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SIMULATING UNCERTAINTY IN MASS BALANCE MODELING FOR FRESH WATER RESERVOIRS; CASE STUDY: DEER CREEK RESERVOIR, UTAH, USA

Ahmad M. Salah
242 Clyde Building
Civil & Environmental Engineering Dept.
Brigham Young University
Provo, UT 84602, U.S.A.

Paul J. Fields
223A TMCB
Statistics Department
Brigham Young University
Provo, UT, 84602, U.S.A.

A. Woodruff Miller
368 Clyde Building
Civil & Environmental Engineering Dept.
Brigham Young University
Provo, UT, 84602, U.S.A.

ABSTRACT

Simple mass balance techniques can be used to build a zero-dimensional model for a fresh water reservoir to quantify the amount of water and certain pollutants flowing into and out of the system. Yet, great uncertainty is involved in the environmental and hydrological factors related to a reservoir and it is useful to build a model that incorporates uncertainty. A generic mass balance model was built for a hypothetical reservoir and applied to Deer Creek Reservoir in Utah. Simulation was used to model the stochastic nature of the inflows and outflows to estimate the distribution of water volume and pollutant concentrations. The historical observations and simulated values were shown to be in good agreement. The model can therefore be used to manage the performance of the reservoir. The modeling process is not site specific, thus it can be used to model any reservoir provided that there are enough data.

1 INTRODUCTION

Uncertainty is present in every aspect of our lives, especially when it comes to modeling future behaviors of a natural system. Most of the time, uncertainty can not be quantified with conventional deterministic practices. With today's computing power, uncertainty can be addressed using simulation techniques, something that was not readily available decades ago.

The mass balance (or materials balance) is a quantitative description of all materials that enter, leave and accumulate in a system with defined boundaries. Mass balance is based on the law of conservation of mass, i.e. mass is neither created nor destroyed. The basic mass balance expression is developed on a chosen control volume and has terms for material entering, leaving, being generated and being accumulated or stored within the control volume. Mass balances are of fundamental importance in the field of civil and environmental engineering. Among the applications are pipe flow, flood routing and reservoir management (Tchobanoglous 1987).

Deer Creek Reservoir is located on the Provo River in Wasatch County, Utah. It serves residents of both Utah and Salt Lake counties by providing a significant amount of drinking and irrigation water, as well as being a popular recreational area. Figure 1 shows the location of the reservoir and its principal inflows. It has a maximum capacity of 2.388e8 m^3 (193,614 acre-feet) , average annual inflow of 4.93e8 m^3 (254,700acre-feet) , average retention time of 16 months and an average depth of 20 meters (65 ft). (State of Utah 2004)

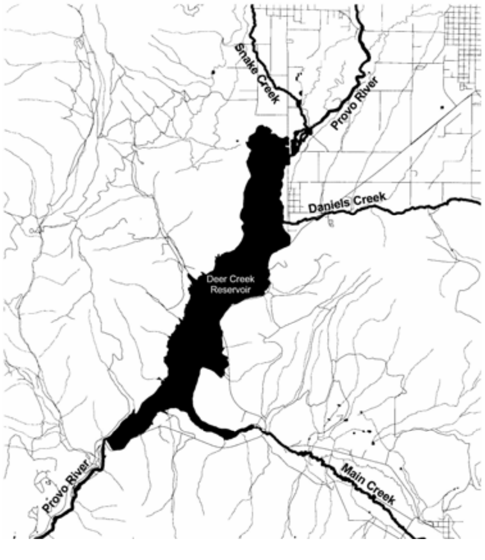

Figure 1: Deer Creek Reservoir and Its Tributaries.

The watershed which drains into Deer Creek Reservoir has an area of 7.669e8 m^3 (189,511 acres), not including any area draining into Jordanelle Reservoir, which is located some 15 kilometers upstream. The watershed can be subdivided into four major sub-watersheds/inflows, i.e. Provo River, Main Creek, Snake Creek and Daniels Creek.

Figure 2 shows the area contributing to the principal inflows whereas figure 3 shows the flow relative input by the various watersheds. (PSOMAS 2002).

There has been several water quality studies conducted on the reservoir, yet most if not all used deterministic modeling techniques. The reservoir has been identified as an impaired water body according to Utah's Year 2000 303(d) list of waters because of low dissolved oxygen levels at the reservoir bottom and high surface water temperatures (PSOMAS 2002).

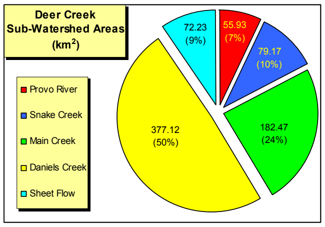

Figure 2: Deer Creek Sub-Watershed Areas.

