Effects of Inland Lake Water Level Fluctuations on Ecosystem Services Due to Predicted Seasonal Precipitation Shifts

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DEDICATION

This work is dedicated to my father and mother for all they have done.

ABSTRACT

This research investigated potential changes to recreational and aesthetic ecosystem services in the BWCAW eco-region due to potential climate pattern changes over the next 100 years.

The research looked at past literature regarding validation and definition of ecosystem service studies, the potential climate changes, and use of water level as an index to assess productivity in the littoral zone. This was accomplished by utilizing historical data available for a large boreal lake and simplified precipitation prediction techniques (two state Markov Chains and maximum likelihood gamma distributions) to create inputs to a model. The HEC-HMS modeled watershed produced outflows which were compared to a pre-prediction period state outflows to ascertain water level fluctuations, indicators of hydrologic alteration (IHA) and degree of impact to watershed ecosystem services.

It became clear that despite a near inversion of base seasonal precipitation patterns and continued growth of total precipitation that snowpack and spring thaws controlled the lake water level response in the scenario researched and that overall behavior remained nearly consistent with little negative impact. The research indicates that if the scenario plays out, long term economic impact through recreation and aesthetic linked ecosystem services will remain stable. It is recommend that future research use more robust modeling software, spatially varying data sets and direct quantitative measurements of seasonal recreational use and value over several years.

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List of Abbreviations and Acronyms

Abbreviation or Acronym	Full Text/Meaning
ATI	Antecedent Index
BWCAW	Boundary Waters Canoe Area Wilderness
CDF	Cumulative Probability Density Function
DAMP	Difference in Amplitude
DEM	Digital Elevation Model
DLTM	Difference Long Term Mean
DNR	Department of Natural Resources
ES	Ecosystem Services
FM	Final Scalar Multiplier
GNIS	Geographic Name Information System
GW	Ground Water
HEC-HMS	Hydrologic Engineering Center – Hydrologic Modeling System
HRMSI	High Resolution Multi-Spectral Imagery
HUC	Hydrologic Unit Code
IGF	Incremental Growth Factor
IHA	Indicators of Hydrologic Alteration
MRLC	Multi-Resolution Land Characteristics Consortium
NAD 83	North American Datum 1983
NCDC	National Climatic Data Center
PDF	Probability Density Function
PEG	Precipitation with Expected Growth
PSP	Predicted Shifted Precipitation
RMSE	Root Mean Square Error
SMA	Soil Moisture Accounting
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WGS 84	World Geodetic System 1984
WLF	Water Level Fluctuations
YPT	Yearly Precipitation Total

Chapter 1: Introduction and Problem Statement

1.1 Background

The Boundary Waters Canoe Area Wilderness (BWCAW or BWCA) and surrounding State Forests are a vast area of nearly untouched lands composed of boreal and a mix of conifer-hardwood forests that spans a considerable amount of the border between Minnesota and Canada (MN State Forests 2013). The protected transboundary wilderness hosts many water bodies residing in both Canada and the United States which see limited human interaction, despite a large amount of annual visitors. The wilderness provides people with an opportunity to experience breathtaking natural beauty of 4411 km^2 (1,090,000 acres) of preserved woodlands. In 2013, approximately 123,300 adults and children visited the BWCAW, with about 31,250 overnight permits issued (Schwaller 2013). This research will focus on the eco-region, specifically on Lake Kabetogama a neighboring lake to the BWCAW which is part of the State Forest system.

Figure 1 – Map of Minnesota with BWCAW and Superior National Forest highlighted (US Forest Service 2014).

Currently, little is known about how predicted climate changes will influence water levels and ecosystem services of large boreal lakes of the BWCAW area. Ecosystem services are the benefits provided to mankind from the natural environment, such as clean drinking water, flood control and food sources. It is possible that the area will experience drier summers and wetter winters with an overall slight increase in temperatures (Meehl et al., 2000). This thesis will review the field of ecosystem services, with both traditional and non-traditional markets (such as aesthetic and recreational use) and look at water level fluctuations in a recreational surface waterbody as an index of ecosystem service value.

This research is accomplished by reviewing prior research on accepted and suitable definitions of ecosystem services, predicted changes to precipitation & temperature patterns based on larger scale models. Predicted climate change affects on a large boreal lake are modeled for future years and water level fluctuation is determined. The model is compared to existing research benchmarks of water level fluctuation as an index. The index is used to assess ecosystem service functions in terms of aesthetics and recreational use in a qualitative manner.

Modeling is conducted through the use of the United States Army Corps of Engineering (USACE) Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) to develop waterbody outflows and storage based on a modeled watershed. Analysis of the watershed model output for potential future climate conditions is compared to historical outflow and water levels to predict the possible future state and statistical differences are calculated through the use of Indicators of Hydrologic Alteration (IHA) software.

In this research the ecosystem services related to water level fluctuation are only addressed for the BWCAW area in terms of recreational use. The patterns of water level fluctuation are local to the region and cannot be applied globally. Recreational use comparison is based on values local to the BWCAW, and is not applicable to other regions.

The research conducted is not wholly limited to Lake Kabetogama and can be applied to lakes in the BWCAW eco-region to assess potential impacts of climate change. Applying this research across the eco-region would help to increase understanding and accuracy of estimated values for ecosystem services and how water level fluctuations may impact the region in environmental and socio-economic ways.

1.2 Objective

The objectives of the research are as follows:

1. Utilize existing research on climate predictions to develop potential precipitation shifts seasonally within a year and over a period of study years. Precipitation prediction is conducted through use of Gaussian probability functions of historical frequencies determining rainfall intensity and two-state Markov Chains to determine occurrence.
2. Input a predicted set of paired precipitation and temperature data to a HEC-HMS modeled watershed to develop a behavioral response of surface waterbody storage and outflows.
3. Assess HES-HMS model output for significant differences when compared to historical records of storage and flow, and comparing the fluctuation in surface water levels to existing research benchmarks to predict potential impacts on aquatic biota and the littoral zone. Response of the littoral zone and hydrologic alteration is used to gauge impact on Ecosystem Services.

1.3 Overview of Thesis

This thesis is separated into six chapters, with the first covering the research goals, plans and description of the research area. The second chapter provides an in depth look at frames of reference for dealing with ecosystem services, a literature review of existing ecosystem service research, past research findings on climate changes and future patterns of precipitation and temperature in the region. The third chapter presents more detailed information about the study region; the modeling software used (including setup and parameters), and discusses historical data available. The fourth chapter describes methodology used to calibrate the HEC-HMS model and reduce potential error. Chapter five details precipitation and temperature prediction methodology to generate inputs to the HEC-HMS model for future years. Chapter six discusses analysis and results of the model output, limitations, conclusions, and future recommendations.

1.4 Introduction to Research Area

An existing watershed was used for a predictive analysis of the relationship of inland lake WLF and ES. Use of a real watershed allows for calibration of the simulation and results with real world historical data. Data sources are combined to develop an overall picture of the physical characteristics, historical processes and trends in order to model the water body.

Due to the remoteness of the BWCAW and limited availability of data sources for the region this research focuses on the Lake Kabetogama watershed. The Kabetogama watershed is selected for proximity to the BWCAW, permanence, physical characteristics and availability of data.

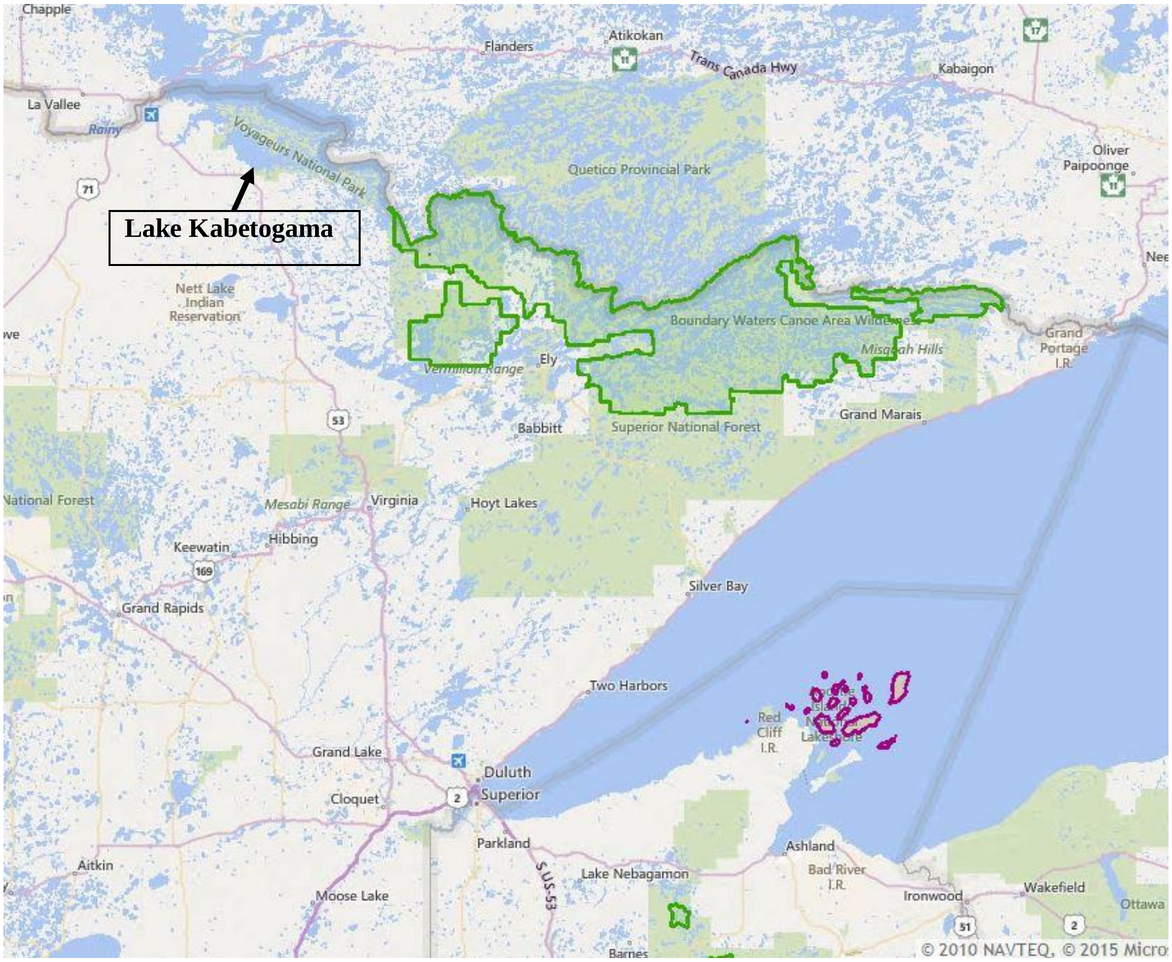


Figure 2 – Map of BWCAW and Lake Kabetogama, the subject of the research study and their relative locations to each other and the US Canadian border (US Forest Service 2009).

Lake Kabetogama is outside the BWCAW but in close proximity (illustrated in Figure 2) and shares many similar physical geological and climactic traits. Lake Kabetogama is a permanent inland lake with well-defined boundaries having a limited number of inflow and outflows (Facts 2013) and digital elevation maps are available (DNR 2013). Well defined watershed boundaries and in/out flows mitigates effects of unknown surface/subsurface flows and simplify calibration.

Lake Kabetogama has measured field data as checked against databases such as the National Climatic Data Center (NCDC) for collected historical data. Average HUC-8 precipitation data is retrieved from the US Forest Service's Water Supply Stress Index (WaSSI) Map Viewer (WaS 13). Locations of data collection for subordinate watersheds (HUC10-14) were retrieved from the NCDC's map of available precipitation data (Pre 13). The historical data present includes gauge height, used to determine fluctuations in surface elevation and discharge (USGS 2013) and precipitation and temperature records from a collection site on the lake shore (Pre 13). A summary of lake properties is located in Table 1 and a map of the water body (Lake Kabetogama) is shown in Figure 3.

Additional information about the watershed and geophysical properties and relationships between lake volume and outflow are discussed in Chapter 3: along with modeling of the watershed.

Table 1 – Lake Kabetogama Physical Properties Summary

Data Type:	**Data:**	**Data Source:**
Watershed Name	Lake Kabetogama	(WaS 13)
Watershed HUC12 #	090300012400	(WaS 13)
Watershed Area km^2	307.92	(DNR 2013)
Water-body Area km^2	90.36	(MN DNR 2012)
Surface Elevation m	339.85	(USGS 1980)
Average Depth m	8.23	(DNR 2013)
Maximum Depth m	24.38	(DNR 2012)
Littoral Zone Area km^2	30.11	(Facts 2013)
Reported Lake Volume m^3	793687590.4	MN DNR Lake Depth Map
Calculated Lake Volume m^3	783319002.6	Calculated
Volume % Difference (Calculated - Recorded)	-1.31	Calculated

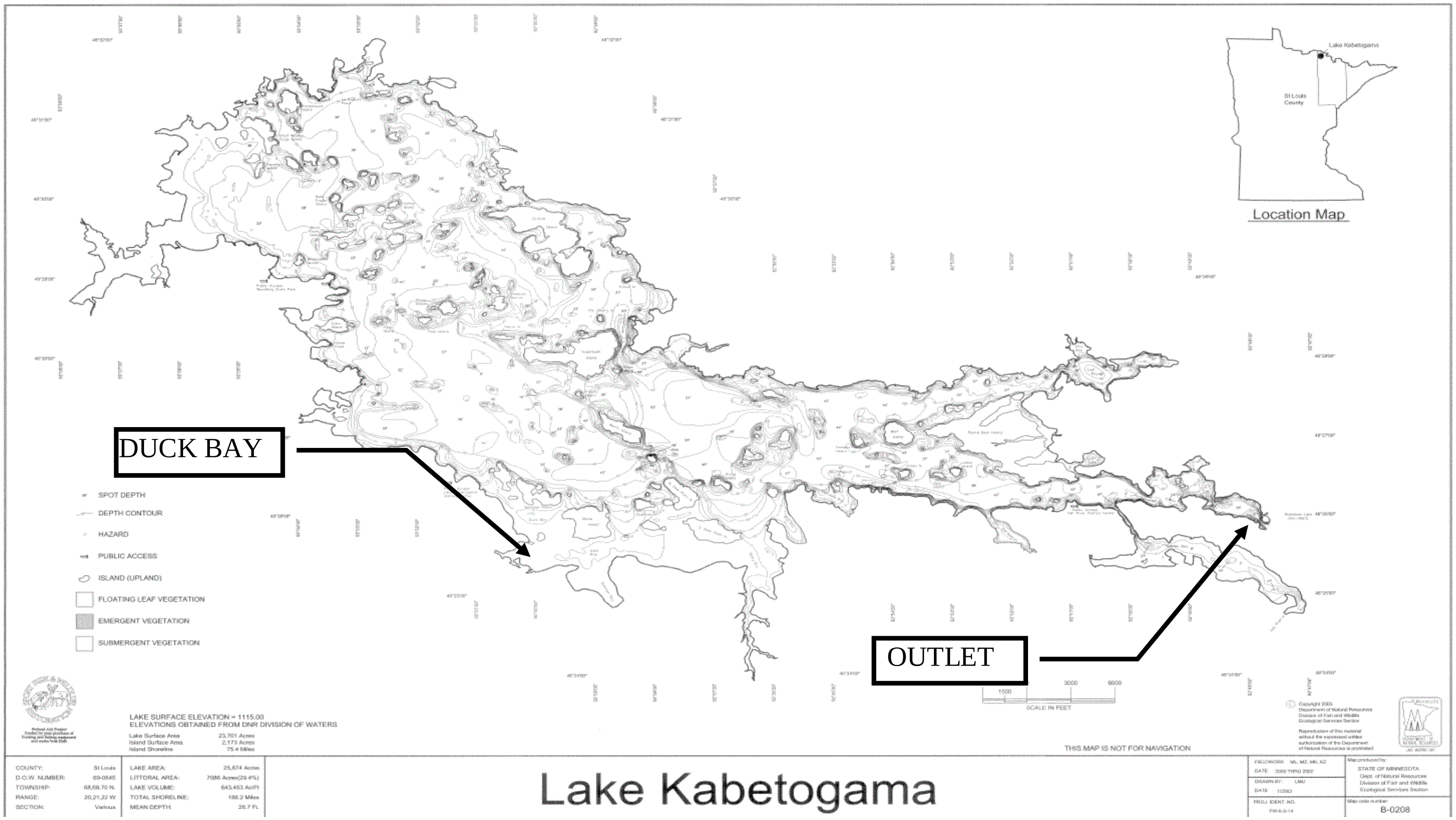


Figure 3 – Map of Lake Kabetogama the lake selected for modeling and includes: location of precipitation gauge in Duck Bay and outlets (Lake 13).

Chapter 2: Literature Review

2.1 Overview

The first portion of this chapter provides an introduction to Ecosystem Services (ES) and defines two of the dominant approaches to handle ES. Beginning with an economics based approach (discussion on relative limitations of an economics definition can be found in the Appendix). Discussion on an environmental based definition follows, before developing a refined definition that combines aspects of the two fields. Descriptions of types of ES are also presented with examples to better illustrate the topic.

The next portion (section 2.6) reviews previous literature applications used to validate ES as an additional tool for decision making concerning natural resources. In addition the literature review discusses the use of Water Level Fluctuation (WLF) as an index to address ES in a qualitative manner. A summary of ES and the definition of ES used for this research are presented in section 2.7.

The remainder of this chapter (sections 2.8 to 2.10) covers predicted climate changes used as a basis for this thesis. Literature is presented that establishes predictions of possible seasonal shifts in precipitation and temperature and how to predict precipitation patterns through Markov Chains.

2.2 Ecosystem Services Introduction

The field of ES was developed to understand the value of natural environmental services and resources on a commensurate metric for which artificial or manmade services (such as water purification) are valued (Jury 2005). ES can qualitatively and quantitatively compare natural process to other processes or sources which perform a similar or identical service (Jury 2005). With regards to ES this thesis is focused on qualitative values to aesthetic and recreational uses and as such the definition of what is an ES has to be discussed.

An introductory definition of ES is: “a method to determine the benefits and impacts of alterations to the natural world through any process (human or naturally induced) by measuring the same type of benefit to humankind in the same way for both a human made process and the natural equivalent” (Comello et al., 2012).

The definition is versatile but vague which leads to problems of scale and interpretation to what qualifies as an ES. The definition does not readily accept aesthetic benefits as there may be no human made equivalent but does provide a starting point. The key aspect in common with this definition and other definitions presented later is that there is some benefit to mankind and only like benefits should be compared when dealing with an ecosystem substitution.

Like comparison, such as the cost of a gallon of water naturally purified compared to water purified through manmade means, ensures that a valuation is not made for two different benefits to mankind. An unlike comparison would be comparing drinking water that meets quality standards due to natural ecological processes (such as wetlands filtration) to the valuation of commercial fish supply raised in aquarium conditions (Comello et al., 2012).

Throughout this thesis several examples are presented which are developed based on previous research to classify ES (Fisher et al., 2009), determine value (Ringler et al., 2006), or assess environmental impact of proposed changes (Comello et al., 2012). The first example discusses hierarchy of classification by applying economic principles while the second example illustrates scope creep when classifying ES. The third example describes development of ES substitutions. Examples four and five cover the unintended consequences of ecosystem alteration and substations for ES that can be made both on purpose and incidentally.

2.3 ES Economics Based Definition

The introductory definition of ES presented in Section 2.2 is somewhat imprecise, thus it is desirable to develop a more precise common definition of what constitutes an ES. Attempts to generate a universal definition of an ES have been made, which require an understanding of the factors influencing definitions and goals that make ES important (Boyd et al., 2007).

The definition of ES must remain flexible to allow for local assessments but must also be limited to valuable and measurable quantities (Fisher et al., 2009). A definition based on an economics viewpoint presented in past literature for ES meeting those guidelines is: “Final ecosystem services are components of nature, directly enjoyed, consumed, or used to yield human well-being.” (Boyd et al., 2007).

Definitions reviewed in this and following sections try to; limit ES to easily defined/established markets, eliminate double counting of values, account for hierarchical classification and divorce the localization phenomenon inherent to the valuation process (Wallace 2007) and overcome inherent limitations to ES studies. Markets, double counting and hierarchy are discussed in the following paragraphs and limitations, such as localization, are discussed in see the appendix.

The economics based definition relates a single direct benefit to mankind with an established market and assesses value. An economics bias definition marginalizes other aspects of ES, which are not easily quantifiable or may not exist in common markets associated with value (Fisher et al., 2009). Examples of marginal aspects include the aesthetic qualities of a natural ecosystem (picturesque landscapes) or the cultural and religious significance of nature to people, which are not directly consumed (Fisher et al., 2009). Tourism for example is marginalized as it is not a direct consumptive use, but the tourism industry is a substantial economic player for many areas with aesthetic draw such as the Grand Canyon.

The economics definition presented eliminates double counting of ES and over inflation or false build up of values (Boyd et al., 2007). Double counting of values occurs when an intermediate process or step, something that serves to assemble the end product consumed, is valued once and then counted for value again in the final product (Boyd et al., 2007). Double counting can greatly inflate the assessed value and avoidance of double counting is of particular interest to the economics approach in order to determine a more accurate value (Boyd et al., 2007).

Intermediate processes introduce a need for a hierarchy of services and provided benefits to avoid double counting of the assessed ES (Fisher et al., 2009). A hierarchy allows for an organized method to determine the series of processes and steps and reduces double counting of an assessed ES. Note that a potential flaw with this approach is that the hierarchy can be a subjective assembly of the series of services and how they are related.

To better understand the economics based definition, double counting, intermediate processes and steps, and hierarchy it is helpful to look at an example. Example 1*: Simplified Hierarchy* illustrates how the value of the subcomponents, including harvesting the natural resources are rolled up into the end product of manufacturing which is the benefit consumed (Boyd et al., 2007).

2.3.1 Example 1: Simplified Hierarchy

A company produces widgets for sale at a market value using mineral resources in the process. If only the widgets are being valued, the values of the mineral resources used to make the widgets are included in the total value of the widget itself. Conversely, when only the value of the mineral resources harvested is being assessed there is a distinct separate market and value. If both widgets and minerals are being assessed the value of the widgets would be reduced to accommodate for the fact that the mineral value has been counted. If the mineral resource is counted at a full separate market value for mineral resources and full value in the widget then double counting occurs and inflates the price.

A simple extrapolation of the relationship between widgets and mineral resources can be made to water quality and fish production by changing Example 1*: Simplified Hierarchy* into terms of water quality and fish productivity. Fish are the final end service which is consumed and given value. Water quality, inherent to increasing fish yields, is counted lower in the hierarchy as part of the series of processes that lead to fish yield and thus accounted for in the direct value of the fish. Because the benefit (final ES) explicitly being valued is fish yield the value of the quality of the water is “hidden” and rolled into the fish value. If the only benefit assessed is water quality, fish yield is irrelevant and the values of other sub-components in the hierarchy of benefits (which contribute to water quality) are rolled into the water quality value.

The definition presented in this section allows for an ES to be a valued for a single end service or market consumable benefit and be accounted for as a portion of the value of a different final end service or consumable at a lower value through the hierarchy (Boyd et al., 2007) despite potential limitations (see Appendix). The economics based definition (Boyd et al., 2007) remains important and practical to this and future work as it includes intermediate process and steps in the final ES value (Comello et al., 2012). However, the economics approach leaves something to be desired when including aesthetic, cultural and recreational uses.

2.4 ES Environmental Based Definition

The economics based definition of an ES (Section 2.3) provides a starting point to work from and addressed some limitations (see Appendix for more information). As there is a wide variation of what to consider for classification (Fisher et al., 2009)and by many economic viewpoints the aesthetic qualities, recreational use and cultural significance are not necessarily ES but are when considered from an environmental basis. Another reason to consider the ES topic from an environmentalist approach is due to the complex extent and duration of manmade substitutions to ES. Additionally, the definition presented prior (Section 2.3) takes into account direct markets but not aesthetic, social or cultural/religious importance, thus it is necessary to understand other approaches to ES such as an environmental based one.

In the economic based approach, ES are currently believed to be replaceable through manmade substitutions (such as water treatment facilities) (Jury 2005), which may not fully account for complexity of natural systems. Long term substitutions will have long term effects driving further changes to the ecosystem. Changes over space and time are just one of several complexities that compound the topic; others include tradeoffs between competing benefits, the global span of the hydrologic cycle, and increasing importance of cultural and aesthetic non direct market uses.

Temporal and spatial dynamic changes (such as flora growth cycle patterns and locations) will occur within any natural system and must be accounted for in order to assess the substitutes (Heagerty et al., 2004). By comparing the long term costs of substitutes, modeling and predicting the dynamic future needs of mankind and comparing that against the modeled productivity of an ecosystem, valuation can be made that more accurately includes all factors of the ES (Heagerty et al., 2004).

In an idealized environment accounting for spatial and temporal changes, (such as climate changes and geophysical properties of water bodies), would be easily accomplished and highly accurate. In reality the natural world is interconnected and relationships between processes and components are not always completely known; the complex relationships often drive second, third or higher order effects and additional changes.

Examples of the complexity of temporal changes and spatial relationships include commercial fishing, which could be considered an ES with value based on the total amount of fish caught in a given time and location at the local fair market value (Boyd et al., 2007). A substitution ES is farm raised fish for commercial consumption. Value of long term impacts of those fish not being present in a natural habitat (limited gene pools and increased effects of diseases) or nutritional value degradation of the farm raised fish should also be accounted for on the long term.

Spatial complexity can be seen in the hydrological cycle, a globally linked natural process with local users typically only concerned with freshwater (Young 2005), there is growing importance placed on how to meet future demands and deal with current issues. One such demand is the ever growing freshwater requirements of Earth's population and economic production which relies on the small fraction of water located in freshwater storage (Young 2005). Increasing demand, such as economic and population growth and the growing weight placed on, aesthetics, cultural and religious significance of water resources leverages additional influences to defining ES. Balance between the two competing benefits of freshwater is desirable.

Complex and paradoxical relationships involving ES exist throughout nature, often times with competing benefits. One example of competing benefits is suppression of carbon (a green house gas) and storage of water supply for most of the U.S. (McNutty et al., 2012). A location of carbon storage is plant life, with larger forests being capable of storing larger amounts of carbon (McNutty et al., 2010). U.S. National Forests are also where most of the freshwater storage is actually located across the U.S. (McNutty et al., 2010).

Increased carbon storage (beneficial) means the increased growth holds more moisture in reserve resulting in decreased available water supply for human use (detrimental) (McNutty et al., 2010). Increased water available for human consumption (beneficial) decreases carbon storage (detrimental) and highlights one pair of competing beneficial ES (McNutty et al., 2010). Both carbon storage and water supply are valued ES and a careful balance must be determined between the two locally and globally dependent ES resources. Carbon storage and water supply illustrate how important determination and understanding of ES is the world.

Balance and trade-offs are also illustrated in developing countries which are faced with a dilemma between competing benefits of water use and preservation. In order to continue economic and population growth developing countries are often forced into difficult decisions that ES study can provide additional information to decision makers of those countries. Either developing countries neglect ES from a sustainable perspective such as regulations, quality and quantity in favor of ES such as timber, consumption and fish production to experience growth (Jury 2005). The same developing countries could otherwise opt to maintain, preserve and plan for sustainable uses of their water resources and experience slower growth rates and potential short term economic hardships by restricting their direct market access and production.

As demands grow a significant generalization can provide a reference baseline for ES, water levels and long term sustainability. As mentioned earlier, a good baseline for natural water resources is that roughly 30% of an average annual flow needs to be maintained for the ecological well being of a surface water body (Jury 2005). The exact amount will vary according to location specific needs and ES study can play a role in finding a limit to how much water can be withdrawn and allocated towards growth while still providing the ES that are valued on the local markets.

Both directly and indirectly (aesthetics, cultural or religious significance) marketable ES are of value to decision makers in developing and developed countries. Comparative analysis provides investors, policy makers, and the public with additional information to continue managing human development and the ecosystem (Bekele et al., 2005). Enhancing the management practices leads to Best Management Practices (BMPs). BMPs increase the ability of consumers of ES to establish and maintain a program of sustainable use to balance global economic needs with the global ecosystem, while helping to preserve cultural, religious and aesthetic ES. Note that human development and the ecosystem need not be mutually exclusive or competitive in nature and can in fact be cooperative in order to create a larger net benefit to both human development and the natural environment (Bekele et al., 2005).

In summary from an environmental stand point understanding the importance of ES must be coupled with local values dependent on the classification of the ES (Fisher et al., 2009). Ecosystems are complex and linked with both spatial and temporal variations. Due to the complexity the approach to defining what benefits are being valued must also allow for variations in space and time based on changes to what is perceived as a benefit (Heagerty et al., 2004). In order to account for those changes in value analysis must take into account not only economical interests but; ecological political and social interests, before conducting valuation of the benefits classified as ES (Fisher et al., 2009). The complex nature described above results in a needed revision of the economics driven definition presented earlier.

2.5 ES Refined Definition

The economics based definition can be further refined to account for environmental based complexities (see Section 2.4 for more) present in a natural system and account for ES beyond traditional consumptive markets to include environmental based viewpoints.

A further revised definition (one used for this thesis) is: “Ecosystem services are the aspects of ecosystems utilized (actively or passively) to produce human well-being”. The key points are that;

1) ES must be ecological phenomena and

2) ES do not have to be directly utilized.” (Fisher et al., 2009).

Refinement of the definitions allows for easier valuation of the non-direct market consumed ES with regards to the objectives of this thesis.

Based on the refined definition, in order to value an ES it must be generated through ecological processes, provide a benefit, and the ecological processes must be directly related to the benefit being valued. If the benefit is not directly utilized by humans, the ES can still be valued (Fisher et. al., 2009). The definition allows for assessment of value for aesthetic and recreation (of concern to this thesis), or even cultural uses as long as these services provide a change to human well being (benefit).

A lake’s recreational benefit as an ES can be assessed for example, on utilization by beach goers, swimmers and watercraft use. That ES would include the value of the water quality added into the total value of ES benefit to swimmers (Boyd et. al., 2007). Poor water quality can cause lakes to be, or seem unusable for swimmers. Watercraft use however, would not be assessable based on water quality; water quality is not directly linked to the ability to use watercraft.

Contrary to being unwilling to consume the service, users can not consume the recreational service if the water depth is too low to physically allow watercraft use (Fisher et. al., 2009). Watercraft use is limited through volume of water (specifically depth), which marginalizes the psychological effects of water quality that would influence recreational use (Young 2005). Users would be less likely to use a water body for recreational watercraft if the water does not look aesthetically pleasing and possess no danger to the immediate health and well being of the user or watercraft, but poor water quality does not explicitly deny the ES benefit (Young 2005).

Value of the watercraft used is an artificially introduced capital asset to the system and is not related to an ecological source; therefore the watercraft itself is not part of the recreational value boating as an ES (Fisher et. al., 2009).

A key point when considering value based on the provided definition is that value should only be assessed on local ES that are used or likely to be used (Young 2005). Recreational value for boating is not an acceptable ES to be valued if the water body is not used for recreation and is not likely to be used for recreation within the time span of the ES value study.

The volume of water in a water body that is situated in an inaccessible portion of a mountain range, or a sub glacial lake is still of interest to ES and value, but it is extremely impractical and expensive (air lifting a watercraft into the mountain range) to utilize the water body for recreational purposes. That volume of water may have other uses besides recreational activities, such as supplying surface water for drinking and irrigation and valuation could be made based on that ES, not recreational watercraft use.

Attempts have been made to create a unified ES definition and classification scheme (Boyd et. al., 2007) in order to produce meaningful results for public and private entities for both long and short term goals by many experts as discussed prior. However as ES are so complex a universal classification scheme is not possible and the classification must remain flexible on a local level (Boyd et al., 2007). The refined definition allows inclusion of cultural, recreational, and religious significance of natural landscapes, ES that are not readily marketable in a traditional sense. Allowing value for these ES is important as humans continue to alter the natural landscapes.

ES is an important aide at a local level in decision making processes, environmental impact assessment, educating the public, private investors, policy makers, understanding, planning for long term sustainable growth, and more efficient use of a linked and limited resource. Flexibility at a local level is needed due to the variable nature of markets, the ecological system itself and temporal and spatial changes that can be forecasted to some degree of accuracy on the local scale. The definition presented allows for local applications, a flexible approach to valuation, adaptability and either direct or indirect use is most applicable to this research and likely the future of ES studies and applications.

2.6 Applications of Ecosystem Services

ES can be used in a number of ways to determine a value for a variety of different cases as indicated by previous uses. The exact method (software, definition, classifications, etc) used and type of study can vary as much as the goal. A few ES studies are discussed and represent the establishment of ES as a valid method of valuation and indicate some established methods and lesson learned.

Existing research explores the economic importance of ES, one example compared cost alternatives for a traditional and porous paver parking lot options (Comello et. al., 2012). Research also compared the cost of mediating sediment filtration from the traditional lot to the passive ES value of sediment filtration of the porous lot. The effective cost of the traditionally paved lot was more expensive than the porous lot after inclusion of the ES values (Comello et. al., 2012). ES study allows decision makers to more effectively balance investment and development costs.

The emergence of ES allows developers to add additional capital through the addition of the value of ES which naturally occur on their property. This knowledge could provide a necessary jump start to incentivizing preservation of ES for financial statements and future holdings (Comello et. al., 2012). More frequent application of ES in current value studies also lends an increased ability for forensic applications through evaluation of ES assets that have been degraded or destroyed (Comello et. al., 2012). More ES studies conducted provide more reference and knowledge base to develop more accurate compensation methods for ES landowners due to destruction of that ES (through pollution, development, etc.) in forensic applications (Comello et. al., 2012).

In addition ES can be used to value natural capital within an area for land owners or managers (Ray 2005). The approach used in the example literature uses U.S. Forest Service software packages and classified High Resolution Multi-Spectral Imagery

(HRMSI) (Ray 2005). Through use of HRMSI, the case study proved multiple assessments of ES with various market prices are possible (Ray 2005). The additional markets included non-traditionally direct consumption markets such as preventative costs associated with health care, tourism or storm water control and provides results for policy and decision makers (Ray 2005). However the case study used classified HRMSI data which may prevent wide spread application of the use of that software or similar software models for ES valuation (Ray 2005). The application presented however was not without drawbacks but establishes ES valuation for traditional and nontraditional markets.

Another literature case study on ES addressed water stress and carbon sequestration as the ES (McNutty et. al., 2010). The study explains that the Eastern Coast of the United States of America has a high potential for increased vegetative growth and forest cover resulting in more carbon sequestration. The East Coast is already densely populated with a high water stress and increasing the forest cover would actually reduce the available water in storage (McNutty et. al., 2010). The study demonstrated possible future applications for management by providing a modeling method that could be used to help determine development and restoration needs. The model, as does this research, utilizes changes in precipitation patterns that may occur. Changes include geographical area and seasonal shifts from peak precipitation in summer months to winter months (McNutty et. al., 2010), similar to this thesis, in order to determine ES values.

A generalized and inversely linked relationship within a watershed between economic consumption and ES output remains nearly linear (Bekele et. al., 2004). The rate at which ES value decreases is somewhat greater than the increase in economic output (Bekele et. al., 2004). Indicating that an optimal (but not necessarily perfect balance between the two) solution for generating the greatest net value (a combination of ES and crop yield), exists weighted slightly beyond the 50/50 balance point towards the natural ES (Bekele & Nicklow, 2004). The linearity of the relationship represented may be due to that particular set of systems, circumstances and localized factors used in that study.

