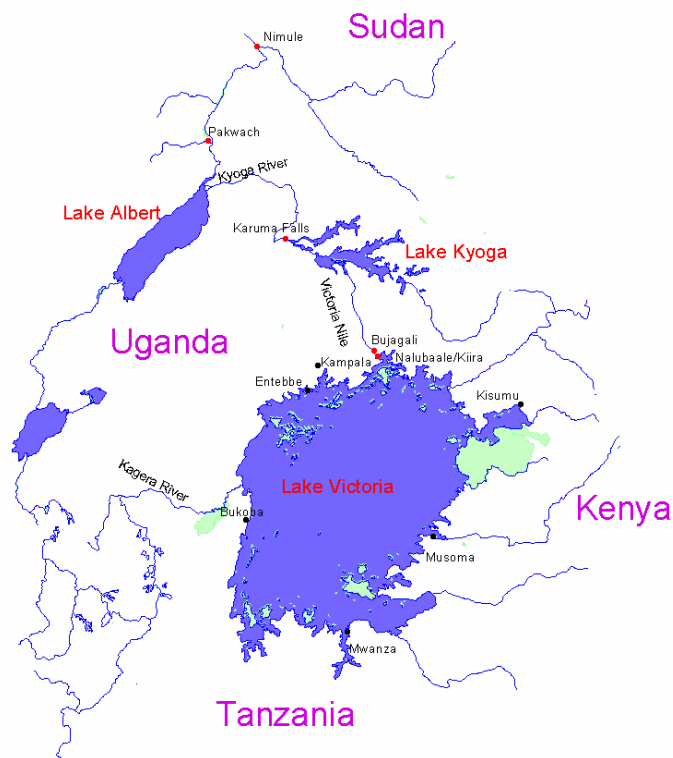


# Study on Water Management of Lake Victoria

## Technical Report 10 Climate Change Impact Assessment

Uganda Ministry of Energy and Mineral Development



Water Resources and Energy Management International Inc.

September 2005



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# Climate Change Impact Assessment

## Executive Summary

This technical report describes the methodologies and the findings of a climate change impact assessment for Lake Victoria. This investigation is carried out under the Power IV Lake Victoria Water Management Study, and aims at assessing the vulnerability of Lake Victoria to potential climate changes.

To answer this question, this study adopts an integrated assessment methodology that uses global climate models, bias correction and downscaling procedures, hydrologic models for the lake watershed, and river basin models for the lake and the downstream river system. Each of these components is consistent with observational data and with the historical climate and lake responses.

The assessment demonstrates that the future climate implies drier hydrologic conditions, lower lake levels, lower outflows, less energy generation, smaller wetland areas, and lower downstream river flows. In particular, the potential changes implied by the A2 climate scenario raise alarming concerns regarding the environmental and ecological integrity of Lake Victoria and of the entire downstream system. This finding underscores the imperative need for *coordinated* and *programmatic* water and energy planning.

# Climate Change Impact Assessment for Lake Victoria

## 1. Introduction and Overview

This technical report describes the methodologies and the findings of a climate change impact assessment for Lake Victoria. This investigation is carried out under the Power IV Lake Victoria Water Management Study, and aims at assessing the vulnerability of Lake Victoria to potential climate changes.

More specific study goals are to answer the following and related questions:

- (i) Is there scientific evidence that the climate of the lake region might experience significant changes in the upcoming decades?
- (ii) How can potential climate changes impact lake hydrology and balance?
- (iii) What are the potential consequences of climate change for Uganda's water and energy resources? What are the potential consequences for the downstream Nile system?
- (iv) What can Uganda do to mitigate the adverse impacts of climate change?

To address these questions, this study adopts an integrated assessment methodology that develops and uses global climate models, hydrologic models for the lake and its watershed, and water resources models. Each of these components is consistent with observational data and with the historical climate and lake responses. The report describes this prototype assessment and its findings, and demonstrates that climate change can have very serious consequences for the lake region, both with respect to water as well as the energy sectors.

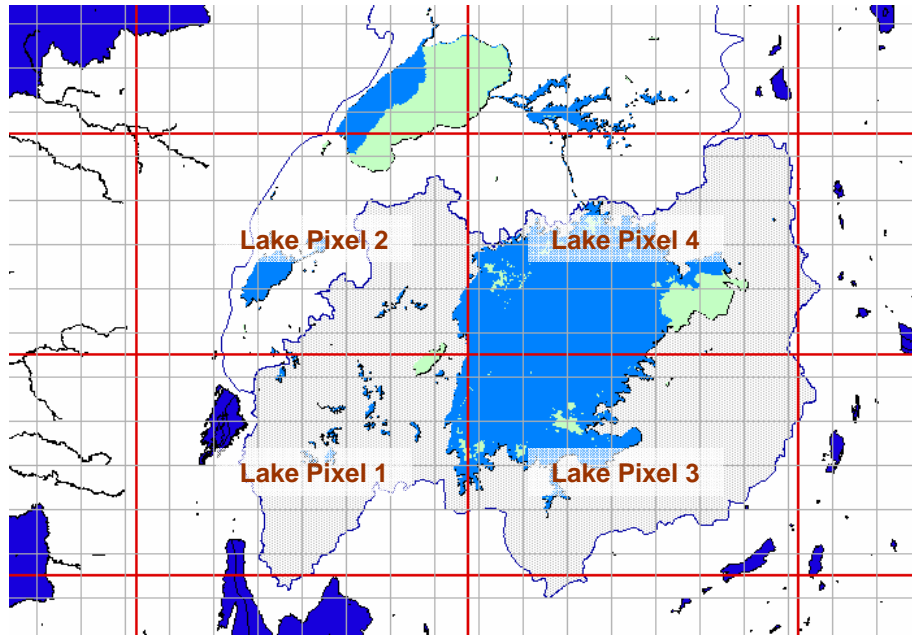
The report includes 5 chapters. Chapter 2 describes the climate model and the procedures employed for bias correction and downscaling. The Chapter ends with the presentation of the future rainfall and temperature sequences that are consistent with the predictions of global climate models. Chapter 3 describes the development and testing of a hydrologic

model for the lake and its watershed. This model simulates the main hydrologic processes that affect lake balance: rainfall, evaporation, and watershed runoff. Chapter 4 discusses the assessment investigations, including assessments of the lake response under the historical climate, and assessments pertaining to the climate and hydrologic scenarios consistent with the predictions of global climate models. Lastly, Chapter 5 summarizes the study findings and recommendations. The reader who is interested more in the practical study findings than the modeling aspects may wish to skip Chapters 2 and 3 and refer to Chapters 4 and 5.

## 2. General Circulation Models and Data Used

General circulation models (GCMs) are mathematical tools that simulate the global atmospheric circulation. GCMs have improved considerably over the past few decades and have been shown to represent the atmospheric circulation on a global scale well. Even so, GCMs still exhibit significant biases at sub-continental scales. Although such regional-scale biases can be large, extensive evaluation and inter-comparison of different models indicates good agreement among many models in predicting climate response *changes* to changing atmospheric forcing. This across-model consistency indicates that GCMs are able to capture the underlying regional climate dynamics (Kittel et al., 1998).

Three of the most commonly used GCMs were evaluated for this assessment. These were the HadCM3 (Hadley Center for Climate Prediction and Research, Pope et al., 2000), ECHAM4 (Max Planck Institute for Meteorology, Roeckner et al., 1996), and the CGCM2 (Canadian Center for Climate Prediction, Flato and Boer, 2000). The evaluation was based on the ability to simulate the observed climate response (temperature and precipitation) over Lake Victoria during the 1961 to 1980 time horizon. The observational data used for this evaluation were the Climate Research Unit TS 2.0 monthly temperature and precipitation series at 0.5 x 0.5 degree resolution (Mitchell et al., 2003). The spatial resolution of this data set corresponds to the gray pixels in Figure 2.1. In these evaluations, HadCM3 performed best and was selected for the assessment. HadCM3 is a coupled atmosphere-ocean GCM with spatial resolution of 2.5 x 3.75 degrees corresponding to the red pixels in Figure 2.1. The following sections detail the methods applied to bias-adjust and downscale the HadCM3 monthly temperature and precipitation data to be used in assessing the potential water resources impacts in Lake Victoria.



**Figure 2.1:** CRU TS 2.0 observed climate grid (grey) and HadCM3 pixels (red)

## 2.1. Seasonal Cycle

Bearing in mind the importance of the seasonal cycle to water resources management, the model was assessed for various seasonal sets. While GCMs generally perform better at longer aggregation periods, for the present application it is necessary to select the best *seasonal* break-down at which the model demonstrates reasonable skill in simulating the seasonal cycle.

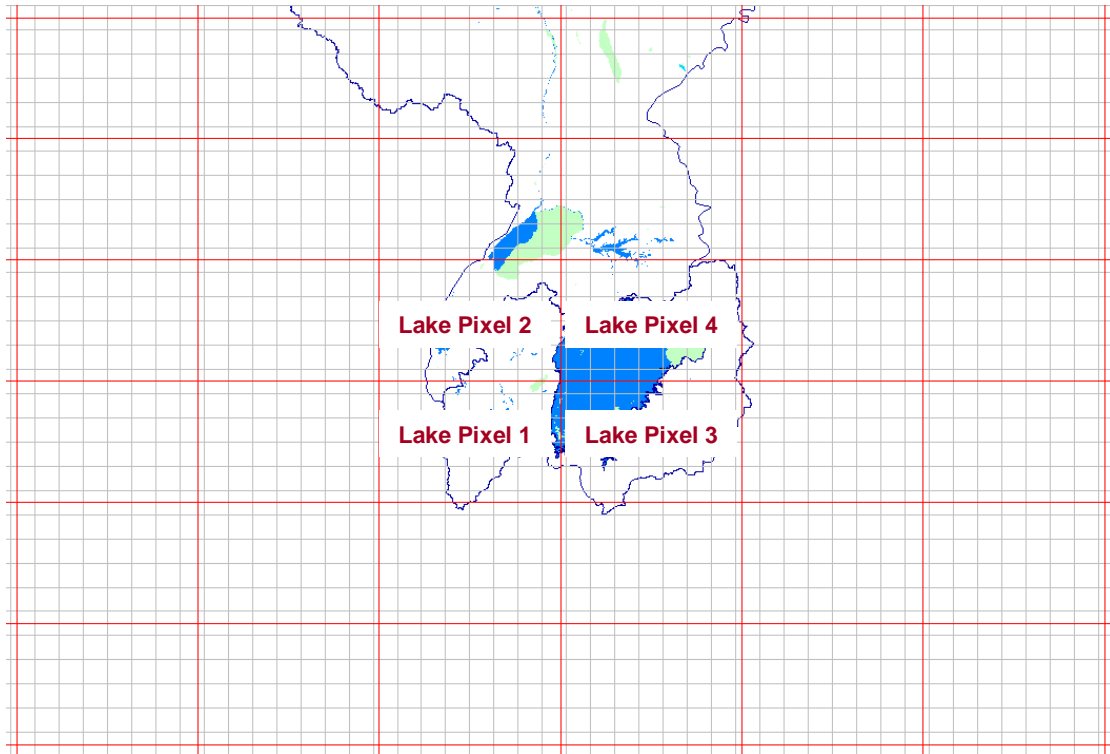
Seasonal and spatial model statistics were compared to observed data statistics for multiple seasonal resolutions. Seasonal schemes included uniformly spaced seasons of 1, 2, 3, 4 and 6 months and irregular seasons corresponding to observed coherent climate patterns of precipitation resulting from a spatial principal component analysis (Camberlin and Philippon, 2002). Based on this analysis, two 6-month seasons (January to June and July to December) were selected as having good correlations with observations and the ability to capture spatial parameter relationships.

## 2.2. Indicator Pixels

Correspondence of HadCM3 temperature and precipitation with observed fields varied considerably across the East African region. This was expected due to the coarse model resolution, 2.5 X 3.75 degrees, and the significant spatial heterogeneity of the East African climate. In light of this, the first step in the analysis is to identify pixels that exhibit high correlation between GCM predictions and historical observations over the 1961 to 1980 time period. The underlying premise is that if these pixels exhibit high correlations over the historical period, the GCM represents correctly associated atmospheric dynamics, and it is most likely to continue to predict the future climate well. These are referred to as indicator pixels. Furthermore, the existing spatial relationships between indicator and lake pixels can be used to predict the climate response over Lake Victoria.

Thirty-six HadCM3 pixels, approximately centered over Lake Victoria (Figure 2.2.1), were evaluated for agreement with the observed climate and for consistency across several years of seasonal averaging. Furthermore, in cases where adjacent pixels apparently demonstrated complementary features, clusters of pixels were spatially averaged and included in the analysis. It is important to note that the strength of the relationship between HadCM3 predictions and historical data was evaluated based on correlations *across a range of time aggregations*. Pixels of interest are those that perform consistently well across all time aggregations.

Correlations between the GCM predictions and the up-scaled historical data were calculated at each of 36 GCM pixels surrounding Lake Victoria, as well as pixel clusters of interest. The procedure was applied for 1-, 2-, 3-, 4-, and 5-year seasonal aggregations, with pixel correlations ranked in descending order for each aggregation period. For example, to evaluate the correlation of the 2-year aggregation of the first season (January to June), the 20 year seasonal data (GCM and historical) are aggregated into 10 values, the averages of two consecutive year first seasons. The correlations of the GCM predictions and historical data are then computed and ranked (lowest rank assigned to the highest correlation) for all time aggregations.



**Figure 2.2.1:** Thirty-Six Indicator Pixel Set

The evaluation of the correlation strength is based on the summation of the correlations at each of the five aggregations for a particular pixel or pixel cluster. This quantity helps evaluate the relative performance of the model at all pixels and across a range of aggregations. Pixels with small correlation sums and consistent cross-aggregation correlations are selected for further analysis. In addition, a bootstrap procedure is used to assess the significance of the correlation sum statistic. The purpose of the bootstrap test is to assess the probability of the correlation sum being high by pure chance. If this probability is very small, the strength of the correlation relationship between GCM and historical data is very likely real.

### 2.3. Bias-Adjustment

Bias correction was based on the 1981-2000 historical temperature and precipitation data. The correction procedure is summarized below:

$$X'_{i,t} = X_{i,t} \left( \frac{\bar{X}_{i,o}}{\bar{X}_{i,m}} \right).$$

In the above equations,  $X_{i,t}$  is the model prediction for season  $i$  of year  $t$ ,  $\bar{X}_{i,m}$  is the baseline model mean for season  $i$ ,  $\bar{X}_{i,o}$  is the 20-year *observed* seasonal average, and  $X'_{i,t}$  is the bias-adjusted model series.  $X$  is either monthly temperature or monthly precipitation at a particular pixel or pixel cluster.

The previous adjustment corrects for mean process bias. A second adjustment is also made to the model results to conform to the variability of the historical data. This procedure takes the sequence anomalies and scales them consistently with the observed historical variability. The correction is as follows:

$$\Delta_{i,t} = X'_{i,t} - \bar{X}_{i,o}$$

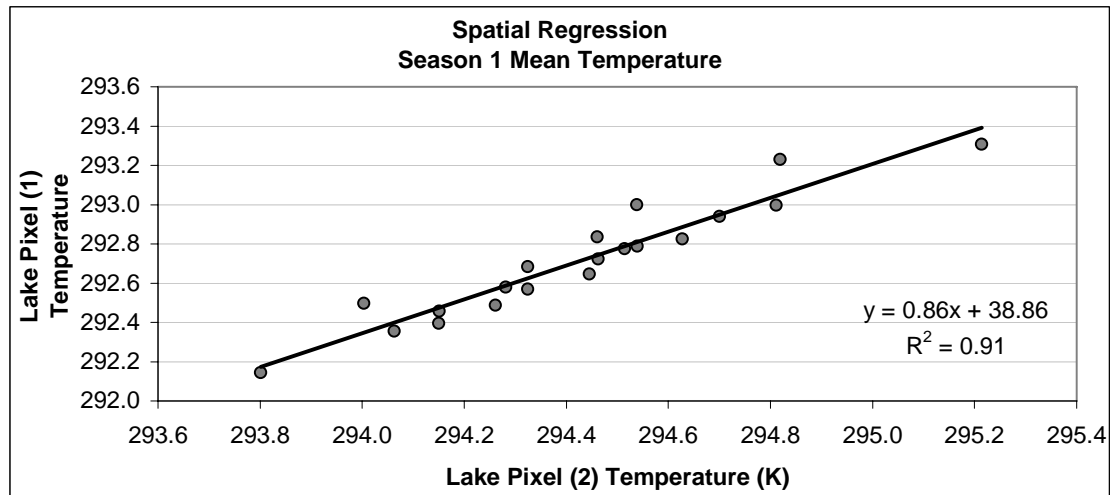
$$X''_{i,t} = \Delta_{i,t} \left( \frac{\sigma_{i,o}}{\sigma_{i,m}} \right) + \bar{X}_{i,o}$$

In the above equation  $\Delta_{i,t}$  is the data anomaly for season  $i$  of year  $t$ ,  $\sigma_{i,o}$  is the historical sequence standard deviation during the baseline period,  $\sigma_{i,m}$  is the standard deviation for the model data over the same period, and  $X''_{i,t}$  is the fully adjusted model data. The final adjusted model sequences exhibit the appropriate baseline mean and variance with respect to the observed data.

## 2.4. Spatial Pixel Relationships in the Lake Watershed

Following selection of the best indicator pixels and data adjustment, the observational record is examined for discernable relationships between the indicator pixels and those directly over the Lake Victoria watershed. As shown in Figure 2.4.1, such relationships may be used to predict the corresponding series for the lake area. The assumption underlying this approach is that the historical spatial relationships between indicator and

lake pixels will continue to prevail in future climates. All applied spatial regressions are included in Appendix A.



**Figure 2.4.1:** Relationship of Historical Data between Indicator and Lake Pixels

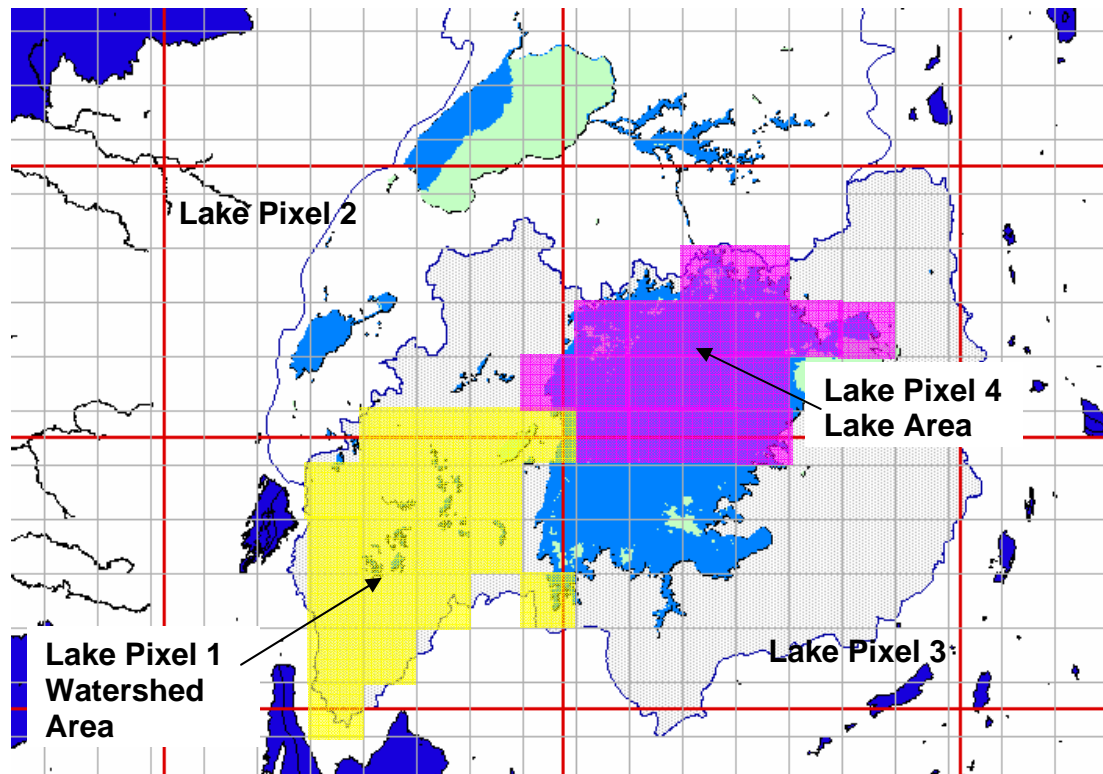
## 2.5. Downscaling

The processed GCM data in its original resolution is too coarse for use in hydrologic modeling. There is thus the need to downscale this data over the lake and watershed areas in each pixel. Downscaling is accomplished by establishing the historical relationships between spatial resolutions. These relationships can be quantified using the observed CRU data (0.5 x 0.5 degree resolution) by spatially aggregating them over each of these areas and comparing them to the overall scaled-up value at the GCM resolution. An example of this aggregation process is shown in Figure 2.5.1.

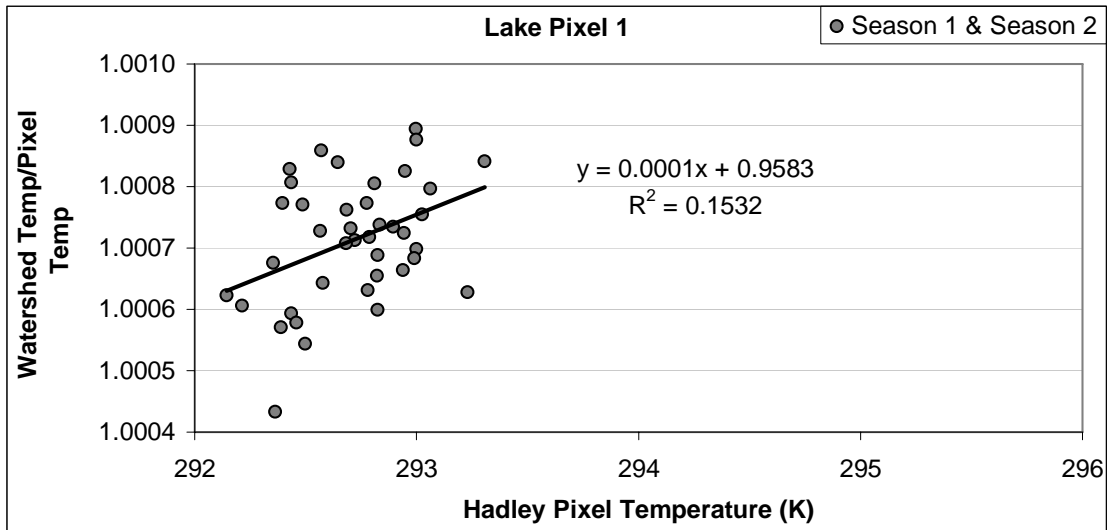
The downscaling procedure employed here establishes the relationship between the large node value and a downscaling factor for each sub-area of interest. The downscaling factor is the ratio of the mean areal value over the sub-area to the average over the GCM pixel. In some cases, the relationship depends on the season of interest, while in many

cases the relationship is invariant from one season to the next (Figures 2.5.2 and 2.5.3). The complete set of downscaling relationships is presented in the Appendix.

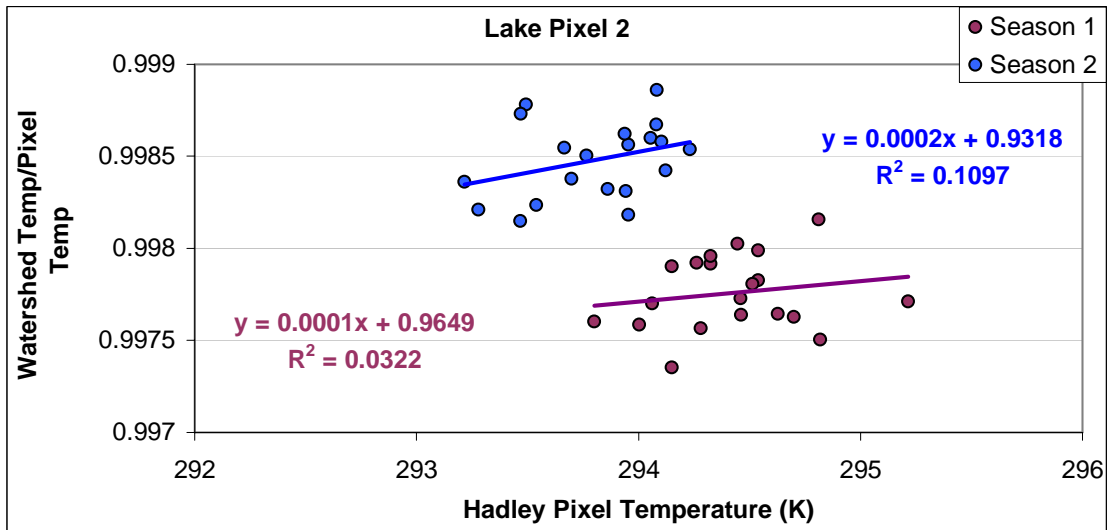
Using these relationships, lake and watershed area sequences are generated by multiplying the large node value (after it has been adjusted for bias and consistency) by the corresponding downscaling factor.



**Figure 2.5.1:** Example of Spatial Aggregation Using the CRU Data Set



**Figure 2.5.2:** Example of Downscaling Relationship; Season Independent



**Figure 2.5.3:** Example of Downscaling Relationship; Season Dependent

## 2.6 Uncertainty Characterization

Several steps in the GCM processing procedure rely on regression equations, which when used alone do not reflect the underlying uncertainty. To account for this uncertainty, at

each stage of the process, the regression errors are recorded. The errors are then applied to the regression results using a bootstrapping method. The GCM data was processed many times, each time with randomly selected errors, forming an ensemble of traces. The ensemble allowed assessment of the uncertainty associated with the spatial regressions and of the downscaling process.

## 2.7. Climate Change Scenarios

At the heart of future climate and climate change assessments are underlying assumptions about atmospheric forcing, not the least of which includes the concentrations of atmospheric gases. In an attempt to encourage standardized comparisons among climate change experiments and assessments, the Intergovernmental Panel on Climate Change (IPCC) has developed a series of potential emission scenarios as part of its Special Report on Emissions Scenarios (SRES) (IPCC, 2000). The SRES describes four families of scenarios, SRES A1, A2, B1 and B2, each of which is based upon differing assumptions about future economic development, population growth, environmental policies and technological change.

The two climate scenarios considered in this report stem from the SRES A2 and SRES B2 emissions. These runs were selected for several reasons, including: SRES A2 and B2 GCM output is most readily available to the impact assessment community; and, the future atmospheric compositions prescribed by these two scenarios span nearly the entire inter-quartile range for all scenarios developed as part of the SRES. Therefore, the A2 and B2 families are representative of a wide range of potential future conditions.

The primary differences between the A2 and B2 scenarios are as follows. The SRES B2 scenario is based upon assumptions of moderate economic and population growth with resulting moderate cumulative emissions between 1990 and 2100 of 1,164 GtC. The A2 scenario also assumes moderate economic growth; however, this scenario assumes more rapid population growth and much higher emissions of 1,862 GtC.

