Mississippi Valley Conservation Authority

Climate Change Implications for Small Waterpower Facilities

– A Watershed Perspective

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Table of Contents

List of Figures

List of Tables

Executive Summary

Early settlement in Ontario relied on river systems for transportation, commerce and waterpower and these uses helped shape development patterns. The Mississippi River in Ontario is an example of this early development and the system continues to provide social, economic and environmental benefits to its residents. Much of this development capitalized on the hydrologic characteristics of the river system as a source transportation, waterpower, tourism, water supply and waste assimilation.

As a result of the inevitable variability associated with natural systems, floods and droughts occurred periodically which led to the construction of reservoirs to mitigate the impact of these extreme events. The design and operation of these water control structures traditionally relied on historic observations of meteorological and hydrologic parameters to provide an understanding of the range of stream flow conditions which these structures may experience on a daily, seasonal and annual basis.

Projections of future climate in Ontario indicate that runoff patterns and stream flow characteristics will likely be altered significantly, resulting in incompatibility with existing reservoir operating regimes for the Mississippi River, in turn resulting in increasing difficulty to meet current water management objectives. As water managers attempt to reach a successful balance between the competing interests of multiple users it will be important to understand the extent to which runoff patterns will change on a daily, seasonal, and annual basis.

The current study, along with a companion study, “Future Water Budget Projections in Mississippi Rideau Watershed Region” (Kunjikutty 2015), examines the runoff patterns for the Mississippi River resulting from future climate projections over a 90 year period (2011-2100) relative to a baseline period (1971-2000). A range of future climate scenarios were considered from different Global Climate Models and emission scenarios to assess the uncertainty associated with the expected hydrologic response in the Mississippi River watershed.

Hydrologic simulation of the baseline and future climate projections were completed to generate projections of reservoir inflows at select points along the river system, and were then used as input to a reservoir simulation model to simulate reservoir response and corresponding release rates based on current reservoir operating rules. The simulation results were evaluated to quantify potential impacts on flood risk, low flow conditions, recreation and hydropower generation under a range of future climate scenarios relative to the baseline condition. The study determined that changes in flood risk could range from a decrease of 7% to an increase of up to 40% while low flow conditions consistently showed a decrease of 28% to 62%. As hydropower on the Mississippi River is contingent on stream flow conditions, the resulting energy production is projected to decrease by 9% to 23%. Reservoir performance in meeting summer recreation water level objectives was found to decrease from the current baseline success rate of 80% to a future success rate of 33% to 53%.

Four adaptation options were evaluated to assess the potential to mitigate the future climate impacts. Along with considering the option of maintaining current reservoir operating rules (Option 1), three adaptation options were also evaluated including; Option 2) removal of all artificial storage reservoirs in which the river would revert to a naturally functioning system, Option 3) introducing revisions to current reservoir operating rules within the physical constraints of the associated water control structures, and Option 4) impounding an additional 2,000 ha-m of reservoir storage at one of the six reservoir sites in conjunction with Option 3. While the options which were assessed demonstrate that future climate impacts can be partially mitigated, there will continue to be residual impacts to the various stakeholders and interests along the river system. The Options considered will have both positive and negative consequences and are presented solely to facilitate future water management planning within the Mississippi River watershed and other similar river systems. The study recommendations are intended to highlight areas for future study or consideration within this broader planning context involving multiple stakeholders.

1. Introduction

In Ontario, owners of waterpower facilities and other dams are subject to the Lakes & Rivers Improvement Act requiring them to prepare and operate in accordance with Water Management Plans1 approved by the Ontario Ministry of Natural Resources and Forestry. These plans define legally enforceable operating regimes for the waterpower facilities and storage reservoirs within a watershed. As many small scale waterpower facilities operate as run-of-the-river, they are dependent on the hydrologic characteristics of a particular waterpower site unless flows are regulated through upstream storage reservoirs.

The operation of waterpower facilities and storage reservoirs typically require careful coordination to balance the multiple interests competing for water along a river system. The objectives of Water Management Plans are to recognize these competing interests and maximize the economic, social and environmental benefits while minimizing associated impacts.

In many of the river systems in eastern Ontario reservoirs have been developed to capture spring snowmelt and release this water during periods of low runoff typically experienced over the summer. Run-of-the-river waterpower facilities have utilized these augmented stream flows to generate power during periods of high power consumption.

Research has demonstrated that projected climatic conditions will fundamentally alter the runoff patterns and hydrologic characteristics of the watersheds on which Water Management Plans were established. Warmer temperatures over the winter months will result in less snow accumulation and more variable stream flow during the winter[3]. This change in runoff distribution has the potential to disrupt the typical reservoir storage-release cycle. As Water Management Plans begin adapting reservoir operation policies in response to these changes in an effort to re-balance the competing interests for water, the flow-duration characteristics of the river system on which waterpower facilities were originally designed may be altered significantly.

This study details how projected changes in climate in the Mississippi River watershed may affect hydrological processes and consequently water levels and streamflows within the watershed.

2. Study Area

Ontario's Mississippi River is a tertiary stream located in eastern Ontario, primarily west of the City of Ottawa, within the Ottawa River basin (Figure 2:1). The Mississippi River watershed is composed of a complex network of rivers, streams and over 250 lakes[2]. The watershed has a drainage area of 3,765 km^2 from its headwaters in Kilpecker Creek, in the Township of Addington Highlands, to its outlet at the Ottawa River in the City of Ottawa.

The river is 212 km in length, and begins at an elevation of 325 m (1,066 ft) in the west and drops 252 m (827 feet) gradually towards the east to an elevation of 73 m (240 ft) at its confluence with the Ottawa River.

Figure 2:1. Study Area – Mississippi River Watershed, eastern Ontario

The watershed has three distinct sub-watersheds (Figure 2:2): the western and central sub-watersheds lie on the Canadian Shield and the eastern sub-watershed lies off the Shield, to the west of the Ottawa River. The western sub-watershed is speckled with deep, glacial lakes, whereas the eastern sub-watershed is dominated by riverine systems, which is a reflection of its topography and surficial geology. The central sub-watershed is a combination of both the western and eastern sub-watersheds, and may be considered a transitional zone between ecological land types and communities.

2.1. Western Sub-watershed

The western sub-watershed's north-western boundary is at Kilpecker Creek, the headwater of the river system, and the subwatershed extends east to the outlet of Crotch Lake. It has a drainage area of 1,061 km^2 and includes the vast majority of the lakes in the watershed and virtually all available reservoir storage. Figure 2:2 shows the western sub-watershed in dark green. This portion of the watershed is generally underlain by Precambrian bedrock with thin soils, which has largely shaped the area's natural history and cultural development.

The headwaters of the Mississippi River originate in Denbigh Township on Kilpecker Creek's Rolufs Lake and Crooked Lake. Mazinaw Lake is the first significant lake on the Mississippi River system. Bon Echo Creek and Semi-circle Creek are the two significant streams which enter the lower Mazinaw Lake. Bon Echo Creek is an unregulated stream, which flows from Bon Echo Lake through the Bon Echo Provincial Park. Semi-circle Creek contains the first major water control structure on the system, located at the outlet of Shabomeka Lake.

From Mazinaw Lake, the river flows through the smaller lakes of Little Marble, Marble and Georgia Lakes into Kashwakamak Lake. The inlet to Kashwakamak Lake is known as Whitefish Rapids, an important walleye spawning site rehabilitated by the Ministry of Natural Resources and Forestry (MNRF). From Kashwakamak Lake the river flows through the Village of Ardoch. This area, known for its wild rice, is of significance to the native Algonquin First Nations who harvest the rice each fall. Wild rice is susceptible to stream flow fluctuations during critical periods of its growing season.

Buckshot Creek, draining an area of 309 km^2, enters the Mississippi River from the north, below the Village of Ardoch and between Farm Lake and Crotch Lake. Mississagagon Lake feeds into Buckshot Creek. From its confluence with Buckshot Creek, the river passes through Side Dam Rapids situated at the inlet to Crotch Lake. Side Dam Rapids is an important walleye spawning ground. Big Gull Lake also flows into Crotch Lake via Gull Creek. This lake is a headwater lake, and has a very limited drainage basin relative to the surface area of the lake which is approximately 18% of the contributing drainage area. The most significant reservoir on the Mississippi River system with regards to flood mitigation and low flow augmentation is Crotch Lake which marks the eastern boundary of this sub-watershed.

2.2. Central Sub-watershed

The central portion of the watershed has a drainage area of 1,837 km^2 which extends from the outlet of Crotch Lake through the High Falls Generating Station and Dalhousie Lake and on past rolling terrain and marginal farmland to its confluence with two large tributaries, the Clyde River and the Fall River, immediately upstream of the village of Ferguson Falls. From here, the Mississippi River flows easterly through Mississippi Lake, which is the last lake on the river system. Lakeshore development in this area is extensive with over 1,700 homes and cottages built along its shores with a recent trend toward converting from seasonal to permanent dwellings. The central sub-watershed is shown in Figure 2:2.

