Deerfield, Pactola and Rapid Creek Systems Analysis Modeling

by
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Abstract

Managed by the United States Bureau of Reclamation, Pactola and Deerfield reservoirs' primary purposes are to provide municipal water supply, irrigation, and flood control; fish, wildlife, and recreation are secondary beneficial functions. A simulation model of the reservoir system was developed in HEC-ResSim to analyze alternative operating scenarios. An operational set representative of published operations was developed based on general operating procedures and historical management of the reservoirs. Four additional operating sets were created for each reservoir by manipulating minimum releases, tandem operations and zone elevations. Sixty-one years of inflow time series data for Deerfield and North Fork Rapid Creek was obtained from HydroMet. To consider a broader range of potential inflow scenarios, synthetic 60-year blocks of inflow time series were created using a Monte Carlo method of random sampling with replacement (bootstrap resampling). The random sampling considered the conditional probability of a wet year being followed by a wet year and a dry year being followed by a dry year based on analysis of the historical data set.

A first-pass evaluation of the nine alternative operations was based on a 40x60-year synthetic inflow time series. The simulation results were evaluated based on minimizing three variables: (1) average yearly spilled water, defined as water released without any specific purpose, due to the pool elevation exceeding the guide curve; (2) probability of Pactola low-water failure, defined as the percent of days Pactola's pool elevation falls below 4520 ft (approximately 1/3 of its capacity); and (3) the percent of Pactola low-release days, defined as flows less than 35 cfs; releases below this threshold detrimentally affect the Rapid Creek trout fishery. These metrics were used to evaluate the alternatives and determine the preferred operational set. A more comprehensive comparison between the preferred and published system operations was done based on simulation of a 500x60-year synthetic inflow time series. Analysis of the 500x60-year inflow data indicates the sample number was sufficiently large to be statistically representative of the population of possible outcomes.

The preferred operational set provides greater winter flow for the trout fishery and allows more inflow during the wet season (spring/early summer) to be captured by the reservoirs. The primary drawback is the potential increase in probability of low-water failure. The simulation results indicate, relative to the published operational set, the preferred operational set reduces: (1) the average yearly spilled water by 2,736 acre-ft (36.1%); (2) Pactola low-water failure days by 0.052%, and; (3) Pactola low-release days by 30.78%. In the 30,000 years of simulation, the preferred alternative results in 127 years in which the pool level fell below the low-water failure criteria during any portion of the year, while the published operations set results in 178 years.

The model developed for this study allows for the evaluation of outcomes for any n-year time period starting from any initial condition. The simulation framework allows for the consideration of inflow conditions beyond the available historical data by modifying the conditional probabilities of wet-wet and/or dry-dry sequences or by directly incorporating synthetic inflows generated by climate and hydrological models. The model allows for direct quantitative comparison of alternative operational sets with either the published or preferred operational set developed in this analysis.

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1. Introduction

1.1. Introduction to Reservoir Management

Construction of new, large scale water resource projects has diminished in the United States and other developed countries. In addition, many large storage projects around the world are not producing the level of benefits which economically justified their initial development (World Commission on Dams, 2000). As a result, attention needs to be directed towards optimizing the performance of existing reservoir systems in order to maximize the project benefits, or objective functions, such as municipal/industrial water supply, flood control, hydroelectric energy, providing minimum streamflow for environmental and ecological purposes, and water-based recreational activities. Optimizing the numerous aspects of reservoir systems requires the assistance of computer modeling tools to provide the information required to make rational management decisions. These tools are being used globally to optimize and improve the management of reservoir systems by analyzing alternate operating scenarios, determining how to schedule releases and movement of water during flood control operations to minimize flooding, and providing real-time decision support with regards to reservoir operations (Labadie, 2004).

When designing and operating a reservoir, water requirements, objective functions and operational rules are crucial factors that need to be considered. For an existing reservoir, each objective function will have its own set of optimum operating rules. Reservoir operators are faced with the challenge of prioritizing these objective functions and managing the reservoir based on the various operating rules in such a way that the maximum benefit, or minimum penalty, results across all objective functions. Currently, most reservoir operating decisions are based on a rule curve which establishes a set of “firm-release” decisions for the delivery of sufficient water to ensure long-term, reliable water supply, hydroelectric energy or other purposes such as low-flow augmentation for navigation and ecological purposes. These releases, often a function of the time of year, are typically considered to be minimum release flows to be met when storage capacity allows for it. In addition, an “upper rule curve” is often provided to help operators determine the reservoir elevation at which minimum releases are to be exceeded and excess water is to be released for beneficial purposes. Similarly, a “lower rule curve” establishes an elevation that, when the reservoir drops below that level, indicates water releases should be reduced (Yevjevich, Hall, & Salas, 1981).

These rule curves help inform operators when releases above or below the minimum should be made; however, the decisions regarding the magnitude of the releases and how quickly the reservoir should be restored to levels indicated by the rule curve are left to the operator. Yevjevich et al. (1981) identified two objectives of reservoir management for conservation. The first is that spill losses, or water released from the reservoir without any sort of benefit or useful purpose, should be minimized. The second is that the frequency and magnitude of deficits in water supply and/or energy production with respect to planned levels should be kept to a minimum. Day-to-day reservoir operations should be guided primarily by these two purposes, along with any other objectives specific to the reservoir being analyzed (Yevjevich, Hall, & Salas, 1981).

1.2. Reservoir Optimization Techniques

Advances in the field of water resources engineering have allowed for the development of optimization techniques for planning, designing, and managing complex water resource systems. After the objectives and constraints of the system have been identified, solution techniques can be utilized to provide an optimized operational strategy. High-speed computers deliver readily available solutions which provide operational alternatives and assist reservoir managers in their decision making (Yeh, 1985).

In general, the available methods of reservoir optimization can be divided into four groups: linear programming (LP), dynamic programming (DP), nonlinear programming and simulation (Labadie, 2004). LP, DP, and nonlinear programming are mathematical programming techniques which prescribe an optimum solution for system operations which meets the system constraints while either maximizing or minimizing some objective. In contrast, simulation models provide the response of a reservoir system based on certain inputs such as physical characteristics of the reservoirs and operational rules. The reservoir manager can analyze the benefits and consequences of operating the reservoir system a certain way without having to make the actual changes. Simulation models are more flexible and versatile when simulating the system response, however, they are limited to a finite number of input decision alternatives. In contrast, mathematical programming techniques typically require assumptions regarding model structure and system constraints for real-world application yet look at all possible decision alternatives in order to find the optimum (Yeh, 1985).

Mathematical models have allowed for the assessment of alternative operating policies for reservoir systems. An example is the Trent River system in Ontario, Canada which consists of 48 reservoirs. This multireservoir system is used for flood control, water supply, hydropower and augmenting flows through the canal system during the summer. Over the years, conflicts have arisen when trying to satisfy the numerous objectives of the reservoir system, resulting in the need to assess alternative operating policies (Sigvaldason, 1976). In order to evaluate these various scenarios, a mathematical model simulating the operation of the system was developed. The model determines the optimal operating strategy for the reservoir system for each time interval by using a nested optimization linear programming submodel which uses the out-of-kilter algorithm. Each reservoir utilized a rule curve and was subdivided into five time-based storage zones. Normal and extended flow ranges were established for each channel which were dependent on the upstream reservoir's zone. Objective functions for each reservoir were derived which contained penalty coefficients representing the "cost" or penalty of operating the reservoir under nonideal conditions. Based on these objective functions, the model computes the minimum penalty response of the system for each time interval within the simulation model. This model was used extensively to assess system response under various operating and hydrologic conditions for the Trent basin. It was converted into an operational model and, as of February 1975, was being used as a tool to aid in the day-to-day operations of the Trent system.

In addition to supporting day-to-day operations, computer models can aid in the evaluation of flood control operations and storage requirements. A study was done on the Bonny Reservoir in eastern Colorado in which the hydrological record was used to evaluate the suitability of the flood control storage and the existing flood control operational policies (Yevjevich, Hall, & Salas, 1981). Extreme flood hydrographs were developed by analyzing storm events for the area. A regional frequency analysis of flood volumes was performed and showed a storm volume of 100,000 acre-feet was equal to a 500-year flood event. The flood storage capacity of Bonny Reservoir is equal to 128,800 acre-feet which indicates that the conservation pool may be raised by 10 feet, increasing the storage by 25,000 acre-feet, with little to no impact on flood control results. In addition, current flood control operation policies for Bonny Reservoir were compared to those found by optimization and simulation techniques by looking at the effects of the downstream reservoir. Five generated storm hydrographs were routed through the reservoir system using a computer algorithm simulating the standard operating procedure and a dynamic programming optimization algorithm. The results indicated that releases were lower for the more extreme events and higher for the less extreme storm events with the optimized dynamic programming algorithm than the simulated standard operating procedure.

Challenges arise with mathematical and simulation models when contending with streamflow and demands of water resource systems. Reservoir optimization techniques which treat stochastic inputs and firm output levels as deterministic or random sets of equally likely sequences, provide an efficient means of finding an optimum solution; however, they often ignore the probability of failure associated with the results. Askew et al. (1971) proposed that Monte Carlo techniques be used to generate long streamflow records as inputs in order to assess the response of a system to periods of greater extremes than what has occurred in the historical record. A study was done on the Shasta Dam located in northern California on the Sacramento River using Monte Carlo techniques (Askew, Yeh, & Hall, 1971). This single multipurpose reservoir was analyzed in order to determine the contract levels which maximized the financial return without exceeding a specified level of risk of failure to meet those levels. The input to the system was a set of 200 generated streamflow records, each with a length of 50 years with initial conditions reestablished at the start of each record. The system was analyzed by initiating simulations with a range of storage levels in each of the 12 months. The reservoir system was said to have "failed" if the system storage was reduced below the active storage level at least once in the 50-year simulation. The probabilities of failure associated with various states of the system were generated as a function of the initial month and storage. This information was provided to the reservoir operator in order to help guide decision-making and release rules.

1.3. Pactola/Deerfield Reservoir System

Centrally located in the Black Hills region of southwestern South Dakota, the upper Rapid Creek basin is a mountainous region with elevations ranging from 7,000 feet in the hills to 3,200 feet at Rapid City, South Dakota. The Rapid Valley Unit of the Pick-Sloan Missouri Basin Program consists of the Pactola Dam and Reservoir located 15 miles west of Rapid City along Rapid Creek and the Deerfield Dam and Reservoir located 28 miles upstream of Pactola on Castle Creek, a tributary of Rapid Creek. The study site for this project extends from Deerfield to Rapid City Regional Airport located 25 miles downstream of Rapid City. Deerfield outflows to Castle

Creek which flows for 19 miles until it converges with the North Fork of Rapid Creek to form Rapid Creek, the primary source of inflow into Pactola, as shown in Figure 1.

