*) of all weather parameters for all the stations have been calculated. Precipitation data for Brigham City weather station (National Weather Service ID- BRGU1, Rainfall (2016); Weather Warehouse (2016)) for the duration of 1974-2015 has been collected and monthly average (Table A2 in *Appendix A*) values have been calculated. Sunshine hour data (Table A2 in *Appendix A*) for Brigham City Airport (KBMC, WU, 2016) has been used for current analysis. Table 4 shows the list of stations and duration of data.

Table 4: Weather stations in Box Elder County and data availability.

Weather station	Records	Duration (years)
Riverside 1433 KUTRIVER4-all	2008-2015	8
2nd East KUTGARLA4 (Garland)	2014-2015	2
Deweyville- MUT28	2008-2015	8
Bear River City- KUTBEARR3	June 15- Mar16	1
Brigham City-KBMC-15	2015	1

7.4.2 Crop Data: Planting dates for different crops of Box Elder County have been collected from field office. Due to differences in evapotranspiration during the various growth stages, the K_c for a given crop will vary over the growth period. The growth period can be divided into four distinct stages: initial, development, mid-season and late season (Allen et al., 1998).

Number of days in different growth stages, K_c, root depth values, critical depletion fraction, and yield response factors for different crops have been taken from FAO manual (Allen et al., 1998). The yield response factor has been taken from FAO Irrigation and Drainage Paper No. 33 (Doorenbos et al., 1979). The references for other crop information have been summarized in Table 5.

Table 5: Crop information for different crops.

Item	Reference
Crop information for Wheat	FAO: Crop Water Information for Wheat, 2015
Crop information for Alfalfa	FAO: Crop Water Information for Alfalfa, 2015
Crop information for Corn	FAO: Crop Water Information for Corn, 2015
Crop information for Pasture	FAO: Crop Water Information for Pasture, 2015
Crop information for Onion	FAO: Crop Water Information for Onion, 2015

7.4.3 Soil Data:

Available soil moisture, infiltration rate, and soil moisture depletion factor have been taken from FAO Manuals (FAO: Soil and Water, 2016; FAO: Infiltration rate and Infiltration test, 2016; and FAO: Soil moisture depletion factor, 2016, respectively).

7.5 Output from CropWat-8.0:

After entering the required data the CWR (Crop Water Requirement) module of CropWat needs to run which gives the irrigation water requirements and irrigation schedules at different growth stages of the crops.

7.6 Irrigation Efficiency and Field Irrigation Requirement (FIR):

CropWat-8.0 applies a default field application efficiency of 70% to calculate net irrigation requirement (NIR) for gravity irrigation system. For flooding irrigation system of Box Elder a field application efficiency of 60% (FAO: Irrigation Efficiencies, 2016) has been applied to calculate NIR. In order to account for the losses of water for unlined canals and clay type soil in Box Elder, a conveyance efficiency of 80% (FAO: Irrigation Efficiencies, 2016) has been applied to calculate field irrigation requirement (FIR), given by the following equation:

$$FIR = \frac{NIR}{E_a * E_c} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (iii)$$

where

FIR is the Field irrigation requirement

E_a is the application efficiency

E_c is the conveyance efficiency.

7.7 Planting date adjustment for different crops:

The crop pattern module of CropWat-8.0 allows the user to modify the planting dates for the crops which in turn servers to manage water demand in peak irrigation season, if desired. As stated previously BRCC faces shortage of irrigation water in the months from July to September, the planting dates of some crops have been adjusted up to two weeks (see table 6) to reduce water demand in the shortage period.

Table 6: Modified Planting Date for different crops.

Types of crops	Existing Crop period (day/month)	Modified planting date (day/month)
Wheat	07/05 – 05/07	01/05 – 29/06
Alfalfa	01/05 – 30/09	Unchanged
Corn	10/04 – 26/09	01/04 – 17/09
Pasture	01/05 – 30/09	Unchanged
Barley	01/07 – 07/09	14/07 – 20/09
Onion	22/05 – 21/08.	07/05 – 06/08.

7.8 Scenario development:

Four scenarios have been developed for BRCC:

(i) Base scenario: The water demands calculated by Utah Division of Water Resources (UDWR, 2011) for BRCC has been considered as a base scenario.

(ii) Second scenario / FIR: Field irrigation requirement (FIR) for the months of April to September calculated by CropWat and water demands calculated by Utah Division of Water Resources (UDWR, 2011) for the remaining months have been considered as second scenario.

(iii) Third scenario / Modified Planting Date (Non-structural alternative): In order to reduce amount of shortage of BRCC in July to September the planting dates of certain crops (wheat, corn, barley, and onion) have been changed up to a maximum of two weeks. These modified planting dates have been entered into “Crop Pattern” module of CropWat and the FIR calculated for the months of April to September by CropWat and water demands calculated by Utah Division of Water Resources (UDWR, 2011) for the remaining months have been considered as third scenario.

