## 2.0 NUMERICAL MODELS

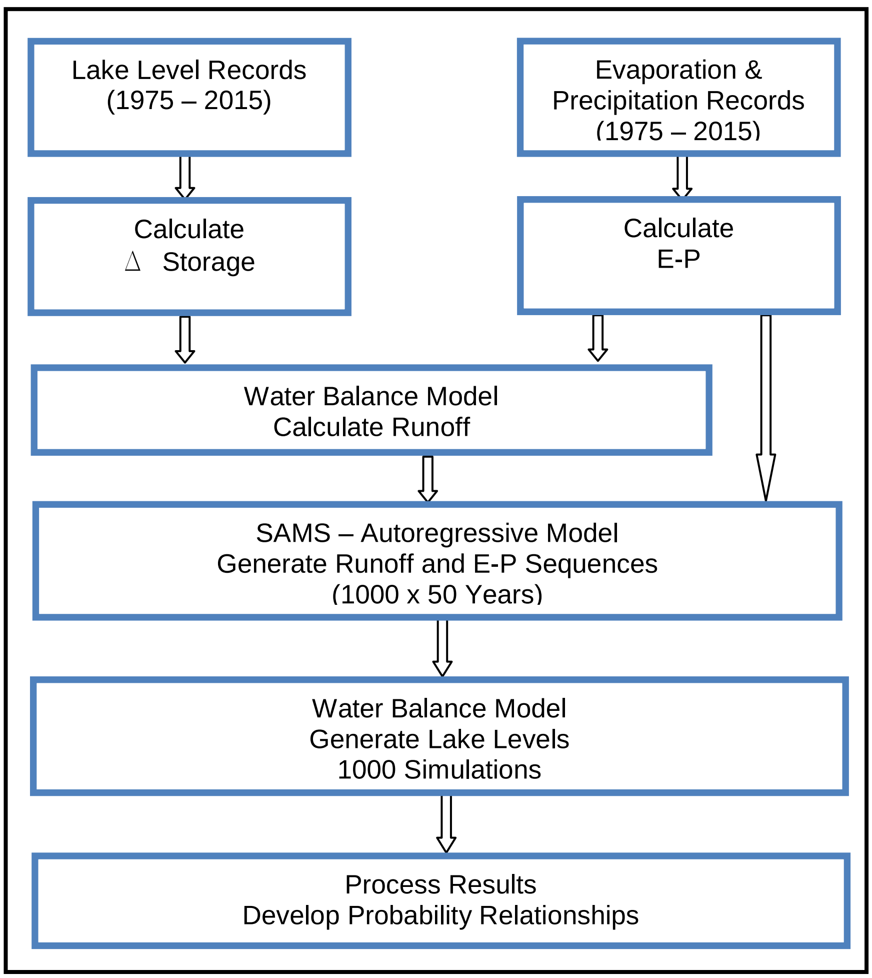
Two numerical models were used to aid in the evaluation of the various flood mitigation options. These included:

- **A Water Balance Model:** This model was used to both (1) determine the historic record of inflow to the lake and (2) to determine water levels on the Quill Lakes for a given runoff sequence.

- **A Monte Carlo Autoregressive Model:** This model was used to produce a number of synthetic runoff sequences based on historical runoff.

An overview of the interaction between the two models is provided in Figure 2. Further details on the water balance model and the autoregressive model are provided in Sections 2.1 and 2.2, respectively.

**FIGURE 2**
**NUMERICAL MODELLING PROCESS**



## 2.1 WATER BALANCE MODEL

The basis of the water balance model is the law of continuity in that the volume of water discharged in a specific time period is equal to the volume of water inflow minus the change in storage, as shown in the equation below.

$$\text{Outflow} = Q_{in} - \Delta\ \text{Storage}$$

Since Big Quill Lake has had no outflow in recent history,

$$Q_{in} = \Delta\ \text{Storage}$$

The IAO consists of runoff, infiltration (assumed constant for each year), precipitation and evaporation and can be calculated as:

$$Q_{in} = R + P - E + I$$

The observed water levels on the Quill Lakes were used to define the change in storage. Precipitation and evaporation (E-P) components were typically calculated separately from the total runoff (R+I) because these served as two different inputs into the autoregressive model. The total runoff (R+I) was calculated as shown below.

$$R + I = \Delta\ \text{Storage} - (E-P)$$

### 2.1.1 Time Step

The water balance model developed for this study used a daily time step for the determination of daily change in storage and the resulting daily runoff volume. A daily time step was adopted to capture the following characteristics in the model:

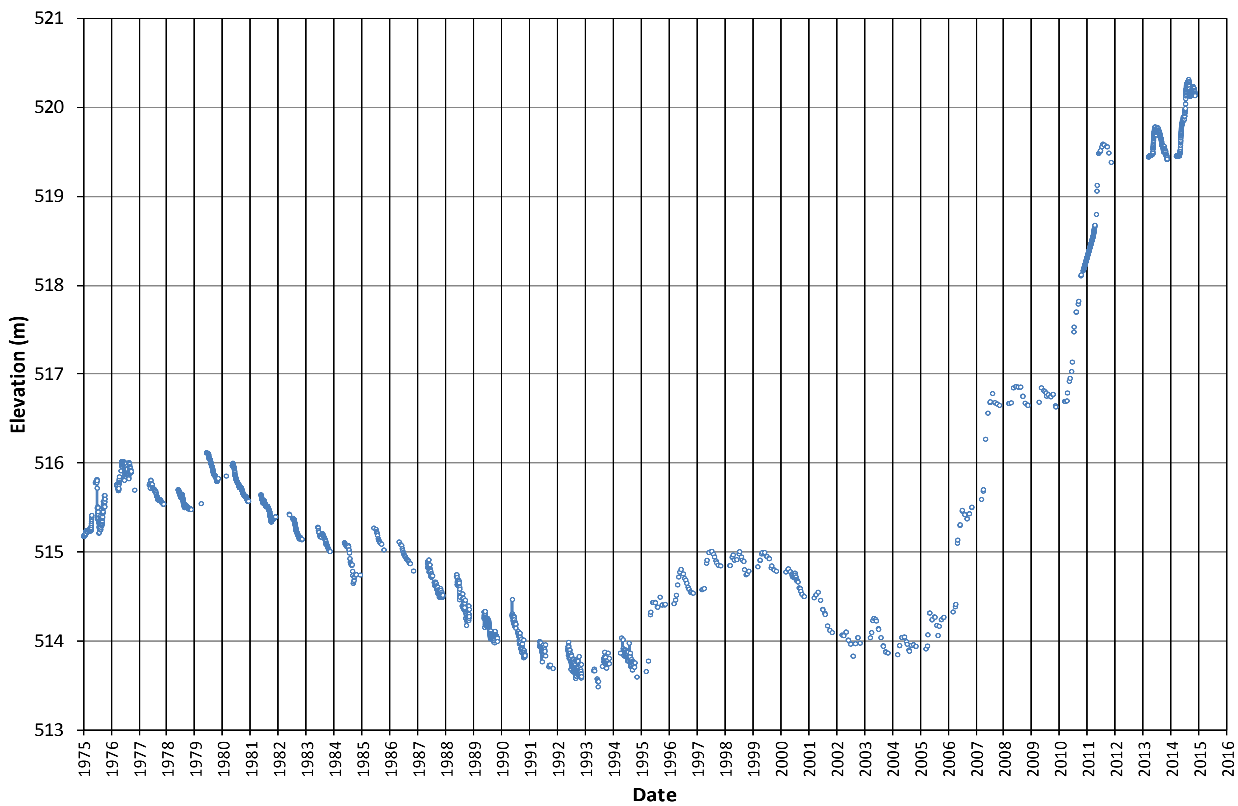
- The lake volume changes due to water level changes: Generally, the smaller the time step, the more accurate the estimation of lake volume changes can be obtained.