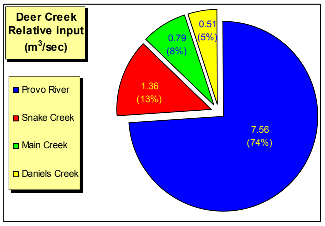

Figure 3: Average Contribution of Flows to Deer Creek Reservoir (1996-1999).

2 OBJECTIVES

The main objectives of this study can be summarized as follows:

- Develop a generic simulation-based model to evaluate the effects of uncertainty involved in the various parameters of mass balance schemes of water volume and a pollutant of interest.
- Apply the developed model to Deer Creek Reservoir in Utah.
- Run sensitivity analysis on the Deer Creek model parameters.
- Validate the model outcome with historical observations for reservoir volume.

First, a generic, non-site-specific model needs to be developed that can be applied universally.

3 MODEL DEVELOPMENT

As outlined earlier, mass balance techniques can be used to quantify changes in the materials entering, leaving and accumulating within a system of interest. The statement for a mass balance can be seen in Equation 1.

$$\text{Accumulation} = \text{Inflow} - \text{Outflow} + \text{Generation} \tag{1}$$

The theoretical background of mass balance is relatively simple and straight forward and the implementation of it into a model is no different. Quantity of water and a pollutant of interest can be simultaneously modeled using Equations 2 and 3.

$$\begin{aligned} V_{end} &= V_i + 0.001 * (P - E) * A_i * T \\ &\quad + 3.156e7 * T * (R_{in} + \text{Agr} + \text{Ind} + \text{Rec} + \text{Dom}_{in} + \text{GW}_{in}) \\ &\quad - 3.156e7 * T * (R_{out} + \text{Dom}_{out} + \text{GW}_{out}) \end{aligned} \tag{2}$$

$$\begin{aligned} C_{end} &= \frac{1}{V_{end}} * \left(V_i * C_i + 0.001 * P * T * A_i * C_p\right) \\ &\quad + \frac{3.156e7 * T}{V_{end}} * \sum \text{Inflows} * \text{Conc} \\ &\quad - \frac{3.156e7 * T}{V_{end}} * \sum \text{Outflows} * \text{Conc}, \end{aligned} \tag{3}$$

where;

- V_{end} : Reservoir end volume m^3.
- V_i : Reservoir initial volume m^3.
- P : Total annual precipitation mm.
- E : Total annual evaporation mm.
- A_i : Reservoir initial surface area m^2.
- T : Duration of the simulation years.
- R_{in} : River inflow m^3/sec.
- Agr : Agricultural inflow m^3/sec.
- Ind : Industrial inflow m^3/sec.
- Rec : Recreational inflow m^3/sec.
- Dom_{in} : Domestic inflow m^3/sec.
- GW_{in} : Groundwater inflow m^3/sec.
- R_{out} : River outflow m^3/sec.
- Dom_{out}: Domestic outflow m^3/sec.
- GW_{iout} : Groundwater outflow m^3/sec.
- C_{end} : End pollutant concentration mg/l.
- C_i : Initial pollutant concentration mg/l.
- C_p : Rain pollutant concentration mg/l.
- Conc : In/outflow pollutant concentration mg/l.

The concepts outlined above can be easily implemented using a unique and definite set of values to solve for two parameters of interest in the whole system (since they are two linear equations). Unfortunately, uncertainty exists in the measurements of most of the parameters involved, either regarding quantity or quality of water, especially if we are predicting future behavior of the system.

Performing the mass balance analysis in a simulation-based framework might account for uncertainties and hence the predictive capability of the model will be greatly enhanced. In this sense, any model parameter that needs to be incorporated with uncertainty has to have some sort of a probability density function (PDF) or probability mass function (PMF), in case of a discrete variable, instead of a single value. Other parameters that do not exhibit a large amount of uncertainty (based on experience or previous model sensitivity analysis or even lack of data) are just entered into the model as a single value.

To build a PDF for a specific parameter, it is necessary to follow three major steps to have a best representing distribution for the parameter under investigation (Bury 1999). First, the variable was examined to see if it is discrete or continuous. Then the physical process behind it was inspected before a simulation package; i.e. @RISK, was used to suggest a few distributions that have statistical relevance to the data. Finally, a single distribution was selected based on physical relevance to the variable examined.

Using Microsoft Excel® simulation add-on package @RISK, the model was built and each uncertain input parameter had a PDF/PMF associated with it. Then the simulation was run to produce two output PDFs; i.e. end volume and end concentration of the pollutant in the reservoir.

The model will, therefore, address three main components, either for the water quantity or quality; i.e. initial conditions, inflows and outflows. They are summarized in the following sections.