(iv) Fourth scenario / Above Cutler Reservoir (Structural alternative): In order to improve the performance of BRCC to serve irrigation demand of Box Elder the demands from third scenario have been input as water demand in WEAP model and the above Cutler Reservoir has been considered to be activated for the fourth scenario.

Monthly demand for BRCC under different scenarios are presented in Table B1 (*Appendix B*).

7.9 WEAP Model:

7.9.1 Introduction: Water supply, demands, and allocations for four stakeholders in the Lower Bear River Basin, Utah have been simulated using Water Evaluation and Planning (WEAP) system (Stockholm Environmental Institute, 2007). Necessary modification in the WEAP area for different stakeholders has been done. The complete WEAP area is presented in figure 3.

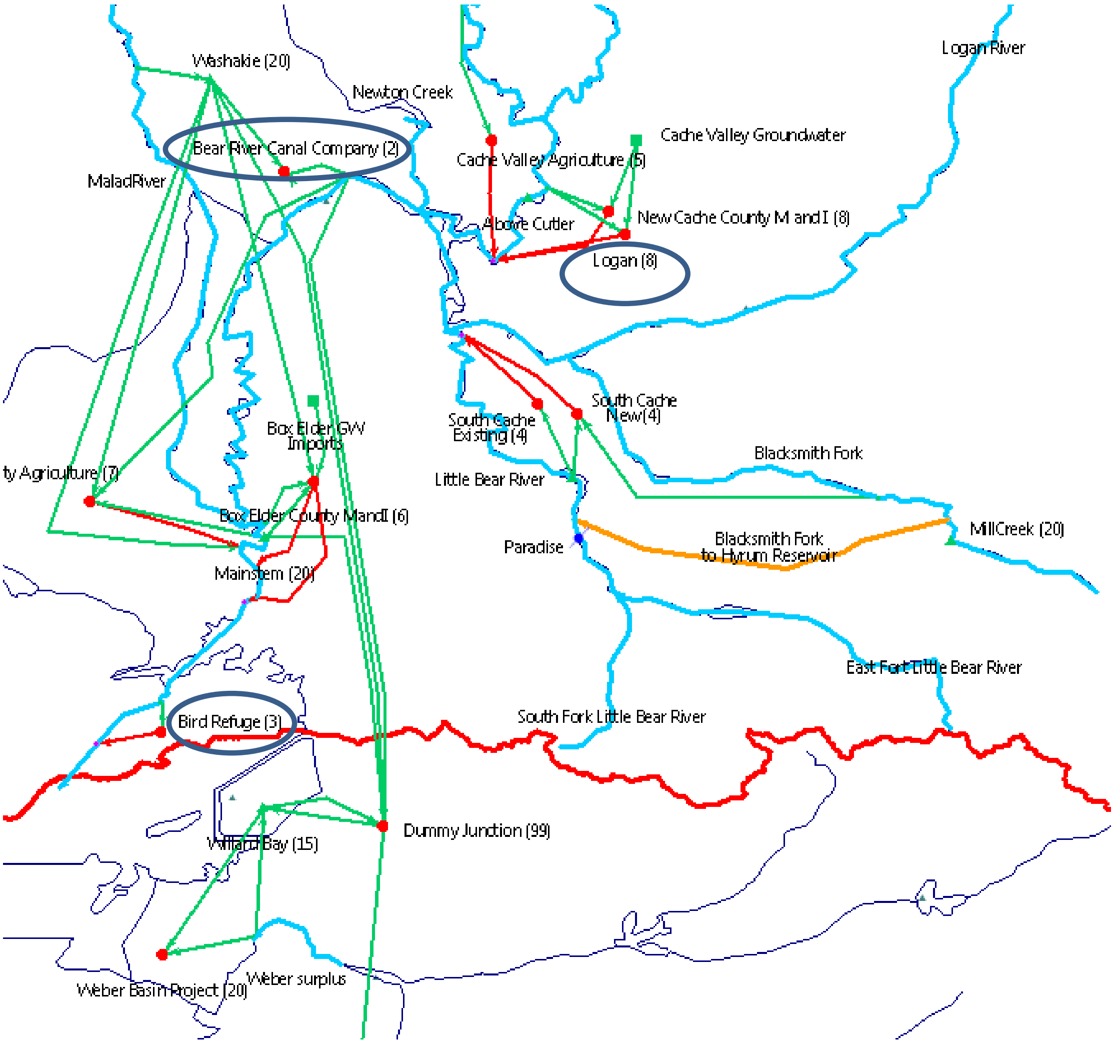

Figure 3. Schematic for the Lower Bear River Basin WEAP Model (Three stakeholders are circled and others are at upstream of Logan City).

