Progress Report of the Term Project: Assessment of the Number of Hedging Rule Points on the Reservoir Operation Indicators

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1. Introduction

Hedging rule in reservoir operation is a linear or nonlinear relationship between the available water (AW) in the reservoir and releases volume (RV) from the reservoir. The AW is total water storage in and inflow to the reservoir, and RV consists of releases to meet the delivery target and also spill volume from the reservoir. One of the famous hedging rules is a hedging rule based on the standard linear operation policy (SLOP) shown in Fig 1.

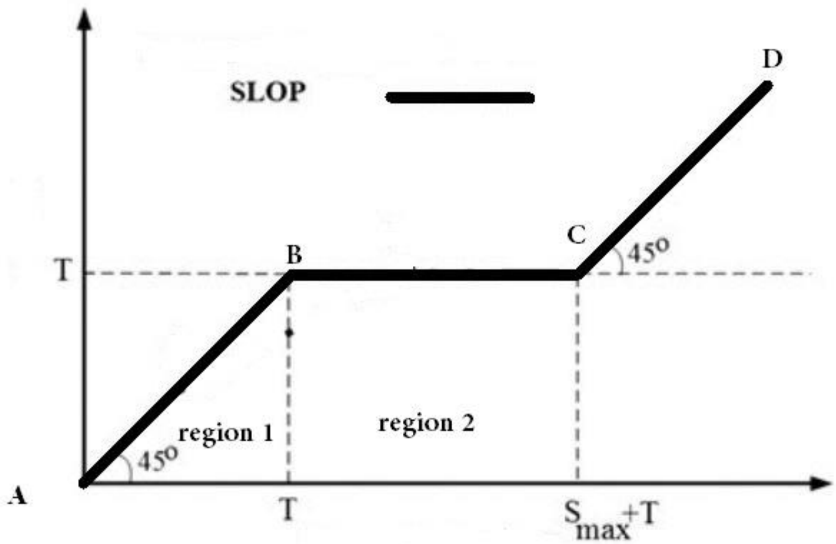


Fig 1. A layout of SLOP

This type of operation policy doesn't have providence feature. Therefore, some investigators conducted researches on modifying SLOP with several approaches (Tu et al. 2003, Shiau and Lee, 2005, Tu et al. 2008, Taghian, 2013). One approach is to modify the SLOP using the non-linear relationship between AW and RV. On the other hand, they replace the linear relationship between region 1 (AB) and 2 (BC) in Fig 1 with a nonlinear relationship. Others divide the regions 1 and 2 into more regions considering *n*-point hedging rules. For instance, a two-point hedging rule is shown in Fig 2.