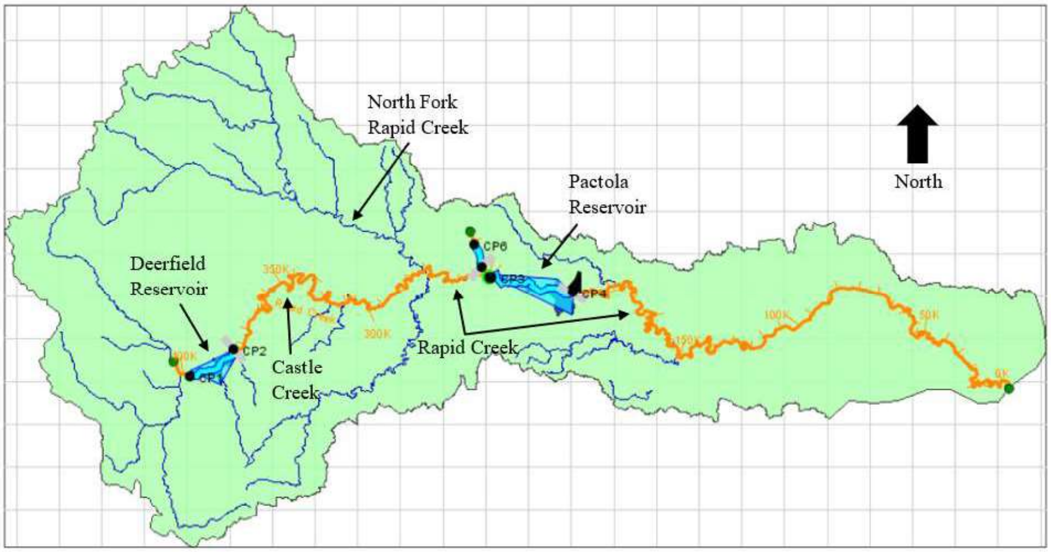

Figure 1: Map of the Rapid Valley Unit

Located nine miles downstream of the confluence and constructed by the United States Bureau of Reclamation (USBOR) in 1956, Pactola's primary purposes are municipal water supply, irrigation and flood control with fish, wildlife and recreation being secondary beneficial functions, as shown in Figure B.1. Pactola provides approximately 55.0 k acre-ft of storage in its conservation pool. Deerfield provides an additional 15.5 k acre-ft of storage, shown in Figure A.1. To put these storage volumes in the context of annual inflow volumes, a histogram of past annual inflow volumes into Pactola is provided as Figure 2, based on data from the USBOR (USBOR, 2018). Between the two reservoirs, a full water supply is provided to Rapid City, including Ellsworth Air Force Base (EAFB), for irrigation and municipal purposes.

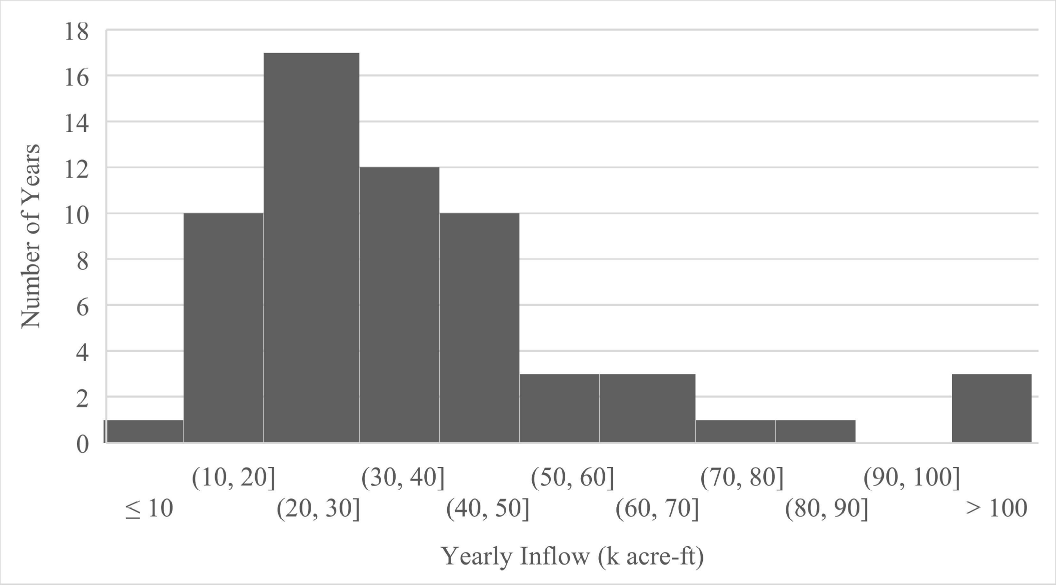

Figure 2: Histogram of yearly inflow into Pactola Reservoir

The most recent contract between the USBOR and the City of Rapid City, dated July 31, 2007, states that the city has a right to 49.0 k acre-feet of storage annually in Pactola Reservoir. Of this 49.0 k acre-feet of storage, up to 3.0 k acre-feet is allocated to EAFB. In addition, 6.0 k acre-feet of Pactola Reservoir's conservation storage is maintained and administered by the BOR to supplement minimum winter release flowrates for beneficial uses compatible with enhancement of fish and wildlife purposes (USBOR, 2007).

The USBOR is responsible for operating the reservoir system under normal operating conditions. These operations are guided by recommended minimum releases for Deerfield and Pactola outlined within the Pooled Storage Operating agreement shown in Table C.1 (USBOR, 2007). Releases exceeding these minimum values are in response to water calls made by the City of Rapid City or done at the discretion of the reservoir operator. A histogram of past annual water call volumes is provided as Figure 3. Given the various sources of the Rapid City water supply, a method to predict water calls based on variables such as precipitation or reservoir inflows does not presently exist. Currently, no simulation models have been developed by the agencies to help manage the reservoir system. When Pactola's pool level exceeds 4580.2 ft and encroaches into the flood control zone, its management is assumed by the U.S. Army Corps of Engineers (USACE) and outflows are dictated per the release schedule shown in Table B.5 (USACE, 1976).

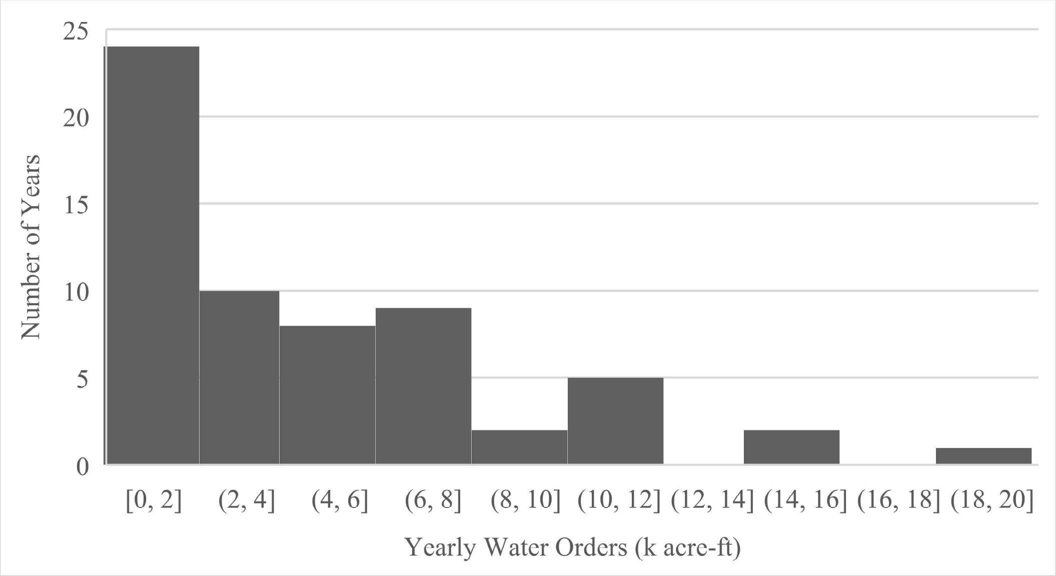

Figure 3: Histogram of yearly water orders

1.4. Objectives of Analysis

The focus of this thesis is combining simulation modeling techniques with a Monte Carlo analysis for the purpose of analyzing alternative operating scenarios for the two reservoirs. Reservoir operations are evaluated based on three parameters: average yearly spilled water, probability of low-water failure of the reservoir system, and Pactola low-release days. Each of these parameters has a relation to the objective functions of the reservoirs (water supply, flood control, etc.) as will be explained in the analysis. The alternative management proposals are compared to the current standard operating procedure with the intent of improving Pactola and Deerfield reservoir system operations.

2. Methods

2.1. An Overview of HEC-ResSim

The Reservoir System Simulation, HEC-ResSim, software is the successor to the "HEC-5" Simulation of Flood Control and Conservation Systems" program (USACE, 2013). Developed by the U.S. Army Corp of Engineers, it is a mass balance software designed to model and optimize the operations of reservoirs and reservoir systems based on a variety of operational goals and constraints. It simulates reservoir operations for flood risk management, low flow augmentation and water supply for planning studies, detailed reservoir regulation plan investigations, and real-time decision support. When making a release decision, HEC-ResSim tries to hold the pool elevation to the guide curve until some constraint, such as a maximum or minimum flow rate, prevents it from doing so. This often results in rapidly fluctuating releases which do not well-represent how Pactola and Deerfield reservoirs are presently operated. The Data Storage System, HEC-DSS is used for storage and retrieval of input and output time-series data. HEC-ResSim consists of three separate functions, or modules: (1) watershed setup, (2) reservoir network, and (3) simulation.

The watershed setup module provides a common framework for creating the watershed and is shared among multiple programs. Within this module, items describing the watershed's physical arrangement (background maps, stream alignment, etc) are compiled and elements (reservoirs, levees, diversions, etc) are configured. In addition, projects can be added, and time-series icons created.

Within the reservoir network module, the foundation of the reservoir network is created based on the configurations generated in the watershed module. Network elements such as routing reaches and junctions are added in order to complete the connectivity of the reservoir system. Once the schematic is finalized, the physical and operational data for each network element is defined. For each reach, a routing method can be selected, and parameters specified. Reservoir physical parameters (stage-volume curve, outlet discharge curves, evaporation rates, etc.) and operational parameters (guide curve, various operating rules, etc.) are specified. Next, alternatives are created which state the reservoir network, operation set(s), initial conditions, and assignment of DSS pathnames (time-series mapping).

Once the reservoir network is complete and the alternatives have been defined, the simulation module is used to configure the simulation and separate the output analysis from the model development process. Within the module, the computations are performed, and results are viewed. When creating a simulation, the simulation time window, computation interval and the alternatives to be analyzed are specified. HEC-ResSim then creates a DSS file for the specific simulation which will contain all the input and output DSS records for the selected alternatives.

2.2. Watershed Setup

For the Deerfield, Pactola and Rapid Creek systems model, the watershed of Rapid Creek was delineated using the USGS StreamStats site and imported into HEC-ResSim as a background map. A shapefile of the South Dakota water bodies was downloaded from the South Dakota GIS Data site (SDGFP, 2018). The water bodies file was clipped using the watershed shapefile in ArcMap 10.5.1 and both shapefiles were imported into HEC-ResSim as background layers. Using the layers as guidance, the stream alignment for Rapid Creek was created, extending from a few miles upstream of Deerfield downstream past Pactola for approximately 31 miles to USGS Gage 06418800 near Rapid City Regional Airport. In addition, Pactola and Deerfield were created in the model as reservoir elements.

Pactola's outlets consist of two regulation and two emergency sliding gate valves and one 10" bypass line and valve. When the regulation gate valves are operated at flows less than 35 cfs, USBOR has reported that cavitation occurs (Wessel, 2018). Therefore, for required outflows less than 35 cfs, the bypass line is utilized, which has a maximum capacity of 20 cfs. Due to standard release decisions used by HEC-ResSim, difficulty was experienced getting the model to preclude outflows between 20 and 35 cfs under all circumstances. To overcome this model limitation, a diversion was added just downstream of the Pactola outlet. When HEC-ResSim specifies a release between 20 and 35 cfs, the diversion reduces the release to 20 cfs and diverts the difference to a hypothetical sink, thus eliminating that volume of water from the system. To compensate for this and ensure mass conservation, a 'hypothetical' storage reservoir, located upstream of Pactola on a separate tributary, supplies this diverted release by adding it back into the reservoir as inflow during the succeeding timestep. The complete watershed setup is shown below in Figure 4 below.