- Natural spilling of flows from the Little Quill Lake to Big Quill Lake: The magnitude of spilling flows depends on the water level changes. The smaller the time step, the more accurate estimation of spilling flows can be obtained.
- The E-P calculation: The E-P calculation at higher water level means more water volume losses than at the lower water level. The smaller time step, the more accurate estimation of water volume losses due to the E-P can be obtained.

### 2.1.2 Quill Lakes Water Levels

Water levels have been recorded on the Quill Lakes by Water Survey of Canada (WSC) for several decades. Recorded water levels on Big Quill Lake and Little Quill Lake are shown in Figures 3 and 4, respectively. Big Quill Lake water levels have been recorded at WSC Gauge 05MA010 near Kandahar since 1956. There are two daily water level records taken in each year from 1957 to 1967, generally one in the spring and the other in the fall. After 1967, the water levels were recorded at least twice per month in the open water seasons.

**FIGURE 3**
**RECORDED WATER LEVELS ON BIG QUILL LAKE – 1975 TO PRESENT**

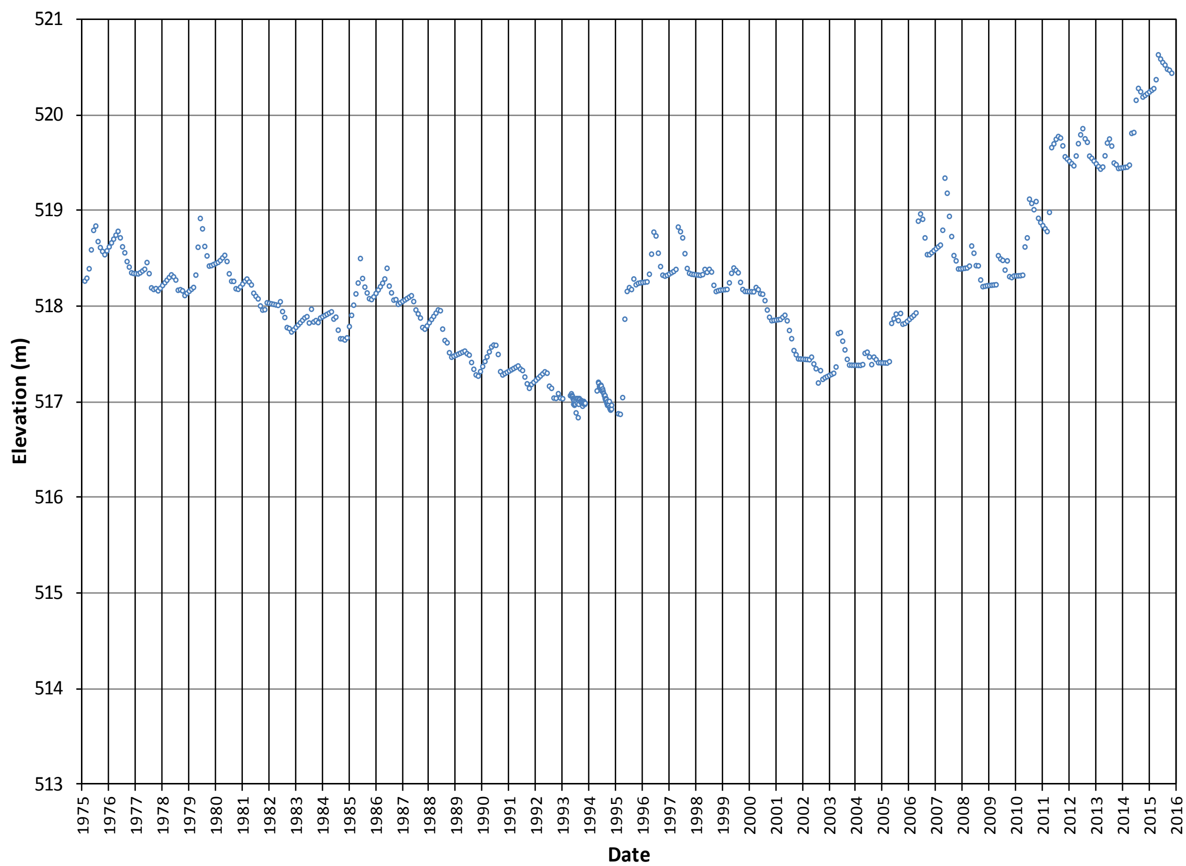



**Note:** 1 m = 3.28 ft

The water levels on Little Quill Lake have been recorded at WSC Gauge 05MA002 near Wynyard since 1919. There are two daily water level records taken in each year from 1957 to 1974, generally one in the spring and the other one in the fall. After 1974, the water levels were recorded at least twice per month in the open water seasons. Since regular water level measurements are not available until after 1975, the water balance model only used data from 1975 to present.

Given the large lake surface area and the relatively slow changes of the lake levels for the Quill Lakes, the water level records from 1975 to 2015, which were taken at least twice per month in the open water seasons, are believed sufficient to capture the lake level changes for the runoff estimation in a high level study. Daily water level records for both Big and Little Quill Lakes were determined by linear interpolation of the observed water levels.