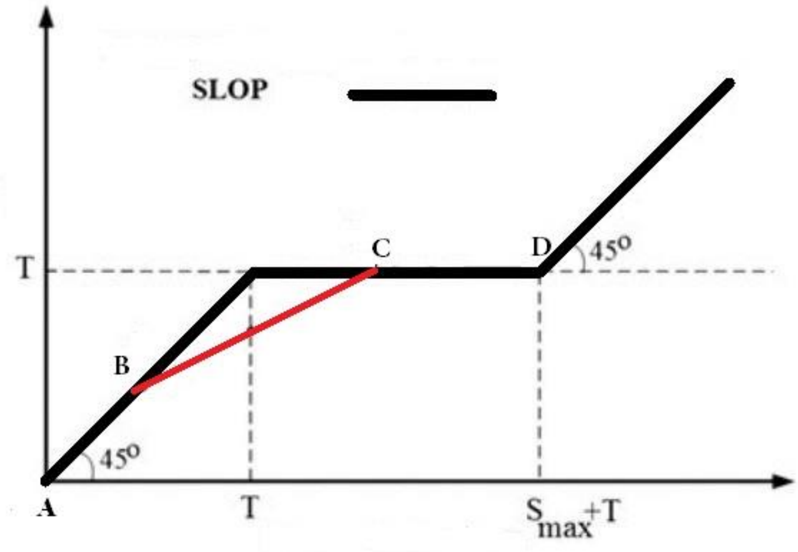


Fig 2. A layout of two-point hedging rule

According to Fig 2, it is evident that having three lines (AB, BC, and CD) in the region 1 and 2 instead of two lines leads to add the providence feature to the operation policy. In this situation, the total available water will not be released for satisfying the demand in the region 1 (Fig 1). However, determination of the optimal locations of points B and C in Fig 2 is the problematic part. One of the mathematical solutions to find the optimal locations of points B and C is to define the objective function such as minimizing the deficit along with limitations and solve it with methods such as Lagrange multiplier based method or evolutionary algorithms (EAs).

The goal of this study is to evaluate the impact of increasing the number of hedging rule points in the agriculture reservoir (Hyrum reservoir) on the performance indices proposed by Hashimoto et al. (1982). For this evaluation, first of all, the optimal locations for different numbers of hedging rule points will be achieved by genetic algorithm (GA) considering the minimizing the deficit. Afterward, as a local scale, the performance indices will be calculated for the Hyrum reservoir and compared with the SLOP. In addition, as a global scale, the performance indices for the entire system (Bear River system) will be simulated based on the results of each hedging rule on a local scale.

In this progress report, the project framework discussed before along with the methodology, case study and future work are described.

2. Methodology

The methodology section has five different parts including (1) the theory of reservoir operation (2) hedging rule, (3) the performance criteria for the reservoir (4) the evolutionary algorithm and (5) Optimization problem for *n*-point hedging rule.

2.1. Reservoir Operation

Regardless of the type of hedging rule, the operation for the agricultural reservoir follows three simple equations and two constraints. The first equation for modeling the agricultural reservoir is to simulate the storage based on the mass balance equation (Eq.1).

$$S_{t+1} = S_t + Q_t - L_t - SP_t - R_t \tag{1}$$

in which S_{t+1} =reservoir storage at the end of the period *t* (or beginning of the period *t+1*); S_t = reservoir storage at the beginning of the period *t*; Q_t = river inflow to the reservoir during the period *t*; L_t = net loss as the volume of evaporation during the period *t*; SP_t = spill volume from the reservoir during the period *t*; and R_t = release from the reservoir during the period *t* for satisfying the demand. The second equation is related to the calculation of L_t (Eq. 2).

$$L_t = (E_t - P_t) \times A_t \tag{2}$$

in which E_t = evaporation during the period *t*; P_t = precipitation during the period *t*; and A_t = surface area of reservoir lake at the period *t*. It should be mentioned that A_t is a function of S_t called height-area-volume that a typical form of that shown in Fig 3.

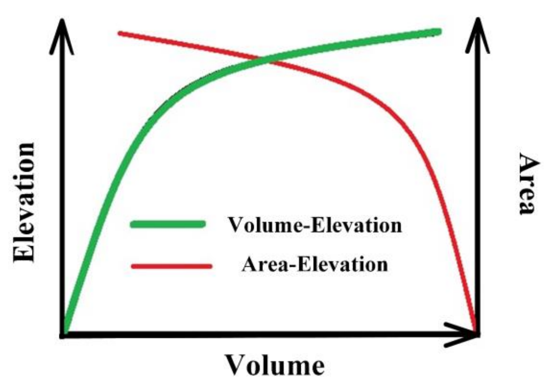


Fig 3. A typical form of a height-area-volume curve

The third equation is a conditional function to calculate the spill volume from the reservoir (Eq. 3).

$$SP_t = \max(S_t - S_{\max}, 0) \tag{3}$$

in which, $S_{\max}$ = maximum storage capacity of the reservoir. According to the Eq.3, it is evident when $S_t \le S_{\max}$; SP_t =0 otherwise $SP_t = S_t - S_{\max}$. Besides these equations, there are two constraints on releases (Eq. 4) and storages (Eq. 5).

$$R_{\min} < R_t < R_{\max} \tag{4}$$

$$S_{\min} < S_t < S_{\max} \tag{5}$$

in which $R_{\min}$ and $R_{\max}$ are minimum and maximum release storage and $S_{\min}$ and $S_{\max}$ are minimum and maximum storage capacity of the reservoir.