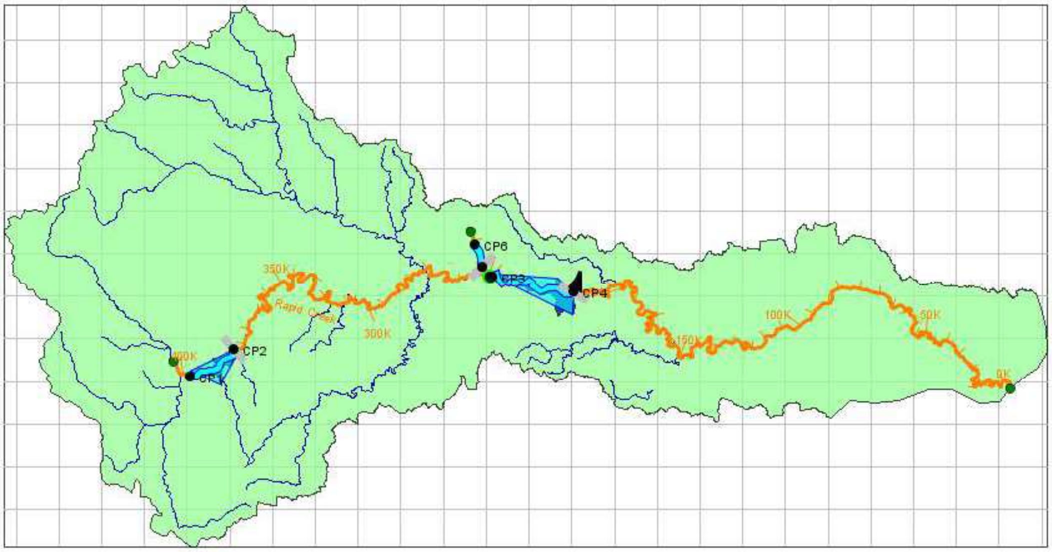

Figure 4: HEC-ResSim watershed setup for model

2.3. Reservoir Network

For the Deerfield, Pactola and Rapid Creek model, a single reservoir network was created from the watershed configuration which contained Deerfield, Pactola and the ‘hypothetical’ storage reservoir. A junction was established at the confluence of Castle Creek and North Fork Rapid Creek in order to add in flows from the tributary. The stream routing parameters, reservoir parameters, operating alternatives and input time series data were also entered. The completed reservoir network schematic is shown in Figure 5 below.

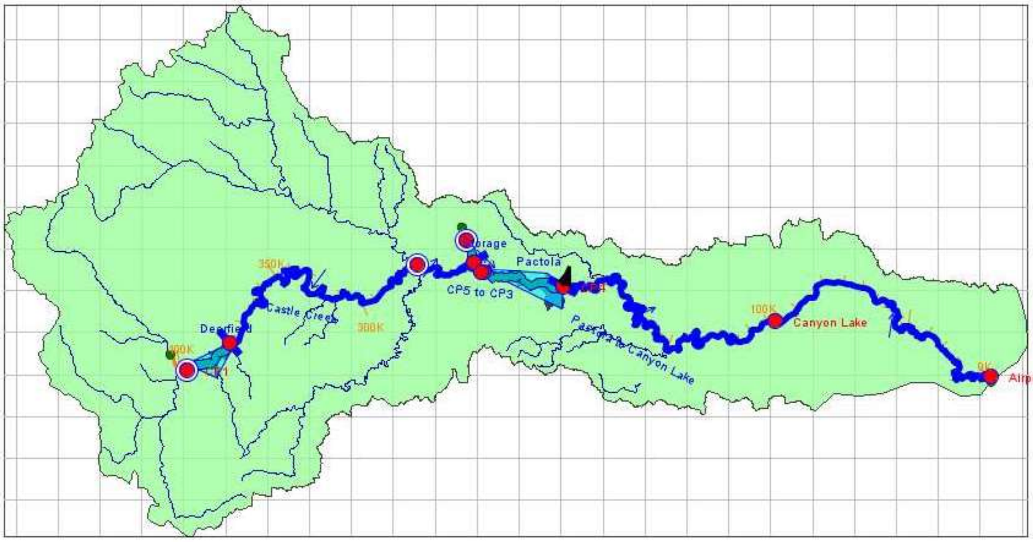

Figure 5: HEC-ResSim reservoir network for model

2.3.1. Stream Routing

2.3.1.1. Muskingum-Cunge Prismatic Channel Flow Routing

The Muskingum method is a hydrologic routing method frequently used to model variable discharge-storage relationships by means of wedge and prism storages within the channel (Chow, Maidment, & Mays, 1988). The total storage within a reach is the sum of the prism of storage, formed by a volume of constant cross section along the length of the prismatic channel, and the wedge of storage that is a result of an incoming or receding flood wave. This relationship is shown below in equation 1

$$S = K[XI + (1 - X)Q] \qquad [1]$$

where S is the storage within the channel, K is a storage constant having dimensions of time, X is a weighting factor expressing the relative influence of inflow on storage levels with the range of $0 \leq X \leq 0.5$, I is input, and Q is output.

Considering the values of space at distance i and $i + 1$ and time j and $j + 1$, the Muskingum routing equation can be written for discharge at $x = (i + 1)\Delta x$ and $t = (j + 1)\Delta t$:

$$Q_{i+1}^{j+1} = C_1 Q_i^{j+1} + C_2 Q_i^j + C_3 Q_{i+1}^j \qquad [2]$$

where C_1, C_2, and C_3 are coefficients that are functions of Δt, K and X shown below in equations 3, 4 and 5.

$$C_1 = \frac{\Delta t - 2KX}{2K(1-X)+\Delta t} \qquad [3]$$

$$C_2 = \frac{\Delta t + 2KX}{2K(1-X)+\Delta t} \qquad [4]$$

$$C_3 = \frac{2K(1-X) - \Delta t}{2K(1-X)+\Delta t} \qquad [5]$$

Cunge (1969) showed that, when K and Δt are constant, K and X can be approximated using equations 6 and 7

$$K = \frac{\Delta x}{c_k} = \frac{\Delta x}{dQ/dA} \qquad [6]$$

$$X = \frac{1}{2}\left(1 - \frac{Q}{B c_k S_0 \Delta x}\right) \qquad [7]$$

where A is the cross-sectional area of the prism which is dependent on Q, S_0, n, and the cross-sectional geometry; c_k is the celerity corresponding to Q and B; B is the width of the water surface; and S_0 is the slope (Chow, Maidment, & Mays, 1988).

2.3.1.2. Data for Model Parameterization

Routing parameterization was performed for Rapid Creek by dividing the stream into two reaches. The first reach extends from USGS Gage 06411500 located below Pactola Dam to USGS Gage 06412500 above Canyon Lake. The second reach extends from USGS Gage 06414000 below Canyon Lake to USGS Gage 06418800 near Rapid City Regional Airport. Gage data does not exist between Deerfield and Pactola, which precludes calibrating model parameters for this reach. The following procedure outlines the steps taken to assign parameter values of length, slope, Manning's n, side slope and bottom width for each reach.

A 30-meter digital elevation map (DEM) of the study area, obtained from South Dakota Department of Energy and Natural Resources (SDDENR, 2015), was imported into ArcMap 10.5.1. Analysis was performed on the sections of Castle Creek and Rapid Creek which extend from the outflow of Deerfield Reservoir down to Rapid City Regional Airport. HEC-GeoHMS 10.1 was used to obtain a river elevation profile from the DEM. From this profile, the elevation change, length and slope for each reach of the river was determined.

The Muskingum-Cunge Prismatic Channel flow routing method was used to model the reaches of Castle Creek and Rapid Creek in HEC-ResSim. Initial estimates of Manning's n, side slope, and bottom width were approximated by referencing FEMA flood control studies and using Google Earth Pro 7.3.2.5776 to take stream width measurements. Each separate reach of the stream was modeled using 15-minute interval time series data from USGS stream gages. Later in the analysis, a 1-day interval will be used; however, a flood wave passes through the entire domain in less than a day, therefore a smaller time interval was required in order to permit model calibration.

2.3.1.3. Relative Sensitivity Analysis

Calibrating a model which has numerous input values can be simplified by identifying which parameters have the most impact on the model results and focusing calibration efforts on those. Using flow data from USGS Gage 06411500 located below Pactola Reservoir and USGS Gage 06412500 above Canyon Lake, a relative sensitivity analysis was done on the reach of Rapid Creek that extends between the two dams. Three separate events were found in which an increase in flow was observed at the upstream gage, propagated through the reach and registered at the downstream gage. The effects of side slope, bottom width, and Manning's n on the modeled hydrograph centroid time at the downstream gage, t_{cent}, were evaluated. The hydrograph centroid time was calculated using equation 8

$$t_{cent} = \frac{\sum_i^n Q_i t_i \Delta t}{\sum_i^n Q \Delta t} \tag{8}$$

where Q_i is the flow at time i, t is the time, and Δt is the time interval.

Using the initial estimates for Manning's n, side slope, and bottom width, simulations for each of the three flow events were run and the initial hydrograph centroid time, $t_{cent,1}$, was calculated for each event. To determine the impact of each parameter on the centroid time, the initial parameter value, p_1, was multiplied by 0.5 and 1.5 yielding p_2 and p_3, respectively. Two additional simulations were run, and the new centroid times, $t_{cent,2}$ and $t_{cent,3}$, were calculated. The percent relative sensitivity, RS, for each parameter was calculated using equations 9 and 10.

$$RS = \frac{\frac{t_{cent,2} - t_{cent,1}}{t_{cent,1}}}{\frac{p_2 - p_1}{p_1}} * 100 \tag{9}$$

$$RS = \frac{\frac{t_{cent,3} - t_{cent,1}}{t_{cent,1}}}{\frac{p_3 - p_1}{p_1}} * 100 \tag{10}$$

Table 1 shows the percent relative sensitivity for each parameter on the centroid time averaged over the three flow scenarios.

Table 1: Average percent relative sensitivity on centroid time

	$p_2/p_1 = 0.5$	$p_3/p_1 = 1.5$
Bottom Width	0.575	0.640
Side Slope	1.024	0.691
Manning's n	4.147	3.725

2.3.1.4. Root Mean Square Error (RMSE) Analysis

To determine the values of Manning’s n, side slope, and bottom width for each reach, root mean square error (RMSE) analyses were performed. For each reach, three flow events were found in which a flow wave recorded on the upstream gage propagated through the reach and registered on the downstream gage. Using the time series data from the upstream gage as the inflow time series into HEC-ResSim, the three parameters were adjusted to reduce the RMSE between the calculated downstream flow and observed downstream gage flow measurement.

Initially, four values of Manning’s n were evaluated for each reach while bottom width and side slope remained constant. For each time simulation and Manning’s n value, the RMSE was calculated using equation 11

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Q_i' - Q_i)^2}{n}} \qquad [11]$$

where Q_i is the observed flow at the downstream gage at time i, Q_i' is the calculated flow at the downstream gage at time i, and n is the total number of time intervals. The overall RMSE for all three flow scenarios for each Manning’s n was calculated using equation 12

$$Overall\ RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Q_{i,1}' - Q_{i,1})^2 + (Q_{i,2}' - Q_{i,2})^2 + (Q_{i,3}' - Q_{i,3})^2}{n_1 + n_2 + n_3}} \qquad [12]$$

where subscripts 1, 2, and 3 refer to the three time simulations. This process was repeated for side slope and bottom width for each reach. The results are displayed in Table 2.

The results of the RMSE analysis were verified by finding a fourth event for each reach in which a flood wave was registered at the upstream gage and propagated through the stream and observed at the downstream gage. The model was run for each reach using the parameters in Table 2 and then compared to the downstream gage flow readings. The RMSE of these simulations, reported in Table 2, indicate a reasonably well-calibrated routing model.