**FIGURE 4**
**RECORDED WATER LEVELS ON LITTLE QUILL LAKE – 1975 TO PRESENT**




**Note:** 1 m = 3.28 ft

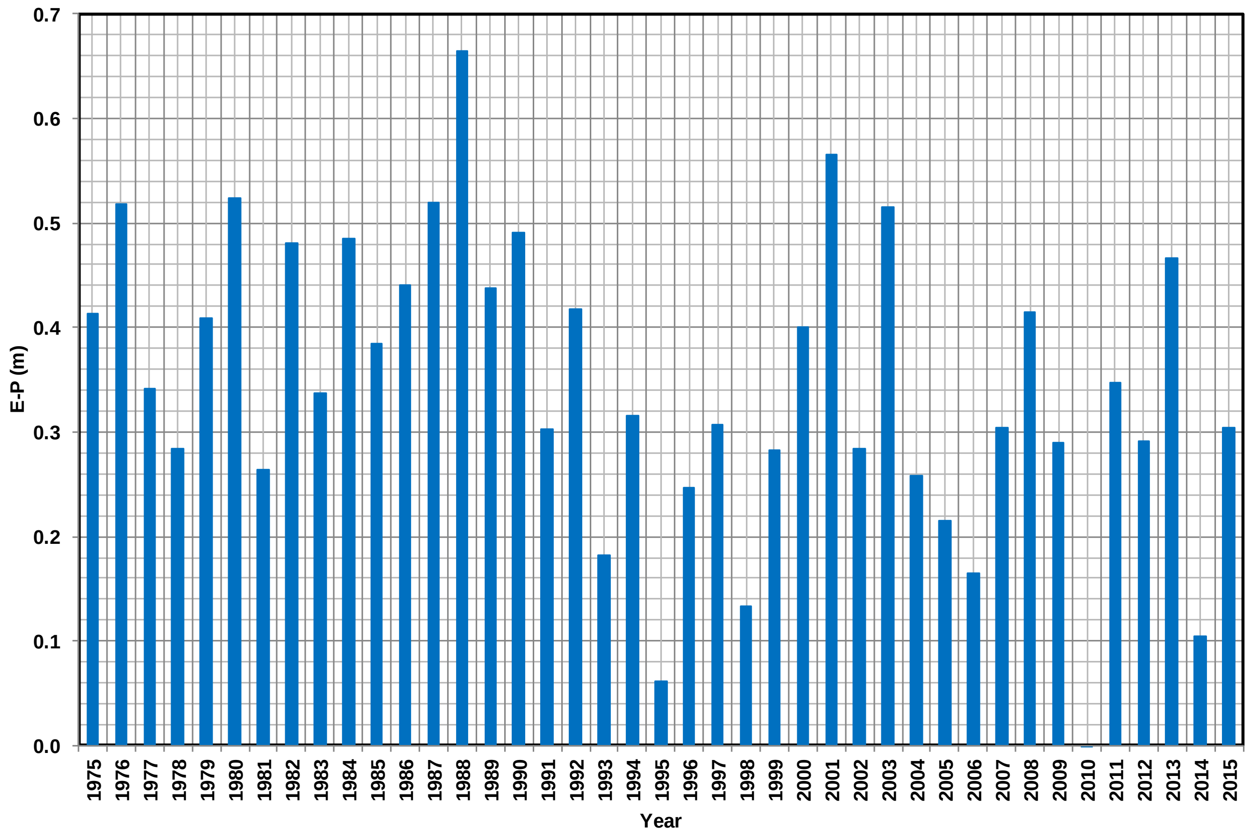
### 2.1.3 Precipitation and Evaporation

Monthly precipitation for the period of analysis from 1975 to present was based on recorded precipitation by the Meteorological Service of Canada (MSC) for the Wynyard, Saskatchewan observation station 4019035 and 40190LN.

MSC has recently revised observed precipitation data for a number of stations to correct for station gauge “undercatch,” primarily due to wind and for smaller effects of evaporation and a wetting factor. The MSC adjustment factors for monthly precipitation at the nearby Kelliher Saskatchewan station were obtained and applied to the recorded MSC data for the Wynyard observation station since these stations are in close proximity to one another and the wind data was considered to be similar at both locations.

Monthly evaporation used in the water balance model was based on published monthly evaporation by Agriculture and Agri-Food Canada (AAFC) for the Prairie Provinces Water Board. AAFC computed evaporation data for a number of locations in the Prairie Provinces using the Meyer evaporation formula. The published data for Wynyard only included data up to 2010. The record was extended by KGS Group to 2016 using the same methodology used by AAFC. Based on the evaporation and precipitation data, an E-P record was developed for the 1975 to 2015 period and is shown on Figure 5.

**FIGURE 5**
**CALCULATED DEPTH OF EVAPORATION MINUS PRECIPITATION ON THE QUILL LAKES**

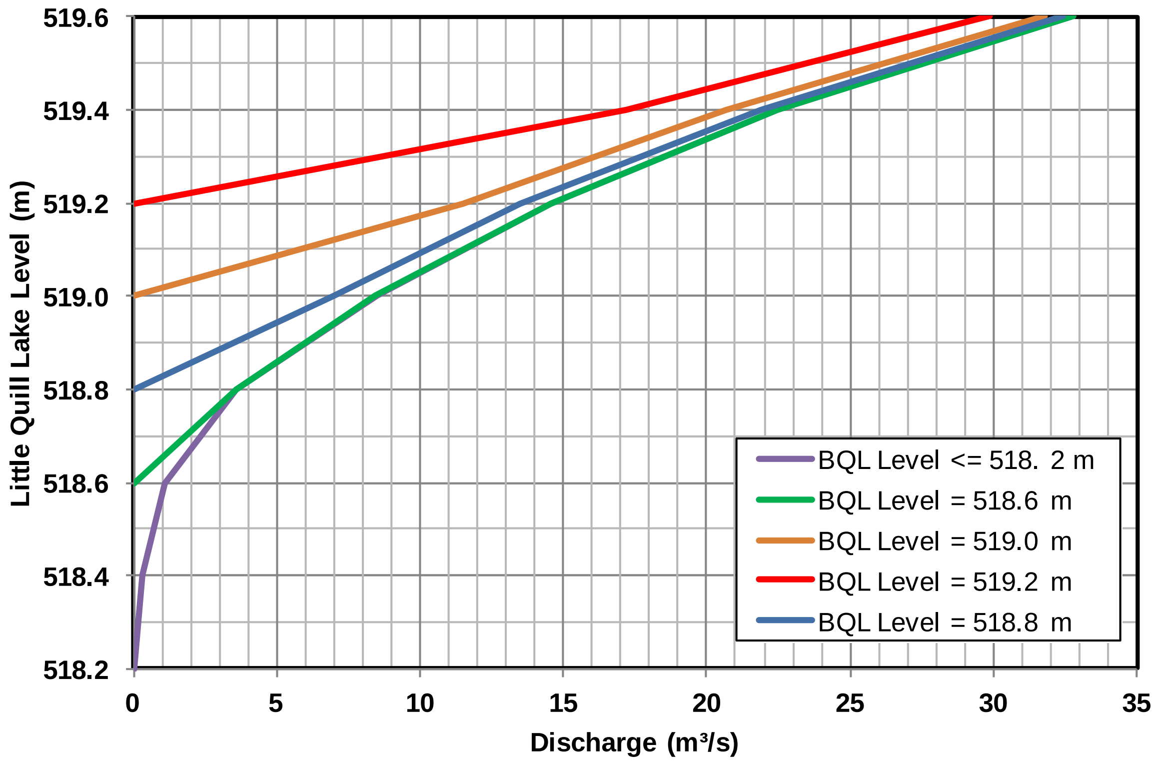



**Note:** 1 m = 3.28 ft

### 2.1.3.1 Computed Spill Volume from Little Quill Lake to Big Quill Lake

The daily spill volume between Big and Little Quill Lakes was calculated using a stage-discharge rating curve that was developed based on a HEC-RAS backwater model between Little Quill Lake and Big Quill Lake. The channel geometry was based on assumed channel dimensions from Google Earth imagery and LiDAR data for areas not under water at the time of the LiDAR capture. The channel invert levels from Big to Little Quill Lake were assumed based on the known Little Quill Lake spill elevation of 518.2 m (1700.1 ft). The computed backwater relationship is shown on Figure 6.