In addition to all variables in Eq.1-Eq.5, there is only one relationship that should be determined to simulate the reservoir operation which is the relationship between AW and RV (the hedging rule). Therefore, for the reservoir operation simulation, the variables shown in the table should be gathered as well as fixing the hedging rule.

Table 1. All required variables for simulation of the reservoir operation

Variable Name	Description
S_1	The reservoir storage at the first period of the operation
Q_t	The time series of the inflow to the reservoir for the operation period
E_t	The time series of the evaporation to the reservoir for the operation period
P_t	The time series of the precipitation to the reservoir for the operation period
$S_{\min}$	The minimum reservoir storage
$S_{\max}$	The maximum reservoir storage
$R_{\min}$	The minimum reservoir release
$R_{\max}$	The maximum reservoir release (Delivery Target)

To sum, the simulation process of the agricultural reservoir operation is shown in Fig 4.

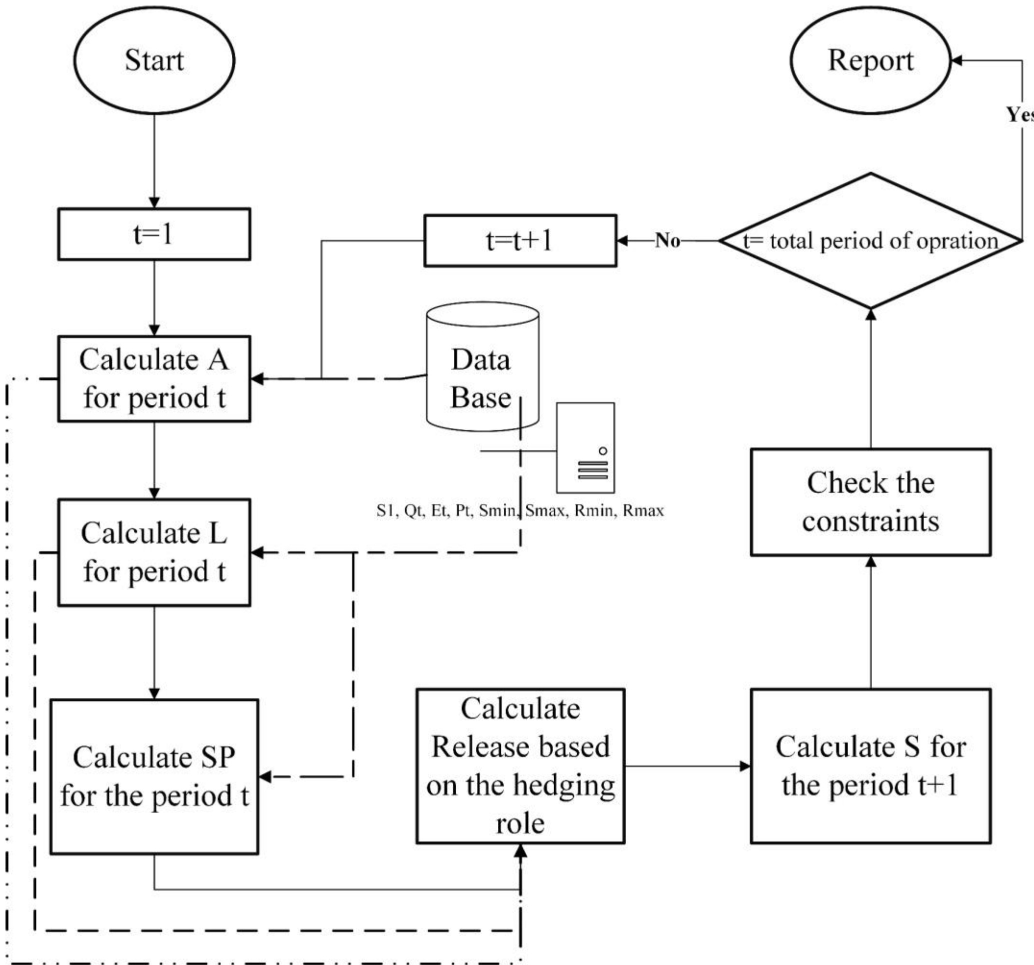


Fig 4. The simulation process of an agricultural reservoir operation

2.2. Hedging Rule in the Reservoir System:

The importance and the rule of hedging rule policy are discussed and shown in the reservoir operation system section and Fig 4. In General, the simplest form of a hedging rule for reservoir policy is SLOP described in the introduction section and Fig 1. Fig 1 illustrated that SLOP is based on releases to stratify demands in each period as much as there is water in the reservoir storage. Therefore, when there is no sufficient water ($S_t \leq Demand_t$) in the reservoir storage, all the water storage should be released which means that the reservoir will be empty in the next period. That's why SLOP doesn't preserve water for the future requirements. There are several approaches to modify this policy. Some researchers use the non-linear forms of hedging rule and evaluate it using performance indicators. Others try to find the optimal values of both 45^o slopes and the threshold of the spill. Moreover, there is another approach to modifying SLOP using breaking the lines (AB, BC, and CD in Fig 2) into more lines with different slopes called *n*-point hedging rule. Fig 2 shows how two lines of SLOP in Fig1 (AB and BC) are breaking into three lines (AB, BC, CD) using two points B and C. Regardless of these approaches to modify the hedging rule, usually, the modification of the hedging rule