For the reach of Castle Creek and Rapid Creek upstream of Pactola, flow data from USGS Gage 06410000 located directly downstream of Deerfield Dam was compared to flow data from USGS Gage 06410500 located on Rapid Creek directly upstream of Pactola Reservoir. By comparing the two sets of gage data, it was determined that the outflow from Deerfield Reservoir only accounts for approximately 10% of the inflow into Pactola Reservoir with the majority being supplied from North Fork Rapid Creek, an ungaged stream. Due to the limited availability of data for this reach of Castle Creek and Rapid Creek, it was assumed that the Manning’s n and side slope of this section were equivalent to the section of Rapid Creek which extends from Pactola Reservoir to Canyon Lake. The bottom width of this section of the stream was determined by taking the average of three representative aerial stream width measurements using Google Earth Pro 7.3.2.5776 and approximated to be 20 feet.

Table 2: Reach routing parameters

	Deerfield to NFRC	**NFRC to Pactola**	**Pactola to Canyon Lake**	**Canyon Lake to Airport**
Length (ft)	100,305	49,518	86,706	73,276
Manning's n	0.070	0.070	0.070	0.030
Side Slope (ft/ft)	5	5	5	5
Bottom Width (ft)	20	20	30	10
RMSE	---	---	0.0374	0.1771

2.3.2. Deerfield Reservoir Parameters

2.3.2.1. Deerfield Reservoir Physical Parameters

Deerfield's physical parameters included the reservoir stage-volume curve, the spillway and main valves discharge curves, and pool evaporation data. The data are shown in Table A.2 and A.3. For the discharge curves for the main valves, a single maximum value of 90 cfs was inputted independent of the reservoir elevation. Although the total maximum discharge capacity of the main valves exceeds 350 cfs, it was inputted as 90 cfs which is the safe channel capacity of Castle Creek (USBOR, 2007). Pool evaporation was determined for both Pactola and Deerfield by obtaining the total monthly evaporation data for Deerfield and Pactola from 1994 through 2018 from HydroMet, a network of automated hydrologic and meteorologic monitor stations maintained by the USBOR (USBOR, 2018). The average total monthly evaporation for Deerfield and Pactola was determined by calculating the average for each month based on the 24 years of data and converting to inches, shown in Table C.2.

2.3.2.1. Deerfield Reservoir Operating Parameters and Alternatives

Inputted operational data for Deerfield included the guide curve, creation of four operating storage zones, maximum and minimum release rules, flow rate of change limits for the main valves specific to each storage zone, and a series of rules which establish a guide curve tolerance. Various alternative operating scenarios were created by manipulating the minimum release criteria, tandem operating rule (how releases are made based on conditions at Pactola), and elevations associated with the storage zones.

Deerfield Reservoir is unique in that it does not have a specified flood control zone, as shown in Figure A.1. General operating procedures specify that the reservoir be filled to the spillway crest, 5908 ft, during summer months and be allowed to drop to 5906.5 ft during the winter (USBOR, 2007). The guide curve, or target elevation, along with the spillway crest and top of the inactive storage, is shown in Figure 6 below.

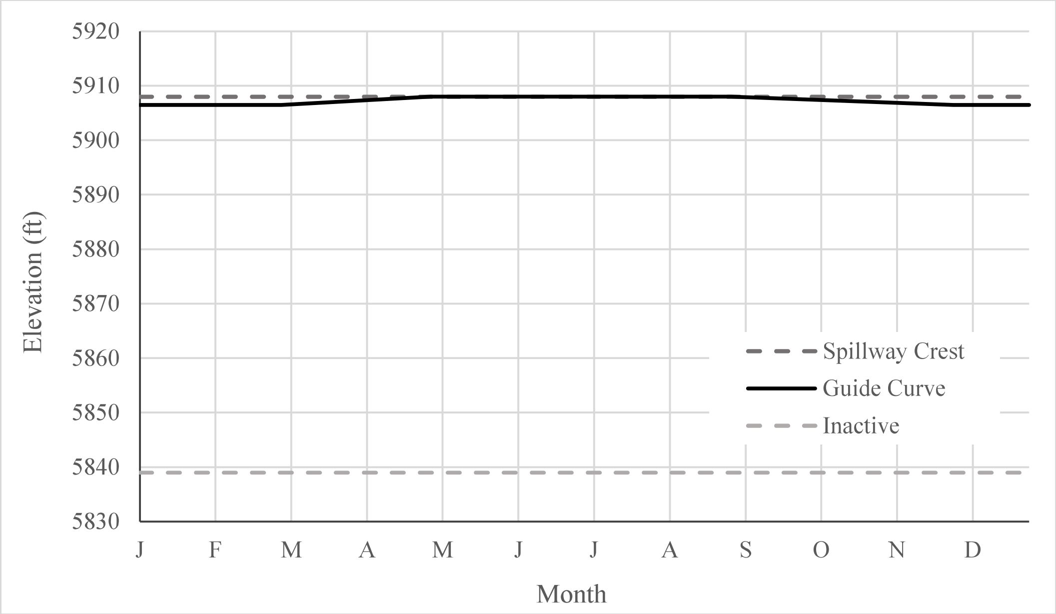

Figure 6: Deerfield guide curve *(USBOR, 2007)*

In order to implement various operating rules for the reservoir, the storage was divided into zones. Daily average inflow, elevation, storage and release data from Oct 1, 1958 through September 30, 2018 for Deerfield was acquired from HydroMet and analyzed (USBOR, 2018). Four storage zones were developed based on historical operating trends and are shown in Figure 7 below, where the top of the zone is indicated by the curve.

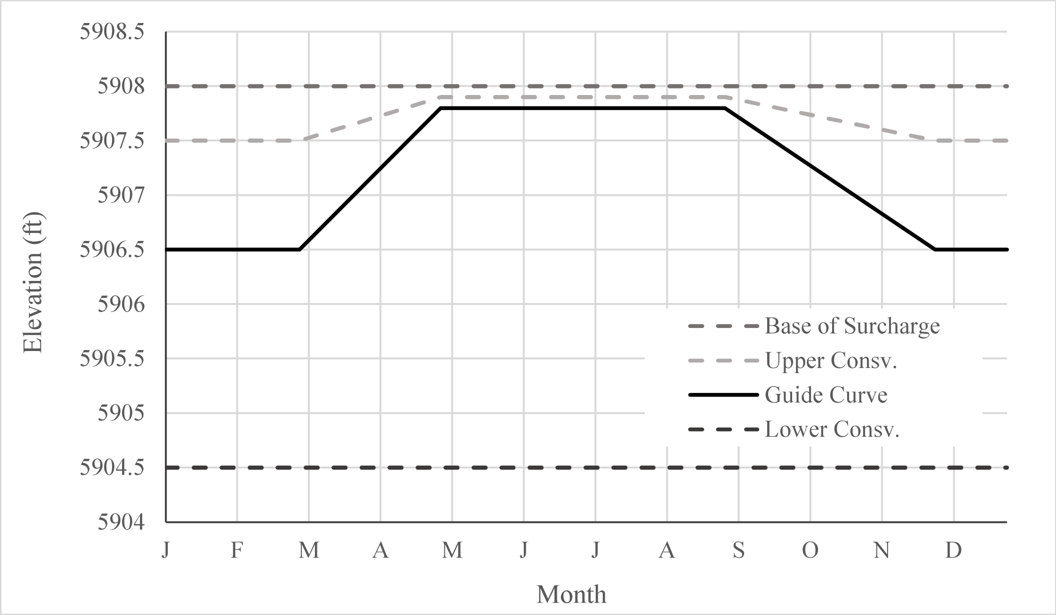

Figure 7: Deerfield operating zones based on historical operating trends

For each zone, a series of operating rules was implemented. The maximum release from the main valves was specified to be 90 cfs for all zones. In order to better represent current reservoir operations, flow rate of change limits and a guide curve tolerance were established. The maximum rate of change of flow in the surcharge zone was specified to be 3 cfs/hr and 1 cfs/hr when the pool elevation is in the remaining three zones. These limits prevent drastic fluctuations in the reservoir outflow and better represent how releases are managed by the reservoir operators. The guide curve tolerance rule specifies that the release remains constant when the reservoir elevation is between the upper and lower conservation zones, reducing the frequency of release adjustments when the elevation is within an acceptable range.

In order to analyze Deerfield's operations, five operating alternatives were developed in which the minimum release from the reservoir, tandem operating rule, and/or reservoir storage zones were manipulated. The tandem operating rule is built into HEC-ResSim. The default implicit system storage balance was used which takes into account the system storage, or total storage from both reservoirs. The desired storage for each reservoir corresponds to both having an equal percentage of the system storage above or below the guide curve of each reservoir (USACE, 2013).

The five reservoir operating alternatives for Deerfield are summarized below:

- DFR_Alt1_PO: An alternative which models the published standard Deerfield reservoir operations. The tandem rule was not implemented for any zone and the minimum release for the main valves was held constant at 2 cfs.
- DFR_Alt2_PO_Tand: An operating procedure similar to DFR_Alt1_PO in that the minimum release is specified to be 2 cfs for all elevations and zones, however the tandem operating rule is implemented in each zone.
- DFR_Alt3_5: An operating procedure in which the minimum flow rate is 5 cfs and the tandem rule is implemented in each zone.
- DFR_Alt4_SS: An alternative which has the minimum flow rate vary based on the reservoir elevation, as shown in Table 3; the tandem rule is implemented in each zone.

Table 3: Deerfield minimum release for Alt4_SS and Alt5_GC

Reservoir Elevation in Feet M.S.L		**Minimum Release (cfs)**
From	**To**	
Below	5880	2
>5880	5890	5
>5890	5898	8
>5898	Above	10

- DFR_Alt5_GC: The minimum releases for this alternative are the same as DFR_Alt4_SS shown in the table above; however, the elevations associated with each zone have been lowered to create a larger buffer between the water surface elevation and the spillway. The modified zones are shown in Figure 8 below.

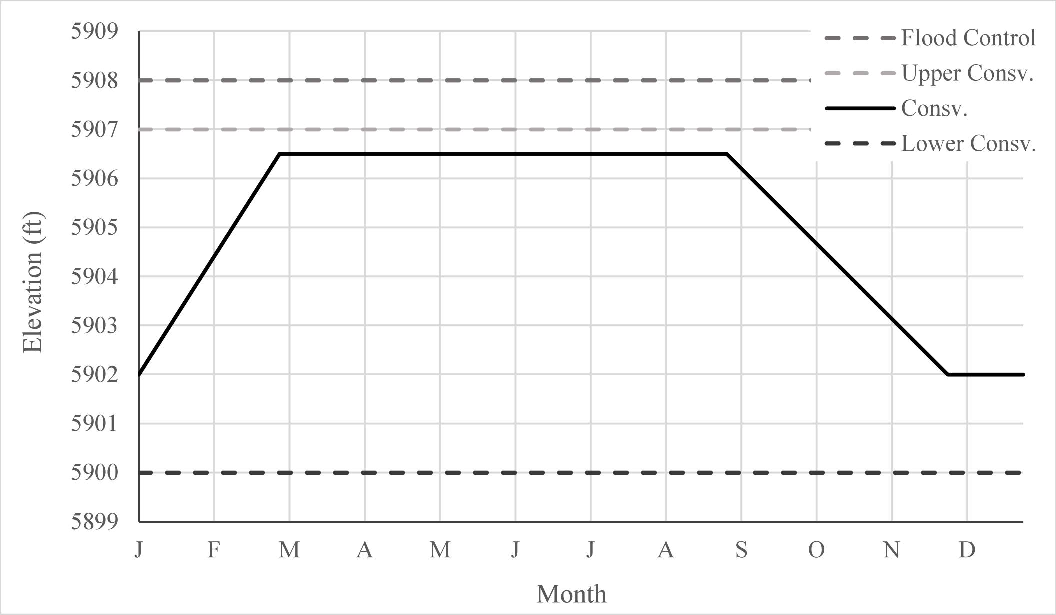

Figure 8: Modified Deerfield storage zones for Alt5_GC

2.3.3. Pactola Reservoir Parameters

2.3.3.1. Pactola Reservoir Physical Parameters

Inputted physical parameters for Pactola Reservoir included the stage-volume curve and discharge curves for the spillway and main valves which are shown in Tables B.2, B.3. and B.4, respectively. Pactola total monthly pool evaporation was determined using the method outlined in section 2.3.2.1 and is shown in Table C.2.