7.9.2 Demand and supply data, and scenarios:

Inflows along the Bear River, three tributaries (Blacksmith Fork, Little Bear, Malad), Weber surplus, and two reach gains and losses (at the Bear-Little Bear confluence and the Bear-Malad confluence) have been considered into WEAP model. The model includes five existing reservoirs (Soda, Grace, Oneida, Hyrum, and Willard Bay) which have been considered for first three scenarios. A new reservoir termed "Above Cutler" has been proposed for activation and considered in the fourth scenario on top of the existing reservoirs in the model.

Monthly demand data of BRCC for four scenarios have been entered into the model. For Above Cutler reservoir scenario, monthly evaporation rates (Table C1; *Appendix C*) and elevation versus volume curve (Table C2; *Appendix C*) has also been entered into the model. Similarly, the reservoir capacity, the top of conservation, the top of buffer, the top of inactive zone, and the buffer coefficient for the proposed reservoir can be found in Table C3 (*Appendix C*). The base scenario input data for three stakeholders have been presented in Table D1 (*Appendix D*). The reservoir capacity, the top of conservation, the top of buffer, the top of inactive zone, and the buffer coefficient for different reservoirs under PacifiCorp used for the model can be found in Table D2 (*Appendix D*). Similarly, the monthly evaporation rates (Table D3; *Appendix D*) for the reservoirs under PacifiCorp has also been entered into the model.

The return flow fraction and water rights for BRCC, Bird Refuge, and Logan City are tabulated in Table E1 and Table E2 (*Appendix E*), respectively. The water right priority (Table F1; *Appendix F*) for the reservoirs are also entered into the model.

7.9.3 Simulation:

After entering the required data WEAP model is run to simulate the monthly historical (1967-2006) water allocation within the basin. The unmet demand for BRCC, Bird Refuge, and Logan City, and hydropower production (MW-hr) for Bear River Hydro-electric Project under PacifiCorp have been extracted to calculate the performance metrics.

7.10 Performance metrics:

7.10.1 Introduction:

Reliability, resiliency, and vulnerability (RRV) measure different aspects of a water resources system performance (Hashimoto et al., 1982). RRV metrics provide one of the most comprehensive approaches for analyzing the probability of success or failure of a system, the rate of recovery of a system from unsatisfactory states, as well as quantifying the expected consequence of being in unsatisfactory states for extended periods (Asefa et at., 2014).

7.10.2 Calculation of RRV metrics:

Based on the unmet demands extracted from WEAP model the RRV metrics have been calculated in an MS Excel spreadsheet for all scenarios on yearly basis. Equations and sample calculation for RRV metrics are presented in *Appendices G1* and *G2*, respectively. Also, average monthly hydropower production for three reservoirs (Soda, Grace, and Oneida) under PacifiCrop have been extracted to evaluate the performance metrics in all scenarios.

8. Results:

8.1 Performance metrics for three stakeholders:

8.1.1 Reliability: Figure 4 shows the annual reliability for three stakeholders under different scenarios.

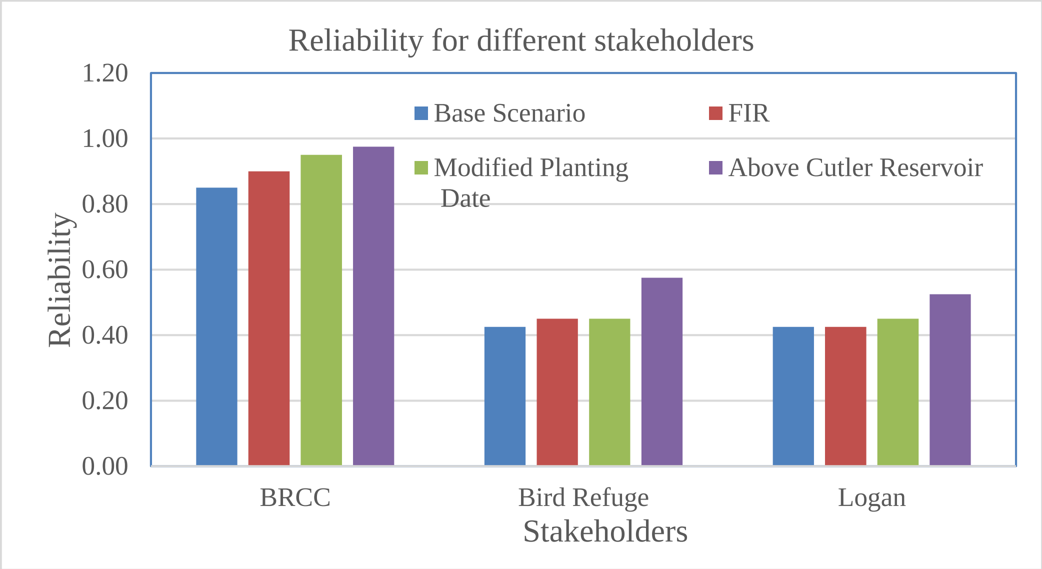

Figure 4: Reliability for different stakeholders.