3.1 Initial Conditions

The initial conditions are general conditions at the beginning of the simulation period. They include the following:

3.1.1 Initial Volume

The initial volume is the reservoir volume at the beginning of the simulation period. Most reservoirs have historical observations of volumes which can be used to construct a PDF for the reservoir initial volume.

3.1.2 Initial Surface Area

The initial surface area is the reservoir surface area that corresponds to the selected reservoir volume. That is, for each simulation, a pair of volume and surface area calculations run with. Most reservoirs have this relationship already established (as an equation or as a graph).

3.1.3 Initial Pollutant Concentration

The initial pollutant concentration is the pollutant concentration at the beginning of the simulation period. In most cases, reservoirs do not have enough data to build a PDF for all pollutants. Thus, a single value is sufficient for this parameter.

3.2 Inflows

The inflows are the amount of water and pollutant arriving to the reservoir from various sources as will be illustrated in the following sections.

3.2.1 Precipitation

Since our model is primarily meant to represent a relatively long period of time; i.e. full year, the annual precipitation values must be used to build the precipitation PDF. It is worth mentioning that for some reservoirs, modelers do not have a single rainfall station that could accurately represent the reservoir, either due to the absence of a working station (long enough to build a reliable PDF) or due to the fact that the reservoir is so big, in area, that aerial estimation of multiple rainfall stations is needed. Aerial estimation of precipitation is beyond the scope of this paper.

3.2.2 River Inflow

This is the average river inflows to the reservoir. It should also be noted that, there can be more than one stream . In this case they can all be combined or they can be entered separately. The later is usually preferred in case there is enough data to build a PDF for each stream.

3.2.3 Industrial Inflow

This is the average flow from any industrial facility directly to the reservoir. Similar to the river inflow, in case there are multiple industrial inflows, they could either be totaled together or entered individually.

3.2.4 Agricultural Inflow

This is the average flow from agricultural drains directly to the reservoir. Similar to the river inflow, in case there are multiple agricultural inflows, they could either be totaled together or entered individually. Non-point source agricultural inflows are dealt with through other model parameters such as groundwater inflow.

3.2.5 Recreational Inflow

This inflow is of a more hypothetical nature, and can be usually ignored. Yet, in some instances, this might be considerable, especially as far as a pollutant is concerned. Very small flows can be considerable if the concentration of the pollutant is significant.

3.2.6 Domestic Inflow

This is the average flow from any sewage treatment plants that discharge effluents to the reservoir. Usually this flow does not experience a large amount of variations and can simply be expressed with a narrow beta distribution.

3.2.7 Groundwater Inflow

This is the only non-point source inflow to the reservoir. As opposed to rivers, and other inflows, groundwater inflow occurs along the fringe of the reservoir. It is the average inflow to the reservoir. This is usually the parameter that requires lots of research effort to find. Luckily it is not a significant contribution to the system. Moreover, analyzing such a system from a simulation standpoint, releases some of the pressure to find exact values for it.

3.3 Outflows

The outflows are the amount of water and pollutant leaving the reservoir through various means as discussed in the following sections. It is assumed that outflows, with the evaporation as an exception, have a concentration of the initial pollutant concentration. This assumption was made to simplify computations.

3.3.1 Evaporation

This is the annual evaporation at the reservoir site. Similar to the precipitation, aerial estimation of evaporation might be necessary. Most of the time, there will be enough historical data (based on field observations or physical models) to build a PDF for evaporation. Another way of representing the evaporation is to link it to the precipitation as will be discussed for Deer Creek Reservoir later in the paper.

3.3.2 River Outflow

This is the average river outflow downstream of the reservoir. Most reservoirs have gauging stations immediately downstream of the reservoir that have enough data to build the PDF for the river outflow. Similar to evaporation, river outflow is almost always possible to be linked to the inflow through a ratio as discussed later in the paper.

3.3.3 Domestic Outflow

This is the average amount of water abstracted from the reservoir or immediately downstream of the reservoir for municipal among any other water use in neighboring cities. This could also be more than one abstraction, and this could be modeled separately or combined.

3.3.4 Groundwater Outflow

This is the only non-point outflow from the reservoir. It is not easy to obtain data especially on a historical basis. Usually, this parameter ends up being modeled along with groundwater inflow.