2.6.1 ES on Transboundary Waters

Any water body that forms a boundary or crosses between two political entities who can claim jurisdiction, such as the BWCAW, is a transboundary water body. The practice of using surface water bodies (like rivers) as boundary markers is prevalent due to historical uses; stationary water bodies are easily identifiable natural barriers and landscape features which present a convenient way to mark borders.

Careful utilization of ES has been used to identify how proposed changes to a transboundary water feature will affect the ecology, ES and the economics of the affected areas (Ringer et al., 2006). Transboundary issues are of continually increasing importance and of particular concern as the research presented in this thesis deals with the BWCAW a transboundary system of rivers and lakes jointly managed by the United States and Canadian governments.

Many transboundary watersheds and surrounding wetlands, such as the Mekong River Basin, are important for transportation and fishing ES (Ringer et al., 2006). Wetlands are often seen as the most productive ecosystem which mankind draws ES from as they frequently have a higher ES value output per unit area than other forms of land

(Ringer et. al., 2006). However, the countries involved in the Mekong River Basin all have loose definitions of what constitutes a wetland prior research indicates that wetlands of concern should be labeled "edible" wetlands or wetlands used for food production to address the local definitions and needs of invested parties (Ringer et. al., 2006). Only those ES identified as edible are those which classified to assess a value for the Mekong River Basin (Ringer et. al., 2006). These include fishing for commercial needs and the regions primary source of protein as well as a mode of travel throughout the region (Ringer et. al., 2006).

In addition to providing insight into transboundary policy on ES definitions and designations; the Mekong River Basin study provides an example of a method that successfully accounted for directly consumptive benefits (fish markets) and non-direct consumptive benefits (travel) (Ringer et. al., 2006). The study found that there would be a nearly 20,000 km^2 decrease in edible wetlands throughout the entire transboundary basin and conservatively estimated the ES value in terms of output per area at US$20/10,000 m^2 (Ringer et. al., 2006). The study demonstrates that changes to the ES can amount to significant costs (20,000 km^2 x $20/10,000 m^2 = US $40 million annually) from disruption and need for replacement or substitutions.

The Mekong River Basin report establishes a working method for assessing a large scale coupling of ES that do not necessarily fall into the direct use category (Ringer et. al., 2006). Furthermore, it establishes precedence that transboundary ES studies can be used for future planning, management and policy maker decisions for the region.

Additionally, the Mekong River Basin report highlights the effect alteration to water level fluctuation can have on a species rich wetland area in terms of human capital. ES studies for future use in transboundary management is of particular interest as the BWCAW is an extensive, popular transboundary system to be managed for future generations to enjoy.

2.6.2 Water Level Fluctuation and ES Background

Water levels of all water bodies fluctuate both intra-annually (within the year) and inter-annually (from year to year) and this has an impact on many components of the waterbody such as water quality and aquatic life (White et. al., 2008). Intra and inter-annual fluctuations are a necessary part of the life cycle of the system. Many species rely on fluctuation to send signals to the aquatic life forms that dictate behavior, such as salmon breeding times (White et. al., 2008). Water level fluctuations (WLF) tend to by cyclical in nature on a roughly 10 year oscillating pattern for a region sharing a similar climate (White et. al., 2008).

Research on effects of WLF on ecosystems is still developing because the extent to which WLF impact ecosystems are still not fully understood (White et. al., 2008). Previous research suggested that ice and winter freeze over played a more important role in controlling effects on ecology (by scouring shallow near shore vegetation) over WLF (White et al., 2008). However, it was found that WLF had more impact during specific times of the year (White et. al., 2008).

When water input to water shed is dominated by winter season precipitation, such as in boreal lakes like those of interest for this research, then WLF control extent and activity of the littoral zone, not factors such as ice depth (Abrahms 2008). The littoral zone is the area with less than 4.6 m depth of water that is part of the water body and is the most ecologically productivity area of a water body (DNR 2014). Ecosystems subjected to dominating winter precipitation are also likely to see a net gain in water level and expansion of wetlands unless dry hot summers cause substantial drawdown (Abrahms 2008).

According to research, a reduction in water level of roughly 1 m is approximately the maximum drop that will have impact on shallow water fish species, further reduction in water levels causes the fish to migrate away from the affected areas (Sutela et. al., 2008). Research also indicates that WLF affects on plant and animal life are more dependent on the timing and amount of precipitation such as in the focus of this thesis (Abrahms 2008).

Existing literature indicates that WLF is important and necessary as there exists a range of WLF that will yield a rich set of aquatic macro-invertebrates which leads to enhanced biodiversity and species productivity (White et. al., 2008). Both biodiversity and productivity of the littoral zone are important influences on ES, including recreational and aesthetic ES of concern to this thesis.

To determine the extent of impact that the predicted precipitation shift used in this research could have on the ecosystem in quantitative or qualitative measures, an index of comparison is necessary. One index is Amplitude of WLF, defined as the difference in the yearly maximum and minimum water surface elevation levels for the duration of time that the surface of the water body is not frozen over (in this case, 01MAY to 30NOV) (White et. al., 2008). Difference from the Long Term Mean (DLTM), is defined as each individual years mean water level for the entire year minus the overall mean water level across all years (White et. al., 2008).

WLF amplitude and DLTM play an important role in understanding the changes to ES that may occur in quantitative and qualitative terms. Literature establishes that Amplitude and DLTM can be used as measures of water level fluctuation for The Laurentian Great Lakes region, an area with similar characteristics of the BWCAW and Lake Kabetogama (White et. al., 2008).

2.7 ES: Summary and Definition Used

There are many ways for ES to be classified and valued (see sections 2.2 to 2.4). Some research has been done to create a more unified approach to classification and valuation and is based on past research literature reviews.

For this thesis the definition used is the refined definition, as described and justified in section 2.5, which is:

"Ecosystem services are the aspects of ecosystems utilized (actively or passively) to produce human well-being". The key points are that;

1) ES must be ecological phenomena and

2) ES do not have to be directly utilized." (Fisher et. al., 2009).

In summary, existing research indicates there are enough examples of aesthetic and recreational valuation conducted for ecosystem services with several different accepted methods for valuation both quantifiable and qualitative (de Groot et. al., 2002) to allow for a more uniform valuation approach. Aesthetic and recreational services are valued in terms of direct market pricing and travel cost (de Groot et. al., 2002). Both methods have been successfully used frequently to determine ecosystem values and are relatable in qualitative and quantitative terms.

Aesthetic and recreational use data varies by individual users visiting the area and for locals of the surrounding region of Lake Kabetogama. The primary recreation and aesthetic use is resort fishing and vacationing for Lake Kabetogama. Lake Kabetogama will have fewer individuals utilizing non fishing ES compared to the BWCAW, where canoeing, camping and aesthetics are more representative of the ES utilized. However, Lake Kabetogama can be considered representative of water bodies within the BWCAW and surrounding area as they are within the Winnipeg Lakes eco-region (Burridge et. al., 2013) and likely to behave in a similar manner.

Existing literature presented from the body of work on ES serve to illustrate that; the field is established and growing, results can be made that are conclusive in both quantitative and qualitative fields and basic comparison of economic values for the ES can be conducted several ways including through modeling of WLF and resultant impact on ES.

2.8 Climate Change Predictions

Natural systems continue to change, evolve and fluctuate, with variation in all spatially and in the time domain which will impact ES. The fluctuation of the natural ecosystems will be subjected to changes in precipitation spatially, temporally, event intensity and temperature patterns as global climates continue to change (Meehl et. al., 2000). The continued changes to global climate patterns will have some impact on the ecological processes and the value of associated ES.

Literature predicts that the climate will continue to experience an overall global temperature increase, but the extent varies depending on the study. Temperatures are predicted to climb steadily anywhere from +4 ^{o}C to +12 ^{o}C (Meehl et. al., 2000). Based on the increase in temperature it is likely that there will be a steady decrease in seasonal snow cover, decreasing the return period for 20 year extreme precipitation events with reductions as much as 10 years within North America for the near future (Meehl et. al., 2000). The expected temperature shifts described above and reduction in snow cover extent it is likely to lead to a drying of midcontinent regions during summer seasons, increasing severity and frequency of drought conditions and an increase in summer season temperatures due to predicted changes (Meehl et. al., 2000).

Temperature is not the only aspect of climate that will change; there is an expected change to the patterns of precipitation, to increased winter precipitation over much of North America which will increase early winter and later spring river flows and overland runoff (Mohammed 2005). Most of the climate change prediction models that have been conducted report that over North America there will be increases in total precipitation (Mohammed 2005), in addition to the climatic temperature shifts.

In the zone between 30 ^{o}N to 85 ^{o}N of North America from the years 1961 to 1990 and 1995 to 2010, the yearly mean value of precipitation from the previous year has been exceeded by the following year (Mohammed 2005). Including droughts such as those experienced in 1930 and 1950 the total precipitation amount has increased roughly 5-10% and total snowfall amounts in Canada have also increased an average of 10% (Mohammed 2005). Recent observations from 1990 to 2010 corroborate the climate trend changes in the Midwest. Cumulative snow fall has increased, winter severity increased and summer dry seasons seem to have lengthened. Based on the research discussed, a combination of seasonal shift from wet summers and dry winters towards drier summers and wetter winters is expected along with an overall increase in total precipitation for North America (Mohammed 2005). Precipitation pattern changes (to wet winter, dry summer) predicted are the basis for this research thesis to investigate potential alterations to WLF and related ES.

2.9 Precipitation Predictions

Precipitation predictions require a two stage calculation; one to calculate likelihood of a precipitation event occurring and one to calculate precipitation intensity. The simplified precipitation occurrence prediction model used in this thesis and common in other literature is based on a two state first order Markov chain (Wilks 1992). The two states are daily occurrences of whether it does or does not rain, referred to as wet and dry days. Wet and dry can be thought of as binary states for daily precipitation (represented as P_{ij}, with i being the present day, j being the following day, and values of 1 being wet and 0 being dry.

The four parameters (P_{ij}) are grouped on a monthly basis (Wilks 1992) and used in the first order Markov chain to determine the resultant vector of probabilities. Through empirical observation the first order Markov chain will stabilize approximately 4 to 7 days into the future. Stabilization is due to the ‘n’ power value (see Equation 1), which is the number of days into the future from a known state. As ‘n’ becomes larger, the outcome probability change is reduced to further decimal places as the solution converges on a stable state. Historical frequencies of a dry day followed by a dry day (P_{00}), or a wet day (P_{01}), and the probability of a wet day followed by a dry day (P_{10}) or a wet day (P_{11}) are developed from daily precipitation data. The historical frequencies are and used in Equation 1 to develop probability of wet or dry day for future predictions. Historical data exists for approximately 10 years allowing for natural patterns to develop (White et. al., 2008).

Randomly generated numbers (between 0 and 1) are calculated for each day of the study period (see Equation 6 in section 5.2.1) and compared to the historical probabilities for days in that month (P_t from Equation 1). If the randomly generated number exceeds the dry day value the result is a wet day, any other value means precipitation does not occur.

Equation 1:

$P_{ta} = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}^n$, where, n = the number of days into the future from time t for predicted probabilities. P_{ta} reduces to:

$P_{tb} = [P_0 \quad P_1]$, which is the probability of a dry day or a wet day (P_0 and P_1 respectively).

2.10 Temperature Shift

In addition to seasonal precipitation pattern shifts, precipitation occurrence and intensity predictions for the study, values of temperature need to be determined to account for things such as spring thaw for regions subject to a freeze thaw cycle such as the BWCAW for this research.

A temperature shift is applied to the minimum temperature values recorded in the historical data and applied as a scalar multiplier over the 100 year prediction range. Applying shifts in temperature only to the minimum daily temperature value is conservative and should represent the daily freeze thaw cycle during spring and summer. A value of 5 ^{o}C is used as the desired end target temperature as values of increase range from the 4 to 12 ^{o}C (Meehl et. al., 2000). Literature uses a forced increase in CO_2 concentrations above current conditions which although predictive of future growth, creates a range weighted towards higher temperature increases. Higher temperature increases may not be representation of future climate changes caused from CO_2 production which may or may not occur.

The temperature shift is applied linearly over the course of the 100 year span to a set of randomly generated temperature values for each day (Fung 2006). The generated temperature is based on the typical range of temperature values for the given month as if they are normally distributed, similar to the precipitation predictions method.

Chapter 3: HEC-HMS Model Setup

3.1 HEC-HMS Introduction & Setup

An introduction to the watershed and Lake Kabetogama was provided in section 1.4; this chapter focuses HEC-HMS, properties of the lake and parameters of watershed used as initial settings for the HEC-HMS Model (sections 3.1.1 to 3.1.4). The second half of the chapter covers precipitation and temperature inputs used in the model (section 3.2).

HEC-HMS is widely used software and is available as a free download through the United States Army Corps of Engineers (USACE), Hydrologic Engineering Center (USACE 2009) HEC-HMS software is a lumped parameter model capable of simulating processes of watershed systems, hydrological events and responses, based off of watershed system parameters including; vegetation, soil properties, climate data, evapotranspiration and snowmelt. The HEC-HMS model, once calibrated, is utilized to predict future behavior of the watershed and WLF.

The HEC-HMS model in this thesis is set up to include the watershed basin, the reservoir (Lake Kabetogama) and a drainage sink. Basin Properties selected are typically default values based off of the HEC-HMS User's Guide information (USACE 2009). Other parameters are summarized in Table 3- Table 5.

3.1.1 Lake Geometric and Physical Data

Watershed area was determined using Arc GIS and watershed Digital Elevation Model (DEM) data (DNR 2013). The water body area used was that reported by the MN DNR and the DEM for the lake was used to calculate volume (DNR 2013). Calculated volume was compared with the recorded volume (Lake 13) and the percent difference was determined as in Table 1. Working upstream from outlet (see Figure 3) the lakebed undulates and an effective drainage barrier is naturally constructed at depth of roughly 6.1 m, correlating to a water surface elevation of 334.67 m representing the dead storage of the lake.

A plot of the incremental volume of the elevation bands (a water storage-elevation relationship) determined from the DEM is shown below in Figure 4. From the illustration it can be seen that the majority of the lakes volume is in the mid to upper elevations The relationship provides a good indicator of effects on inland lake water levels, illustrating each step down in surface elevation's varying change to incremental volume stored at that level. The upper changes in surface elevation have larger changes to volume of water stored quickly degrading to very small incremental changes as the dead storage level is approached.

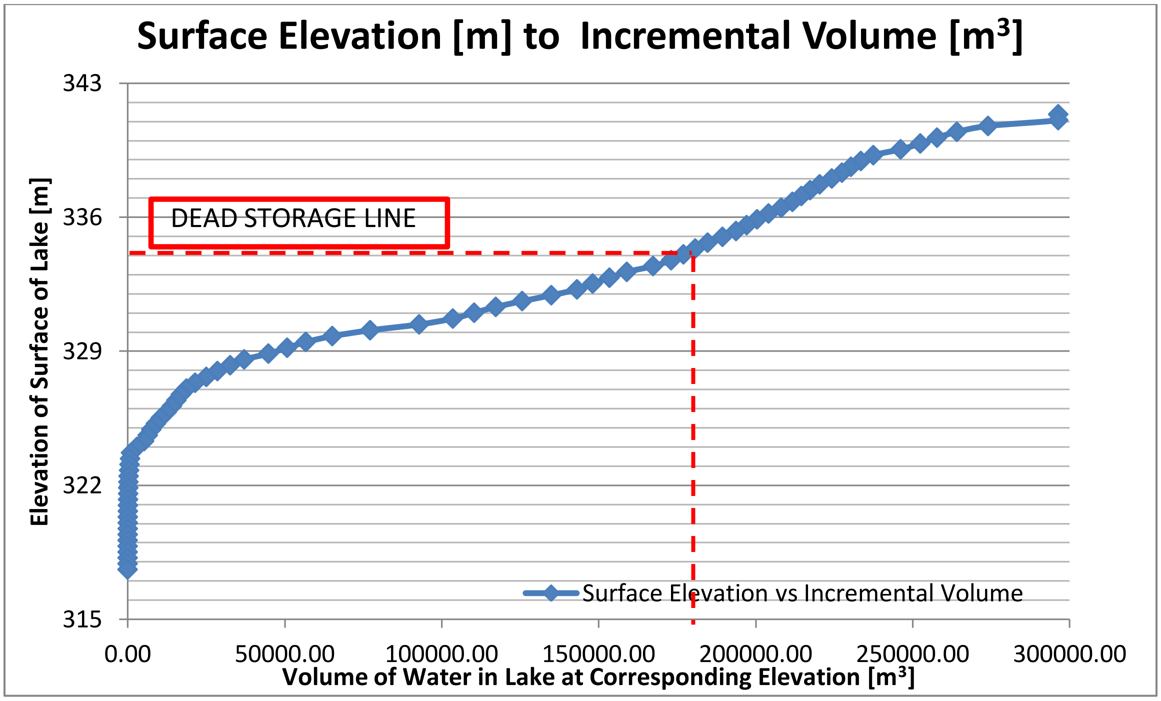


Figure 4 – Surface Elevation to Incremental Volume illustrates the volume of water stored at each surface elevation value, with the typical surface elevation for the lake being at 341.07 m for the purposes of this study.

3.1.2 Storage-Discharge Relationship

A storage-discharge relationship was developed based on observed historical data gathered from online databases (USGS 2013). The gauge height and flow data available is from 01SEP2010 to 08NOV2013 in 15 minute intervals. Both discharge m^3/s and gauge height m and are used to develop associated elevations. The maximum gauge height recorded was 5.61 m and the corresponding discharge is 22.17 m^3/s, which translates into a corresponding surface elevation of 341.38 m based on surface elevation and volume storage relationships. Table 2 summarizes the key recorded discharge data and gauge heights, as well as the corresponding surface elevation.

Table 2 – Summary of Historical Discharge and Gauge Heights on a 15 minute interval taken from 01SEP2010 to 08NOV2013 (USGS 2013)

	Maximum	Minimum	Mode	Median
Recorded Gauge Height m	5.61	3.94	5.28	5.00
Corresponding Discharge m^3/s	22.17	0.13	13.65	8.58
Corresponding Surface Elevation m	341.38	339.85	341.07	340.77

Analysis of lake topography illustrated that the undulating lake bed surface, numerous islands and overall lake geometry required use of the elevation-storage-discharge relationship option for the storage method used in HEC-HMS (USACE 2009). Complete data sets (for storage, elevation, discharge, temperature and precipitation) are not included within this report due to the volume of information (over 3600 data entries for the smallest data set).

Observation of discharge to gauge height relationships indicates discharge values ramp up rapidly from minimum to maximum recorded gauge heights (such as experienced during flood stages). An exponential growth trend was used to determine discharge values for gauge heights and corresponding surface elevations above the maximum data present.

Values below the recorded minimum gauge height were determined to decay off from the 0.13 4.50 m^3/s present at 339.85 m elevation to 0.0 m^3/s at dead storage or 334.67 m surface elevation. It was found using the elevation-storage relationship a surface elevation of 341.07 m has a storage of 7 336 478.6 m^3 and a discharge of 13.65 m^3/s. The elevation-storage and storage-discharge relationships correlate a specific storage value to specific discharge rate and the conversion was completed for the remaining elevation (gauge height)-discharge values, including the interpolated values to yield the storage discharge relationship in Figure 5.

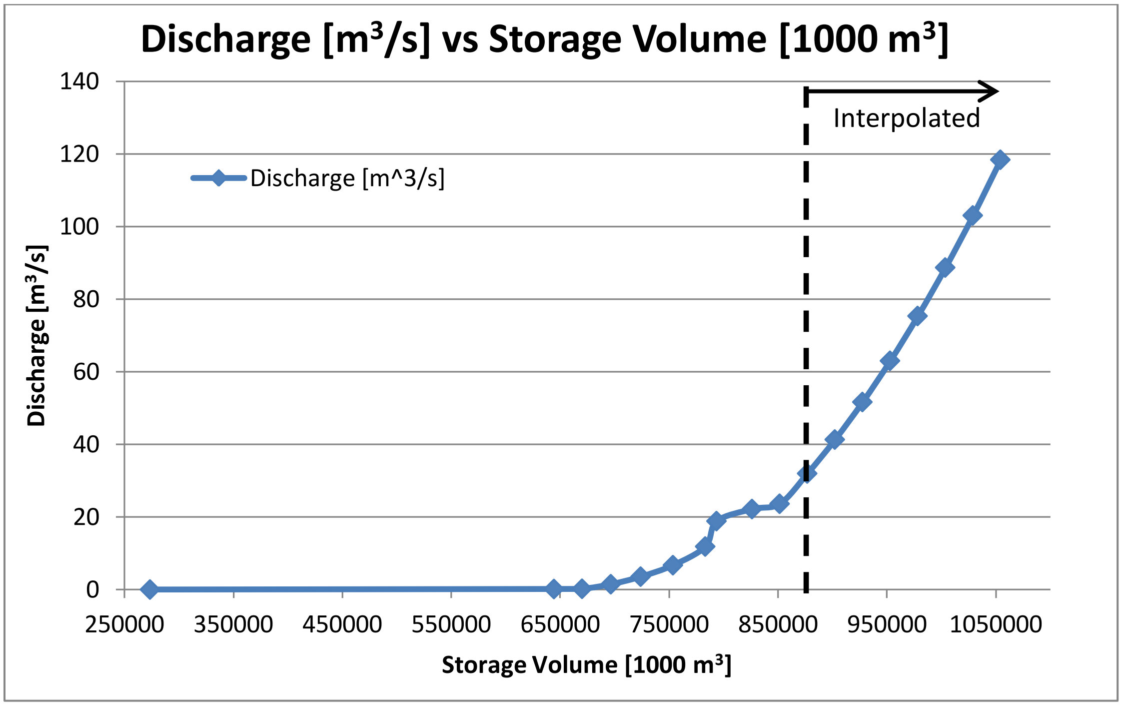


Figure 5 – Discharge - Storage Relationship used in the HEC-HMS simulation based on watershed historical data with discharge above recorded data interpolated based on curve fitting.

3.1.3 Surface Elevation Calibration

A discrepancy was found between the data sources used regarding surface elevation of the lake. The recorded typical lake surface elevation is 339.9 m (GNIS data) with a volume of 793,687,590.4 m^3 (USGS 1980). The typical lake surface elevation based on the DEM data set is 341.1 m with a calculated volume of 783,319,002.6 m^3 (DNR 2013). Due to the discrepancy between elevations, it was necessary to calibrate the location of typical surface elevation prior to HEC-HMS modeling. Contributing area of the elevation bands created from the DEM and Gauge heights are used to develop the correction.

Based on uppermost lake surface elevation bands from the DEM and gauge height water levels, the lake surface area for a surface elevation of 341.07 m is 7.34 km^2. The elevation bands above contribute minimal surface areas (72.8 m^2 at greatest), therefore the 341.07 m surface elevation should represent a common gauge height and storage volume. Gauge height data (discussed later) indicates the lake level fluctuates 1.5 m throughout the time period recorded. The maximum gauge height is approximately 5.49 m, with the minimum being 3.96 m and the average at 5.28 m. The 5.49 m maximum gauge height likely occurs at the maximum DEM elevation of 341.38 m DEM, thus the 5.28 m gauge height would correlate to the DEM's typical elevation of 341.07 m.

Elevation is further established by differences in reported maximum depth from multiple sources. Maximum depth is reported as 24.38 m (DNR 2012) and 23.47 m from the DEM (DNR 2013) which is likely more accurate. The difference would shift the typical surface elevation up 0.91 m from the associated surface elevation of 339.9 m (USGS 1980) to 340.77 m, as both the DEM and GNIS rely on National Elevation Datasets. Therefore a typical elevation would be between the DEM at 340.77 m and typical gauge height data of 341.07 m. The gauge height provides more precise measurements due to the frequency of sampling intervals (every 15 minutes) finalized the calibration to set the surface elevation to 341.07 m a total difference of 0.3 m.

The source of the elevation discrepancy could likely be accounted for based on the multitude of differing elevation data sets such as NAD83, WGS 84 and UTM that are commonly used. The second most likely source of discrepancy is time of year that the surface elevation measurements were recorded at and the fluctuating WLF cycle.

Table 3 –HEC-HMS Watershed Basin Parameters

Watershed Property:	Setting:	Notes: (Explanation of selection & sources)
Canopy Method	Simple Canopy	Non-gridded simulation, water stored in vegetative growth of watershed, (USACE 2009)
Canopy Initial Storage %	0	Start time of simulation is mid-winter, little to no vegetative growth water storage
Canopy Max Storage mm	27	Douglas Fir typical, (Wang et. al., 2002)
Surface Method	Simple Surface	Non-gridded simulation, no gridded soil data sets readily available
Soil Water Storage %	0	Start time of simulation is mid-winter, little to no ground water storage available in upper soil layers
Maximum Storage mm	3.8	(USDA 2013)
Loss Method	Soil Moisture Accounting (SMA)	Non-gridded simulation, (Gyawali et. al., 2013)
Soil %	50	(USACE 2009: USDA 2013: Gyawali et. al., 2013)
Groundwater 1 %	38	(USACE 2009: USDA 2013: Gyawali et. al., 2013)
Groundwater 2 %	62	(USACE 2009: USDA 2013: Gyawali et. al., 2013)
Max Infiltration mm/hr	10	(USACE 2009: USDA 2013: Gyawali et. al., 2013)
Impervious %	0.5	(USACE 2009: USDA 2013: Gyawali et. al., 2013)
Soil Storage mm	83	(USACE 2009: USDA 2013: Gyawali et. al., 2013)
Tension Storage mm	41.5	(USACE 2009: USDA 2013: Gyawali et. al., 2013)
Soil Percolation mm/hr	130	(USACE 2009: USDA 2013: Gyawali et. al., 2013)
GW 1 Storage mm	160	(USACE 2009: USDA 2013: Gyawali et. al., 2013)
GW 1 Percolation mm/hr	0.1	(USACE 2009: USDA 2013: Gyawali et. al., 2013)
GW1 Coefficient hr	800	(USACE 2009: USDA 2013: Gyawali et. al., 2013)

Table 4 –HEC-HMS Watershed Basin Parameters, continued

Transform Method	**Clark Unit Hydrograph**	(Chu et al., 2009)
Time of Concentration hr	23.6	(Mays 2011)
Storage Coefficient hr	161.7	(Mays 2011)
Baseflow Method	**Recession**	ability to reset after storm events for continuous simulation
Initial Type	Discharge	(USACE 2009)
Initial Discharge m^3/s	0.753	Historical discharge value for date & time of start of simulation
Recession Constant	0.9	(USACE 2009)
Threshold Type	**Ratio to Peak**	(USACE 2009)
Ratio	0.2	(USACE 2009)

Table 5 – HEC HMS Reservoir Parameter Settings data table provides a summary of reservoir parameters and settings with reasoning and source, storage, discharge and elevation are discussed in section 3.1.2.

Reservoir Parameter	Setting:	Notes: (Explanation of selection & sources)
Method	**Outflow Curve**	Applicable to natural systems with measured discharge (USACE 2009)
Storage Method	Elevation-Storage-Discharge	(USACE 2009)
Storage-Discharge Function	Storage-Discharge	(USACE 2009)
Elevation-Storage Function	Elevation-Storage	(USACE 2009)
Primary	Storage-Discharge	(USACE 2009)
Initial Condition	Elevation	(USACE 2009)
Initial Elevation m	340.9	(USACE 2009)

3.1.4 HEC-HMS Watershed Properties

Land cover type information (type, impervious area, etc) was determined from MN DNR Data Deli and the Multi-Resolution Land Characteristics Consortium (MRLC) (U.S. Dept. Interior 2013). DEM and MRLC analysis both indicate the vast majority of the area is a mix of evergreen and deciduous forests (oak and aspen), followed by open water, then a combination of grasslands and wetlands, with a small amount of developed area.

Impervious area was determined to be almost negligible, approximately 1.74 km^2 of the 307.97 km^2 present yielding a 0.6% impervious area (U.S. Dept. Interior 2013). Impervious surface area was further collaborated with existing research on land use and cover in the BWCAW of 0.5% (Geospatial Analysis Laboratory 2007). 0.5% is the value used as it is a measurement and not a calculation and Lake Kabetogama is similar in use and extent of development.

The majority of the vegetation in northern boreal forest is predominately; fir, spruce, aspen pine, maple, and birch (MN State Forests 2013). Water volume uptake for Douglas Fir is 26.9 mm (Wang et al., 2002) and is used for the HEC-HMS as canopy max storage. Douglas Fir species is used because the species displays a representative value of storage, not prone to drought or high water usage demands (Con 14). Douglas Fir has medium water consumption demands when compared to: Black and Norway Spruce, Paper Birch and Jack Pine, and other common forest species within the area (Con 14).

HEC-HMS loss method is set to SMA, applicable as existing research corroborated its use in continuous longer term simulations (Chu et al., 2009). Cross reference of other existing research supports the use of the Soil Moisture Accounting (SMA) (see Table 3) for the HEC-HMS soil moisture loss method (Gyawali et al., 2013). The SMA method accounts for long term interactions between the canopy, ground surface, infiltration into the upper and tension storage zones and up to two layers within the soil profile (Gyawali et al., 2013).

Soil water properties from existing databases (USDA 2013) are cross referenced with information from the HEC-HMS help file (USACE 2009) and existing research (Gyawali et al., 2013). Additional HEC-HMS model inputs are pulled from the same sources.

Literature suggested several ranges for the various SMA parameters within the geographical region (Gyawali et al., 2013). Suggested values are as initial values in SMA due to similar soil properties for the region in those studies and the Lake Kabetogama region.

Where data from existing soil databases (USDA 2013) was not present, a determination was made through cross reference of the suggested ranges published (Gyawali et al., 2013). For example; if ranges for reported for soil percolation are 56.9-136.9 mm/hr (USDA 2013), and other properties (like infiltration rate) of the geological area aligned with high end of their range from past research (Gyawali et al., 2013), an appropriate value near the high end of the soil percolation range is used for initial input. These values would later be calibrated by running the model against the known historical outflow records.

The weighted average slope determined for the watershed is 0.8% based on Equation 2 (Mays 2011). The velocity was determined to be 7.62 cm/s based on graphical interpretation of the forest with heavy ground litter curve interception with a slope of 0.8% (Mays 2011). The total travel length was determined as roughly 6437.4 m from (USDA 2013).

Equation 2*:

$$t_c = \frac{L * 100}{3600 * V}, where:$$

$$t_c = time\ of\ concentration\ =\ 23.57\ hr$$

$$L = travel\ length\ = 6437.4\ m$$

$$V = velocity =\ 7.62\ cm/s$$

*Note: Equation 2 is Equation 8.8.4 (Mays 2011).

The SCS Curve number method for transformation method had the most readily available data but was proven to be suspect in long term runs (Chu et al., 2009). Clark Unit Hydrograph is used for the HEC-HMS model as a specific hydrograph was not available and the model was not being run in a gridded method. The use of the Clark Unit Hydrograph is also corroborated with past research on continuous studies spanning several months (Chu et al., 2009). The base flow method selected was recession based and threshold type set to “Ratio to Peak”, due to the ability to reset after storm events (USACE 2009) for a continuous simulation.

All other parameters are selected based off of need for continuous simulation, with data sets that are not spatially gridded. Initial storage values when not available in published data are set to zero, as the simulation run time begins in mid winter when water storage within vegetation and soil will be negligible (USACE 2009). As HEC-HMS is a lumped parameter model the duration of continuous simulation is based on prior research and limited to sets of 11 year time spans (Meenu et al., 2013). The first year overlaps from prior set and is used as warm up time to compensate for initial value settings and to reach operating values typical for continuous simulations (USACE 2009) and only the ten non-overlapping years are used for results (Meenu et al., 2013).

3.2 Precipitation & Temperature Data

The precipitation and temperature data was gathered from a site approximately 2.41 km south-west of Duck Bay on Lake Kabetogama (NCDC), located at the intersection of US Highway 53 and Gamma Rd, or 48.4088^o Latitude and -93.0484^o Longitude) (Cli 13). This was the closest proximity sampling site with precipitation data and was on a greater frequency (daily intervals) than the overall watershed monthly average available from HUC-8 data sources (WaS 13). The time period of data available spanned from 25MAR2003 to 13MAY2013; use of roughly 10 years of historical data for model output will reach nearly full oscillation pattern development and should capture natural cyclical trends (White et al., 2008).

As with the discharge and gauge height data, precipitation and temperature data was examined for missing time steps and erroneous readings. After review it was found that there were a small number of days with missing data similar to gauge height and flow data.

Zero value data points are inserted in precipitation data in order to align the time windows used by HEC-HMS with the data. Zero was chosen for the data value as it is a conservative approach to resolve the time step and data point issues (Fung 2006). Even a close proximity precipitation gauge may see some precipitation and the location in question could see no precipitation due to the inherent nature of precipitation events being spatially variant.

Temperature data had missing data points similar to precipitation data. However, missing temperature data cannot be set to a zero value as missing data occurred throughout the calendar year. Minimum temperature was utilized for the HEC-HMS model as minimum temperatures were conservative and would better represent the above and below freezing temperature cycle throughout the day, effectively re-trapping the water in storage. A value of zero temperature for the day is possible in both June and December, but only likely in December, thus missing data points were developed using interpolation similar to that discussed in the Appendix section A.5.

3.2.1 HEC-HMS Meteorological Models

The majority of values used for the meteorological model are recommended by the HEC-HMS User's Guide (USACE 2009). Precipitation is set to gauge weights based on data source for temperature and precipitation records. No evapotranspiration historical data was readily available and that setting remained zero. Snow melt method was set to temperature index and individual temperature index settings, rain rate limits, etc. were adjusted accordingly as summarized in Table 6.

Table 6 – HEC-HMS Meteorologic Parameters Summary

Meteorologic Model Parameters	**Setting:**	**Notes: (explanation of selection & sources)**
PX Temperature ^{o}C	1	Lowest temperature threshold for precipitation, not snow (USACE 2009)
Base Temperature ^{o} C	0	(USACE 2009)
Wet Melt Rate mm/^{o}C day	64	National Resources Conservation Services (Mockus et al., 2004)
Rain Rate Limit mm/day	0.7	Low end precipitation event limit from historical data and (USACE 2009)
ATI-Meltrate Coefficient	0.98	(USACE 2009)
ATI-Meltrate Function	Developed Curve	Interpolated user developed curve (Marie 2007)
Meltrate Pattern	None	Locked value when using meltrate functions, (USACE 2009)
Cold Limit mm/day	2	(USACE 2009)
ATI-Coldrate Coefficient	0.84	(USACE 2009)
ATI-Coldrate Function	Developed Curve	Interpolated user developed curve (Marie 2007)
Water Capacity %	5	(USACE 2009)
Groundmelt mm/day	0	(Anderson 2006),

PX temperature is set to 1 ^{o}C as any precipitation occurring below this temperature (0 ^{o}C or lower) will fall as snow, not rain and base temperature is set to 0 ^{o}C as recommended (USACE 2009). Wet-melt rate was initially set to 64 mm/^{o}C-day, selected from the range of 14.08 to 89.1 mm/^{o}C-day as recommended by the National Resource Conservation Services (Mockus et al., 2004). 64 mm/^{o}C-day is used as it creates marginally more snowpack melting and during calibration procedures produced a lower root mean square deviation than 40.96 mm/^{o}C-day. Alternatively, literature suggested a value of 40.96 mm/^{o}C-day can be used when data is limited as (Mockus et al., 2004).