2.3.3.1. Pactola Reservoir Operating Parameters and Alternatives

Inputted operational data for Pactola Reservoir included the guide curve, creation of five operating storage zones, maximum and minimum release rules which take into account Rapid City water supply requirements, flow rate of change limits for the main valves specific to each storage zone, and a series of rules which establish a guide curve tolerance. Various alternative operating scenarios were created by manipulating the minimum release criteria.

Pactola Reservoir's pool is allocated into five divisions as shown in Figure B.1. The guide curve outlined within the general operation procedure specifies that Pactola be filled to the top of the conservation pool at 4580.2 ft during the summer and reduced to 4576.2 ft during the winter months as shown in Figure 9.

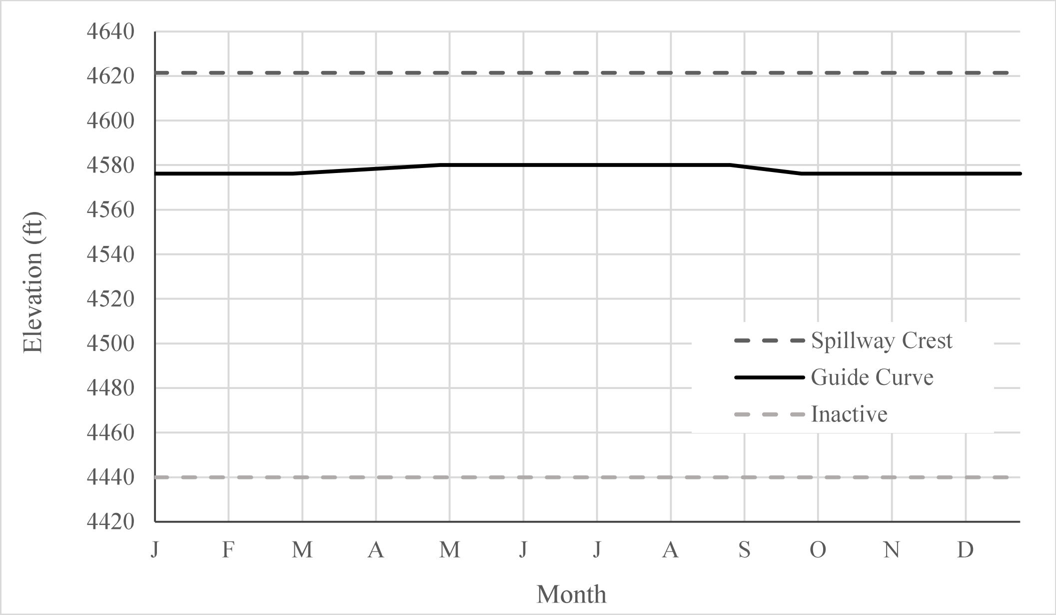

Figure 9: Pactola guide curve *(USBOR, 2007)*

When modeling Pactola, the flood control pool (elevation greater than 4580.2ft) was divided into two zones and the active conservation pool was divided into three zones.

The zones within the flood control pool consisted of the lower flood control zone, which extends from 4580.3 ft to 4582.0 ft, and the flood control zone which extends from 4582.0 to the top of the flood control pool at 4621.5 ft. The position and releases of both zones are dictated by the U.S. Army Corps of Engineers and are shown in Table B.5. The active conservation pool (elevation less than 4580.2ft) was divided into a lower conservation, conservation, and upper conservation zone shown in Figure 10. The location of these zones was determined by analyzing the historical operating trends of Pactola from 1958 through 2018 which were obtained from HydroMet (USBOR, 2018).

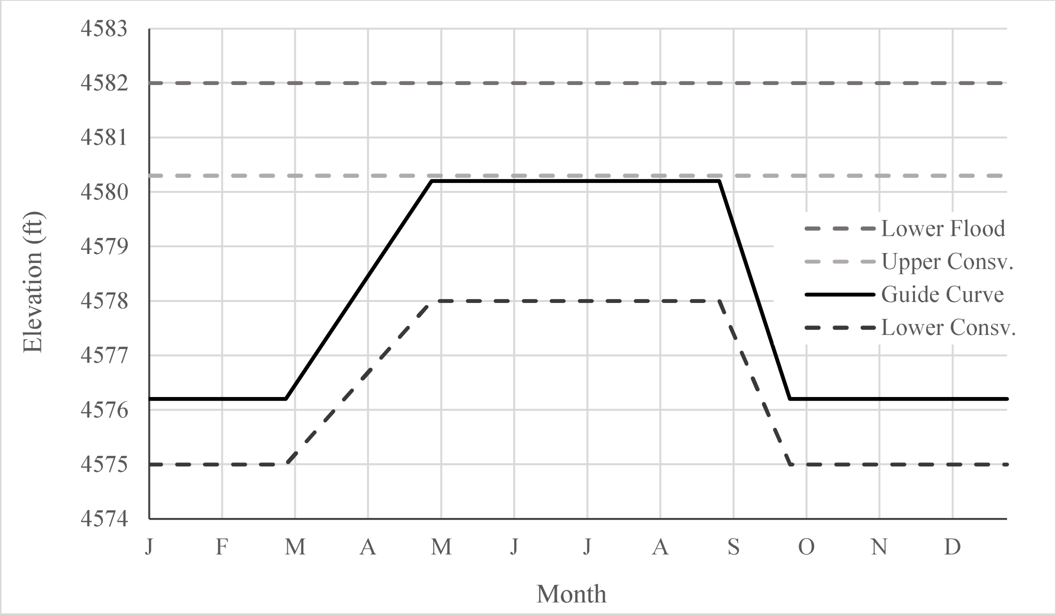

Figure 10: Pactola operational zones based on historical operating trends

Operating rules implemented within the three conservation zones and lower flood control zone included a maximum release limit from the main valves, flow rate of change limits, a series of rules which established a guide curve tolerance and a minimum release requirement which takes into account the water orders from the City of Rapid City. The maximum release from the valves within these four zones was specified as 250 cfs

(USACE, 1976). In order to limit drastic fluctuations in outflow and better represent actual operations, a flow rate of change limit of 2.0 cfs/hr was added when the pool elevation is in the lower flood control zone and 0.75 cfs/hr when the pool elevation is in the three conservation zones. In addition, a guide curve tolerance was implemented which eliminates changes in release when Pactola's elevation falls between the lower and upper conservation zones.

Taking into account the water calls associated with the City of Rapid City and the Rapid Valley Conservation District is problematic due to the complexity of the water order system and variance in the orders. Based on conversations with the various groups involved, it was determined that a flow rate of 12-15 cfs needs to be maintained from May 1 through September 30 at the USGS gage 06421500 near Farmingdale, SD, approximately 20 miles downstream of Rapid City. In order to determine the Pactola release that corresponds to this minimum flow rate, daily average discharge data from the Farmingdale gage and USGS gage 06411500 located below Pactola Dam were compared. The average outflow from Pactola which was associated with a flow at Farmingdale between 10-15 cfs was calculated to be 50 cfs. Therefore, the minimum release for all zones and operating alternatives from May 1 through September 30 was inputted as 50 cfs in order to approximate water orders.

Five reservoir operating alternatives were created for Pactola by manipulating the winter minimum release requirement from October 1 through April 30. These are summarized below.

- PTR_Alt1_PO: This operating alternative is based on the published standard operating procedures of Pactola. The winter minimum release fluctuates from 7 cfs to 20 cfs per Table 4 below (USBOR, 2007).

Table 4: Minimum releases from Pactola for PTR_Alt1_PO

Elevation (ft)		**Date**	**Release (cfs)**
From	**To**		
Below	4540	10/1-4/14	7
		4/15-4/30	20
		5/1-9/30	50
≥4540	Above	10/1-2/28	15
		3/1-4/30	20
		5/1-9/30	50

- PTR_Alt2_35: An operating alternative which establishes a winter minimum release of 35 cfs from Pactola independent of the reservoir elevation.
- PTR_Alt3_35_7: An operating procedure which has the winter minimum flow rates from Pactola set as 7 cfs or 35 cfs based on Pactola's reservoir elevation per Table 5 below.

Table 5: Minimum releases from Pactola for PTR_Alt3_35_7

Elevation (ft)		**Date**	**Release (cfs)**
From	**To**		
Below	4540	10/1-4/30	7
		5/1-9/30	50
≥4540	Above	10/1-4/30	35
		5/1-9/30	50

- PTR_Alt4_SS: An alternative in which the winter minimum release ranges from 7 cfs to 50 cfs (excluding the cavitation range between 20 and 35 cfs) depending on the reservoir elevation as shown in Table 6.

Table 6: Minimum releases from Pactola for PTR_Alt4_SS

Elevation (ft)		**Date**	**Release (cfs)**
From	**To**		
Below	4540	10/1-4/30	7
		5/1-9/30	50
≥4540	4550	10/1-4/30	15
		5/1-9/30	50
≥4550	4560	10/1-4/30	20
		5/1-9/30	50
≥4560	4570	10/1-4/30	35
		5/1-9/30	50
≥4570	4573	10/1-4/30	40
		5/1-9/30	50
≥4573	4576	10/1-4/30	45
		5/1-9/30	50
≥4576	Above	10/1-9/30	50

- PTR_Alt5_4560_35: This operating procedure has minimum release flow rates of 7, 15, 20, or 35 cfs depending on Pactola's water surface elevation as shown in Table 7.

Table 7: Minimum releases from Pactola for PTR_Alt5_4560_35

Elevation (ft)		**Date**	**Release (cfs)**
From	**To**		
Below	4540	10/1-4/30	7
		5/1-9/30	50
≥4540	4550	10/1-4/30	15
		5/1-9/30	50
≥4550	4560	10/1-4/30	20
		5/1-9/30	50
≥4560	Above	10/1-4/30	35
		5/1-9/30	50

2.3.4. 'Hypothetical' Storage Reservoir and Diversion Parameters

The purpose of the 'hypothetical' storage reservoir upstream of Pactola and the 'hypothetical' diversion at the outflow of Pactola is to represent the reservoir's inability to release ranges between 20 cfs and 35 cfs due to cavitation. The diverted flow is a function of the outflow from Pactola as shown in Figure 11 below. Therefore, any calculated outflows between 20 cfs and 35 cfs are reduced to 20 cfs and the difference is diverted to a ‘hypothetical’ sink that eliminates that volume from the model domain. This diverted outflow is then added back into Pactola as inflow in the following timestep via the storage reservoir to ensure mass conservation. The ‘hypothetical’ storage reservoir outflow converges with Rapid Creek just upstream of Pactola Reservoir. The ‘hypothetical’ storage reservoir was designed with a large elevation (10,000,000 ft) and storage capacity (10,000 k acre-ft) to ensure it did not run out of water during the simulations. The release from the controlled outlet valve was inputted as a function of the previous release from Pactola’s main valves and specified as shown in Figure 11.