**FIGURE 6**
**QUILL LAKES BACKWATER RATING CURVE**



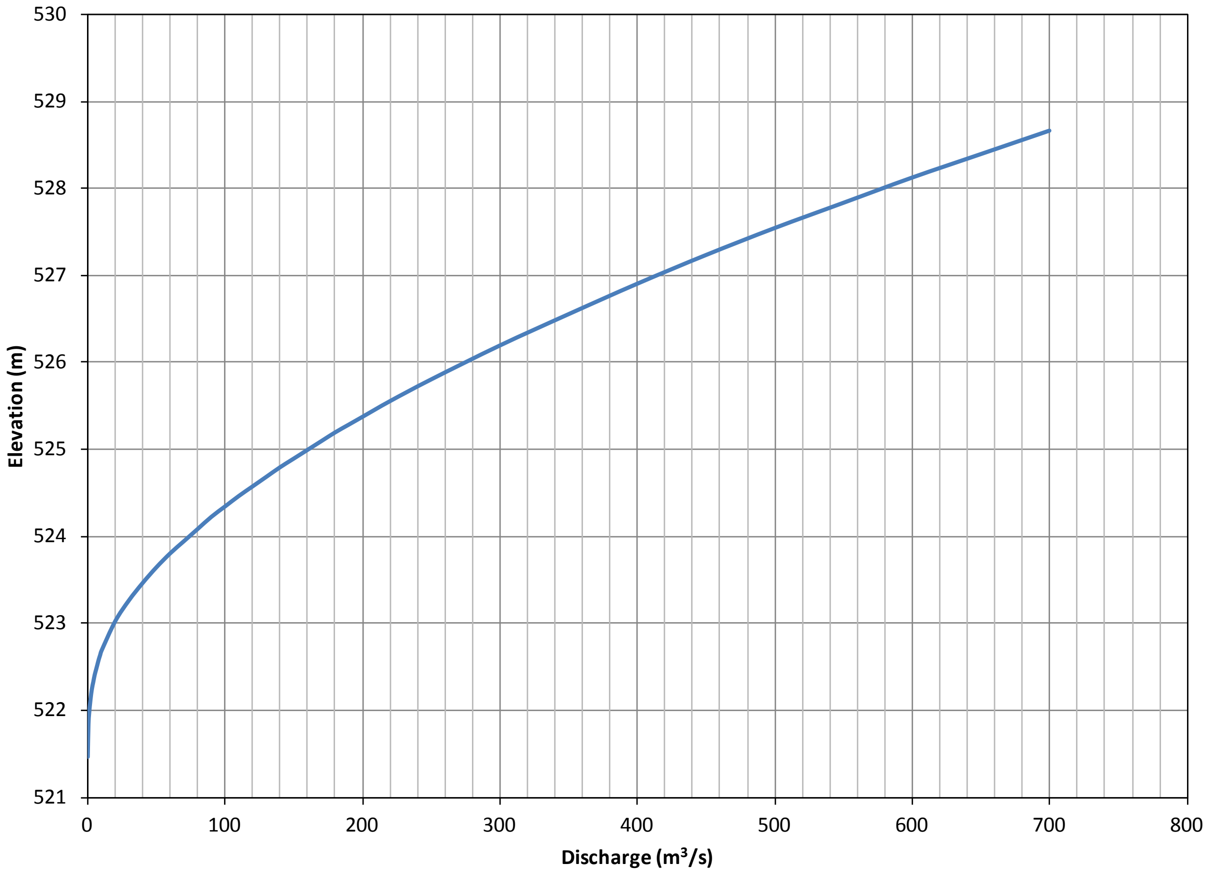

**Note:** 1 m = 3.28 ft
1 $m^3$/s = 35.315 cfs

Based on the surrounding topography, it was estimated that Big Quill Lake and Little Quill Lake will rise and fall independently until the water level on Little Quill Lake reaches approximately El. 519.2 m (1703.4 ft). At this point the lakes begin to rise and fall as a single water body since water is passed through the Grid Rd. 640 bridge. Once the water level exceeds El. 519.6 m (17.04.7 ft), Grid Rd. 640 is overtopped.

### 2.1.3.2 Computed Spill Volume from Big Quill Lake to Last Mountain Lake

The daily spill volume between Big Quill Lake and Last Mountain Lake can be calculated using the stage-discharge rating curve shown in Figure 7. The curve was developed based on a HEC-RAS backwater model between Big Quill Lake and Last Mountain Lake. The channel geometry in the model was based on surveys completed in 2015 as well as LiDAR data. To date, water has not exceeded the natural spill point of Big Quill Lake (El. 521.47 m or 1710.86 ft) and there have been no overflows into Last Mountain Lake.