is considered under a specific objective function (convert to an optimization problem). The objective function can be an improvement in the performance criteria such as reliability, resiliency or vulnerability or even minimizing the deficit. As described before, this project is designed to achieve the optimal location of *n*-point hedging rule using GA for modifying the SLOP policy of an agricultural reservoir operation and examine the impacts of this modification on the performance criteria of the reservoir considering minimizing the deficit as the objective function.

2.3. Performance Criteria of the Reservoir System

To evaluate the performance of a water resources system, it is necessary to develop and use indices. The most famous indices have been introduced by Hashimoto et al. (1982) and developed by many researchers (Loucks et al. 1981 and Sandoval-Solis et al. 2011). The Hashimoto's risk-based indicators are reliability, vulnerability, and resiliency that quantify the frequency, size, and length of the system failures, respectively. The sustainability is another index that shows the efficiency of the system calculated based on reliability, vulnerability, and resiliency. The formulations of these indices are as follows:

$$R_l = 1 - \frac{f_n}{T} \tag{6}$$

$$Res = \frac{1 + \sum_{t=2}^{T} \begin{cases} \mathrm{Q}_{t-1} < \mathrm{Demand}_{t\text{-}1} \quad \text{and} \quad \mathrm{Q}_t \geq \mathrm{Demand}_t & 1 \\ \text{Otherwise} & 0 \end{cases}}{T - \sum_{t=1}^{T} \begin{cases} \mathrm{Q}_t \geq \mathrm{Demand}_t & 1 \\ \text{Otherwise} & 0 \end{cases}} \tag{7}$$

$$V_n = \underset{t=1}{\overset{T}{Max}}(Def_t) \tag{8}$$

$$V_{n(scaled)} = \underset{t=1}{\overset{T}{Max}}(Def_t) \Big/ Demand_{t_{\max}} \tag{9}$$

$$S_{s(Loucks)} = R_l \times R_s \times (1 - V_{n(scaled)}) \tag{10}$$

$$S_{s(Sandovol)} = (R_l \times R_s \times (1 - V_{n(scaled)}))^{1/3} \tag{11}$$

in which R_l = reliability index; f_n =number of failure periods; T= number of operating periods; R_s = resiliency index; f_s = number of continued failure periods; $Demand_t$ = the demand at operation period t; V_n = vulnerability index; Def_t = volume of deficit in period t; $V_{n(scaled)}$ = scaled vulnerability index; $Demand_{t_{\max}}$ = the demand at the period that maximum deficit happens ($t_{\max}$); $S_{s(Loucks)}$ = sustainability index proposed by Loucks et al. (1981); $S_{s(Sandoval)}$ = sustainability index proposed by Sandoval-Solis et al. (2011) .