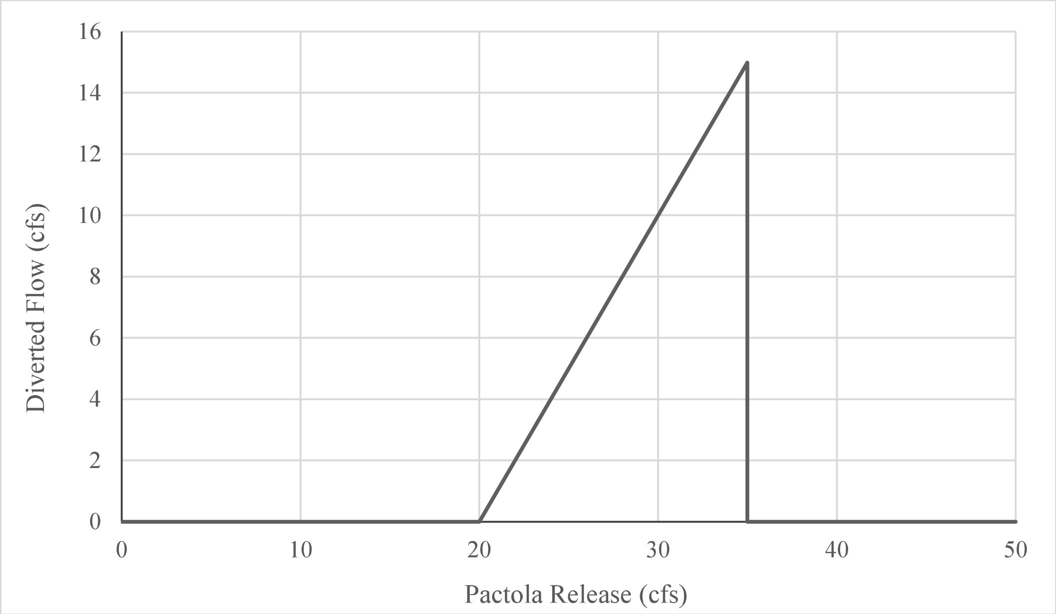

Figure 11: Relationship between the diverted flow as a function of Pactola's release

2.3.5. Time Series Data

Inflow time series were inputted into the model for Deerfield inflow, inflow from North Fork Rapid Creek and other tributaries between Pactola and Deerfield, and an inflow time series into the ‘hypothetical’ storage reservoir. The inflow time series into the ‘hypothetical’ storage reservoir specified a zero inflow; the data for the other two time series were obtained using HydroMet. Daily average Deerfield inflow and outflow data and Pactola inflow data was obtained from HydroMet for October 1, 1958 through September 30, 2018 (USBOR, 2018). To determine the portion of Pactola inflow contributed by North Fork Rapid Creek and the other tributaries, the difference between the Pactola inflow and Deerfield outflow was calculated for each day. This set of time series data was used as the model’s second inflow series.

2.3.6. Monte Carlo Time Series Generation

Data generation techniques, or Monte Carlo simulations, have been widely used in hydrology in order to examine numerous outcomes or possibilities from a system. In this analysis, 500 time series of 60 years were generated using the bootstrap method. The method creates a time series by repeatedly randomly selecting with replacement an annual inflow hydrograph from the existing data set of 61 annual inflow hydrographs. The random sequence is combined to create a long continuous time series.

Initially, the 61 years of time series inflow data from Deerfield and North Fork Rapid Creek were analyzed and the total yearly inflow, October 1 through September 30, from these sources was calculated. Each year was classified as “dry” or “wet” based on whether it was less than or greater than the median yearly inflow. Based on the observation that wet and dry years tend to occur in multiyear blocks, the conditional probability of a wet year being succeeded by a wet year and a dry year being succeeded by a dry year was calculated and is shown in Table 8. When creating each 60-year block of inflows, the first year was a random draw from the 61 years. The year was identified as either “wet” or “dry” and a random number generator in Microsoft Excel, VBA, was used to determine whether the following year would be a wet or dry year, based on the conditional probability. For example, the first year drawn is identified as a dry year and a random number is generated between 0 and 1. If the value of this random number is less than 0.633, the succeeding year will be chosen from the list of years identified as “dry” years. If the random number generated is greater than 0.633, the succeeding year will be chosen from the list of “wet” years. This process was repeated for each year within the 60-year time frame. The 60-year data sets were grouped into blocks of 40 sequences, which start on October 1, 2100 and ended September 30, 4500. A total of 500x60-year data sets were generated.

Table 8: Conditional probability of yearly climate trends

Year i	Year i+1	Probability (%)
Dry	Dry	63.3
Dry	Wet	36.7
Wet	Wet	66.7
Wet	Dry	33.3

2.4. Simulation

2.4.1. 40x60-year Monte Carlo Simulations of Operating Sets

Extensive computational time was required to evaluate 500x60-year blocks for a single combination of Deerfield and Pactola operation sets. To reduce the number of operating sets for full evaluation, a first pass evaluation of a smaller time series was implemented. The first pass time series evaluated was a sequence of 40x60-year blocks.

Nine combinations of Deerfield and Pactola operation sets were run for one 40x60-year block, from October 1, 2100 to September 30, 4500. At the end of each 60-year time frame, Deerfield and Pactola outflows and elevations were reset to their initial values per Table C.3. Initially, the five operation sets of Pactola were run and evaluated while Deerfield's operation set remained constant. The operation set for Pactola, PTR_Alt4_SS, was selected for further evaluation based on performance with respect to several evaluation metrics, while the different Deerfield operation sets were run and evaluated, as shown in Table 9 below.

Table 9: Alternative operation set combinations

	Operation Set	
Alternative	**Deerfield**	**Pactola**
1	DFR_Alt1_PO	PTR_Alt1_PO
2	DFR_Alt1_PO	PTR_Alt2_35
3	DFR_Alt1_PO	PTR_Alt3_35_7
4	DFR_Alt1_PO	PTR_Alt4_SS
5	DFR_Alt1_PO	PTR_Alt5_4560_SS
6	DFR_Alt2_PO_Tand	PTR_Alt4_SS
7	DFR_Alt3_5	PTR_Alt4_SS
8	DFR_Alt4_SS	PTR_Alt4_SS
9	DFR_Alt5_GC	PTR_Alt4_SS

2.4.2. 500x60-year Monte Carlo Simulations of Seleted Operating Sets

Alternative 7 was determined to be the most promising combination of operational sets for Pactola and Deerfield based on three evaluation metrics. Further analysis of this alternative, as well as Alternative 1, was done by running 500x60-year simulations using the generated time series inflow data. Statistical analysis was done on the yearly total inflow into the watershed to determine if enough simulations had been run for the results to be statistically representative of the full population of possible outcomes. The total volumetric inflow for each 60-year block, V_t, was determined using equation 13

$$V_t = \sum_{i=1}^{n} .00198 Q_i \qquad [13]$$

where V_t is the total volumetric inflow for the 60-year block in k acre-ft, Q_i is the daily average total inflow into the watershed in cfs, *n* is the number of days within the 60-year time frame, and 1.98E-03 is the conversion from cfs to k acre-ft in one year. The average yearly inflow, $\overline{V_t}$, for each 60-year block was determined using equation 14.

$$\overline{V_t} = \left(\frac{1}{60}\right) \sum_{i=1}^{60} V_t \qquad [14]$$

The average yearly inflow for block simulation 1 through m, $\overline{V_{t,m}}$, was calculated per equation 15 and plotted.

$$\overline{V_{t,m}} = \left(\frac{1}{m}\right) \sum_{j=1}^{m} \overline{V_{t,J}} \qquad [15]$$

Additionally, the variance, σ^2, of $\overline{V_{t,m}}$ was calculated per equation 16 and plotted.

$$\sigma^2 = \frac{\sum_{j=1}^{m} \left(\overline{V_{t,J}} - \overline{V_{t,m}}\right)^2}{(m-1)} \qquad [16]$$

Skewness, S, of $V_{t,m}$ was calculated per equation 17 and plotted.

$$S = \left(\frac{m\sqrt{m-1}}{m-2}\right) \frac{\sum_{j=1}^{m} \left(\overline{V_{t,J}} - \overline{V_{t,m}}\right)^3}{\left(\sum_{j=1}^{m} \left(\overline{V_{t,J}} - \overline{V_{t,m}}\right)^2\right)^{3/2}} \qquad [17]$$

3. Results

3.1. Evaluation Parameters

Alternatives were evaluated based on minimizing average yearly spilled water, the probability of failure of the reservoir system and low winter flow rates in Rapid Creek downstream of Pactola for ecological purposes. These three evaluation parameters were not evaluated on a common currency; rather the raw results are presented in the attempt to maintain clarity. Spilled or “wasted” water is defined as excess water released from the reservoir system that does not serve a specific purpose. In the case of this model, spilled water was quantified as Pactola releases which exceeded 50 cfs when Pactola’s pool elevation was at or above the guide curve elevation. Minimizing the amount of spilled water indicates that the system is being managed more efficiently by storing water when additional outflow is not needed and releasing this water during periods when it serves a beneficial purpose. Minimizing the volume of spilled water is considered a primary metric of reservoir operational performance.

The second evaluation parameter was the probability of low-water failure of the reservoir system. This variable has previously been defined as the reservoir reaching the bottom of the conservation pool and being unable to fulfill its water contract at any point in the simulation (Askew, Yeh, & Hall, 1971). In the case of this model, few alternatives resulted in Pactola’s elevation reaching the bottom of the conservation pool at any point during the simulation time interval. Therefore, to differentiate between the various operating sets, the percent of days in which Pactola’s pool elevation fell below 4520 ft was used to quantify the probability of low-water failure of the reservoir system. This elevation equates to approximately 1/3 of Pactola’s storage capacity; at this level, the reservoir system is at risk of not being able to satisfy a larger than historically experienced annual water order. Minimizing the probability of low-water failure is considered a primary metric of reservoir performance.

The third evaluation parameter was Pactola low-release days. South Dakota Game, Fish and Parks has indicated that winter releases of 35 cfs or more positively correlate to the health (biomass, number of fish, etc.) of the fish population within Rapid

Creek downstream of Pactola. Therefore, the percent of days with Pactola releases less than 35 cfs was calculated. Minimizing Pactola low-release days is considered a secondary metric of reservoir performance.

Operating Pactola over a wider range of elevations impacts the various reservoir objective functions. A lower reservoir elevation provides more storage for Pactola to attenuate a flood wave before encroaching into the flood control zone, where releases are dictated by the USACE, and reduces spilled water. In addition, allowing the reservoir elevation to drop further into the conservation pool permits higher winter flows in Rapid Creek downstream of Pactola which positively correlate to the health of the fish population. However, a lower reservoir elevation increases the risk of failure, or inability of the reservoir to provide the contracted water supply, of the reservoir system and negatively impacts recreation.

3.2. Analysis of Alternative Operating Scenarios Using 40x60-year Blocks

Five different operating sets were analyzed for each reservoir with the intent of minimizing the three evaluation parameters and improving reservoir system performance. The set of nine alternatives was evaluated using the first-pass 40x60-year blocks. The operating sets are described in Sections 2.3.2 and 2.3.3. The results are shown in Table 10.