**FIGURE 7**
**BIG QUILL LAKE OVERFLOW RATING CURVE**




**Note:** 1 m = 3.28 ft
1 $m^3/s$ = 35.315 cfs

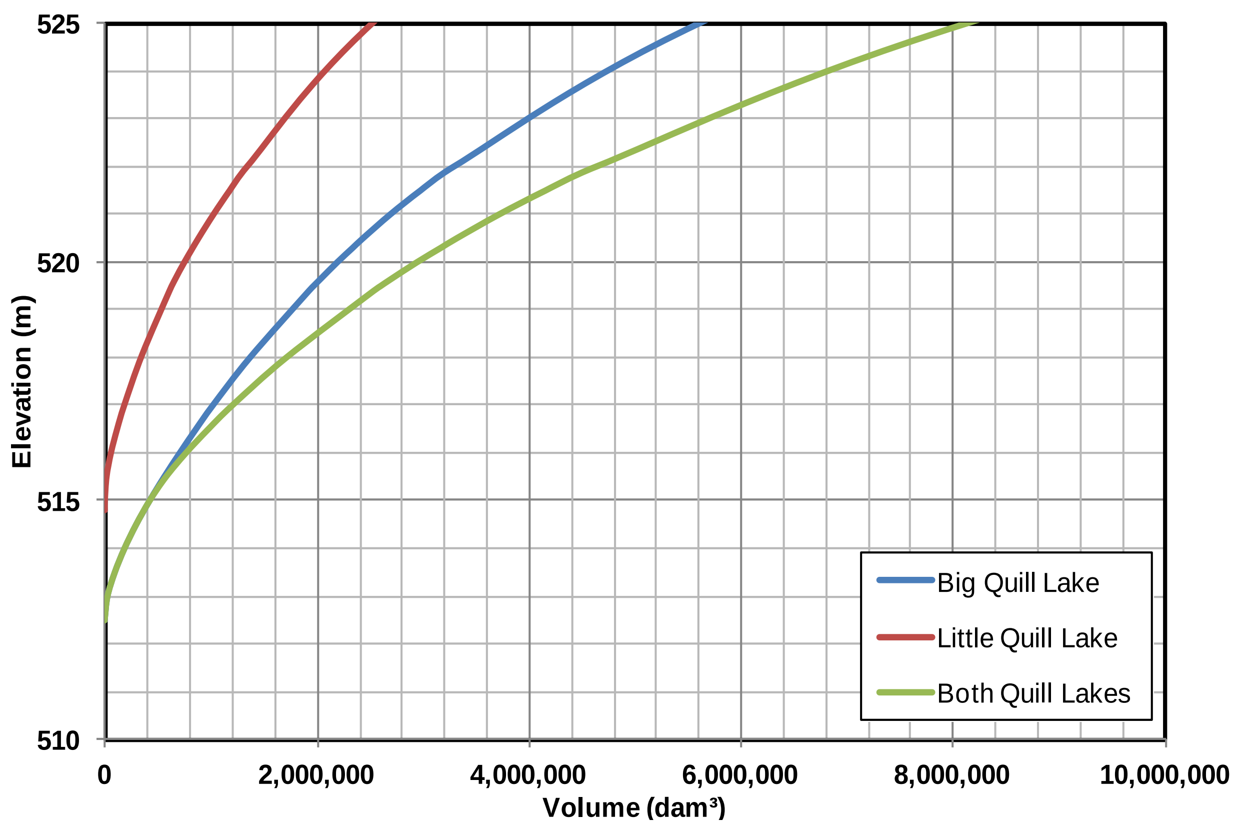
### 2.1.3.3 Stage-Storage Relationships

Stage storage curves for Big Quill Lake and Little Quill Lake are shown in Figure 8. These curves were derived from data provided by WSA and from KGS Group analyses using LiDAR surveys. Specifically, the following data was used to develop the storage relationships:

- Area and capacity curve for elevations up to 519.5 m (1704.4 ft) for Big Quill Lake and 519.65 m (1704.89 ft) for Little Quill Lake and Mud Lake are based on satellite imagery dated July 16, 2011 by WSA.
- Area and capacity for elevations 520.0 m (1706.0 ft) to 530.0 m (1738.9 ft) are based on LiDAR imagery dated August 13, 2012 by WSA.

At the current (spring 2016) water level of approximately 520.5 m (1707.7 ft), the total surface area of the lakes was estimated to be 78,000 ha (193,000 ac) [6]. From Figure 8, it follows that the volume of water within the lakes is approximately 3,500,000 $dam^3$ (2,800,000 ac-ft). At this elevation, the volume of water in the top foot of the lakes is approximately 237,750 $dam^3$ (193,000 ac-ft).

**FIGURE 8**
**STAGE-STORAGE CURVES FOR THE QUILL LAKES**




**Notes:** 1 m = 3.28 ft
1 $dam^3$ = 0.81 ac-ft

### 2.1.4 Runoff Computation

The net inflow ($Q_{in}$) to the Quill Lakes consists of runoff from the watershed (R), infiltration (I), precipitation (P) and evaporation (E). The net outflow of the Quill Lakes ($Q_{out}$) is zero since the Quill Lakes basin is a near-terminal basin with no defined outflow. The Quill Lakes have a natural outlet to Last Mountain Lake when the lake level exceeds El. 521.47 m (1710.86 ft). However, no outflows from the lake have been recorded since observations began in the

1880's. Therefore, the net flow only includes runoff, the precipitation minus the evaporation, and groundwater infiltration.

The runoff components of the inflow consist of stream flow on tributaries to Big and Little Quill Lakes and infiltration inflow. Tributary inflow for Quill Lakes watershed is measured only partially at a several locations in the basin around the Quill Lakes. The estimation of the total runoff to the Quill Lakes could be done by prorating the gauged runoff on the basis of the gauged drainage area to the total drainage area. The accuracy of this estimate, however, would depend on the degree of homogeneity in the drainage basins and the estimate of the effective and ineffective drainage areas with each sub-basin. These factors are not that well defined. In addition, the groundwater inflow (infiltration) cannot be measured and would have to be estimated.

Given the above uncertainties, the estimation of runoff using observed inflows was considered to be too approximate and was not appropriate for this study. Instead of using measured streamflow to define the runoff, the procedure used in this study was based on the process referred to as inflow available for outflow (IAO). This procedure uses changes in the observed water levels on Big and Little Quill Lake to define the net inflow to the lakes. The change in water level includes all components of inflow including runoff, infiltration, precipitation and evaporation.

The computed daily runoff to Big Quill Lake and Little Quill Lake was determined separately based on the recorded water levels on each lake and their respective stage-storage relationships. The computation procedure for the daily runoff is detailed in the series of steps below. A detailed example of the runoff calculation is provided in Appendix A.

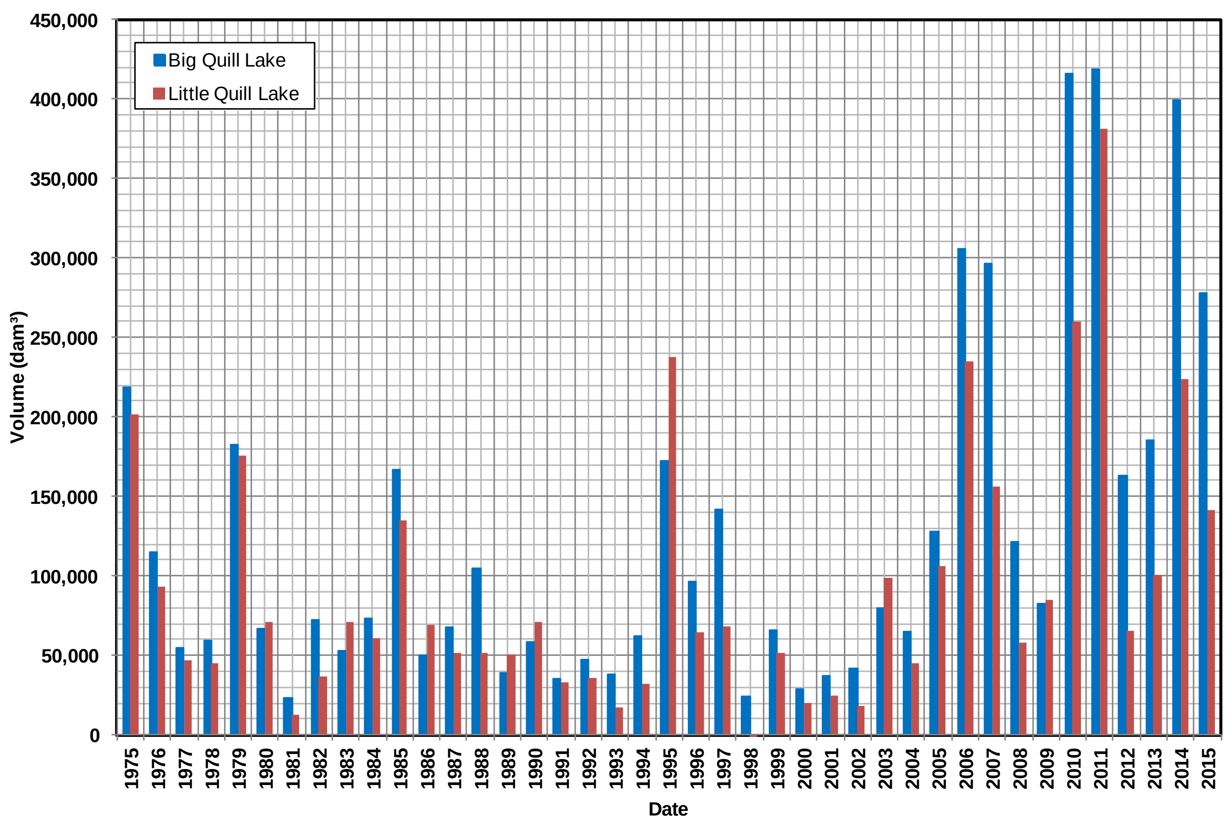
1) Calculate the daily lake volume increment due to the water level change.
2) Calculate the daily lake volume loss due to the E-P correction.
3) Calculate the volume of water spilled from Little Quill Lake to Big Quill Lake using the rating curve shown on Figure 6.
    - Water spills only when the Little Quill Lake level > 518. 2 m (1700.1 ft)
4) Calculate the volume of natural outflow to Last Mountain Lake from Big Quill Lake using the rating curve shown on Figure 7.
    - Water only spills when the BQL level > 521.47 m (1710.9 ft)