2.4. Evolutionary Algorithm

The evolutionary algorithms such as GA are methods to solve an optimization problem. These algorithms can reach to the near optimal solution using an intelligent searching algorithm. They start with a randomly guess as a preliminary solution and then correct the solution in an iterative process using modification functions. GA uses the mutation and cross-over function inspired by the nature process of the human evolution to correct the guess in each iterative. Moreover, the mutation function enables GA to escape of trapping in local optima. This iterative continues until the stopping criterion is satisfied.

2.5.Optimization problem for *n*-point hedging rule

As discussed before, in this project, the optimization problem considering minimizing the deficit as the objective function is designed (Eq. 12). In the optimization problem, the coordinate location of hedging points (such as B and C in Fig 2) are the decision variables that determine the function *f* in Eq. 12. The optimization model of the agriculture reservoir based on the hedging rule is as follows.

$$\operatorname{Min} z = \sum_{t=1}^{T} (Demand_t - R_t)$$

Subject to:

$$\begin{aligned} & R_t + \max(S_t - S_{\max}, 0)_t = f(S_t + Q_t) \\ & S_{t+1} = S_t + Q_t - R_t - \max(S_t - S_{\max}, 0)_t - (E_t - P_t) \times A_t \\ & R_{\min} < R_t < Demand_t \\ & S_{\min} < S_t < S_{\max} \end{aligned} \qquad (12)$$

To solve the optimization model, the classic version of GA is used. The optimization problem is run for several values of *n* and for each of those, the Hashimoto's indicators are calculated once for Hyrum reservoir and once for the entire system. Finally, the impact of different values of *n* on the objective function and performance indices is examined. The procedure of these steps is illustrated in Fig 5.