3.4 Simulation Settings

In most cases, some of the model parameters outlined above are inter-related and there is some sort of dependency of one upon the other. For example, one could assume a great linkage between precipitation and evaporation, since they share the same driving force; i.e. climate. Similarly, there is a dependency between the inflows and the outflows. Some of these dependencies are essential and can not be ignored. A good example of that is the relation between the reservoir surface area and volume as they both depend on the underlying bathymetry of the reservoir. Some of the dependencies were assumed non-existent for the sake of simplicity and/or the lack of information. In that sense the model assumed the following dependencies:

1. Reservoir volume/capacity to surface area: Usually there is an equation that could link the two together. It is very specific and unique for each reservoir. For the sake of simplicity also, the model assumes no uncertainty along this equation.
2. Precipitation to evaporation: This is another indispensable dependency. However, there is no available physically based equation that can relate one to the other. Thus, the model handles this linkage on an observed ratio basis. That is, the ratio between precipitation and evaporation is to be computed on an annual basis and a PDF is to be constructed out of the historical records of this ratio. It is simulated with one of them as the controlling variable (the one that is entered as a PDF) and the other one is computed from the PDF-selected value multiplied by that ratio.
3. River inflow and outflow: Similar to precipitation and evaporation, a ratio is constructed from the historical observation of both. One of the parameters is entered into the model as a PDF whereas the other is computed from the PDF-selected value multiplied by the corresponding ratio.

The model assumes that the reservoir is completely mixed and follows a long-term average approach. It is assumed to start at the end of January at any given year and run for one complete year. A shorter duration of the model is also applicable, but, with a great deal of assumptions that may or may not be valid, especially as far as the pollutants are concerned.

4 DEER CREEK RESERVOIR

The generic model developed above will be used to model Deer Creek Reservoir, Utah. As outlined above the model consists of multiple components. These components will be addressed in the following sections.

4.1 Initial Conditions

Initial model conditions include initial volume, reservoir surface area and pollutant initial concentration in the reservoir.

4.1.1 Initial Volume

Daily volume data were obtained from the United States Bureau of Reclamation (USBR) website (USBR 2005) for the last 55 years. Earlier data (9 more years) were not used as they might introduce some bias in the PDF. These 9 years are closer to end of dam construction. (Usually reservoirs need initial time to stabilize after construction). January data were averaged through the 55 records and used to build the PDF for the initial volume.

4.1.2 Initial Surface Area

As discussed in the general model description section, the initial surface area is directly linked to the initial volume through an equation/chart. Data from the USBR (USBR 2005) and USGS (USGS 2004) were used to construct the area-capacity curve for Deer Creek Reservoir (Figure 4). It is worth mentioning that the developed equation/chart is not meant for extrapolation beyond its limits.

4.1.3 Initial Pollutant Concentration

The model was applied to Total Phosphorous (TP) and an average (three dimensional and time) value in the reservoir was set to be equal to the recommended target value of 0.025 mg/l (PSOMAS 2002).

4.2 Inflows

The following describes how PDFs for various inflows to Deer Creek Reservoir were created.

4.2.1 Precipitation

Annual precipitation values were obtained since 1940 (NOAA 2005). They were then used to build the PDF for the rainfall. A lognormal distribution function was used to simulate precipitation. The assumed TP concentration of zero in the rainfall is well defendable.

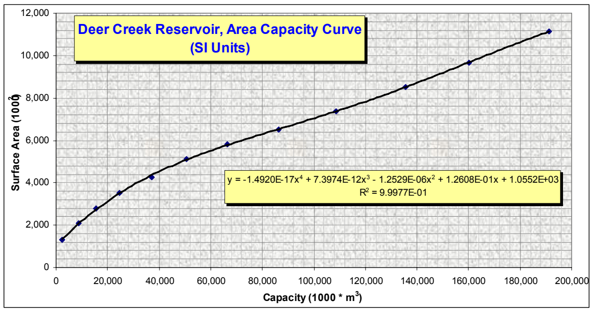

Figure 4: Deer Creek Reservoir Area-Capacity Curve.

4.2.2 River Inflow

As seen in Figures 1 and 3, Deer Creek Reservoir has 4 main river inputs. There are available data for Provo River, Snake Creek and Daniels Creek, but there are not sufficient data for Main Creek which contributes about 8% of the inflows to the reservoir. Since Provo River inflow contributes about 74% (on average) of the total inflows to the reservoir, it was considered the main river inflow.

Historical data were obtained for a couple of stations along the Provo River upstream of the reservoir, i.e. 10155500 (Charleston) and 10155000 (Hailstone) (USGS 2005). The closest station to the reservoir, i.e. 10155500, has data for two time windows, 1939 to 1949 and 1992 to present. The old data range was neglected because of climate and hydrological changes that took place and might contribute to biased estimates. The recent data might not be sufficient to construct a reliable PDF for river inflow.

The 12 years of overlapping data between the Charleston and Hailstone stations were thus used, along with the station just down stream of the reservoir, to build a multiple regression model (Equation 4) which was later used to estimate the values for the Provo River inflow back to year 1960.

$$\text{Charleston} = 0.168 * \text{Hailstone} + 0.726 * \text{DownDeerCreek} - 1.103 \tag{4}$$

Some of the regression parameters are not significant for this model, yet they were left in to incorporate uncertainty. The above equation was then used to estimate flows in the desired station. The average value of concentration of TP in Daniels Creek was found to be 0.03 mg/l (PSOMAS 2002).