Table 10: Evaluation parameter results for the first pass 40x60-year simulations

Alt	**Operation Set**		**Average Yearly Spilled Water (acre-ft)**	**Pactola Low-Water Failure Days (%)**	**Pactola Low-Release Days (%)**
	DFR	**PTR**			
1	Alt1_PO	Alt1_PO	7,222	0.191%	49.40%
2	Alt1_PO	Alt2_35	4,397	21.251%	0.00%
3	Alt1_PO	Alt3_35_7	4,992	1.670%	9.93%
4	Alt1_PO	Alt4_SS	5,016	0.453%	21.60%
5	Alt1_PO	Alt5_4560_SS	5,473	0.407%	20.44%
6	Alt2_PO_Tand	Alt4_SS	4,702	0.081%	19.48%
7	Alt3_5	Alt4_SS	4,633	0.081%	19.53%
8	Alt4_SS	Alt4_SS	4,637	0.086%	19.60%
9	Alt5_GC	Alt4_SS	4,662	0.110%	20.04%

Alternative 1 is representative of the published general operating procedures for Deerfield and Pactola. Table 10 shows that operating the reservoirs in this manner results in a 0.19% probability of Pactola low-water failure; however, the average yearly spilled water and Pactola low-release days are 7,222 acre-ft and 49.40%, respectively. Alternatives 2 through 5 assess various Pactola operation sets, which adjust the minimum release from Pactola, while Deerfield's operation set remained constant. Alternative 2, which increases the winter minimum releases to 35 cfs independent of reservoir elevation, results in the lowest amount of spilled water; however, the low-water failure days increase to over 21%. Alternative 4, which utilizes PTR_Alt4_SS operational set, was determined to be the preferred operation procedure for evaluating in combination with the other Deerfield operation alternatives. The operational set has seven specified releases varying from 7 cfs to 50 cfs dictated by Pactola's water surface elevation, as shown in Table 6. When compared to Alternative 1, the risk of low-water failure is increased by 0.26% however it reduces spilled water by 2,206 acre-ft/year (30.5%), and low-release days by 27.8%.

Alternatives 6 through 9 evaluated Deerfield's operations while Pactola's operation remained constant. Comparison of Alternative 4 (no tandem operation) with Alternative 6 (tandem operation) indicates significant improvement in reservoir system performance when Deerfield is operated in tandem with Pactola. In Alternative 6, the system storage is attempted to be distributed between the two reservoirs in such a way that each reservoir is an equal percent above or below its guide curve. Not only are the amount of spilled water and low-release days reduced by 314 acre-ft (6.26%) and 2.12% respectively, but Pactola's risk of low-water failure is diminished by 0.372%.

Alternatives 7 through 9 adjust the minimum releases and zone elevations of Deerfield. Based on the analysis of the operation sets, all three evaluation parameters indicate better reservoir system performance when minimum releases from Deerfield are set to 5 cfs. Alternatives 6 and 7 performed best at reducing Pactola's risk of low-water failure and were similar in Pactola's low-release days however Alternative 7 minimizes spilled water by an additional 69 acre-feet per year. When compared to Alternative 1, Alternative 7 was determined to be the preferred set of operations and results in a reduction in (a) average yearly spilled water by 2,589 acre-ft (35.8%); (b) Pactola low-water failure days by 0.11%, and; (c) Pactola low-release days by 29.87%. Additional analysis was performed on these two alternatives.

3.3. Analysis of 500x60-year Simulations

3.3.1. Analysis of Alternatives 1 and 7 in 500x60-year Simulations

Alternatives 1 and 7 were run for 500x60-year simulations. The three evaluation parameters were calculated and are shown in Table 11 below.

Table 11: Evaluation parameter results for 500x60-year simulations

Alt	Average Yearly Spilled Water (acre-ft)	Pactola Low-Water Failure Days (%)	Pactola Low-Release Days (%)
1	7,582	0.139%	48.73%
7	4,846	0.087%	17.95%

The 500x60-year simulations indicate similar results to the initial 40x60-year simulations. When compared to Alternative 1, Alternative 7 reduces (a) the average yearly spilled water by 2,736 acre-ft (36.1%); (b) Pactola low-water failure days by 0.052%, and; (c) Pactola low-release days by 30.78%.

Additional comparison of Alternatives 1 and 7 was done by calculating the number of years in which water was spilled and calculating an adjusted average yearly spilled water which only considers these years. Simulation results indicate that, when compared to the published operations, the preferred operation set reduces the number of total years in which water is spilled from 19,256 to 11,246 (41.5%) which indicates this alternative better utilizes Pactola's available conservation storage. Table 12 shows Alternative 7 has a higher adjusted average yearly spilled water when compared to Alternative 1, indicating that the preferred operation set has fewer years in which small amounts of water are spilled. In addition, the number of years was calculated in which Pactola has a low-water failure at any time during the year. The preferred operation set reduces the number of low-water failure years by 51 years (28.7%) when compared to the published operational set.

Table 12: Adjusted average yearly spilled water and Pactola low-water failure years

Alt	**Number of Spilled Water Years**	**Adjusted Average Yearly Spilled Water (acre-ft)**	**Pactola Low-Water Failure Years**
1	19,256	11,848	178
7	11,246	12,980	127

3.3.2. Statistical Analysis of 500x60-year Simulation Time Series

Statistical analysis was performed on the total inflow into the watershed which was the sum of the Deerfield and North Fork Rapid Creek inflow time series. The average yearly inflow for simulation 1 through m, $\overline{V_{t,m}}$, was calculated and plotted. In addition, the variance, σ^2, and skewness, S, of $\overline{V_{t,m}}$ were calculated and plotted as shown in Figure 12 below. The goal was to determine if the number of 60-year blocks adequately characterized the total population of possible outcomes; this is indicated by reaching a condition where the statistics of the sample were no longer changing by including additional blocks in the sample.

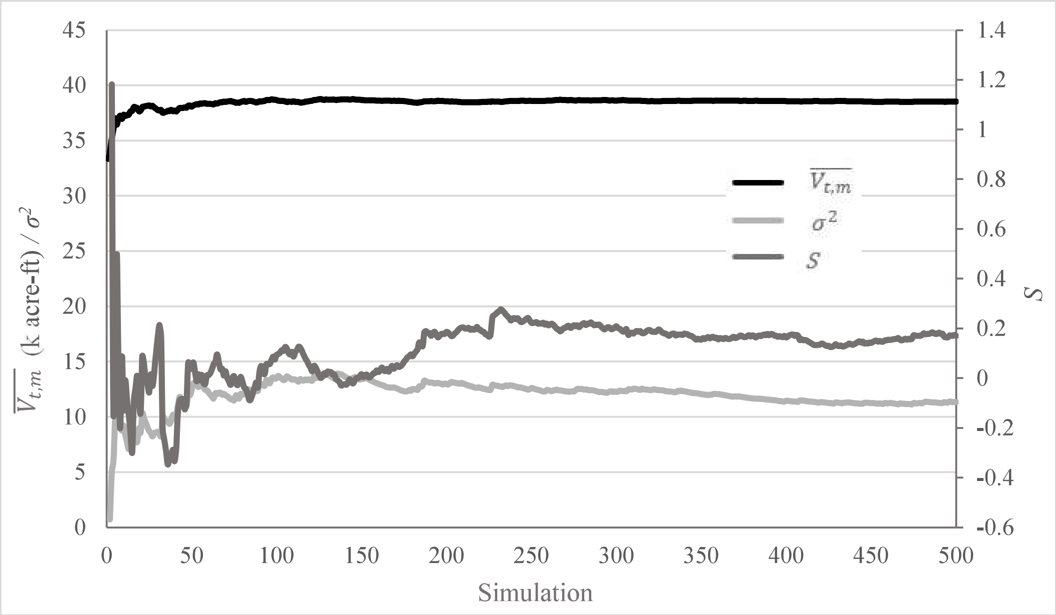

Figure 12: Statistical analysis of the 500x60-year block time series

$\overline{V_{t,m}}$ approaches a constant value after approximately 100 simulations, however significant fluctuations in variance and skewness remain at this point. Fluctuations in variance and skewness stabilize after 400 and 425 simulations, respectively. All three parameters approach an average, stable value by the 500th simulation which indicates that an adequate number was run for the results to represent the population of possible outcomes. The values for $\overline{V_{t,m}}$, variance, and skewness for all 500 simulations are shown in Table 13 below.

Table 13: Statistical analysis results of the 500x60-year block time series

$\overline{V_{t,m}}$ (k acre-ft)	σ^2 (k acre-ft)^2	S
38.54	11.34	0.171

4. Discussion and Conclusions

4.1. Primary Uncertainties and Future Modeling Suggestions

Primary uncertainties for this model include the inflows and demands. This model relies on historical inflow data from HydroMet to create synthetic inflow time series in order to consider a broader range of potential inflow scenarios than what has been observed in the past 61 years. However, the method outlined in this study does not take into consideration potential conditions which lie outside of historical observations and the model is not equipped to do any sort of forecasting. Future reservoir system analysis could benefit from a hydrologic model of the watershed able to generate stream flows based on forecasted climate conditions which could be used in the simulation model.

Currently, no model or relationship exists for predicting municipal or irrigation water demands. A minimum flow rate of 50 cfs from May through September was implemented within the model to approximate water orders based on conversations with the various groups involved. However, climate change and city development have the potential to significantly alter this value. Simulation modeling could benefit from the development of a relationship to predict current and future water demands based on watershed precipitation or reservoir inflows.

The above method outlines an approach to analyze alternative operating scenarios of reservoirs and reservoir systems by creating a simulation model and generating numerous time series from historical data via the Monte Carlo method. The disadvantage of using a simulation model versus a mathematical programming technique, such as LP, DP, or nonlinear programming, is that potential solutions are limited to the number of operating alternatives created. System modeling could benefit from making use of an optimization model to determine the reservoir operations which result in the highest benefit or least amount of penalty to be incurred. HEC-ResPRM is an optimization model designed to be used in tandem with HEC-ResSim. It determines the optimum release for each monthly time step based on current inflows and hydrologic foresight of future inflow conditions. For this model to be an effective tool, penalty functions need to be developed for each reservoir objective, such as water supply, flood control, recreation, and ecological purposes, in order to establish a common currency. Difficulties arise when assigning penalty values to each of these objectives due to the subjectivity of the valuation. In addition, the model requires a time series of known or forecasted future inflows in order to prescribe an optimum outflow for each time interval; the ability to forecast inflows for a one-month or greater time frame does not currently exist for this region. However, if these issues were to be resolved, utilization of the optimization model would result in a true optimum solution. The procedure in this thesis could then be used to create and analyze alternatives designed off the optimum solution.

4.2. Summary and General Recommendations

This study outlines a method for analyzing reservoir system operations using a simulation model and synthetic flow data generated by the Monte Carlo method. Five operating scenarios, including one which represents published reservoir operations, were developed for each reservoir by manipulating minimum releases, tandem operations and zone elevations. A first-pass evaluation of the nine alternatives was based on a 40x60-year simulation. Simulation results were evaluated based on minimizing three variables: (1) spilled water, (2) probability of low-water failure, and (3) Pactola low-release days. These metrics were used to determine the preferred operation set. A more comprehensive simulation of the published and preferred operations was done with a synthetic 500x60-year inflow time series. Statistical analysis of the 500x60-year inflow data indicates that the sample size is large enough to be statistically representative of the population of all possible outcomes.

The preferred operational set provides greater winter flow for the trout fishery and allows more inflow during the wet season (spring/early summer) to be captured by the reservoirs, before the conservation pools are filled and water begins to be spilled. The primary concern of this operational set is the potential increase in probability of low-water failure. Results from the 500x60-year simulation indicate that, relative to the published operational set, the preferred operational set reduces: (1) the average yearly spilled water by 2,736 acre-ft (36.1%); (2) Pactola low-water failure days by 0.052%, and; (3) Pactola low-release days by 30.78%. The preferred operation set reduces the number of years in which water is spilled by 41.5%, indicating better utilization of Pactola's available conservation storage. In addition, in the 30,000 years of simulation, the preferred alternative results in 127 years in which the pool level fell below the low-water failure criteria at any time during the year, while the published operations set results in 178 years. The analysis indicates that operating the reservoirs according to the preferred operational set would improve the beneficial functions provided by the reservoir while not increasing the risk of low-water failure. The general recommendation is that the regulating agencies and stakeholders consider changing the existing operational rules to rules more aligned with the preferred operational set.