- Spill has never occurred in the period from 1975 to 2015.

5) Calculate runoffs for Big Quill Lake and Little Quill Lake separately based on above calculations.
   - Little Quill Lake: Daily Runoff = (1) – (2) + (3)
   - Big Quill Lake: Daily Runoff = (1) – (2) – (3) + (4)

The resulting daily runoff values were aggregated into annual records for each lake so that a frequency analysis on runoff volume could be completed. The calculated annual runoff volume for the Quill Lakes between 1975 and present is shown in Figure 9. It is evident from Figure 9 that the period from 1975 to 2015 includes both periods of relatively dry and wet climate conditions. The period from 1975 to 2005 contained multiple dry periods and is considered to be relatively dry while the period from 2005 to the present is considered to be representative of a wet climate period.

**FIGURE 9**
**ANNUAL RUNOFF VOLUME FOR THE QUILL LAKES – 1975 to PRESENT**

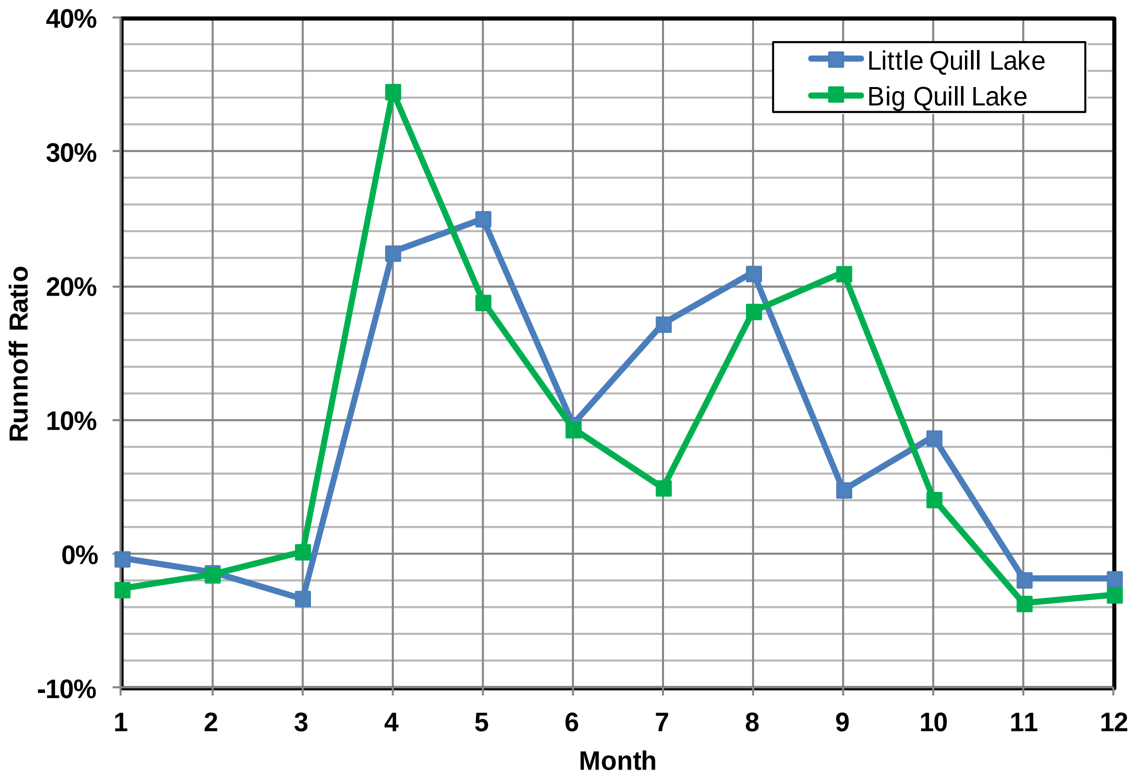



**Note:** 1 dam$^3$ = 0.81 ac-ft

### 2.1.5 Disaggregation of Annual Runoff and E-P Data

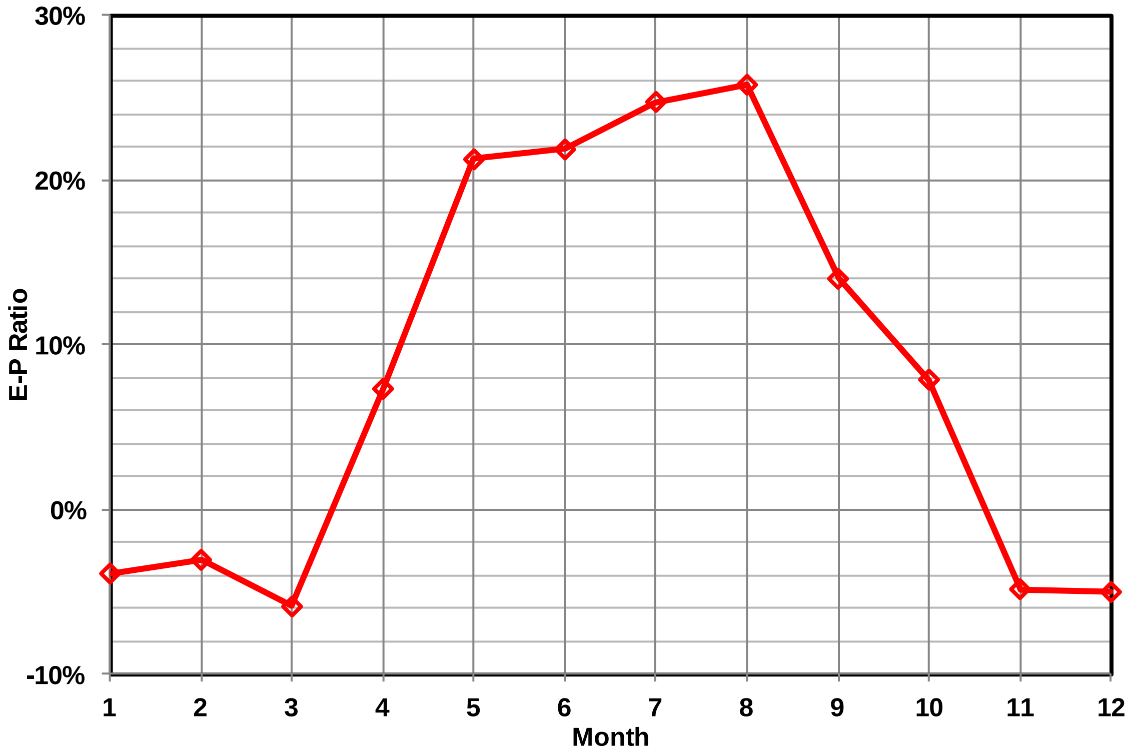
Since the water balance model uses a daily time step the annual runoff and E-P data series had to be disaggregated into daily values. The disaggregation of annual runoff to monthly data for Big and Little Quill Lakes was conducted manually using the computed median monthly values from the historical data. Median monthly runoff values were determined as a percent of the annual runoff. This monthly runoff distribution for the two lakes is shown in Figure 10. Monthly runoff volumes were subsequently divided by the number of days in each month to produce daily runoff volumes for input into the water balance model.