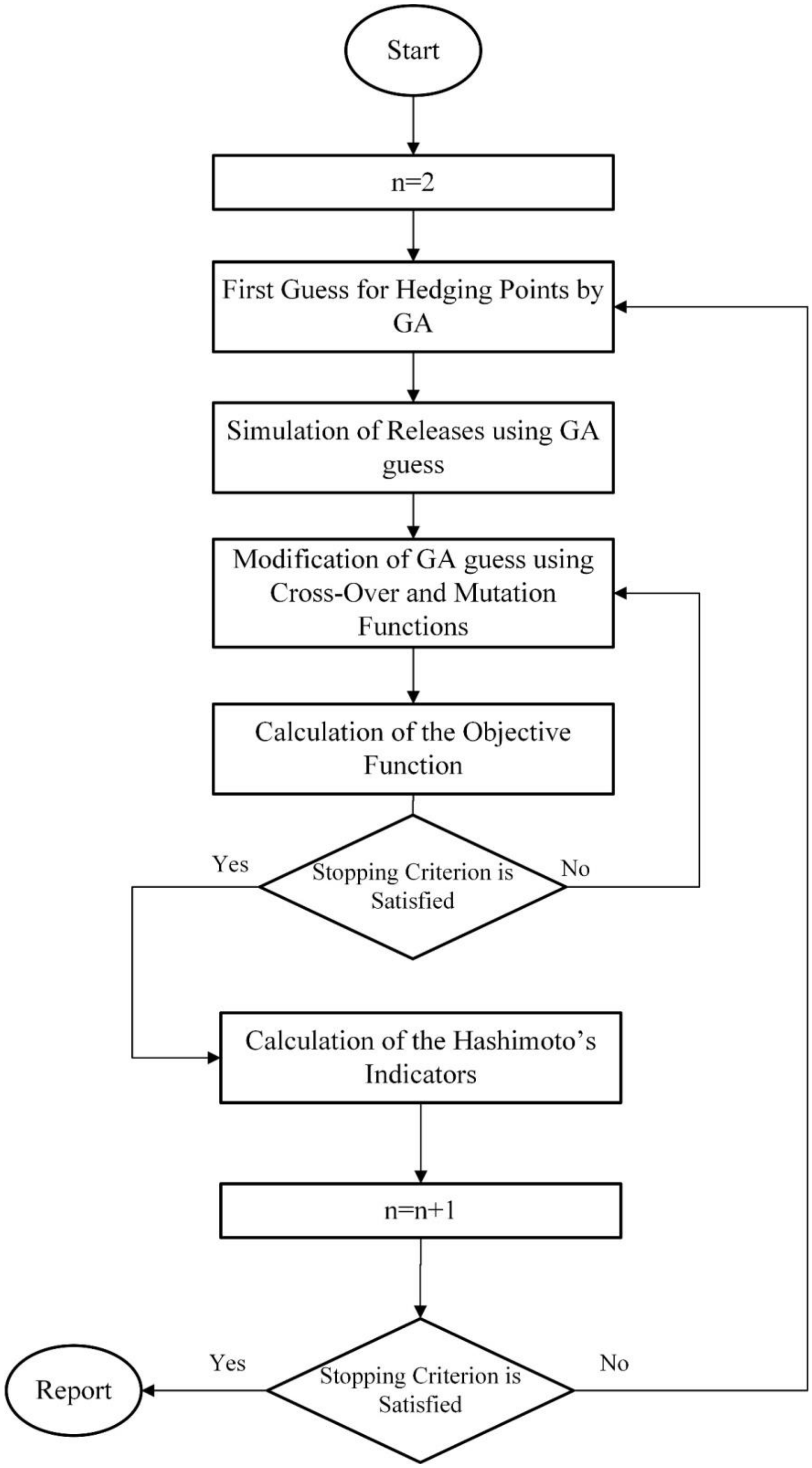
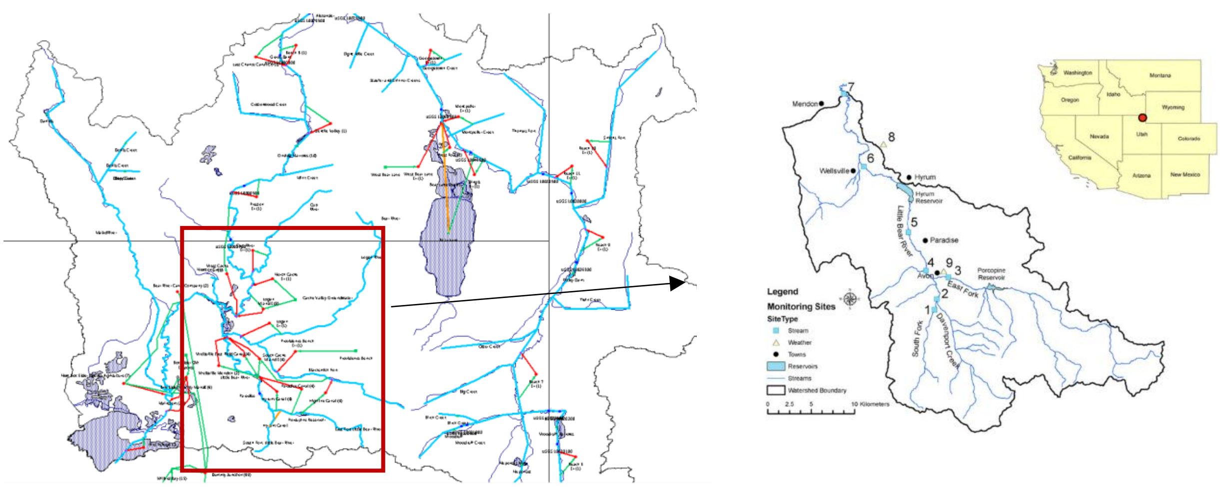