4.2.3 Industrial Inflow

Since there is no direct industrial inflow, and we have more than one tributary to the reservoir, we used this field to represent flow from Daniels Creek station (10157500) which only has data back to 1994 (USGS 2005). Thus it can not be used to build a reliable PDF. Regression analysis was, therefore, used to estimate values from 1960 to

1993. After scrutinizing precipitation and Provo River inflow and outflow at those 9 years of available data as explanatory variables, it is concluded that the following model is to be used for Daniels Creek (Equation 5).

$$\text{DanielsCreek} = 0.0714 * \text{ProvoInflow} - 0.1517 \qquad (5)$$

The above equation was used to estimate flows in the desired station. Those values were then used to construct the industrial flow PDF. A lognormal distribution function was used to simulate Daniels Creek inflow. The average value of concentration of TP in Daniels Creek was found to be 0.07 mg/l (PSOMAS 2002).

4.2.4 Agricultural Inflow

Similar to the industrial flow, there is no agricultural drain that flows into the reservoir as a point source. This field has been used to represent flow from Snake Creek station (10156000) which has discontinued data. The recent set of data is dated back to 1994 (USGS 2005). Similar to Daniels Creek, multiple regression was used to build the following model (Equation 6).

$$\begin{aligned}\text{SnakeCreek} = {} & 0.08688 - 0.00029*\text{Precip} \\ & +0.2506*\text{ProvoInflow} - 0.124*\text{ProvoOutflow}\end{aligned} \qquad (6)$$

The above equation was used to estimate flows in the desired station. Those values were then used to construct the agricultural flow PDF. A Weibull distribution function was used to simulate Snake Creek inflows. The average value of concentration of TP in Snake Creek was found to be 0.027 mg/l (PSOMAS 2002).

4.2.5 Recreational Inflow

There were not enough data for this model parameter; thus, this field was used to represent flow from Main Creek. However, there were not enough historical data to build the PDF. Yet, as outlined above, Main Creek contributes only approximately 8% of the total inflows to Deer Creek. The PDFs for Provo River, Daniels Creek and Snake Creek were therefore used to create a PDF (based on weighted average values) for Main Creek. A Weibull distribution function was used to simulate Main Creek inflow. The average value of concentration of TP in Daniels Creek was found to be 0.06 mg/l (PSOMAS 2002).

4.2.6 Domestic Inflow

A recent study (PSOMAS 2002) has indicated that there is no direct effluent from Heber City Waste Water Treatment plant to the reservoir. Hence a value of zero was used in the flow and concentration fields for this model parameter.

4.2.7 Groundwater Inflow

The same study (PSOMAS 2002) has indicated that the average value of groundwater inflow into the reservoir is 1.73 m^3/sec at an average TP concentration of 0.04 mg/l. The authors still believe there is high uncertainty in this parameter, thus, a Beta distribution function was used to simulate ground water inflow. This is done so that we can see if this is a sensitive parameter in the model or not.

4.3 Outflows

The following describes how PDFs for various outflows from Deer Creek Reservoir were created.

4.3.1 Evaporation

There were not enough historical data to build a reliable PDF for evaporation from Deer Creek Reservoir. On the other hand, and as discussed earlier, there is some sort of dependency between precipitation and evaporation.

Evaporation data were available on Utah lake, (40 km south west of Deer Creek) up to the year 1940 (NOAA 2005). There are also detailed evaporation studies (Morton 1986), (Miller et al 2004) for the last 4 years on a monthly basis, for both lakes. Since the two lakes were believed to be some how correlated, the available recent data were used to build a regression model to estimate evaporation from Deer Creek Reservoir (Equation 7).

$$\text{Deer Creek Evaporation} = 0.9188 * \text{Utah Lake Evaporation} - 4.117 \qquad (7)$$

The obtained values were then used to estimate the annual precipitation-evaporation ratio. A PDF was built for this ratio using a Weibull distribution.

Evaporation values, used in the model simulations, were then computed for every simulation by multiplying the instantaneous precipitation by the corresponding ratio from the obtained PDF.

Even though the regression model between Utah Lake and Deer Creek Reservoir was built based upon recent data, i.e. 2001, 2002, 2003 and 2004, we assumed the regression parameters remained the same throughout the sixty four years of precipitation records. We assumed so, because the relative climatic conditions would remain the same, even though there might be a general trend of change which will happen to both lakes simultaneously. We used this assumption to go back as early as 1940 and use the data to build the evaporation distribution for Deer Creek Reservoir.