**FIGURE 10**
**MEDIAN MONTHLY RUNOFF TO THE QUILL LAKES**




Similarly, the median monthly E-P values recorded between 1975 and 2015 were determined and compared to the total annual E-P to determine the distribution of monthly E-P as a percent of the annual E-P. This relationship is shown in Figure 11. Monthly E-P was subsequently divided by the number of days in each month to produce E-P for input into the water balance model.

**FIGURE 11**
**MEDIAN MONTHLY EVAPORATION MINUS PRECIPITATION TO THE QUILL LAKES**




### 2.1.6 Computation of Water Levels

The water balance model was used to compute water levels on Big and Little Quill Lakes for the simulation period using the computed runoff sequence for the period of 1975 to present and the corresponding historical E-P values. The water level at the end of a time period was computed as the starting water level plus the change in water level on each lake as shown in the equation below. The change in water level was determined based on the change in storage, as discussed in Section 2.1.

$$WL_{end} = WL_{start} + \Delta WL$$

The total annual runoff volumes and total annual E-P values for the period from 1975 to 2015 were disaggregated into monthly values to be used in the water balance model (as described in Section 2.1.5). Daily runoff and E-P values were determined by dividing the monthly runoff and E-P by the number of days in each month.

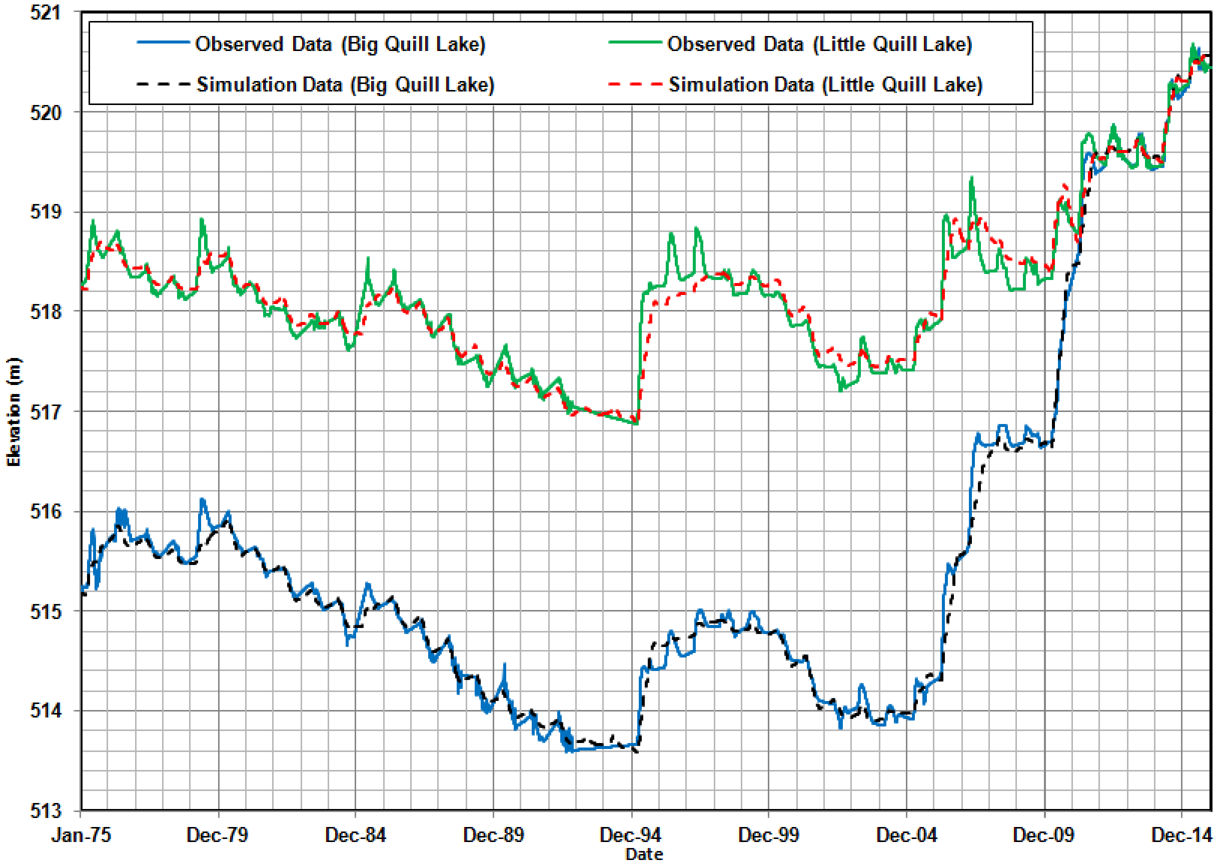
### 2.1.7 Calibration of Water Balance Model

The water balance model was calibrated by adjusting the distribution of total basin runoff that flows into Big and Little Quill Lakes. The distribution to each lake was determined by trial and error. A percent distribution was assumed and the water balance model was simulated using the assumed distribution. The resulting water levels on Big and Little Quill Lakes were compared to the historical water levels to determine whether the model could accurately reproduce the historical records. This process was repeated until a good fit between the simulated and observed data was found.

It was found that a flow distribution of 45% (for Little Quill Lake) and 55% (for Big Quill Lake) of the total basin runoff produced best fit between the computed and observed water levels. Figure 12 shows a comparison of the computed and observed water level, and indicates that they are in good agreement for the entire period of record.

Although a good fit between the computed and observed water levels was obtained using the calibration methods discussed above, it is possible that the flow distribution could be calculated based on the distribution of gross and effective drainage areas or based on streamflow measurements. These calculation methods could be considered in the next phases of design, however ratios of gross and effective drainage areas can differ from year to year depending on the soil moisture conditions in the basin.