Fig 5. The procedure of the suggested term project

As it is shown in Fig 5, in the first loop, *n* value set to 2 and in the second loop GA randomly guess a preliminary solution (i.e. coordinate location of points B and C in Fig 2 because of *n*=2). The reservoir releases will be simulated based on the hedging rule that is a function of the coordinate location of those points and the objective function will be calculated. Then, the preliminary solution will be modified using the cross-over and mutation function until the stopping criterion is satisfied. In this moment, the Hashimoto's indicators are calculated based on the optimal coordinate location found by GA for the Hyrum reservoir and for the entire system. These indicators will be compared with the indicators calculated under SLOP rule. Afterward, the outer loop will be reset, *n* will be set to *n+1* and the same procedure for inner loop will be executed until stopping criterion for the outer loop is satisfied (*n* < i.e:100).

Case Study:

In this project, the Hyrum reservoir (local scale) and the impact of different hedging rule for that case on the Lower Bear River Basin (global scale) are considered as the case studies. The current situation of LBRB using 33 rivers, 20 reservoirs, 4 aquifers and 36 demand site are symbolized in the WEAP environment (Fig 6).



(a) (b)

Fig 6. (a) A layout of LBRB symbolized in the WEAP model (b) the magnified layout of Hyrum dam adopted from Horsburgh et al. (2011)

Hyrum reservoir located on the Little Bear River, Utah was completed in April 1935. The storage capacity of this dam is 18684 ac-ft. and the volume elevation curve which is useful for calculation of the net loss (Eq. 2) is shown in Fig 7.

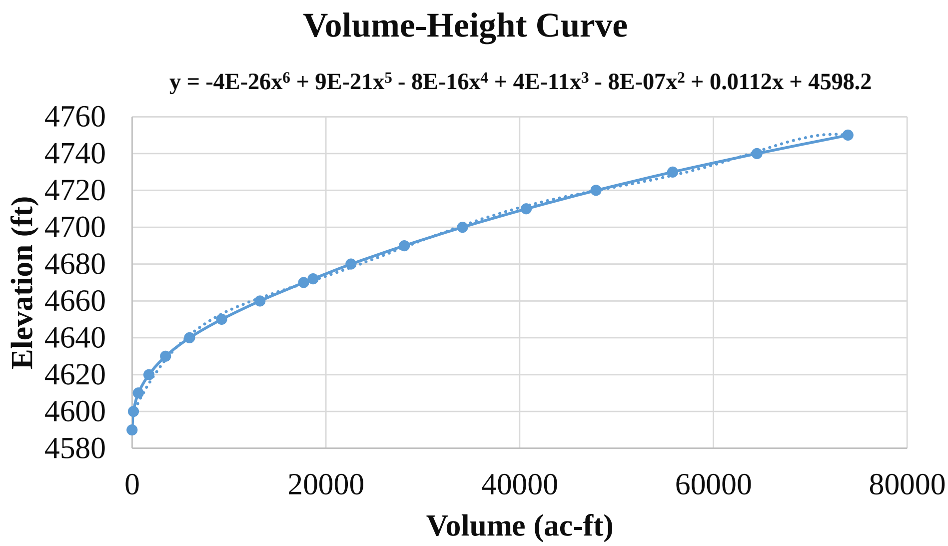


Fig 7. The volume-height curve for the Hyrum reservoir

Moreover, net evaporation chart for the Hyrum reservoir is shown in Fig 8. [$(E_t - P_t)$ term in Eq. 2.]