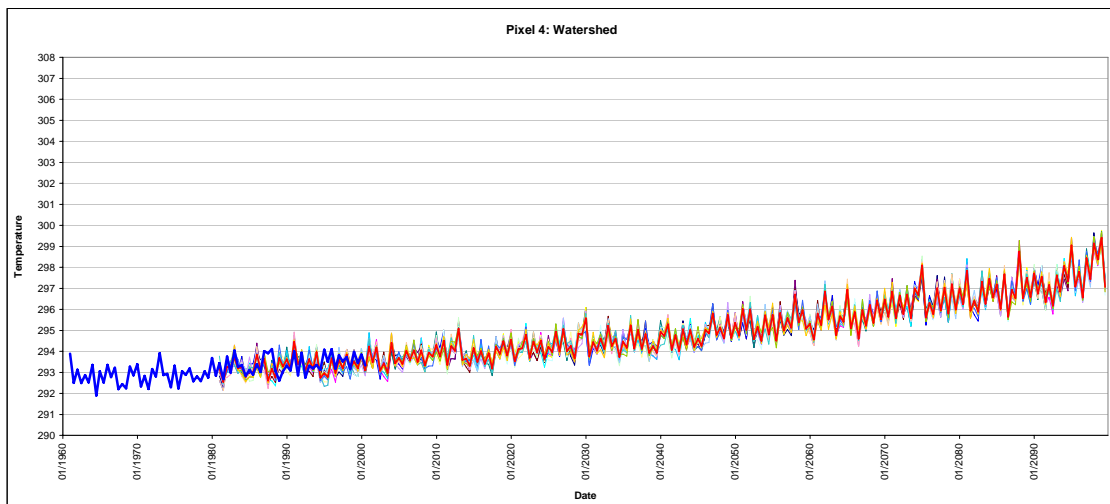
The final sequences of temperature and precipitation were generated for both watershed and lake surface areas. An ensemble of 20 traces was generated for each pixel area using the bootstrapped residuals as mentioned in the previous section. Hadley pixels 1 and 2 did not contain appreciable lake area and therefore only have corresponding watershed sequences. Pixels 3 and 4 include considerable lake and watershed areas and consequently have both downscaled sequences. The final results for both the A2 and B2 scenarios are presented in the Appendix, with only a few graphs reproduced at the end of this section.

The results show an increasing trend in temperature for all sequences and in both A2 and B2 scenarios. Bias-correction has ensured that all sequences have the appropriate baseline climatology corresponding to the observed historical data; however, the A2 and B2 temperature trends begin to diverge around 2040. At this point of separation, which is observed in all watershed and lake sequences, both trends continue to increase but with the A2 temperatures increasing at a considerably greater rate than B2. In the final year, 2099, the A2 and B2 ensemble means differ by approximately 3 degrees C for the watershed sequences and approximately 2.5 degrees C for the lake sequences. Note that in the final two decades, 2080s and 2090s, the B2 sequences taper off and become approximately horizontal, while the A2 sequences continue to exhibit an upward trend.

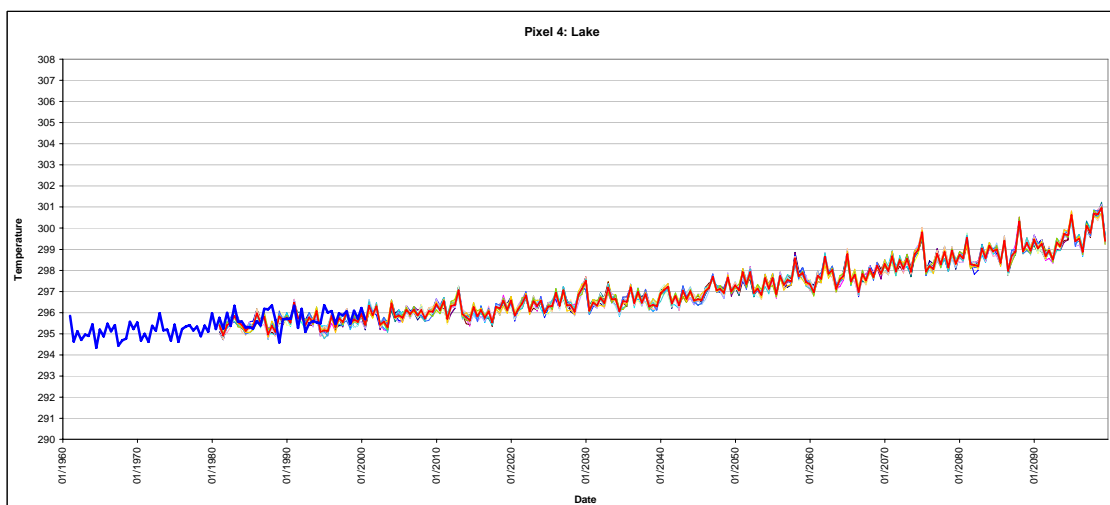
The range between temperature minima and maxima changes from the historical period to the final decades of the runs. An increase in this range is most evident in the A2 scenario after 2070. Watershed pixels 1 and 2 show a near doubling of this range, while pixels 3 and 4 for both lake and watershed areas show an approximate 25% increase. B2 sequences show very little, if any, increase in the minima to maxima ranges.

Lastly, the temperature results show that the uncertainty introduced by the errors of the regression and downscaling relationships is relatively small in comparison to the seasonal and inter-annual climate variability. Because of this, the ensemble traces stay relatively near each other.

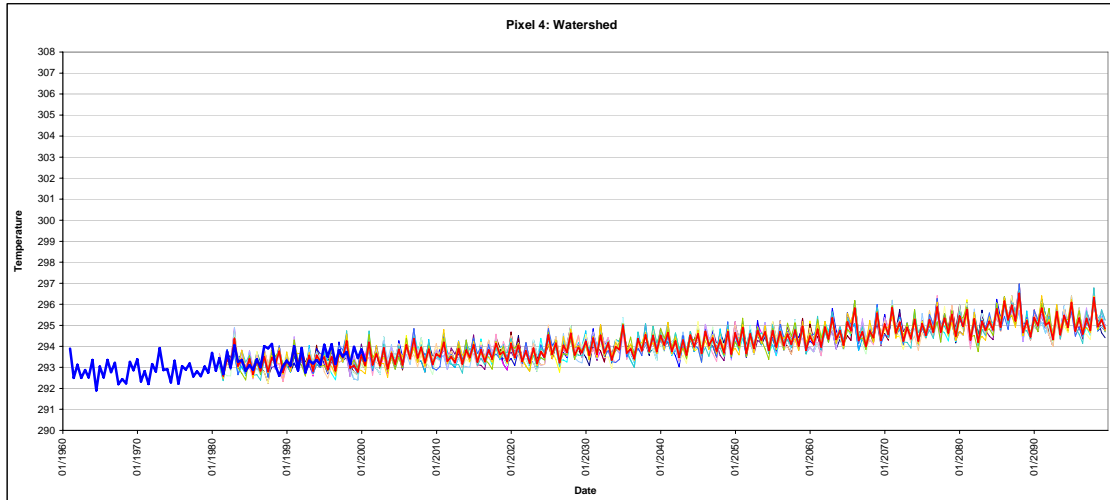
The primary precipitation result for both the A2 and B2 scenarios is that the GCM does not have significant and consistent skill in predicting precipitation patterns. The A2 results suggest some ability of the model to pick up some features of inter-decadal variability, but for the most part both model runs demonstrate limited ability to capture finer precipitation features, which are generally drowned by model noise. In the seasons and areas that some skill exists, there is no indication of any long term change in precipitation patterns. Thus, the resulting precipitation sequences follow the historical patterns.



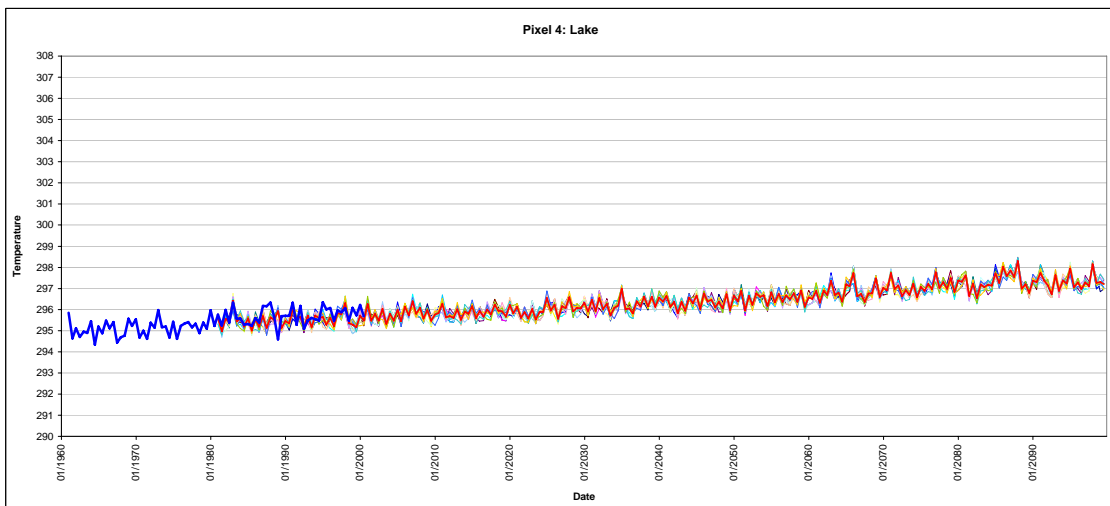
**Figure 2.7.1:** A2 Temperature sequences for Watershed Pixel 4



**Figure 2.7.2:** A2 Temperature sequences for Lake Pixel 4



**Figure 2.7.3:** B2 Temperature sequences for Watershed Pixel 4



**Figure 2.7.4:** B2 Temperature sequences for Lake Pixel 4

### 3. Hydrologic Modeling

The purpose of the hydrologic modeling is to relate atmospheric forcing (precipitation and temperature) to watershed outflow. Watershed outflow is an important component of lake water balance which determines the changes that lake storage undergoes in response to precipitation, evaporation, and watershed outflow sequences:

$$S(k+1) = S(k) + P(k) - E(k) + Q(k),$$

where  $S(k)$  represents lake storage at the beginning of time period  $k$ ,  $P(k)$  represents lake precipitation,  $E(k)$  lake evaporation, and  $Q(k)$  watershed outflow into the lake.

Precipitation and mean temperature sequences for the lake and watershed areas have already been developed in the previous section consistent with the A2 and B2 HADCM2 climate scenarios. This section uses this data to develop the hydrologic quantities that enter in the lake water balance.

#### 3.1. Lake Evaporation

Lake evaporation assumed to take place at the climatic potential rate and can be estimated from the Malmstrom potential evapotranspiration formula (Dingman, 2004):

$$PET(k) = 40.9 \cdot 0.611 \cdot \exp \left[ \frac{17.3 (T_{\text{mean}}(k) - 273.16)}{T_{\text{mean}}(k) - 273.16 + 237.3} \right].$$

In the above expression,  $T_{\text{mean}}(k)$  is the monthly mean air temperature over the lake in degrees Kelvin, and  $PET(k)$  is the potential evapotranspiration rate in millimeters per month. The constant 273.16 serves to convert degrees Kelvin into degrees Celsius. The above equation conveniently relates air temperature to open water evaporation and is used extensively in hydrologic investigations. A more elaborate method due to Linacre (...) was also applied in this study, but the results were comparable to those obtained by the Malmstrom formula. The comparison between these two methods was performed over the historical period for which additional data on wind speed, cloud cover, humidity, and incoming radiation were also available. Such data however, could not be obtained for the HADCM2 scenarios, and in view of the methods' comparable performance, the present assessment study will use the Malmstrom lake evaporation equation.

## 3.2. Watershed Evapotranspiration

The Lake Victoria watershed is distinguished in four sub-watersheds, one for each of the four HADCM2 pixels that encompass the lake and watershed areas (Figure 2.1).

Specifically, the southwest HADCM2 pixel includes the Kagera River watershed and is referred to as Watershed 1; the northwest HADCM2 pixel includes lake watersheds in southwest Uganda (Watershed 2); the southeast HADCM2 pixel mainly includes lake watersheds in northern Tanzania (Watershed 3); and the northeast HADCM2 pixel includes Nzoia, Nyando, Nyala, and other watersheds in northwest Kenya (Watershed 4).

As part of the HADCM2 scenario analysis of the previous section, bias adjusted precipitation and mean temperature sequences have already been developed for all four lake sub-watersheds. The temperature sequences can be converted into watershed evapotranspiration using the Pike evapotranspiration equation (Dingman, 2004):

$$ET = \frac{P}{\sqrt{1 + [P/PET]^2}},$$

where ET is the annual evaporation, P is the annual precipitation, and PET is the annual potential evapotranspiration which can be estimated from the Malmstrom equation. The Pike evapotranspiration has been shown to apply in areas where evapotranspiration is limited by the availability of water as opposed to solar energy (radiation). Being on the equator, the Lake Victoria region certainly falls in this category. Second, the equation uses annual quantities. In this study, however, consistent with the aggregation of the HADCM2 climate scenarios, the equation is used to estimate watershed evapotranspiration over six month intervals. In light of the relatively small seasonal temperature variation in the Lake Victoria region, this application is not expected to introduce significant errors. The validity of this assumption will be assessed by the ability of the model to replicate field observations.

## 3.3. Watershed Model

The choice of the watershed model depends on the data available for its calibration.

Generally, three data categories are necessary in developing watershed models:

precipitation, evapotranspiration, and streamflow. As discussed earlier, historical precipitation and evapotranspiration data are indeed available for each sub-watershed. However, with the exception of a few individual rivers (such as the Nzoia and partially the Kagera), complete and consistent streamflow data are lacking for the four sub-watershed areas. Unfortunately, this situation rules out the calibration of hydrologic models for each sub-watershed. Watershed outflow is only observable in an aggregate sense (from all four sub-watersheds) through its impact on lake levels after the effects of lake precipitation and evaporation are subtracted out. Thus, the only plausible modeling approach is to relate rainfall and evapotranspiration of the individual sub-watersheds to total watershed outflow.

Let  $Q(k)$  denote total watershed outflow into Lake Victoria over a six-monthly period  $k$ ;  $P(k)$  lake precipitation volume during period  $k$ ;  $PET(k)$  lake evaporation volume during period  $k$ ;  $\Delta S(k)$  change in lake storage during period  $k$  (i.e.,  $\Delta S(k) = [S(k+1) - S(k)]$ );  $P_i(k)$  precipitation volume over sub-watershed  $i$  during period  $k$ ; and  $ET_i(k)$  evapotranspiration volume over sub-watershed  $i$  during period  $k$ . Then,  $Q(k)$  can be estimated from

$$\Delta S(k) = P(k) - PET(k) + Q(k) \Leftrightarrow Q(k) = \Delta S(k) - P(k) + PET(k) .$$

Then, the development of the watershed model amounts to identifying an analytical relationship between  $Q(k)$  and  $\{P_i(k), ET_i(k), i=1,2,3,4\}$  that satisfactorily explains the historical observations.

After the comparative evaluation of several analytical forms, the following model was shown to exhibit the best overall performance:

$$\frac{Q(k)}{\sum_{i=1}^4 P_i(k)} = \alpha_0 + \sum_{i=1}^4 \alpha_i \frac{ET_i(k)}{P_i(k)} ,$$

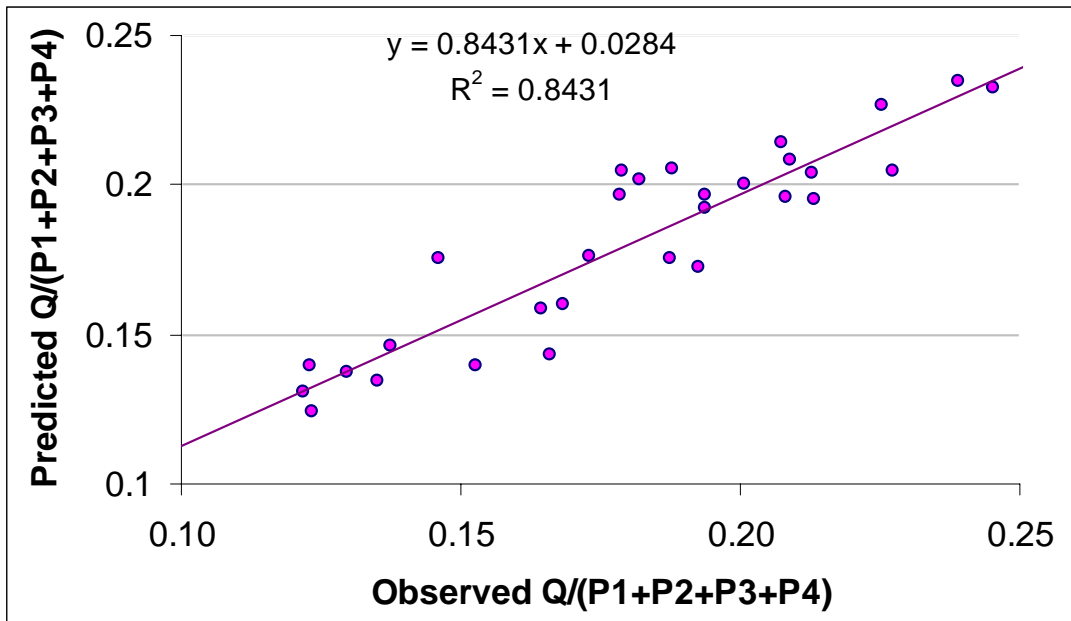
where  $\{\alpha_0, \alpha_1, \alpha_2, \alpha_3, \text{ and } \alpha_4\}$  are constant coefficients (independent of period  $k$ ). Using data from the 1960 to 1980 time period, these coefficients were estimated (via linear regression) to have the following values:

<b>Coefficient</b>	<b>Value</b>
$\alpha_0$	0.4514714
$\alpha_1$	-0.0729379
$\alpha_2$	-0.0164612
$\alpha_3$	-0.5018568
$\alpha_4$	0.2980258

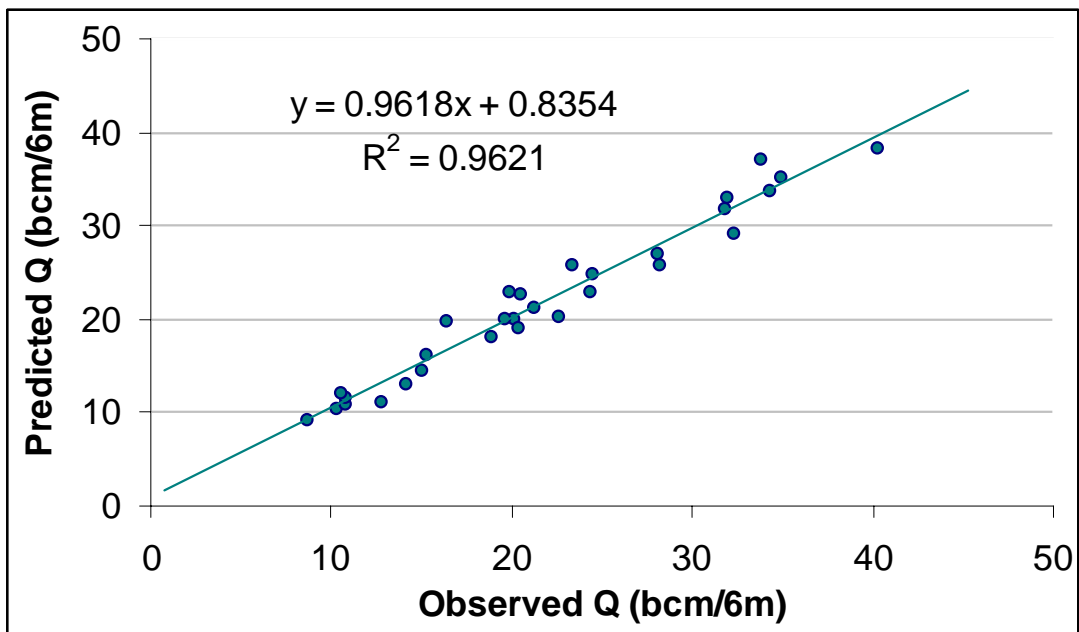
These coefficient values assume that all quantities are expressed in billion cubic meters per six months. The data of the 1960 to 1980 period were chosen because they were collected as part of the HYDROMET project and are most reliable.

Figures 3.3.1 and 3.3.2 compare observed and predicted (modeled) results over the calibration period (1960 to 1980). It is noted that approximately a quarter of the data were clearly erroneous and were excluded from the calibration exercise. These were data for which a significant number of monthly watershed outflows, estimated from the lake water balance, were negative, indicating significant inconsistencies in the hydrologic sequences. The data inconsistencies stem from unreliable precipitation estimates over the vast lake area (nearly 70,000 square kilometers), most of which was and remains ungauged.

The figures illustrate good correspondence between observed and predicted results over a wide range of outflows, and support the conclusion that the model is unbiased and represents the watershed outflow process well. Specifically, the standard error of the watershed outflow is 1.685 billion cubic meters per six months, which is less than 10% of the mean outflow. It is noted that the aggregation of six months plays a significant role in the performance of the model. Finer time aggregations (i.e., monthly and tri-monthly) were also used but the results were unsatisfactory. The reason for this is attributed to the long time lags between rainfall and outflow for some lake basins (e.g., the Kagera). The six months resolution appears to be longer than these time lags and can represent the basin hydrologic response more reliably.



**Figure 3.3.1:** Hydrologic Model Results (Q/P) versus Observations



**Figure 3.3.2:** Hydrologic Model Results (Q) versus Observations

## 4. Historical and Future Climate Assessments

### 4.1. Historical Climate Assessment

In this section, the hydrologic model is used to investigate the relative significance of the lake water balance terms: What is the magnitude of the average lake precipitation? How does lake precipitation compare with watershed precipitation? What are the relative magnitudes of watershed outflow, lake precipitation, and lake evaporation?

Such questions have been the focus of several previous studies, but although they could ordinarily be answered through a straightforward analysis of field data, past conclusions vary. For example, long term mean lake precipitation estimates range from 1100 to nearly 1600 millimeters per year, the main reason being the lack of precipitation measurements over most of the lake surface. The present study takes a different approach in that it *estimates* lake precipitation based on (1) land (watershed) precipitation and temperature measurements, (2) the hydrologic model, (3) measurements of lake levels and outflows, and (4) lake water balance. The underlying concept is to only use quantities that can be measured reliably (such as land measurements) and estimate lake precipitation from hydrologic relationships. The estimates thus derived are expected to be more accurate and consistent with the natural lake and watershed response.

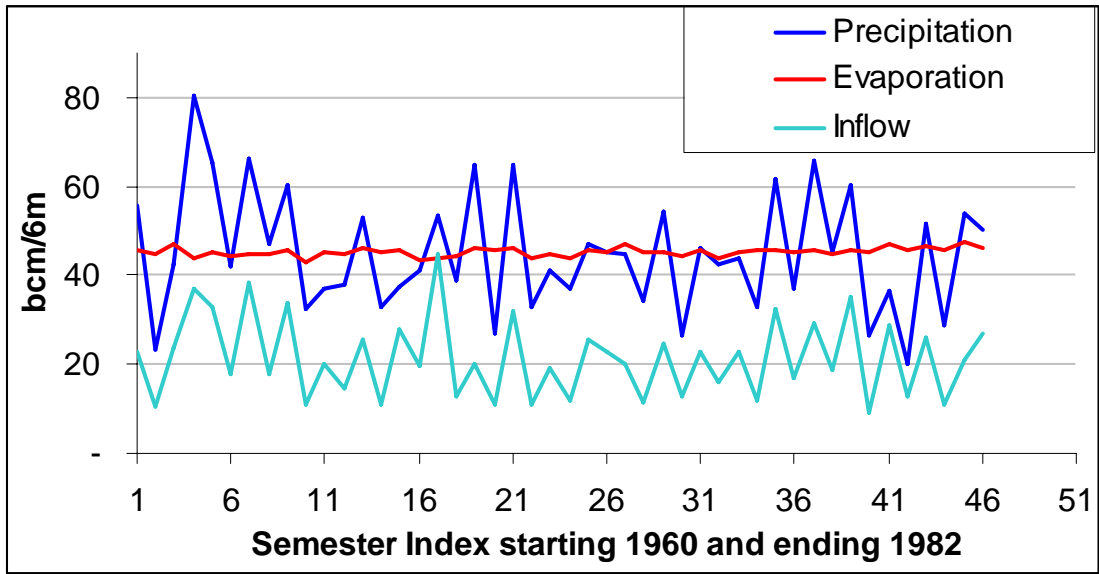
This assessment was carried out for the 1960 to 1982 time horizon and led to the results shown on Figures 4.1.1, 4.1.2, and 4.1.3. Several conclusions are noted:

- The mean annual lake precipitation over the 1960-1982 time period is 1299 mm/yr;
- The mean annual precipitation over the four sub-watersheds in the 1960-1982 period are as follows:
  - Watershed 1: 1193 mm/yr (Kagera Basin);
  - Watershed 2: 1245 mm/yr (southwestern Uganda);
  - Watershed 3: 999 mm/yr (northern Tanzania);
  - Watershed 4: 1500 mm/yr (western Kenya).

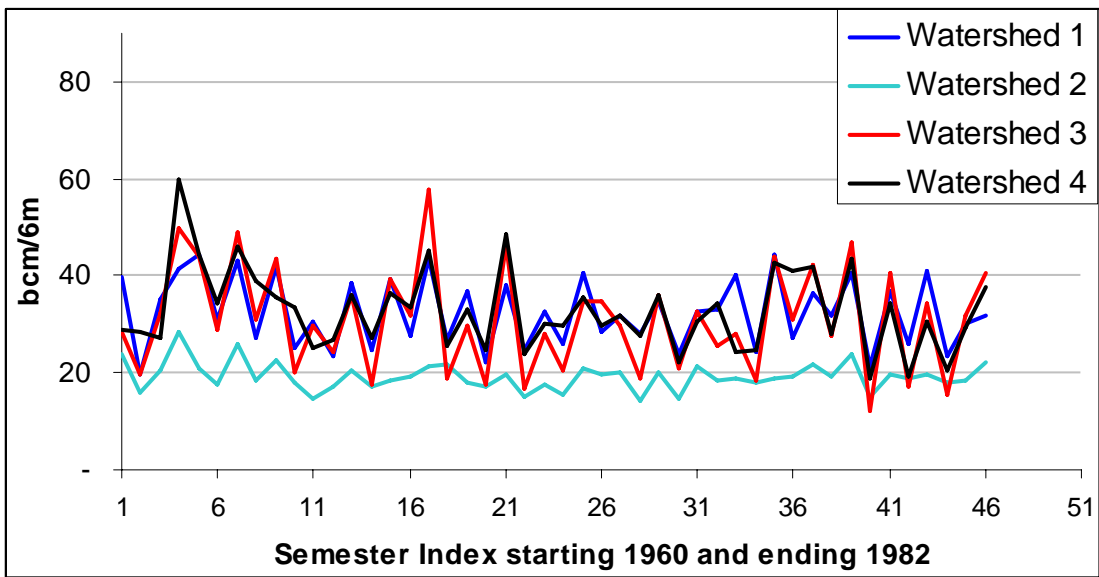
Thus, lake precipitation exceeds watershed precipitation in three of the four sub-watersheds in a mean annual sense. The highest mean annual precipitation is

experienced in Watershed 4 (western Kenya). Generally, regional precipitation increases from south to north and from east to west.