The model developed for this study allows the evaluation of outcomes for any n-year time period starting from any initial condition. The simulation framework allows for the consideration of inflow conditions beyond the available historical data by either modifying the conditional probabilities of wet-wet and/or dry-dry sequences or by directly incorporating synthetic inflows generated by climate and hydrological models. A nearly infinite number of alternative operating scenarios can be developed, and it is not currently feasible with this model to either develop or properly evaluate all such alternatives. The model allows for direct quantitative comparison of alternative operational sets with either the published or preferred operational set developed in this analysis.

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6. Appendices

Appendix A. Deerfield Reservoir Information

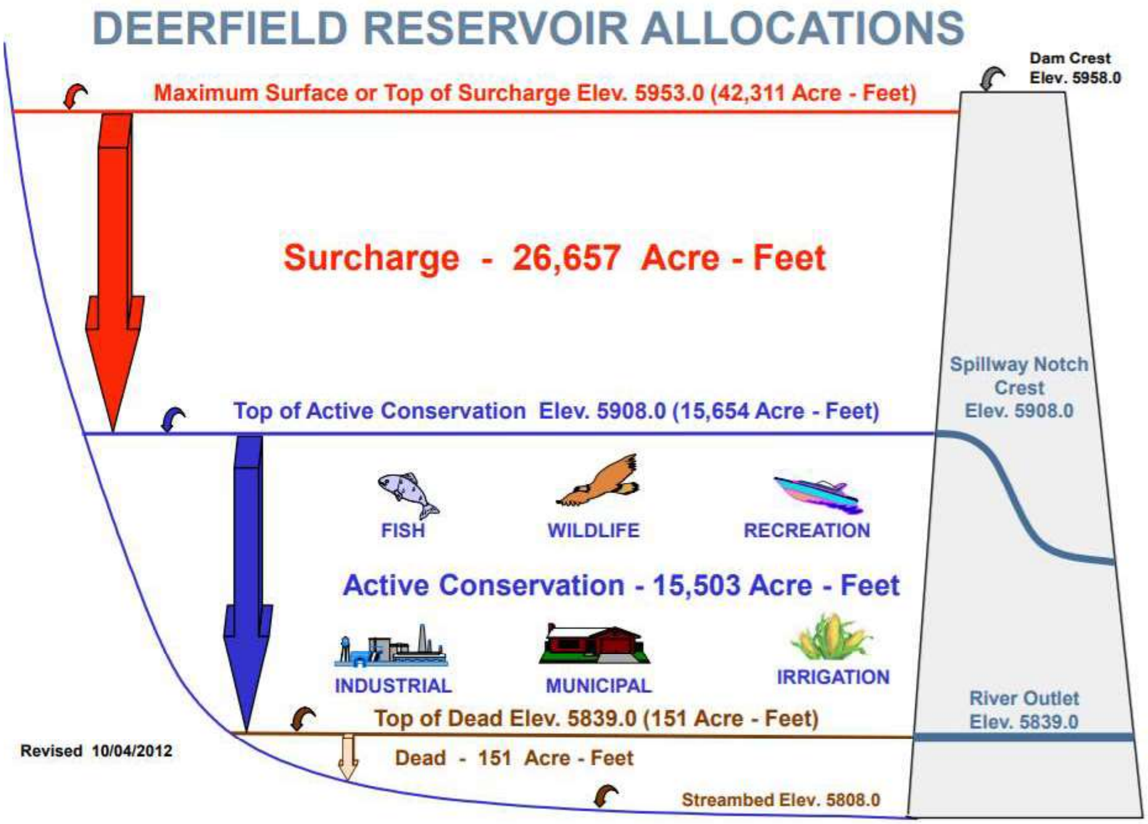

Figure A.1: Deerfield Reservoir allocations (USBOR, 2012)

Table A.2: Data that defines Deerfield stage-volume and area-capacity curve (USACE, 1976)

Elevation (ft)	Storage (acre-feet)	Area (acre)
5810	0	0
5815	10	4
5820	45	10
5825	112	17
5830	220	26
5835	380	38
5839	565	55
5840	622	59
5845	967	79
5850	1417	101
5855	1965	118
5860	2612	141
5865	3385	169
5870	4298	197
5875	5338	219
5880	6511	250
5885	7818	274
5890	9263	305
5895	10858	332
5900	12603	365
5905	14503	395
5908	15718	415
5910	16561	428
5915	18776	458

Table A.3: Data that defines Deerfield spillway discharge curve (USACE, 1976)

Elevation (ft)	**Discharge (cfs)**
5908.0	0
5908.5	333
5909.0	750
5909.5	1300
5910.0	1800
5910.5	2600
5911.0	3500
5911.5	4400
5912.0	5500
5912.5	6600
5913.0	7800
5913.5	9200
5914.0	10500
5914.5	12000
5915.0	13600

Appendix B. Pactola Reservoir Information

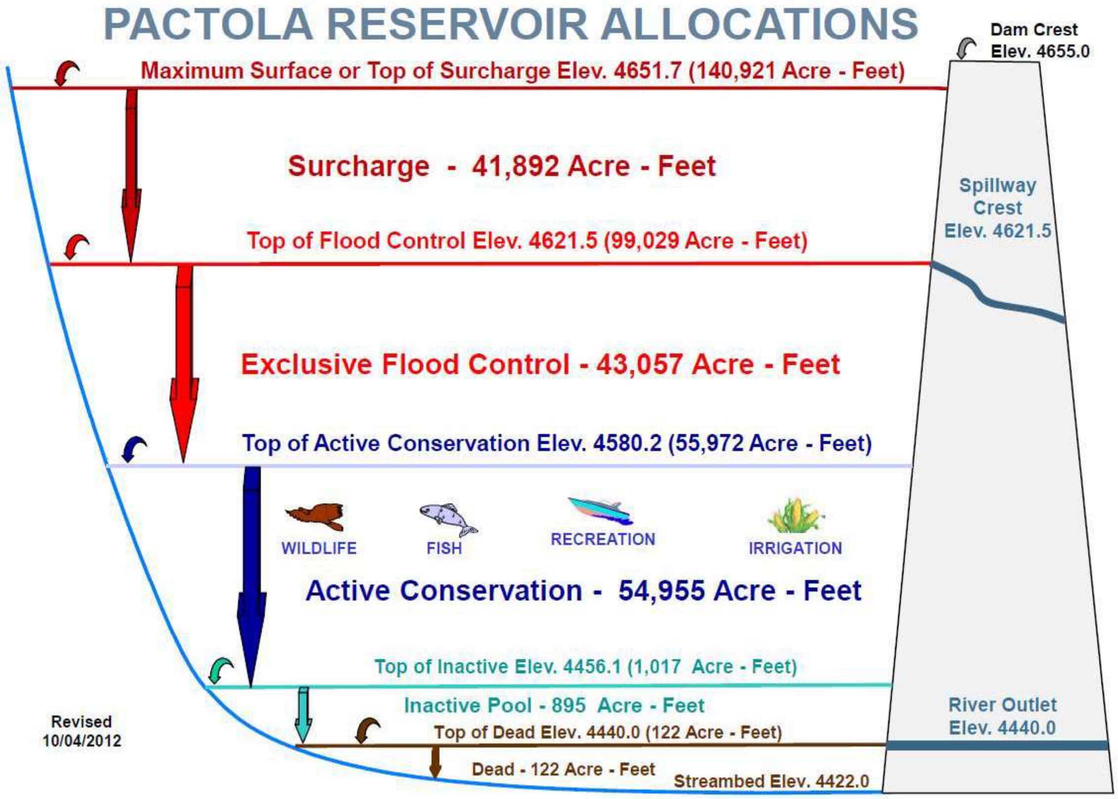

Figure B.1: Pactola Reservoir allocations (USBOR, 2012)

Table B.2: Data that defines Pactola storage-volume and area-capacity curve (USACE, 1976)

Elevation (ft)	Storage (acre-feet)	Area (acre)
4460.0	1500	125
4480.0	5500	250
4500.0	11000	340
4520.0	18000	420
4540.0	28000	540
4560.0	40000	680
4580.0	56000	860
4600.0	74000	1030
4621.5	99018	1232
4633.7	114797	1355

Table B.3: Data that defines Pactola spillway discharge curve (USACE, 1976)

Elevation (ft)	Discharge (cfs)
4621.5	0
4624.5	5000
4626.4	10000
4627.9	15000
4629.2	20000
4630.5	25000
4631.7	30000
4633.0	35000

Table B.4: Data that defines Pactola main valves discharge curves where total max capacity is the sum of both regulation valves (USACE, 1976)

	Max Capacity (cfs) per Valve for Gate Setting (%)										
Elevation (ft)	10	20	30	40	50	60	70	80	90	100	Total Max Capacity
4460	35	55	75	100	120	150	175	200	210	420	840
4480	43	67	91	120	144	179	208	239	258	516	1032
4500	50	79	107	140	168	208	241	278	306	612	1224
4520	58	90	122	160	191	236	274	316	354	708	1416
4540	65	102	138	180	215	265	308	355	403	806	1612
4560	73	114	154	200	239	294	341	394	451	902	1804
4580	80	125	169	220	263	323	374	433	499	998	1996
4600	88	137	185	240	286	351	407	471	547	1094	2188
4620	96	150	200	260	310	380	440	510	595	1190	2380

Table B.5: Pactola Reservoir flood control release schedule (USACE, 1976)

Reservoir Elevation in Feet M.S.L		Required Release (cfs)
From	**To**	
Below	4580.2	Conservation Requirement
4580.20	4582.0	Inflows up to 250
4582.01	4583.0	300
4583.01	4585.0	400
4585.01	4590.0	500
4590.01	4595.0	700
4595.01	4600.0	900
4600.01	4621.5	1000

Appendix C. Pactola and Deerfield Reservoir Combined Data

Table C.1: Pactola and Deerfield minimum release requirements (USBOR, 2007)

Date	Pactola Storage (k acre-ft)	Pactola Minimum Release Criteria (cfs)	Deerfield Minimum Release Criteria (cfs)
October 1 to March 1	>29	15	2
March 1 to October 1	>29	20	2
October 1 to April 15	<29	7	2
April 15 to October 1	<29	20	2

Table C.2: Pactola and Deerfield total monthly evaporation

Month	Deerfield Evaporation (in)	Pactola Evaporation (in)
Jan	0.00	0.00
Feb	0.00	0.00
Mar	0.00	0.00
Apr	0.00	0.00
May	2.46	2.95
Jun	3.30	4.02
Jul	3.70	4.36
Aug	3.05	3.56
Sep	2.37	2.72
Oct	0.00	0.00
Nov	0.00	0.00

Table C.3: Initial values for Pactola and Deerfield elevation and outflow

	Deerfield	Pactola
Elevation (ft)	5906.5	4576.2
Release (cfs)	10	35.0

7. Vita

Rosemary Squillace was born on October 23, 1992 in Iowa City, Iowa. Two years later, her family moved to Rapid City, SD where she was raised. She graduated from Stevens High School in 2011. In May 2015, she graduated with her Bachelor of Science in Chemical Engineering from South Dakota School of Mines and Technology. Rosemary moved to Parker, CO and worked as an application engineer for Applied Control Equipment for six months before moving to Iowa in December 2015. As part of her application engineer training, she worked at Fisher Controls International in Marshalltown, IA for six months before moving back to Colorado. In June 2018, Rosemary left her position at Applied Control and returned to South Dakota School of Mines and Technology to pursue her master's degree in civil engineering with an emphasis in water resources.