Rain rate limit value is initially set to 0.0762 cm/day as this was a frequent lower end precipitation event intensity that occurred throughout the year, including fall freeze and spring thaws. Setting the value above the lowest observed precipitation event intensity in January (0.0254 cm/day) enables the model to better account for precipitation events during deep winter months and spring thaws (USACE 2009). The lowest January value would cause winter storms to act as rain fall, not snow fall, and be a contributor to wet melt. The higher value (0.0762 cm/day) allows precipitation to strike the snowpack as rain (freezing or not) and transfer thermal energy resulting in melting (USACE 2009). Additionally, the lowest intensity even was infrequent and the slightly large event intensity was more common.

ATI-Meltrate function was initially established through iteration as demonstrated in previous literature (Marie 2007) and corresponding ATI-Coldrate Function was determined in a similar manner to the meltrate (Marie 2007). Temperature gauge settings are set to user input temperature gauge (time-series data) and in this case the only temperature gauge available for the location is used. Lapse rate is reported to be -0.065 ^{o}C/1000 m (Ritter 2006) with initial elevation of the temperature gauge set to 341 m. In this research there exists no other temperature or precipitation gauges at different elevations and the watershed is relatively flat so changes in elevation will have little effect on temperature and precipitation, thus gauge weights are set to 100% accordingly.

Ground snowmelt patterns are based on Equation 3 (Anderson 2006) as measuring specific attributes of the watershed was not possible.

Equation 3:

$$M_f = \frac{\Delta t_t}{6} * (S_v * A_v * (MFMAX - MFMIN) + MFMIN)$$ (Anderson 2006)

$$S_v = 0.5 * \sin(\frac{N * 2\pi}{366}) + 0.5$$

where;

N = day number since March 21st
MFMAX = maximum melt factor – June 21st = 0.0014 in / (^{o}F*6hrs)
MFMIN = minimum melt factor – Dec. 21st = 0.0005 in / (^{o}F*6hrs),
A_v = seasonal variation adjustment:
When latitude < 54° North, A_v = 1.0, and
When latitude ≥ 54° North:
A_v = 0.0 from September 24 to March 18,
A_v = 1.0 from April 27 to August 15, and
A_v varies linearly between 0.0 and 1.0 from 3/19-4/26 and between 1.0 and 0.0 from 8/16-9/23.

Maximum latitude of the watershed is roughly 48.6^{o} North and Av = 1.0 is used accordingly. The groundmelt pattern function yields a bell shaped Gaussian distribution and is automatically plotted in HEC-HMS which is capable of interpolating between the input data points (USACE 2009).

Chapter 4: Model Calibration

4.1 Initial Results

Chapter 3: discussed the parameters used for initial settings of the model, including the 11 year simulation duration to produce 10 years of results. Initial parameters must be consistent with continuous simulations and other HEC-HMS models used in past literature for similar areas. The model simulation is run with the initial parameter values and historical temperature and precipitation input to compare the historical outflow from Lake Kabetogama with simulated outflow. Parameters are adjusted during calibration to more closely match simulated outflow with the historical outflow and to account for any unknown or missing information necessary to the model. Some of the missing information includes effects of groundwater movements into the lake which are unaccounted for in the available data bases.

4.1.1 Uncalibrated Simulation Results

Initial simulation results are used to determine that the model is built correctly in order to run continuous long term simulations without errors, prior to calibration. Ensuring that all the discussed settings meet or fall within the range of accepted values for similar studies and limits of the software for continuous simulation will improve outcome.

Initial results (see Figure 6) illustrate the elevation storage relationship over time on the upper window and the outflow over time on the lower prior to calibration. The lower window contains both historical and simulated results and is of primary concern.

The lower window compares simulated and recorded (upper darker jagged line) outflows of the lake and illustrates the yearly cyclic nature in both historical and simulated outflows, with a poor fit between the two. The upper window is of little concern to this research at this stage as it does not compare historical and simulated values.

Simulated peaks and peak timing do not synchronize well with the historical data shown in Figure 6. Peak “A” exhibits good timing as both peaks occur at close to the same date, but the difference in magnitude of total outflow discrepancy is large. Peak “B” of recorded data occurs earlier than simulated, with a large magnitude difference. Peak “C” exhibits relatively good timing but the magnitude continues to be substantially off. Some timing discrepancies of peaks may be attributable to the model spin up time. The outflows do not synchronize with respect to timing or magnitude of peaks and less difference between magnitudes should be attainable through calibration of the model.

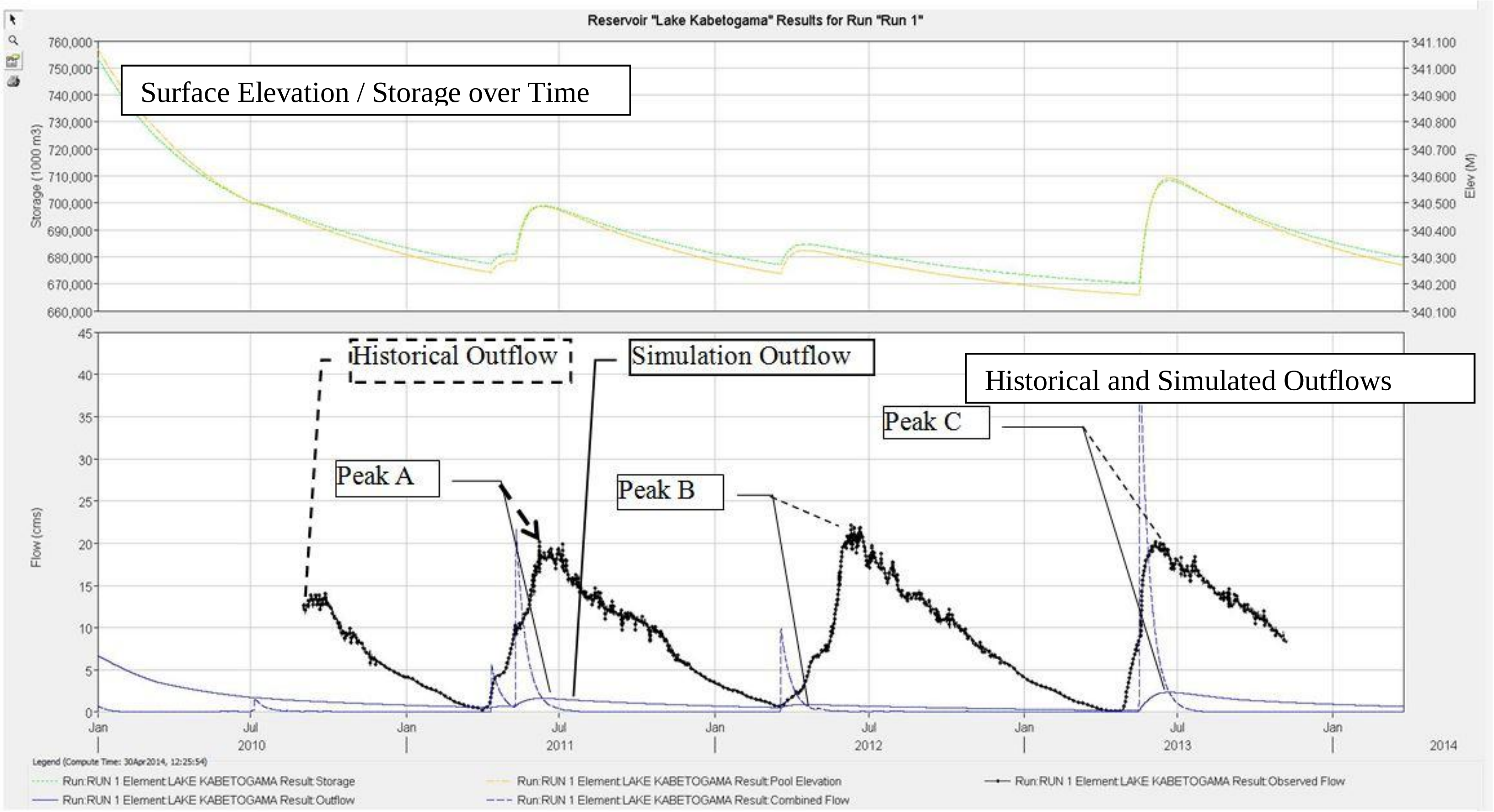


Figure 6 – Uncalibrated Results Upper window indicates change in simulated storage and elevation over time. The lower window illustrates the simulated outflow (thin blue solid line on lower half) compared to the recorded outflow (thicker dark jagged on lower half).

This chapter focuses on the methodology used to calibrate the HEC-HMS model so that simulated results using recorded data as inputs match closely to historical outflows in order to predict future flows and lake water levels. As evidenced by Figure 6 there are discrepancies within the simulated outflows and historical records which could be linked to several issues with the simulation including data used to generate simulation output.

4.2 Parameter Adjustment for Calibration

As seen in section 4.1.1 the model is not calibrated and results of the simulation would not be accurate. The focus was on reducing discrepancies between timings of the peaks seen in Figure 6 and overall shape of the curve. It was found that a few interdependent parameters had controlling influence on the calibration process and a more detailed description of calibration process can be found in the appendix.

The calibration utilizes the known inputs for the watershed, in this case the precipitation and temperature paired data historical records and seeks to reduce differences between simulated outflow and known historical outflow for the recorded inputs. Calibration is conducted through parameter analysis and adjustment to reduce the Root Mean Square Error (RMSE) and % difference in total outflow to minimums.

Determination of ranges of values for the parameters was established based on steps described in the Appendix, and iterative manual incremental changes of a single parameter were made to minimize the RMSE. Given that the model represents a highly complex natural system obtaining zero RMSE is not practical and the minimum RMSE value achieved is used to establish the calibrated state. Parameter changes and calculated RMSD and % difference can be seen in Table 8 (Appendix) along with simulation time frame windows (Table 9, Appendix).

The calibrated output is shown in Figure 7 with a comparison to the initial setup output for reference. As observed from Figure 7 the calibrated model simulated results more closely match the historical outflows. One reason for the continued discrepancies in calibration between the known outflows and flows generated with known precipitation inputs is due to time steps. The know outflows are on a 15 minute time step where as the known input precipitation for that time period is on a day time step scale.

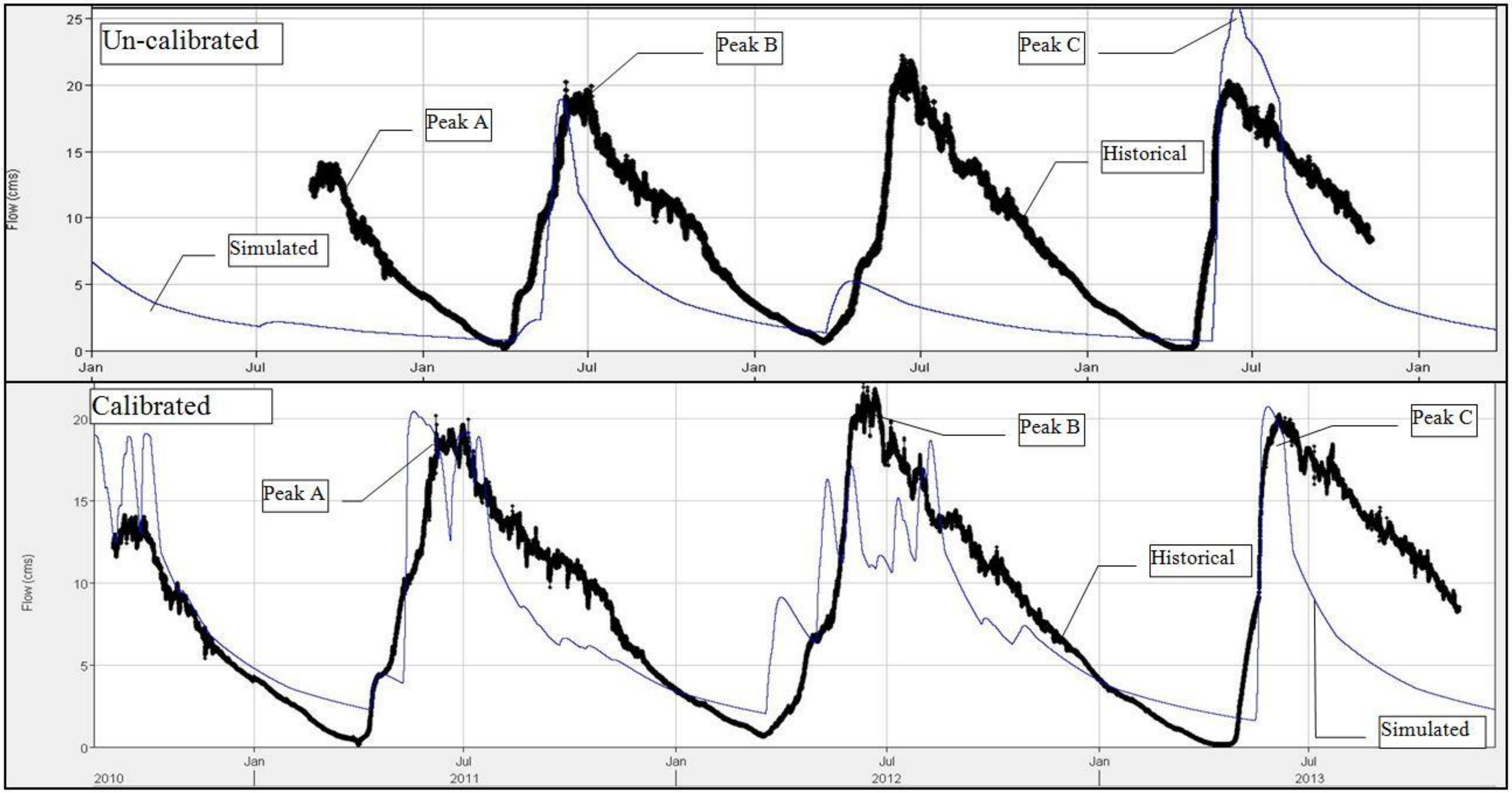


Figure 7 – Comparative Analysis of Calibration comparison between peak locations, magnitudes and down slopes between initial uncalibrated state (upper) and calibrated model (lower). Simulated outflow is thin line and recorded historical data is thicker black line.

Peak timing, as well as down slopes after peaks and magnitudes of simulation results post calibration more closely match historical outflows. With the exception of Peak C, where the slope does not degrade or match after peak, the overall fit is more accurate. Peak C and the differences in down slope noise (simulated to historical) may account for the majority of RMSE not reducing further. Taking into account data set limitations and unknowns the visual analysis of the plots and the least RMSE and percent difference obtained (see Table 8 in the Appendix) represent a reasonably well calibrated model.

In summary calibration was conducted through iterative means tracking single variable parameter changes and comparing both visual outputs and RMSE (of simulated and historical outflow) and percent differences of total outflow. The lowest RMSE value was still higher than ideal but with limitations in data and other uncertainties the calibration although not perfect is reasonable and the HEC-HMS model can be used to predict future outflow.

Chapter 5: Precipitation Shift, Predictions and Methodology

5.1 Introduction

This chapter provides an overview of the process used to develop the precipitation and temperature shifts for future years and the prediction method for both precipitation event occurrence and intensity. Information on the relative climate research and background information to develop the seasonal shifts of precipitation patterns was presented in sections 2.8 to 2.10.

5.2 Development of Precipitation Shift

A shift from wet summers and dry winters towards drier summers and wetter winters is predicted, coupled with an increase in total precipitation in North America (Mohammed 2005). The extent of precipitation shift is not clear and for the purposes of this thesis the shift will fully invert the patterns. A shift to historical precipitation data is developed and applied in order to construct the inverted future precipitation patterns and overall growth in line with prior research climate predictions. The shifted precipitation trends and growth are used in this research with the HEC-HMS model to predict future lake outflows and impacts on ES through WLF.

The focus of the thesis was to develop the precipitation predictions; the HEC-HMS model only provides a basic demonstration of how the predicted precipitation could affect Lake Kabetogama. Although HEC-HMS is suitable for continuous simulation spanning a number of years (Chu et al., 2009), the overall time span of predicted climate change is much larger. Even breaking down the simulation into smaller discrete simulations (10 year spans (Meenu et al., 2013)) cannot fully overcome the limitation of continuous simulation need for the 100 year time span. Additional recommendations to compensate for the time span are discussed in section 6.5.

An expected growth of 5-10% increase in total precipitation is expected over the next 100 years (Mohammed 2005); the median value of 7.5% will yield a representative average. The predicted 7.5% growth in total precipitation above historical means is distributed across the 100 year time frame. The result is each year experiences a linear Incremental Growth Factor (IGF) of 0.075% growth over the 100 year research time frame. The IGF is then applied as a scalar coefficient to increase the historical precipitation to account for the expected growth. The IGF is increased each year according to Equation 4, to account for the total yearly precipitation growth predicted from prior literature.

Equation 4:

$$IGF = 1 + (n * 0.00075)$$
$$where\ n = years\ from\ 1\ to\ 100$$

A second scalar factor is based on the expected drier summers and wetter winters predicted (Meehl et al., 2000). This thesis proposes to shift precipitation patterns to be inverted from current yearly precipitation patterns. The shift interpolated from literature moves locations of peak precipitation months from summer (traditionally wet months) to winter (traditionally dry months) and vice versa. The distribution of available historical precipitation data is analyzed to determine which months or seasons are considered the wet months and dry months. Note that for convenience sake precipitation data is grouped by month rather than other means such as seasonal, weekly or arbitrary date stretches.

Monthly grouping is not only convenient but also representative of annual precipitation cycles, if parameters for prediction of rainfall are developed from the actual calendar months (Wilks 1999). Precipitation shifts based on a daily scale, not monthly basis are possible, but analysis of historical data indicates that many more years of records would be needed.

Historical precipitation data is available from 2003 to 2013 for Lake Kabetogama and is used to determine each year's total historical precipitation. Total precipitation for each month for each year of data available is compared to that year's total precipitation to determine the contribution a given month has to that years precipitation totals. See Appendix A, Table 11 to Table 13 for more information. The average of percent contribution of each month to its respective yearly total for the 10 year span of available data is used to determine each month's representative percent contribution to yearly precipitation (see Figure 8 below).

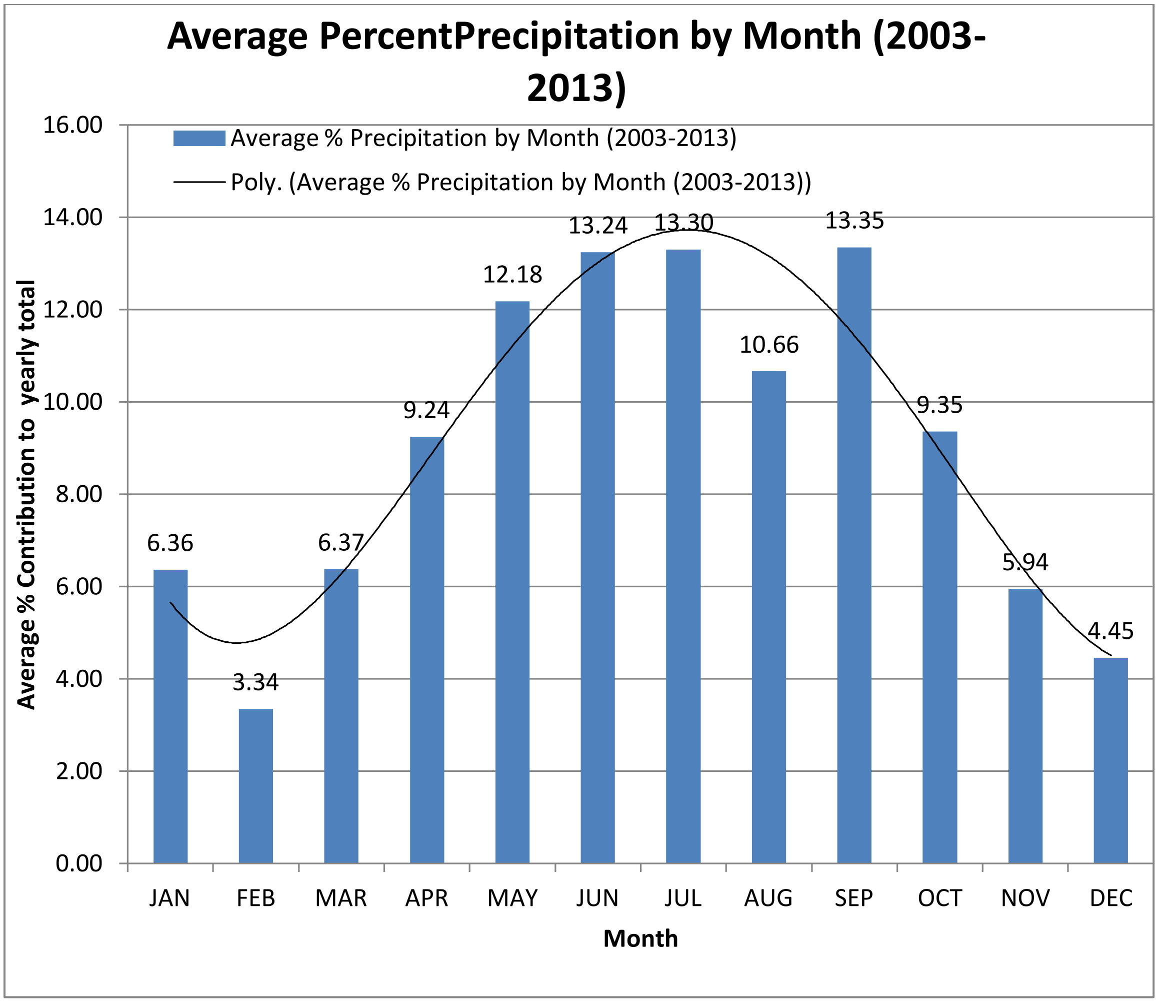


Figure 8 – Historical Average Percent Precipitation illustrates historical average of each individual calendar month’s contribution to yearly total precipitation values. This serves as the basis for developing the predicted seasonal shifts described above.

Wet and dry portions of the year are to be inverted in this thesis. The month with the highest average percent contribution to yearly total precipitation is translated along the calendar year to the month with the lowest contribution. Translational shifts of the months continue in a sequential manner. The contribution for the month following the wettest month is moved to the month following the driest, so that in the end the yearly precipitation total stays the same but calendar month distribution has been inverted (see Figure 9).

Note that it is not an exact inverse of the historical data as it is offset by approximately one month. The historical high point occurs in July (based on a polynomial best fit curve of Figure 8) but the expected low point post 100 year seasonal shift occurs in June instead of July, if an exact inverse of contributions was performed.

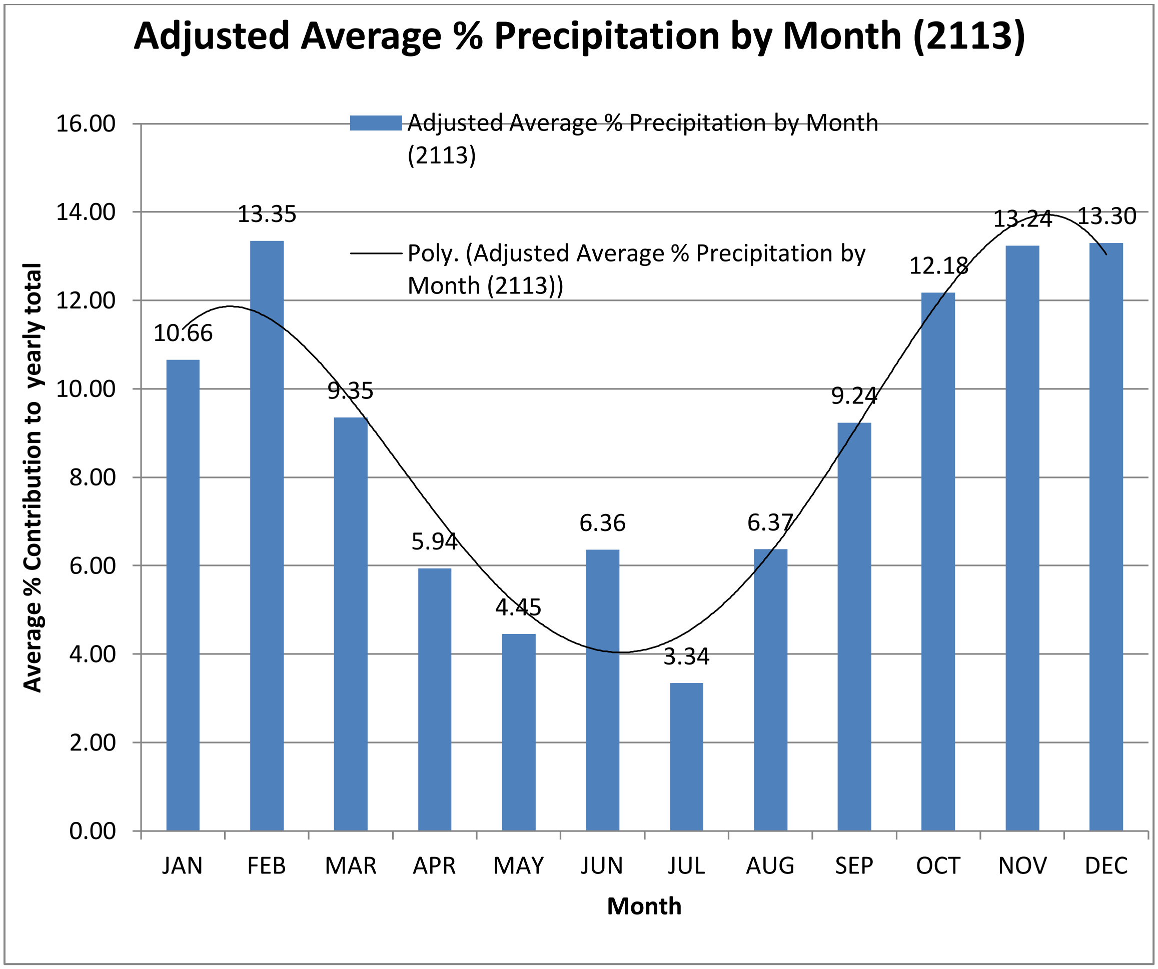


Figure 9 – Shifted Average Percent Precipitation plot above shows the expected shift in percent contribution for each month to the total precipitation at the end of the 100 year time span (the year 2113).

The wettest month historically is July (with an average 13.3% contribution to yearly totals) and the driest month historically is February (with 3.3% average contribution), these months have their respective contribution percents swapped. From there August (the next sequential month from maximum, with historically 10.6% contribution) is swapped with the next sequential month following the driest month. The next driest month in this case is March (historically 6.3%) next in sequence after February (the driest). August and March have the respective contribution percentages swapped, and Table 7 summarizes the changes to each month's % contribution.

Table 7 – Historical and Shifted Contribution Values

	JAN	FEB	MAR	APR	MAY	JUN
Historical AVG%	6.361	3.343	6.371	9.238	12.178	13.240
Shifted 100 year%	10.657	13.349	9.352	5.942	4.454	6.361
Ratio (shift to hist.)	1.675	3.993	1.468	0.643	0.366	0.480
	JUL	AUG	SEP	OCT	NOV	DEC
Historical AVG%	13.303	10.657	13.349	9.352	5.942	4.454
Shifted 100 year%	3.343	6.371	9.238	12.178	13.240	13.303
Ratio (shift to hist.)	0.251	0.598	0.692	1.302	2.228	2.986

The ratio of new precipitation contribution (the shifted value) to historical is determined and over the 100 year time frame of this thesis to get a scalar factor representing incremental shift per year of the 100 year time frame.

Each month's distributed ratio factor (see term one of Equation 5) and the IGF are multiplied together to determine the final scalar multiplier (FM) used to adjust precipitation values that will be predicted. The final values are used to adjust each months predicted precipitation values for each of the 100 years that prediction of precipitation will be calculated. Prediction of precipitation is done on a daily level for both occurrence and intensity and described later (see 5.2.1 and 5.3).

Equation 5:

$$FM_{N,i} = \left\{1 + \left(\left(\frac{(Ratio_i - 1)}{100}\right) * N\right)\right\} * \left\{1 + \left(\left(\frac{(Growth * N)}{100}\right) * \frac{1}{100}\right)\right\}$$

Where: $FM_{N,I}$ = Final Scalar Multiplier for the Nth Year and i'th month

N = number of the year being predicted (1 to 100)

$\text{Ratio}_\text{i} = \frac{Shifted\ \%\ Contribution_i}{Historical\ \%\ Contribution_i}$

Growth = 7.5%

Verification of the steps described above was done by hand (see Appendix A.5) for the June values described above). Each month was individually verified and all months were reasonably close with very minute differences as described in Step 6 of the Sample Calculation in Appendix A.5.

5.2.1 Precipitation Intensity Predictions

Precipitation intensity and occurrence are two outcomes of the predicted shift in precipitation patterns which will have influence on the ES and WLF researched. To develop an understanding of the proposed pattern changes on ES, values of daily precipitation intensity must be predicted for the time frame of this study. Currently, precipitation patterns and intensity vary on both temporal and spatial scales which produce different runoff conditions and overall contributions to lake WLF. For simplification purposes the precipitation intensities are assumed to be representative of the entire average daily precipitation levels for the entire watershed, rather than continually varying temporally and spatially.

Historical daily precipitation data is used to generate parameters for prediction of future precipitation intensity. Precipitation, however is not a typical Gaussian Probability Density Function (PDF), but instead is defined by a Gamma PDF (Wilks, 1992). Alpha and Beta parameters for the Gamma PDF are calculated from the historical data using a software solver utility (Excel 2010), based on the most frequent historical precipitation intensity. The second most frequent precipitation intensity value is used as a constraint in determination of alpha and beta parameters for the Gamma PDF, similar to maximum likelihood estimates. The process uses Equation 6 (Wilks 1992), an equation widely referenced in literature on precipitation.

Equation 6:

$$f_r = \frac{(\frac{r}{\beta})^{\alpha-1} * e^{(-\frac{r}{\beta})}}{\beta * \Gamma(\alpha)} \text{ Where: } r, \alpha, \beta > 0 \text{ (Wilks 1992)}$$

where: $\Gamma(\cdot)$ is the Gamma Function.

Missing parameters (α and β) are solved for using observed probabilities of the most frequent intensity value observed, with 0.3 mm of precipitation being the lower bound of precipitation to qualify as a rain day. 0.3 mm was selected as that was the lowest recorded precipitation value in available historical data, which did not include lower values or even “trace” amounts. The observed probability is used as a constraint for a software utilities iterative solver (Excel 2010). The solver alters α and β values of Equation 6 until the calculated probability output reaches the observed probability for the most frequent observed intensity.

Results are displayed below for the month of June for historical data as shown in Figure 10. Both the Excel 2010’s built in Gamma PDF and Equation 6 (labeled as fr) are displayed for the calculated α and β values. From observance of Figure 10 both automatically generated Gamma PDFs and the “fr” function Equation 6 generate curves representative of the distribution seen for the observed intensities and frequency.

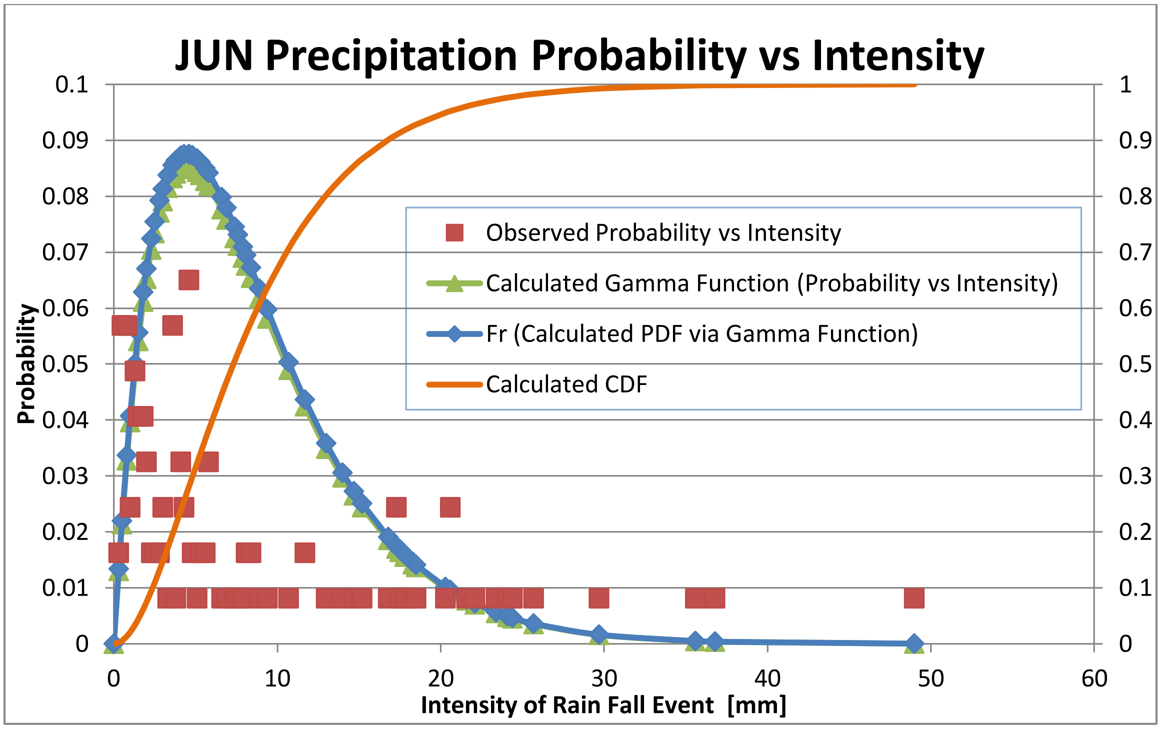


Figure 10 – June Precipitation Probability Distribution

The figure above illustrates the observed historical frequency of specific precipitation intensity levels with the calculated Gamma PDFs (software Gamma PDF and results of Equation 6 (Wilks 1992) shown to illustrate the full range of possible precipitation intensity values. Note that for a month with relatively low noise (such as the month shown) both Gamma PDFs match well.

The Cumulative Probability Density Function (CDF) for the software function is also shown on the secondary axis for reference and verification that fr generates a true probability curve. The CDF allows a randomly generated probability input to determine a corresponding rainfall intensity. Generated intensities are later adjusted using Equation 5 to fully develop the precipitation shift from histroical to predicted values.

5.3 Generation of Prediction Data

Precipitation event occurrence and intensity is determined through a two stage process. Stage one determines whether or not precipitation will occur by generating a random number P_n, between 0 and 1 for each day of the study, which represents the likely hood of an event for that day. P_n is then compared to the corresponding monthly $P_t = [P_0 \quad P_1]$ (see section 2.9) and if P_n is less than or equal to P_0 (the probability of a dry day) there is no precipitation event. If an event does occur a second unique random number for that day is generated, P_r also between 0 and 1. P_r for a day is used with the corresponding monthly CDF and Alpha and Beta parameters described in 5.2.1 to determine the intensity of the rainfall event.

The sets of paired precipitation and temperature daily input values are generated based on prediction methods described (see also section 2.9 and 2.10). Fully continuous simulation is not recommended and the 100 year study period is divided into 10 year periods, based on prior literature recommended values ranging from four (Lim et al., 2010) to 10 years (Meenu et al., 2013). Simulation time spans used are actually 11 year increments, relying on the first year being model ramp up, yielding 10 years of relevant data. Several trials of predicted paired data are simulated on a separate continuous 100 year simulation span for comparison to the decadal approach above.

The individual yearly average water level amplitude (see Section 6.1) for each year in the 100 study years is averaged over the multiple separate simulation trials in both decadal and continuous approaches. The resulting averages of simulation amplitudes become increasingly linear with decreasing variance as additional simulation trials were calculated for both continuous and decadal approaches. Due to the trend towards linear results a full scale Monte-Carlo approach to simulation was not used. Linear results are not representative of the natural system which will experience non-linear behavior.