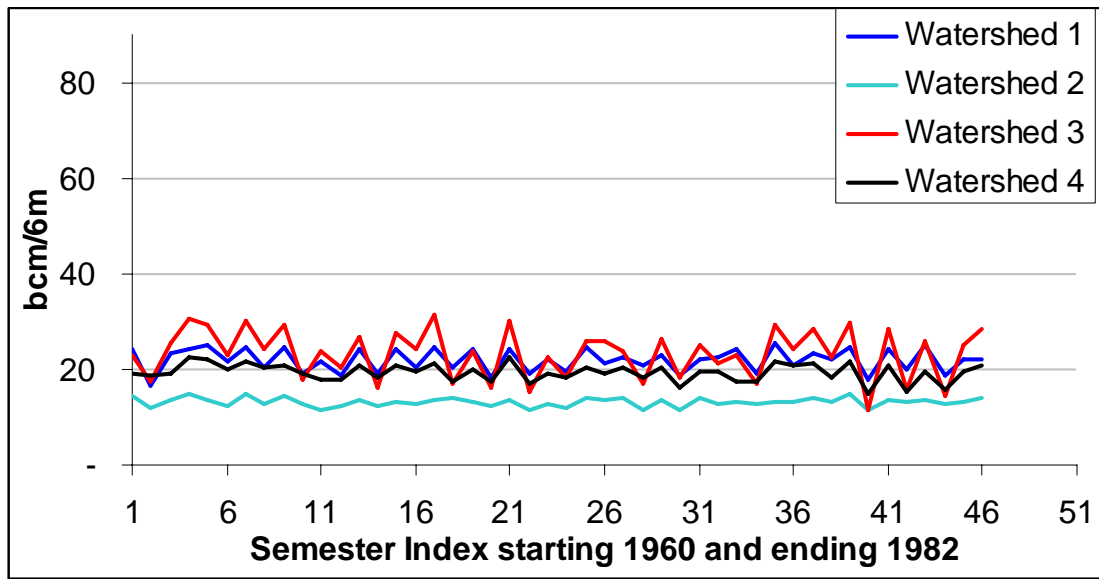
- Over the 1960-1982 time horizon, mean annual lake precipitation was nearly equal to mean annual lake evaporation, each amounting to approximately 90 billion cubic meters per year. Thus, long term lake outflow was equal to watershed outflow, the latter estimated at 42.9 billion cubic meters per year or 48% of the mean annual lake precipitation.
- The most variable annual precipitation over the 1960 – 1982 time frame was exhibited by Watershed 3 (northern Tanzania) with a coefficient of variation (CV) equal to 0.35. Lake precipitation exhibited the second highest variability (CV = 0.3), and was followed by Watershed 4 (Kenya; CV = 0.26), Watershed 1 (Kagera; CV = 0.22), and Watershed 2 (Uganda; CV = 0.15). Watershed outflow was more variable than precipitation with a CV of 0.41.
- In the last six months of 1961, lake precipitation reached 2323 millimeters per year, nearly 100% higher than its average value. Very high precipitation rates (approximately 50 to 60% higher than average) were also recorded in the first six months of 1962 (1884 mm/yr), the first six months of 1963 (1912 mm/yr), and the first six months of 1964 (1739 mm/yr). As a result, the lake rose by 2.5 meters during the 1961 to 1964 time frame. This rise is clearly due to excessive regional rainfall that impacted the lake as well as the lake watersheds (Figure 4.1.2).



**Figure 4.1.1:** Lake Sequences



**Figure 4.1.2:** Watershed Precipitation Sequences



**Figure 4.1.3:** Watershed Evapotranspiration Sequences

## 4.2. Future Climate Assessments: Lake Hydrology

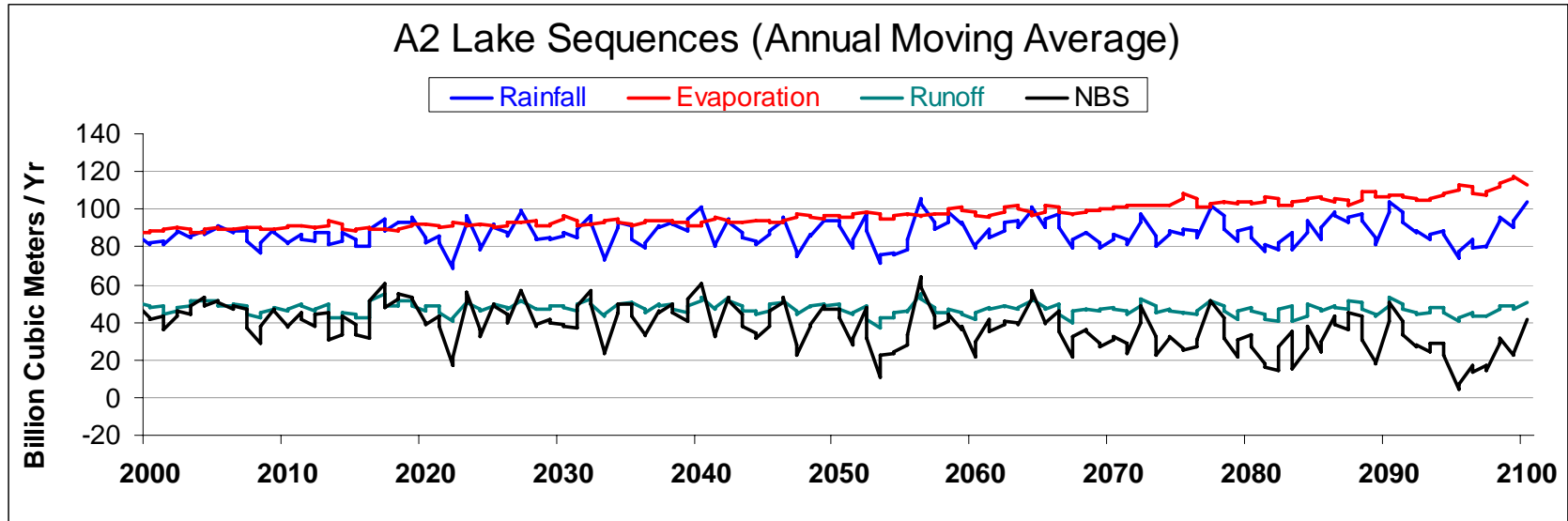
The future hydrologic lake response is assessed using the rainfall and temperature sequences generated by HadCM3 global circulation model (Section 2.7) and the hydrologic models described in Section 3. Figures 4.2.1 and 4.2.2 summarize the results for the A2 scenario.

Figure 4.2.1 includes four sequences corresponding to annual lake rainfall, lake evaporation, watershed runoff, and lake net basin supply (NBS). All sequences are expressed in billion cubic meters per year and are plotted from 2000 through 2099. Each sequence represents the average of several ensemble members generated as outlined in Section 2.6. As such, the sequences on Figure 4.2.1 are significantly less variable than the individual ensemble members. For comparison, Figure 4.2.2 includes the same sequences for a particular ensemble trace. The results support the following comments:

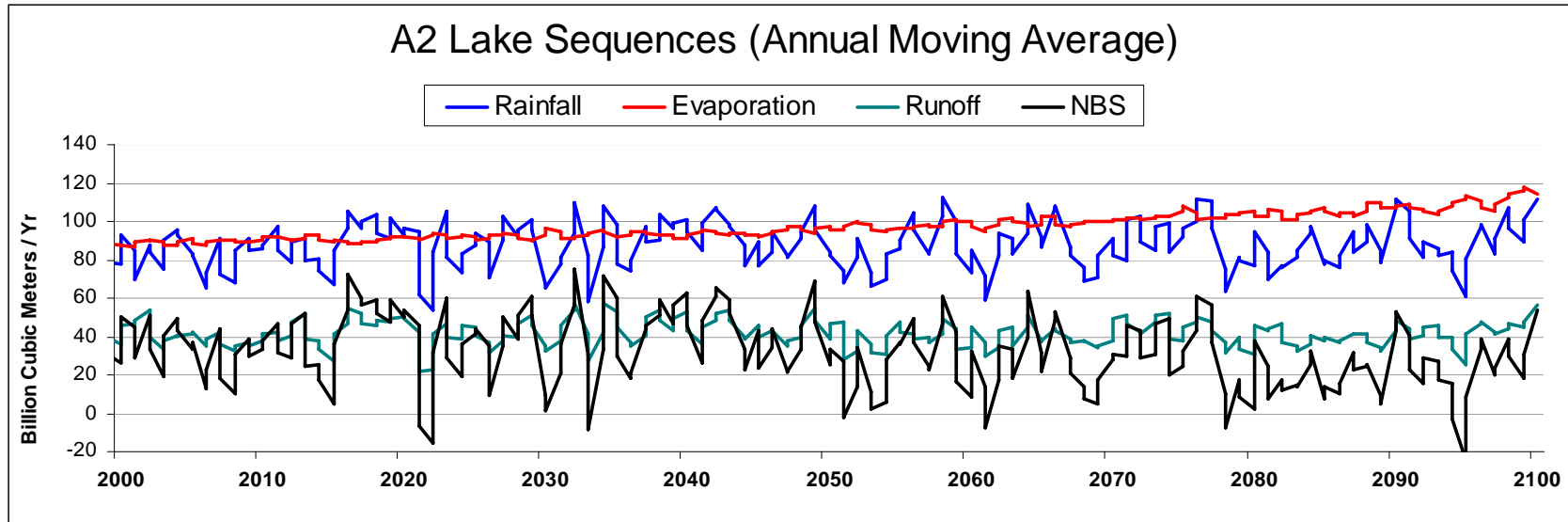
- Mean lake rainfall fluctuates around its historical levels throughout the time horizon and shows neither a positive nor a negative trend. This result is certainly valid with respect to the last six months of the year, when HadCM3 exhibits skill in predicting rainfall in the lake region. For the first six months (long rains), however, HadCM3 exhibits no significant skill in rainfall prediction. It is thus possible that a rainfall trend might exist, but the model simply cannot ascertain its existence. Second, the variability of the mean annual rainfall somewhat increases in the second half of the century.
- Lake evaporation shows a steadily increasing trend, a direct consequence of temperature increase. Up to 2025, the increase is very mild, and lake evaporation and rainfall nearly balance out as in the historical past. From 2025 on, however, lake evaporation becomes consistently higher than lake rainfall with this deficit exceeding 20 billion cubic meters per year toward the end of the century. This result is very significant because temperature increase is predicted by all global circulation models, not just HadCM3. It thus appears inevitable that, if the rainfall process remains stationery, climate warming will disturb the historical balance of lake rainfall and evaporation, and will create serious deficits.

- Watershed runoff also exhibits a mild downward trend as a consequence of temperature increase. However, watershed evapotranspiration depends on both temperature *and* rainfall availability, and mean runoff reduction is not expected to exceed 5 to 10% by the end of the century.
- Finally, mean lake net basin supply (rainfall + runoff – evaporation), exhibits a clear and very significant downward trend. Comparing the beginning and ending periods of the century, mean annual NBS decreases by up to 50% or up to 20 billion cubic meters per year. Net basin supply is a critical lake indicator as it is the process that maintains lake levels and supports all other water resources uses. A 50% NBS reduction will undoubtedly have severe consequences for the lake and its ability to meet the region’s water resources needs. Second, the NBS series indicates a significant increase in the frequency of extreme droughts. Thus, toward the end of the 21<sup>st</sup> century, the lake is expected to experience more frequent and prolonged droughts during which NBS will be negligible or even negative (indicating that lake evaporation would be higher than the sum of lake rainfall and watershed runoff). These NBS trends and changes will undoubtedly have adverse water resources consequences which are further assessed in the following section.
- The previous conclusions are also reflected on Figure 4.2.2 which displays one of the several traces that make up the mean sequences of Figure 4.2.1. As noted earlier, the variability of these sequences is much more pronounced than the mean sequences, leading to potentially very serious deficits.

Assessments for the B2 climate scenario were also carried out. The results show that the lake hydrologic trends are similar to those described above. However, the changes relative to the historical regime are approximately half of the A2 climate scenario.



**Figure 4.2.1:** Future Climate Assessment, A2 Scenario Mean Sequences



**Figure 4.2.2:** Future Climate Assessment, A Trace of the A2 Scenario

### 4.3. Future Climate Assessments: Water and Energy Resources

This section aims to assess the implications of climate change on lake levels and water uses including hydropower. In addition to net basin supply (NBS), lake level and water use impacts also depend on regulation policies. To facilitate comparisons with historical conditions, the assessment investigations presented herein employ two regulation alternatives: (1) Agreed Curve (AC), and (2) Energy Demand (ED) driven releases. In the agreed curve release policy, the lake releases according to the natural lake outflow curve, while in the energy demand driven policy, releases aim to meet energy demand.

The assessments are carried out using the scenario assessment module of the Lake Victoria Decision Support Tool (LVDST). The methodology is described fully in the LVDST Technical Report. For convenience, a brief summary of the assessment process is included here too.

First, the following elements are defined for the scenario to be assessed:

- (i) Regulation and power facility configuration, characteristics, and commissioning dates;
- (ii) Power demand scenario; and
- (iii) Net Basin Supply sequence.

In these assessments, the net basin supply sequences correspond to the A2 or the B2 sequences generated earlier, and the assessment period is from 2001 to 2098. Uganda's power demand is assumed to increase by 5% per year, and new power plant commissioning is scheduled to avoid energy deficits.

Following scenario definition, the model simulates the system response over the assessment horizon. Namely, at each time period of the simulation horizon (10 day time step), the inflow forecasting model is activated first to generate forecasts of the upcoming 12 months inflows or net basin supplies. Second, the long range model is activated to simulate the lake and facility response over the control horizon and determine a release sequence that optimizes the system objectives. Third, the optimal release for the first 10 day period is applied and the storage and power projects are simulated to determine the

system condition during and at the end of the 10 day period. Specifically, the model simulates the flow of water through the system elements, lake levels (and storage) at the end of the period, energy generation, spillage, water supply deficits, wetland area, and other quantities of interest. This process is repeated at the next and all subsequent 10 day periods until the end of the assessment horizon. At the end of the computational process, the sequences of lake levels, river flows, wetland areas, energy generation, energy revenues, water supply deficits, and other quantities of possible interest are analyzed and compared with baseline sequences to assess system performance.

Figure 4.3.1 displays three net basin supply sequences. The first portion of the graphs (1960 to 2001; green line) is the historical NBS sequence. The other two lines begin from 2001 and represent the mean A2 NBS sequence (blue line) and the mean B2 NBS sequence (red line). These NBS sequences are the basis for the assessments that follow. As mentioned earlier, the A2 and B2 sequences exhibit less variability than the historical sequence because they are the *mean* ensemble sequences. The variability of the individual ensemble members is comparable to that of the historical sequence.

#### 4.3.1. Agreed Curve Release Policy

Figure 4.3.1.1 displays lake level results for the AC release policy. The results show that the A2 scenario gradually depletes the lake down to its lowest historically observed level. Under the B2 scenario and the AC release policy, the lake relatively maintains its level throughout this century. Figure 4.3.1.2 displays the associated lake release sequences. The A2 releases exhibit a marked downward trend, becoming alarmingly small by the end of the century. The B2 releases are fairly constant but never return to their 1960 - 1980 historical levels.

Figure 4.3.1.3 shows the sequence of the Sudd wetland storage. This quantity is directly related to wetland extent, if one assumes (as in the LVDST model) that wetland depth is approximately one meter. Thus, one billion cubic meters of storage corresponds to one thousand square kilometers of wetland area. The results show that the Sudd wetland area

will continue to fluctuate as in the historical past, albeit the permanent swamp area (i.e., the minimum annual swamp area) will gradually decline. This wetland area decline has a historical precedence in the early part of the 20<sup>th</sup> century (Chapter 5, LV DST Technical Report, Figure 5.1.4), and is thus within the historical response. It is noted, however, that this assessment does not consider potential climatic changes in the Sudd region. It is thus possible that the actual fluctuation range may exceed the historical response.

Figure 4.3.1.4 compares the potential changes of the White Nile flows at Malakal, at the Sudd exit before the Sobat junction. The B2 flows are similar to the historical flows. However, the A2 flows are consistently lower, and toward the end of the century fall below historically recorded levels.

Figures 4.3.1.5, 4.3.1.6, and 4.3.1.7 display and compare the results in the form of frequency curves. It is clear that future climates (both A2 and B2) imply drier conditions, lower lake levels, smaller wetland areas, and lower downstream river flows. In particular, the potential changes implied by the A2 scenario raise alarming concerns regarding the environmental and ecological integrity of Lake Victoria and of the entire downstream system.

Lastly, Figure 4.3.1.8 compares the energy generation sequences with Uganda's energy demand assuming a 5% annual increase. In this comparison, new hydro plants are included when current capacity is insufficient to meet energy demand. The figure shows that scenario A2 requires 3 to 7 years earlier hydro plant installation than scenario B2. Furthermore, the results indicate that *demand change* will compromise the ability of the power system to meet energy demand much sooner than *climate change*. It is thus expected that by 2045, the installed capacity of Bujagali (192.5 MW), Karuma Falls (220 MW), Kalagala (450 MW), Ayago North (304 MW), Ayago South (234 MW), and Murchison Falls (420 MW) will be unable to meet Uganda's energy demand.

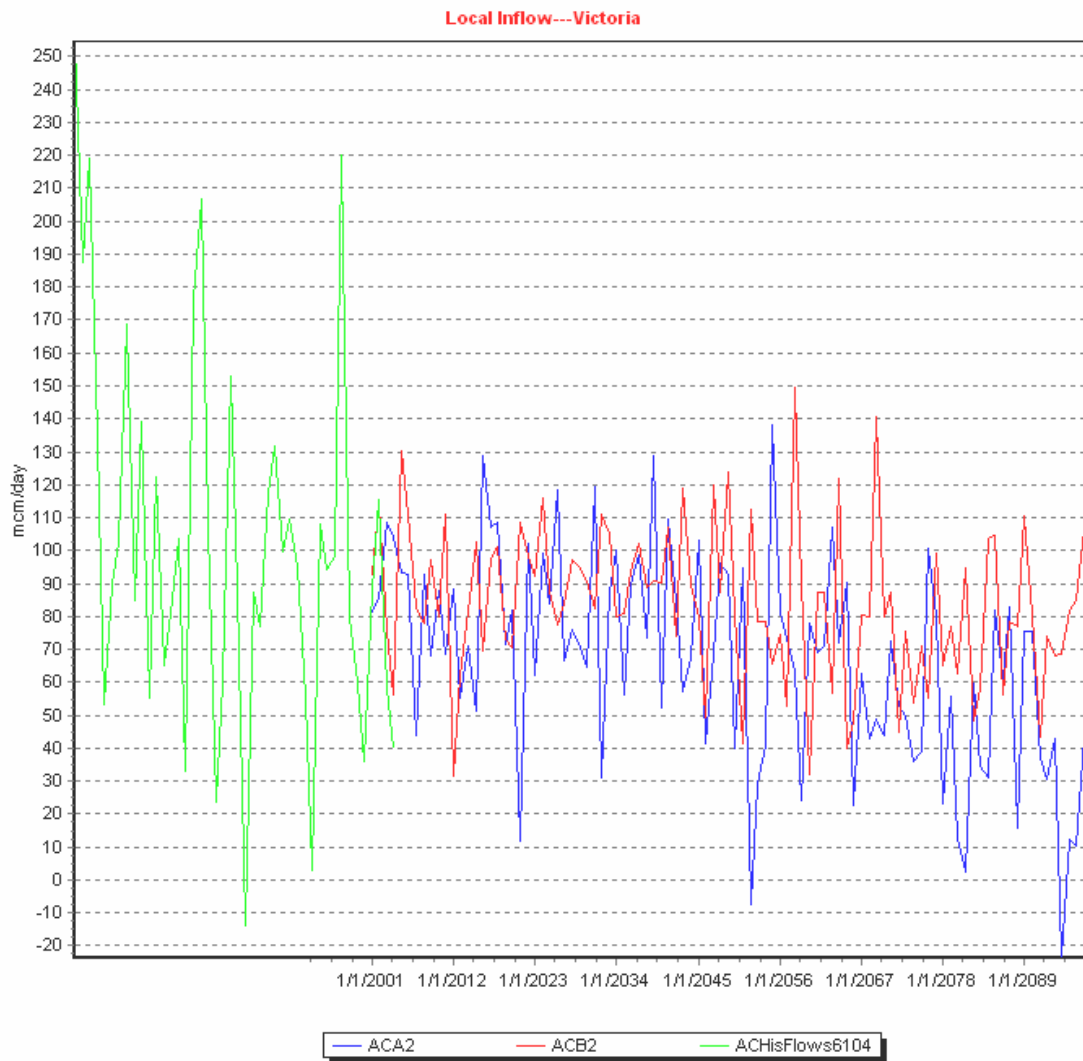
### 4.3.2. Energy Demand Release Policy

In this section, assessment results are presented for the energy driver release policy. Figure 4.3.2.1, as Figure 4.3.1.8, compares the energy generation sequences and actual demands. The figure shows that the ED policy somewhat extends the adequacy of the hydro power system, in comparison to the AC policy, up to 2050. However, beyond 2050, the hydro system becomes increasingly inadequate.

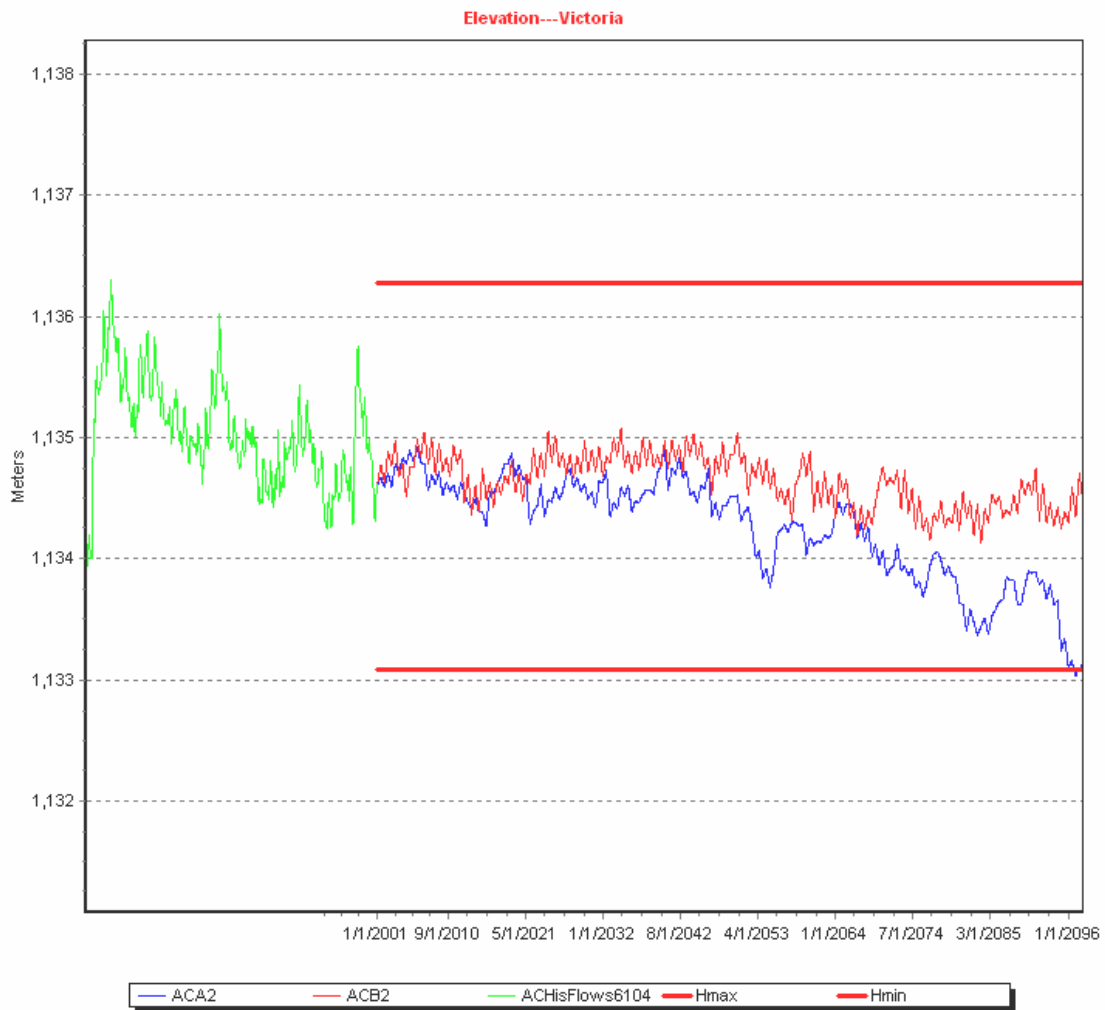
Figure 4.3.2.2 shows the effect of the ED policy on lake levels under A2 and B2 and it is analogous to Figure 4.3.1.1. This comparison shows that during the first half of the 21<sup>st</sup> century, the ED policy maintains higher lake levels than the AC policy, despite climatic change. However, when the hydro system capacity becomes inadequate, the ED policy causes deep and irreversible drawdowns. This result underscores the imperative need for *coordinated* water and energy planning, showing that poor energy planning can have devastating lake level impacts.

Figures 4.3.2.3, 4.3.2.4, and 4.3.2.5 present comparisons of Lake Victoria outflow, Sudd wetland storage (or area), and river flow at Malakal under the ED policy, and are directly analogous to Figures 4.3.1.2, 4.3.1.3, and 4.3.1.4 of the AC policy. During the first half of the century, the responses of the two policies are comparable, with the ED policy sustaining higher lake levels. However, as the hydro system becomes inadequate, the ED policy leads to more negative environmental impacts.

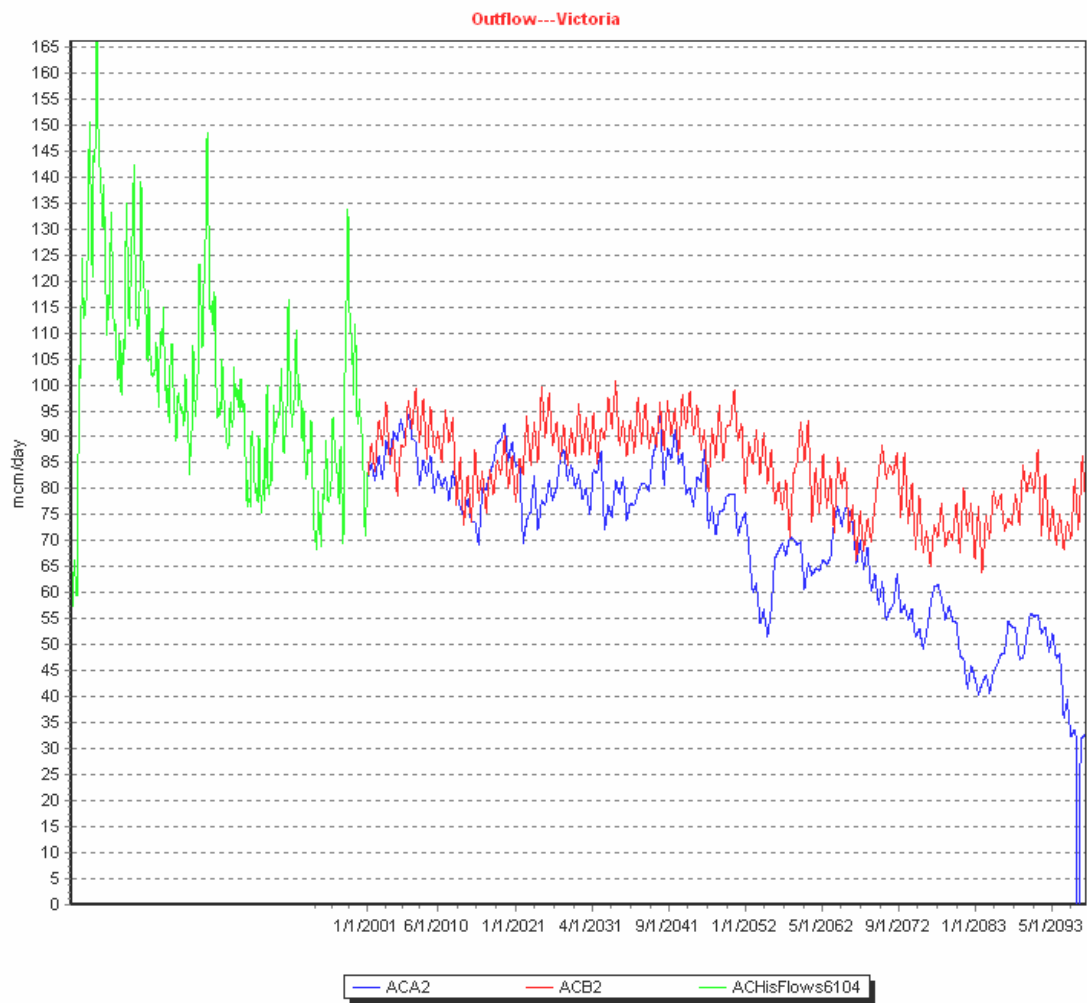
Table 4.3.2.1 reports the plant commissioning year of each hydro plant under the aforementioned scenarios of climate and lake regulation.