4.3.2 River Outflow

There is enough data, dated back to 1960, to build a PDF for the Provo River outflow (USGS 2005). A Weibull distribution function was used to simulate River outflow. The average value of concentration of TP in the outflow was set to the initial concentration of the reservoir, i.e. 0.025 mg/l.

On the other hand, and similar to the evaporation-precipitation ratio, a ratio was estimated on an annual basis between the Provo River inflow and outflow. This ratio was also simulated using a Weibull PDF function to get a corresponding estimate of the Provo River inflow.

It is also worth mentioning that most reservoirs have some sort of “dead storage”. Dead storage is the lowest elevation in the reservoir from which water can be drawn by gravity to the river downstream. The top of dead storage for Deer Creek Reservoir is at 5305 ft (USBR 2004). This factor was incorporated in the sense that the model did not allow any abstractions, except groundwater outflow, if the water surface elevation is below the dead storage level.

4.3.3 Domestic Outflow

There were enough data to build a PDF for the abstraction to Salt Lake City through the Salt Lake City aqueduct (CUWCD 2005). A Beta distribution function was used to simulate the domestic outflow. The average value of concentration of TP in the outflow was set to the initial concentration of the reservoir, i.e. 0.025 mg/l.

4.3.4 Groundwater Outflow

Similar to the groundwater inflow, there were not enough data on this model parameter. Thus, a Beta distribution function was used to simulate ground water outflow. This is done so that we can see if this is a sensitive model parameter or not. The average value of concentration of TP in the outflow was set to the initial concentration of the reservoir, i.e. 0.025 mg/l.

4.4 Simulation Settings

As indicated above, the model was assumed to start at the end of January at any given year and run for a duration of one complete year.

In this simulation, some of the used data were dated back to 1940 whereas others were dated back to 1960. This should not be confusing since the data were primarily used to build PDFs. Generally speaking, the more data available, the better the PDF in representing the parameter in question

5 RESULTS AND DISCUSSION

The model was run to obtain the end volume of the reservoir and the end concentration of total phosphorous. The results were obtained as a statistical distribution rather than as single values. This allows modelers to access the probability of exceedance for a certain volume and/or pollutant concentration. This is a great help to water resources managers because it can be considered with other managerial factors in the decision making process.

Sensitivity analysis revealed the importance of changes in different factors on the sensitivity of the model results, i.e. end volume/TP concentration. These are summarized in Tables 1 and 2 and Figures 5 and 6.

To the surprise of the authors, evaporation is not the main concern, neither is the evaporation-precipitation ratio. Yet, model results seem to be more sensitive to changes in this ratio than in precipitation values. This can possibly be attributed to their relatively small contribution compared to initial volume and other inflows/outflows.

Moreover, it looks like both model results, i.e. end volume and TP concentration, are sensitive to changes in ground water inflow. This definitely encourages collecting more data for better model results.

Table 1: End Volume Sensitivity Analysis

Parameter	Sensitivity Factor
Provo In/Out Ratio	0.524
Initial Volume	0.501
Provo River Outflow	(0.472)
Groundwater Inflow	0.317
Daniels Creek Inflow	0.253
Snake Creek Inflow	0.164
Main Creek Inflow	0.136
Salt Lake Supply	(0.103)
Evap-Precip Ratio	(0.085)
Precipitation	(0.038)

Table 2: End Concentration Sensitivity Analysis

Parameter	Sensitivity Factor
Provo River Outflow	0.340
Provo In/Out Ratio	0.184
Initial Volume	(0.142)
Snake Creek Inflow	(0.059)
Precipitation	0.045
Groundwater Inflow	0.035
Evap-Precip Ratio	0.031
Salt Lake Supply	0.011

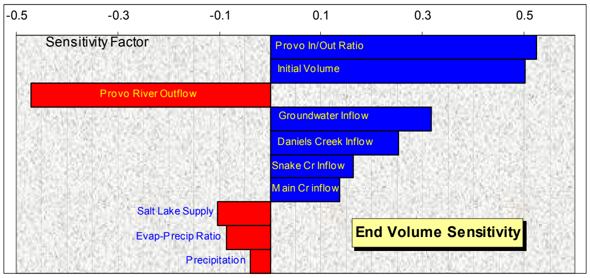

Figure 5: End Volume Sensitivity.

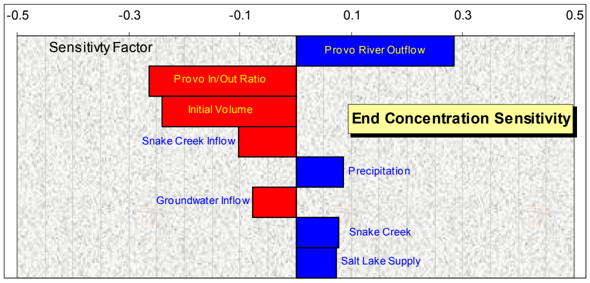

Figure 6: End Concentration Sensitivity.