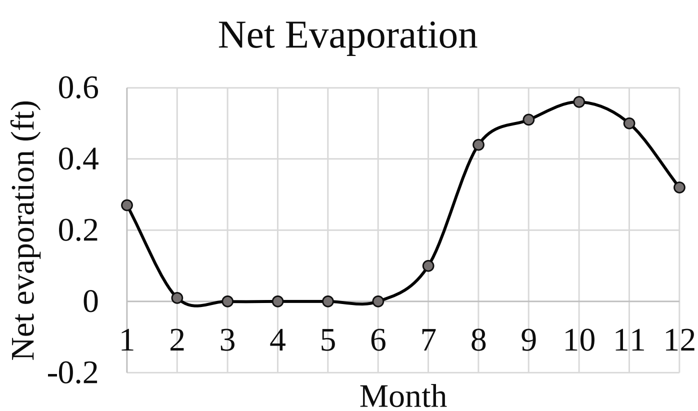


Fig 8. The monthly net evaporation of Hyrum reservoir

The top of inactive volume and top of buffer volume for Hyrum is 3405 ac-ft. and 8000 ac-ft., respectively compared to the 18684 ac-ft. as the total storage. The primary purpose of the reservoir is to provide irrigation water for two demand sites including Wellsville East Field Canal and Wellsville Mendon. The monthly inflow of Little Bear River and delivery targets of these sites are shown in Fig 9.

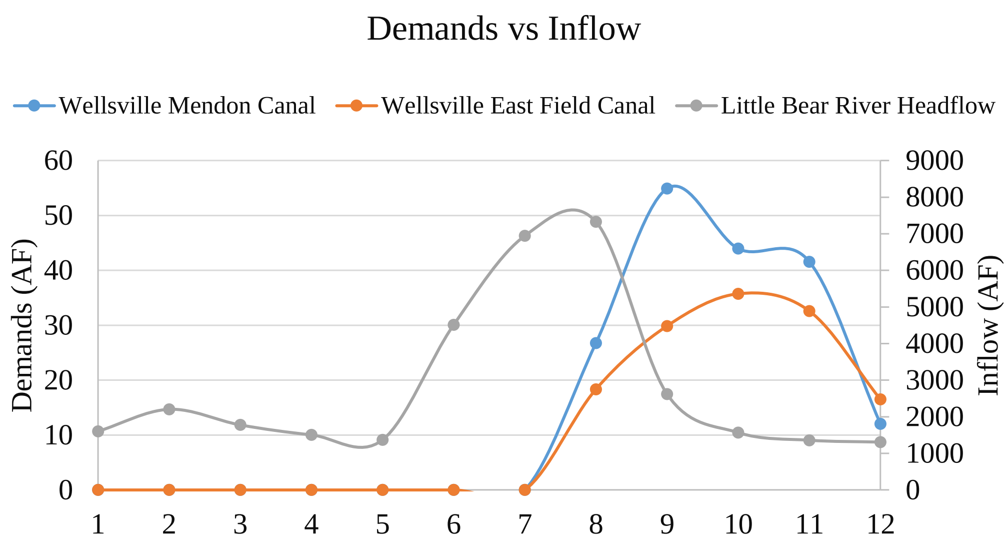


Fig 9. Wellsville East Field Canal and Wellsville Mendon demands versus Little Bear River head flows to Hyrum reservoir

To sum, the sources data for variables listed in Table 1 to simulate the Hyrum reservoir are as follows:

Table 2. The sources data for all required variables to simulate the Hyrum reservoir

Variable Name	Source/Value
S_1	18684
Q_t	Fig 9
$E_t - P_t$	Fig 8
S_{min}	3405
S_{max}	18684
R_{min}	0
R_{max}	Fig 9 (Demands at both sites)
Hedging Rule	Will be provided by GA

Summary of Work Done:

- Gathering Data (All variables required for simulation)
- Write a code in MATLAB to simulate releases from Hyrum reservoir
- Write a code in MATLAB to implemented GA with the mentioned form of optimization problem
- Link GA code to simulation code

Summary of Future Steps:

- Applying the priority of supplying demand sites in simulation code
- Decide on whether the return flow from demand sites to the Little Bear River should be considered or not.
- Verifying the simulation process
- Find a way to call WEAP in MATLAB to calculate the performance criteria for Bear River Basin (global scale) based on the hedging in rule found with GA or manually compute these indices for Bear River Basin.
- Prepare the final report

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