The fully continuous set of simulations yielded nearly linear results with only three pairs of generated inputs used, where the decadal approach produced more varied results more representative of a naturally fluctuating system. The fully continuous approach method results are not presented due to their linearity. Results presented are for a set of 13 randomly selected sets of input (paired temperature and precipitation) from the pool of 100 for the decadal approach. Thirteen simulation runs provided enough input for the linear trend to develop; but still allowed for variation in average yearly water level amplitude. Variation in average water level amplitudes is desired in a natural system rather than a purely linear set of amplitude.

In order for a more valid comparison of prediction results (the 100 year study) to historical records to be conducted the 10 years of historical precipitation and temperature data are used to generate outflows from the calibrated model. The new outflows from the 10 years of historical inputs are then used in place of the three years of observed historical outflow data for comparison.

After running the historical precipitation and temperature data through the calibrated model, the resulting outflows are analyzed in a similar manner to the predicted input pairs for WLF, average amplitudes, and etcetera.

The process of using historical input creates a comparative history of outflows and is justifiable as the calibrated model is used to generate outputs from both the 10 year historical and 100 year predicted inputs. Both simulated outflows for historical and future predictions should behave similarly and render increased relevance to comparison of pre and post precipitation shift behavior.

Chapter 6: Analysis, Conclusions, Recommendations

6.1 WLF Amplitude Analysis

The following sections cover WLF and measurements amplitude changes and other indicators of WLF, see Section 2.6.2. Amplitude is the difference in yearly open water season maximum and minimum lake surface water level. Amplitude values are determined for each year of the study (2014 to 2113) for each trial, and minimum, maximum and average values for all 13 trials were recorded and plotted see Figure 11 & Figure 12.

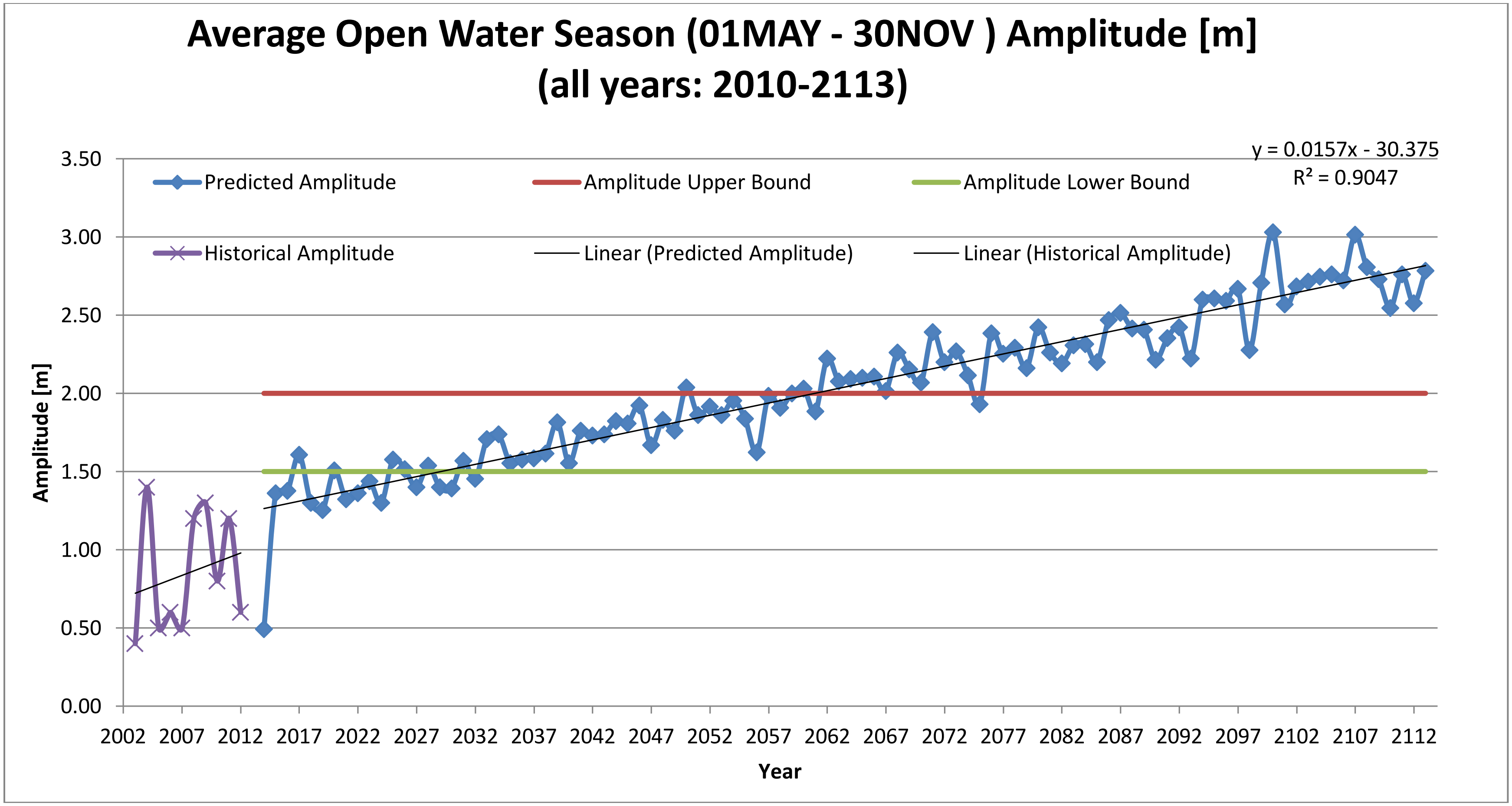


Figure 11 – Average Amplitude for the Decadal Approach Method

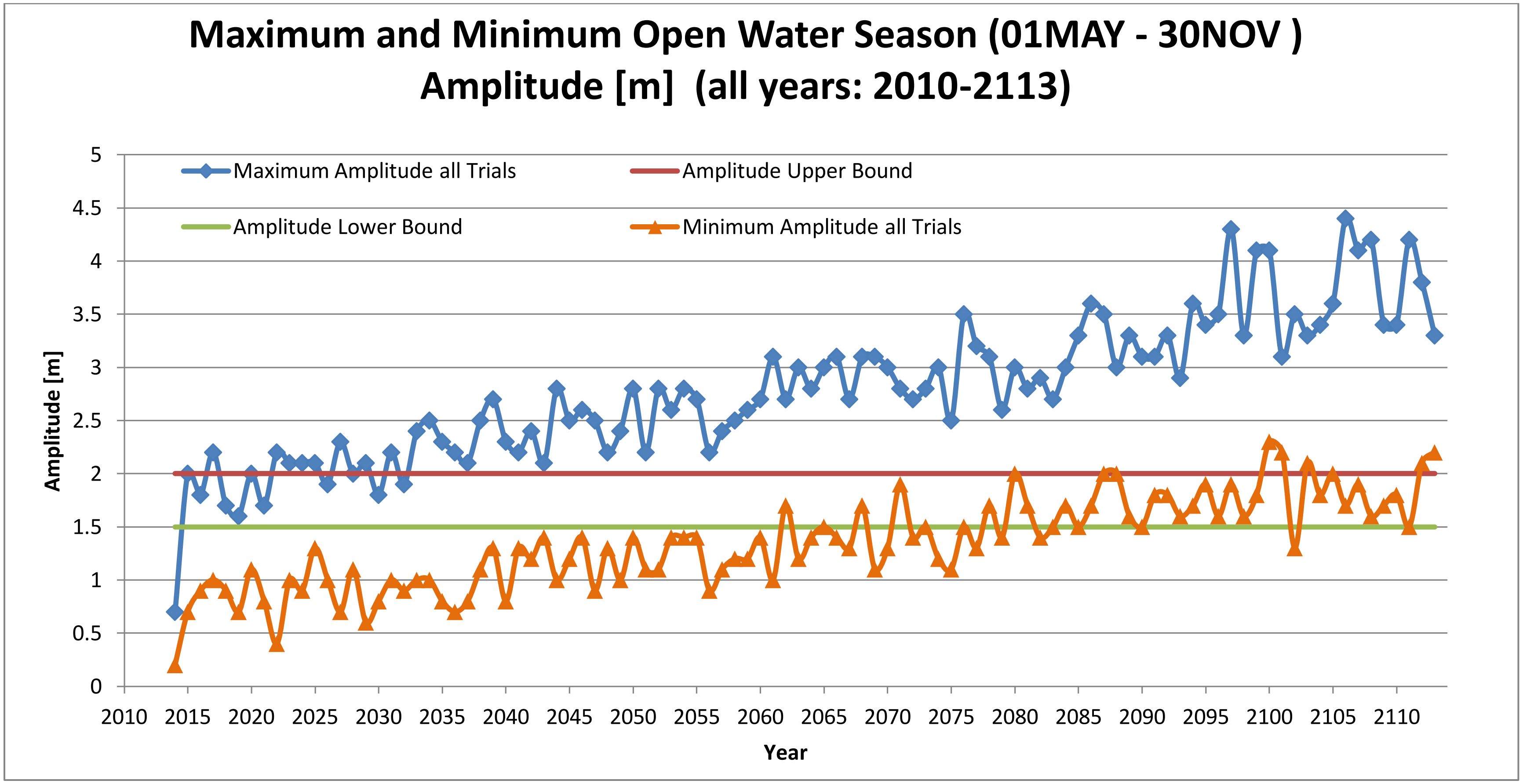


Figure 12 – Maximum and Minimum Amplitudes

Amplitude (see Figure 11 & Figure 12) indicates there is a large portion of study time that will fall within the ideal 1.5 m (lower bound) to 2.0 m (upper bound) range (White et al., 2008). Historical precipitation output from the simulation indicates the lake may currently be under performing compared to the ideal amplitude range. Historical output also trends towards increasing amplitude, bringing amplitudes within the 1.5 to 2.0 m range in the near future.

Additionally, for each study year (2013 to 2113) the yearly fluctuation in amplitude or Difference in Amplitude (DAMP) is calculated. DAMP is the amplitude from the previous year minus the current year. DAMP is values are representative of the amount of fluctuation of amplitude between consecutive years. Amplitude and DAMP (measurements of WLF) are important in order for aquatic species to survive they must have appropriate amounts of water during the right season (White et al., 2008). Amplitude measurements shown occur during the growing and reproductive cycles of most species (White et al., 2008).

Based on past literature the maximum fluctuation that will not have long term impacts on the aquatic life is 2.0 m (White et al., 2008). From Figure 13, it can be seen that the predicted outcomes from this research do not fluctuate as much as historical, but would remain within the literature bounds of 2.0 m.

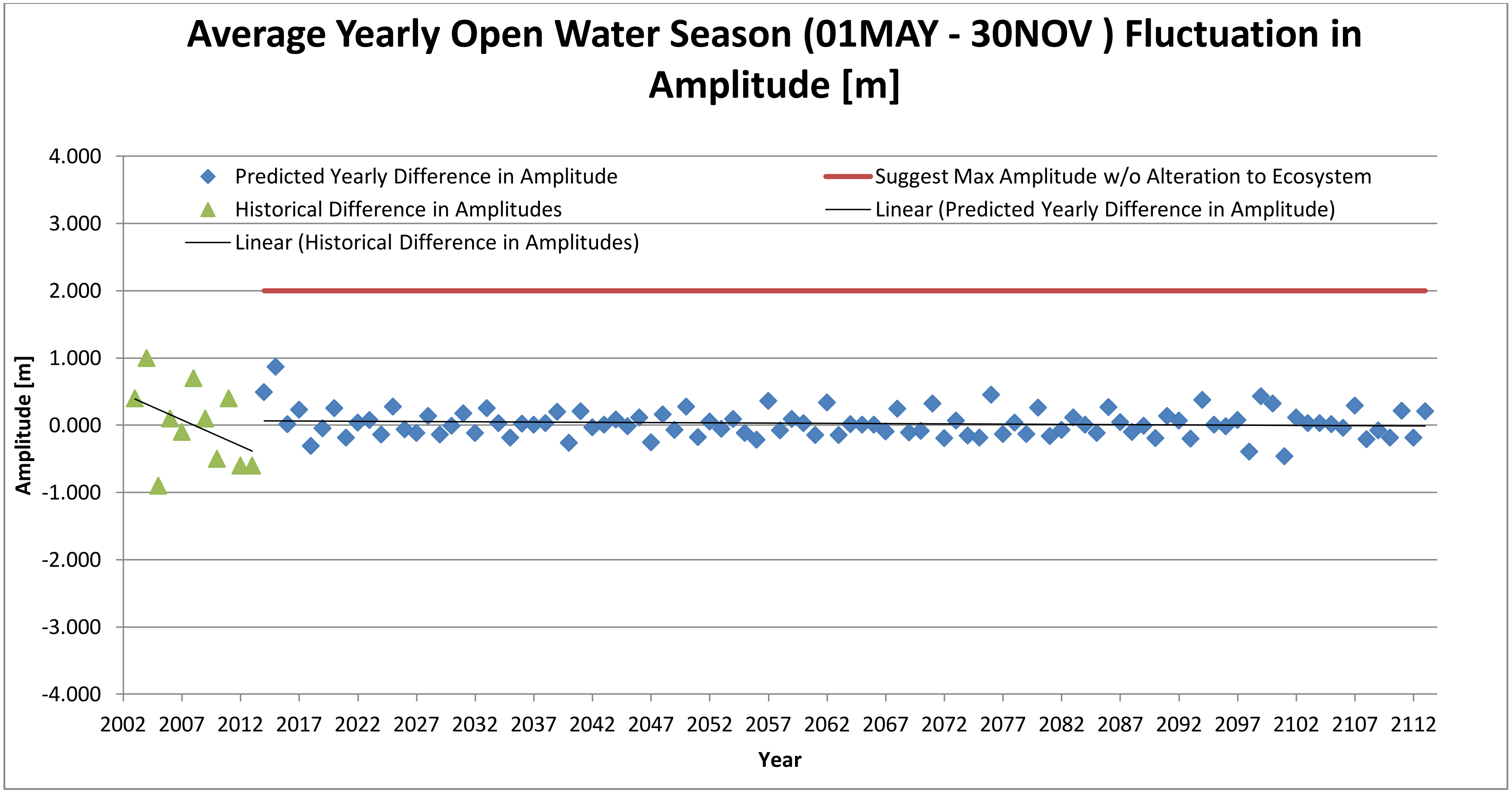


Figure 13 – Fluctuation in Amplitude by Year

The linear trend of amplitude expressed by the simulation predictions indicates that a period of 34 years falls within the optimal range (see Figure 12). As the lake is currently healthy and productive, previous years also effect the total time with minimal disturbance to biota due to WLF. Approximately 50 years of normal to optimal productivity should occur based on this prediction with the described temperature and precipitation shifts which will have a limited ability to induce adverse effects.

Effects of any alterations to the watershed properties over time are unknown at this time; it is likely that the lake will continue to perform in a productive manner for some time based on the model predictions. Uncertainty increases over time and is amplified due to the static model parameters and results are not likely as accurate at the far end of the study time span. It is possible that given the slow increase in amplitude and uncertainty with results further along in the 100 year span, that species will be able to adapt to Lake Kabetogama's change in WLF.

6.1.1 WLF Difference Long Term Mean Definition and Analysis

Difference in Long Term Mean (DLTM) values indicate fluctuation for the entire year compared to the long term water level for all seasons and all years. DLTM for the predicted results only and historical data are determined and compared (see Figure 14). DLTM with inclusion of historical means are closer to the historical model and indicate that the overall effect of WLF on biota may be very little because the rate of increase is slow.

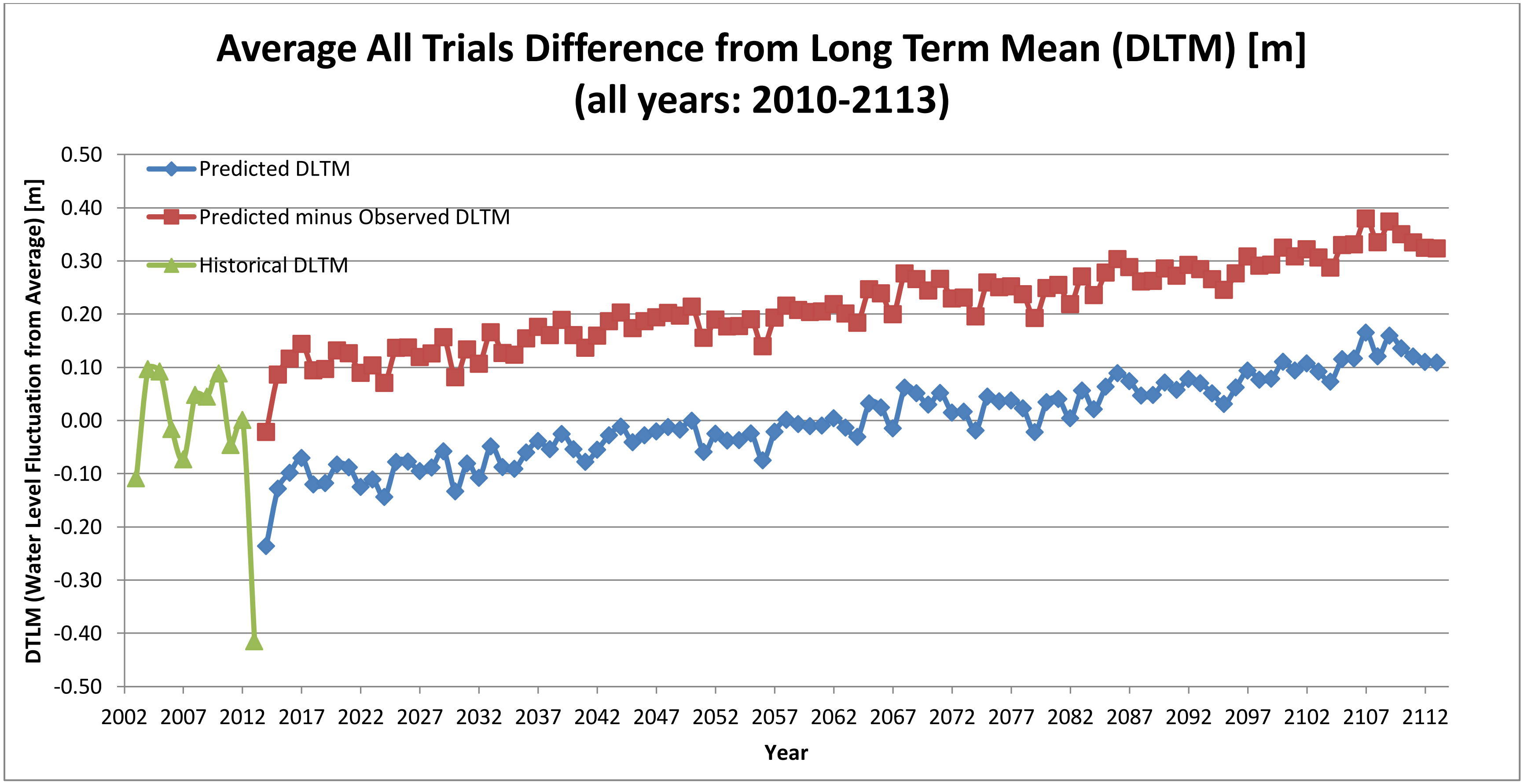


Figure 14 – Difference in Long Term Mean

Higher species richness yields a more productive water body (White et al., 2008) which will increase the ES value of recreational activities, such as fishing, which is one of the primary activities of Lake Kabetogama. The optimal DLTM range is approximately +/- 0.2 m (White et al., 2008) in similar boreal lakes, and appears somewhat Gaussian, with maximum species richness of aquatic macro invertebrates just negative of the zero DLTM mark. Sampling of actual biota and aquatic life was not possible for this study.

Analysis of the predicted results shows that DLTM for the predicted inputs over the study period alone fall within the +/- 0.2 m bounds and the DLTM including observed data, falls within the ideal ranges. The predicted results do not consistently breach the +/- 0.2 m range until reaching somewhere within the 80-85 years of simulation mark, sufficiently along in the study time period that many other factors could come into play.

The results of DLTM analysis signify that over time there will be little change positive or negative within productivity of the aquatic life in the littoral zone based on the predicted precipitation shift and long term WLF. However, the small impact of WLFs does not include other potential disturbance factors (i.e. direct human interaction with the ecosystem, changes to the local regions ecology and development) from having an impact on ES.

6.2 Hydrologic Alteration Information and Analysis

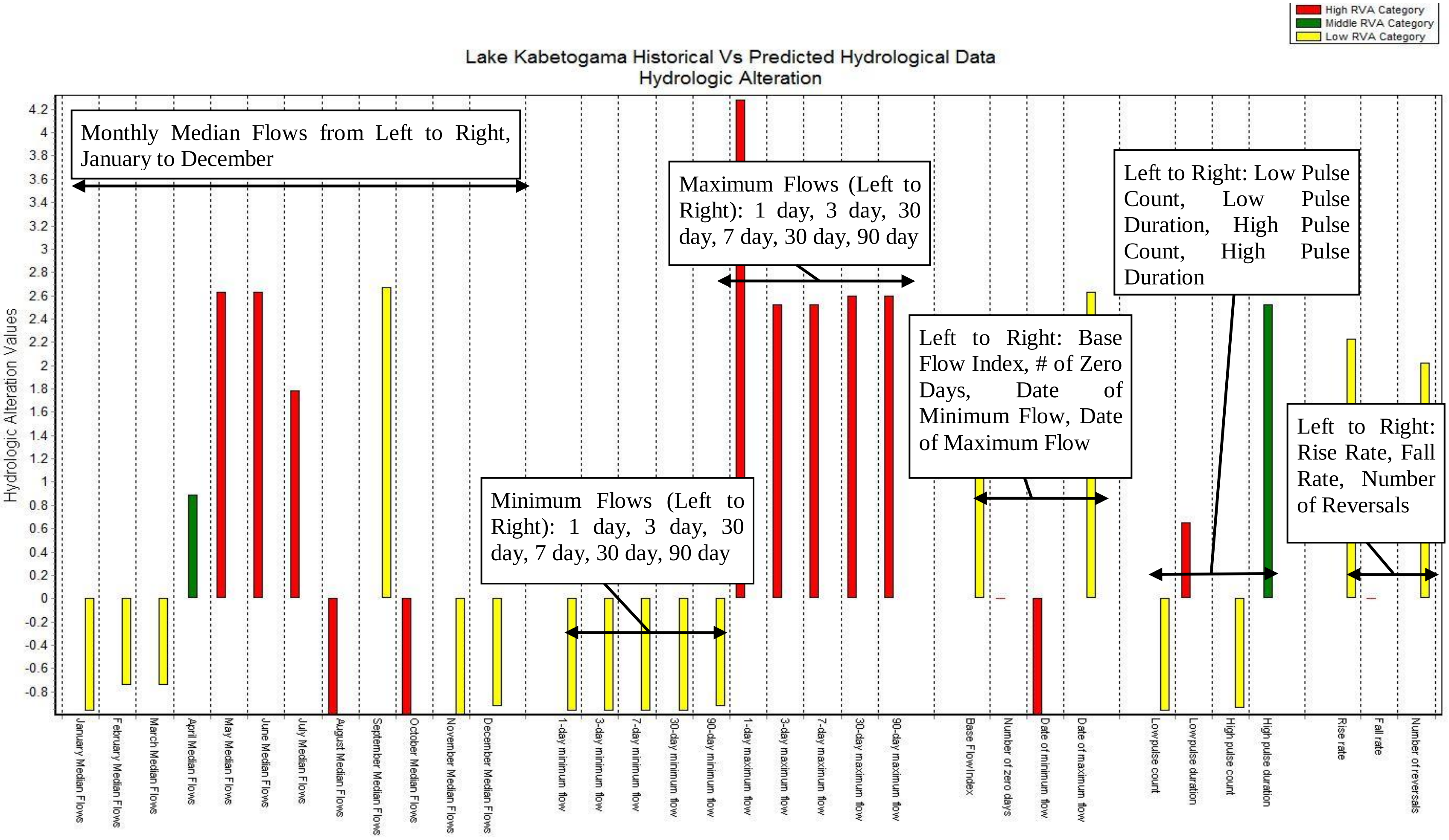
Hydrologic alteration, which includes inter and intra-annual variation is another important tool for understanding changes to flow levels in water bodies. Hydrologic alteration compares the natural cycles that occur to cycles occurring after some sort of event that alters the system to determine the extent and magnitude of impact on essential ecological functions (Richter et al., 1996). Analysis of the flows produced, timing and durations of high and low flows, in a manner that is quantifiable and statistically relevant can then be used to help determine possible responses of the ecological system to induced alteration (Richter et al., 1996).

Data analysis for hydrologic alteration is conducted through the Indicators of Hydrologic Alteration (IHA) (Nature Conservancy 2012), commonly used software. IHA statistically analyzes the lake outflow data and generates plots of water body flow events and temporal variability to account for the inter and intra-annual effects. The comparison is conducted between the 10 year historical precipitation and corresponding HEC-HMS outflows as the pre-event period (left side set of data on subsequent figures) and the post event period is the 100 years of precipitation input and corresponding outflows (right side set of data). Note that all outflow data for HEC-HMS is on a time step scale of one day.

Based on the statistical analysis provided by the program it can be seen which of the factors measured comparatively against the others has the greatest impact on system (see Figure 15). Figure 15 displays comparative impacts of alterations, numerical values represent frequency of the factor impacting the system. Positive values range from zero to infinity and negative values range from zero to negative one. The maximum impact is the 1-Day Maximum Flow (Figure 18), with an alteration rating of 4.2, the next highest is the spring flows May and June at 2.8. From Figure 20 it can be seen that spring thaw months

(May and June) and pre-dominantly the 1-Day Maximum Flow alter the hydrologic cycle the most.

Overall average monthly flows for both historical and predicted are presented in Figure 16 for comparison purposes, using average monthly data from the 100 year study. Magnitude of the predicted spring thaw flows is heavily influenced by the simulated climate and precipitation changes developing over time, resulting in rapid melting of increased snow pack spiking spring flows. Individual monthly flows are presented in the Appendix.



Monthly Median Flows from Left to Right, January to December

Maximum Flows (Left to Right): 1 day, 3 day, 30 day, 7 day, 30 day, 90 day

Left to Right: Low Pulse Count, Low Pulse Duration, High Pulse Count, High Pulse Duration

Left to Right: Base Flow Index, # of Zero Days, Date of Minimum Flow, Date of Maximum Flow

Left to Right: Rise Rate, Fall Rate, Number of Reversals

Minimum Flows (Left to Right): 1 day, 3 day, 30 day, 7 day, 30 day, 90 day

Figure 15 – Greatest Hydrologic Alteration Factors

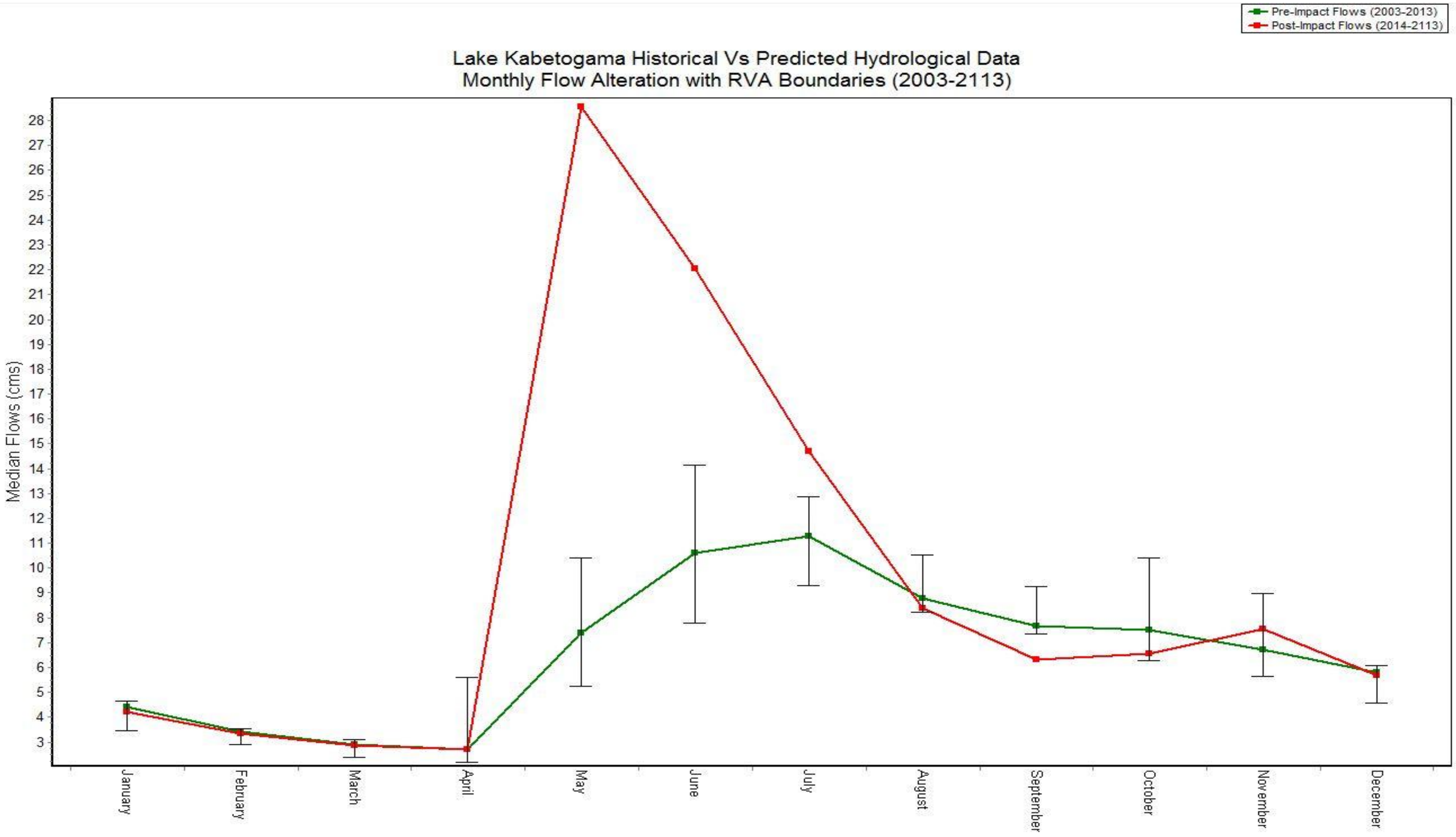


Figure 16 – Average Monthly Flows

6.2.1 Base Flow Index of IHA

The resulting base flow for both time periods (historical and simulated) are similar with historical mean of 0.3 and predicted of 0.27 for 7-Day minimum flow / annual mean flow (see Figure 17). The predicted time period displays a slowly decreasing trend in base flows with less variety in values. Low variation in base flow index and monthly flow alteration indicate that the results are reasonable and follow expectations of the predicted drier warmer summer. The predicted climate would affect the open water season base flows negatively as increased summer temperatures and lower precipitation would cause lake drawdown. Open water season lake draw down reduces the magnitude and variability of summer flows, but has little impact on winter flows as they are predominantly controlled by factors such as temperature and ice thickness, not precipitation.

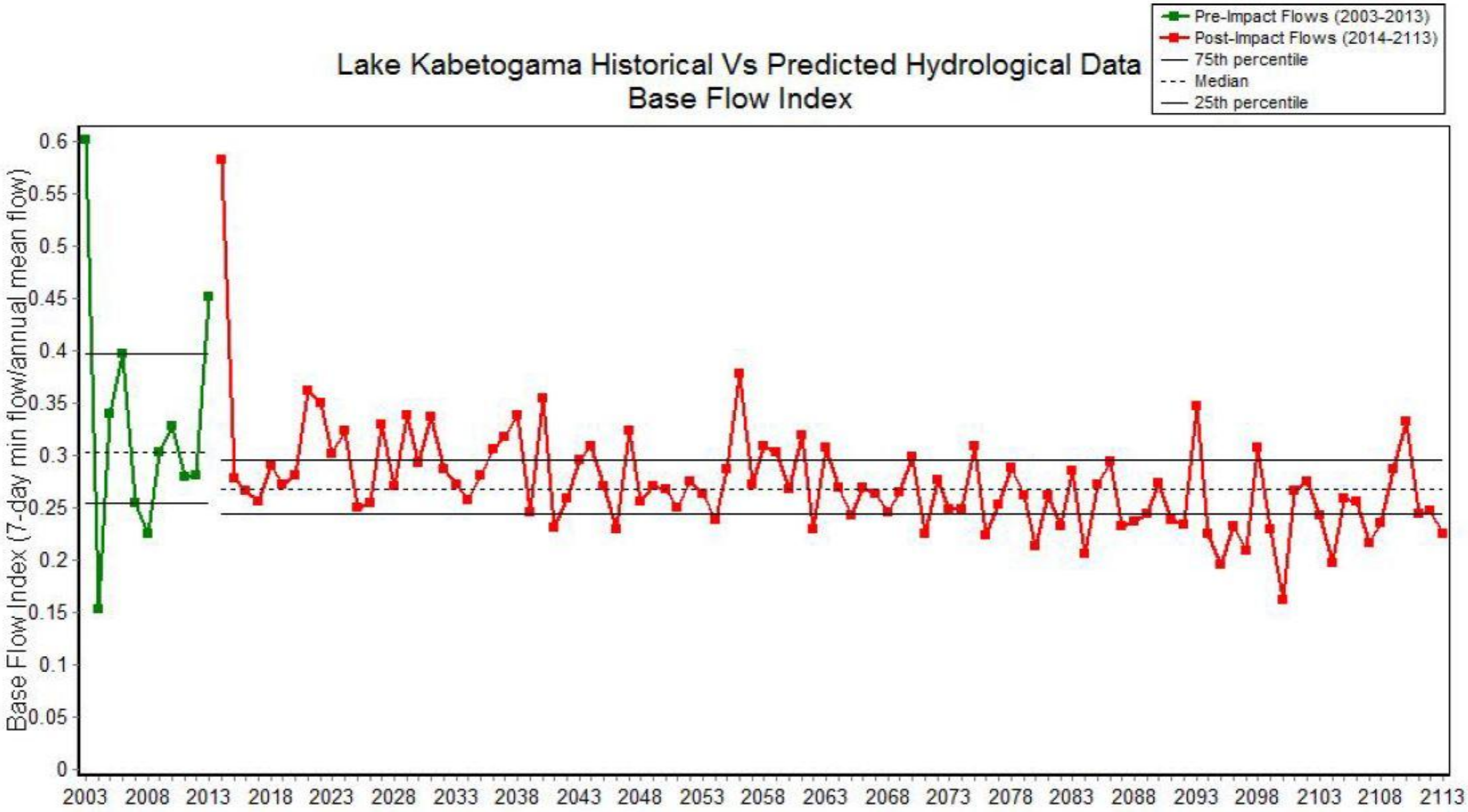


Figure 17 – Base Flow Index of Predicted 100 Year Time Period

6.2.2 Maximum Flows

Maximum flow data is generated for one, three, seven, 30 and 90 day periods. For results other than 90-day maximum flows, there exists a large increase in median flows in 2014 (study initiation year) from 18.9 m^3/s to 32.0 m^3/s. Predicted data also displays a linear increasing trend that brings flows well into the 45-55 m^3/s range during the last two decades of study, values over double the historical high flows. In reality, similar to WLF information, flows at the far end of the study time period will experience increasing effects from external influences and like all results represent only a possible future flow state.