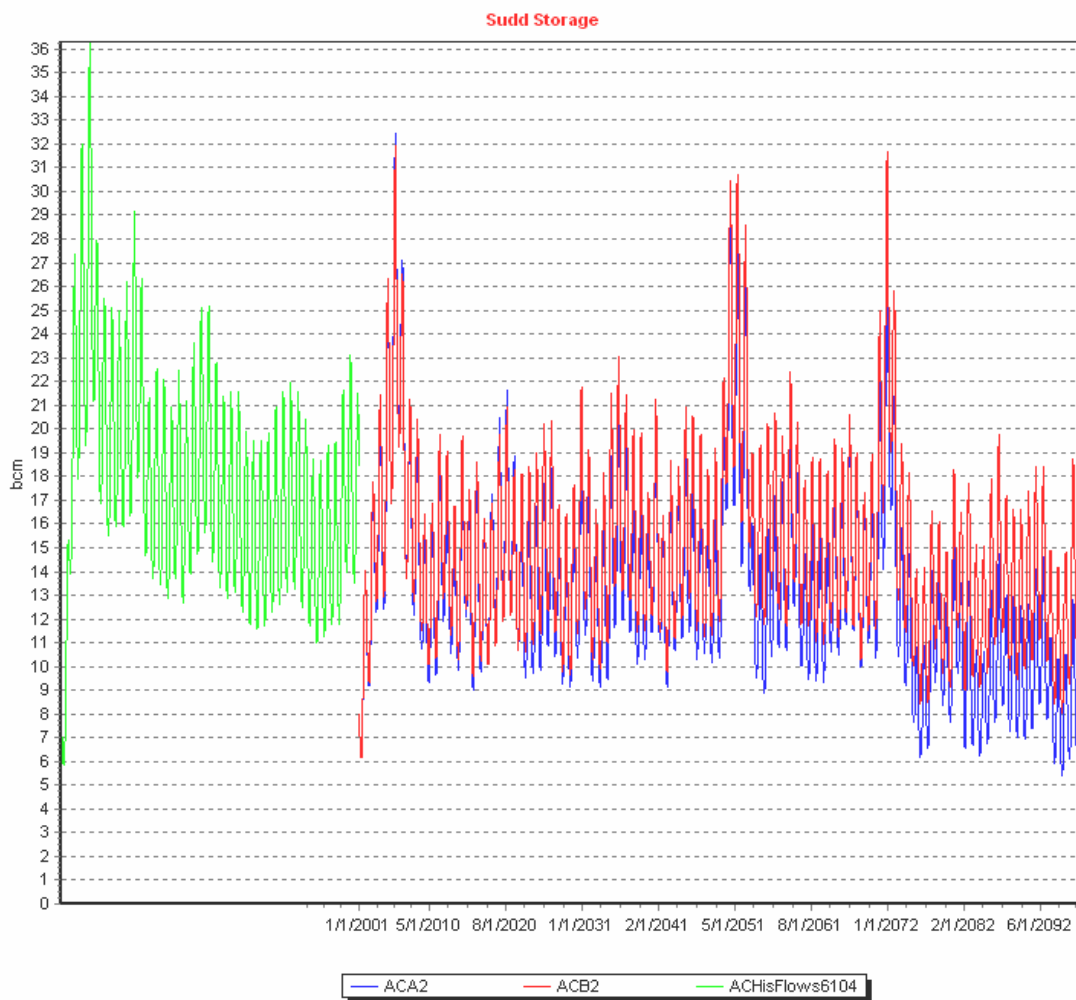
**Figure 4.3.1:** A2 and B2 Net Basin Supply Scenarios



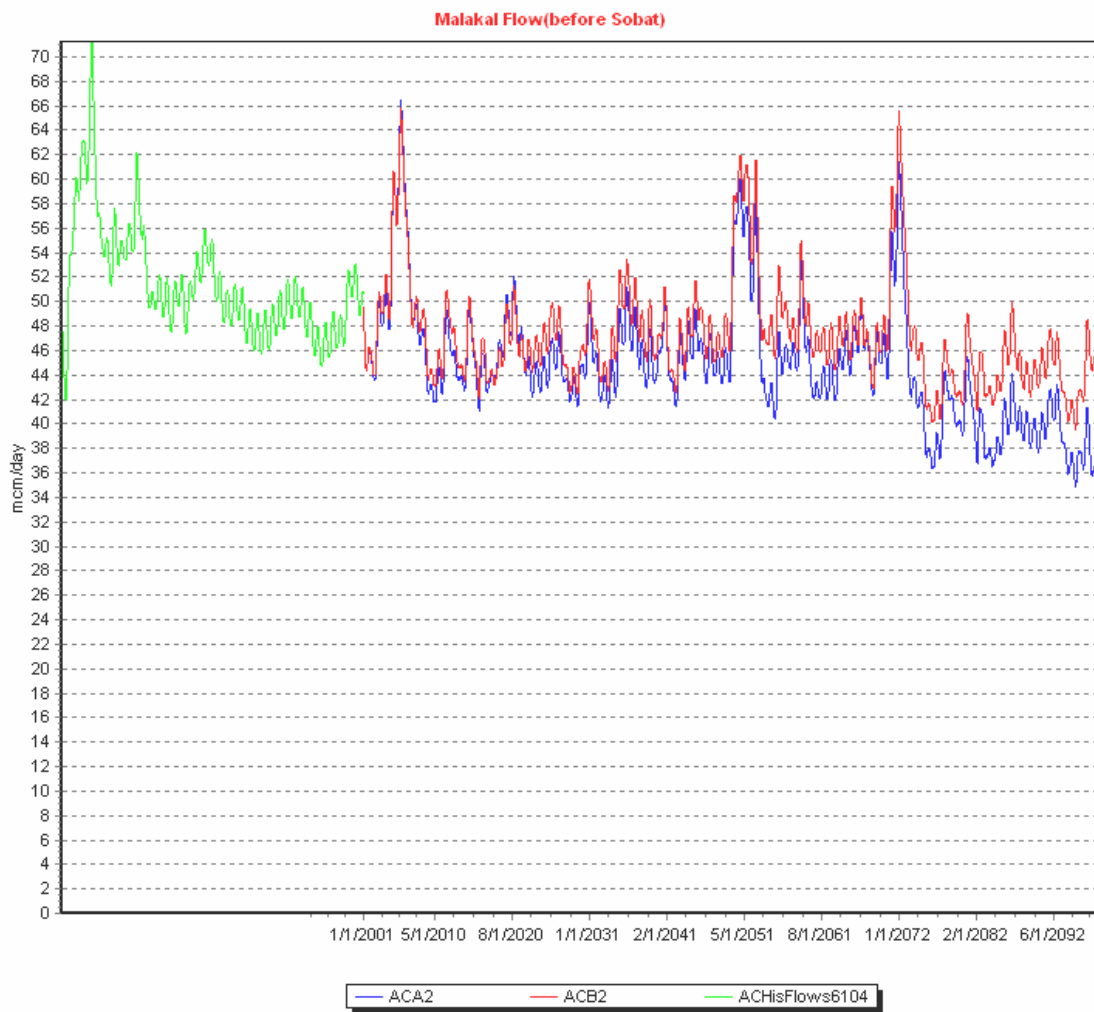
**Figure 4.3.1.1:** Lake Water Balance Assessment; Lake Levels; AC Policy



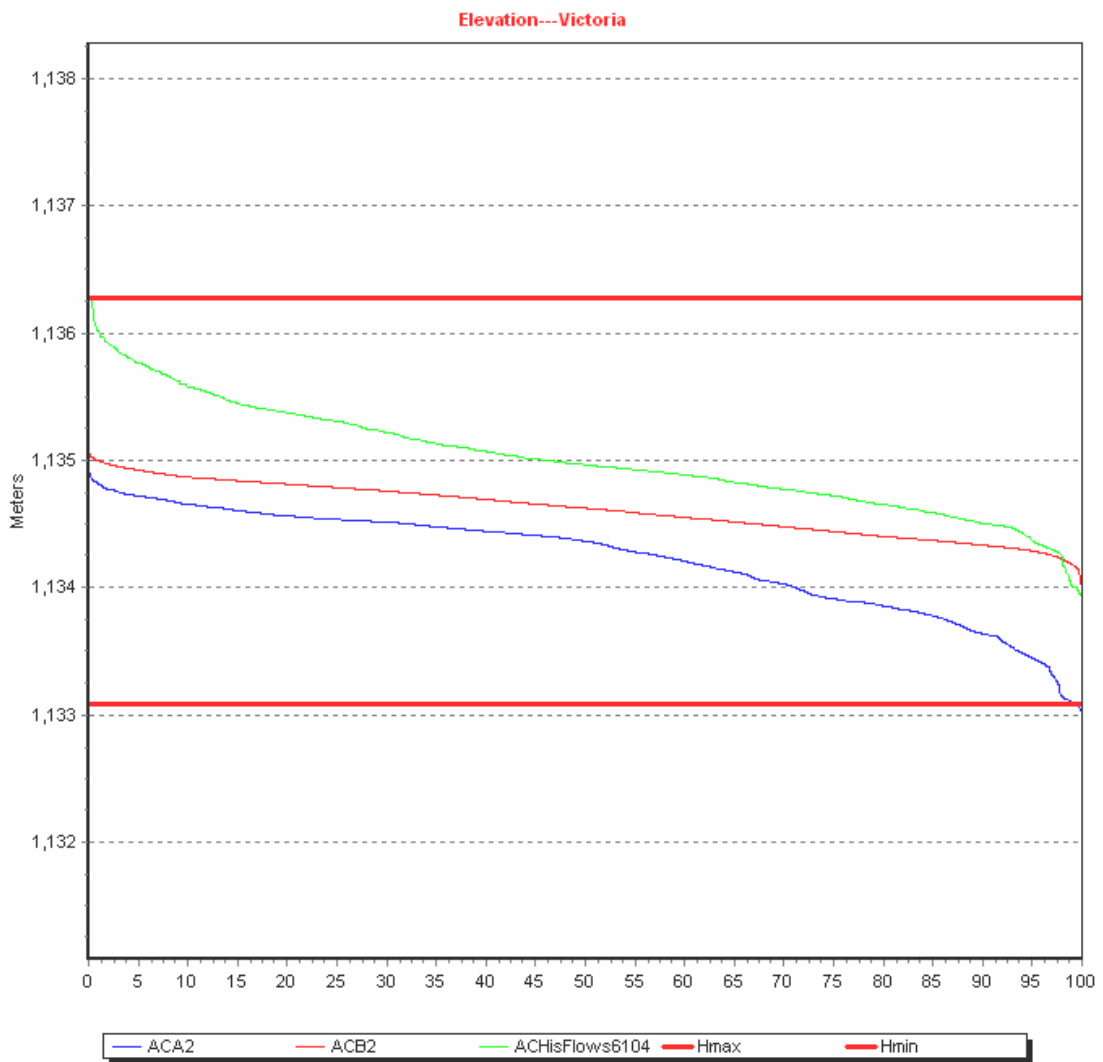
**Figure 4.3.1.2:** Lake Water Balance Assessment; Lake Releases; AC Policy



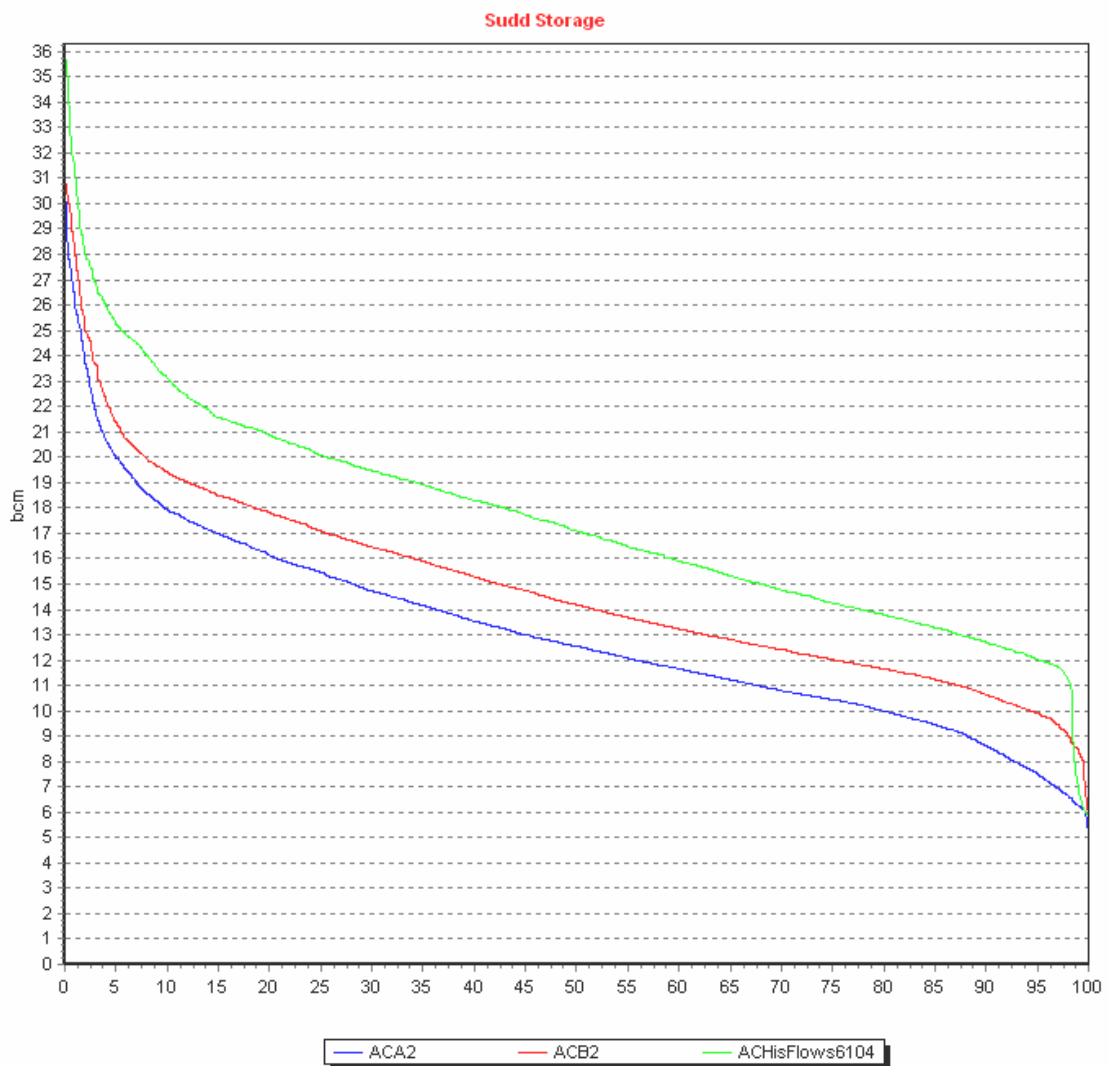
**Figure 4.3.1.3:** Downstream System Assessment; Sudd Wetlands; AC Policy



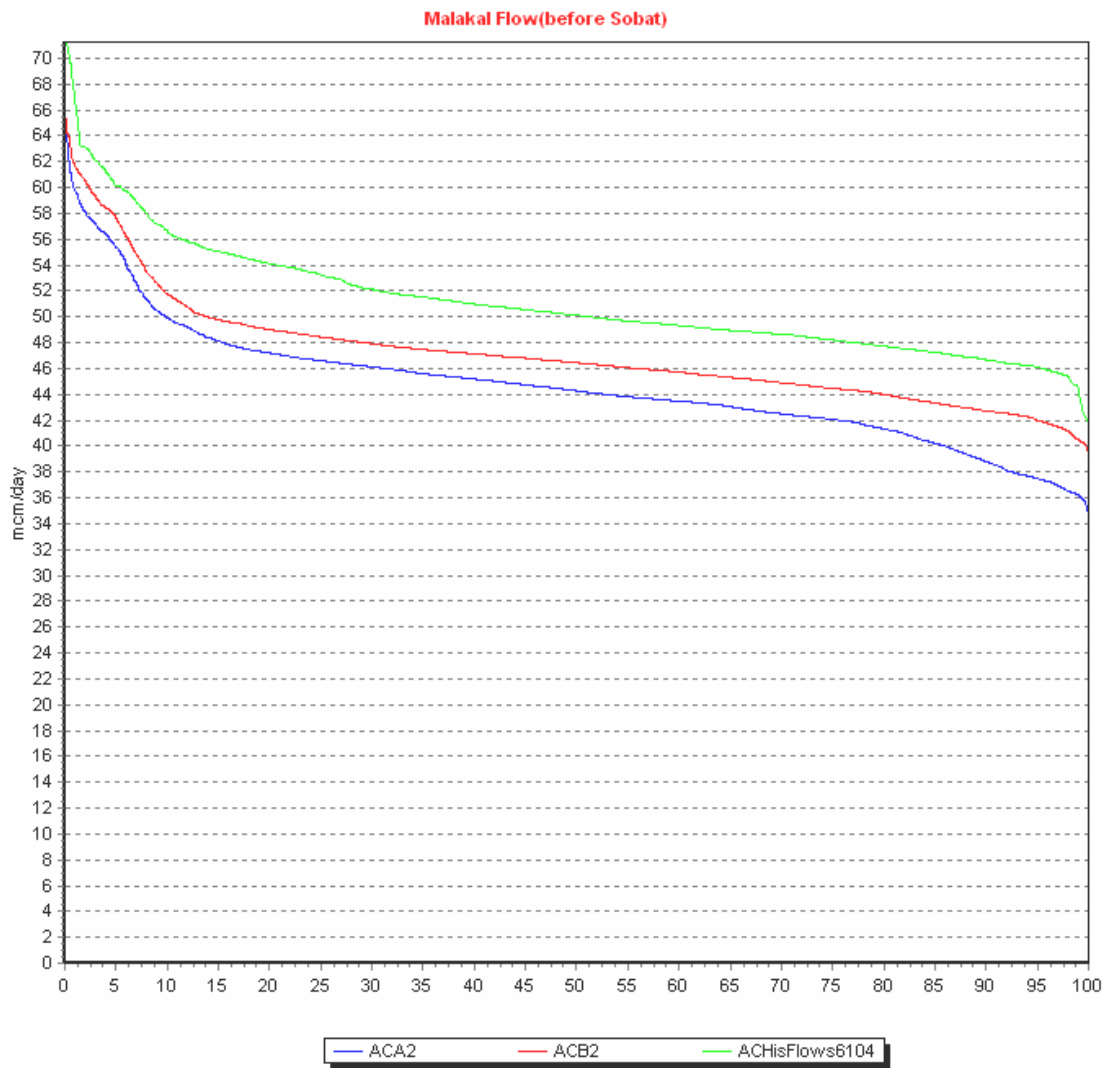
**Figure 4.3.1.4:** Downstream System Assessment; Malakal Flow; AC Policy



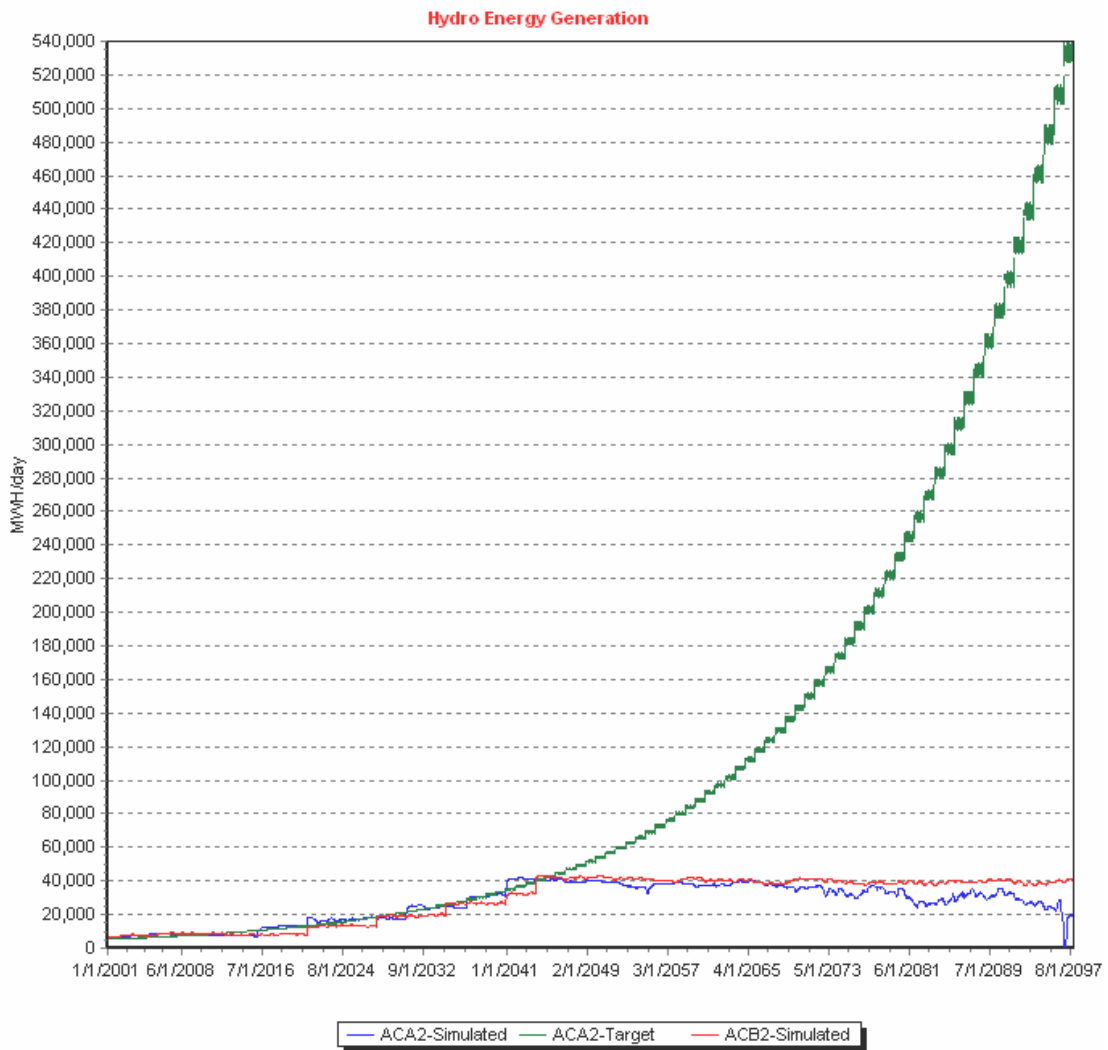
**Figure 4.3.1.5:** Lake Assessment; Lake Level Frequency Curves; AC Policy



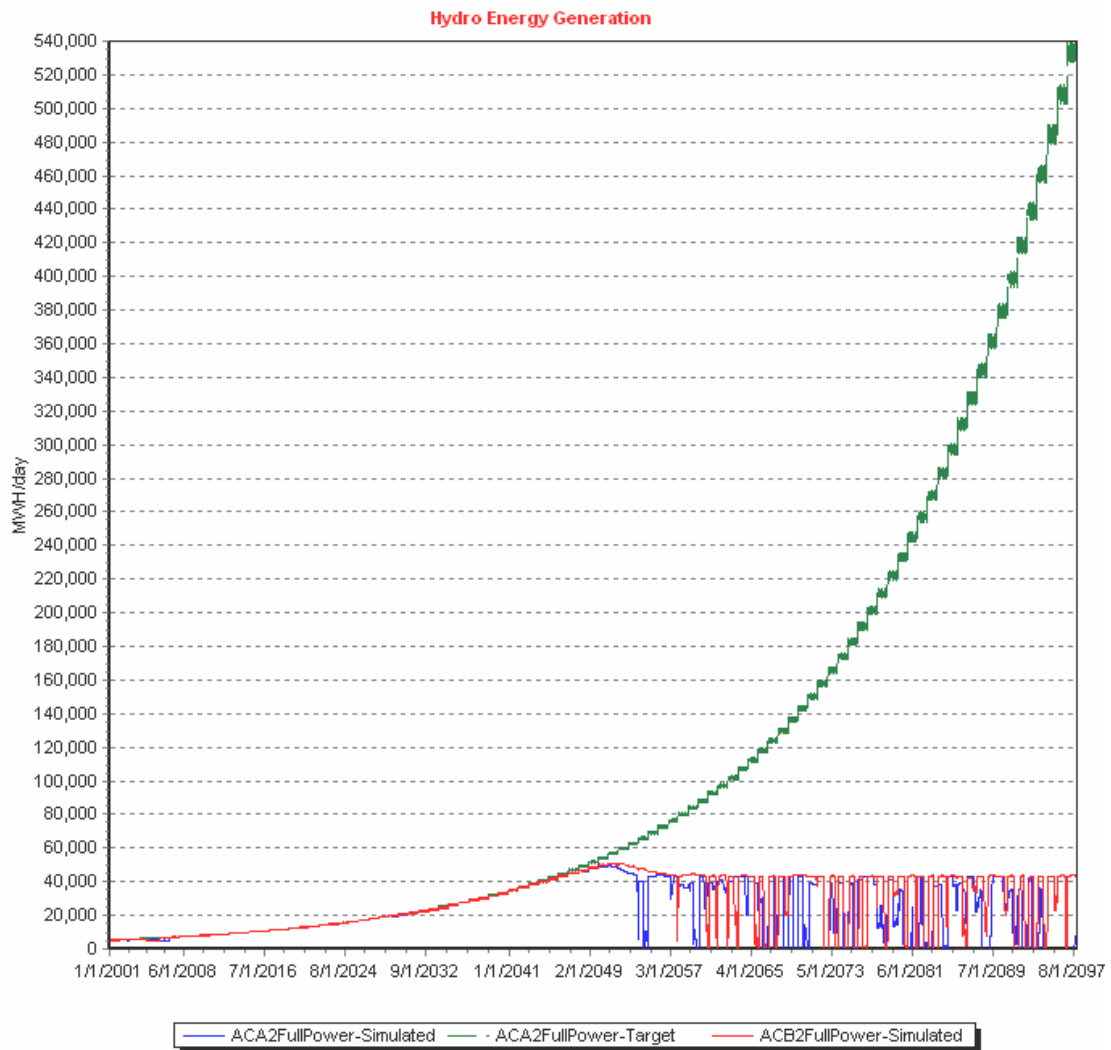
**Figure 4.3.1.6:** Downstream Assessment; Sudd Wetland Frequency Curves; AC Policy



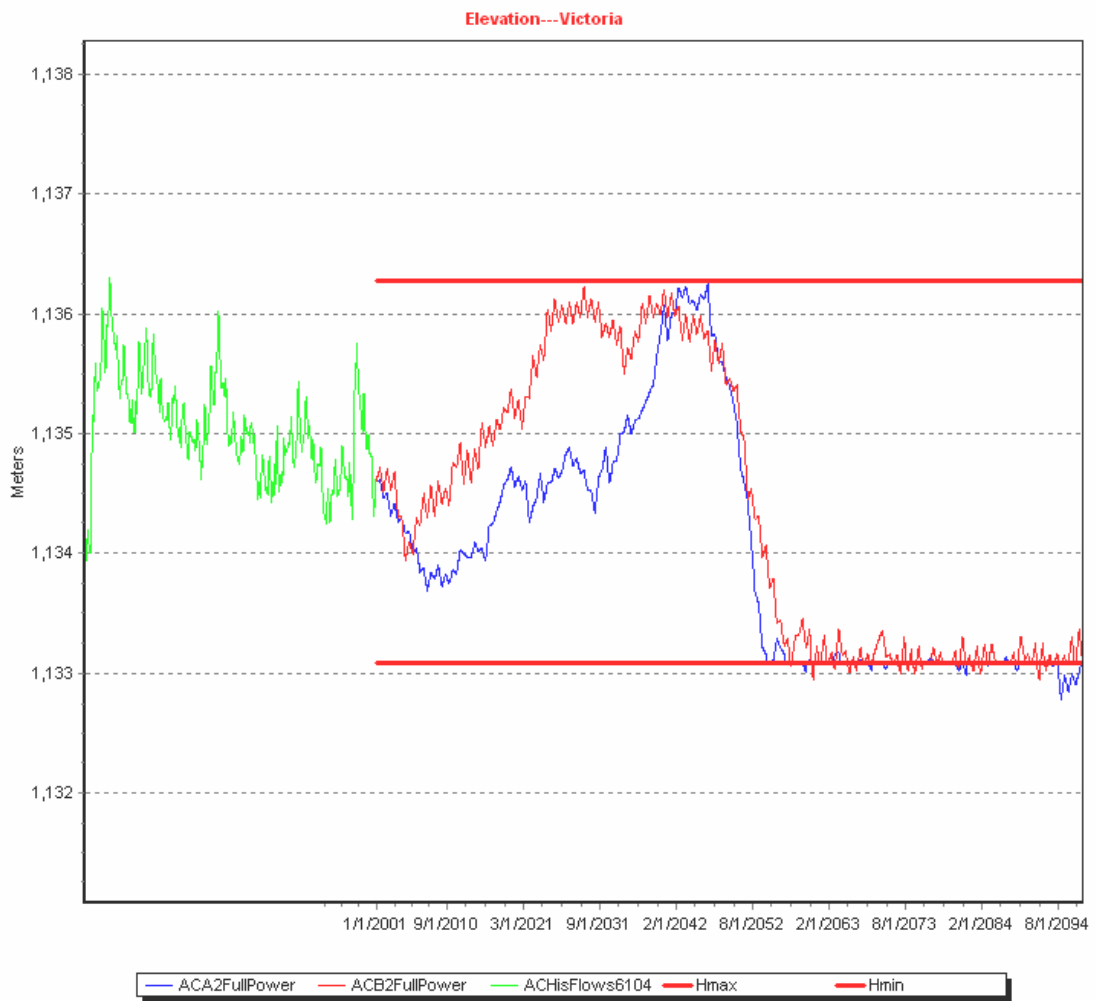
**Figure 4.3.1.7:** Downstream Assessment; Malakal Flow Frequency Curves; AC Policy