The annual reliability of BRCC is 0.85 at base scenario which increases to 0.90, 0.95, and 0.98 for FIR, Modified planting date, and Above Cutler Reservoir scenarios, respectively. The annual reliability of Bird refuge is low at 0.43 for base scenario which does not improve much with second and third scenarios but increases up to 0.58 with the fourth scenario which is 35% more in compared to the base scenario. Similarly, the annual reliability of Logan City is low at 0.43 for base scenario which does not improve much with second and third scenarios but increases up to 0.53 with the fourth scenario which is 23% more in compared to the base scenario.

8.1.2 Resiliency: Figure 5 shows the resiliency for three stakeholders under different scenarios.

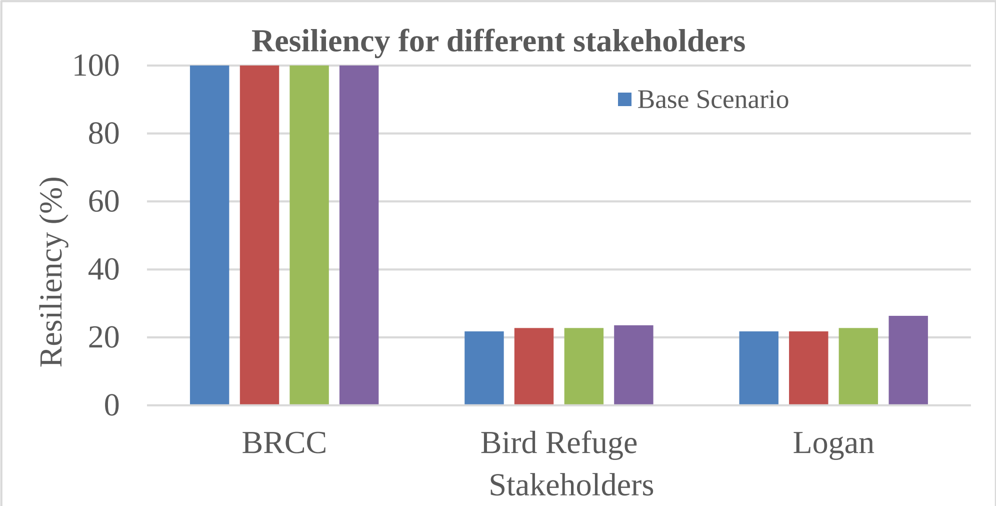

Figure 5: Resiliency for different stakeholders.

The resiliency of BRCC is 100% for all the scenarios. The resiliency of Bird Refuge is low at 21.74% in base scenario which increases up to 23.53% for the fourth scenario. The resiliency of Logan City is also low at 21.74% in base scenario which increases (up to 26.32%) a little bit more than that of Logan City for the fourth scenario.

8.1.3 Vulnerability: Figure 6 shows the vulnerability for three stakeholders under different scenarios.

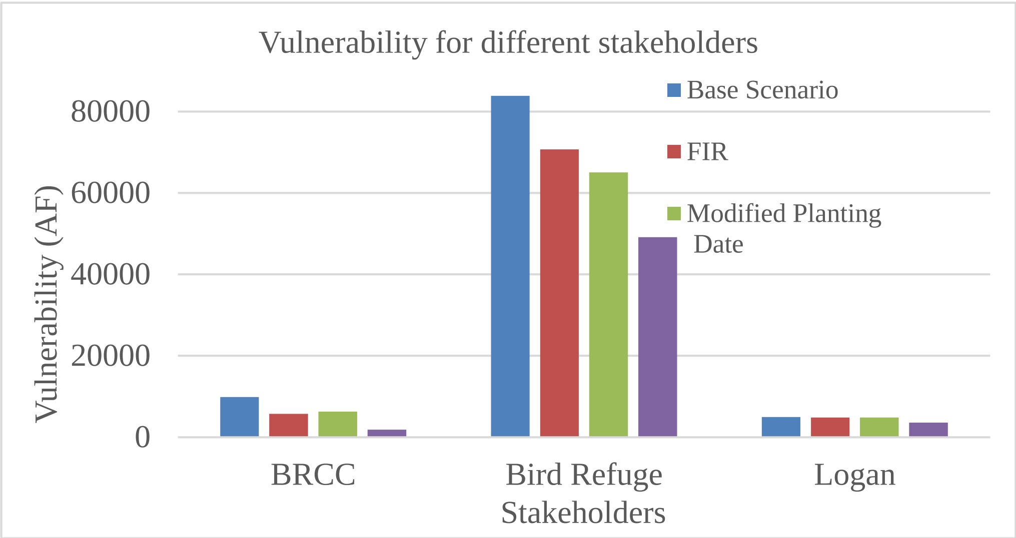

Figure 6: Vulnerability for different stakeholders.