In one-day maximum flow (Figure 18), historical flows are greatly exceeded as evidenced by the lower 25th percentile of flows for the simulation are greater than the highest flows of the historical period. It should be noted that for the first 20-25 years predicted flows, although exhibiting low variability behave nearly within the historical periods. Low variability may indicate that despite increased spring flooding and saturation of nearby wetlands, several decades will pass before flows higher than historical normal to be reliably established for spring flood periods.

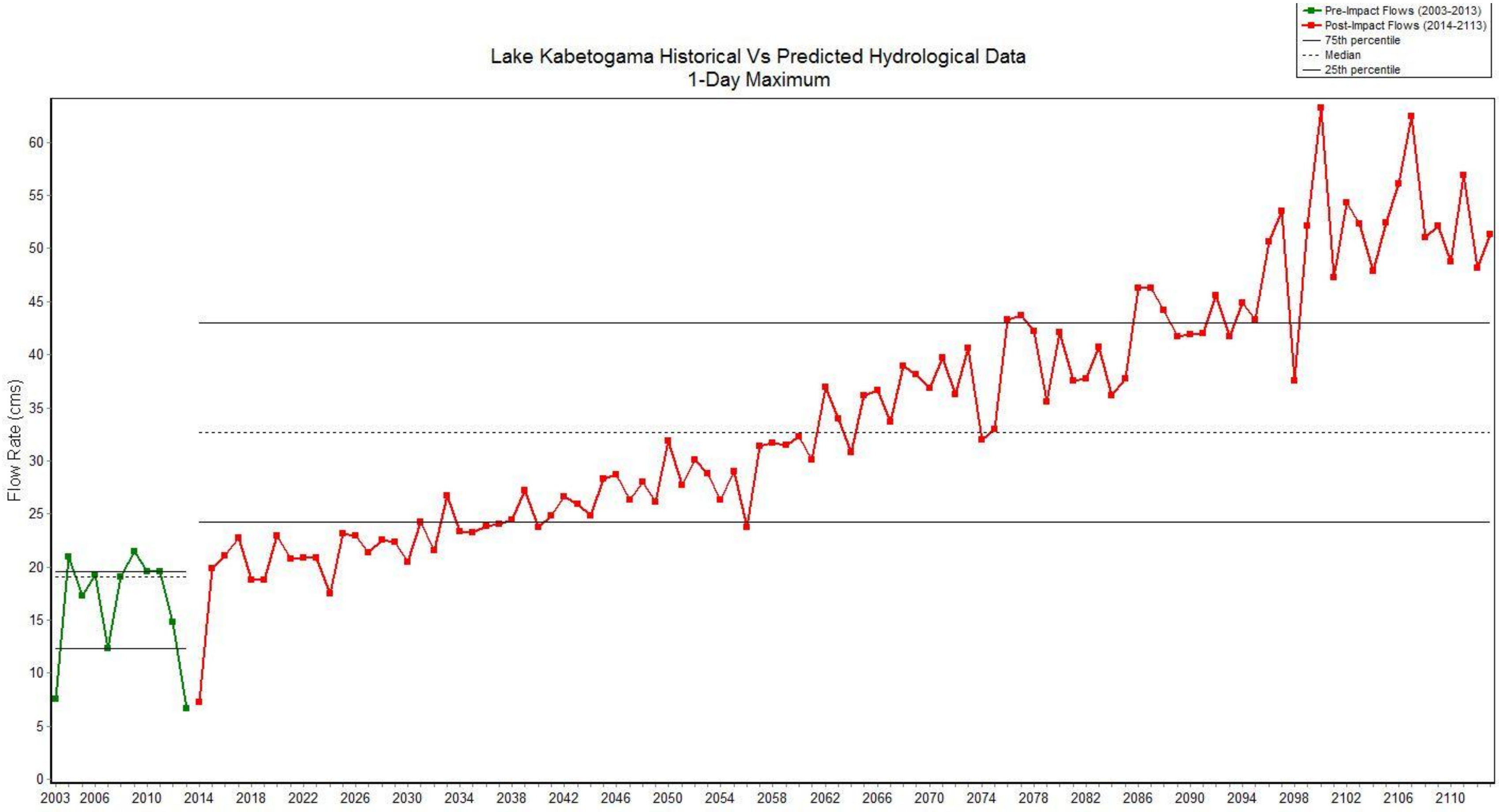


Figure 18 – 1 Day Maximum Flows Historical and Predicted

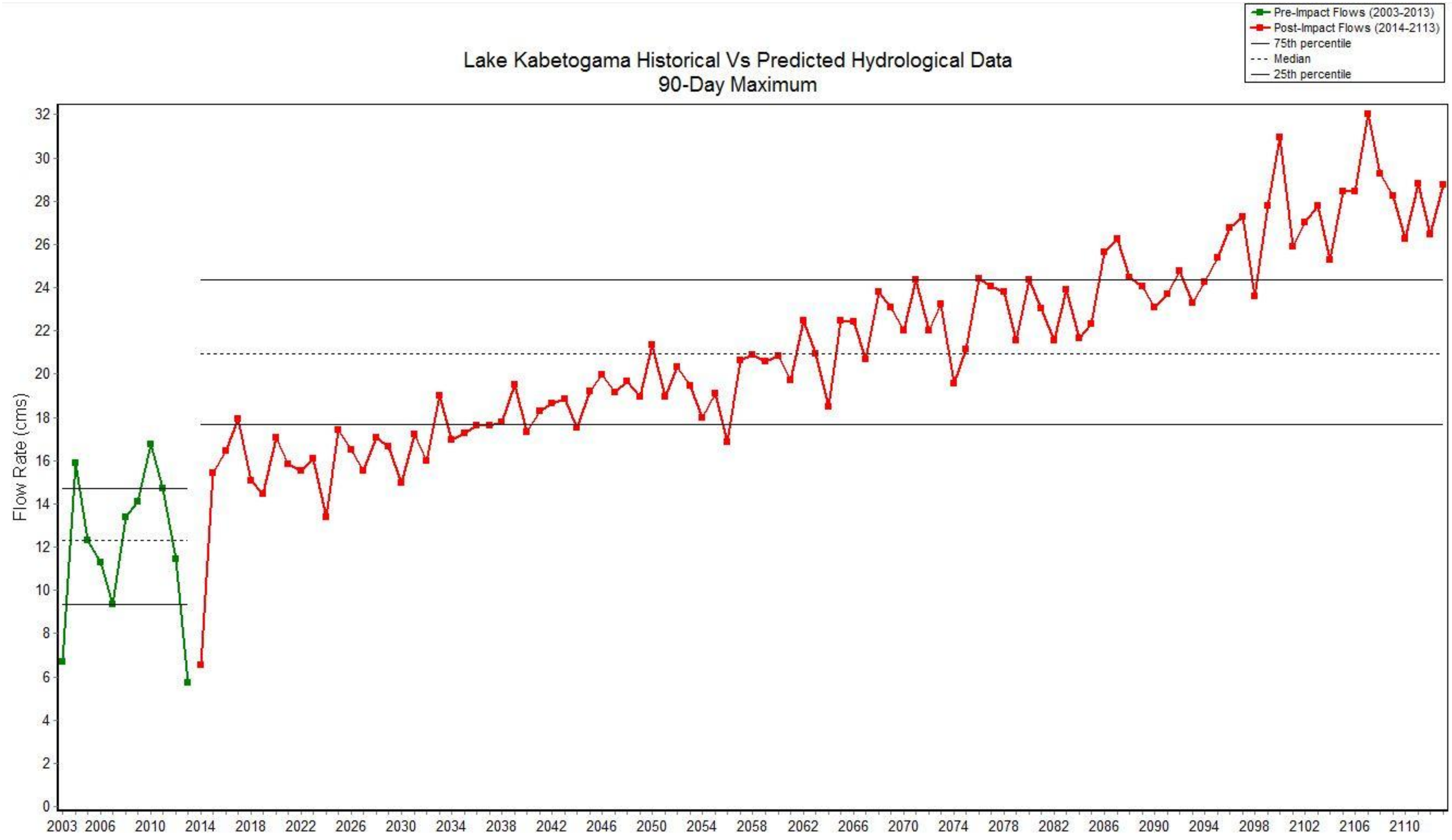


Figure 19 – 90 Day Maximum Flows, Historical and Predicted

90-day maximum flow values (Figure 19) range from within the historical range of 226.5 to 4927.1 cm^3/s for a short period (first 9-12 years) to much higher ranges of 17,585 to 32,763 cm^3/s for the latter years in study. High flow time periods experienced are limited in durations to less than one season (three months) and will recede afterwards, consistent with the mean annual flows experienced observed in Figure 16. 90-day maximum flows indicate that if the predicted precipitation and temperature shifts are accurate there will be substantial increase in the 90 day flow periods and associated seasonal flooding not long into the future.

The date of maximum flows (Figure 20) in the predicted response no longer varies seasonally as in the historical model, when summer and fall storms controlled the date of greatest flow. Instead the date of occurrence is relatively stable and remains in late May and early June, reinforcing that spring thaw flooding appears to dominate maximum flow in this prediction. Additionally duration of flood state (see Figure 21) varies on the low end but rarely exceeds the median of 92 days, which would coincide with the spring thaw and early summer storms leading into the dry summers. Stability of dates of high flows further supports the likely hood of the May dominated flows being attributed to spring thaw.

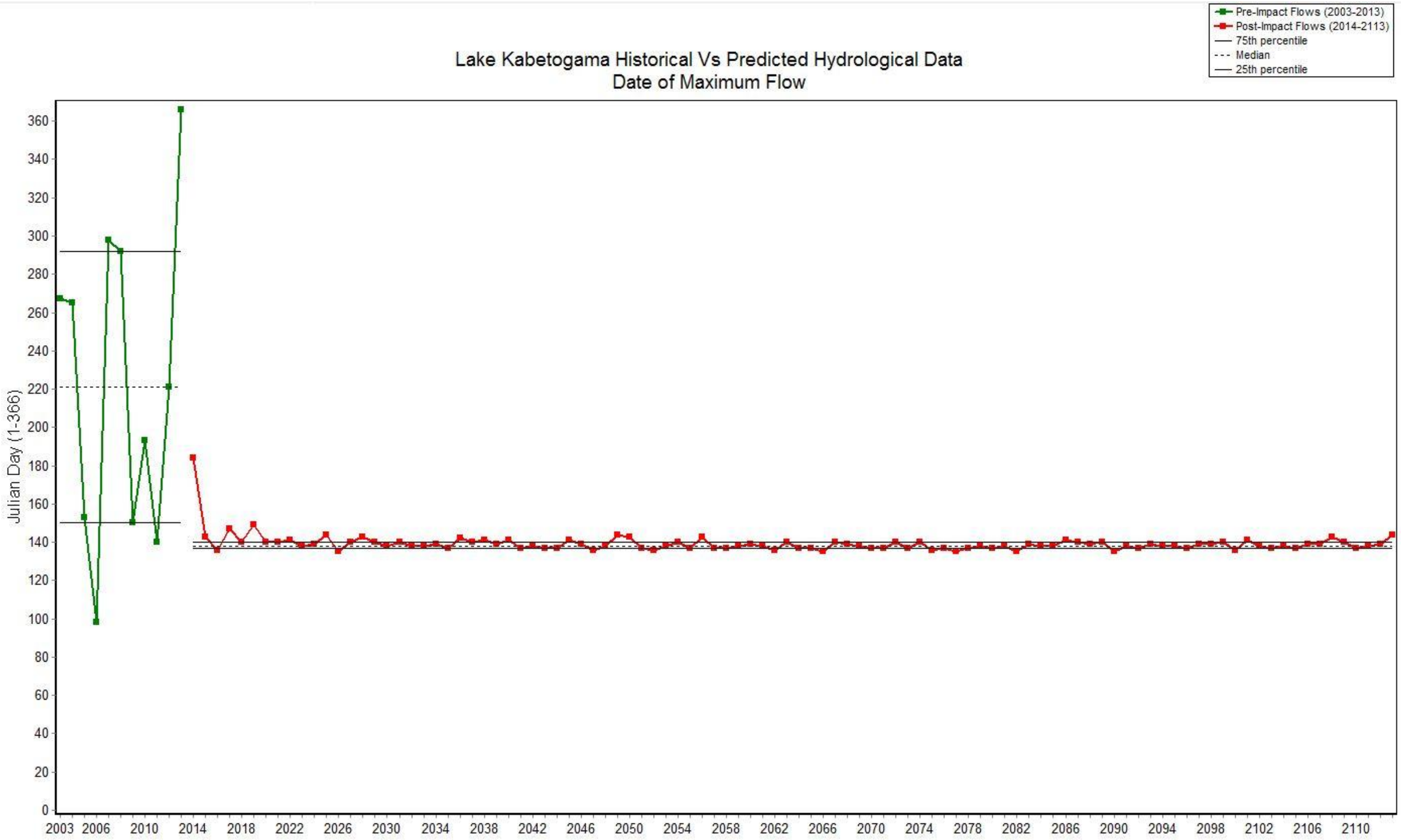


Figure 20 – Date of Maximum Flows Historical and Predicted

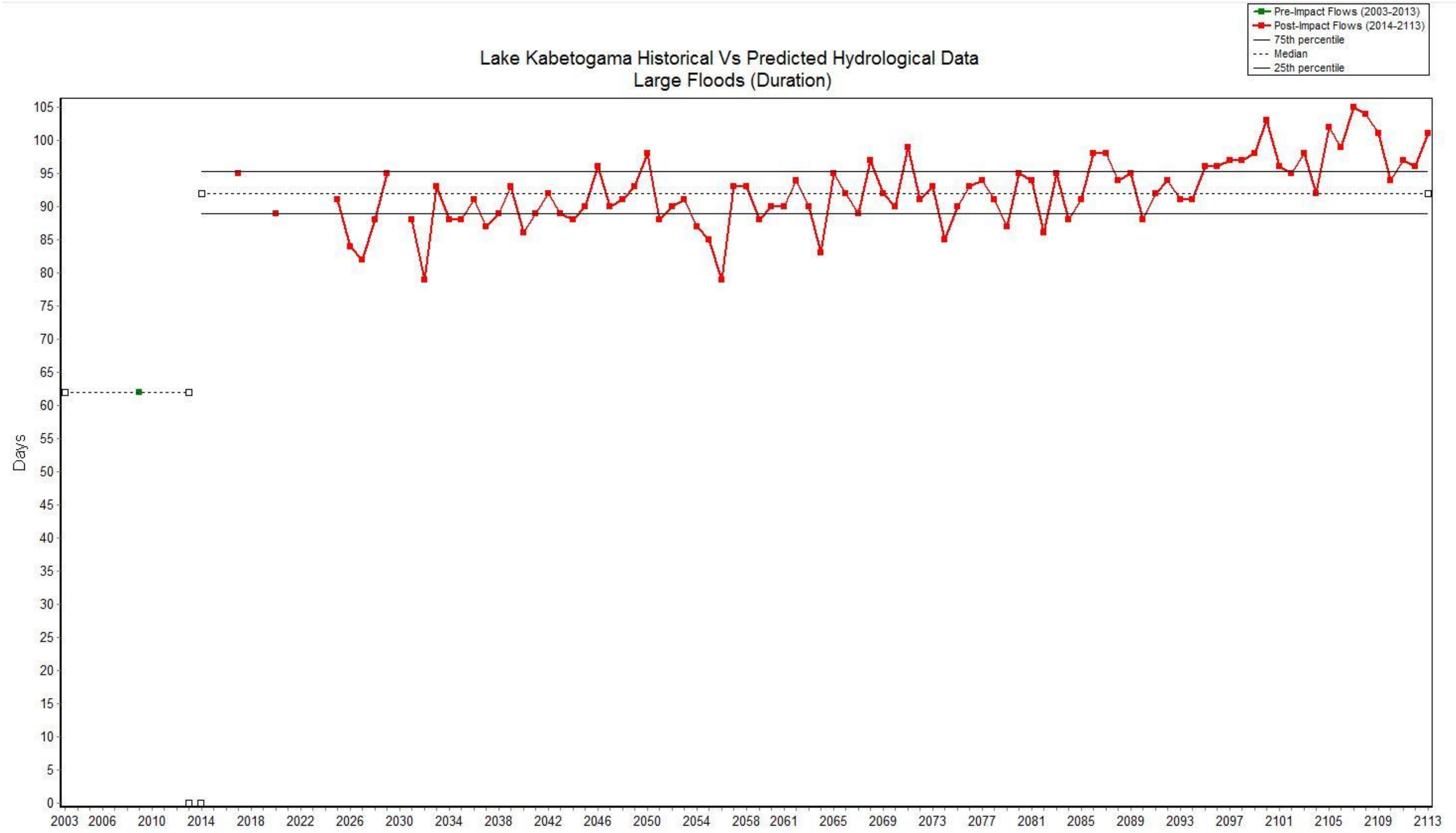


Figure 21 – Large Flood Durations of Historical and Predicted Flows

In summary the data from maximum flows is representative of a likely increased spring thaw being the controlling influencer for lake behavior. The spring flooding will cause saturation to the nearby surroundings for roughly a month and inundate the buffering wetlands. Likely causes are due to increased snowpack, later thaw time and drier summer periods experienced for the prediction time frame.

6.2.3 Minimum Flows

Minimum flow data is also generated for the same single and multi day scales as for maximum flows. Similarly to the maximum flows, the periods of 1 to 30 day minimum flow show a step up increase in median flow from historical levels and a linear increasing trend. The step up and increase of the minimum flows are not to the same magnitude and the slope of linear increase is less than that in predicted maximum flows. The minimum flow plots indicate more stability of low flow periods and magnitude for the prediction. Plots of 1-Day, 90-Day Minimum flows, Timing of Minimum Flow and Duration are shown in Figure 22 to Figure 42. Minimum flows compared to maximum flows, conform to the bounds of observed flow much better, with a trend of a slow reduction in the value of minimum flow. Discontinuities in Figure 25 represent no qualifying duration minimum flow events. The behavior appears to be consistent with slow draw down of the lake during drier summer months predicted.

Alterations to minimum flows suggest there will be less frequent and less severe low flow conditions as the lower 25th percentile for post prediction is greater than historical median. Overall the plots are very similar, with a slight increase in values and decreased variability.

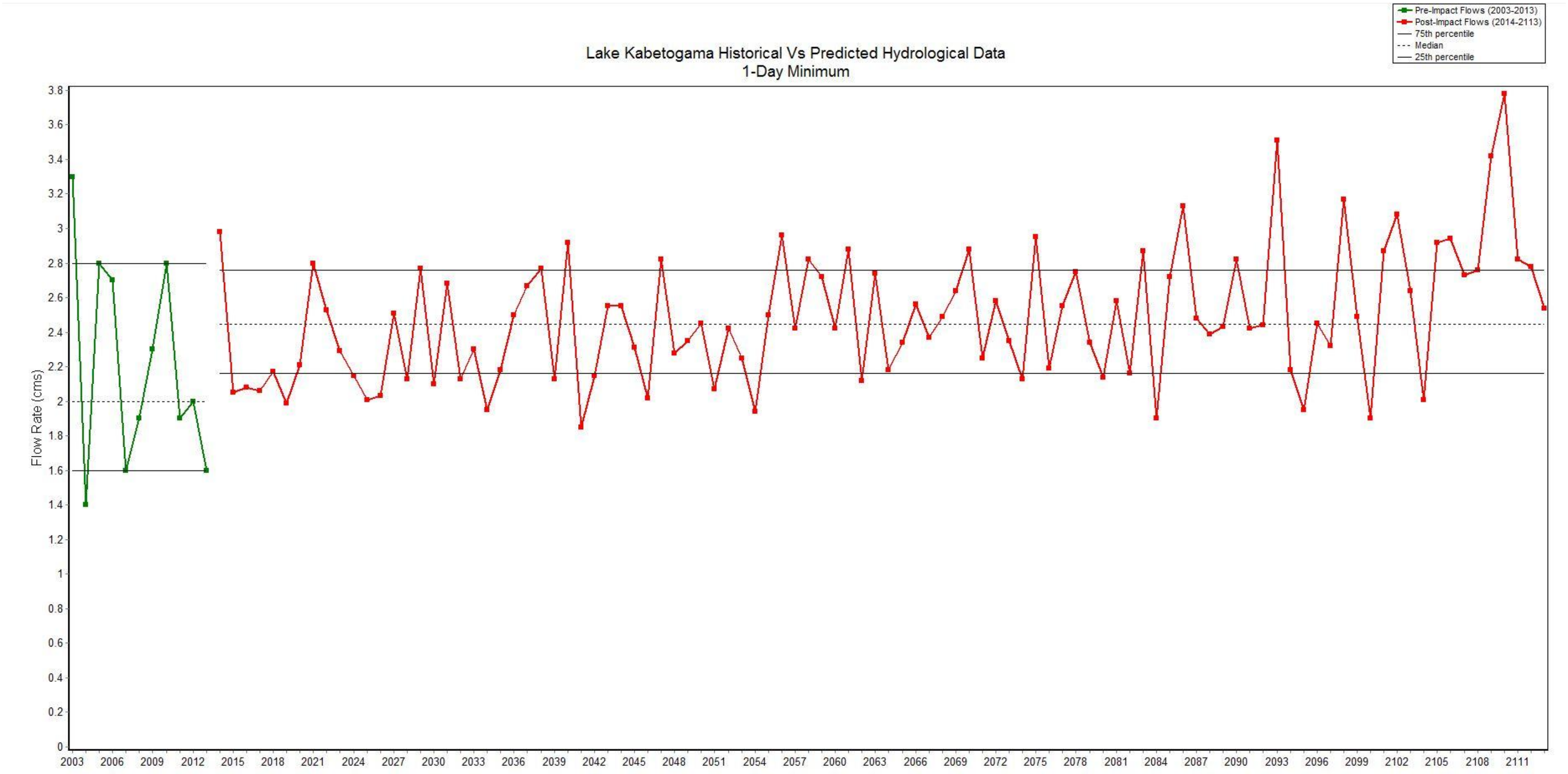


Figure 22 – 1 Day Minimum Flows for Historical and Predicted Outputs

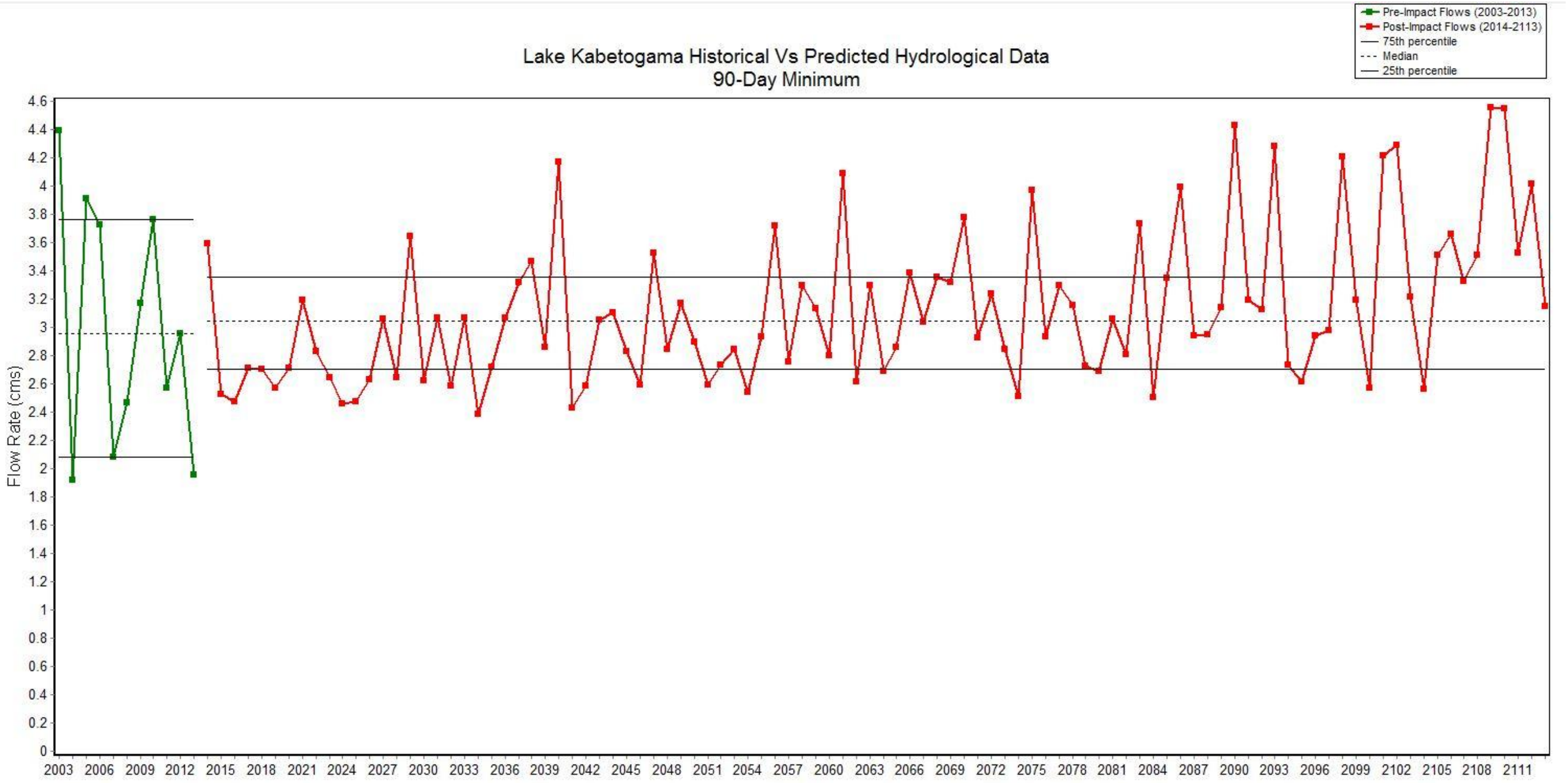


Figure 23 – 90 Day Minimum Flows for Historical and Predicted Outputs

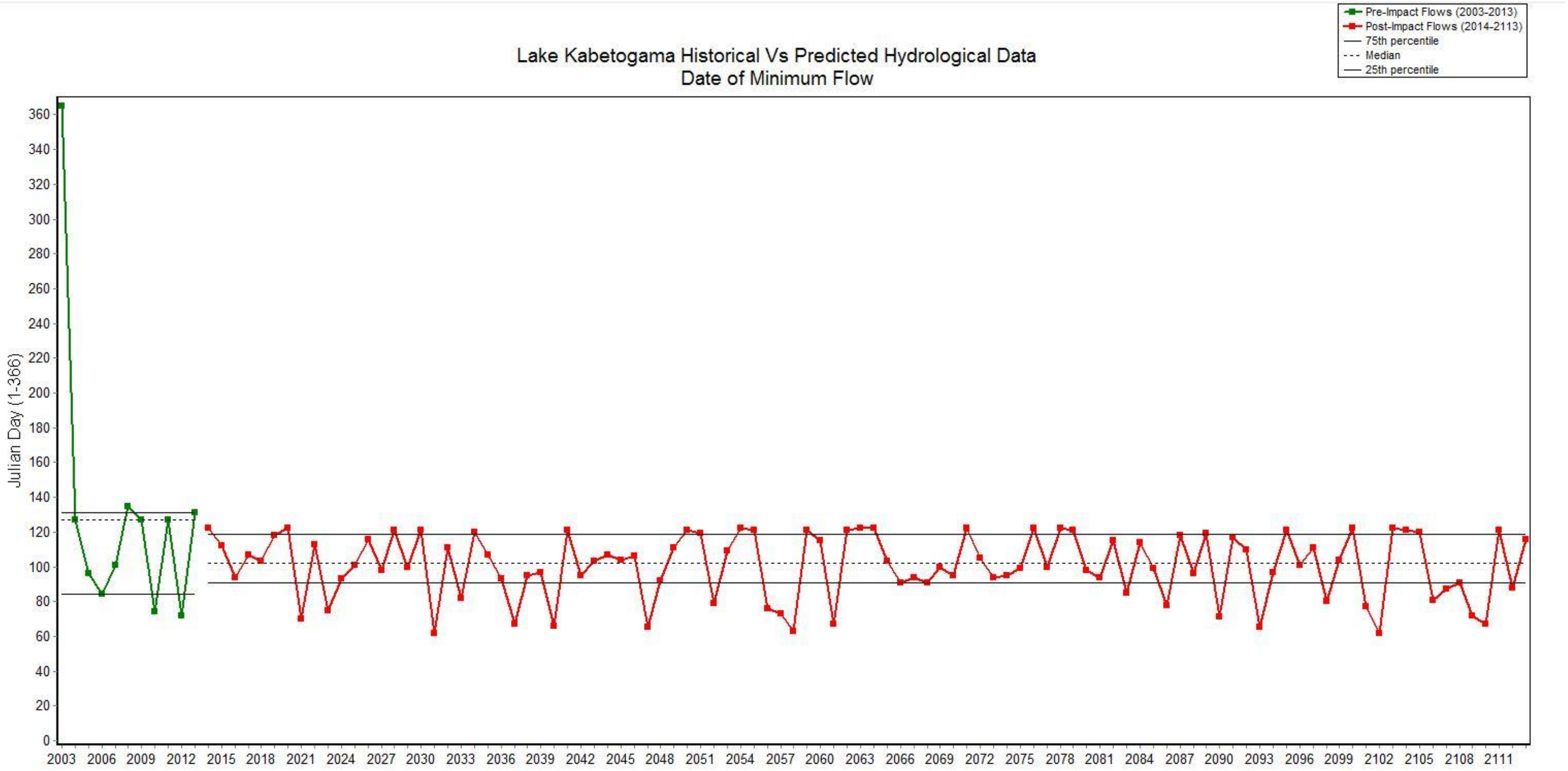


Figure 24 – Date of Minimum Flows for Historical and Predicted Outputs

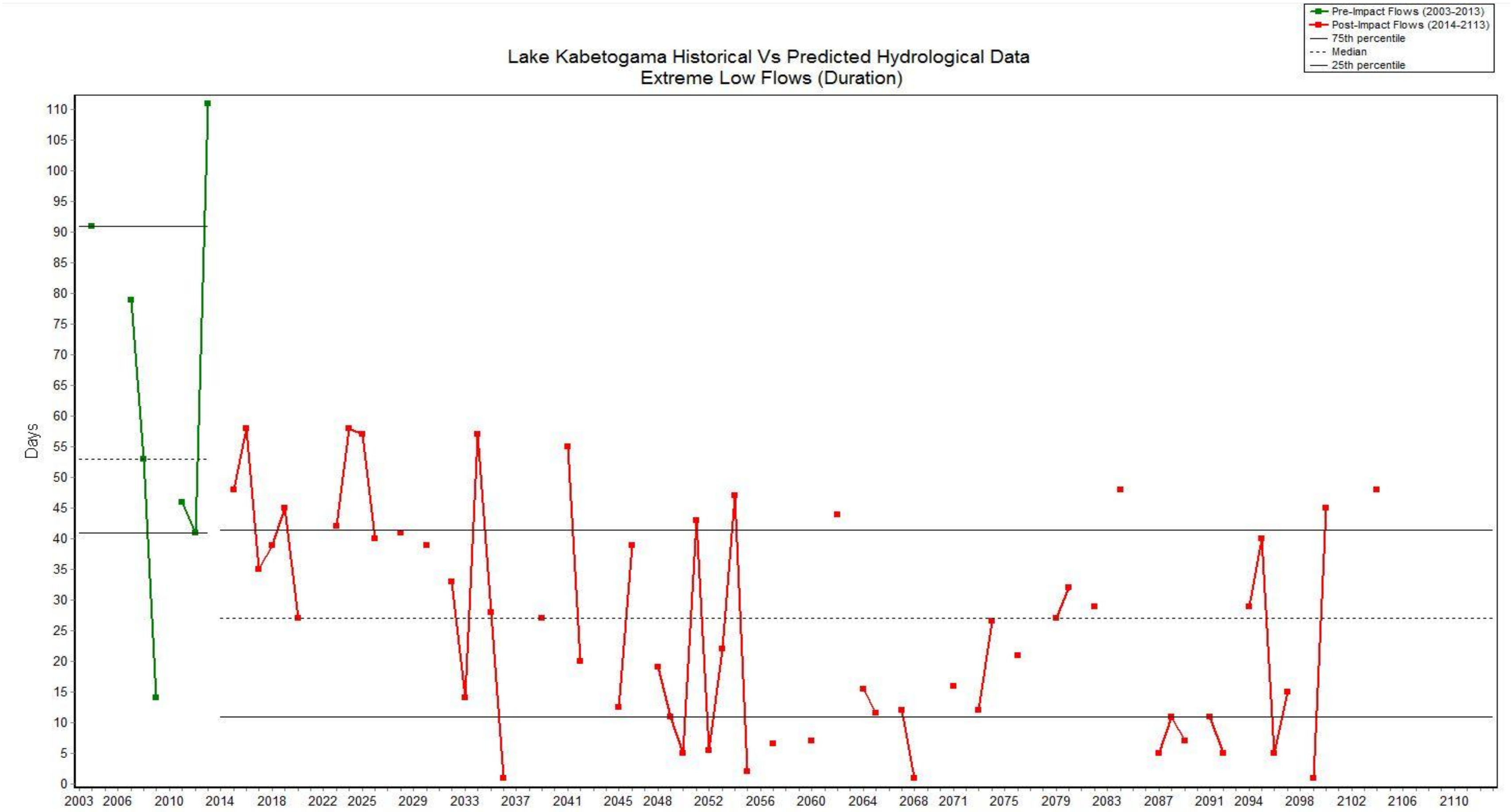


Figure 25 – Duration of Extreme Low Flows

The date of minimum flow in the historical model occurs typically in mid April to early May, representing the slow draw down of the lake during winter months. Winter months would have little to no substantial inflow, with outflow increasing as thaw begins. The mid to late winter cold snap typical of the region will cause ice depth creep and begin to dam up the outlets allowing only a small amount of the free flowing ground and lake water to flow through the water body. In the predicted simulation, a similar trend is seen but with greater variation in date range. Duration of extremely low flow (flows less than 10% of median) events decreases steadily from the 54 days historical model to 28 days. Frequency of extremely low flow events remains relatively constant over the study period, which may be attributable to the increased temperatures expected during the prediction years. The increased temperatures, even during winter months would add a small increase to winter inflows and mitigate occurrence of extremely low flow events to some degree.

6.2.4 Summary of IHAs

Monthly flow alteration (Figure 16) illustrates overall predicted change on the long term for median flow values compared to historical on a monthly scale. The predicted model sees flow values that spike significantly during the spring thaw period and early summer in the later years of the study thus the resulting high peak in May (Figure 16) for the predicted flow is skewed to some degree.

In summary the maximum and minimum flows indicate that according to the simulation the lake will behave similar to the historical trends over the short term, but with more pronounced spring melt and run off. The information also coincides with that displayed by the mean flow data which is taken over the 100 year study span (later years also have skewed values of maximum and minimum flows). Interpreting the data described indicates the primary method of alteration to the water body is through the maximum flows peak, duration and timing. The prime alteration is physically measurable in spring melt and run off, consistent with what is to be expected of increased snow pack and increased summer temperatures.

As the peak flow timing would be advanced two months forward (from July to May), any species that rely on peak flows as signal indicators for reproduction or growth periods may be negatively impacted. Other potential outcomes are that increased depth of water during early spring will impair the growth of aquatic plant life that in the lake's interior edge of the littoral zone. Reduction in early spring plant life may experience some rebounding in late summer and early fall as mean water levels dip below historical, however the dip could cause near shore vegetation to have less water available for growth.

6.3 Limitations, Information Gaps, Sources of Error

There exist inherent limitations, information gaps and possible sources of error in any research study and those specific to this study and the possible impacts are expanded on in the following paragraphs.