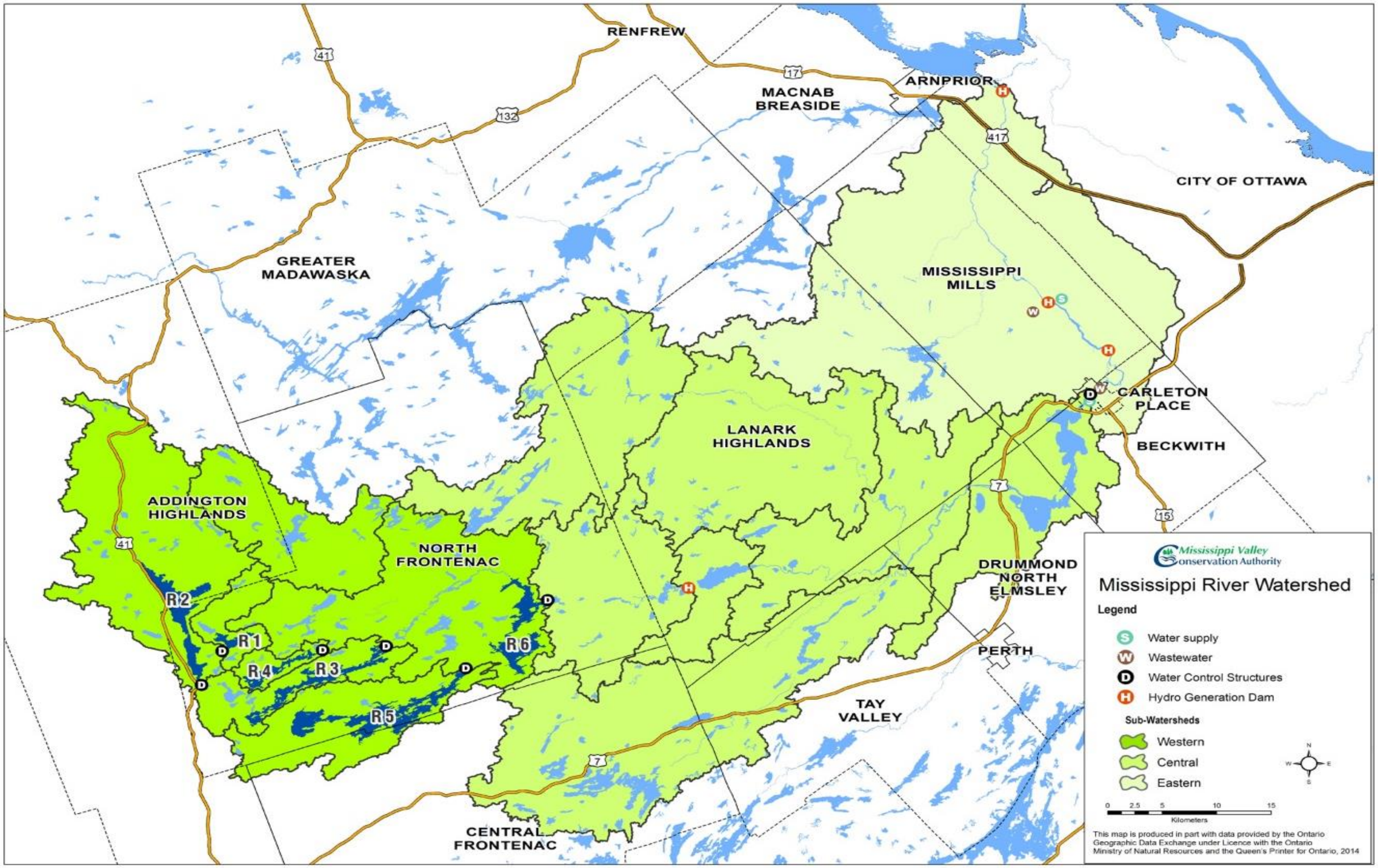
2.3. Eastern Sub-watershed

The eastern sub-watershed has a drainage area of 867 km^2 and contains several communities including Carleton Place, Almonte, Pakenham, Galetta and a portion of the City of Ottawa. It is shown in Figure 2:2 as the light green area. The terrain is much flatter along this portion of the river with farmland dominating the rural areas outside of the communities.

From Carleton Place the river flows through the community of Appleton. The Appleton Generation Station was built here in 1993 at the site of an abandoned and derelict structure formally belonging to a textile mill. The river continues north through the Town of Mississippi Mills (Almonte), where two generating stations are located. The first station, the Enerdu Generating Station was originally constructed in as a mill in 1842, while the Mississippi River Power (formerly Almonte PUC) Generating Station, was originally constructed in 1890.

The river then flows through the Village of Galetta, which is the last community on the river system, through the Galetta Power Generating Station before its confluence with the Ottawa River at Chats Lake, just above the Chats Falls Generating Station.

Figure 2:2. Mississippi River Watershed



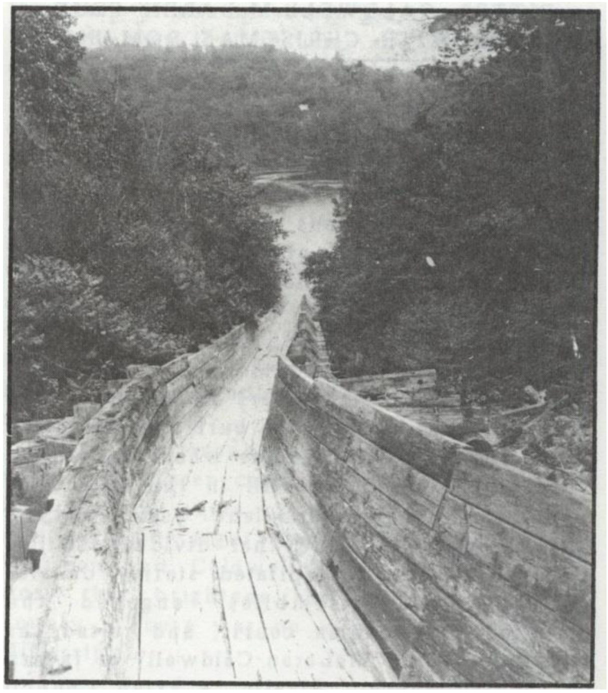
This map is produced in part with data provided by the Ontario Geographic Data Exchange under Licence with the Ontario Ministry of Natural Resources and the Queen's Printer for Ontario, 2014

2.4. History

This brief historical account of the river system highlights the evolution of a management regime on the Mississippi River which has supported over a century of economic development in the watershed.

The Mississippi River watershed is typical of watersheds in eastern Ontario which originate on the Precambrian Shield. It remains heavily forested with approximately 66% forest cover and exhibits a large percentage of open water. In the early 1800s the vast expanse of timber attracted the timber trade while the rivers provided a means to transport the logs to mills located further downstream and as far as Quebec City. Dams were constructed on many of the lakes to hold the logs until they could be floated downstream to market.

Figure 2:3. Log Slide at High Falls on Mississippi River



Source: MVCA Archives.

By the early 1900s many of the large pine in the area had been harvested when a group of business interests in Almonte and Carleton Place formed the Mississippi River Improvement Company (MRIC). The MRIC charter was to hold title and maintain dams and reservoirs on several lakes in the watershed for the purpose of augmenting flows in the downstream reaches to operate woolen and grist mills. By 1919, the Hydro Electric Power Commission of Ontario began development of hydro-electric facilities along the downstream reaches of the Mississippi River and subsequently acquired a majority interest in the MRIC. This resulted in the Commission assuming day to day operations of the company and its water control structures. Over the ensuing decades, the reservoir lakes attracted tourism and recreational interests which resulted in pressure to stabilize water levels on the reservoir lakes over the summer months. The resulting restrictions on using reservoir storage to augment flows over the summer months from several of these reservoirs prompted the eventual transfer of the water control structures to the Mississippi Valley Conservation Authority in 1991 and Ontario Hydro. The Mississippi River Improvement Company was subsequently dissolved.

Throughout this period the Towns of Carleton Place and Almonte continued to develop and eventually required the installation water distribution systems, with the Town of Carleton Place relying on surface water from the Mississippi River. The installation of sewage treatment plants in Carleton Place and Almonte also occurred with resulting discharges to the Mississippi River.

As a result of de-regulation of the Ontario electricity market in 2001, the Ontario Ministry of Natural Resources ordered the preparation of a Water Management Plan for the Mississippi River to prevent inappropriate manipulation of flows and water levels to the benefit of power generation while at the expense of other social and environmental interests.

2.5 Physical Resources

Geologic Features - The geologic features within the watershed are quite complex, with the area being divided by underlying Precambrian bedrock to the west and Palaeozoic bedrock formations to the east. The Mississippi River generally follows the contact of these two formations which extend from the Village of Galetta to a point in the vicinity of Bells Corners in Bathurst Township. The surficial geology is largely a result of glaciation, from which till was deposited in the characteristic forms of moraines, drumlins and till plains, creating the lacustrine systems in the west, and other features found on the river system including eskers and spillways of clay and sand plains dominated by riverine systems in the east. These landforms have a more sorted and uniform composition as a result of their origin from glacial and post-glacial waters.

The Precambrian complex consists of crystalline limestone, quartzite and gneiss which were intruded, deformed and metamorphosed by bodies of granite, syenite and other igneous rocks. The Palaeozoic rocks consist of sandstone, limestone, dolomites and shale that were deposited approximately 500 million years ago.

Soils - The soils within the watershed are closely related to the bedrock and surficial geology. The nature and properties of the soils are related to the characteristics of the parent materials from which they developed. The irregular terrain of the western sub-watershed has very shallow soils with frequent outcroppings. Internal drainage of these soils is good due to the coarse texture of the deposit. The soils in the eastern sub-watershed, which are underlain by the flat Palaeozoic rock formation, are more basic, finer textured and generally deeper. The types of soils in this area are numerous and inconsistent in nature as a result of the variable parent materials and active geologic processes which operated. Internal drainage within these soils is also variable, ranging from very poor to good.

The Mississippi River watershed can be described as consisting of broad geographic areas defined by the underlying geologic features, topography and settlement patterns

2.6 Biological Resources

The Mississippi River system contains both cold and warmwater fish species. Historically, lake trout lakes dominated the watershed, but now only a few lakes in the western sub-watershed continue to be managed as coldwater fisheries. The central and eastern sub-watershed lakes are managed as warmwater, walleye and bass dominated fisheries, and the river reaches' water levels and flow are managed to protect fish spawning. The watershed has many natural heritage features including several locally and provincially significant wetlands, rare species and species at risk, other significant natural features such as wild rice, a migratory bird sanctuary and Areas of Scientific and Natural Interest (ANSIs), Parks, Conservation Reserves and Crown land.

The river system has diversified aquatic habitats upon which fish and other aquatic species depend on to directly or indirectly to carry out their life processes, including spawning grounds, nurseries, rearing, and food supply and migration areas. Many of the important fish spawning areas are located below sections of rapids and dams and along shorelines of lakes and the river proper.

In general, water levels and flows are important to fish species during the spawning and incubation periods of the eggs which can last from ice break-up to early summer for most species. Walleye spawn in spring, generally from mid-April to mid-May, on rocky areas in white-water below dams or rapids in the river. Walleye in lakes will spawn on cobble or gravel on shoals. Bass will spawn in late May to early June. Lake trout spawning occurs mainly in the fall from mid-October to early November, depending on temperature, on rocky shoals found in lakes. Lake trout spawning success is also susceptible to water levels. If fall drawdowns occur after spawning, some shoals may be uncovered or unprotected, exposing the eggs to the drying and freezing conditions of the winter air.

In the western sub-watershed, most lakes support populations of walleye, although lakes such as Mazinaw contain lake trout and support both warm and coldwater populations. The central and eastern sub-watersheds contain primarily warmwater fish species such as northern pike, walleye, large and smallmouth bass, bluegill, pumpkinseed, rock bass, yellow perch and American eel.