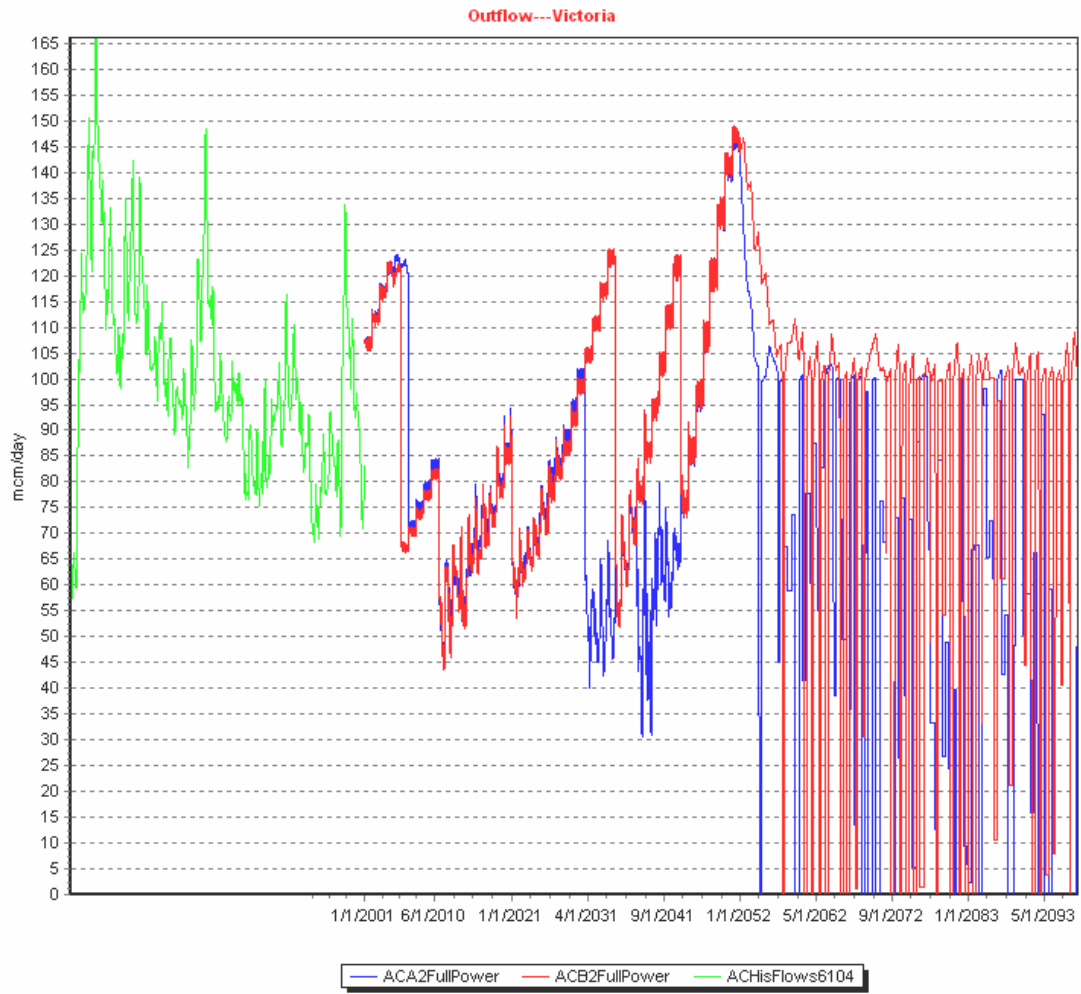
**Figure 4.3.1.8:** Energy Assessment; AC Policy



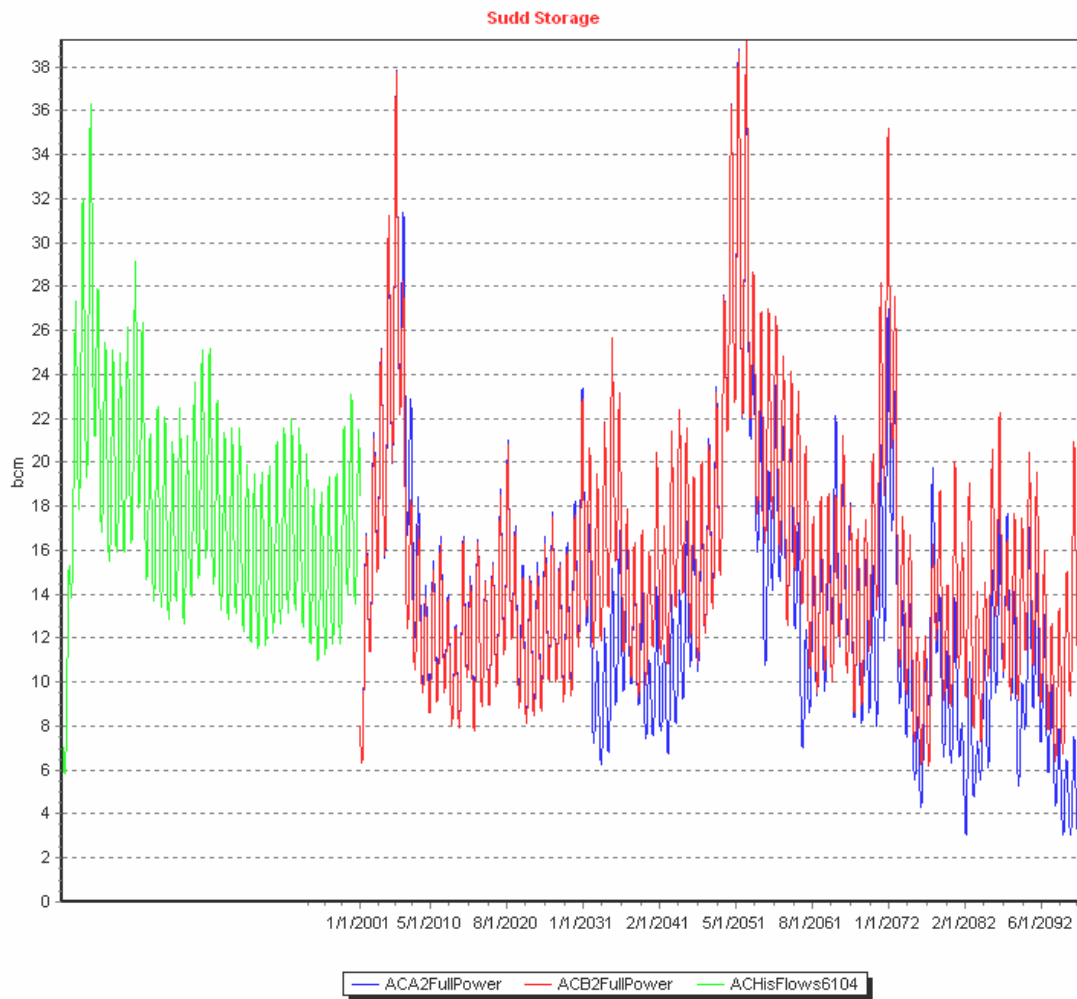
**Figure 4.3.2.1:** Energy Assessment; ED Policy



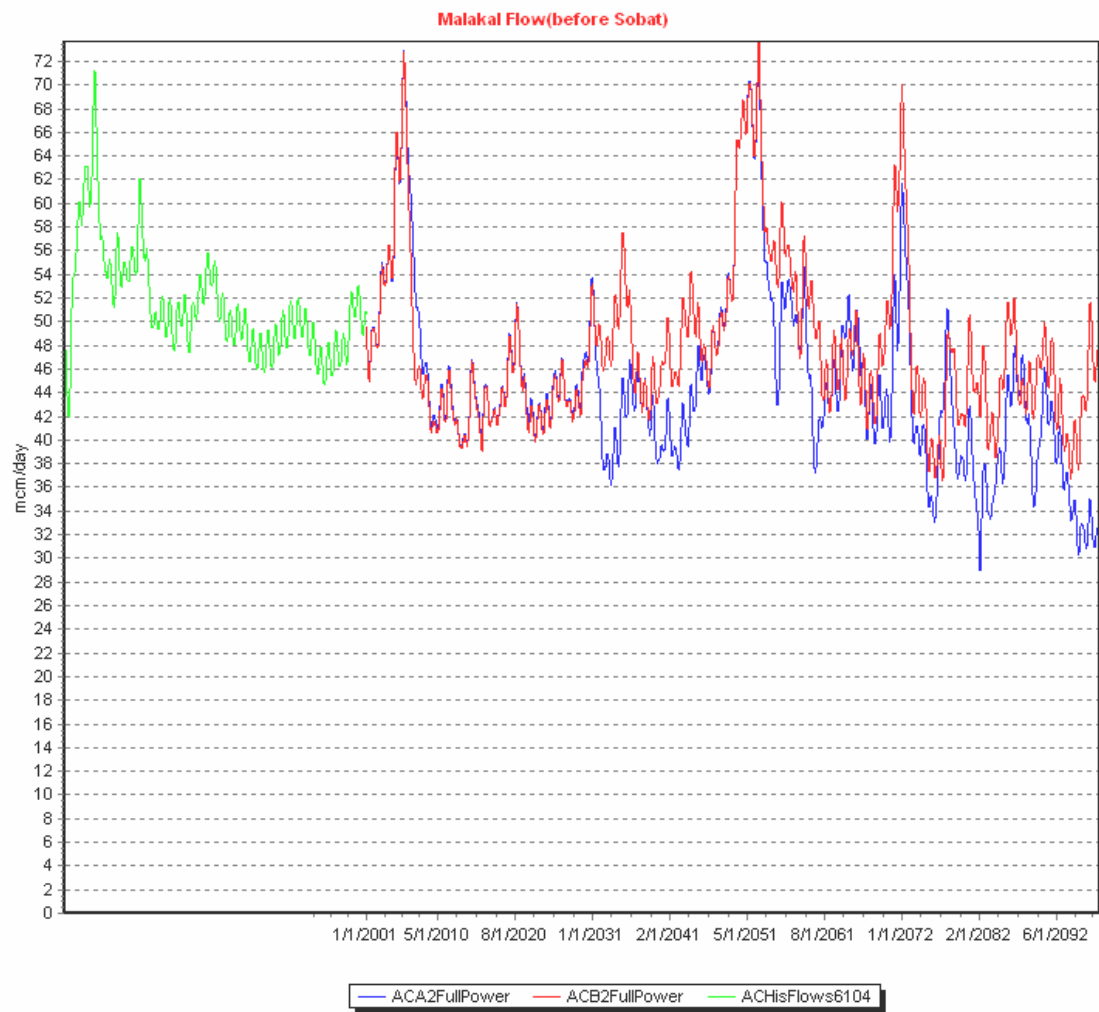
**Figure 4.3.2.2:** Lake Water Balance Assessment; Lake Levels; ED Policy



**Figure 4.3.2.3:** Lake Water Balance Assessment; Lake Releases; ED Policy



**Figure 4.3.2.4:** Downstream System Assessment; Sudd Wetlands; ED Policy



**Figure 4.3.2.5:** Downstream System Assessment; Malakal Flow; ED Policy

**Table 4.3.2.1: Impact of Climate and Release Scenarios on Hydro Plant Commissioning**

	<b>A2 – AC</b>	<b>B2 - AC</b>	<b>A2 - ED</b>	<b>B2 - ED</b>
Nalubaale/Kiira (390 MW)	0	0	0	0
Bujagali (292.5 MW)	0	0	6	5
Karuma Falls (220 MW)	15	20	10	10
Kalagala (450 MW)	20	27	20	20
Ayago North (304 MW)	30	34	30	34
Ayago South (234 MW)	36	40	30	34
Murchison Falls (420 MW)	40	43	38	43

## 5. Conclusions and Recommendations

This report documents a climate change impact assessment for the Lake Victoria region. The assessment investigation includes the use of global climate models, bias correction and downscaling procedures, hydrologic models for the lake watershed, and river basin models for the lake and the downstream river system. The assessments are driven by two potential emission scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). These two scenarios are named A2 and B2 and represent a wide range of all scenarios developed by IPCC. The B2 scenario assumes moderate economic and population growth with resulting moderate cumulative carbon emissions between 1990 and 2100. The A2 scenario also assumes moderate economic growth; however, this scenario assumes more rapid population growth and much higher carbon emissions.

### 5.1. Conclusions

The principle findings of this assessment are summarized below:

1. Climate model predictions indicate an increasing trend in temperature for both A2 and B2 scenarios. According to the A2 climate change scenario, the average air temperature over the lake and its watersheds is expected to increase by 4 to 5 degrees Celsius by the end of the 21<sup>st</sup> century compared to present conditions. The corresponding temperature increase for the B2 climate scenario is about half.
2. With respect to precipitation, only scenario A2 demonstrates significant prediction skill for the last six months of the year. The A2 results also indicate some ability of the model to pick up features of inter-decadal variability, but for the most part both climate scenarios demonstrate limited ability to capture finer precipitation features. In the seasons and areas showing predictability, there is no indication of any long term change in precipitation patterns. It is, however, possible that a precipitation trend might occur, but the model simply cannot ascertain this possibility.
3. A historical assessment of the lake response over the 1960 to 1982 time frame leads to the following conclusions:

- The mean annual lake precipitation over the 1960-1982 time period was 1299 mm/yr;
  - The mean annual precipitation over the four lake sub-watersheds in the 1960-1982 period were follows:
    - Watershed 1: 1193 mm/yr (Kagera Basin);
    - Watershed 2: 1245 mm/yr (southwestern Uganda);
    - Watershed 3: 999 mm/yr (northern Tanzania);
    - Watershed 4: 1500 mm/yr (western Kenya).
  - Thus, lake precipitation exceeds watershed precipitation in three of the four sub-watersheds in a mean annual sense. The highest mean annual precipitation is experienced in Watershed 4 (western Kenya). Generally, regional precipitation increases from south to north and from east to west.
  - Over the 1960-1982 time frame, mean annual lake precipitation was nearly equal to mean annual lake evaporation, each amounting to approximately 90 billion cubic meters per year. Thus, long term lake outflow was equal to watershed outflow, the latter estimated at 42.9 billion cubic meters per year or 48% of the mean annual lake precipitation.
  - In the last six months of 1961, lake precipitation reached 2323 millimeters per year, nearly 100% higher than its average value. Very high precipitation rates (approximately 50 to 60% higher than average) were also recorded in the first six months of 1962 (1884 mm/yr), the first six months of 1963 (1912 mm/yr), and the first six months of 1964 (1739 mm/yr). As a result, the lake rose by 2.5 meters during the 1961 to 1964 time frame. This rise is clearly due to excessive regional rainfall that impacted the lake as well as the lake watersheds.
4. A future climate impact assessment over the period 2000 through 2099 leads to the following conclusions:
- Mean lake rainfall fluctuates around its historical levels throughout the time horizon and shows neither a positive nor a negative trend. However, the variability of the mean annual rainfall somewhat increases in the second half of the century.

- Lake evaporation shows a steadily increasing trend, a direct consequence of temperature increase. Up to 2025, the increase is very mild, and lake evaporation and rainfall nearly balance out as in the historical past. From 2025 on, however, lake evaporation becomes consistently higher than lake rainfall with this deficit exceeding 20 billion cubic meters per year toward the end of the century. This result is very significant because temperature increase is predicted by all global circulation models. It is thus inevitable that, if the rainfall process remains stationary, climate warming will disturb the historical balance of lake rainfall and evaporation, and will create serious deficits.
  - Watershed runoff also exhibits a mild downward trend as a consequence of temperature increase. However, mean runoff reduction is not expected to exceed 5 to 10% by the end of the century.
5. Finally, mean lake net basin supply (rainfall + runoff – evaporation), exhibits a clear and very significant downward trend. Comparing the beginning and ending periods of the century, mean annual NBS decreases by up to 50% or up to 20 billion cubic meters per year. Net basin supply is a critical lake indicator as it is the process that maintains lake levels and supports all other water resources uses. A 50% NBS reduction will undoubtedly have severe consequences for the lake and its ability to meet the region’s water resources needs. Second, the NBS series indicates a significant increase in the frequency of extreme droughts. Thus, toward the end of the 21<sup>st</sup> century, the lake is expected to experience more frequent and prolonged droughts during which NBS will be negligible or even negative (indicating that lake evaporation would be higher than the sum of lake rainfall and watershed runoff).
  6. *Agreed Curve Release Policy*: The A2 scenario gradually depletes the lake down to its lowest historically observed level. The A2 lake releases exhibit a marked downward trend, becoming alarmingly small by the end of the century. Under the B2 scenario, the lake maintains its level throughout this century. The B2 releases are fairly constant but never return to the levels they had during the 1960 to 2000 historical period. Under both A2 and B2, the Sudd wetland area varies as in the historical past, but the permanent swamp area (i.e., the minimum annual swamp area) experiences a significant decrease. Similarly, the White Nile flows at Malakal are

lower than those observed during the 1960 to 2000 historical period. Toward the end of the century, the A2 Malakal flows are expected to fall below historically recorded levels.

7. *Energy Generation under the Agreed Curve:* The main impact of dry climate scenarios is to require earlier installation of power plants. Thus, scenario A2 requires 3 to 7 years earlier hydro plant installation than scenario B2. A second important finding is that *demand change* will compromise the ability of the power system to meet energy demand much sooner than *climate change*. It is thus expected that by 2045, the installed capacity of Bujagali (192.5 MW), Karuma Falls (220 MW), Kalagala (450 MW), Ayago North (304 MW), Ayago South (234 MW), and Murchison Falls (420 MW) will be unable to meet Uganda's energy demand.
8. *Energy Demand Release Policy:* Compared to the AC policy, the ED policy prolongs the adequacy of the hydro power system for approximately 5 years. However, beyond 2050, the hydro system becomes increasingly inadequate. During the first half of the 21<sup>st</sup> century, the ED policy maintains higher lake levels than the AC policy, despite climatic change. However, when the hydro system capacity becomes inadequate, the ED policy causes deep and irreversible drawdowns. During the first half of the century, the responses of the two policies are comparable, with the ED policy sustaining higher lake levels. However, as the hydro system becomes inadequate, the ED policy leads to more negative environmental impacts.

## 5.2. Recommendations

The assessment shows that future climates (both A2 and B2 scenarios) imply drier hydrologic conditions, lower lake levels, smaller wetland areas, and lower downstream river flows. In particular, the potential changes implied by the A2 scenario raise alarming concerns regarding the environmental and ecological integrity of Lake Victoria and of the entire downstream system. This finding underscores the imperative need for *coordinated* and *programmatic* water and energy planning.

With respect to climate change, Uganda and its neighbors should strongly advocate reduction of atmospheric emissions. However, even in the best of circumstances, global warming may persist for several decades. It is thus critical for Uganda to carefully

monitor climatic and hydrologic changes, plan and implement promptly its hydro development program, and explore alternative energy generation options. In this regard, the tools, knowledge base, and detailed recommendations developed under the various components of the Lake Victoria Management Study are timely and should be used in planning the way forward.

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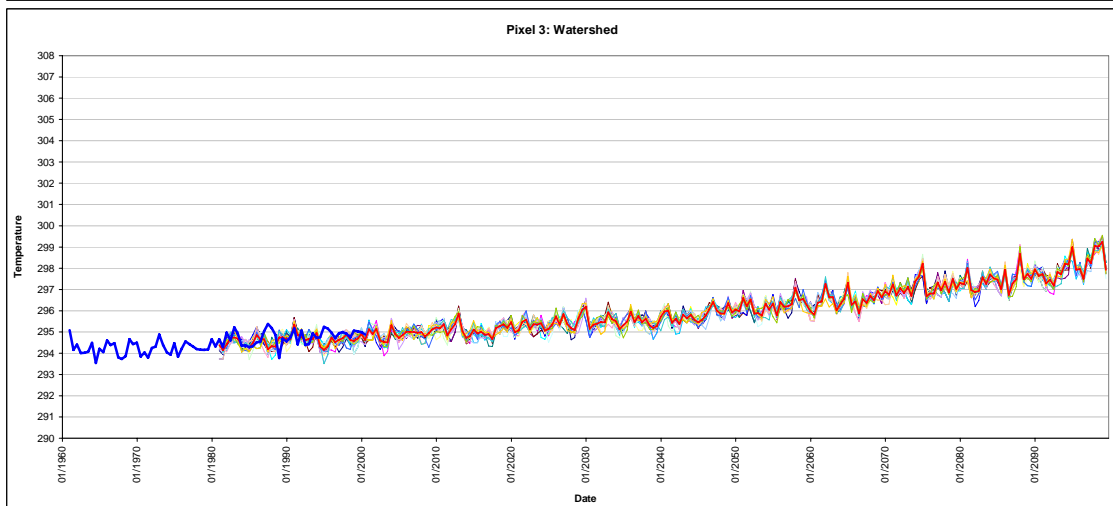
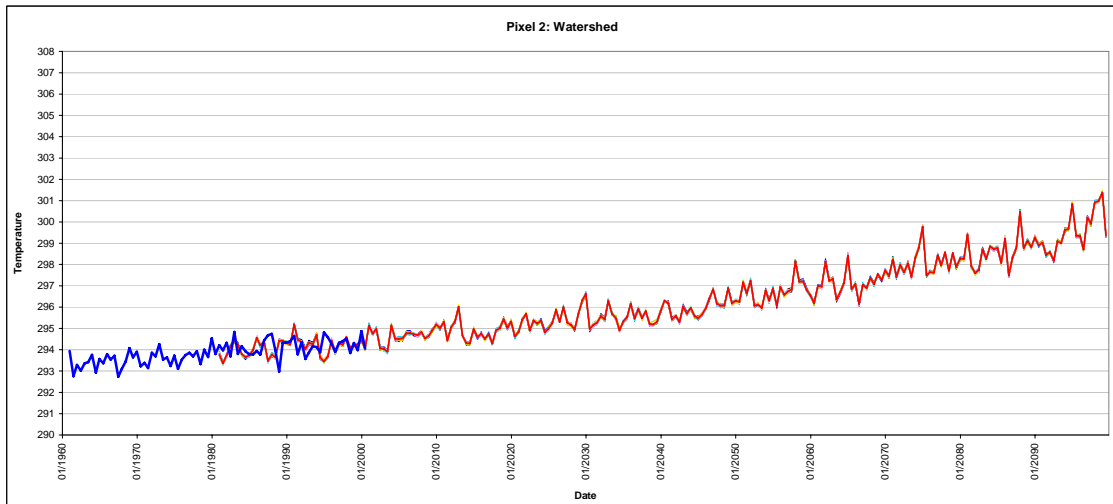
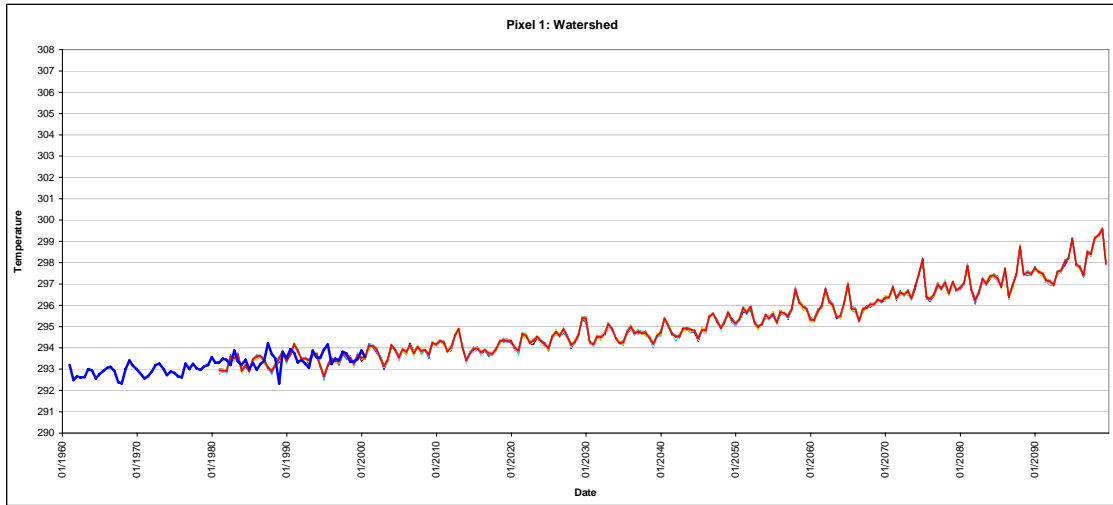
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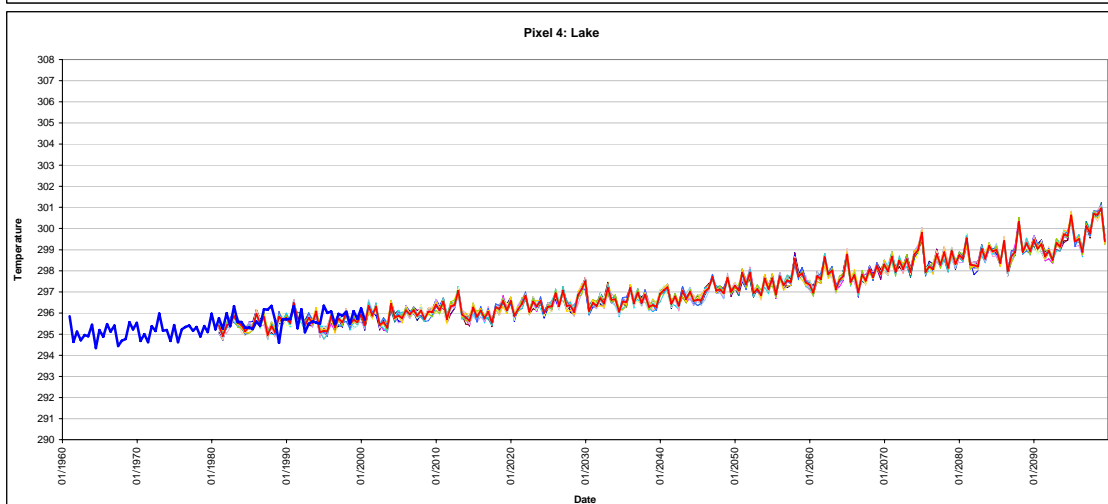
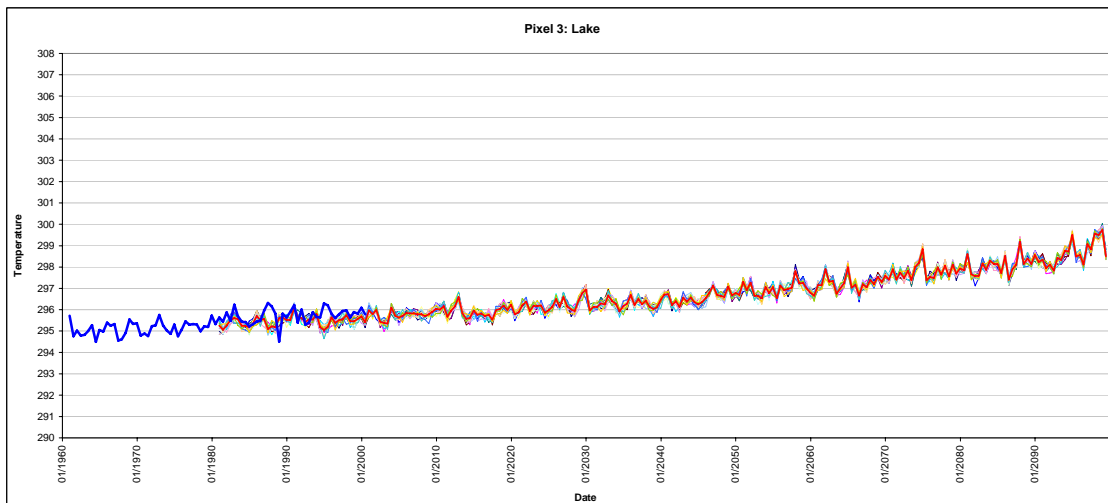
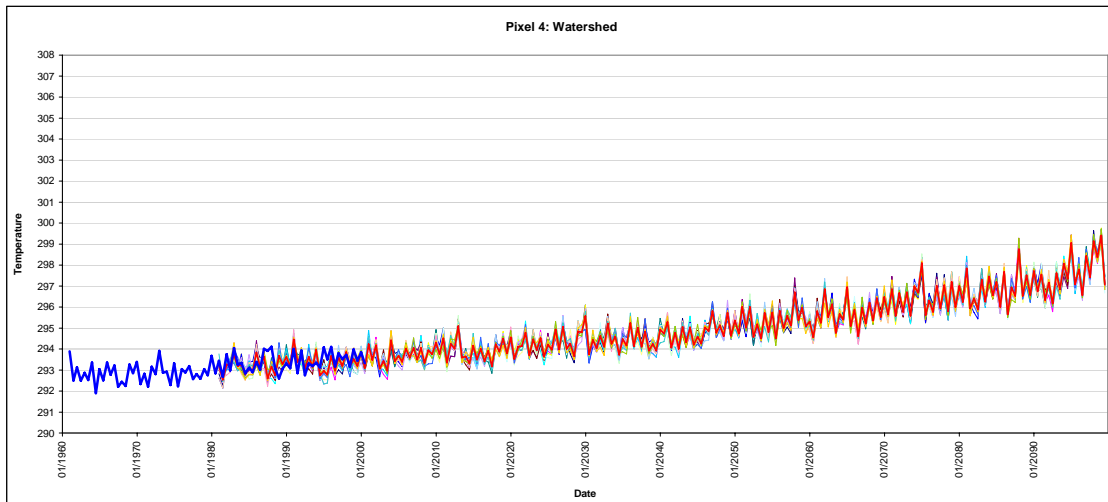
Roeckner, E., K. Arpe, L. Bengtsson, M. Christoph, M. Claussen, L. Dümenil, M. Esch, M. Giorgetta, U. Schlese, and U. Schulzweida, 1996. The atmospheric general circulation model ECHAM4: Model description and simulation of present-day climate. Max Planck Institut für Meteorologie, Report No. 218, Hamburg, Germany, 90 pp.