Limitations of the study begin with the modeling software used as HEC-HMS utilizes a set of static parameters that do not change with respect to time (USACE 2009). For the study period of 100 years there could be significant alteration to conditions of the watershed that would alter parameters. In its present state HEC-HMS is not capable of dynamic parameters but future versions may (USACE 2009). In addition the time step used is a daily scale which will degrade resolution of resultant outflows. As a result the predicted model's accuracy will be reduced in the later years of the study.

Other limitations include the availability of historical flow precipitation data records and physical watershed information. The available records are for a relatively short period of time around 3-10 years depending on data type. 10 years is typical of cyclical trends (White et al., 2008) and data sets spanning less than 10 years could result in trends not being fully developed. Lack of trend development in data analysis reduces the value of direct comparison and statistical significance.

Soil property data was limited to the south western segment of the watershed, which introduces potential error as soil properties cannot be assumed to be completely uniform throughout the entire watershed. Given that most of the watershed has similar land cover, is a relatively undisturbed state, and the assumption that soil data available is representative of the entire watershed was made. In the future more availability of soil data for the entire watershed would increase accuracy. Groundwater contributions are not fully captured by the model which also leads to some inaccuracies.

Qualitative valuation of ES, in this study measured in terms of predicted change, limits extent of the accuracy of the value. The limitation is due to variation in intrinsic values on an individual basis for recreation and aesthetic services.

For example two people with a career and personal life that demands much of their time may place distinctly different values on the recreation and aesthetic services. One individual may find that these services are worth a considerably large amount due to the demands of their career, where as another may find that due to the marginal costs (time commitment) devoted to utilization of these resources, the personal value may be reduced compared to the first person.

Due to the remoteness of the study watershed information available for many parameters used in the study has gaps. Resolution of information gaps could alter the watershed properties used in the HEC-HMS model which would change the outputs. Other information gaps occur within the historical data records in the form of missing time stamps. The impact of these missing data points is likely negligible but could still potentially decrease accuracy of predictions and comparisons.

Sources of error include the discrepancy noted with the surface elevation measurements perviously discussed. This type of error in data was accounted for during elevation calibration described prior, but more precise field measurments could further enhance accuracy. The surface elevation of the lake is an important parameter for the study as it effects discharge rates, initial conditions and outputs greatly. Additionaly, as this lake is relatively large, the effects of WLF are potentially minimized due to innate buffering of the large volume of the water body.

6.4 Conclusion

Based on the simulated response of Lake Kabetogama in this study to predicted precipitation and temperature shifts (based on previous research by others), the qualitative value to ES of the impact of WLF on ecological processes being valued will be minimal. Minimal changes mean that current recreational and aesthetic ES will remain stable over near time frames, despite the influences studied. It was not possible to further qualitatively describe the extents of these changes, for example through the number of resort fishing trips booked or likely to be booked. Quantitatively if changes are to be minimal then the annual economic impact of $100 Million (American Rivers 2013), from the BWCA to the region should also remain relatively stable.

Changes in water level amplitude increase slowly over time, allowing for some adaptation. Amplitude values also remain near the optimal output level for some time, yielding little negligible change to the current state. The WLF of the predictions consistently occur within the bounds yielding maximum species richness. WLF as seen in this study would have negligible impact on aquatic life due to the changes in hydrologic conditions. Hydrologic alteration is primarily due to what appears to be increased snowpack and spring melt run off from the precipitation shift, and slightly decreased summer precipitation and water levels due, to the expected temperature and precipitation pattern shifts.

The most likely source of negative alteration and impact to the ecosystems on the near and long term, and their services is from direct human interaction. The HEC-HMS simulation cannot account for dynamic parameters such as potential and unknown future human interactions; as such this source of alteration was not addressed. Future human influence is unknown, but the land surrounding Lake Kabetogama falls within the Voyageurs National Park, a protected area similar to the BWCAW and human impact will be minimal so long as current policies regarding protected lands remain in place.

As expansion continues, pristine wilderness will become increasingly rare which could drive up use of the area and cause direct human impact and disturbances to the ecological system. Increased future travel costs (time, fuel, etc., which are part of ES valuation) may counteract the increased demand but the extent of these impacts is unknown. As undisturbed and protected lands become encroached on and water resources become scarcer it is possible political impacts may alter protection policies either in favor of or against increasing human alteration and those effects on ES cannot be determined at this time.

6.5 Further Recommendations and Future Studies

This study serves as one of several starting points in understanding the impacts of the predicted climate changes and WLF responses. The potential changes of aesthetic and recreational ES will vary depending on whether the watershed is largely free of human interference and influence. The results are only a prediction of the many possible outcomes and future studies would refine and improve upon this work.

Future study could include further revision of the HEC-HMS model to include spatial variance with input data through the use of gridded data sets or use of modeling software to allow for a fully continuous 100 year simulation. This thesis created a method to predict precipitation for the local eco-region and provided a basic analysis of the affects through HEC-HMS and better modeling software will provide more accurate results.

Gridded data sets are not currently available for Lake Kabetogama; however other lakes could be studied. Other revisions could include the use of increased historical data records for precipitation, temperature, lake surface level and outflows. Revision of inputs could be accomplished by revisiting the study after several years when more data has been collected and would increase accuracy through model calibration and provide more statistical significance for comparisons.

In addition to use of different software to continuously simulate the 100 year time span, coupling the decadal approach with predictions of changes to the watershed, such as human population growth and expansion, over 10 year spans would increase accuracy. Coupling the parameters and inputs in this manner could, for example determine if there will be increased human expansion in the area and alter the amount of impervious area present and how the lake will respond. A similar process could be applied to tree species and growth to determine if trends in forest extent may have a significant impact on the area. By conducting an iterative prediction process it would be possible to overcome some of the limitations of static parameters with the version of HEC-HMS used.

The study did not allow for long term samples to be collected from Lake Kabetogama. It is further recommended that future studies sample density of biota population counts within the littoral zone and water level at varying times of the year, conducted over the course of several years to further establish the relationship between WLF and the amount of aquatic life. The principles of the study could also be applied to additional water bodies as a framework for conducting studies of other watersheds and the ES present.

Lastly recommendations regarding valuation for quantitative purposes are advised to improve accuracy of the study and knowledge of the relationship between the study and the targeted ecosystem services. This could be conducted through several means including increased time scale devoted to the study to allow for several seasons of data collection of use from local industry. For example the study does not take into account winter recreational uses, such as ice fishing which may or may not be have a strong correlation to WLFs. Additional partnerships with the US Forest Service, Canadian governmental organizations, the DNR and USDA would leverage increased resources and expertise to better study the impact of WLF and value of ES of the BWCAW.

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Appendix A:

A.1 Supplemental IHA Figures

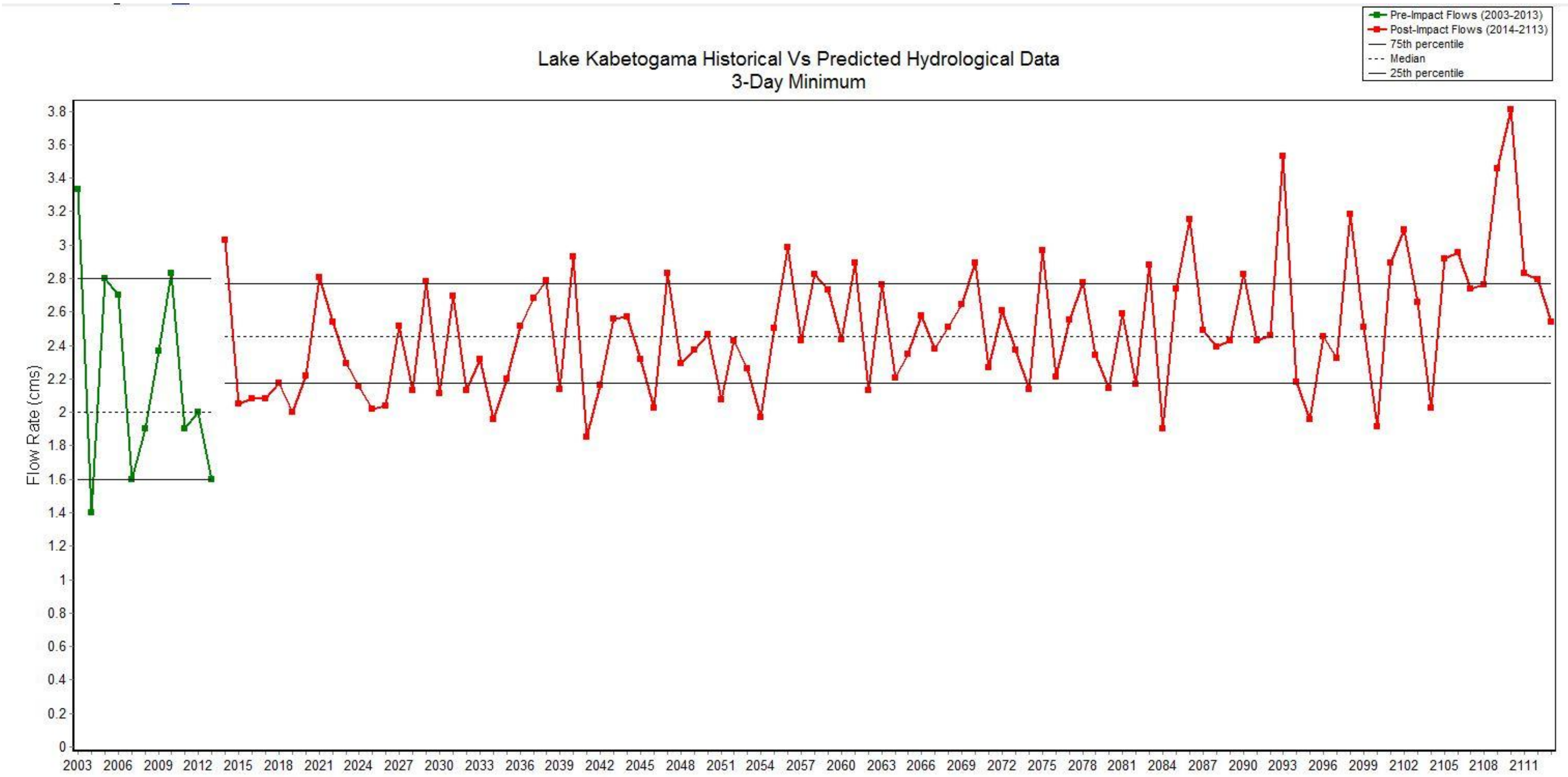


Figure 26 – 3 Day Minimum Flows

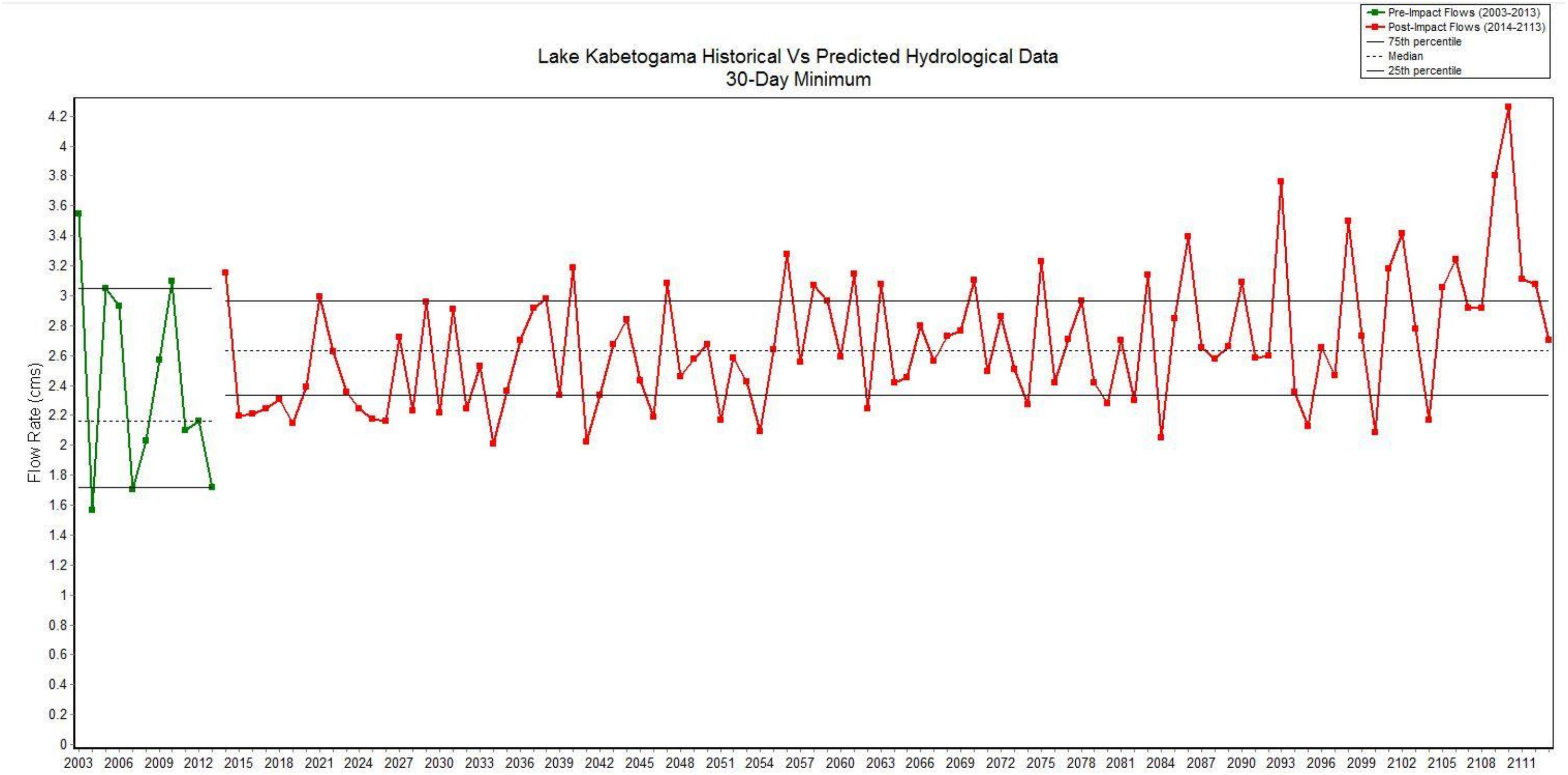


Figure 27 – 30 Day Minimum Flows

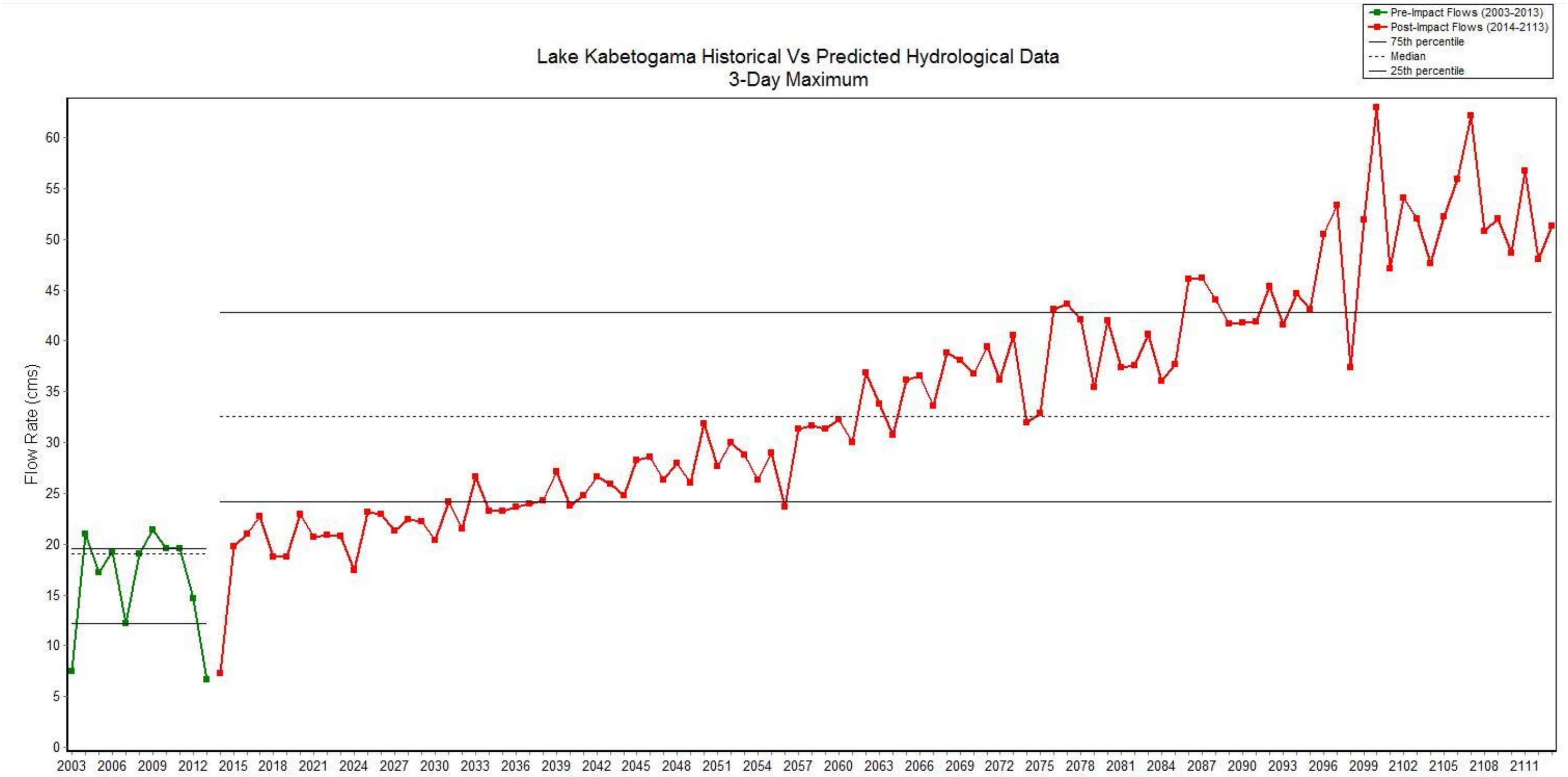


Figure 28 – 3 Day Maximum Flows

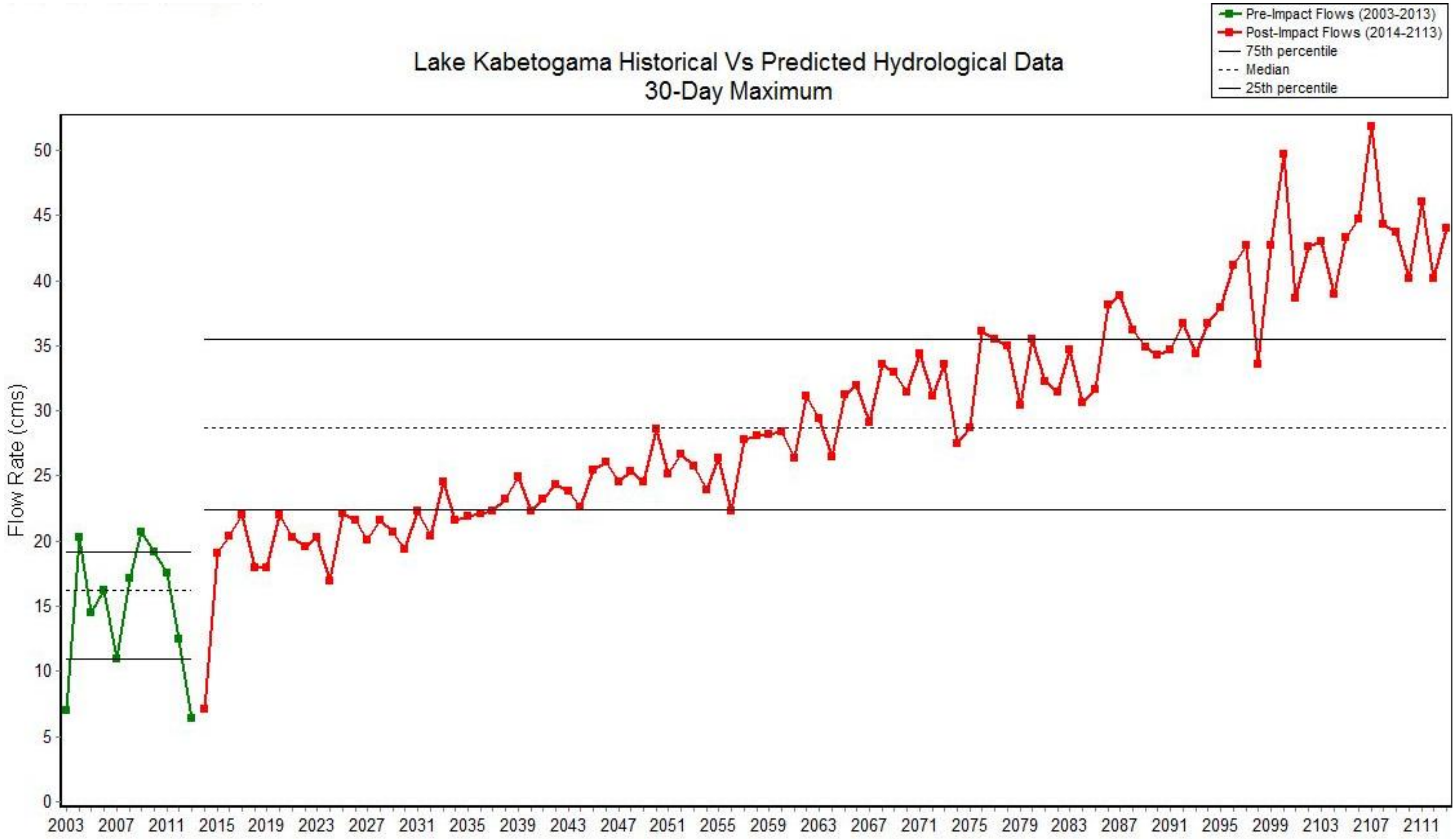


Figure 29– 30 Day Maximum Flows

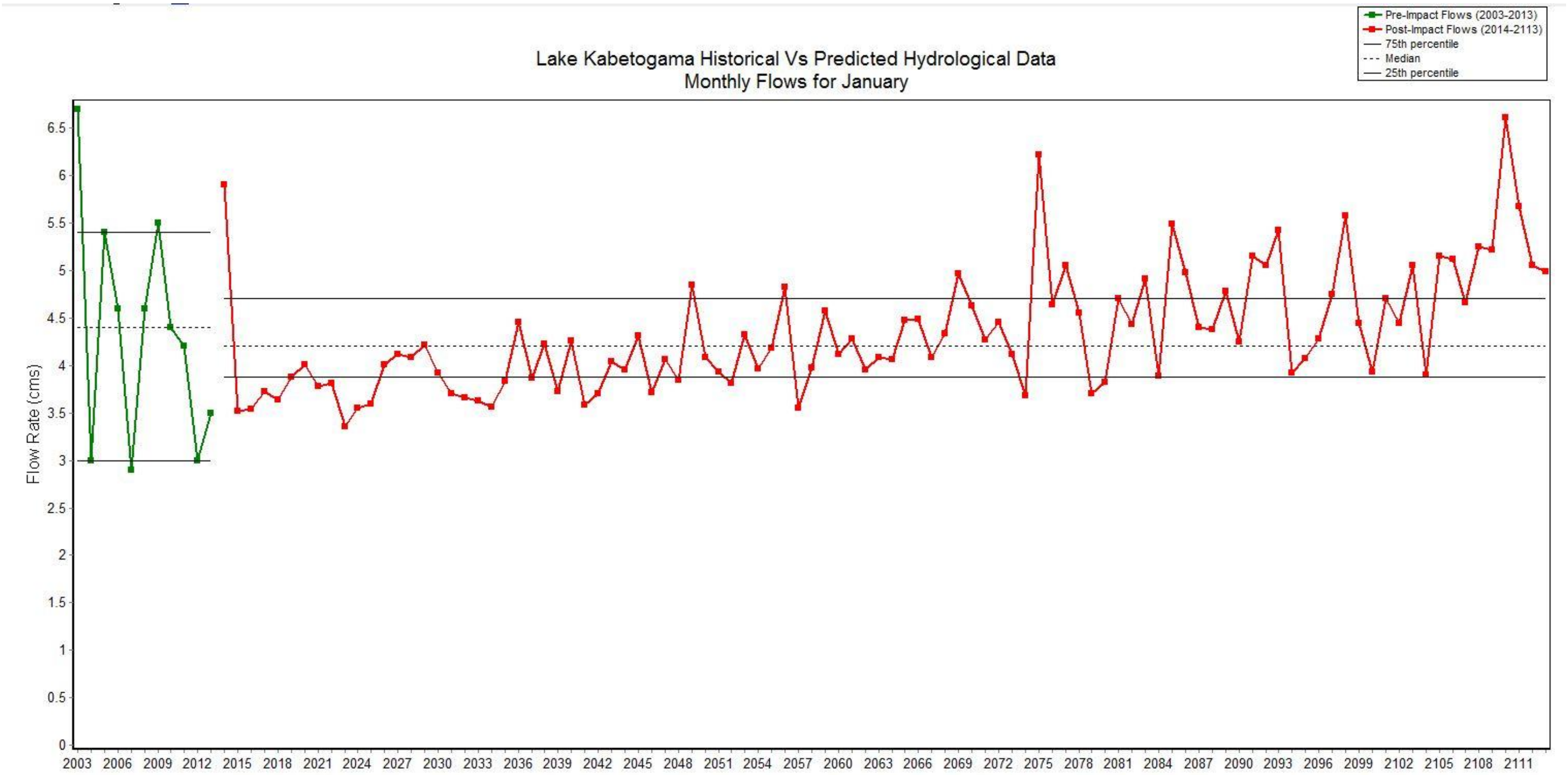


Figure 30 – January Monthly Flows

January flows remain close to the historical simulation, with a slight upward trend and increased lowered bound, indicating the predicted temperature shift will increase flows slightly for the month of January.

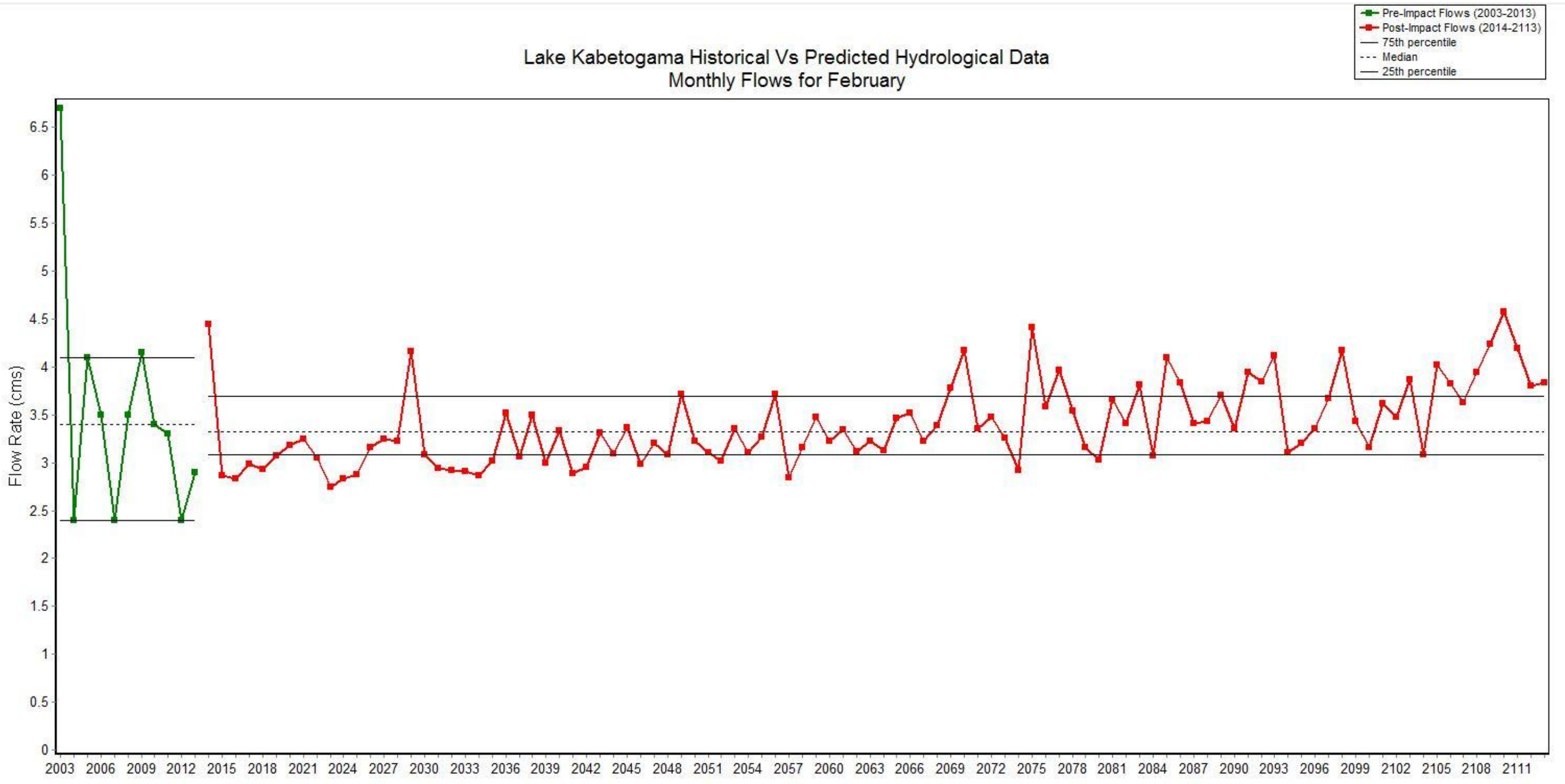


Figure 31 – February Monthly Flows

Flows in February remain nearly the same, even with respect to mean and fluctuation.

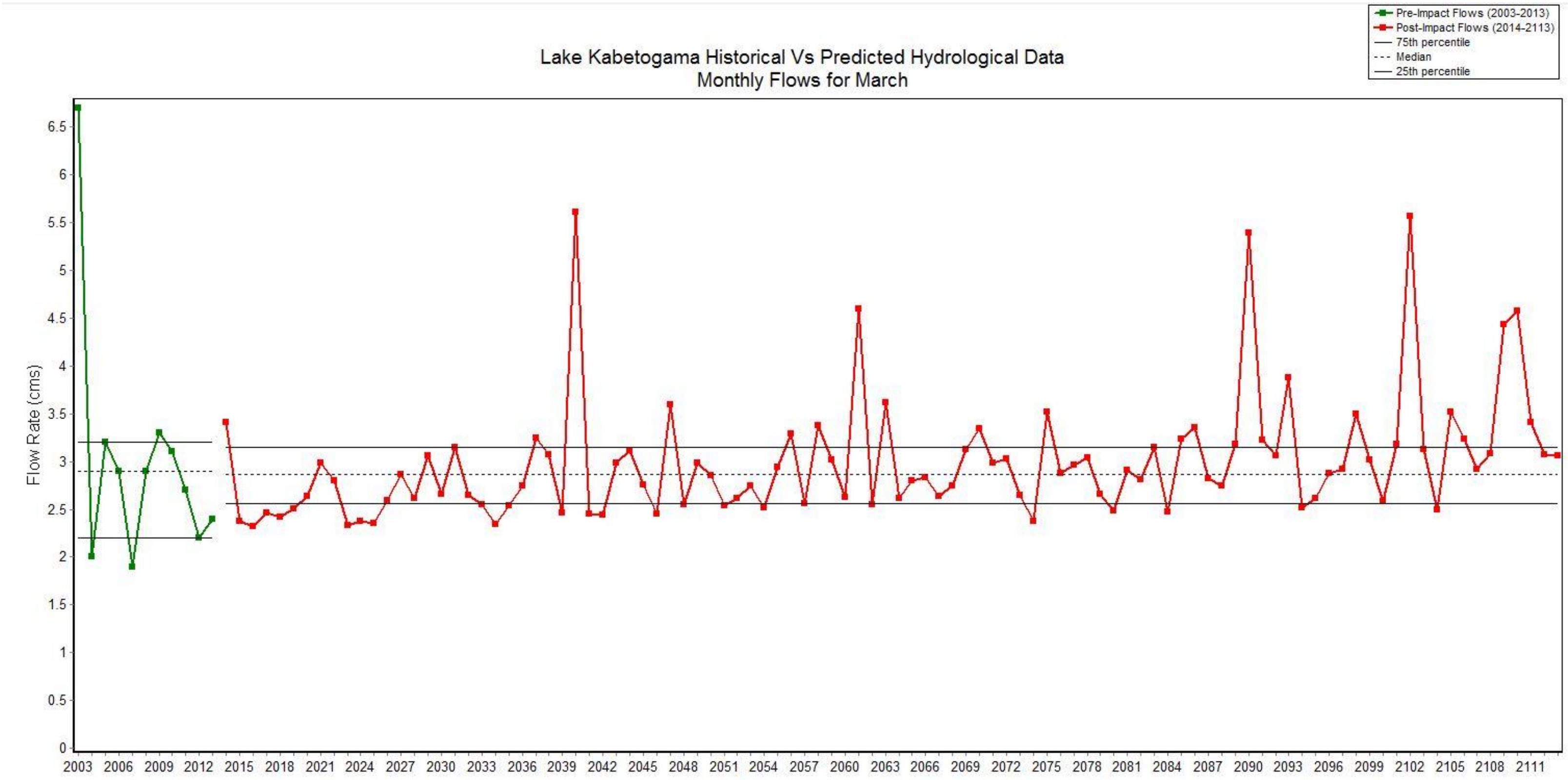


Figure 32 – March Monthly Flows

March flows are within the normal range but with increased variability compared to historical precipitation outputs, and a very slight upward trend.