The Mississippi River's surrounding terrestrial lands are home to a wide diversity of mammal, reptile and amphibian, insect and bird species. In many cases the life-cycles of these species are directly related to the river and the corresponding land-water interface. One example of this important linkage are the numerous wetland areas found along the river and the shores of some lakes. Loons, ducks and other waterfowl use these wetlands for nesting and staging areas. Furbearing mammals such as beaver, muskrat and raccoon derive food and shelter from wetlands. Reptiles depend on wetlands for much or all of their life-cycle and osprey and herons benefit from the shallow water feeding opportunities they provide.

The Mississippi River system is also home to several rare species and species designated as species at risk, considered to be of concern because so few populations exist in Ontario. The river supports a number of rare species including four dragonfly species, two fish species,two bird species, and one turtle that are dependent upon the river system and are afforded protection against wilful persecution, harm and destruction of their critical habitat. Certain wetland habitats on Kashwakamak Lake provide suitable habitat for a rare turtle species known as Blanding's turtle.

As well, the Mississippi River is the site of many natural heritage features. Natural heritage refers to ecological features that perform various beneficial functions on the landscape. These natural heritage features include, wetlands that form the interface between aquatic and terrestrial ecosystems, fish habitat, species at risk habitat, and Areas of Natural and Scientific Interest (ANSI) which provide recognition and protection to significant natural features.

Wild rice is an edible wild grain which is found in the Mississippi and is considered a natural heritage feature that is a staple for aboriginal communities and is still harvested today. An integral part of shallow lake and river ecosystems, this tall aquatic grass provides food for waterfowl and habitat for snails and water insects which are also eaten by waterfowl. Wild rice beds also provide habitat for furbearers and other wildlife. Water levels are important for maintaining wild rice stands as high water levels can drown these plants and low water levels can dry them up.

2.7 Surface Water Hydrology

Stream flow in the Mississippi River is monitored at several locations, the most downstream of which is located at Appleton (WSC 02KF006) immediately downstream of the Town of Carleton Place, as shown on Figure 2:4. Based on the stream flow record at this site for the years 1972 through 2000 the mean daily stream flow in the Mississippi River is 34 cubic metres per second (m^3/s or cms). The highest flow, recorded in 1998, was 282 m^3/s and the lowest, in 1999,was 2.19 m^3/s. Figure 2:4 depicts the mean stream flow hydrograph over that period.

Mean annual precipitation recorded at the Drummond Centre climate station (6102J13) between 1985 to 2006 is 878 mm with 705 mm falling as rainfall and 173 mm as snowfall. The mean annual runoff at

Appleton is 362 mm and the potential evapo-transpiration is approximately 825 mm. The monthly distribution is shown in Table 2-1.

2.8 Reservoir Management

As noted in Section 2.4, reservoir management has been a significant part of the watersheds hydrologic characteristics for over a century. There are 23 water control structures scattered throughout the watershed including 5 waterpower facilities and six reservoirs, with a total storage capacity of 12,160 hectare-metre (ha-m), which are used to regulate stream flow along the Mississippi River (Figure 2:2). Reservoir operation policies for the Mississippi River have been primarily defined on the basis of historic hydrologic conditions to continue achieving the objectives established through the Mississippi River Water Management Plan (2006)[2]. These objectives in essence reflect stakeholder expectations with respect to water levels and stream flow which have largely evolved since the early 1900s.

Figure 2:4. Mean Stream Flow 1972-2000

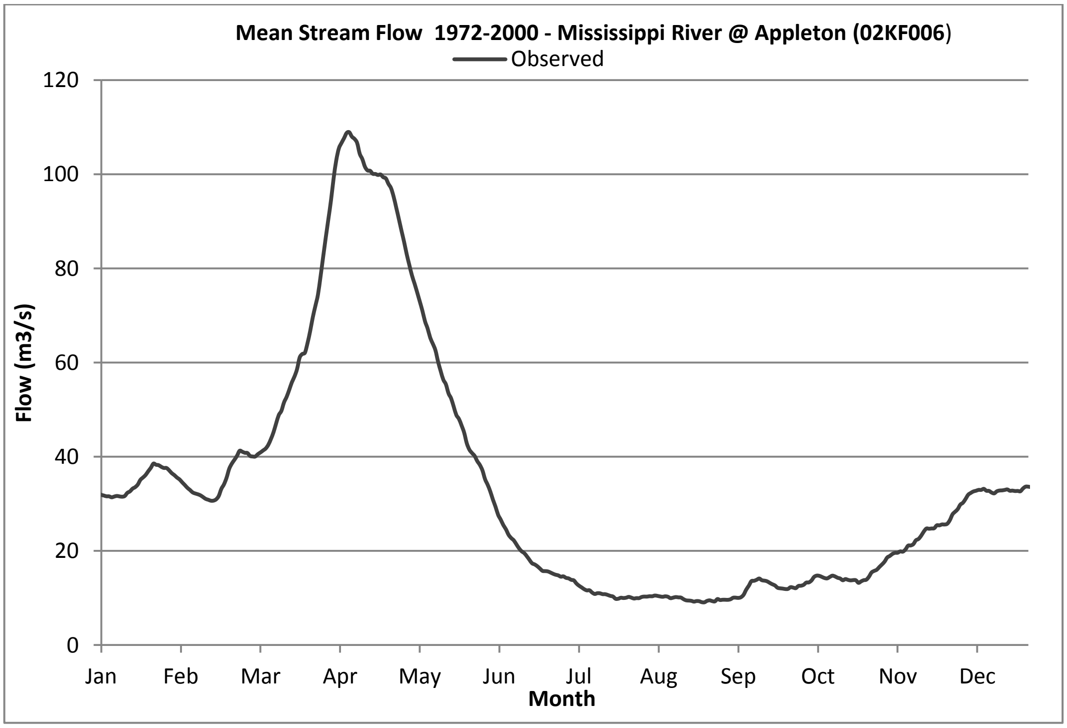
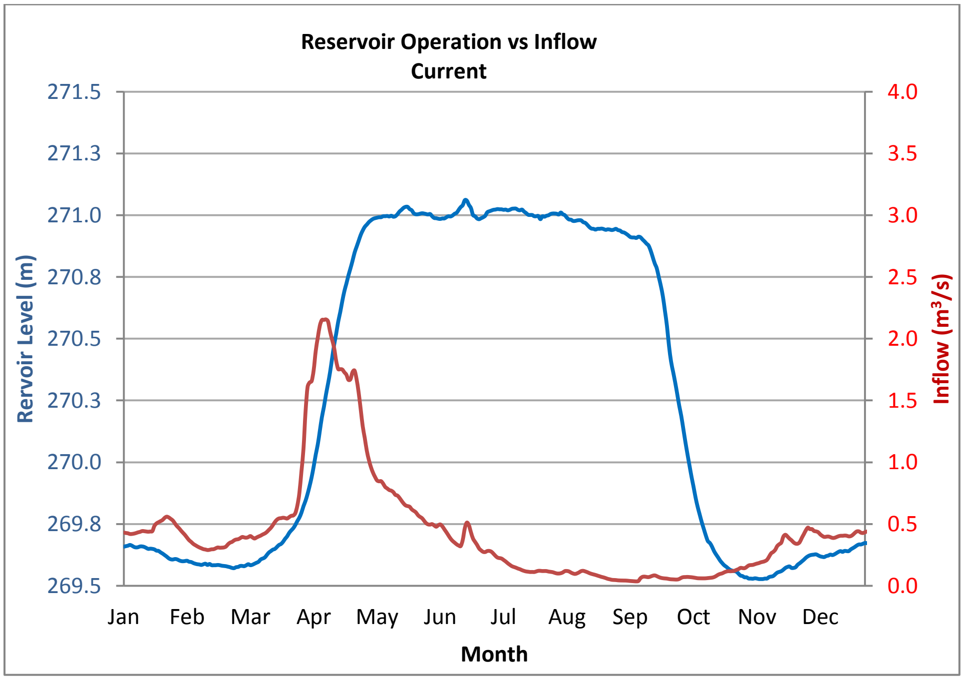


Table 2-1. Mississippi River Historical Water Budget 1972-2000

Month	Rainfall(mm)	Snow(mm)	Total(mm)	Runoff(mm)	PET(mm)
Jan	24.1	43.6	67.7	31.1	42.2
Feb	15.9	35.4	51.2	28.3	38.7
Mar	27.3	26.6	53.9	48.9	47.1
Apr	53.0	11.1	64.2	88.1	52.0
May	76.9	0.2	77.0	53.0	60.3
Jun	82.4	0.0	82.4	18.9	66.5
Jul	85.1	0.0	85.1	10.3	86.7
Aug	71.8	0.0	71.8	8.9	107.1
Sep	94.9	0.0	94.9	10.6	108.7
Oct	78.2	2.3	80.4	13.1	96.1
Nov	68.5	16.3	84.8	20.5	68.5
Dec	27.1	37.6	64.7	29.8	50.6
Total	**704.9**	**173.1**	**878.0**	**361.5**	**824.6**

The five upstream reservoirs,Shabomeka Lake, Mazinaw Lake, Mississagagon Lake, Kashwakamak Lake and Big Gull Lake, denoted as R1 – R5 in Figures 2:2 and 4:2, are filled in the spring from snowmelt and rainfall runoff to achieve a suitable summer recreation level on the reservoirs and to reduce potential downstream flood risk from snowmelt during freshet high flow periods. These levels are maintained until the fall (depending on local fish habitat or navigational requirements at certain sites) when the water is gradually released from storage until a low winter holding level on the reservoirs is established. This winter holding level is maintained, depending on runoff conditions over the winter, until the following spring when the reservoirs are again refilled (Figure 2:5).

Figure 2:5. Current Reservoir Operation vs Inflow (Reservoirs R1 – R5)



The most downstream of these reservoirs, Crotch Lake (denoted R6), is also filled in the spring from snowmelt and rainfall runoff. Once stream flow recedes in the lower reaches of the river system, usually by early July, water is released from storage in reservior R6 to augment downstream flow throughout the summer months to aid in hydropower generation, recreation and waste assimilation. Typically there is sufficient storage to maintain a minimum stream flow objective of 5 m^3/s until late October when the reservoir will reach its minimum level. With the release of water from the five upstream reservoirs in the fall, excess water is retained in storage at this reservoir to augment downstream flows over the winter period until the next spring freshet (Figure 2:5).