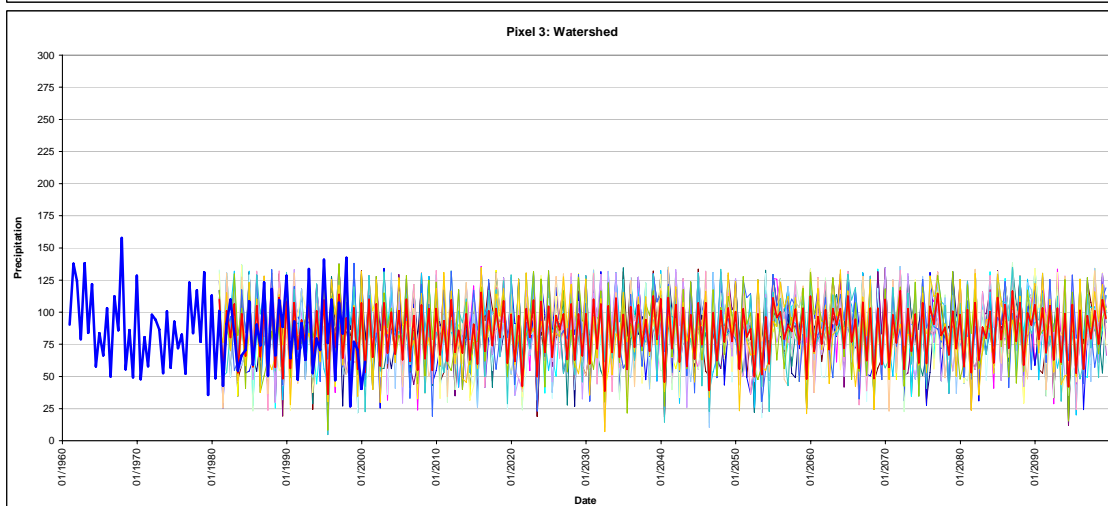
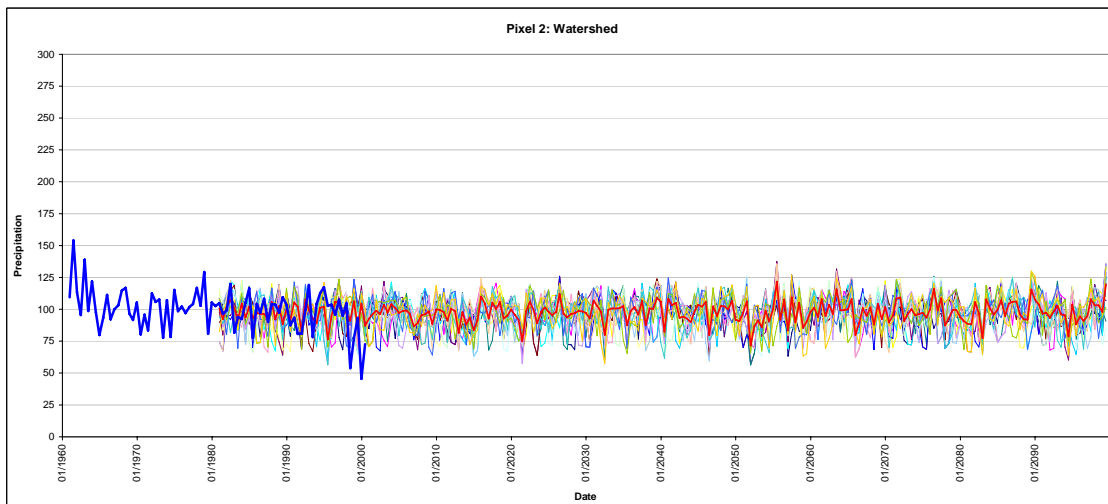
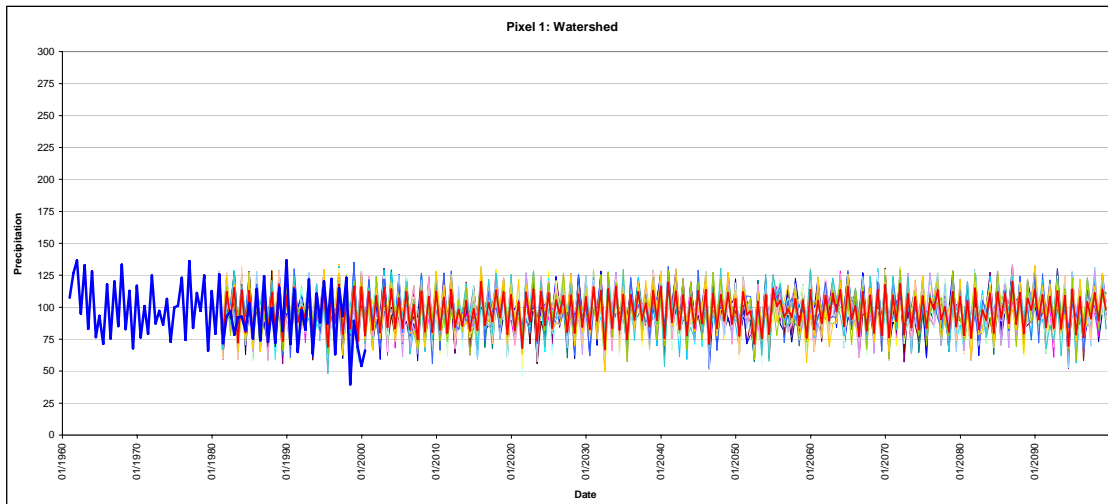
Special Report of the Intergovernmental Panel on Climate Change, 2000. Nebojsa Nakicenovic and Rob Swart (Eds.), Cambridge University Press, UK. pp 570.

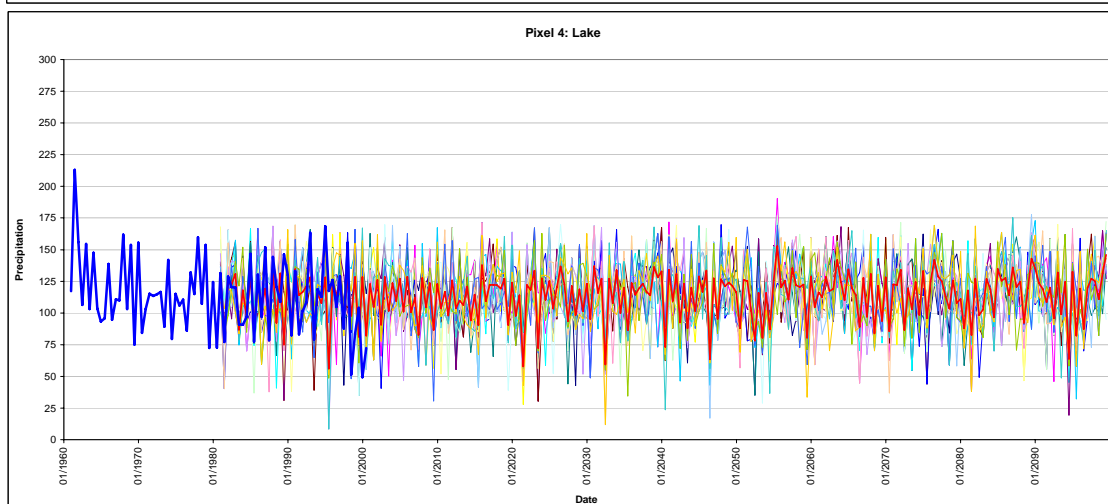
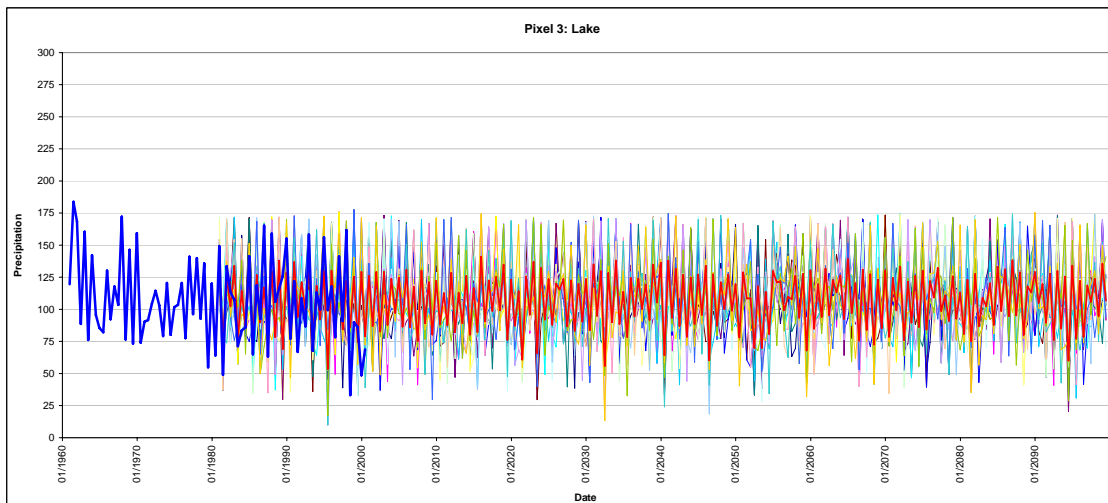
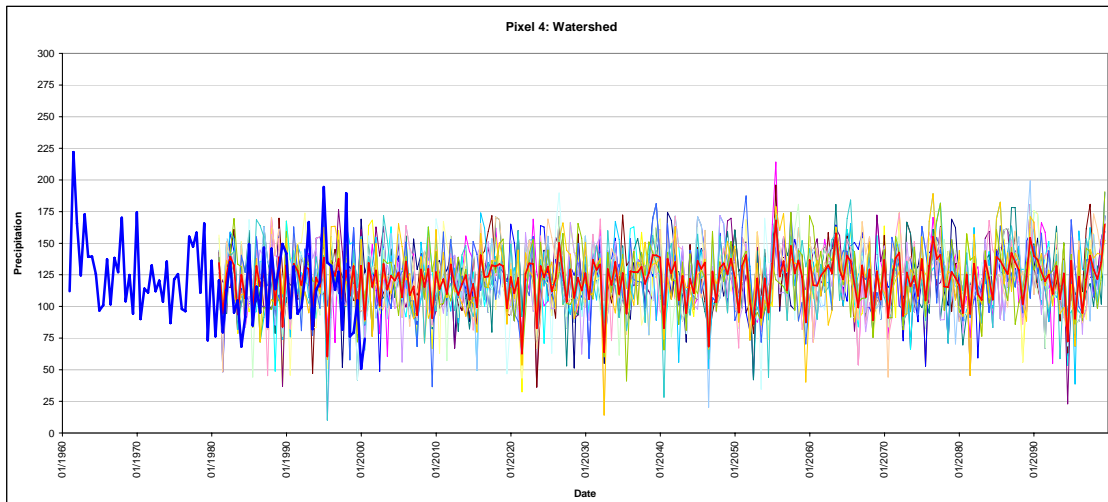
# Appendix A

## **A2 Scenario Results**

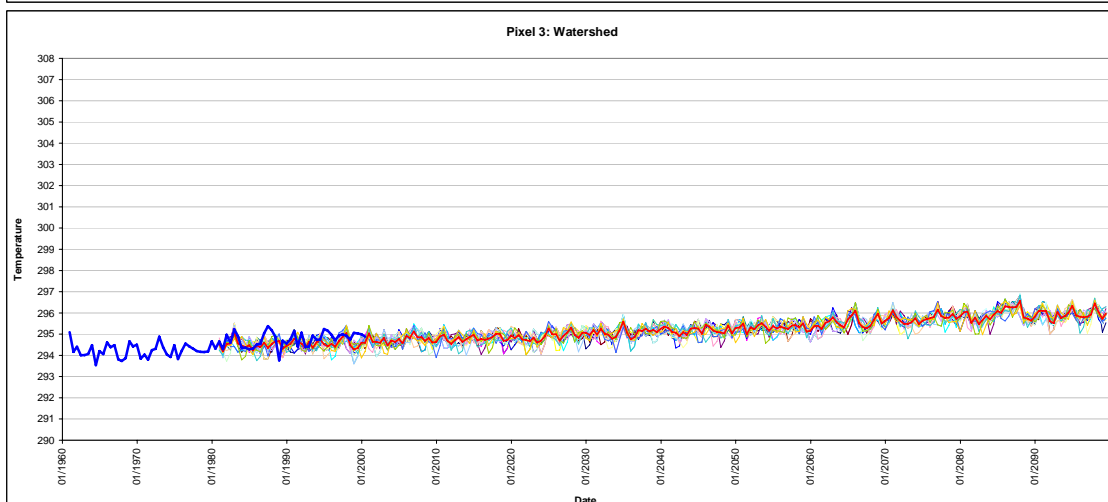
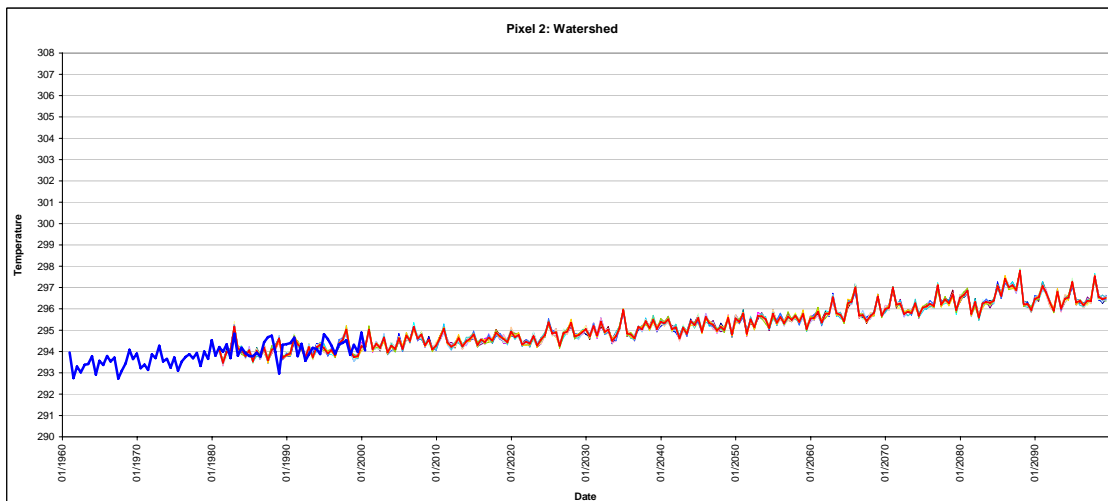
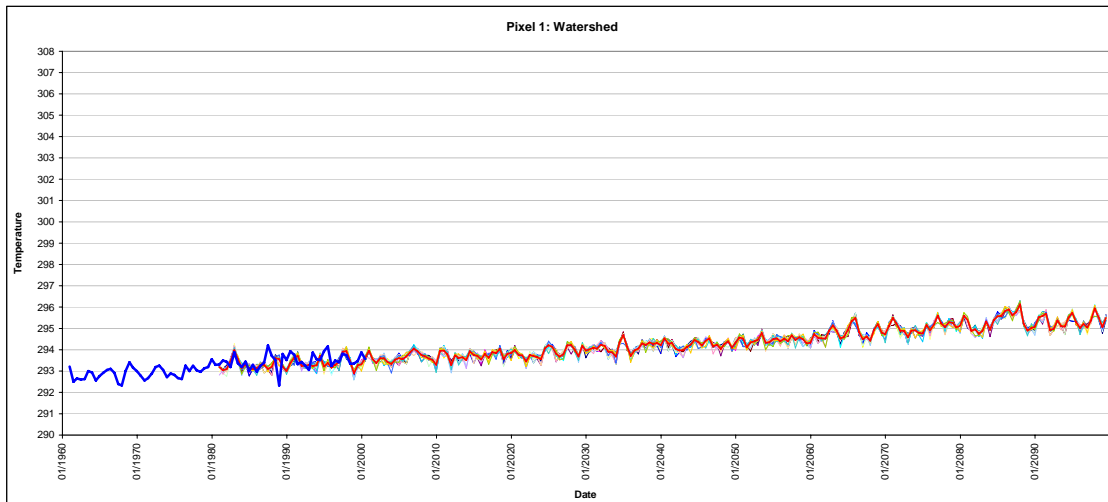


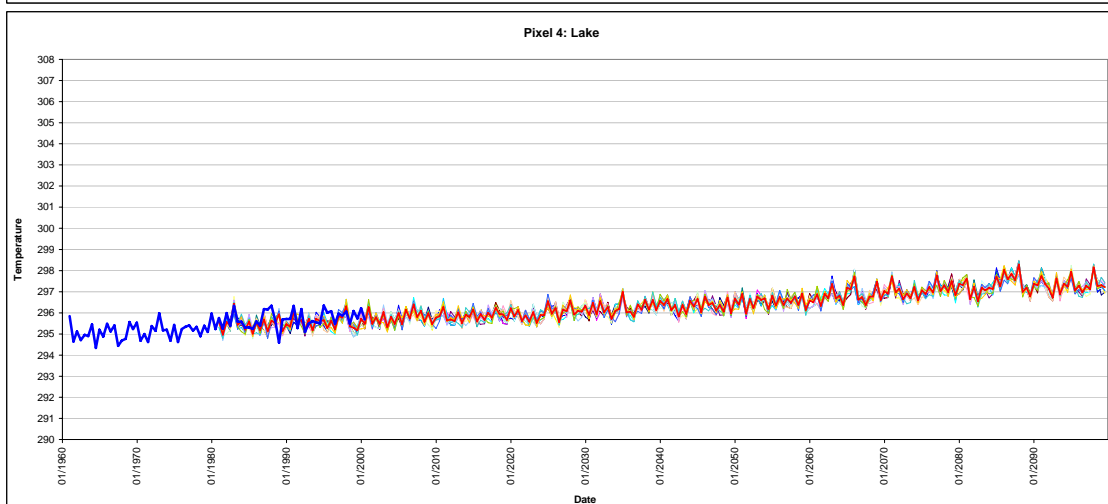
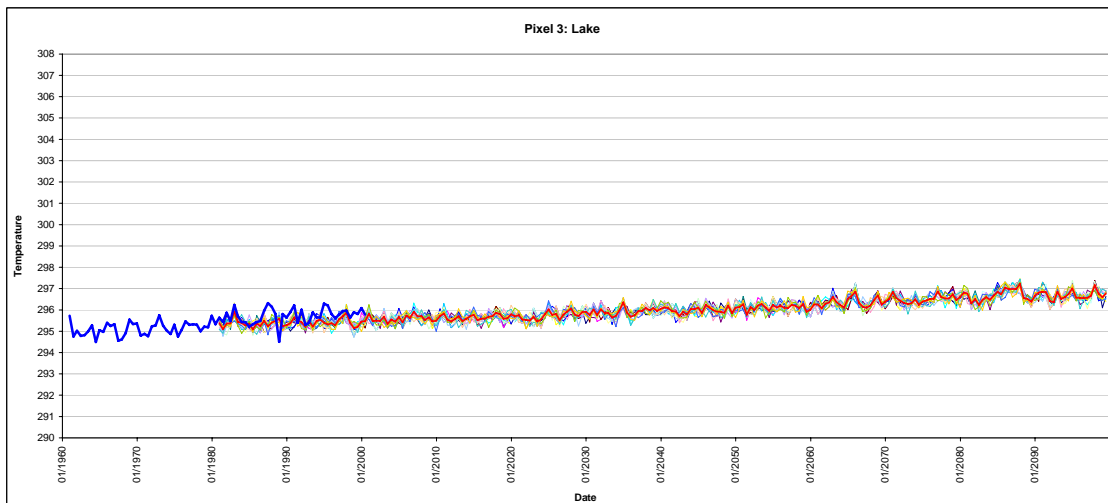
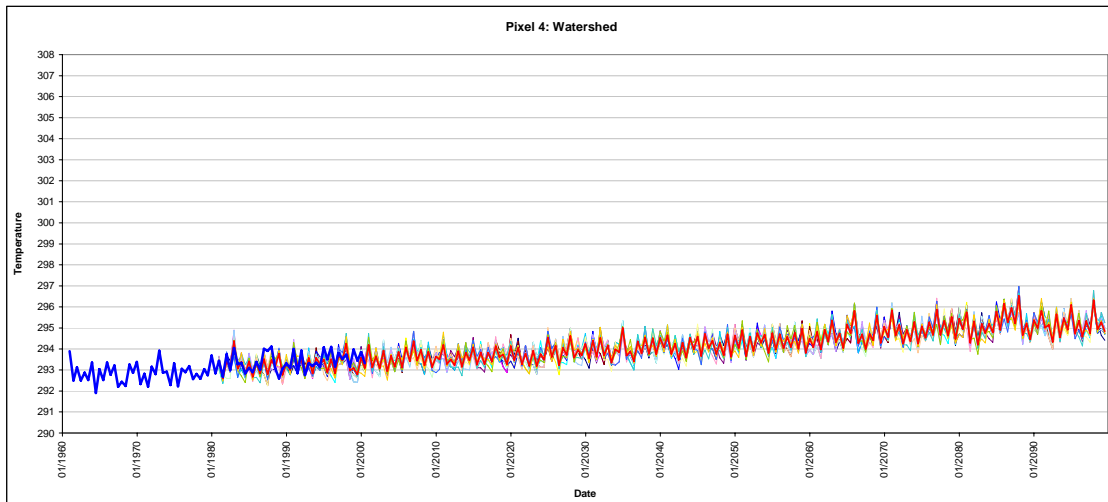


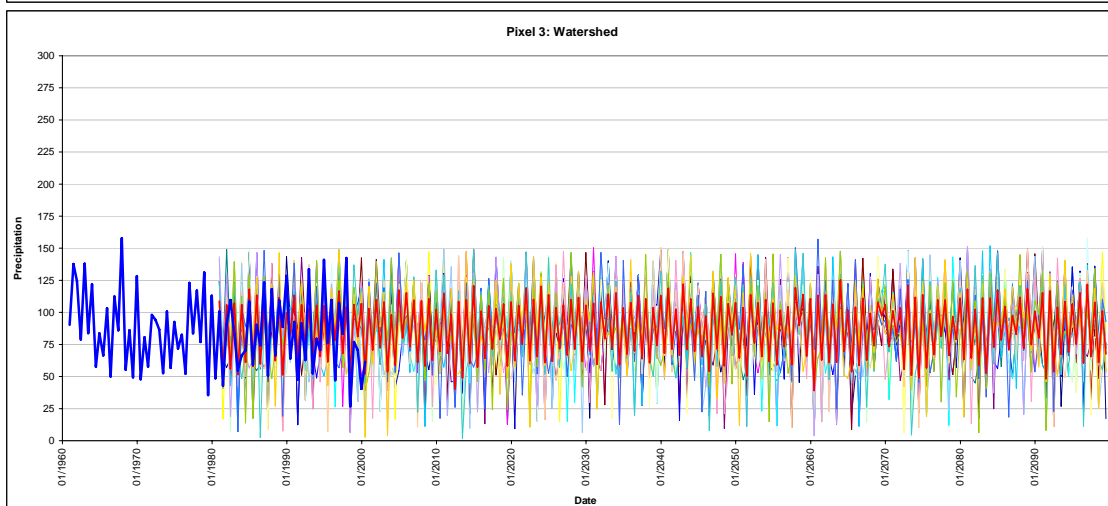
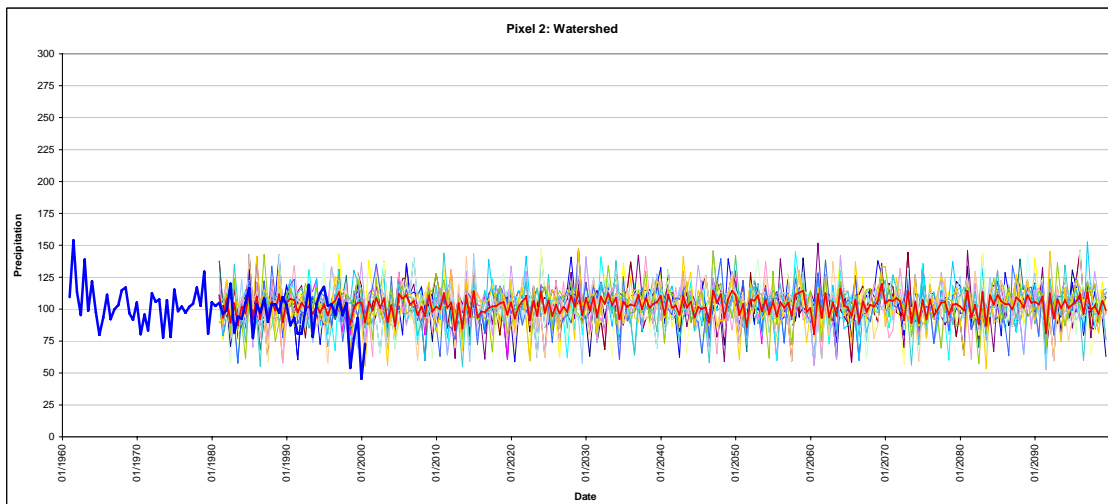
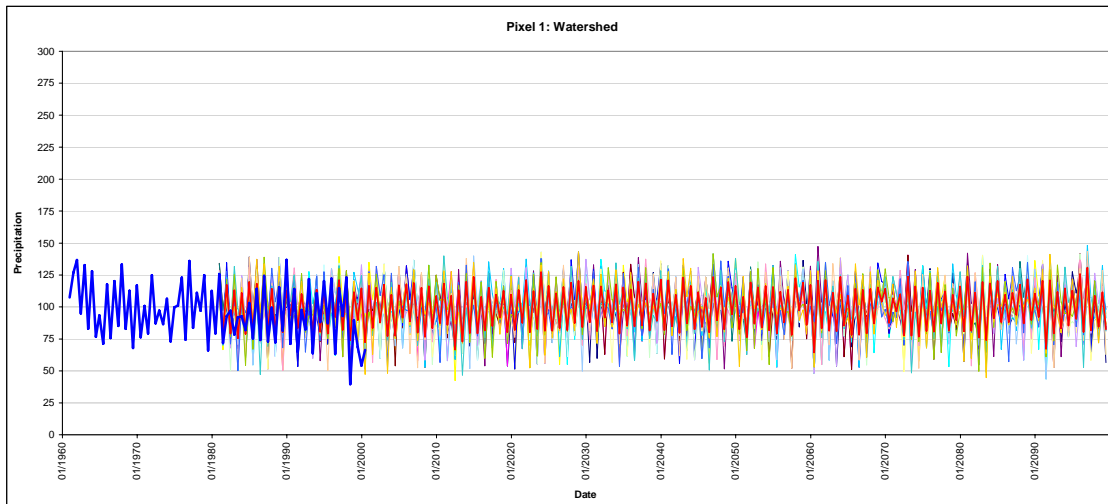