The vulnerability of BRCC is 9871 AF in base scenario which decreases to 5740 AF in FIR scenario followed by an increase up to 6296 AF with Planting Date Adjustment scenario and again decreases to 1849 AF in Above Cutler Reservoir scenario.

The vulnerability of Bird Refuge is quite high at 83849 AF in base scenario which decreases to 70682, 65046, and 49154 AF for FIR, Planting Date Adjustment, and Above Cutler Reservoir scenarios, respectively.

The vulnerability of Logan City is 4969 AF in base scenario which does not change much with FIR and Planting Date Adjustment scenarios but decreases by 28% with the Above Cutler Reservoir scenario in compared to the base scenario.

8.1.4 Hydropower Production:

Figure 7(a), 7(b), and 7(c) show the average monthly hydropower production for Soda, Grace, and Oneida reservoirs, respectively under different scenarios.

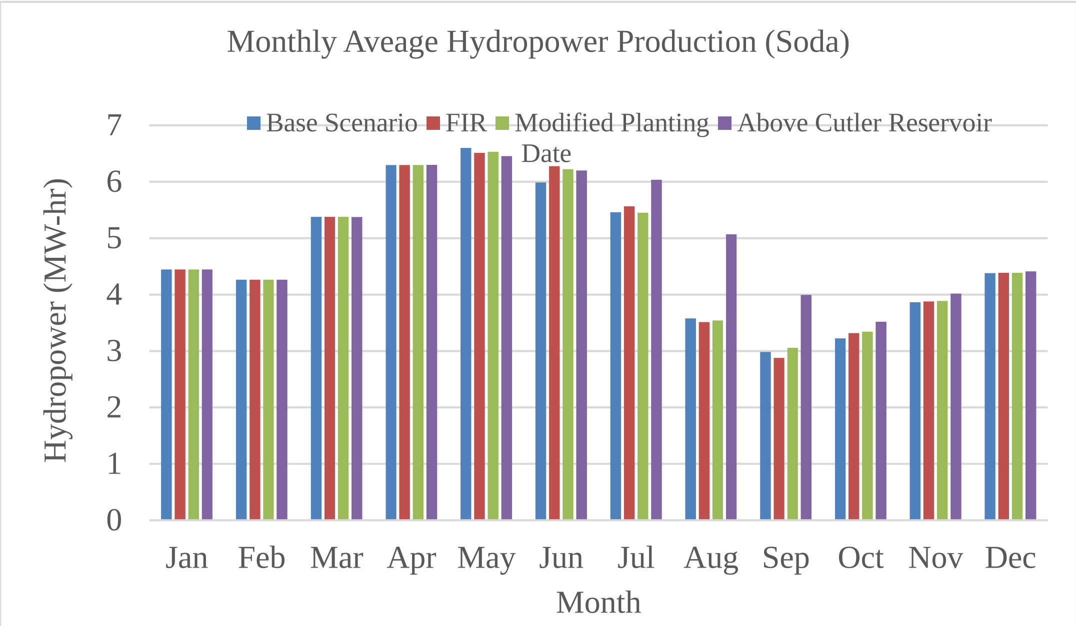

Figure 7(a): Hydropower generation for Soda.