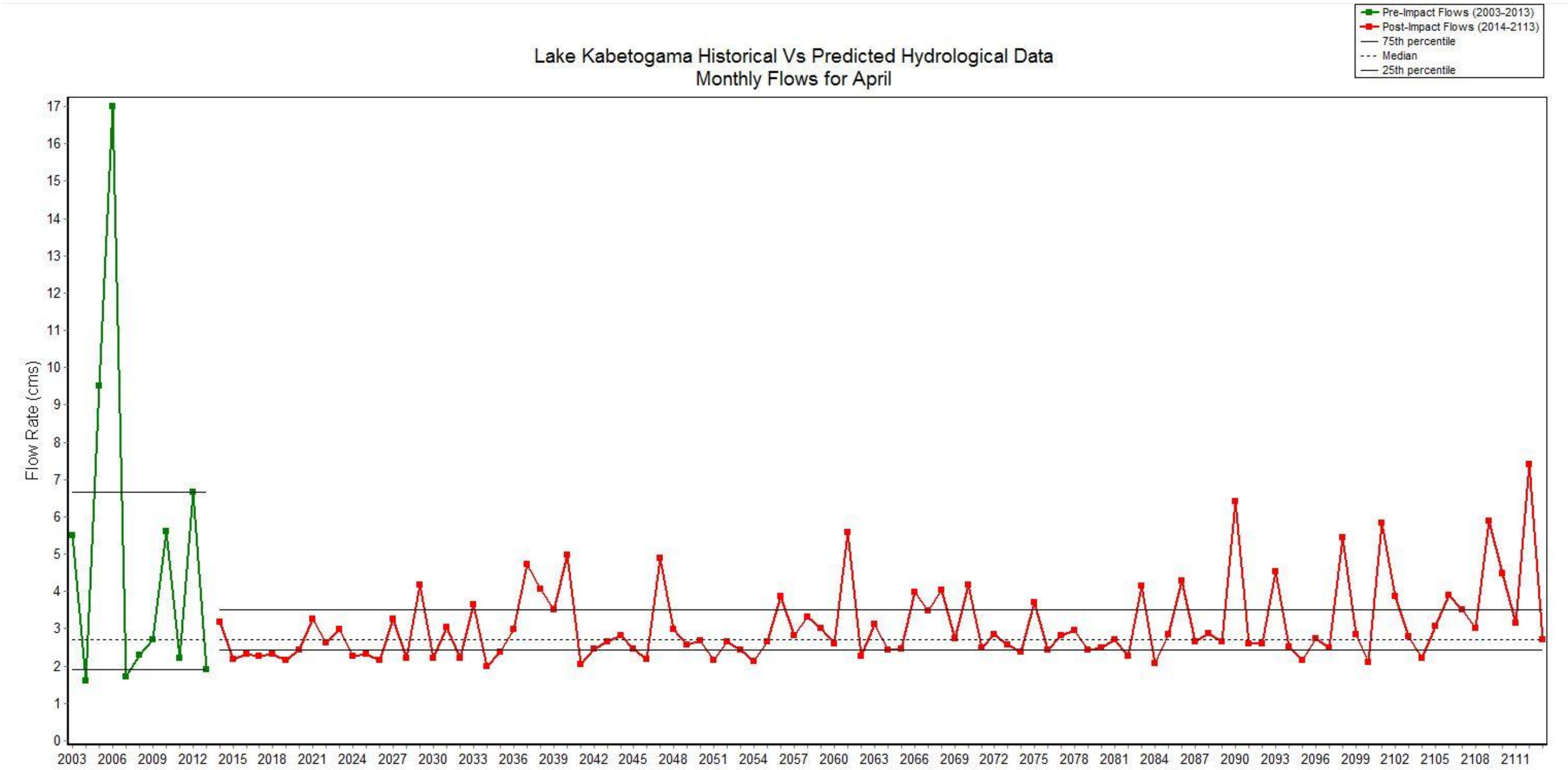


Figure 33 – April Monthly Flows

April monthly flows are decreased compared to historical precipitation outputs, indicative of ice creep described earlier.

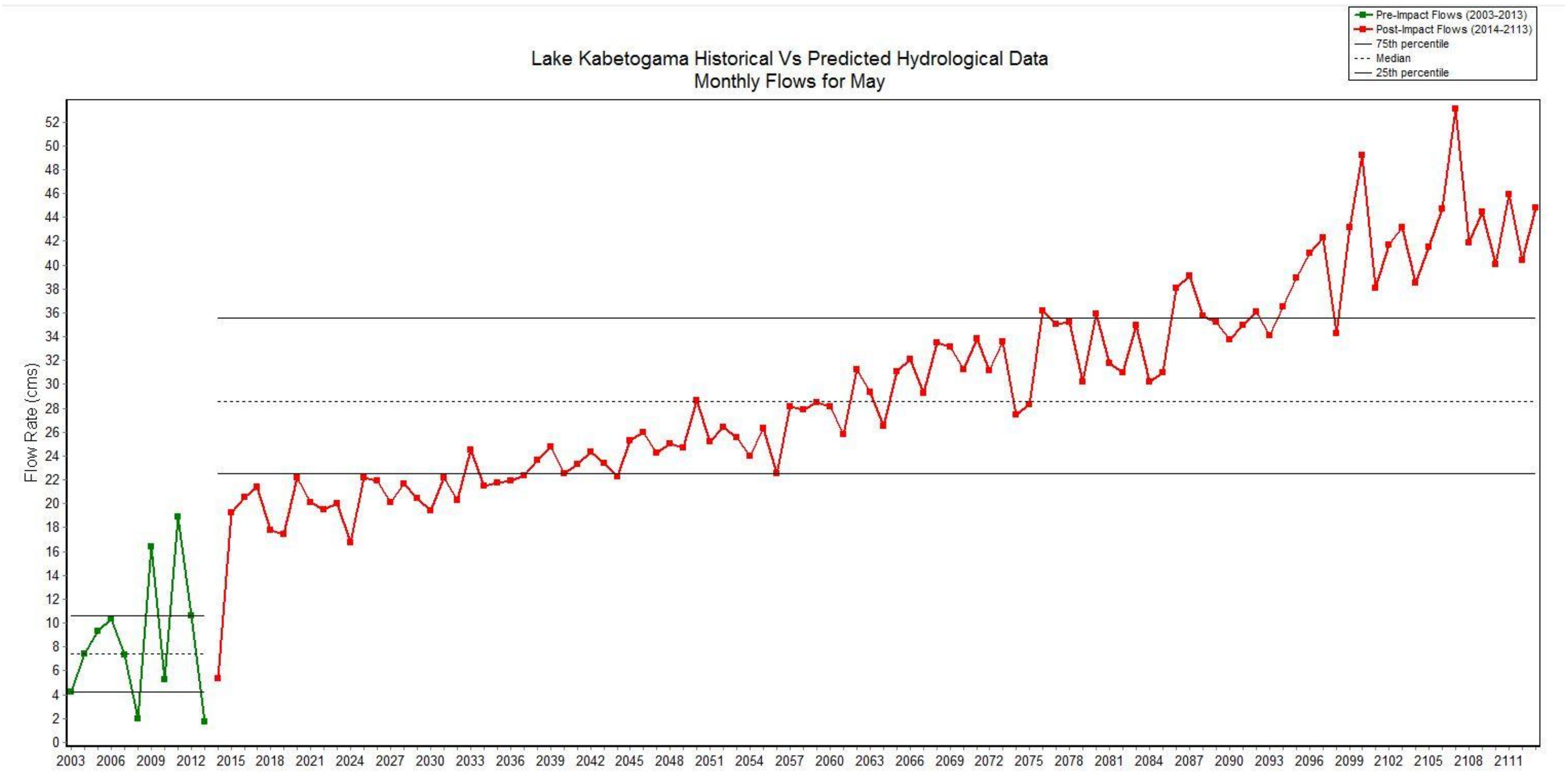


Figure 34 – May Monthly Flows

Historical May monthly flows show an increasing trend, and predicted flows follow but at an advanced pace. The increase is in keeping with literature predictions, but the extremely sharp increase possibly indicates an issue with the model or predicted data.

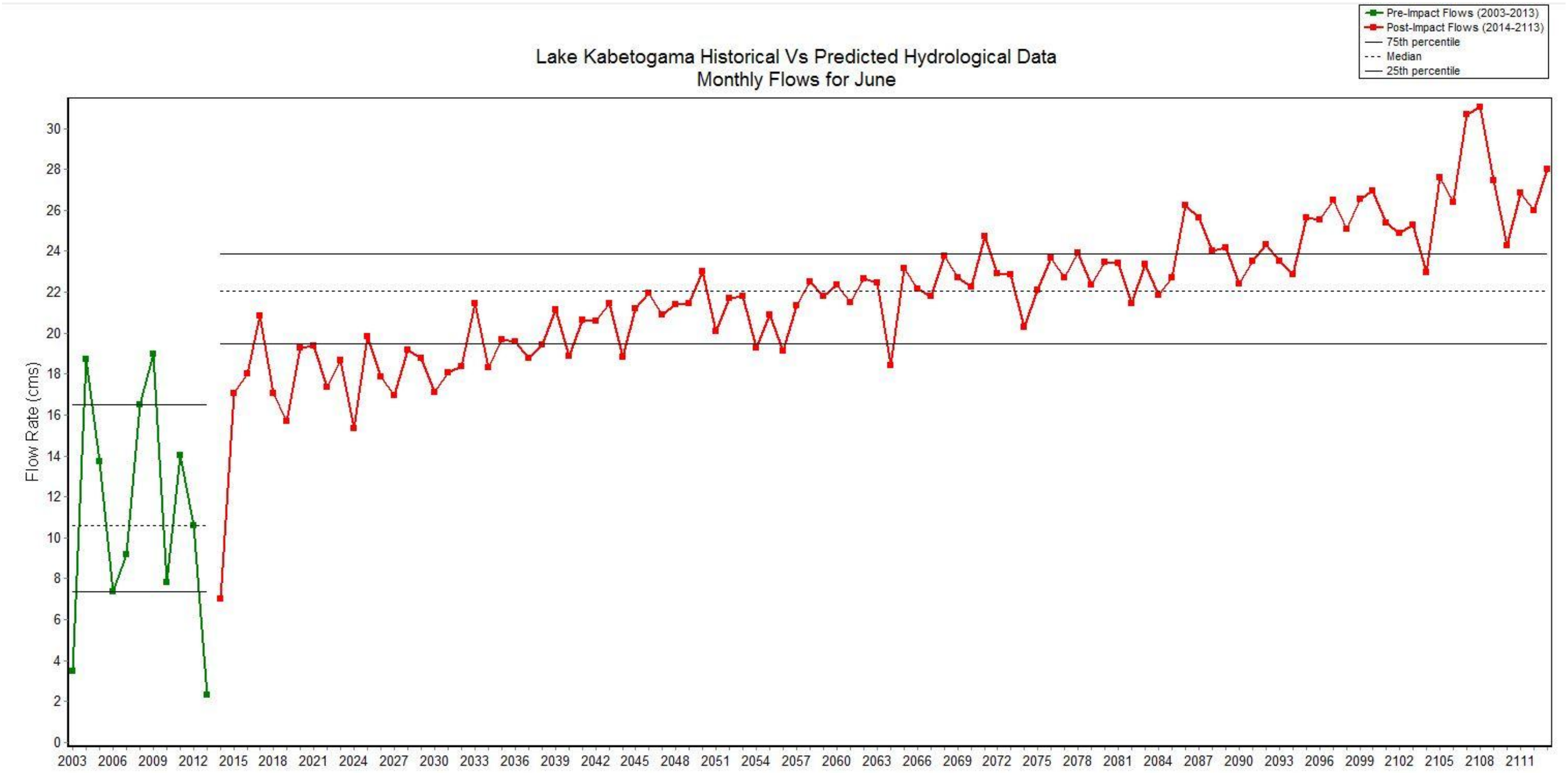


Figure 35 – June Monthly Flows

June flows also show an increasing trend, the extent and magnitude are more within line of historical trends and suggests that the predicted temperature shift data and precipitation are more likely to occur and reinforces the probability that any issues with the model are localized to the month of May and spring thaws.

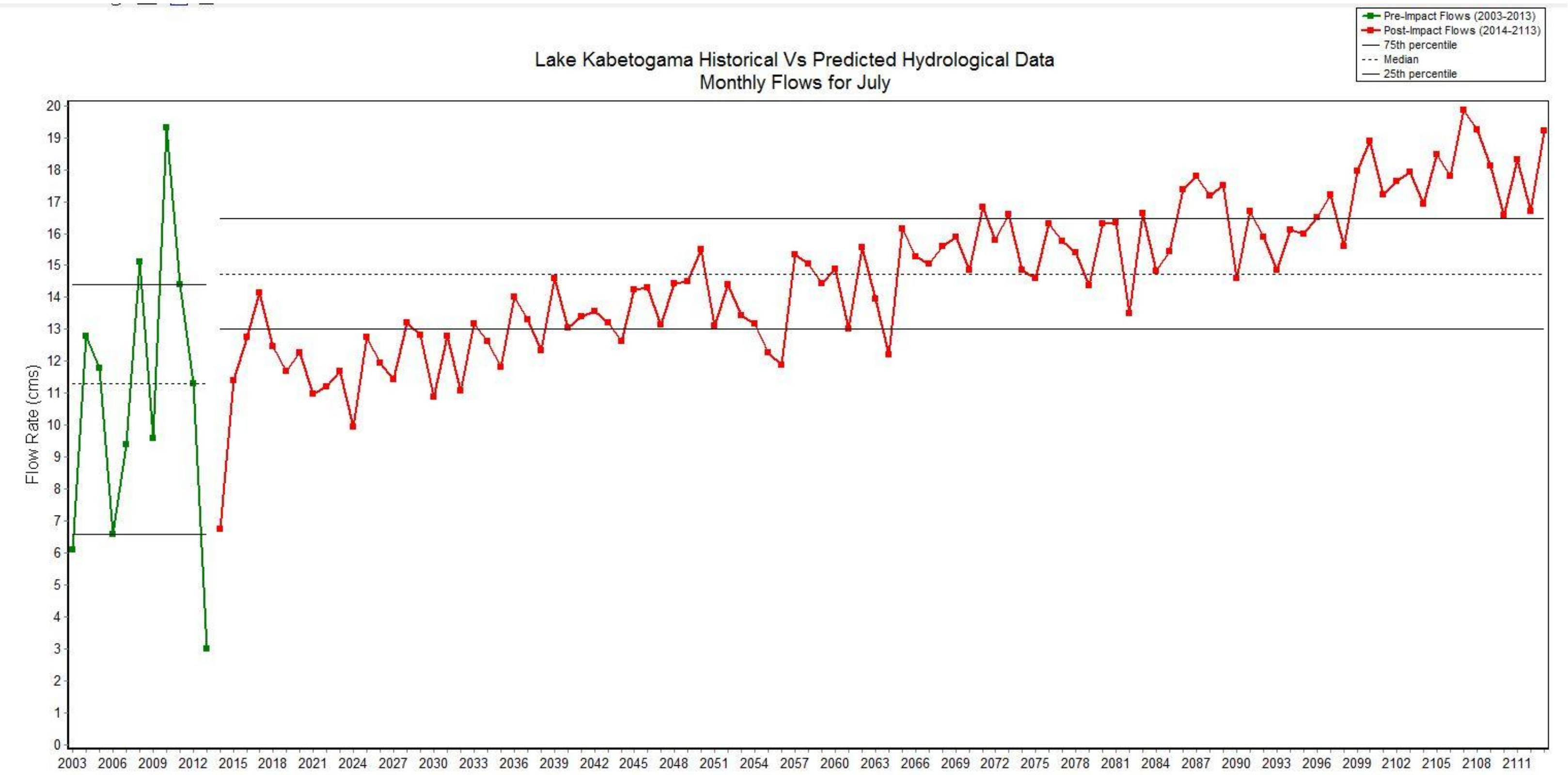


Figure 36 – July Monthly Flows

July flows show a slight increase, which is not representative of the predicted drier summers, but as the magnitude of increase is relatively small it is probably indicative of the predicted growth.

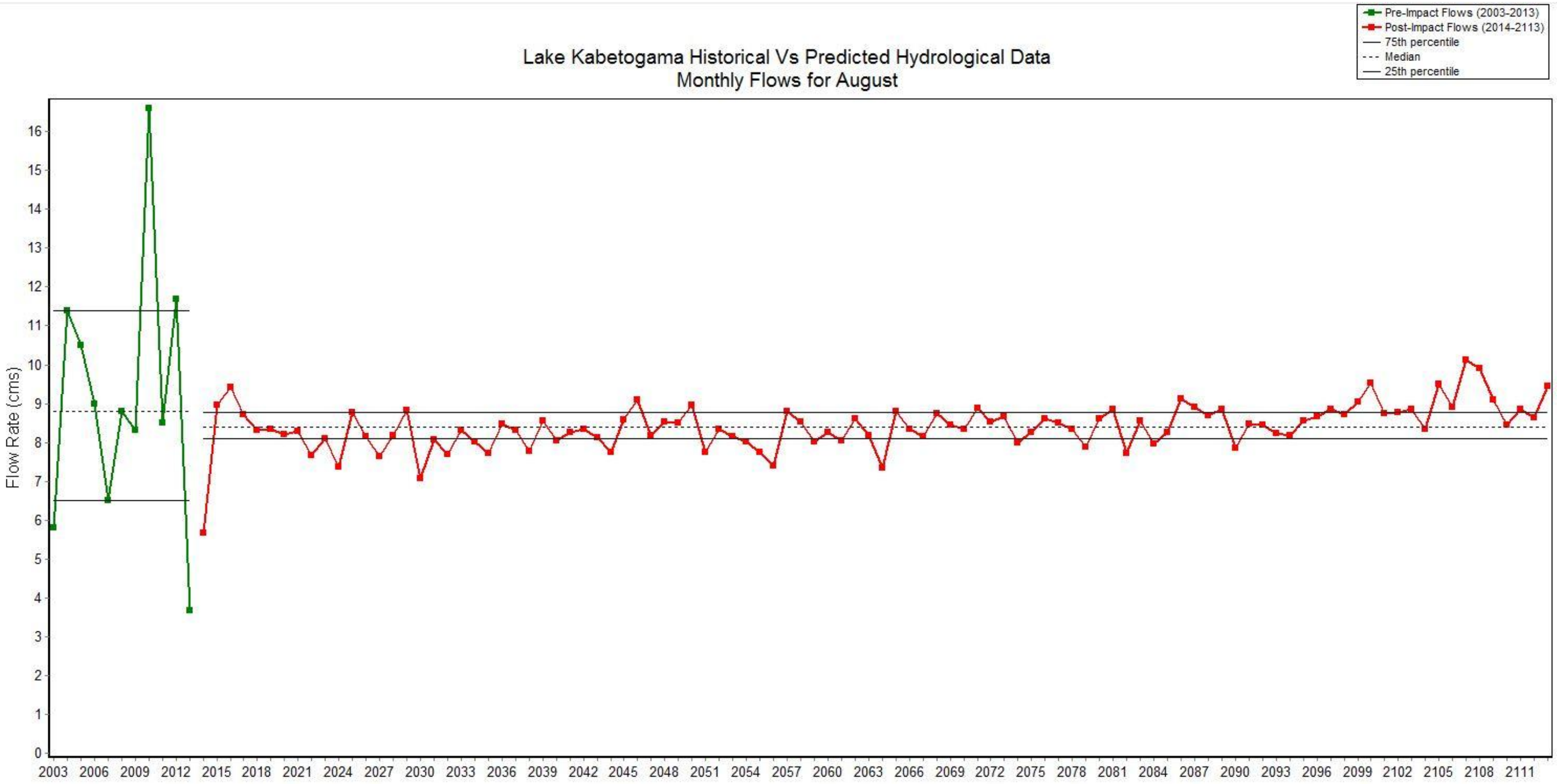


Figure 37 – August Monthly Flows

August flows are nearly linear with limited fluctuation which supports the predicted drier summer. The delay in stabilization of flows in the calendar year to later summer may be due to the storage volume of the lake buffering the impact of decreased precipitation.

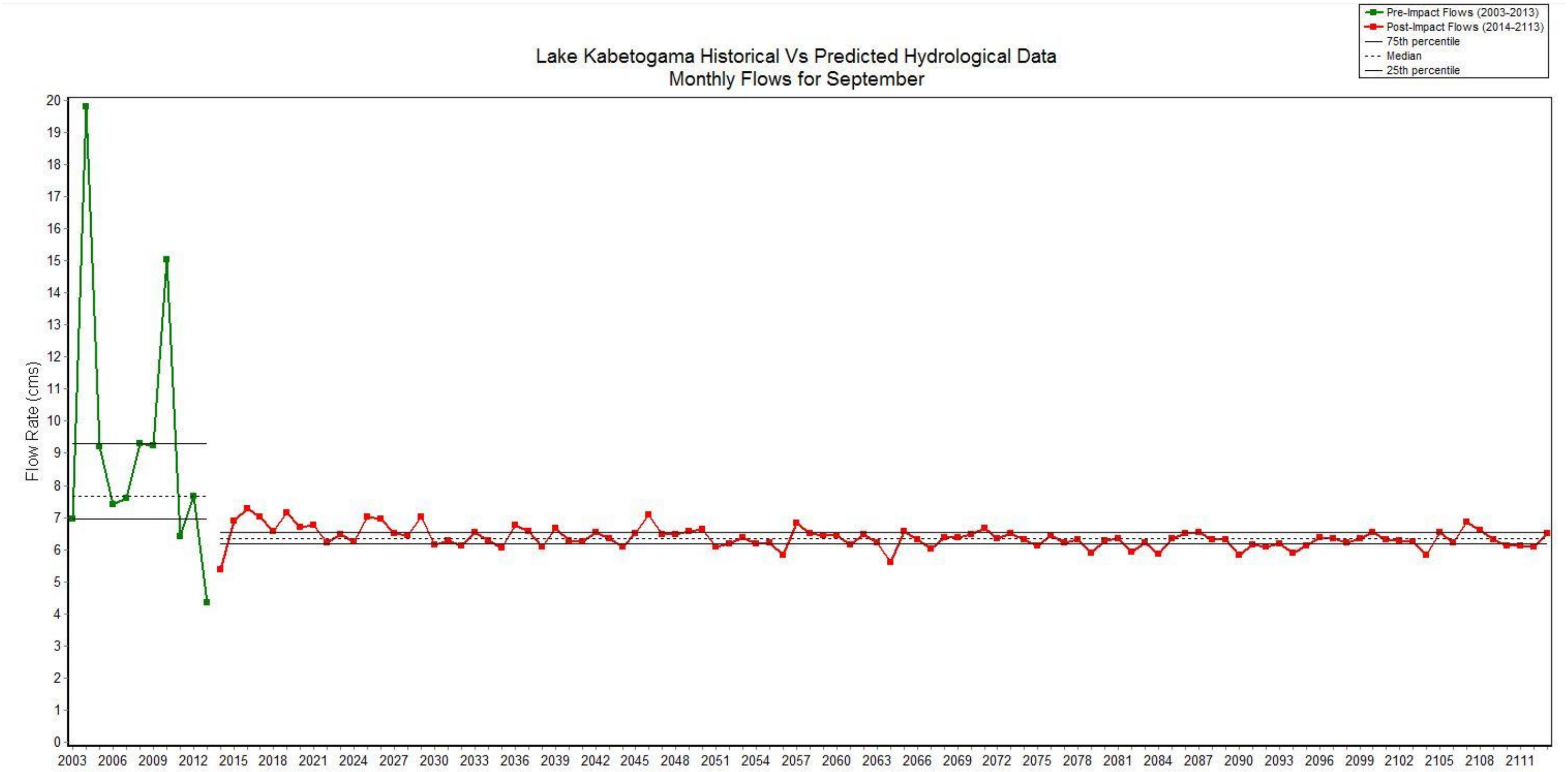


Figure 38 – September Monthly Flows

September monthly flows are slightly decreasing and very stable illustrating the predicted shift to dry summers as the lake draws down and limited precipitation causes little to no variation in output.

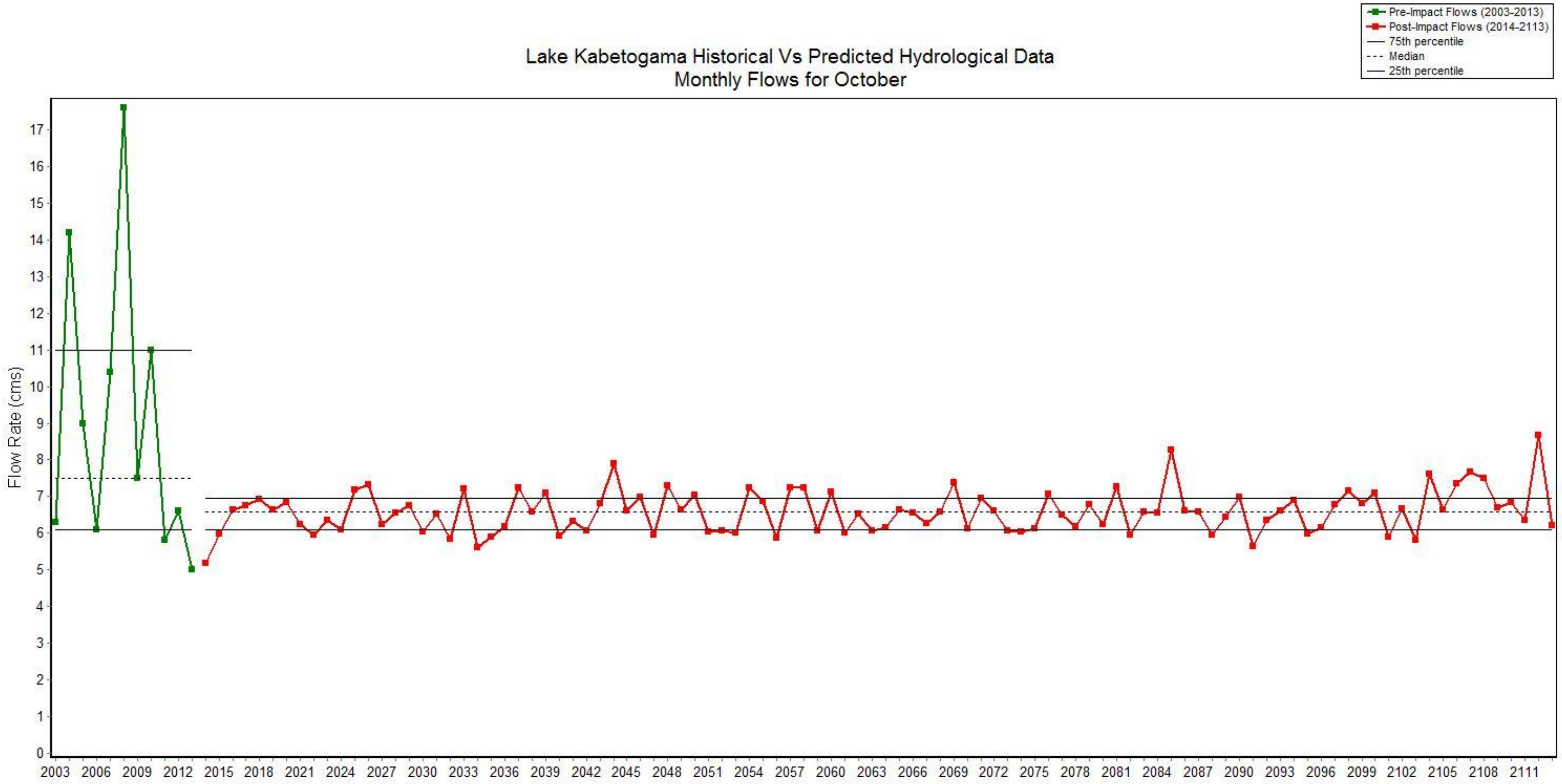


Figure 39 – October Monthly Flows

October monthly flows continue the decreased flow trend of the season with flow rates below historical means that begin to rebound and increase near the end of the study period.

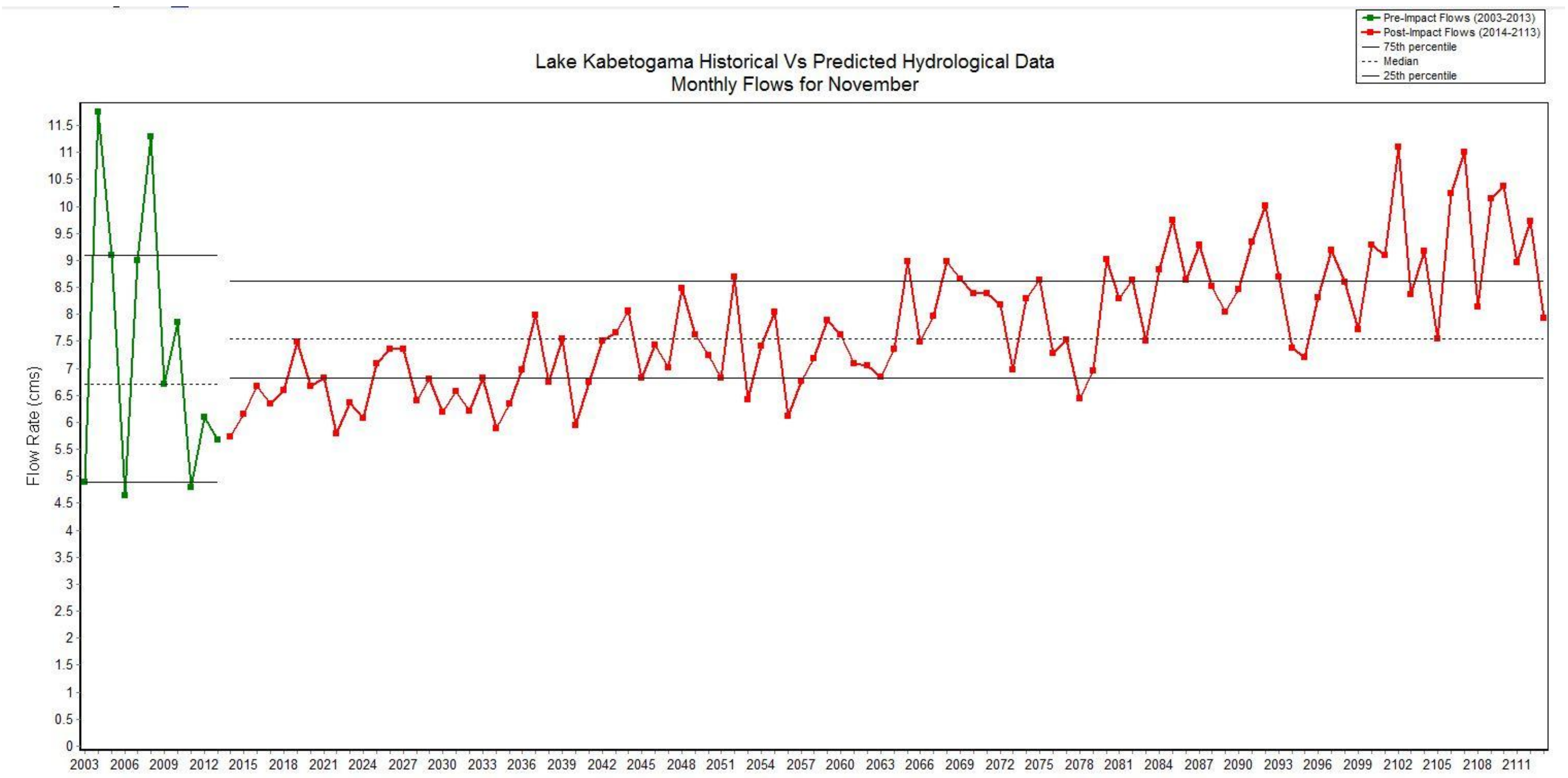


Figure 40 – November Monthly Flows

The flow rates in November begin to show more of the winter month increased precipitation and rebound of flows before winter freeze takes hold.

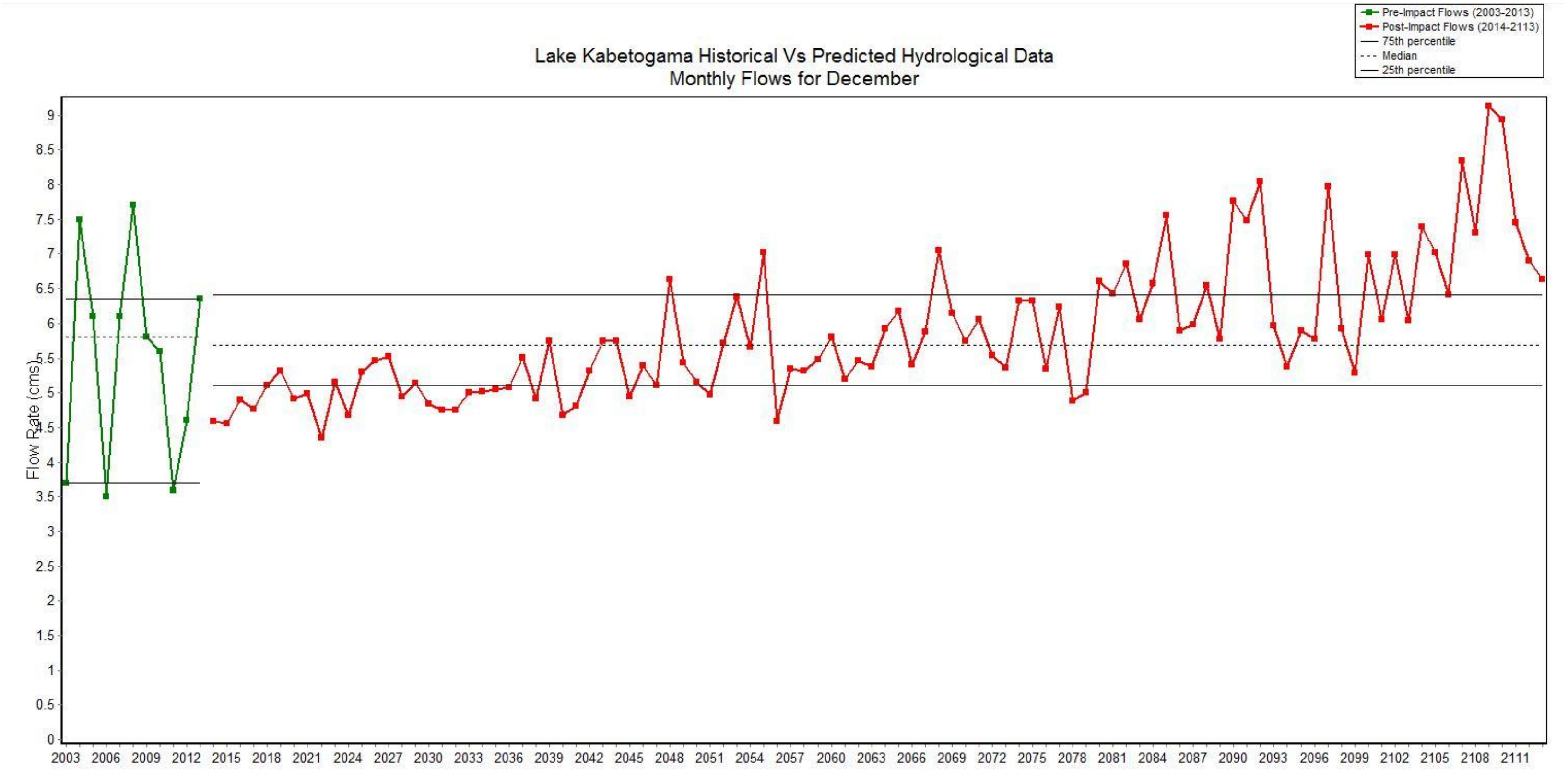


Figure 41 – December Monthly Flows

Flows continue to show an increasing trend, but are lower in total magnitude than November, which also supports the predicted growth and shift.

A.2 ES Limitations: Definitions

As mentioned earlier (section 2.3) one limitation of ES research is the lack of a standardized unifying definition or universal classification systems and designation of what specifically is an ES (Boyd et al., 2007). The definition and classification limitation can be partially resolved through refinement of the economic definition of an ES (see section 2.4 and 2.5).

Other important factors which limit ES studies include: scope, multiple objectives, spatial and temporal variability, limited understanding of complex physical (or natural) relationships, and guidelines to accommodate these factors. Limitations presented are related to traditional economics (i.e. scope) and provide some background importance of the economic definition and reasoning to revise the definition to include environmental viewpoints.

ES Limitations: Scope

The scope of ES valuation is based on the process of clearly defining which ES to count within the chain of related and interdependent ES and requires extensive hierarchical mapping of each ES and the intended goal (Fisher et al., 2009: Wallace 2007). Hierarchical mapping allows generation of a net value for an associated portion of an ecosystem, with benefits being valued and clearly defined as illustrated in the example below.

Example 2: ES Scope Creep

If human developmental infringes on the wetland an environmental impact assessment is conducted and can include certain ES study goals. A wetland ecosystem is home to a diverse set of animal and plant life with a unique spatial geometry, soil profile and water flow rates and provides numerous ES (such as flood control). ES values should be included in the decision making process to determine if the alteration is an improvement over the baseline value (Jury 2005). In order to develop the wetland an artificial method of flood control will need to be constructed to compensate for the change to the wetland. The value of the natural flood control can be determined and compared to the costs of the artificial flood control (Ray 2005). If the wetland also supports a commercial fish operation, changes to fish quantities that the wetland supports due to changes in water quantity and quality should be included in the value of the wetland (Ringer et al., 2006). If the wetland also supplies drinking water, the water quality is valued comparatively to the cost or value of supplying the same quality and quantity of water artificially (Comello et al., 20120). Example 2 illustrates that scope can rapidly expand and become increasingly more complicated, including more and more ES.