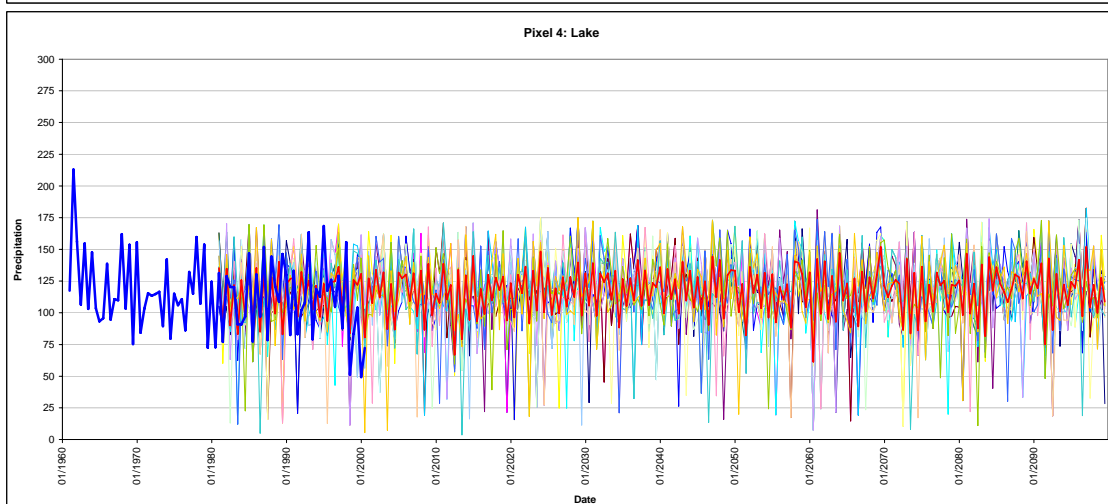
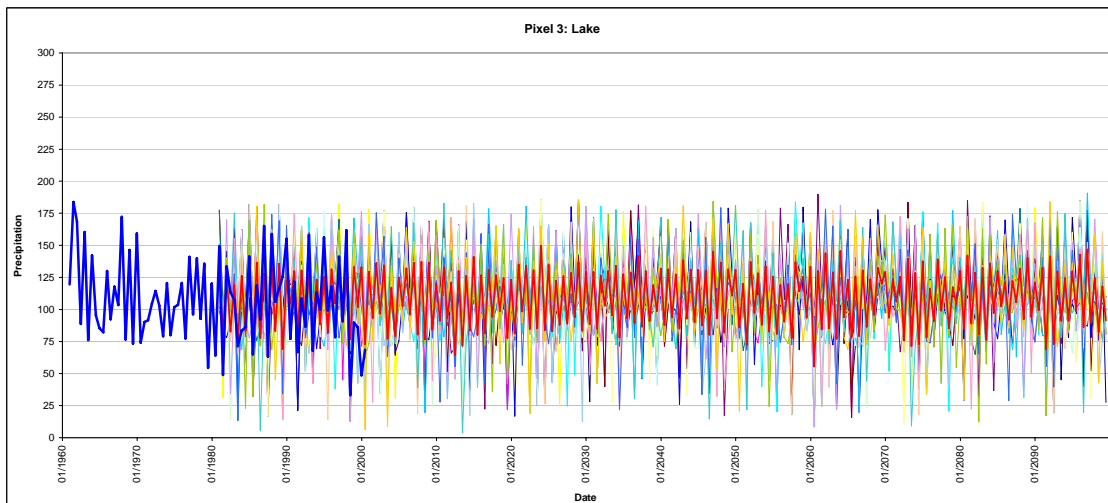
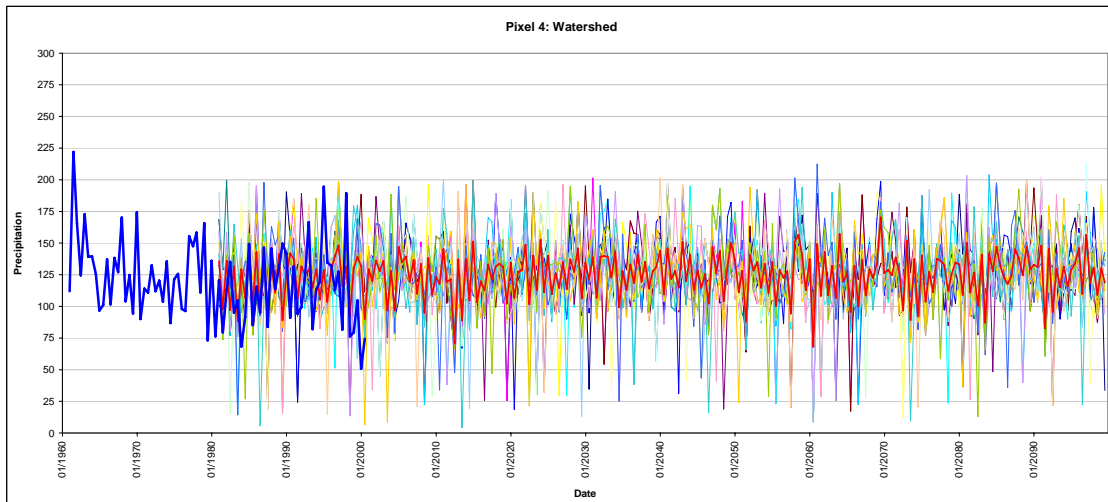


**B2 Scenario Results**

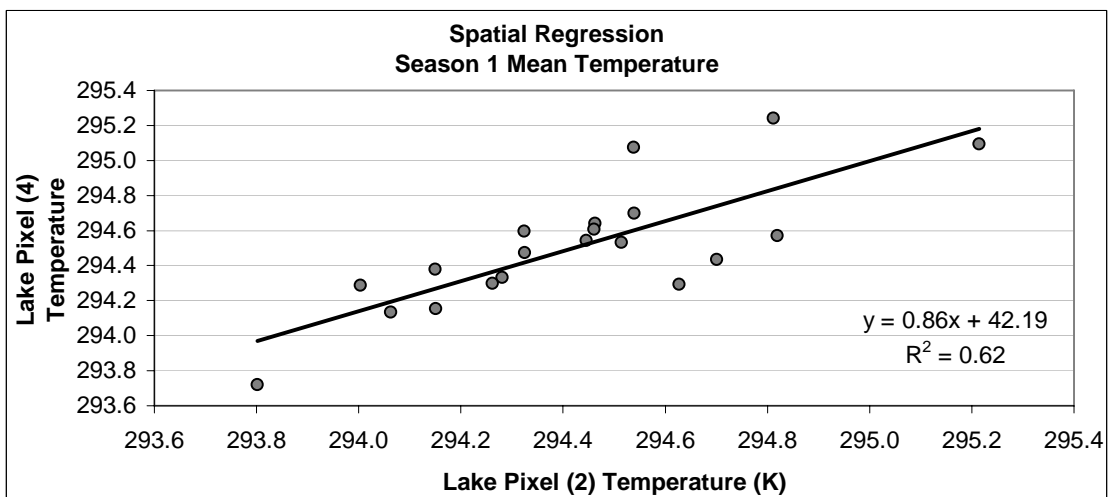
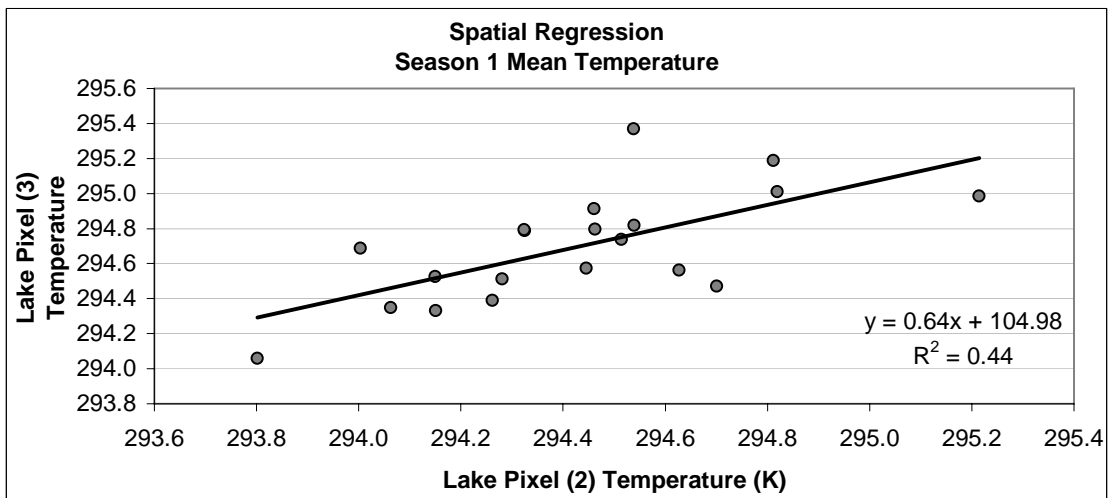
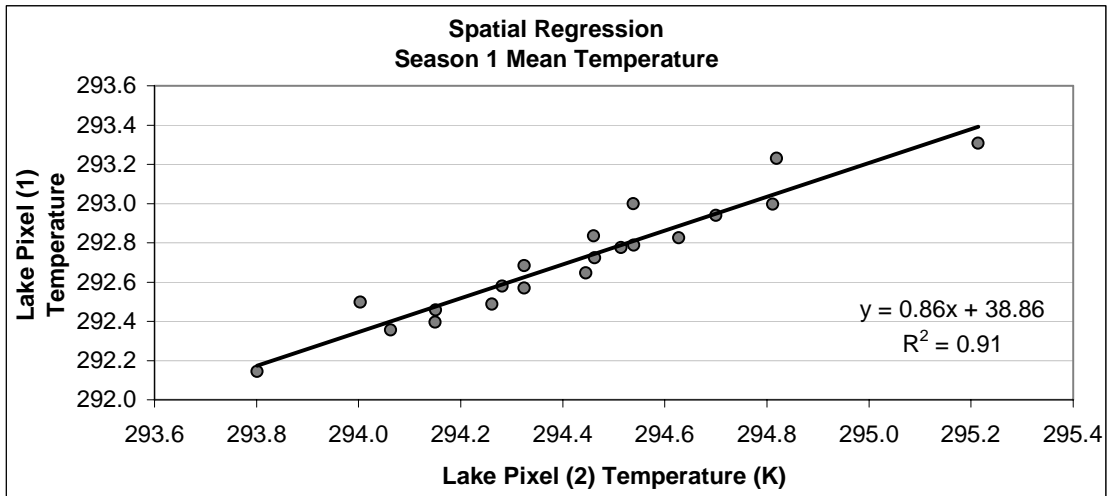


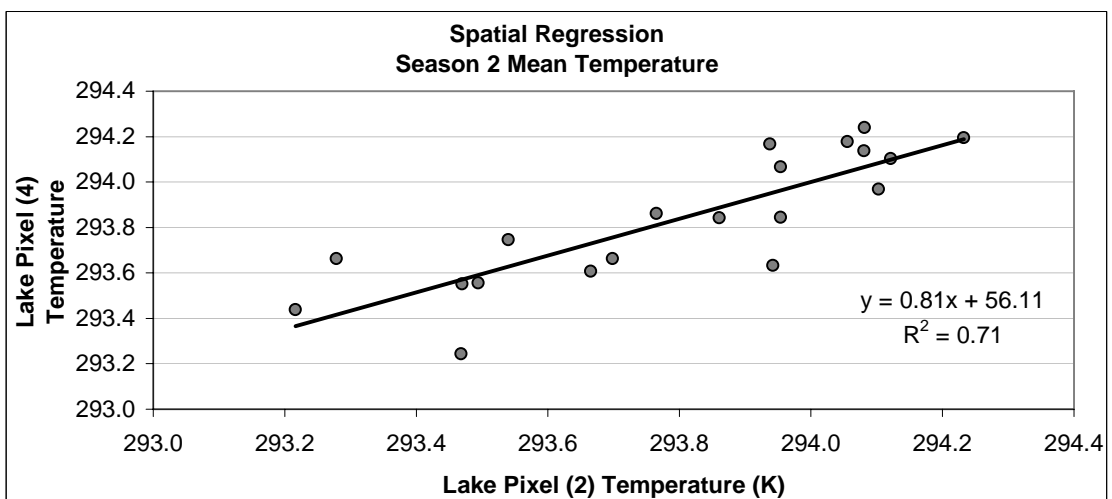
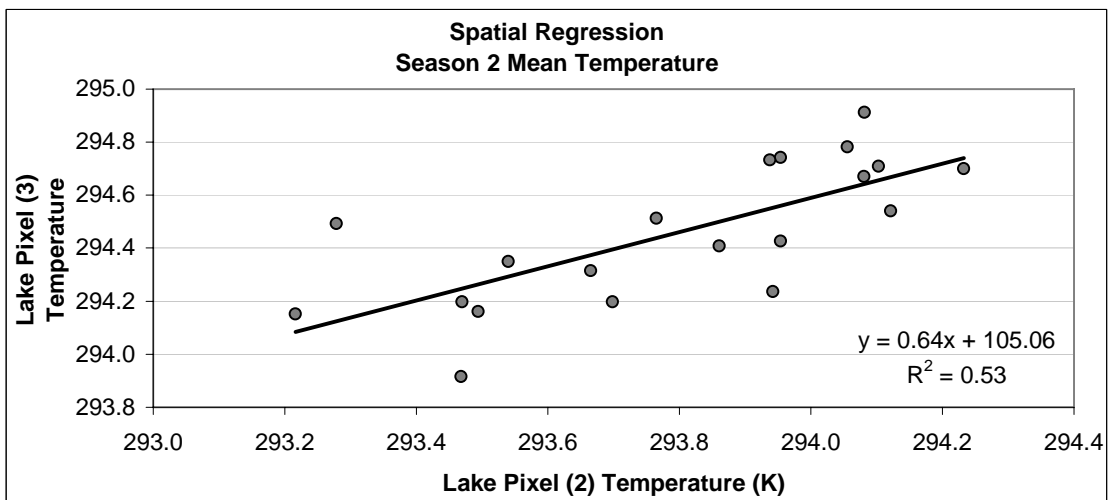
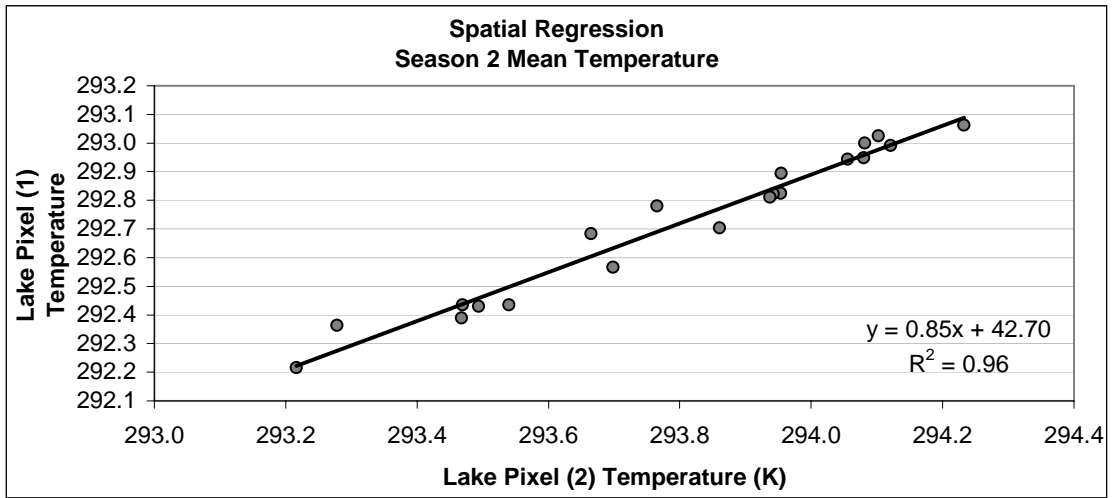


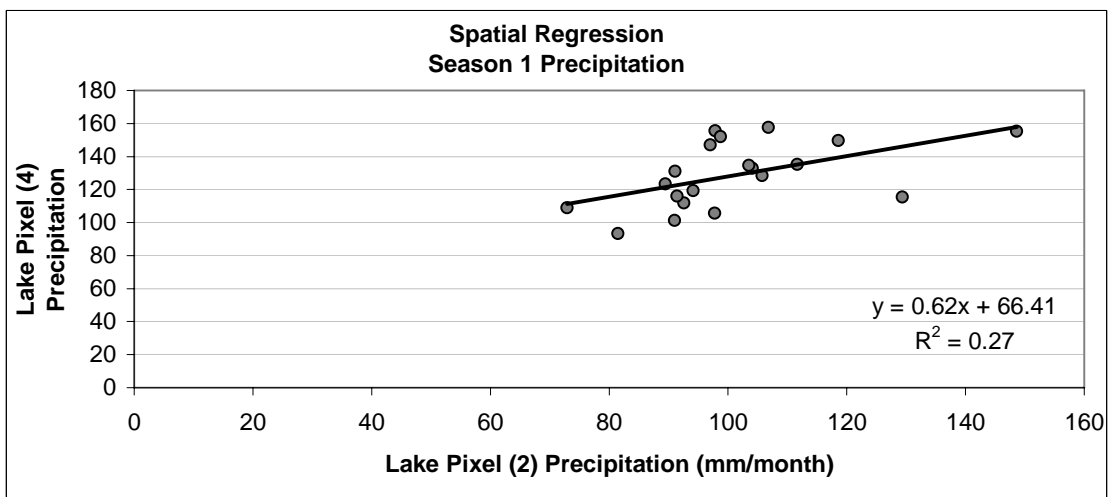
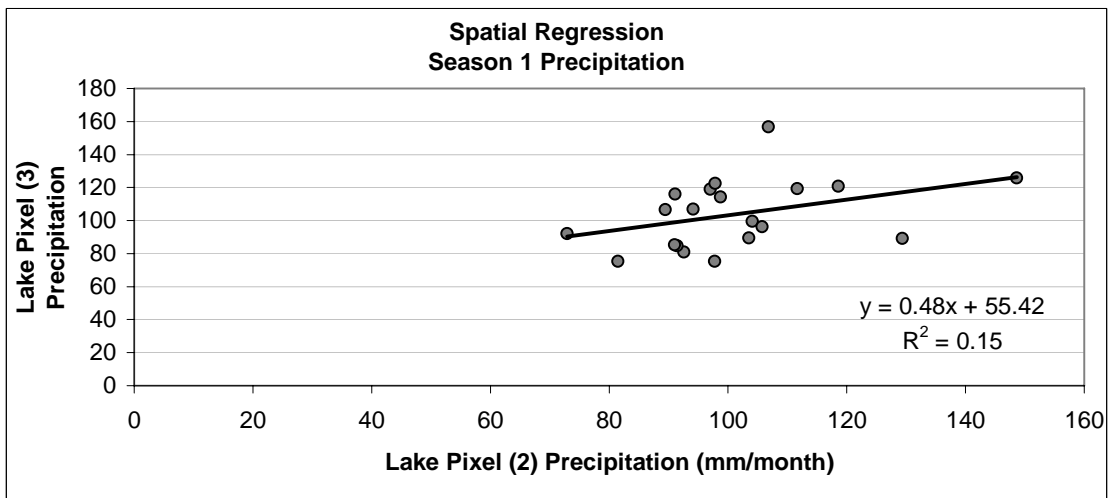
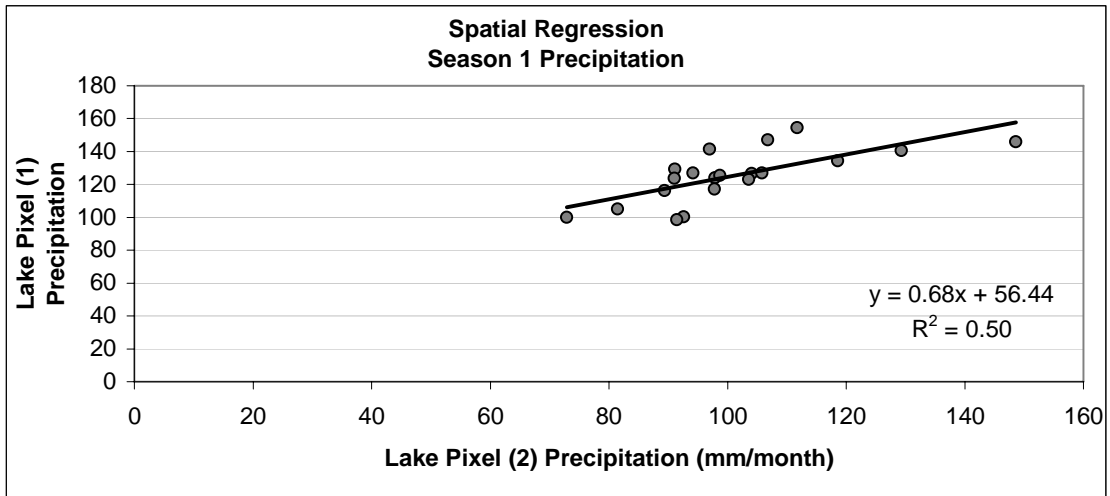


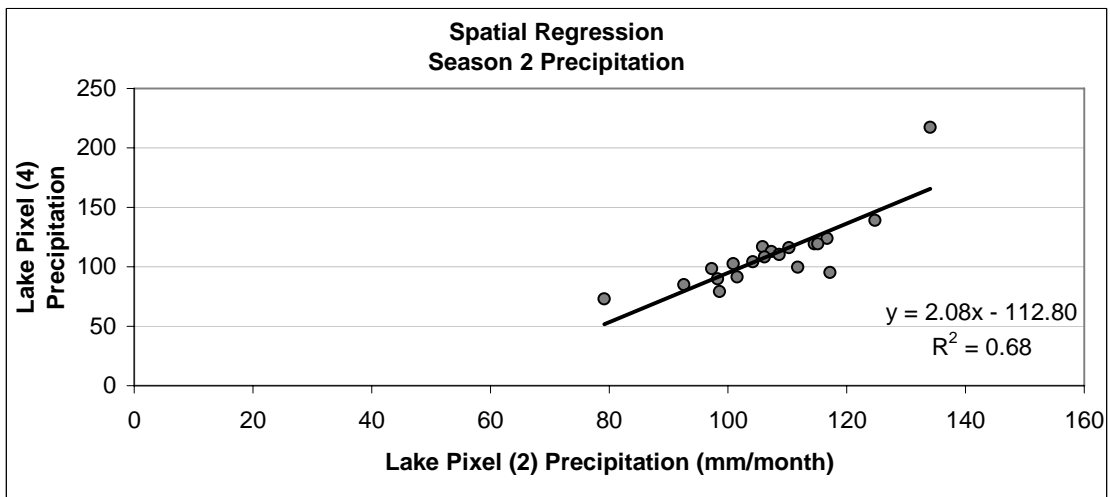
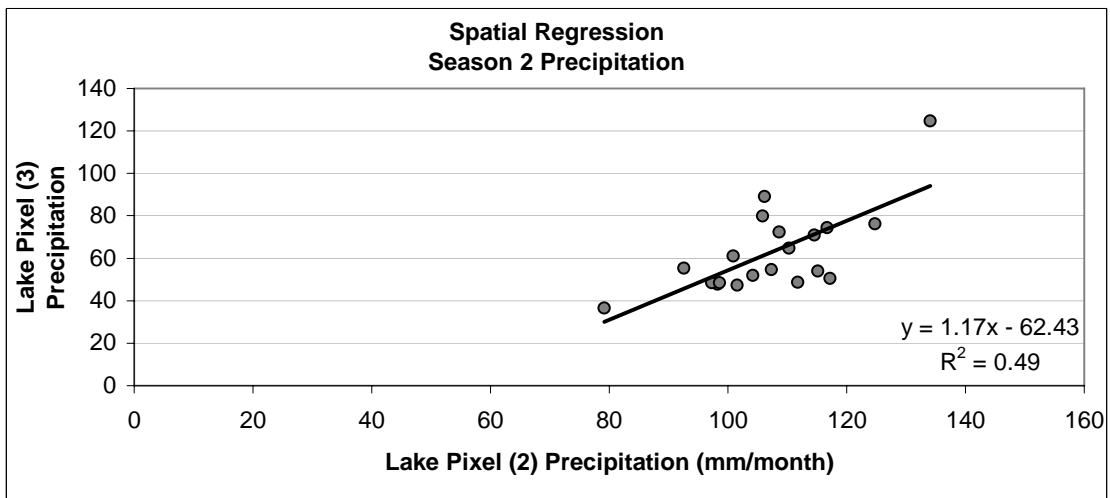
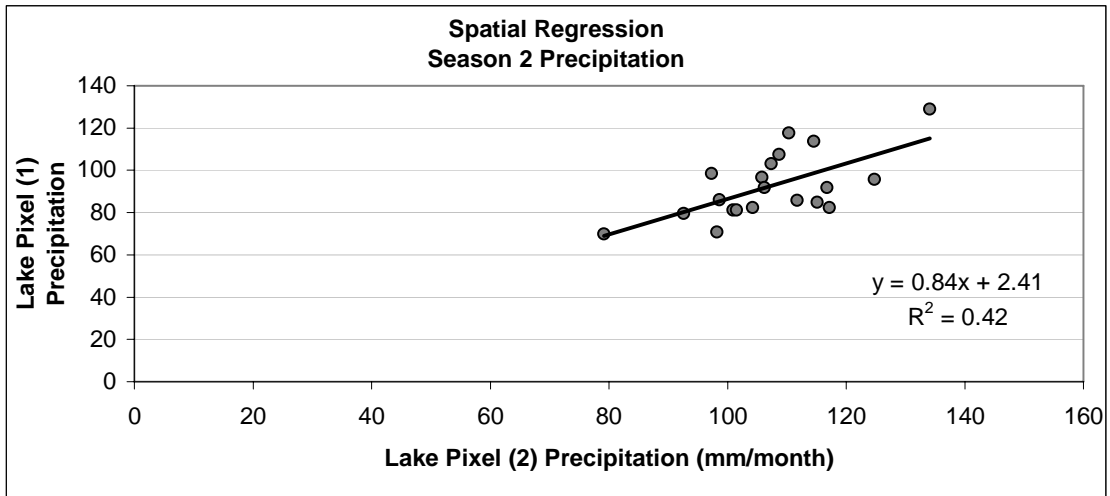