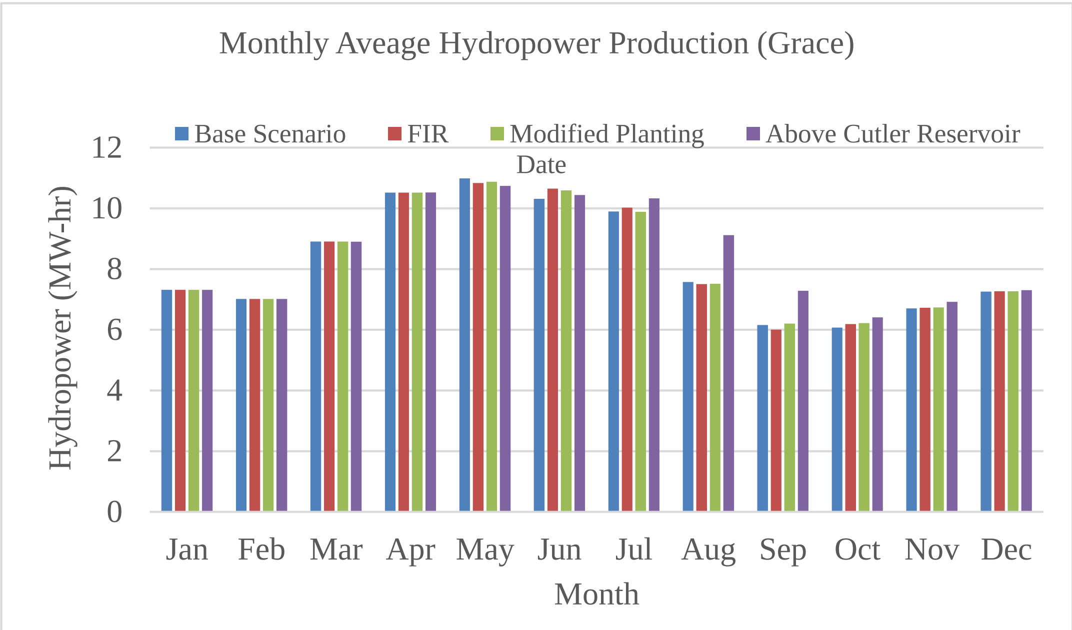

Figure 7(b): Hydropower generation for Grace.

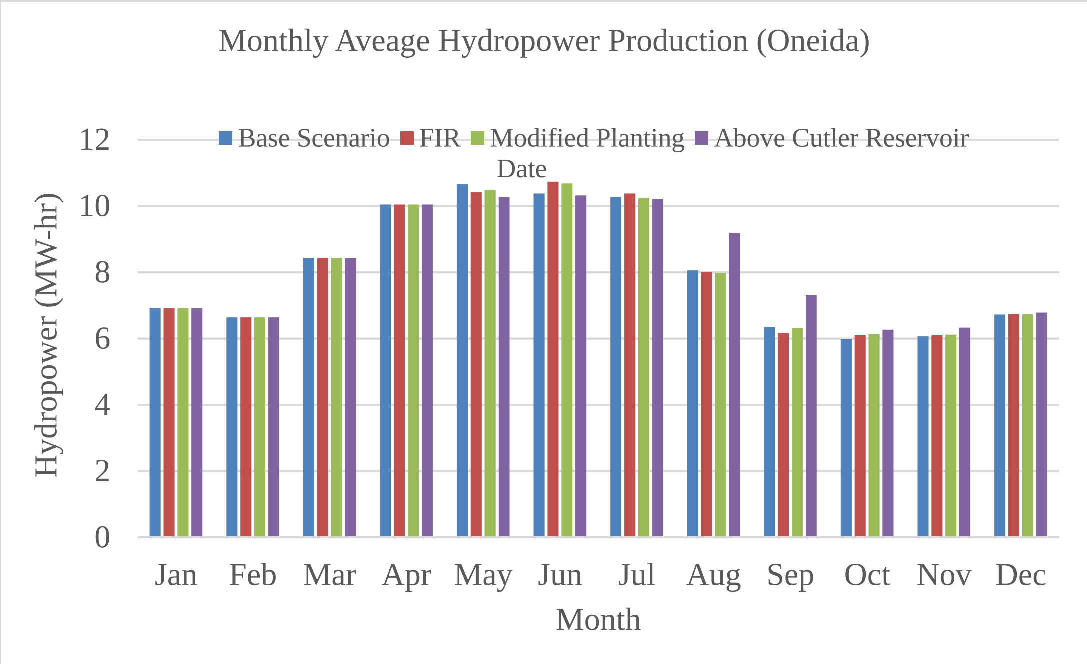

Figure 7(c): Hydropower generation for Oneida.

In general, hydropower production is maximum in the months of April to July for the three reservoirs in all scenarios.
In the months of August and September, Above Cutler reservoir scenario tends to make the highest increase in hydropower production in compared to all other scenarios for all reservoirs.

9 Discussion and Conclusion:

9.1 Reliability:

Being the senior most water right holder in the basin BRCC has a relatively high reliability at 0.85 with base scenario in compared to the other stakeholders. The FIR scenario came up with relatively lower demands in July to September in compared to the base scenario. As reported earlier, BRCC faces shortage of water in July to September. Thus FIR scenario tends to increase the reliability of BRCC from 0.85 to 0.90 in compared to base case. The modified planting date scenario further decreased the demands in July to September which increases the reliability of BRCC up to 0.95.

On the other hand, Bird refuge, the third senior water right holder in the basin, has a low reliability at 0.43 for base scenario. From May through September the water demand of BRCC is quite high. After meeting the demands of BRCC, Bird refuge gets their share which results in low reliability for this stakeholder in base scenario. As stated earlier, FIR scenario came up with lower water demands in May and September in compared to the base scenario. The water thus saved goes to Bird Refuge and the reliability slightly increases to 0.45. Although modified planting date scenario decreased water demands in July to September and increased in April to June for BRCC, this scenario did not improve the reliability of Bird refuge.