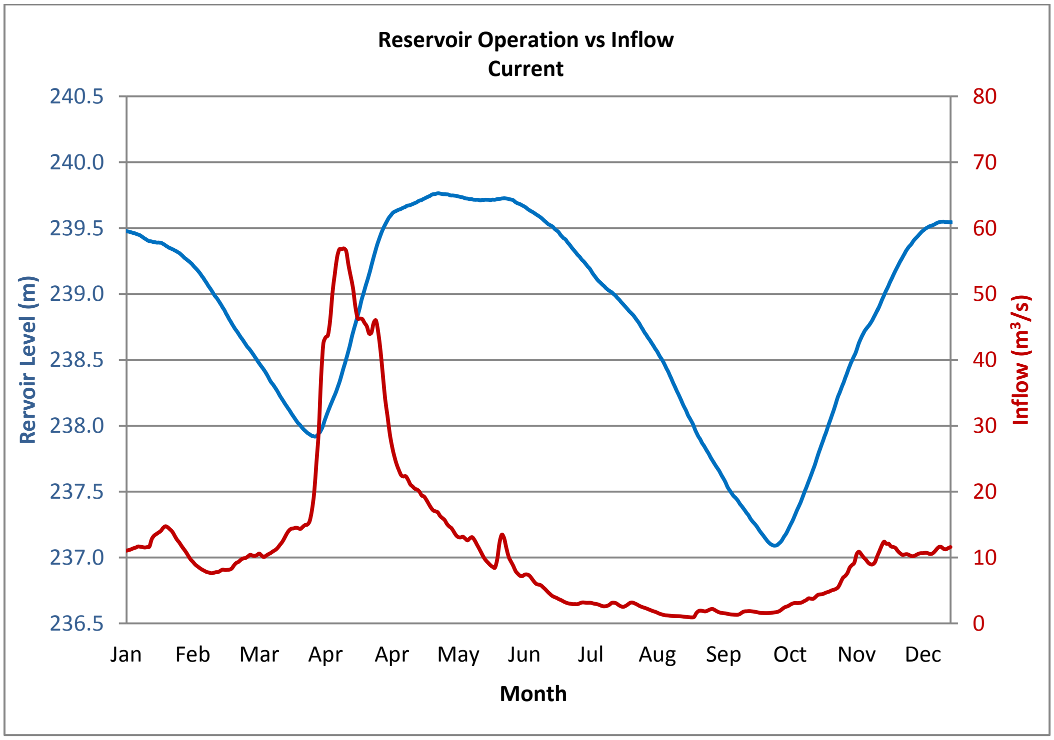
3. Study Objectives

To evaluate the performance of current operating policies and potential adaptation measures under future climate scenarios, the following methodology was followed in the current study:

1. Assess uncertainty associated with future climate projections from a range of climate models,
2. Assess the impact which projected changes in climate would have on basin hydrology,
3. Assess the capacity of the existing reservoir system and management protocols to respond and adapt, to projected runoff conditions,
4. Evaluate the capacity and willingness of users to adapt and,
5. Assess potential implications to stream flow conditions and waterpower facilities.

Stream flows in the Mississippi River can be significantly influenced by the six upstream reservoirs, particularly during periods of low flow. In addition to the surface water supply for the Town of Carleton Place and sewage treatment facilities at Carleton Place and Almonte, the five waterpower facilities which operate on the Mississippi River benefit from the stream flow regulation provided by these reservoirs.

Figure 3:1. Reservoir Operation vs Inflow (Reservoir R6)



A previous study[3] conducted in the watershed has demonstrated that projected changes in climate will result in significant changes to seasonal runoff distribution with less snow accumulation, earlier spring freshets, less runoff during the spring and summer months and higher stream flows in the fall and winter months. This study concluded that future low flow conditions on the Mississippi River would be 44% lower than present and would persist 28% longer. It also concluded that in general recreational interests could be satisfied on the upper reservoirs lakes, although existing reservoir capacity would be insufficient to meet downstream low flow augmentation objectives under extreme conditions and suggested that additional reservoir volumes of 2000 to 3500 ha-m may be required.

The previous study parameters were limited to assessing stream flows and reservoir response to the mean runoff conditions projected for the three future periods (2010-2039, 2040-2069 and 2070-2099) based on climate projections from the Coupled Global Climate Model CGCMII output. While the mean runoff conditions from one climate model provided invaluable insight into the potential implications for reservoir operations and average stream flow conditions, the analysis masked the range of variability in reservoir impacts from year to year and the uncertainty associated with climate projections.

As described in Section 4, a continuous time series of reservoir inflows were simulated for four 30 year periods; Baseline (1971 – 2000) and three Future Periods (2011 – 2040, 2041 – 2070 and 2071 – 2100). The three Future Periods were further simulated under three climate scenarios representing Dry, Average and Wet climate conditions. The three climate scenarios are provided to examine the uncertainty associated with the range of climate projections and the implications for water management planning. For reporting, only the Dry and Wet climate scenarios are referenced. These time series were subsequently used to simulate reservoir response according to user defined rule curves and management protocols.

3.1 Dealing with Confidence and Uncertainty

Inherent to the development and interpretation of any type of future projections, whether in the stock market, population, or climate, the degree of confidence in outcomes will vary depending on many factors and identify them all is crucial for accurate or near to perfect projections. Though stock market projections continue to be an important component of our economic system and population projections are regularly incorporated into multiple types of planning by all levels of government, the uncertainty and confidence levels in climate projections or climate change science are often cited as a reason for not moving forward in adopting adaptive and mitigation measures. It is important not to allow these concerns to unduly hamper adaptation plans and implementation efforts.

One of the first steps to addressing this issue is to determine the degree of accuracy required to create useful outcomes. Knowing what degree of accuracy is needed then provides a benchmark to determining how best to use available projection information. In any sector, 100% accuracy in the quantification of impacts is not necessary to move forward in developing or integrating good, relevant climate adaptation measures.

Outcomes of projections are often presented as a range of outcomes versus as a single number and, as in the case of climate projections, may be associated with scenarios which are representative of a set of conditions and the methodology by which the projections are generated. The key is to identify and utilize the similarities and variability in results and build on these similarities to understand where the certainties lie within a range of confidence in variability. For example, from available information we are certain and have high confidence that there will be a wider range of precipitation volumes compared to that which has been historically experienced and with that generalization in mind a number of decisions in water management and many other sectors can be made which will incorporate allowances for that range in uncertainity. We are also certain that under recent observed conditions, and even more under climate projection scenarios, the current water management approach for the Mississippi River watershed will be subject more frequently to increased risks of not meeting compliance levels.

The bottom line is to determine how to best move forward with the most complete information available and to develop plans and processes in such a way that they are flexible enough to incorporate new information as it becomes available, which necessitates an adequate feedback loop of periodic plan review and revision. This approach initiates the task of climate change adaptation while recognizing that revisions may necessary in the future if and when new information becomes available, and is a fundamental approach to good project management of any type.

4. Future Water Budget Projections

Climate change studies show a rise in temperature and high variability in the frequency and intensity of precipitation. As noted in Section 3.1 there will always be varying degrees of uncertainty which exist in climate projections which may affect our understanding of the likely effects of a changing climate and in turn what changes there may be to hydrological regimes and water resources. Water resources are one of the vulnerable sectors that face significant challenges with climate change and it is important to ensure, to the best of our ability, that they are managed properly. Change in precipitation patterns or changes in patterns of snow and ice melt alters hydrological systems and the quality and quantity of water resources available.

This study draws on work completed for the "Future Water Budget Projections in Mississippi Rideau Watershed Region[17] which is a subproject of this project. It should be noted that while the Kunjikutty study was completed for this project, it will support work in a parallel project titled the "Mississippi Rideau Climate Change Vulnerability Assessment Project". The study compares future climate projections from different Global Climate Model (GCM) scenarios and projects future water budget parameters in the watershed. Multi-model, multi-scenario climate projections using the change field method were analyzed to assess uncertainty in projected future hydrologic components. Similar to many climate change studies, the focus of this study is not to predict the future data, but to better understand uncertainties that could affect implementation of climate adaptation decisions under a wide range of possible future projections.

The GCM scenario climate data were obtained from the Ministry of Natural Resources and Forestry (MNRF). There are 76 different scenarios available from 28 GCMs and 3 emission scenarios. Daily climate data, generated using the change field or delta method, was used in the study. The data was downscaled to the Drummond Center climate station for use in the Mississippi River watershed.

The baseline period of 1971 to 2000 and future periods of 2011-2040, 2041-2070, and 2071-2100 were selected. Ten scenarios were chosen for each 30-year periods using the percentile method. In this method, the scenarios were selected to correspond to different percentiles assigned to the rank average annual change field values for precipitation and temperature separately. The Thornthwaite water budget model, modified by Johnston and Louie (1983) and provided by the Ontario Ministry of the Environment and Climate Change, was used to generate the water budget parameters for the future and baseline climate.

For the climate station selected, the study shows good consistency within the selected GCM scenarios in projecting future climate for 2011-2100 periods. The annual average temperature increases to 9.8°C in the Mississippi River watershed from its baseline temperature of 5.7°C. The results indicate a 1.3° to 4.1°C increase in the annual average temperature and a 4%-9% increase in precipitation by 2100.

Seasonally, the temperature increase is in a similar range of 1.2°C to 4.5°C. The largest increases in temperature and precipitation are observed in the winter months. While the precipitation increases annually, on a seasonal average, precipitation decreases by up to 2% during the summer period with decreases of up to 6% on a monthly basis. The largest observed increase in temperature which occurs in the winter will shift the timing and increase the amount of runoff. This has the potential to reduce the capacity of the snow pack storage and reduce the volume of water that could infiltrate the soil for soil moisture or groundwater recharge.

Snow in the watershed is consistently projected to decease between 26% and 75% and the water deficit is projected to increase between 22% and 177%. Annually, the mean runoff increases between 1% to 6%, but it consistently decreases in the spring and the summer months, which is significant for water management during the low flow season. During the low flow season there appears to be little or no runoff occurring from July through September, and this low flow period appears to occur earlier and last progressively longer from 2011-2100 with consistent decreases in the depth of runoff. This situation along with low projected summer precipitation, higher temperatures and increasing evapo-transpiration has the potential to be extremely important in managing flows and water levels in the watershed

The study confirms the limitations of the delta method in generating the climate data. Upon breaking down the 30-year periods it became evident that the 15-year trend analysis presumes that the future climate generated from GCMs, using the delta method for any climate station will follow the patterns of their baseline data while incorporating the future GHG emissions. Therefore the climate projections using the delta method are not recommended for studies where a potential change in inter arrival time, duration, or spatial extent of climatic extremes are concerned (e.g. droughts and floods). In any climate change and adaptation study both the selection of GCM and the downscaling method crucially depend on the objective of the study.

A key limitation of this method is not capturing the potential changes in the variability or time series behaviour of temperature and precipitation. It captures a certain amount of intensity of climatic extremes from the GCM simulation, but fails to incorporate potentially changing inter-arrival time, duration, or spatial extent of climatic extremes (e.g. droughts and floods. Therefore, in any climate change and adaptation study, both the selection of GCM and the downscaling method crucially depend on the objective of the study.