The negative bars (bracketed values) indicate that the effect of the parameter is negative indicating that as the parameter increases the end volume/concentration decreases and vice versa. From the above tables and figures, it is clear that the initial volume of the reservoir has a significant effect on the modeled end volume as expected especially for relatively high reservoir volumes.

Also, both model outputs seem to be highly sensitive to Provo River outflow. This can be understood because it is the main abstraction from the reservoir.

Looking at the resultant end volumes, it is important to assess the validity of the model by considering whether the results could represent the population out of which the observed volumes could have originated. To do that, the means, medians and variances of the two data sets were tested. Furthermore, the normality of both observed and modeled volumes were tested.

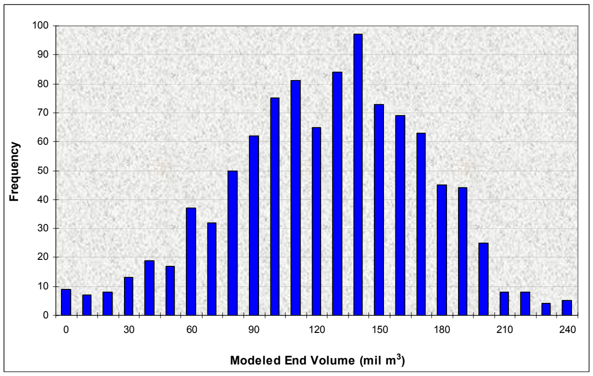

Figure 7: Modeled End Volume of Deer Creek Reservoir.

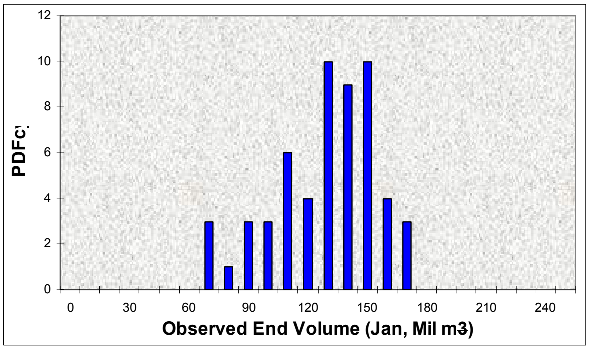

Figure 8: Observed Deer Creek Reservoir Volume.

Visual inspection of the expected (modeled) end volume and observed values (Figures 7 and 8) suggests general agreement between the two and the modeled end volume distribution appears to be a plausible representation of the population from which the observed volume could have originated. Yet, it is necessary to statistically test this assertion. The difference in means, medians and variances are tested using a t-test, a non-parametric test and F-test respectively. A X^2 goodness of fit test was carried out to test the normality of both modeled and observed end volumes. Results of the five tests are listed in Table 3.

Table 3: Statistical Tests Comparing Expected and Observed Reservoir Capacity

Test	**p-value**	**Inference**
T-test	0.232	No-diff.
Wilcoxon Rank Sum Test	0.549	No-diff.
Equality of Variance (F-test)	0.002	Not equal
Lavene's Test (variance)	0.000	Not equal
Modeled Volume Normality X^2	>0.100	Normal
Observed Volume Normality X^2	>0.150	Normal

As shown in Table 3, the tests comparing the mean and the median (t-test, Wilcoxon respectively) indicated that there is no evidence of a difference between the two data sets. The goodness of fit on both observed and modeled indicated they are approximately normally distributed which actually supports the natural behavior and the visual inspection. Both F-test and Lavene's test indicated that the variance of the two data sets are not equal and that the variance of the modeled volume is higher than observed. (95% C.I. 43.9 to 48.6 for modeled volumes as opposed to 20.9 to 32.3 for the observed volume). Since the objective of our model is to estimate probabilities and since a distribution with higher variance is usually more conservative, thus the model is actually safer to use for managerial decision-making.

The second main outcome of the model is the distribution of the expected concentration at the end of the modeling period for the selected pollutant, i.e. TP (Figure 9).

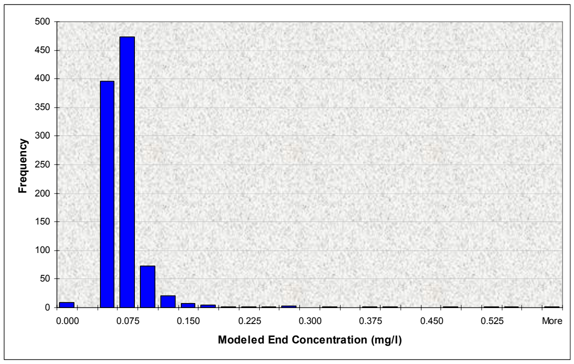

Figure 9: Expected End TP Concentration in Deer Creek Reservoir.