Control of scope creep is integral to the definition of ES and what ES are to be assessed. Furthermore scope should include the time domain when determining values (McNutty et al., 2012), not just present conditions. Long term costs, inflation, possibility of changes to flood frequency, are all part of the scope of an ES study and need a decision to include them as factors into the value of ES (Heagerty et al., 2004).

ES Limitations: Localization

Examples presented illustrate ways of comparing aspects of the natural complex relationships which make up ecological processes in easily understood human terms, such as monetary value. One limitation of ES is that universal value can not necessarily be established for each service (artificial and natural) because differing areas may place increased weighted value on an ES (Fisher et al., 2009).

Variance in value of water resources is typically dependent on the sector of the end user (Young 2005). Values typically have prioritized sector importance that may differ among developed and developing countries. Ecosystems require some level of quality and quantity of water resources to maintain health. The balance between human use and nature requires continual study (Jury 2005).

A baseline flow index is that 30% of a surface water bodies average annual flow is required for ecological well being (Jury 2013) ES assessment will likely determine a more accurate localized value of minimum annual flow that is required for current and near future time frames for specific ES. Each ES may require a different minimum flow, which can lead to an iterative process to establish a “minimal” flow to optimize either a specific ES or the overall total ES value. Temporal variations should also be accounted for when assessing ES (McNutty et al., 2010). Value and scope are both limited to a local region or economic climate and a specific natural ES or the artificial service and the local economic climate to produce more accurate ES studies (Fisher et al., 2009).

ES Limitations: Substitutable

The premise that ES are substitutable through manmade means (Jury 2005) does not mean it will be substituted or that a market for the ES or substitution will develop. The market economics approach and development of substitutions are simplifications of a much larger more complicated system with many marginal or opportunity costs that are difficult to track and account for.

Non-direct market costs and values are generally ignored in basic economics and valuation studies, but as ES research continues to develop inclusion of the more complicated market and value system can be made. Increasing economic market complexity will also generate a larger variety of substitutions as more natural ES are depleted and rendered ineffective.

ES studies provide a tool to allow market pricing (direct and otherwise, including aesthetics and cultural values) of substituted ES as a baseline value, but an ES study does not provide the market.

Example 3: Substitution Feasibility

If the water level of one lake in a region with several recreational use lakes were to be depleted to the point where recreational use is not valid, it is unlikely a market will develop to support an indoor recreational use venue. Neither is it likely a market would develop to redirect or transport water to the depleted water body, while other nearby water bodies remain viable.

The example demonstrates a limitation to the feasibility of substitutes. The example further amplifies the need for a thorough ES valuation study before critical decisions are made to determine if markets are available or are likely to develop in order to effectively substitute ES.

In summary literature identifies a need for and presents an accepted economic based definition of ES (Boyd et al., 2007). Literature also covered the need for a definitive classification scheme of ES based on local levels (Fisher et al., 2009). Furthermore, literature and this research presented reasoning to value ES at local levels, especially those linked to non-traditional markets (social, cultural, religious ES) (Wallace 2007) to overcome some limitations.

A.3 Types of Artificial ES

Artificial (a.k.a. purpose built) ES are manmade and intended to provide a specific singular function (Comello et al., 2012). Artificial sources may include: alterations to natural ecosystems by humans, byproducts, side effects (intended or not) of specifically constructed artificial sources or through. Artificial sources of ES that are side effects of another intended artificial source will be referred to as incidental artificial sources in this thesis.

Example 4: Purpose Built Services

An example of a purpose built artificial service is a waste water treatment facility expansion. If an area of a wetland is to be developed a comparison can be made between the intended development's value and how much it would cost to deliberately provide the same filtration service through an expansion to an existing treatment facility. The comparison can be based on the quantity of water that can be filtered through the portion of wetland being developed in a specific unit of time (for example one day) against the cost to operate a treatment facility filtration system for the same quantity of water, unit of time, and quality standard. The comparative analysis can be used to better inform decision makers about the impacts of both processes.

Example 5: Incidental Artificial Services

An example of an incidental artificial service is treated water from the wastewater treatment facility leaves a discharge pipe which is some distance above the surface elevation of the water body. Falling discharged water mixes into the water body and draws air (specifically oxygen) into the water through the localized turbulent zone at the base of the effluent stream. The discharge aeration is an incidental artificial service if it was not an intended design feature of the waste water treatment facility. One method of natural aeration is water travelling turbulently over rocks which causes air to be mixed into solution with the water. ES studies can compare aeration caused by discharge from the treatment facility to naturally occurring aeration from rapidly moving surface water bodies or another aeration source. An additional capital value of the treatment facility can then be calculated based on the cost of another artificial source of aeration for the surface water body. In this example, that source could be commercially supplied oxygen which is forced into the surface water body through bubblers.

A.4 Iterative Parameter Analysis for Calibration

Calibration better fits the simulated outflows with observed outflows and accounts for key assumptions and missing or unmeasured data for the watershed. Key assumptions of the model are: subsurface ground water flows effects are negligible, physical properties of the watershed are well established or not likely to be significantly inaccurate, including watershed area and lake surface area.

For calibration purposes the time window spans from 01JAN2010 00:00 to 25MAR2014 23:45 allowing both start up time for the model and extension past the recorded data to ensure complete encapsulation of the observed data period. Calibration began with scrutinizing the data for errors and omissions to eliminate the three primary data sets used (discharge, precipitation and temperature) as input as the source of the discrepancies. Calibration proceeded with parameter analysis to determine which parameters impact the simulation outflows the most and reduce differences between simulated outflows and historical.

Parameters not part of key assumptions (i.e. canopy storage) are adjusted in large increments to determine if they have any noticeable impact on output. Visual comparison of historical and simulated outflow plots is conducted with the large scale adjustments and no appreciable difference was observed for many of the parameters. The process was repeated for all parameters to determine which parameters affected the simulation outflow the most. Once the controlling parameters were established finer calibration methods were used.

A Root Mean Square Error (RMSE), analysis was conducted on outflows for the time period covered by historical discharge data, which excludes model ramp up and cool down periods (see Table 8). Both RMSE and a percent difference between incremental and total volume of outflows were compared for parameter changes. The goal is to minimize both RMSE and the percent difference to ensure a best possible degree of calibration and more accurate outputs.

The parameters of the watershed or reservoir, that were found to have controlling affects on peak timing, peak magnitude and slope matching post peak were focused on. The 14 parameters were all found to be linked to the watershed sub-basin properties or part of the SMA Loss Method, Clark Unit-Hydrograph Transform or Recession Baseflow method settings of the HEC-HMS model.

Lag Time Analysis for Calibration

Time of concentration, which adjusted locations of peak flows with respect to time, was one of the controlling parameters analyzed. It was found that smaller values than initial setting moved peaks earlier in time and larger values later in time. Through visual analysis, RMSE and percent difference an empirically found upper bound produced outflow that more closely resembled the temporal location of historical peak flows.

The increase in time of concentration indicates that the initial data regarding soil slope and over land distance were not a strong representation of the conditions of the watershed. Calibration of this parameter corrects the issue with the watershed existing outside of the limits of readily available soil data (USDA 2013). Obtaining accurate field measurements was outside the limits of this thesis. Future research could gather more precise data about the watershed's slope and soil properties which effect peak timing and provide improved simulated outflows and calibration.

Baseflow Method Calibration

Based on early experimental attempts (results not shown) to calibrate it was found that the initial model was predominantly influenced by a few variables as mentioned earlier. Figure 7 (see section 4.2) illustrates the calibrated and uncalibrated states and variables and adjustments are discussed in this and the following section.

Some of the variables included, time of concentration variable, the delay in precipitation reaching the water body and being transformed into outflow, had significant impacts on calibration. Shifts in time of concentration variable adjust timing locations of peaks and valleys of the HEC-HMS model outflow.

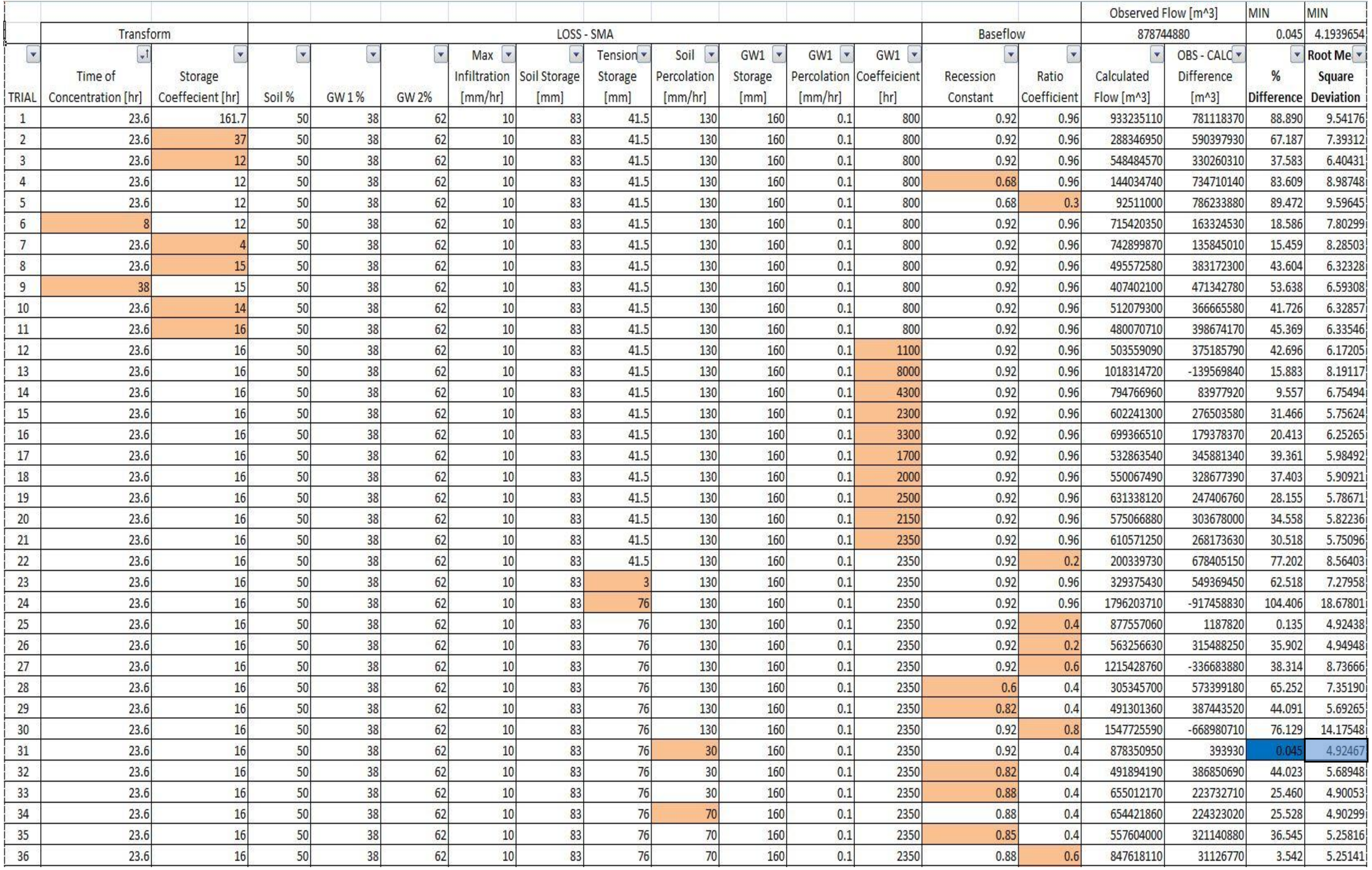
Additional influencing variables are the recession constant parameter and ratio coefficient, which influence the behavior of flows after storms as they return to base flow values, giving shape to tails after peaks.

The recession constant parameter in baseflow settings influenced peak magnitudes and through visual observation values ranging from 0.7 to 0.8 produced simulation results with peak magnitudes closer to historical outflows. The recession constant values displayed a high dependency on values for the time of concentration adjustments, but some influence was attributable to the ratio coefficient.

The ratio coefficient (also a baseflow parameter) was influenced heavily by both time of concentration and recession constant. The ratio constant effected the matching of the down slope portions after peak outflows, but did not have appreciable effects on the minimum flow values experienced between peaks. Due to the three-way relationship it was necessary to perform iterative calibration, manually adjusting values in order to minimize both RMSE and % difference.

The storage coefficient was found to have some control over timing of peaks, with a more pronounced control of magnitude of the peaks. Initial adjustments reduced the parameter in a large step down (from 161.7 hrs to 37 hrs and yielded peak outflows that more closely resembled historical records. Finer adjustments were made during later stages of calibration.

Table 8 – Calibration Results data table is a sample of results of the calibration iterations, with highlighted cells representing the parameter changed or the minimum RMSE/difference combination (4.92467 and 0.045% respectively).



															Observed Flow [m^3]		MIN	MIN
	Transform		LOSS - SMA										Baseflow		878744880		0.045	4.1939654
TRIAL	Time of Concentration [hr]	Storage Coeffecient [hr]	Soil %	GW 1 %	GW 2%	Max Infiltration [mm/hr]	Soil Storage [mm]	Tension Storage [mm]	Soil Percolation [mm/hr]	GW1 Storage [mm]	GW1 Percolation [mm/hr]	GW1 Coeffeicient [hr]	Recession Constant	Ratio Coefficient	Calculated Flow [m^3]	OBS - CALC Difference [m^3]	% Difference	Root Me Square Deviation
1	23.6	161.7	50	38	62	10	83	41.5	130	160	0.1	800	0.92	0.96	933235110	781118370	88.890	9.54176
2	23.6	37	50	38	62	10	83	41.5	130	160	0.1	800	0.92	0.96	288346950	590397930	67.187	7.39312
3	23.6	12	50	38	62	10	83	41.5	130	160	0.1	800	0.92	0.96	548484570	330260310	37.583	6.40431
4	23.6	12	50	38	62	10	83	41.5	130	160	0.1	800	0.68	0.96	144034740	734710140	83.609	8.98748
5	23.6	12	50	38	62	10	83	41.5	130	160	0.1	800	0.68	0.3	92511000	786233880	89.472	9.59645
6	8	12	50	38	62	10	83	41.5	130	160	0.1	800	0.92	0.96	715420350	163324530	18.586	7.80299
7	23.6	4	50	38	62	10	83	41.5	130	160	0.1	800	0.92	0.96	742899870	135845010	15.459	8.28503
8	23.6	15	50	38	62	10	83	41.5	130	160	0.1	800	0.92	0.96	495572580	383172300	43.604	6.32328
9	38	15	50	38	62	10	83	41.5	130	160	0.1	800	0.92	0.96	407402100	471342780	53.638	6.59308
10	23.6	14	50	38	62	10	83	41.5	130	160	0.1	800	0.92	0.96	512079300	366665580	41.726	6.32857
11	23.6	16	50	38	62	10	83	41.5	130	160	0.1	800	0.92	0.96	480070710	398674170	45.369	6.33546
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13	23.6	16	50	38	62	10	83	41.5	130	160	0.1	8000	0.92	0.96	1018314720	-139569840	15.883	8.19117
14	23.6	16	50	38	62	10	83	41.5	130	160	0.1	4300	0.92	0.96	794766960	83977920	9.557	6.75494
15	23.6	16	50	38	62	10	83	41.5	130	160	0.1	2300	0.92	0.96	602241300	276503580	31.466	5.75624
16	23.6	16	50	38	62	10	83	41.5	130	160	0.1	3300	0.92	0.96	699366510	179378370	20.413	6.25265
17	23.6	16	50	38	62	10	83	41.5	130	160	0.1	1700	0.92	0.96	532863540	345881340	39.361	5.98492
18	23.6	16	50	38	62	10	83	41.5	130	160	0.1	2000	0.92	0.96	550067490	328677390	37.403	5.90921
19	23.6	16	50	38	62	10	83	41.5	130	160	0.1	2500	0.92	0.96	631338120	247406760	28.155	5.78671
20	23.6	16	50	38	62	10	83	41.5	130	160	0.1	2150	0.92	0.96	575066880	303678000	34.558	5.82236
21	23.6	16	50	38	62	10	83	41.5	130	160	0.1	2350	0.92	0.96	610571250	268173630	30.518	5.75096
22	23.6	16	50	38	62	10	83	41.5	130	160	0.1	2350	0.92	0.2	200339730	678405150	77.202	8.56403
23	23.6	16	50	38	62	10	83	3	130	160	0.1	2350	0.92	0.96	329375430	549369450	62.518	7.27958
24	23.6	16	50	38	62	10	83	76	130	160	0.1	2350	0.92	0.96	1796203710	-917458830	104.406	18.67801
25	23.6	16	50	38	62	10	83	76	130	160	0.1	2350	0.92	0.4	877557060	1187820	0.135	4.92438
26	23.6	16	50	38	62	10	83	76	130	160	0.1	2350	0.92	0.2	563256630	315488250	35.902	4.94948
27	23.6	16	50	38	62	10	83	76	130	160	0.1	2350	0.92	0.6	1215428760	-336683880	38.314	8.73666
28	23.6	16	50	38	62	10	83	76	130	160	0.1	2350	0.6	0.4	305345700	573399180	65.252	7.35190
29	23.6	16	50	38	62	10	83	76	130	160	0.1	2350	0.82	0.4	491301360	387443520	44.091	5.69265
30	23.6	16	50	38	62	10	83	76	130	160	0.1	2350	0.92	0.8	1547725590	-668980710	76.129	14.17548
31	23.6	16	50	38	62	10	83	76	30	160	0.1	2350	0.92	0.4	878350950	393930	0.045	4.92467
32	23.6	16	50	38	62	10	83	76	30	160	0.1	2350	0.82	0.4	491894190	386850690	44.023	5.68948
33	23.6	16	50	38	62	10	83	76	30	160	0.1	2350	0.88	0.4	655012170	223732710	25.460	4.90053
34	23.6	16	50	38	62	10	83	76	70	160	0.1	2350	0.88	0.4	654421860	224323020	25.528	4.90299
35	23.6	16	50	38	62	10	83	76	70	160	0.1	2350	0.85	0.4	557604000	321140880	36.545	5.25816
36	23.6	16	50	38	62	10	83	76	70	160	0.1	2350	0.88	0.6	847618110	31126770	3.542	5.25141

Table 9 – Time Windows Used, table is a summary of the time windows of data availability or simulation run time for comparison of overlaps and use in calibration.

Time Windows	**Begin**	**End**	**Ramp Up**	**Ramp Down**
Precipitation	25-Mar-03	13-May-13	N/A	N/A
Temperature	25-Mar-03	13-May-13	N/A	N/A
Discharge	1-Sep-10	8-Nov-13	216 days	137 days
Simulation Run Time	1-Jan-10	25-Mar-14	N/A	N/A

A.5 Sample Calculation for Development of Precipitation Shift

Step 1: Calculate Ratio_i

$$i = June$$

$$Shifted\ \%\ Contribution_i = 6.3608$$

$$Historical\ \%\ Contribution_i = 13.2404$$

$$\text{Ratio}_i = \frac{Shifted\ \%\ Contribution_i}{Historical\ \%\ Contribution_i} = \frac{6.3608}{13.2404} = 0.4804$$

Step 2: Calculate $\text{FM}_{N,i}$

$$N = 100, \qquad i = June$$

$$FM_{100,June} = \left\{1 + \left(\left(\frac{(0.4804 - 1)}{100}\right) * 100\right)\right\} * \left\{1 + \left(\left(\frac{(7.5 * 100)}{100}\right) * \frac{1}{100}\right)\right\}$$

$$FM_{100,June} = 0.5164$$

Step 3: Calculate Historical and Shifted Precipitation Values

Let Yearly Precipitation Total (YPT) = 1000 mm

Then YPT*$Historical\ \%\ Contribution_i$ = Historical Precipitation (HP_i)

Then YPT*$Shifted\ \%\ Contribution_i$ = Shifted Precipitation (SP_i)

$$YPT * HP_i = 1000\ mm * \left(1 + \left(\frac{13.2404}{100}\right)\right) = 132.404\ mm = HP_{June}$$

$$YPT * SP_i = 1000\ mm * \left(1 + \left(\frac{16.3608}{100}\right)\right) = 63.608\ \ mm = SP_{June}$$

NOTE: that June post shift experiences January's % contribution to yearly totals; see Table 7. That is why SP_{June} = 63.608 mm, which would be January's monthly precipitation total given 1000 mm as the yearly total.

Step 4: Determine Shifted Month's Precipitation with Expected Growth (PEG_i)

$$PEG_i = SP_i * \left\{1 + \left(\left(\frac{(Growth * N)}{100}\right) * \frac{1}{100}\right)\right\}$$

$$PEG_{June} = SP_{June} * \left\{1 + \left(\left(\frac{(Growth * 100)}{100}\right) * \frac{1}{100}\right)\right\}$$

$$PEG_{June} = 63.608\ mm\ * \left\{1 + \left(\left(\frac{(7.5 * 100)}{100}\right) * \frac{1}{100}\right)\right\}$$

$$PEG_{June} = 68.378\ mm$$

Step 5: Determine Predicted Shifted Precipitation Value (PSP_i)

$$PSP_i = FM_{N,i} * HP_i$$

$$PSP_{June} = FM_{100,June} * HP_{June}$$

$$PSP_{June} = 0.5164 * 132.404\ mm$$

$$PSP_{June} = 68.373\ mm$$

Step 6: Verify Predicted Shifted Precipitation (PSP_i) equals Precipitation with Expected growth (PEG_i)

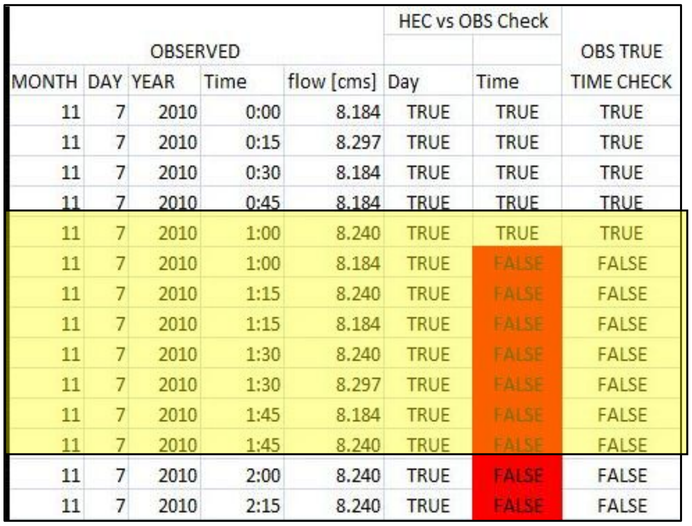
$$Does: PSP_i = PEG_i\ ?$$

$$PSP_{June} = 68.373\ mm \quad \approx PEG_{June} = 68.378\ mm$$

The values are reasonably close with difference likely due to rounding. $FM_{N,i}$ is accurate for prediction purposes for this research and predicted intensities will more than likely accurately represent the intended seasonal shifts and expected growth of precipitation.

A.6 Historical Storage Discharge Data Errors

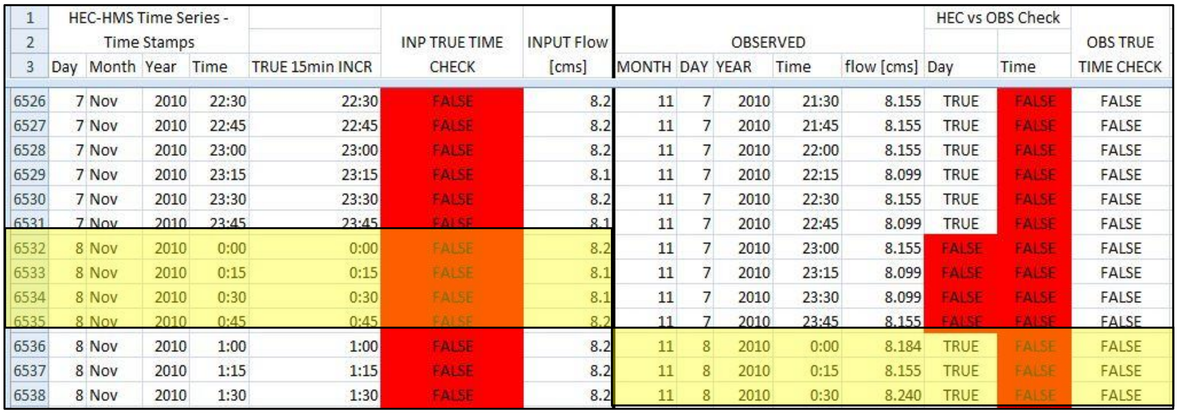
In parsing the data, it was observed there were numerous instances of time miss matches between the simulation time steps and reality or repeated time steps in recorded data. Miss matches occur when calendar dates changed in observed historical data at later points in the data set than should have occurred if data followed a true 15 minute time step. Repeated time steps occur in the data when the time stamps assigned to individual gauge and discharge rates appear twice for the same date with differing flow rates. Differing flow rates suggest that the data is being recorded correctly, but not time stamped appropriately. The highlighted bands (see Figure 42 & Figure 43) illustrates repeated time steps in the observed historical data or when the date changes from 07NOV2010 to 08NOV2010 in the HEC-HMS data table, and that this change does not occur until four entries later in the observed data. The disjoint between the HEC-HMS model and the recorded physical data will cause errors with the simulation when importing the unadjusted data directly into HEC-HMS.



					HEC vs OBS Check		
		OBSERVED					OBS TRUE
MONTH	DAY	YEAR	Time	flow [cms]	Day	Time	TIME CHECK
11	7	2010	0:00	8.184	TRUE	TRUE	TRUE
11	7	2010	0:15	8.297	TRUE	TRUE	TRUE
11	7	2010	0:30	8.184	TRUE	TRUE	TRUE
11	7	2010	0:45	8.184	TRUE	TRUE	TRUE
11	7	2010	1:00	8.240	TRUE	TRUE	TRUE
11	7	2010	1:00	8.184	TRUE	FALSE	FALSE
11	7	2010	1:15	8.240	TRUE	FALSE	FALSE
11	7	2010	1:15	8.184	TRUE	FALSE	FALSE
11	7	2010	1:30	8.240	TRUE	FALSE	FALSE
11	7	2010	1:30	8.297	TRUE	FALSE	FALSE
11	7	2010	1:45	8.184	TRUE	FALSE	FALSE
11	7	2010	1:45	8.240	TRUE	FALSE	FALSE
11	7	2010	2:00	8.240	TRUE	FALSE	FALSE
11	7	2010	2:15	8.240	TRUE	FALSE	FALSE

Figure 42 – Observed Data Time Step Repeats

The figure above illustrates when time steps are repeated in the observed data, but water discharge had unique flow values suggesting an issue with the data recording. The error is further corroborated in comparing the time stamps from HEC-HMS to observed record. Figure 43 illustrates the miss match between date changes due to the previous figures hour miss match



1	HEC-HMS Time Series -												HEC vs OBS Check		
2	Time Stamps					INP TRUE TIME	INPUT Flow			OBSERVED					OBS TRUE
3	Day	Month	Year	Time	TRUE 15min INCR	CHECK	[cms]	MONTH	DAY	YEAR	Time	flow [cms]	Day	Time	TIME CHECK
6526	7	Nov	2010	22:30	22:30	FALSE	8.2	11	7	2010	21:30	8.155	TRUE	FALSE	FALSE
6527	7	Nov	2010	22:45	22:45	FALSE	8.2	11	7	2010	21:45	8.155	TRUE	FALSE	FALSE
6528	7	Nov	2010	23:00	23:00	FALSE	8.2	11	7	2010	22:00	8.155	TRUE	FALSE	FALSE
6529	7	Nov	2010	23:15	23:15	FALSE	8.1	11	7	2010	22:15	8.099	TRUE	FALSE	FALSE
6530	7	Nov	2010	23:30	23:30	FALSE	8.2	11	7	2010	22:30	8.155	TRUE	FALSE	FALSE
6531	7	Nov	2010	23:45	23:45	FALSE	8.1	11	7	2010	22:45	8.099	TRUE	FALSE	FALSE
6532	8	Nov	2010	0:00	0:00	FALSE	8.2	11	7	2010	23:00	8.155	FALSE	FALSE	FALSE
6533	8	Nov	2010	0:15	0:15	FALSE	8.1	11	7	2010	23:15	8.099	FALSE	FALSE	FALSE
6534	8	Nov	2010	0:30	0:30	FALSE	8.1	11	7	2010	23:30	8.099	FALSE	FALSE	FALSE
6535	8	Nov	2010	0:45	0:45	FALSE	8.2	11	7	2010	23:45	8.155	FALSE	FALSE	FALSE
6536	8	Nov	2010	1:00	1:00	FALSE	8.2	11	8	2010	0:00	8.184	TRUE	FALSE	FALSE
6537	8	Nov	2010	1:15	1:15	FALSE	8.2	11	8	2010	0:15	8.155	TRUE	FALSE	FALSE
6538	8	Nov	2010	1:30	1:30	FALSE	8.2	11	8	2010	0:30	8.240	TRUE	FALSE	FALSE

Figure 43 – Model and Observed Data Time Stamp Miss Match

Correction of the time step can be obtained manually at points of divergence by omitting the second of repeating time stamp entries as this shifts the rest of the time stamps one hour forward and eliminates the date change miss match seen in Figure 42. The correction results in both the observed data and HEC-HMS to have matching time stamps and total number of data entries. However omitting data, even if there is little difference between adjacent data points and additional data entries can induce some degree of error.

Occasionally, dates and time stamps are missing and information needs to be developed for the missing data points. prior to correction for time steps a total of 74 missing data points in the observed outflow data set were found (spanning 01SEP2010 to 08NOV2013) compared to the HEC-HMS data set. The infrequency (74 of 111,800 or 0.6%) of missing data points, the observed data set does not merit throwing out the observed data.

In order to resolve the missing data issue, time steps are inserted into the recorded data and calculated through interpolation techniques and intuitive estimations for missing values (Fung 2006). Traditional approaches use curve fitting techniques such as linear interpolation (Fung 2006). In this thesis a smoothed moving average centered on the needed data point is used as an intuitive estimator, similar to a Box-Jenkins method (Fung 2006). The neighboring three time steps on both sides of the missing data are used to determine a smoothed average for the missing data points, see Equation 7 and Table 10.

Equation 7:

$$D_t = \frac{\sum_{i=1}^{i=\mathrm{n}} D_{t-\mathrm{i}} + \sum_{i=1}^{i=\mathrm{n}} D_{t+\mathrm{i}}}{2n} \qquad \text{(Fung, 2006)}$$

where: D_t = the missing data point and n = number of neighboring steps used (in this case 3)

Table 10 – Example Resolution of Time Step Error The data table is an example of the low variation of observed data over time and with the application of Equation 7 to create the missing time step data point: **D_t**.

Time Step	Date	Time	Gauge Height ft	Discharge cfs
D_{t-3}	9/1/2010	0:45	17.08	430.00
D_{t-2}	9/1/2010	1:00	17.07	428.00
D_{t-1}	9/1/2010	1:15	17.08	430.00
D_t	**9/1/2010**	**1:30**	**17.076**	**429.33**
D_{t+1}	9/1/2010	1:45	17.08	430.00
D_{t+2}	9/1/2010	2:00	17.07	428.00
D_{t+3}	9/1/2010	2:15	17.08	430.00

Table 11 – Precipitation Totals by Year

YEAR	Total Precipitation mm	Notes
2003	516.3	
2004	911.6	WETTEST
2005	852	
2006	852	
2007	686.9	
2008	867.5	
2009	685.6	
2010	897.9	
2011	563.5	DRIEST
2012	760.1	AVERAGE
2013	194.2	
Precipitation mm		
AVERAGE	MAX	MIN
786.34	911.60	563.50

Table 12 – Historical Monthly Precipitation Totals

MONTH - YEAR TABLE (Precipitation mm)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
2003	0	0	3.6	53.8	44.2	106.7	82.1	69.4	61.8	33.3	38.3	23.1	516.3
2004	55.1	10.3	31.6	33	114.5	61.8	129.1	113	177	116.7	10.7	58.8	911.6
2005	56	15.5	6.9	27.9	155.2	91.9	110.2	100.2	22.6	122	122.3	21.3	852
2006	17	17.6	56.4	35.2	62.3	70.3	95.7	54.4	85.4	25.1	11.7	39.1	570.2
2007	7.8	18.5	61	19.8	87.9	98.5	42.4	37.8	161.7	103.8	17.4	30.3	686.9
2008	9	8.6	12	89.4	86.9	153	62.2	31.6	204.6	81.9	92	36.3	867.5
2009	20	28.7	87.2	48.3	76.8	59.8	0	161.1	44.7	68.1	42.4	48.5	685.6
2010	23.3	3.5	17.1	11.6	110.2	80.4	259.1	117.5	155.5	34.3	56.5	28.9	897.9
2011	39.1	7.6	2.8	81.6	72.9	131.2	58.7	47.1	45.8	42.6	22.8	11.3	563.5
2012	29.1	25.2	84.6	65.8	114	67.7	156.8	40.6	40.9	73.6	36.2	25.6	760.1
2013	57.4	28.1	25.3	65	18.4	0	0	0	0	0	0	0	194.2

Table 13 – Historical Monthly Contribution to Yearly Totals

MONTH - YEAR TABLE (Percent Contribution %)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
2003	0.0%	0.0%	0.7%	10.4%	8.6%	20.7%	15.9%	13.4%	12.0%	6.4%	7.4%	4.5%	1
2004	6.0%	1.1%	3.5%	3.6%	12.6%	6.8%	14.2%	12.4%	19.4%	12.8%	1.2%	6.5%	1
2005	6.6%	1.8%	0.8%	3.3%	18.2%	10.8%	12.9%	11.8%	2.7%	14.3%	14.4%	2.5%	1
2006	3.0%	3.1%	9.9%	6.2%	10.9%	12.3%	16.8%	9.5%	15.0%	4.4%	2.1%	6.9%	1
2007	1.1%	2.7%	8.9%	2.9%	12.8%	14.3%	6.2%	5.5%	23.5%	15.1%	2.5%	4.4%	1
2008	1.0%	1.0%	1.4%	10.3%	10.0%	17.6%	7.2%	3.6%	23.6%	9.4%	10.6%	4.2%	1
2009	2.9%	4.2%	12.7%	7.0%	11.2%	8.7%	0.0%	23.5%	6.5%	9.9%	6.2%	7.1%	1
2010	2.6%	0.4%	1.9%	1.3%	12.3%	9.0%	28.9%	13.1%	17.3%	3.8%	6.3%	3.2%	1
2011	6.9%	1.3%	0.5%	14.5%	12.9%	23.3%	10.4%	8.4%	8.1%	7.6%	4.0%	2.0%	1
2012	3.8%	3.3%	11.1%	8.7%	15.0%	8.9%	20.6%	5.3%	5.4%	9.7%	4.8%	3.4%	1
2013	29.6%	14.5%	13.0%	33.5%	9.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1
Average	3.8%	2.1%	5.6%	9.2%	12.4%	13.2%	13.3%	10.7%	13.3%	9.4%	5.9%	4.5%	
Median	3.0%	1.8%	3.5%	7.0%	12.4%	11.6%	13.5%	10.7%	13.5%	9.6%	5.5%	4.3%	