The study assesses the extent of uncertainty which exists in all the projected future hydrologic parameters and this would allow us to estimate the likelihood of future impacts in the MR region. As GCMs may carry large uncertainty in the climate projections, choosing a GCM is crucial and any climate impact and adaptation study based on a single GCM should be interpreted with great care. It is difficult to predict future flows correctly, but a water practitioner could and should include the uncertainty of future hydrologic parameters in water management plans in the watershed.

For more detailed information please see Future Water Budget Projections in the Mississippi Rideau Watershed Region (2015)[17].

4.1. GCM Scenario Selection for River Modeling

Building on the results of the Future Water Budget Projections in the Mississippi Rideau Watershed Region[17] the percentile method was applied to all 76 GCM scenarios to select three future climate scenarios representing average, wet and dry conditions for further stream flow modeling in the Mississippi River watershed (Table 4-1).

For the average climate condition, CGCM3T47-Run3, a Canadian GCM model with scenario SRA1B was selected as the precipitation and temperature rankings were between 51% and 67%, for all three future periods.

For the wet climate condition, CGCM3T47-Run2 with scenario SRA2 was assessed based on the precipitation ranking and NCARPCM with scenario ARA1B was assessed based on the temperature ranking. CGCM3T47-Run2 with scenario SRA2 was selected for the stream flow modeling as it was found to be the most conservative.

Table 4-1. Scenario selections for average, wet and dry conditions

	Precipitation Rank (%)			**Temperature Rank**				
	2020s	**2050s**	**2080s**	**2020s**	**2050s**	**2080s**		
Average condition								
CGCM3T47-Run3 _SRA1B	57	51	67	52	64	44	*Canada*	√
Wet condition								
CGCM3T47-Run2_SRA2	92	97	96				*Canada*	√
NCARPCM_SRA1B				5	7	17	*USA*	
Dry condition							-	
HadCM3_SRB1	5	7	23				*UK*	
Echo G_SRB1	8	4	15				*Germany/Korea*	√
INMCM3_SRB3	11	5	8				*Russia*	
INGV-SXG_SRA2	0	0	4				*Italy*	
CGCM3T63_SRA2				73	81	88	*Canada*	
NCARCCSM3_SRA2				88	88	85	*USA*	

In considering the dry climate condition, there were no Canadian or USA models which consistently projected an extreme dry condition based on the precipitation rankings. Among the HadCM3, Echo, INMCM3, and INGV-SXG models, the first three models include a comprehensive land/ice sheet model capability. Without the land or ice sheet component, INGV-SXG was considered most suitable for mountainous and southern maritime climates.

The Echo 3 model captures the El Nino/La Nina influence better, while the INMCM3 model includes the most comprehensive range of vegetation types. The HadCM3 model was considered to have a realistic GHG scenario which was appropriate for Ontario's climate - the Ontario Ministry of Environment and Climate Change is building upon this model to generate regional climate modeling (RCM) data. The RCM projections appear to provide an improved resolution of the Great Lakes effect compared to the GCM's. It has the advantage that local projections consider local climate physics (e.g. Great Lakes) and are adjusted on a spatial and temporal scale. As future studies are anticipated to focus on extreme events such as flooding or drought the temporal and spatial distribution within the RCM data will be an important consideration. Therefore the HADCM3 model with scenario SRB1 was selected for the dry climate condition in the stream flow modeling.

4.2 Rainfall Runoff modeling

Hydrologic models are an important tool in water resource management as stream flow is a vital parameter required in many hydrologic analyses for flood warning, drought forecasting, optimal reservoir operation, and hydro power generation. Models use simplified, conceptual representations of the hydrologic cycle and provide projections of hydrologic parameters to better understand the hydrologic processes within the catchment area.

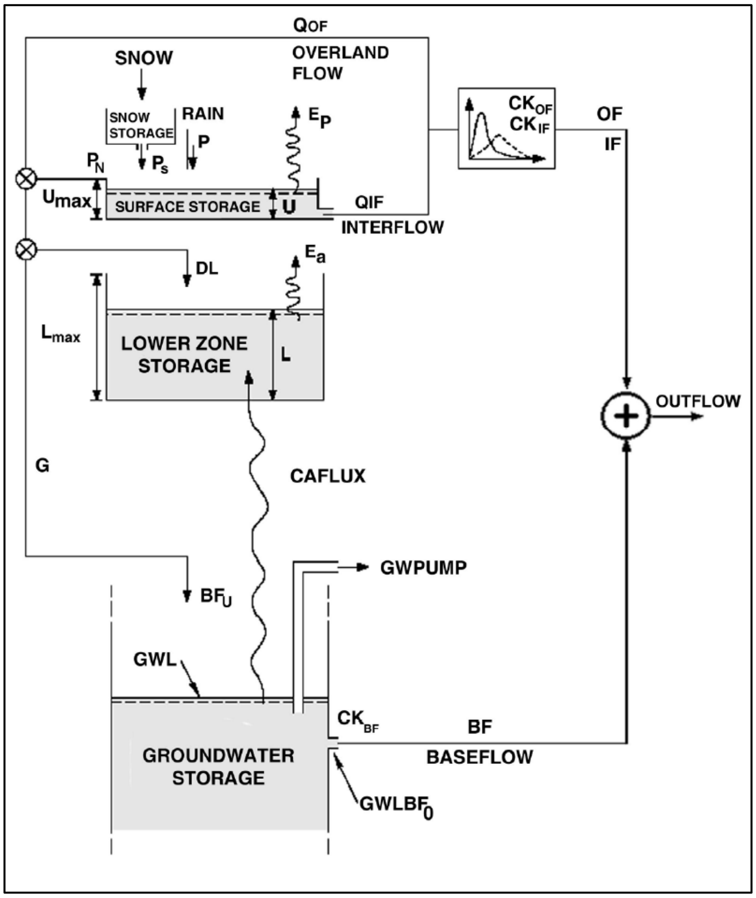
Existing hydrologic models are grouped into three types; lumped conceptual models, physically distributed models, and empirical models. Modeling attempts to simulate a complex process and it relies on high quality data for precipitation, evaporation, transpiration, abstractions, topography and soil characteristics[20]. In order to address the effect of land use and climate changes in hydrological and environmental interactions, the selected modeling approach needs to provide an adequate description of the governing physical processes and catchment properties[19].The lumped conceptual model approach which requires a significant degree of calibration and a good understanding of the catchment characteristics was considered suitable for this study. One of such models, the MIKE 11-NAM model [21] has been applied in previous studies[3] and was subsequently used in this study.

4.3. MIKE 11 NAM Model

The Nedbør Affstrømnings Model (NAM), meaning precipitation-runoff-model, is a deterministic, lumped, conceptual rainfall-runoff model, which is part of the MIKE 11 model developed by the Danish Hydraulic Institute (DHI). The model simulates the rainfall-runoff process by continuously accounting for the water content in four different and mutually interrelated storages which represent snow storage, surface storage, lower or root zone storage, and groundwater storage[18].The NAM model structure with its four different storage components and their corresponding flows is shown in Figure 4:1.

The NAM model is based on physical structures and equations, which treats each catchment as a single unit. While some of the model parameters can be evaluated from physical catchment data, final parameter estimation must be confirmed through a calibration process and compared to available time series of hydrologic observations.

Figure 4:1. NAM model schematic



Meteorological data (temperature, precipitation and potential evapo-transpiration), model parameters, initial conditions and stream flow are the basic data required to calibrate and validate the model. Snow accumulation and melt are important hydrologic processes in a river basin where the snowpack acts as storage so precipitation is retained during the cold season and subsequently released as melt water during the warmer periods. A snow melt component of the runoff process is an integrated module within the NAM model in which temperature data is required for the snowmelt modeling. During periods when the ground is not frozen precipitation enters surface storage, however during the winter periods precipitation is retained in the snowpack storage which is released when it is melted in warmer periods.

Based on the meteorological input data, the model simulates catchment runoff and other elements of the hydrologic cycle. The model output consists of catchment flow over time, subsurface flow contributions to the channel, and other elements of the hydrologic cycle, such as soil moisture content and ground water recharge[18]. The simulated catchment runoff is distributed conceptually between overland flow, interflow and baseflow components.

4.4. Stream Flow Simulation

There are limited stream flow records available for hydrologic model calibration within the study area; these are required for reservoir inflow simulation. Previous studies[3] have demonstrated that stream flow records from an unregulated stream in an adjacent, hydrologically similar catchment area can provide a reasonable estimate of reservoir inflow.

The catchment area of the Clyde River at Gordon Rapids stream gauge station (02KF013) was selected for the NAM model calibration and validation as the catchment area is predominately natural and unregulated with similar hydrologic characteristics to the catchment areas of interest. The drainage area above the Clyde River stream gauge station is 287.8 km^2 (Figure 4:2, hatched area). Two other stream gauge stations on the system are found on Mississippi River at Dalhousie Lake (02KF019) and the Mississippi River at Appleton (02KF006). Location of these gauges can be found in Figure 4:2.