## **Spatial Pixel Relationships used for A2**

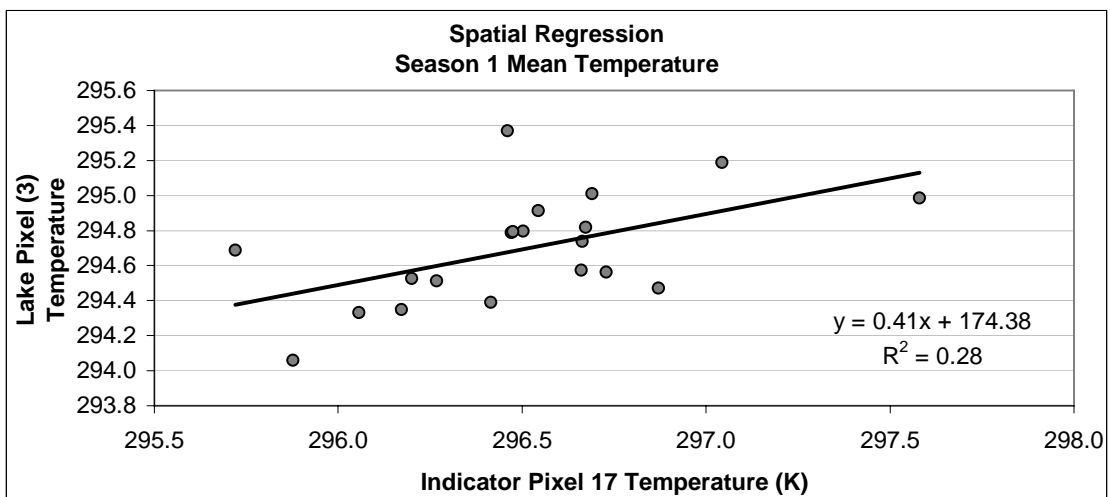
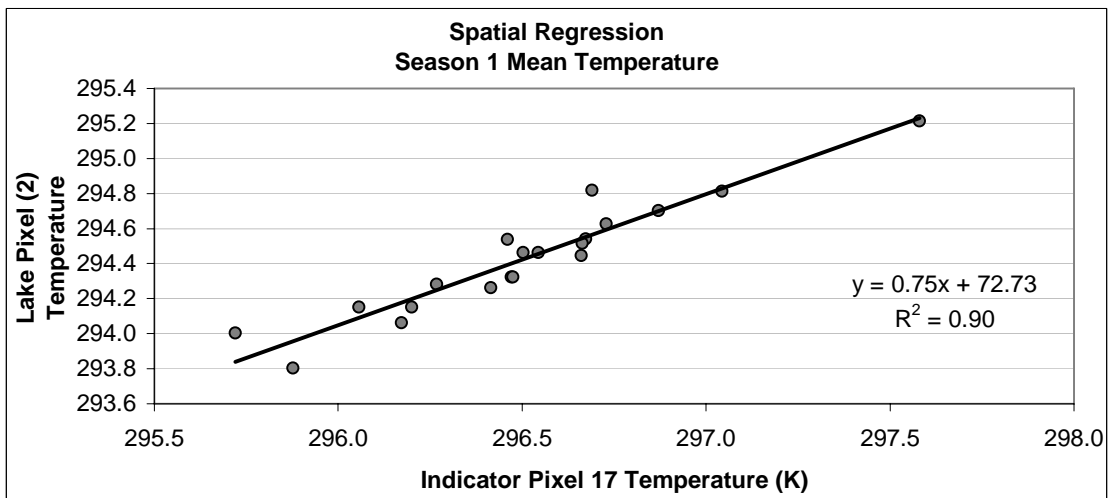
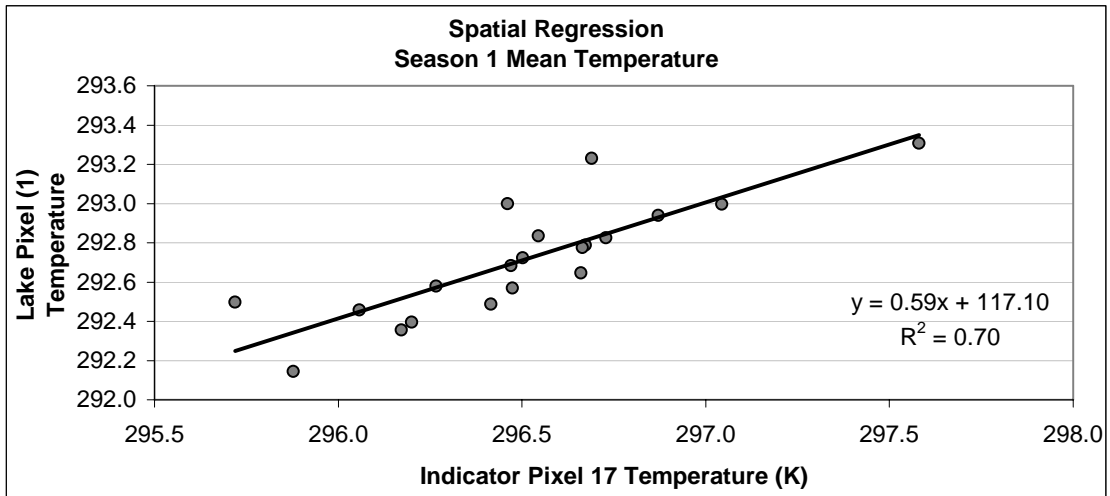


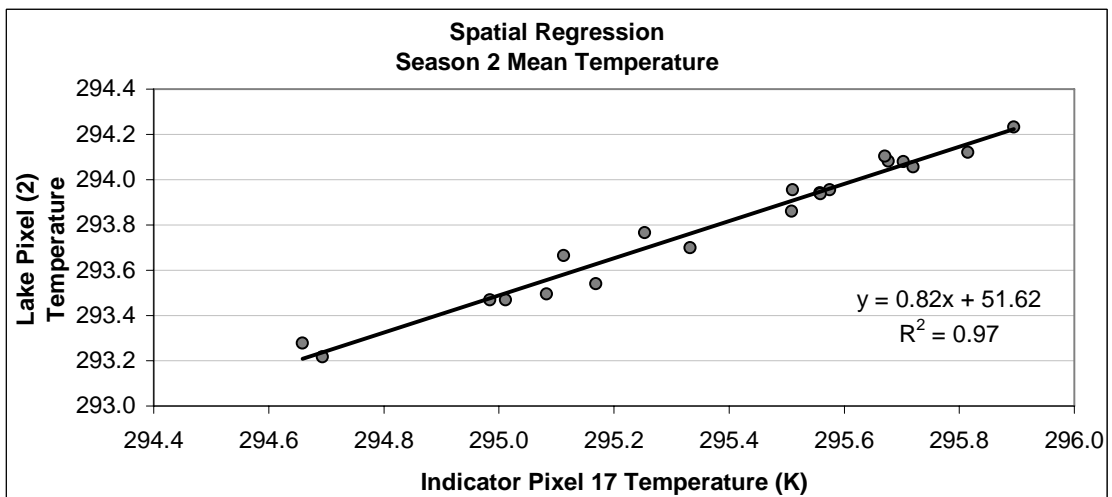
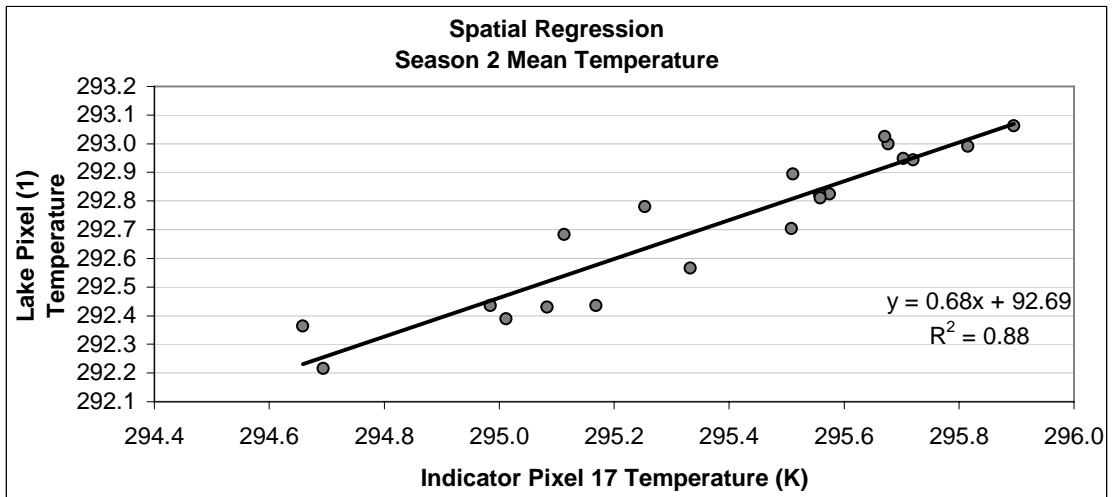
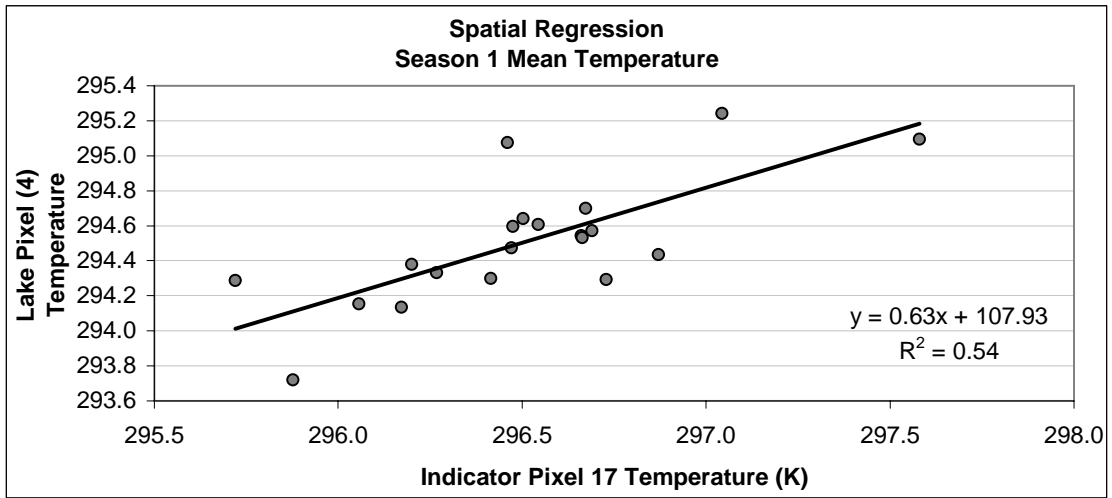


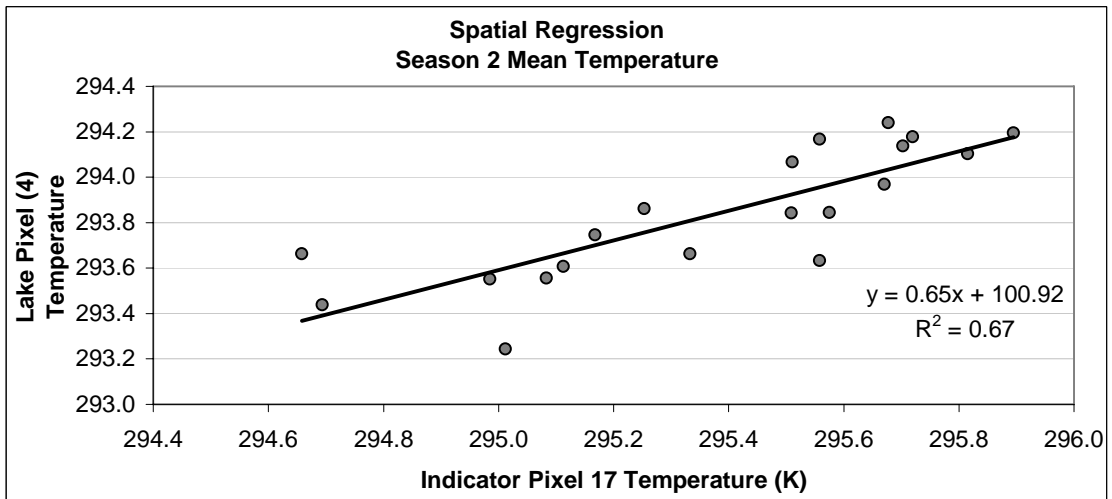
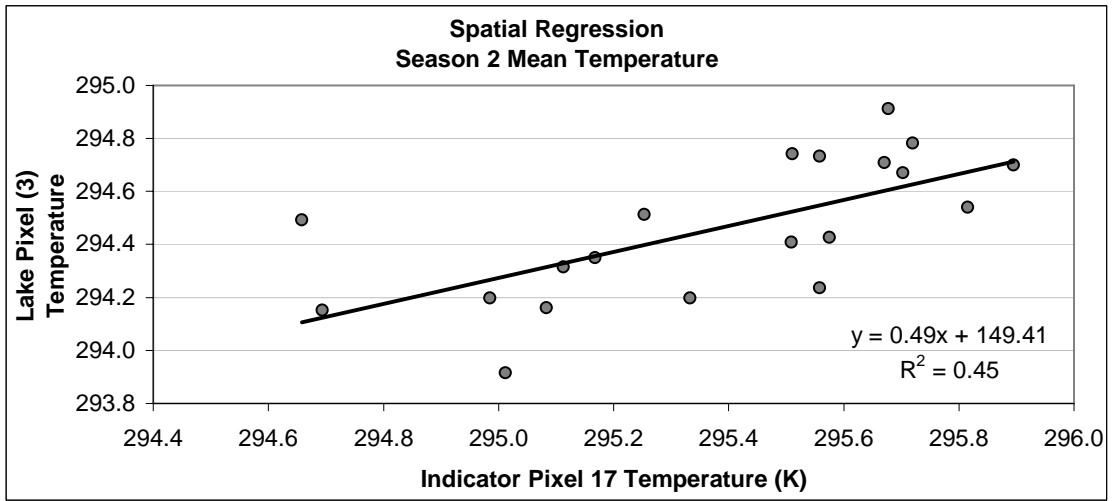


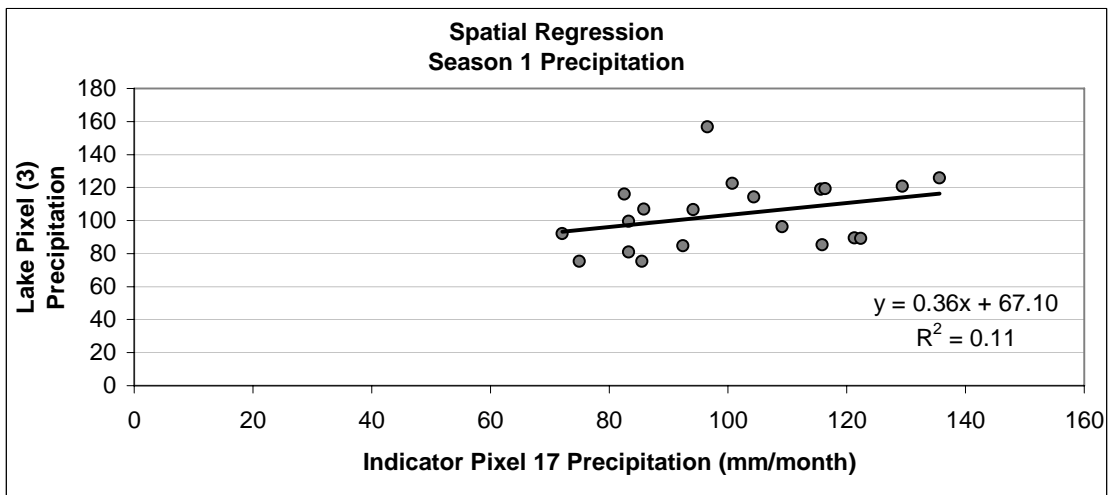
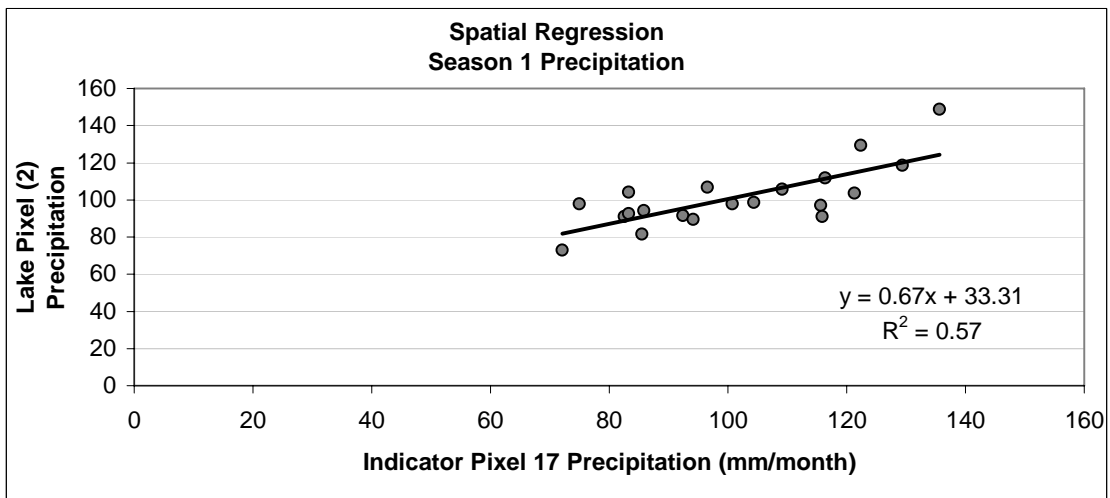
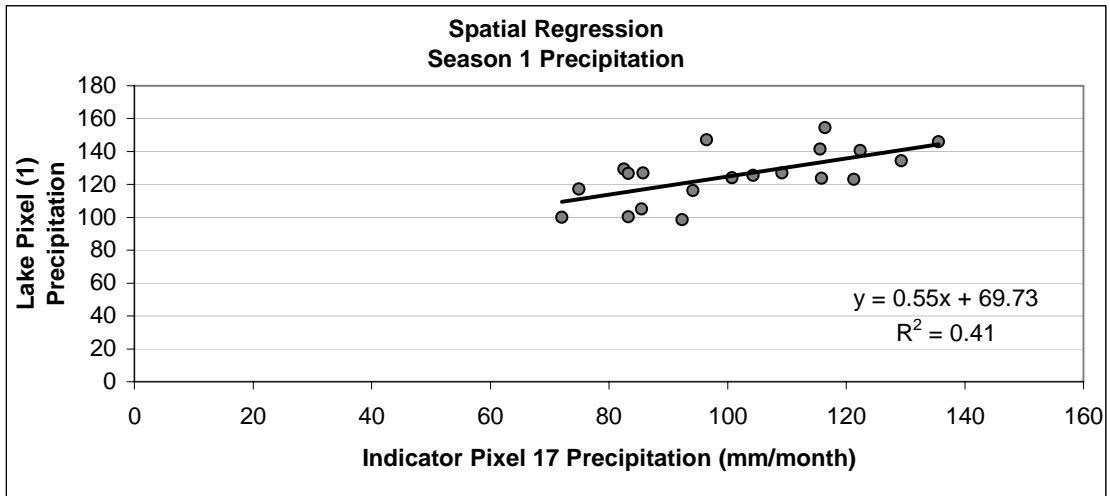


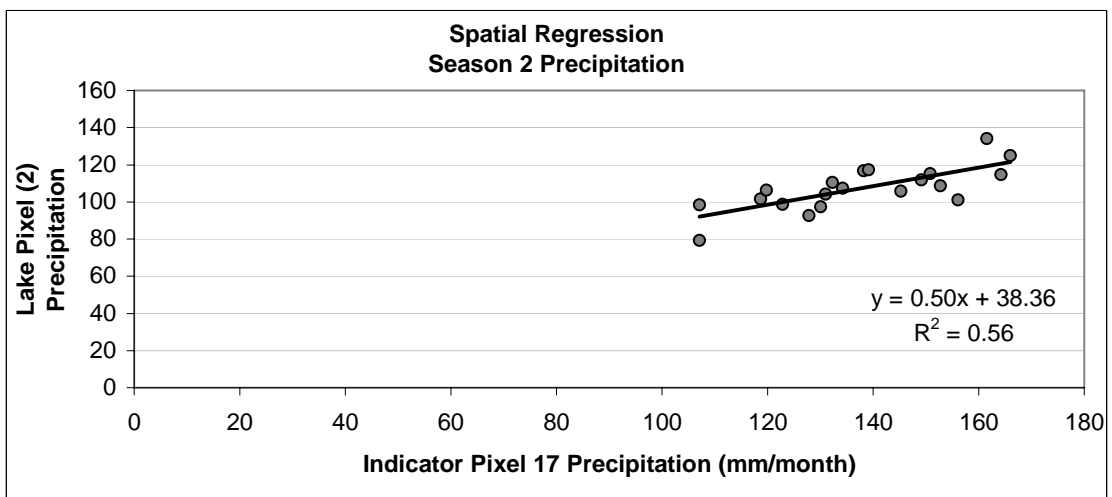
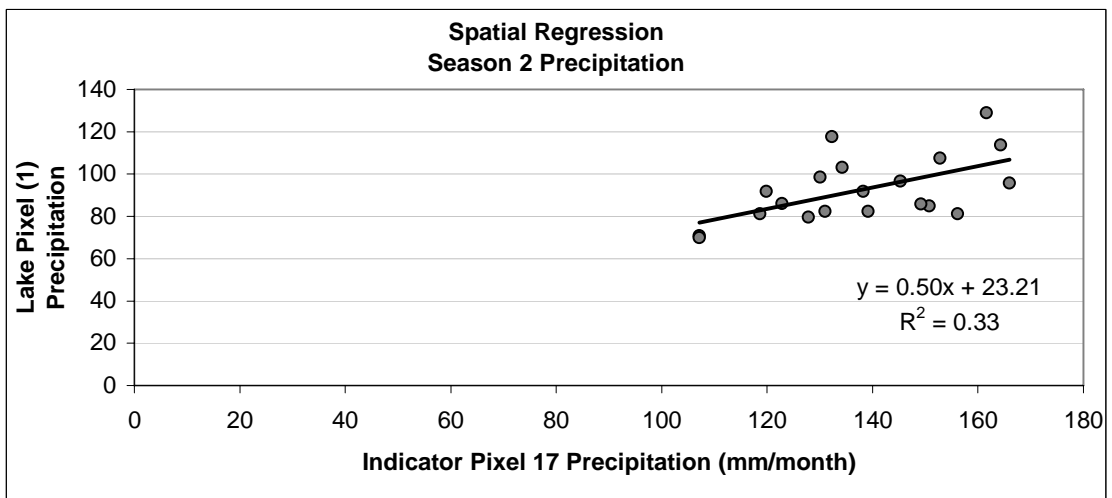
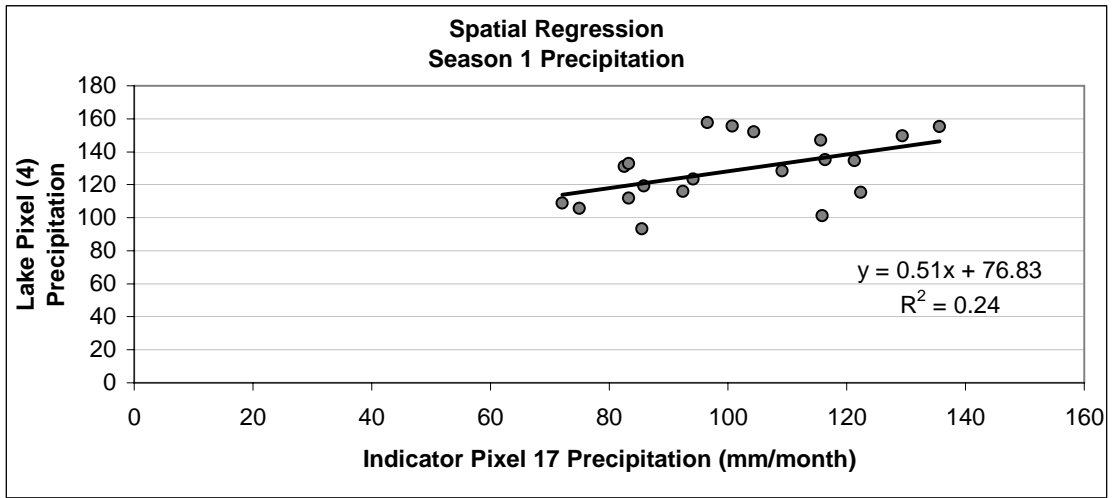
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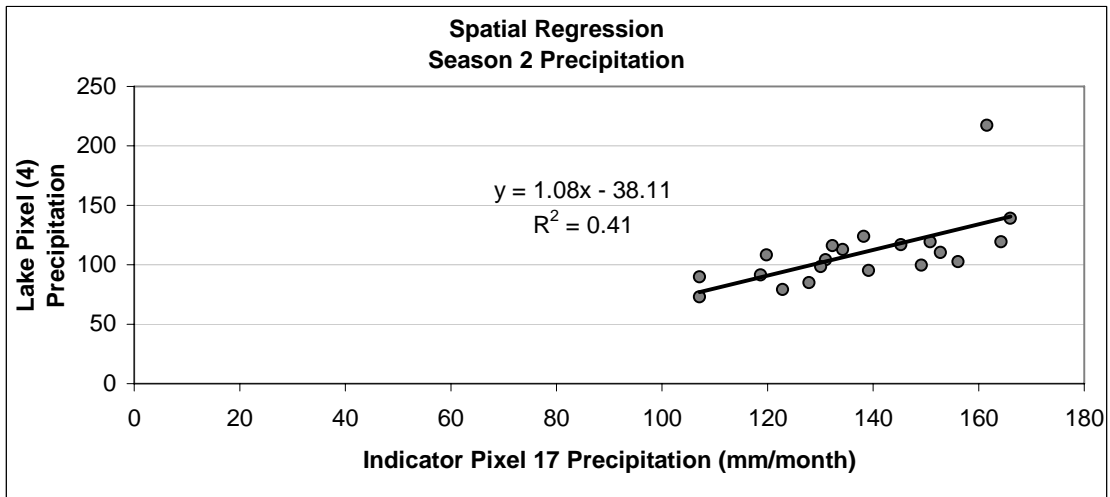
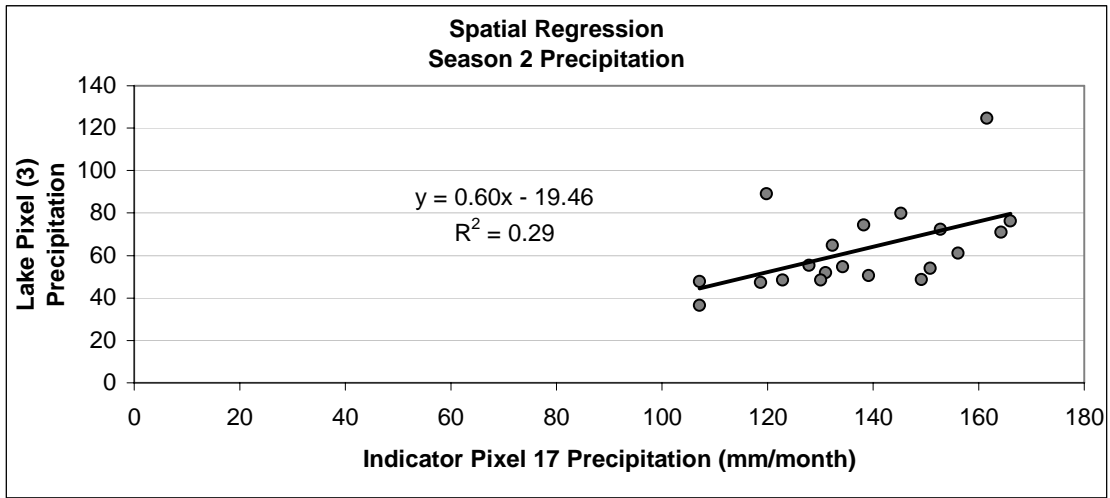












## **Downscaling Relationships**