With FIR scenario the reliability of Logan City does not improve because of having low water rights in compared to the other stakeholders. Although Logan City being lower water rights holder than Bird Refuge, in modified planting date scenario the reliability of Logan City increases a little bit whereas the reliability of Bird refuge does not change in compared to the FIR scenario.

In general, Above Cutler reservoir operation improves the reliability of the three stakeholders in compared to the other scenarios.

9.2 Resiliency:

The resiliency of Bird refuge and Logan City is low again for being lower water rights holders in the basin in compared to BRCC. Above Cutler reservoir operation makes more increase in resiliency of Bird refuge and Logan City in compared to the other scenarios.

9.3 Vulnerability:

The FIR scenario tends to reduce the vulnerability of all stakeholders because of lower water demands in the months of May and September for BRCC in compared to the base scenario. Modified planting date scenario reduces the number of failure events of BRCC but increased shortage amounts in remaining failure events. Thus the vulnerability of BRCC increases with the Modified planting date scenario in compared to the FIR scenario.

In general, Above Cutler reservoir operation reduces the vulnerability of the three stakeholders in compared to the other scenarios.

9.4 Hydropower production:

Bear River Project of PacifiCorp is located at upstream of the other three stakeholders in the basin. Water demand for all the downstream demands sites is higher in April to July compared to the other months of the year. Thus with higher release of water for downstream demand sites the production of hydropower is maximum in April to July.

10. Recommendation:

Above Cutler Reservoir Scenario improves the performance of all the stakeholders in Bear River Basin. This reservoir is now under construction which may take time to come in operation. Modified planting date scenario improves the performance of BRCC to meet the irrigation demand of Box Elder County. So, BRCC is suggested to implement this scenario immediately until the Above Cutler Reservoir comes in operation.
Parallel to Above Cutler Reservoir, the other reservoirs in the basin like Mainstem, Washakie, and Millcreek should come in operation to improve the performances of all stakeholders in the Lower Bear River Basin.

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Appendices:

Appendix A: Monthly average weather parameters:

Table A1: **Average monthly maximum and minimum temperature, humidity, and wind speed for Box Elder County.**

Month	T max ^0C	T min ^0C	Humidity (%)	u_2 (km/day)
Jan	-0.25	-9.23	78.49	204.48
Feb	3.58	-5.38	73.16	259.27
Mar	10.10	-0.83	60.70	286.42
Apr	13.91	1.59	54.21	285.78
May	19.73	6.84	52.04	282.81
Jun	26.50	11.71	43.75	290.40
Jul	32.05	16.04	37.49	223.63
Aug	30.89	14.60	39.06	234.02
Sep	26.08	10.01	43.03	222.13
Oct	17.32	3.93	55.06	239.31
Nov	8.52	-2.35	64.42	226.30
Dec	0.94	-7.24	77.51	205.79

Table A2: **Average monthly sunshine hours and rainfall for Box Elder County.**

Month	Sunshine (hr)	Rainfall (mm)
Jan	8.39	4.64
Feb	9.68	3
Mar	10.65	3.81
Apr	9.6	4.32
May	9.17	5.32
Jun	11.73	3.19
Jul	10.97	0.94
Aug	11.06	1.35
Sep	11.1	0.94
Oct	11.13	4.48
Nov	8.43	1.94
Dec	7.77	4.68

Appendix B: Water demands:

Table B1: Water demand of BRCC for different scenarios.

Month	Demand (AF) for different Scenarios			
	Base	FIR	Modified Planting Date	Above Cutler Reservoir
Oct	16691.00	16691.00	16691.00	16691.00
Nov	4576.00	4576.00	4576.00	4576.00
Dec	1561.00	1561.00	1561.00	1561.00
Jan	1277.00	1277.00	1277.00	1277.00
Feb	787.00	787.00	787.00	787.00
Mar	298.00	298.00	298.00	298.00
Apr	2544.00	1828.37	2482.04	2482.04
May	34448.00	15423.05	20154.71	20154.71
Jun	45953.00	45775.59	46572.94	46572.94
Jul	50966.00	49920.53	48359.94	48359.94
Aug	47804.00	46088.21	41547.60	41547.60
Sep	35537.00	23827.56	21357.84	21357.84

Appendix C: Above Cutler Reservoir data:

Table C1: Rate of Evaporation for Above Cutler Reservoir.