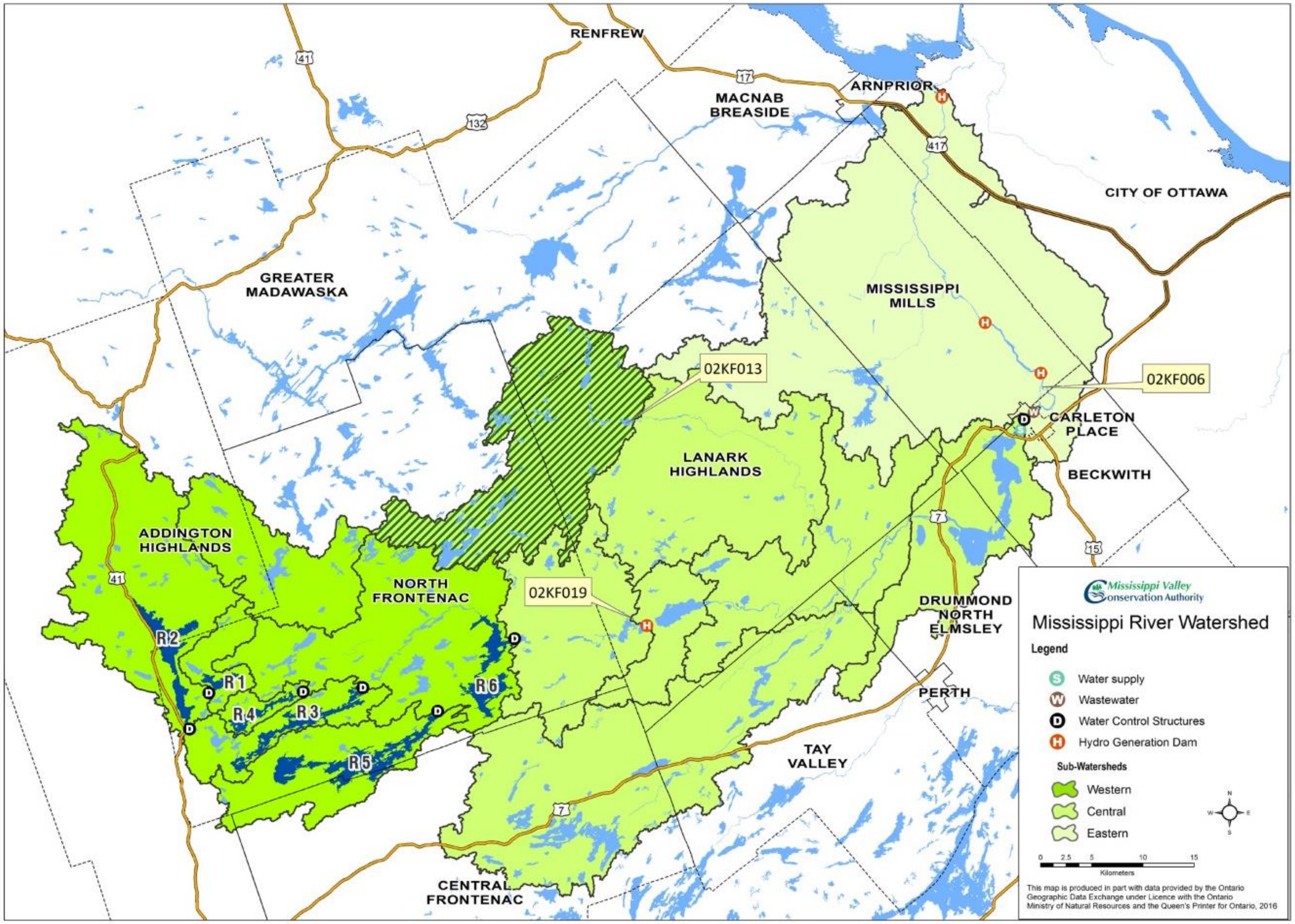
Data from four climate stations was considered and is shown in Figure 4:2. Two stations are located within the Clyde River catchment area. The Ompah-Seitz station is monitored by volunteers and records precipitation and temperature while the MVCA monitors precipitation at the stream gauge site. Two additional climate stations managed by Environment Canada (EC) are the Drummond Centre climate station which is the nearest EC station to the study area and the Ottawa Airport station which is located further to the northeast. Both of these stations have a long record period of climate data, exceeding 30 years.

Review of the climate data from the four climate stations resulted in the rain data from the Gordon Rapids gauge station being excluded from the analysis as it exhibited significant differences from the other data sets[22]. The Ompah-Seitz station data was subsequently used for the Mike 11 hydrologic model calibration and validation. Potential Evapotranspiration (PET) data were estimated with the Penman-Monteith equation using the climate data from the Ompah Seitz station.

Snow accumulation and melt are important hydrologic processes which occur during the spring freshet. Use of daily average temperature was not considered sufficient to capture the implications of daily variations in snowpack accumulation and melting. Air temperature throughout a day is typically low at night and reaches its maximum by early afternoon. The minimum and maximum temperature in each day was used to construct a semi-daily temperature data series assuming the minimum temperature occurred at 3:00 AM and the maximum occurred at 3:00 PM. The degree-day coefficient is the dominant parameter controlling the snowmelt rate. A time-varying degree-day coefficient was used to calibrate the snowmelt timing and hydrograph simulation during the freshet period[22].

The streamflow monitoring station located on the Clyde River at Gordon Rapids has a consistent period of stream flow records from 1971. A review of the soil, land use and topography (10 m x 10 m DEM) data for the study area concluded the soil type as sandy loam, the dominant land cover to be forest, and the elevation difference approximately 250 m. As a result, further division of the catchment area into sub-catchments was not considered necessary. The location of the streamflow gauge site was used to define the catchment area for the Mike 11 Model calibration and validation exercise. The period from 1996-2006 was selected for model calibration and the 2007-2012 period selected for model validation.

Figure 4:2. Streamflow Gauge Sites on the Mississippi River



4.5 Model calibration

There are both automatic and manual calibration options available in NAM model. The auto-calibration tool in the NAM model can be used to speed up the calibration of the model. Based on up to four objectives (water balance, overall hydrograph shape, peak flows and low flows), the auto-calibration tool will find the best fit between simulated and observed hydrographs. A global optimization routine called the Shuffled Complex Evolution (SCE) algorithm takes care of the actual parameter optimization. It will optimize nine different model parameters including maximum water content in surface storage (Umax), maximum water content in root zone storage (Lmax), overland flow runoff coefficient (CQOF), time constant for interflow (CKIF), time constant for routing interflow and overland flow (CK12), root zone threshold value for overland flow (TOF), root zone threshold value for interflow (TIF), baseflow time constant (CKBF), and root zone threshold value for groundwater recharge (TG). Manual calibration can also be applied to the above nine different parameters within the permissible minimum and maximum values (Table 4-2).

Table 4-2. NAM Model - Auto or Manual Calibration Model Parameter Ranges

Parameter	Unit	Range	Parameter	Unit	Range
U_{max}	Mm	5 - 35	TOF	-	0 – 0.9
L_{max}	Mm	50 – 400	TIF	-	0 – 0.9
CQOF	-	0	TG	-	0 – 0.9
CKIF	Hours	200 - 2000	CK_{BF}	hours	500 - 5000
CK_{12}	Hours	3 – 72			

Typically model calibration should start from a snow-free period as it is difficult to estimate the initial snowpack condition during the winter. Therefore, the model simulation period was chosen to be 1-Sept-1996 to 31-Dec-2006.

Since the model calibration starts when the soil column is relatively dry, the U/Umax parameter value set as 0.5 and the L/ Lmax parameter value as 0.85. The initial baseflow (BF) was set as 0.2 m^3/s which was estimated from the observed hydrograph. The Ompah-Seitz station is located at the very upstream end of the catchment area and therefore not all precipitation events may be entirely representative throughout the study area. Therefore, the calibration process was supplemented using precipitation data from the Drummond Centre station.

Figure 4:3 shows the comparison of observed streamflow with simulated streamflow for the period of 1-Sept-1996 to 31-Dec-2006 at the gauge site. The overall water balance error for the calibration period was 0% and the coefficient of determination was 0.67. Figure 4:4 shows the comparison of cumulative flows between observed and simulated in which the simulated streamflow matches well with observed streamflow.

Figure 4:3. Observed vs simulated flow for calibration period 1996-2006

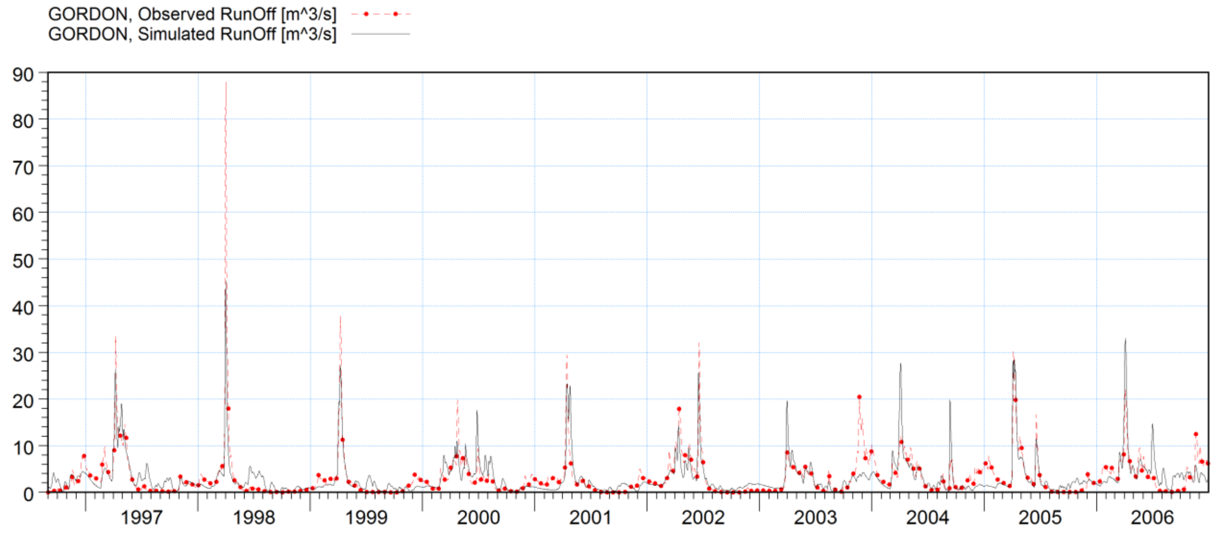
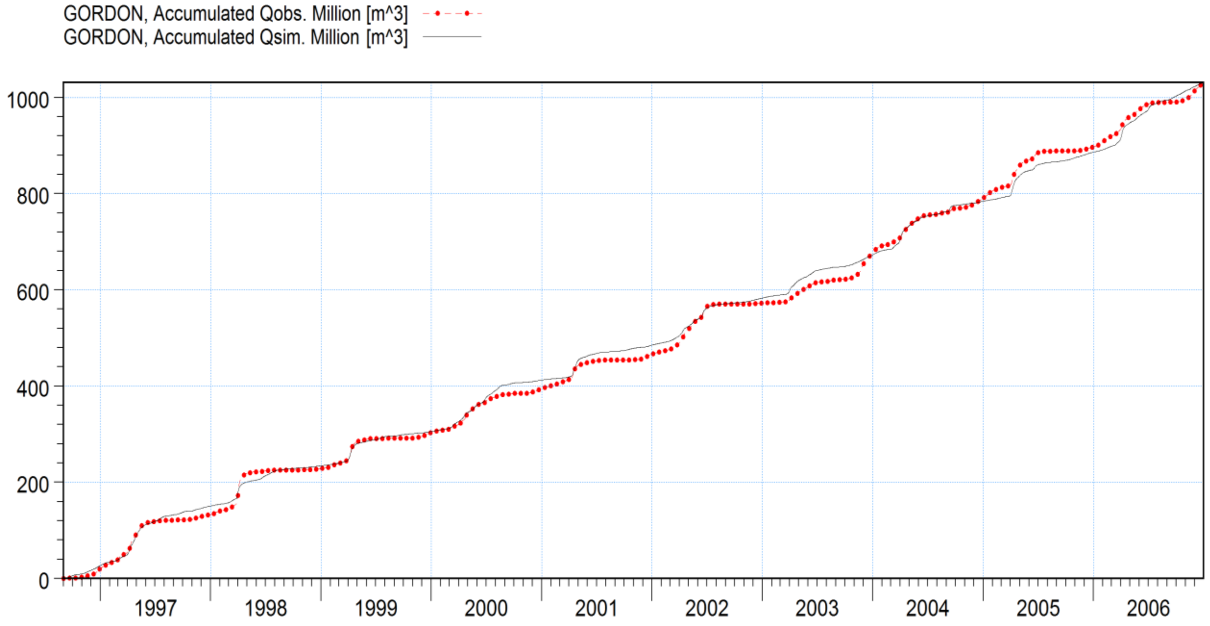


Figure 4:4. Cumulative observed vs simulated flow for the calibration period 1996-2006



The major model parameters and calibrated values are provided in Table 4-3.