This graph shows that there is 4.9% probability that the TP concentration at the end of the simulation period in the reservoir would exceed 0.1 mg/l. This limit is considered, among other factors and indices a sign for a eutrophic water body. The TP water quality standards of 0.025 mg/l has a probability of almost 99%. This conforms to previous research (PSOMAS 2002), that water in Deer Creek Reservoir exceeds water quality standards for TP.

It is clear that both modeled PDFs; i.e. end volume and concentration can be used to estimate the probability of exceeding a certain threshold rather than the selected values.

6 RECOMMENDATIONS

The developed model was found to be consistent with historical data and thus it can be used to model Deer Creek Reservoir volume and pollutant concentrations while addressing uncertainty. It can also be used on other reservoirs, provided that necessary data are available and incorporated in the model as illustrated in this case study.

Evaporation and precipitation are not of main concern to the management of Deer Creek Reservoir, as opposed to other inflows/outflows incorporated in this model.

The groundwater inflow is among the most sensitive parameters for both end volume and concentration of TP. Thus, it is recommended that, for more reliable results, more attention should be given to the ground water inflows/outflows to the reservoir.

In general, recreational inputs are not as sensitive and in most cases they can be ignored. Yet, for cases where the recreational activities are extremely high in pollutant concentrations, it is advisable to model them more accurately.

For useful results, it is recommended to obtain more accurate measurements on pollutants of interests. Simulated pollutant concentration is recommended if there are enough data, in order to incorporate uncertainty in the water quality perspective of the model.

Provo River inflow regression analysis could be enhanced by incorporating measurements from the USGS flow gauging station number 10155300 (Provo River near Midway) as another explanatory variable.

There is a high probability that the TP concentration would exceed the target value of 0.025 mg/l if the same practices/conditions remain the same. To achieve this target or lower, further controlling measures need to take place to reduce the TP input to Deer Cree Reservoir.

Obviously, the sensitive parameters for the Deer Creek Reservoir are not to be generalized for any other case study. Most of these parameters are site-specific. Yet, the model can be used to perform sensitivity analysis and generate a set of the most sensitive parameters for the reservoir under study. These sensitive parameters should determine if (1) more attention should be directed towards obtaining data for it and (2) this parameter should be controlled on the ground, from a management perspective.

Once the model has been setup, it can be used to examine various pollutants for the same reservoir as data become available. This model is scalable, that is, it can incorporate either deterministic or stochastic values for pollutants. One could start with the deterministic values and then expand the model to be fully stochastic, i.e. quantity of water and concentration of pollutant, if data allow.

Since this model is simulation-based, it is robust and expected to perform well on small, mid and large size reservoirs. There might be some issues regarding the adjustment of the input parameters such as the aerial estimation of precipitation. Yet, the idea remains the same, that the model takes a "representative" input. It is the responsibility of the modeler to represent the reservoir as accurately as desired.

It looks like forty to fifty years or more of continuous data can be sufficient to produce reliable PDFs for hydrological parameters. On the other hand, further research should address the interdependencies between the various model parameters

The power of simulation overcomes the disadvantage of missing data. Even if we do not have sufficient data, we can still build different PDFs for the variable in question and see the effect on the result. Sensitivity analysis can help significantly in this case. Simulation is a powerful tool that can be used to address uncertainty involved in water resources/quality fields.

Interested readers are recommended to contact the paper primary author at `<asalah@byu.edu>` for more details on data used in this paper.

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AUTHOR BIOGRAPHIES

AHMAD M. SALAH is an research associate in the Environmental Modeling Research Laboratory (EMRL), part of the Civil and Environmental Engineering Department at Brigham Young University (BYU). He is doing his PhD on spatio-temporal uncertainty of water resources/quality modeling. He is part of the software development team to program Watershed Modeling System (WMS). He is a member of American Society of Civil Engineers (ASCE) and American Water Resources Association (AWRA). His e-mail address is `asalah@byu.edu` and his Web address is `http://www.et.byu.edu/~asalah`

PAUL J. FIELDS is an associate professor of Statistics at Brigham Young University (BYU). His research interests include simulation and nonparametric methods in applied statistics. His email is `pjfields@byu.edu` and his Web address is `http://statistics.byu.edu/faculty/faculty.php?person_id=80`.

A. WOODRUFF MILLER is the chair of Civil and Environmental Engineering Department at Brigham Young University (BYU). He teaches hydrology and hydraulics for undergraduate and graduate students. His research interests are hydrologic modeling including watershed modeling and evaporation modeling, satellite hydrology, hydraulic systems, and water quality evaluations on lakes and streams. His e-mail address is `wood_miller@byu.edu` and his Web address is `http://www.et.byu.edu/ce`.