**FIGURE 12**
**COMPARISON OF OBSERVED AND SIMULATED WATER LEVELS – 1975 TO PRESENT**




**Note:** 1 m = 3.28 ft

## 2.2 AUTOREGRESSIVE MODEL

Water levels on the Quill Lakes have been observed since the late 1800's. As shown on Figure 1, the data indicates that the lakes have cycled through both wet and dry periods in which the water levels increased or dropped over a number of years in response to changes in patterns of the climate variables, including rainfall and evaporation. The historical period used in this analysis (1975 to present) also includes periods of wet and dry conditions and is considered to be a representative sample of future conditions. It includes both the maximum and the minimum water levels in the 120 year period of record.

The historical water levels between 1975 and the present were used in conjunction with an autoregressive model to determine possible future runoff scenarios to Quill Lakes. The software used for this study, Stochastic Analysis, Modeling, and Simulation (SAMS), was developed by the Colorado State University and the US Bureau of Reclamation for the stochastic analysis of hydrologic time series of annual and seasonal stream flow.

The SAMS program was used for two purposes:

- To analyze the stochastic features of the historical data to test for long term dependence and memory of time series.
- Generate synthetic sequences of flow data. The computed annual flow series values are rearranged by the SAMS program to generate synthetic series of flows using principals of a “Monte Carlo” procedure.

### 2.2.1 Stochastic Analysis of Annual Flow Data

The SAMS program was used to analyse the annual total runoff to Quill Lakes from 1975 to 2015 and the annual total E-P values to determine the statistical properties of the data. Based on the analysis, it was determined that a log normal transformation of the runoff data resulted in the best probability fit. For E-P values, a transformation of the data was not required.

The historical annual runoff generated by the water balance model, as well as the historical annual E-P data were tested for independence using the SAMS software. The software analyzes the statistical properties of the data and determines the correlation between the runoff and E-P values in a given year compared to values from previous years to determine whether runoff or E-P in one year has an effect on the runoff or E-P in the following year. Cross correlation between runoff and E-P values was also determined using SAMS to investigate how the runoff is influenced by the E-P values (or vice-versa). Based on the results of the analysis, the best correlation was shown to occur with a lag of 4 years. This indicates that the runoff and E-P values can be influenced by conditions from the 4 previous years.

### 2.2.2 Synthetic Flow Series Generation

The SAMS program was used to generate possible future runoff and E-P scenarios based on the historical record. A number of stochastic models are available from the SAMS software to synthetically generate runoff and E-P values, each utilizing slightly different methods. Various models were tested, considering the statistical properties of the data and the correlation between runoff and E-P values. Based on the results of the models, the multivariate autoregressive model (MAR) was selected and the autocorrelation lag time of 4 years was confirmed. More information about the MAR model is available from the Applied Modelling of Hydrologic Time Series Publication [7].

When simulating a sequence of runoff and E-P values over many years, each of the runoff and E-P values synthetically generated by the MAR model takes into account the values that were generated for the 4 previous years. This method enables the model to simulate periods of dry and wet conditions that are representative of the historical record while maintaining the statistical properties of the data.

The autoregressive model was used to generate 1000 synthetic annual runoff and E-P series, each 50 years in length. The annual values were subsequently disaggregated to produce daily values following the methodology discussed in Section 2.1.5.

### 2.2.3 Synthetic Water Level Computation

The resulting daily time series of runoff and E-P were input to the water balance model to generate corresponding time series of Quill Lakes water levels, following the methodology described in Section 2.1.6. In total, 1000 water level time series, each 50 years in length were developed.

Ultimately, the time series data was analyzed using a duration analysis of computed water levels to determine the potential future trends for the Quill Lakes water level regime. The model assessment of the existing basin configuration is presented in Section 3.0. The model was also used to simulate a number of flood mitigation alternatives and compare the estimated future trends to the existing conditions to illustrate potential benefits of each alternative. The results assessment for the flood mitigation alternatives is presented in Section 5.0.

## 2.3 MODELLING ASSUMPTIONS AND CONSIDERATIONS

The models described in the preceding sections are considered to be accurate representations of the conditions in the Quill Lakes basin. However, during model development, numerous assumptions were made. These assumptions, along with their implications, are summarized below.

- **Precipitation and Evaporation Data** – Precipitation data was obtained from the Wynyard observation station. Due to its proximity to the lakes, it was considered a good estimate of precipitation on the lakes. Evaporation data cannot be measured. Rather is calculated via empirical relationships that take into account many variables including air pressure, wind velocity and water temperature. While these formulae typically provide reasonable estimates of evaporation, assumptions are often required when input data is not available. Errors in precipitation and evaporation data could potentially affect the synthetic E-P series that were generated.

- **Rating Curves** – Two rating curves were used to calculate outflows within the water balance model: (1) spill from Little Quill Lake to Big Quill Lake and (2) spill from Big Quill Lake from Last Mountain Lake. These rating curves were generated from HEC-RAS models that were developed using LiDAR and survey data (where available). Modifications to these rating curves could result in changes to the simulated Quill Lakes water levels due to an increase or decrease in outflows from the Lakes.

- **Historical Period of Analysis** – The period of analysis chosen for this project was 1975 to the present. This period was chosen primarily because prior to 1975 water level records for the Quill Lakes were sparse. The period of 1975 to present includes periods of wet and dry conditions, as well as both the maximum and the minimum water levels in the 120 year period of record. As a result, it was considered to be a representative of the historic conditions and it was assumed that future conditions would be similar to the 1975 to 2015 period. However, if an alternate period of record was selected, the resulting frequency distribution may be different. This could potentially alter the synthetic runoff series that were generated. Furthermore, non-stationary of the data and any paradigm shifts in hydrology, if they exist, including climate change or changes in weather patterns have not been assessed as part of this analysis.

- **Runoff Distribution** – The runoff distribution between Little and Big Quill Lake was determined through a trial and error process. Although a good fit between the computed and observed water levels was obtained using this calibration method, it is possible that the flow distribution could be calculated based on the distribution of gross and effective drainage areas or based on streamflow measurements.

- **Selection of Stochastic Model** – The MAR model was selected and utilized to generate the synthetic runoff and E-P series for this study. Different runoff and E-P series might have been obtained had a different model been selected.

- **Starting Water Level** – The starting water level for all simulations was El. 520.45 m (1707.51 ft), which was the recorded water level on December 31, 2015. Choosing an alternate (lower) starting water level would produce lower water levels in the short term, but long term levels (over 50 years) would be similar. In addition, the model did not differentiate whether the actual conditions prior to the first day of simulation were occurring as part of a wet or dry cycle. Therefore the model result over the first five years may be bias towards an average condition as opposed to the more likely wet conditions that have actually been occurring in the past few years.

- **Operation Range of Mitigation Options** – It was assumed that water would be removed, diverted, or stored upland regardless of the water level on the Quill Lakes. This assumption was made in order to quantify the maximum possible benefits of each mitigation option. However, it is possible that operation policies could be developed that mandate that mitigation measures are only to be utilized once the lake level reaches a particular threshold. Applying a range of operation to the model would affect water levels.