Table 4-3. Major model parameters and calibrated values

Calibrated Parameters	Calibration values
Umax	43.7
Lmax	129
CQOF	0.535
CKIF	511.9
CK1	47.5
TOF	0.84
TIF	0.0415
TG	0.968
CKBF	1413
CQLOW	41.9
CKLOW	19368

4.6. Model validation

The objective for the model calibration exercise was to achieve an overall water balance based on the resulting root mean square error (RMSE).

Based on the calibrated model, during the validation period the model appears to consistently over-estimate flows in the lower half of the range, and consistently under-estimate flows in the upper range (Figure 4:5). Although it is possible to calibrate for peak flows or low flows, these must be performed separately and it was considered more important to maintain agreement on the water balance for reservoir simulation. The comparison of the cumulative observed flow to simulated flow for the validation period of 2007-2012 are provide in Figure 4:6.

Figure 4:5. Observed vs simulated flow for the validation period 2007-2012

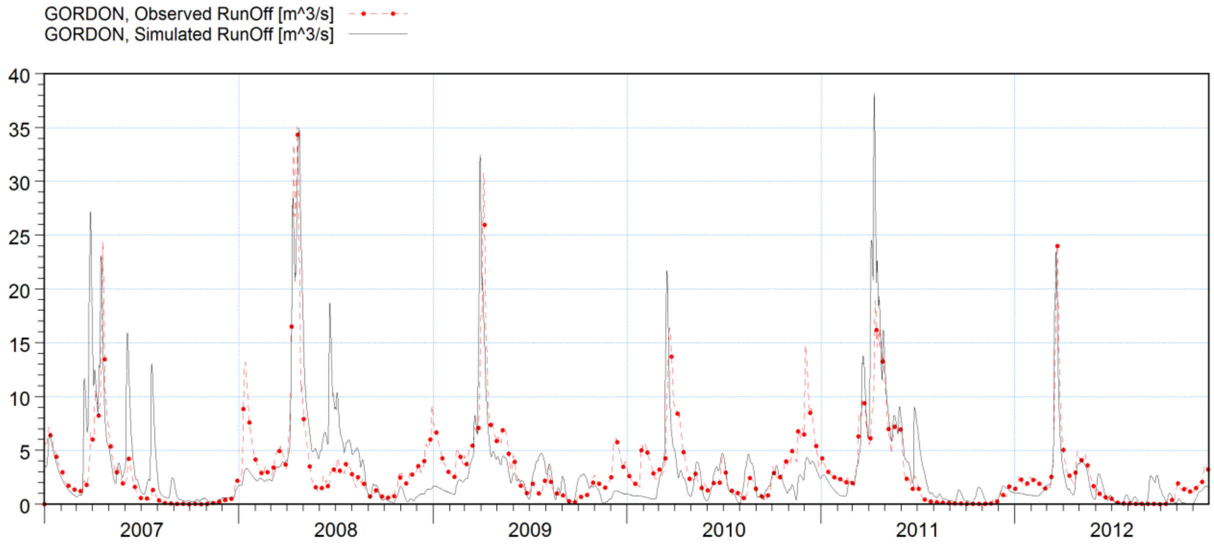
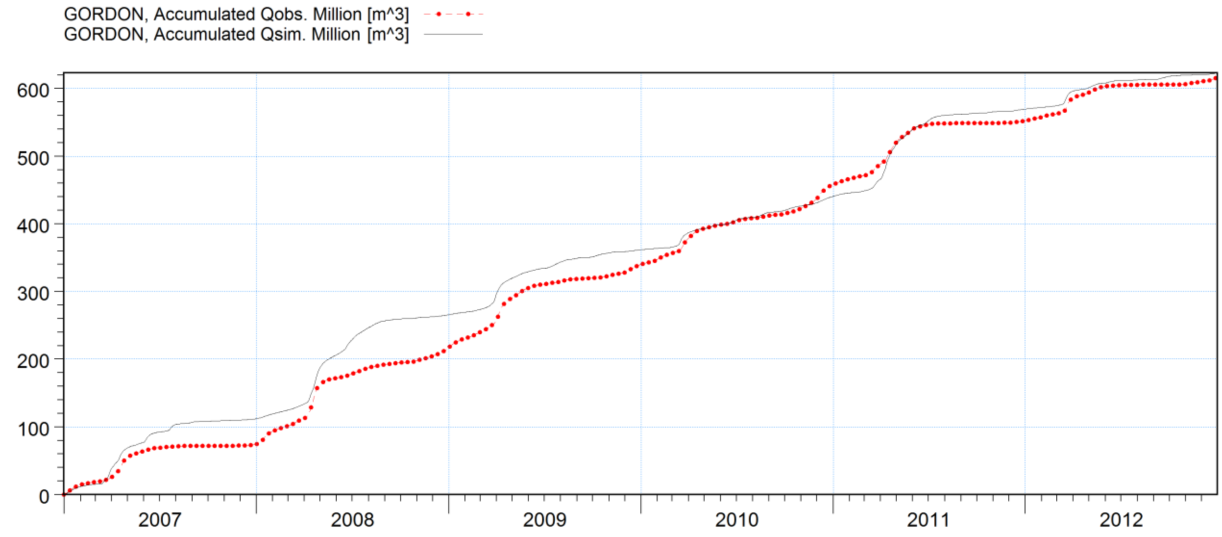


Figure 4:6. Cumulative observed vs simulated flow for the validation period 2007-2012



4.7. Simulated Flows Adjustment

Considerable effort was made during the calibration exercise to achieve a best match between the observed and simulated flows for all months of the year, while minimizing the error in the overall water balance. It was observed that while the overall water balance in the validation exercise performed well, the simulated flows in the high and low ranges did not produce good results. In addition to the calibration parameters, other sources of error also contributed to the model's performance. PET was estimated based on the Drummond Centre climate station which is located outside of the catchment area and is based on single station data and therefore may not be representative of the catchment area.

To correct for the differences in simulated and observed flows during the spring and summer months, the ratio between the average monthly totals for the observed and simulated flows were determined and used to adjust the daily simulated flows. Figure 4:7 illustrates the mean annual hydrograph for the observed, simulated and adjusted simulated flows. The adjusted simulated flows match very well with the observed flows in all months (Figure 4:8). These ratios were similarly applied to the simulated future daily flows for 2011-2100 for each of the average, wet, and dry conditions.

Figure 4:7. Adjusted simulated vs observed flows at Gordon Rapids

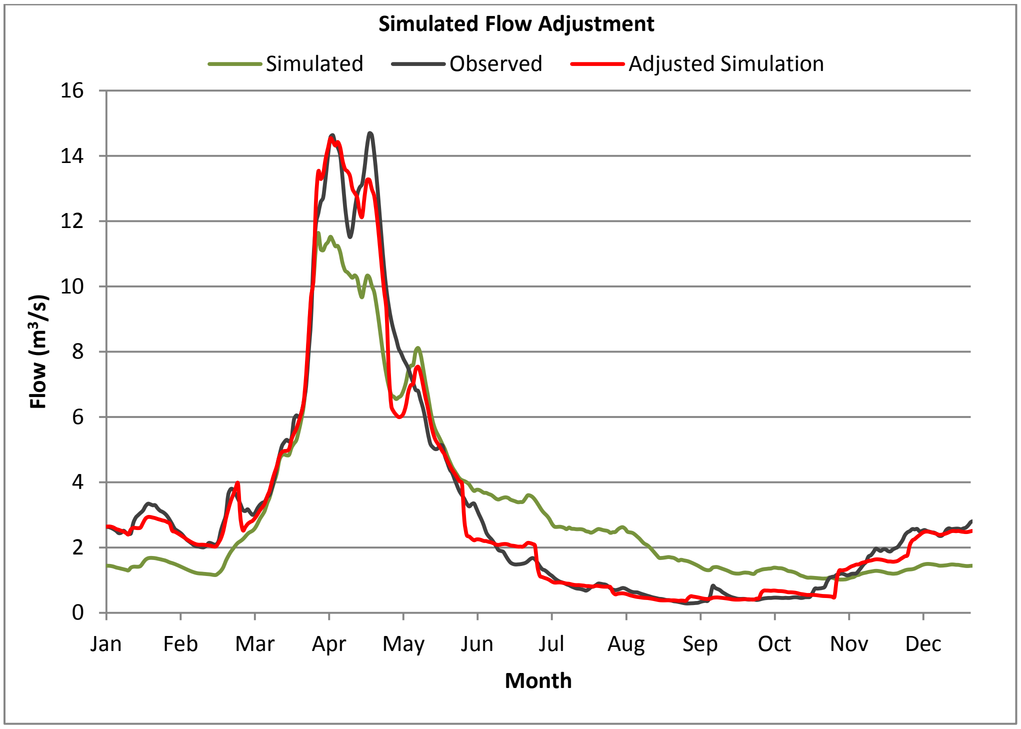
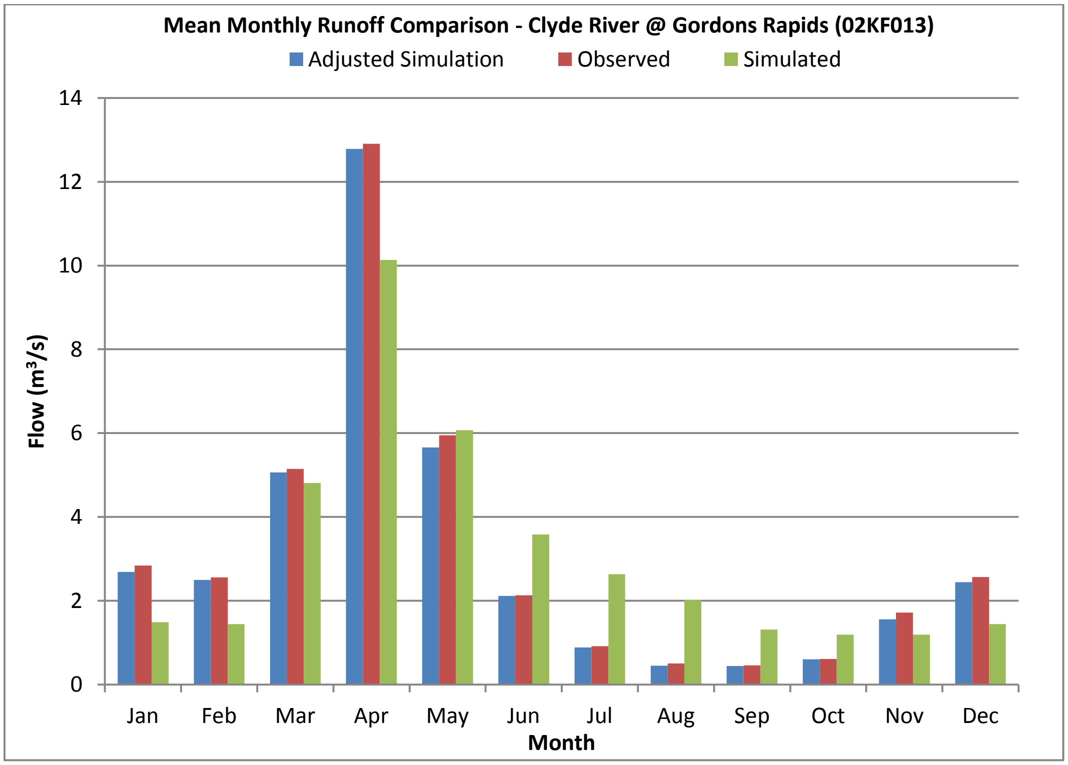