Month	**Evaporation Rate (ft)**
October	0.05
November	0
December	0
January	0
February	0
March	0.02
April	0.13
May	0.22
June	0.36
July	0.43
August	0.39
September	0.2
Total	1.79

Table C2: **Elevation versus volume relationship for Above Cutler Reservoir.**

Elevation (ft)	Storage (Acre-Feet)
4,410	0
4,415	1,786
4,420	9,259
4,425	21,723
4,430	41,367
4,432	51,342

Table C3: **Physical and Operation condition for Above Cutler Reservoir.**

Storage Capacity (AF)	51342
Top of conservation (AF)	51342
Top of buffer	20% of storage capacity
Top of inactive zone	0
Buffer Co-efficient	1

Appendix D: Stakeholder data and reservoir operation for PacifiCorp):

Table D1: **Demand data for three stakeholders in base scenario.**

Demand Site	Monthly Demand (AF)											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
BRCC	16,691	4,576	1,561	1,277	787	298	2,544	34,448	45,953	50,966	47,807	35,537
Bird Refuge	42,150	3,406	-	-	4,258	60,884	59,181	61,309	46,834	50,240	43,002	54,497
Logan City	1,440	384	384	384	384	384	1,440	1,440	1,440	1,440	1,440	1,440

Table D2: Physical and Operation condition of different reservoirs of PacifiCorp for all scenarios.

Parameter	Reservoir		
	Soda	Grace	Oneida
Storage Capacity (AF)	16300	320	10880
Top of conservation (AF)	16300	320	10800
Top of buffer	0	0	0
Top of inactive zone	0	0	0
Buffer Co-efficient	1	1	1

Table D3: Rate of Evaporation for different reservoirs of PacifiCorp.

Month	**Evaporation rates for reservoirs (ft)**		
	Soda	**Grace**	**Oneida**
October	0.27	0.27	0.27
November	0.01	0.01	0.01
December	0	0	0
January	0	0	0
February	0	0	0
March	0	0	0
April	0.1	0.1	0.1
May	0.44	0.44	0.44
June	0.51	0.51	0.51
July	0.56	0.56	0.56
August	0.50	0.5	0.5
September	0.32	0.32	0.32

Appendix E: Return flow and water rights for three stakeholders:

Table E1: <u>Return flow for different stakeholders.</u>

Month	Return flow (%) for stakeholders		
	BRCC	Bird Refuge	Logan City
Oct	0	0	27
Nov	0	0	73
Dec	0	0	73
Jan	0	0	73
Feb	0	0	73
Mar	0	0	73
Apr	0	0	27
May	0	0	27
Jun	0	0	27
Jul	0	0	27
Aug	0	0	27
Sep	0	0	27

Table E2: <u>Water rights for different stakeholders.</u>

Stakeholder	Water right priority
BRCC	2
Bird Refuge	3
Logan City	8

Appendix F: Water rights for active reservoirs:

Table F1: <u>Water rights for the active reservoirs in the basin.</u>

Name of reserovir	Water right priority
Soda	10
Grace	10
Oneida	10
Willard Bay	15
Hyrum reservoir	10

Appendix G: Definition of metrics and calculation:

Appendix G1: <u>Definition / Equations.</u>

<u>Reliability:</u> Reliability is the fraction of time the system is in a satisfactory state and is given as:

$$Reliability = \frac{\#\ of\ observations\ that\ are\ satisfactory}{Total\ \#\ of\ observations} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (G1)$$

<u>Resiliency:</u> Resiliency is the likelihood for the system to recover from an unsatisfactory state and is given as:

$$Resiliency = \frac{\#\ of\ transitions\ from\ failure\ in\ time\ t\ to\ success\ in\ time\ t+1}{Total\ \#\ of\ failures} \ldots\ldots (G2)$$

<u>Vulnerability:</u> Vulnerability is the average difference from the threshold for unsatisfactory states and is given as:

$$Vulnerability = \frac{\sum_{t\ is\ at\ failures} |P_t - Threshlod|}{Total\ \#\ of\ failures} \ldots\ldots\ldots\ldots (G3)$$

Where, P_t = Value of the parameter when the system is in unsatisfactory state

Threshold = Threshold value of the parameter in question for identifying the system to be in satisfactory state.

Appendix G2: <u>Calculation for RRV in base scenario:</u>

(i) RRV calculation for fulfilling the yearly delivery target of BRCC:

Total # of observations = 40

Total # of observations at satisfactory state = 34

$$Reliability = \frac{34}{40} = 0.85$$

Total # of transitions from failure in time t to success in time t+1 = 6

Total # of observations at unsatisfactory state = 6

$$Resiliency = \frac{6}{6} = 1.00$$

Sum of absolute differences between observed values and threshold values for the unsuccessful cases = 59228

$$Vulnerability = \frac{59228}{6} \cong 9871.$$