Figure 4:8. Monthly average flows: observed, simulated and adjusted simulated flows



5. Watershed Modeling

Reservoir simulation was conducted using the Mississippi River Watershed Model (MRWM) which is an in-house reservoir operation model developed by MVCA. Local reservoir inflow and stream flow from unregulated sub-catchments was derived by transposing the simulated stream flow from the calibrated Clyde River @ Gordons Rapids Mike 11 model, on the basis of relative drainage area;

$Q(d) = Q(gr)*DA(d)/DA(gr)$

Where:
$Q(d)$ = transposed stream flow at destination site (m^3/s)
$Q(gr)$ = simulated stream flow at Gordons Rapids site (m^3/s)
$DA(d)$ = drainage area at destination site (km^2)
$DA(gr)$ = drainage area at Gordons Rapid site (km^2)

This model routes reservoir inflow hydrographs through each reservoir using the storage-indication method, based on calibrated structure rating curves and reservoir stage-storage relationships. In its original form, the model allows the user to adjust dam settings at each time step of the simulation. The resulting discharge hydrograph is subsequently routed to the next downstream reservoir or stream confluence using the Muskingum method and then added to local basin inflows. The Muskingum routing parameters were calibrated through trial and error based on historical water level and available stream flow records (Table 5-2). This process was continued through the river system, incorporating each storage reservoir and intermediate sub-watershed inflow to simulate the stream flow at the Mississippi River @ Appleton stream gauge site.

Table 5-1. Sub-watershed Drainage Areas

Sub-watershed	Drainage Area (km^2)
Shabomeka Lake Reservoir (R1)	40.23
Mazinaw Lake Reservoir (R2)	295.52
Kashwakamak Lake Reservoir (R3)	76.92
Mississagagon Lake Reservoir (R4)	21.26
Buckshot Creek	186.24
Big Gull Lake Reservoir (R5)	141.69
Crotch Lake Reservoir (R6)	299.59
High Falls GS	203.13
Dalhousie Lake (02KF019)	79.72
Gordons Rapids (02KF013)	287.80
Clyde River	371.17
Fall River	432.58
Ferguson Falls	254.34
Carleton Place Dam	207.90
Appleton (02KF006)	47.91

Table 5-2. Muskingum Routing Parameters

Routing Reach	K	X
Semi-circle Creek	6	0.2
Marble Lake	24	0.1
Farm Lake	48	0.1
Ardoch	48	0.1
Gull Creek	6	0.2
High Falls	36	0.1
Sheridans Rapids	36	0.2
Clyde	24	0.2
Lower Clyde	24	0.2
Ferguson Falls	36	0.2
Appleton	12	0.3

User-Defined Operating Rules

Descriptions of a variety of user defined input variables follows:

Fp1 – Short range forecast period

Fp2 – Long range forecast period

Qmin – Minimum environmental reservoir outflow which must be maintained until the *Inactive Zone* (L1) is breached.

Date 1 – Earliest date at which reservoir filling will commence.

Date 2 – Julien date at which reservoir drawdown will commence.

T2a – Minimum mean 7-day air temperature at which reservoir filling will commence.

Delta – Recession rate at which reservoir release will be reduced during reservoir filling if Qfp has not been determined and reservoir outflow is greater than Qlim.

ROCR – Default recession value.

Spawn Period – The julien dates between which walleye spawn is in progress and reservoir outflow rates will not be allowed to recede at a rate greater than a default value specified in ROCR.

5.1 Reservoir Response Simulation

In order to assess the performance of the existing reservoirs and associated operation policies under projected climate conditions, it was necessary to simulate the reservoir response to many different data sets. MRWM, which is written in Visual Basic, requires manually specifying the setting of each water control structure at each time-step of the simulation. Due to the extensive number of simulations required, it was necessary to employ a model which could simulate the operation of several reservoirs based on predefined rules and objectives. While several models exist which provide this capability it was considered advantageous to integrate this functionality into the MRWM model in order to maintain flexibility and to incorporate operator best practices and experience in the simulation process. MRWM was re-coded to incorporate pre-defined rule curves, decision variables and trade-off functions to simulate reservoir outflow with sufficient flexibility to allow manipulation in response to future hydrologic and climatic conditions.

The basic decision process for the operation model is to release outflow from the reservoir, at each time-step of the simulation, equal to the forecasted inflow plus the change in reservoir storage required to satisfy reservoir operational objectives;

$$O = I + \Delta S$$

Where: O is Outflow at current time step
I is forecasted inflow
ΔS is change in reservoir storage

The reservoir simulation model evaluates a series of operating rules depending on which specific operating strategy is in effect. The operating strategies are defined for the reservoirs as described below. Typically the simulation would begin during the winter holding period after drawdown has been achieved.

Each reservoir was assigned an Inactive Zone (L1) and Flood Zone (L2). L1 is the minimum level which the reservoir is permitted to reach and the operation strategy cannot release water from this zone. L2 requires maximum discharge through the structure once this reservoir level is exceeded.

5.2 Reservoirs R1 – R5

Between L1 and L2, the reservoirs are operated to follow a pre-defined Rule Curve (Figure 5:1) The Rule Curve transitions between a Winter Holding Level and a Summer Holding Level which is achieved following the spring freshet when runoff from snowmelt and rainfall is captured to fill the reservoir. Transition back to the Winter Holding Level is initiated on a predefined date when water is gradually released from storage (Figure 5:1). Between L2 and the Rule Curve the reservoir can be utilized for flood management, while reservoir storage between Rule Curve and L1 can be used to augment reservoir outflow based on defined operating rules.

The transition period in the spring when the operators are reliant on runoff from the spring freshet to fill the reservoirs can be quite complex and is dependent on a variety of operational considerations as described in Section 5.4.

5.3 Reservoir R6

Reservoir R6 employs a different *Rule Curve* than reservoirs R1 – R5 as shown in Figure 5:2. The *Rule Curve* follows a semi-annual drawdown regime designed to augment downstream flows. The reservoir is filled through runoff from snowmelt and rainfall following the spring freshet to achieve a *Maximum Reservoir Level* by the beginning of July. After July 1st, the reservoir is gradually drawn down to maintain downstream flows above 5 m^3/s and will reach a *Minimum Reservoir Level* by mid-October. After mid-October the upstream reservoirs R1 – R5 will release water from storage based on their drawdown schedule, which will be retained in Reservoir R6 until mid-January at which time the water will be released to augment downstream flows over the winter. As with the upstream reservoirs, the reservoir can be used for flood management to a maximum reservoir level of L2.

Figure 5:1. Reservoirs R1 – R5 Operating Zones

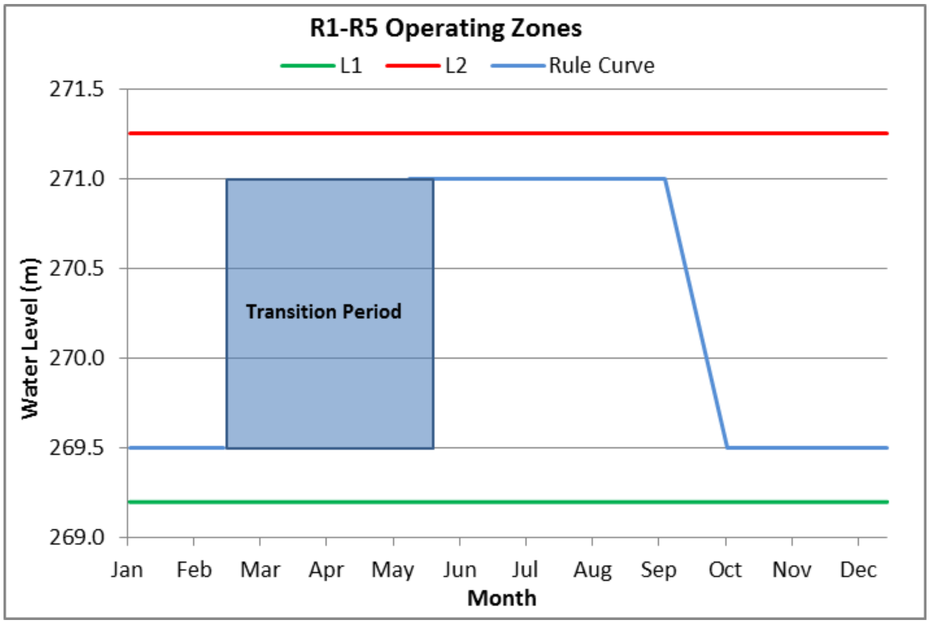
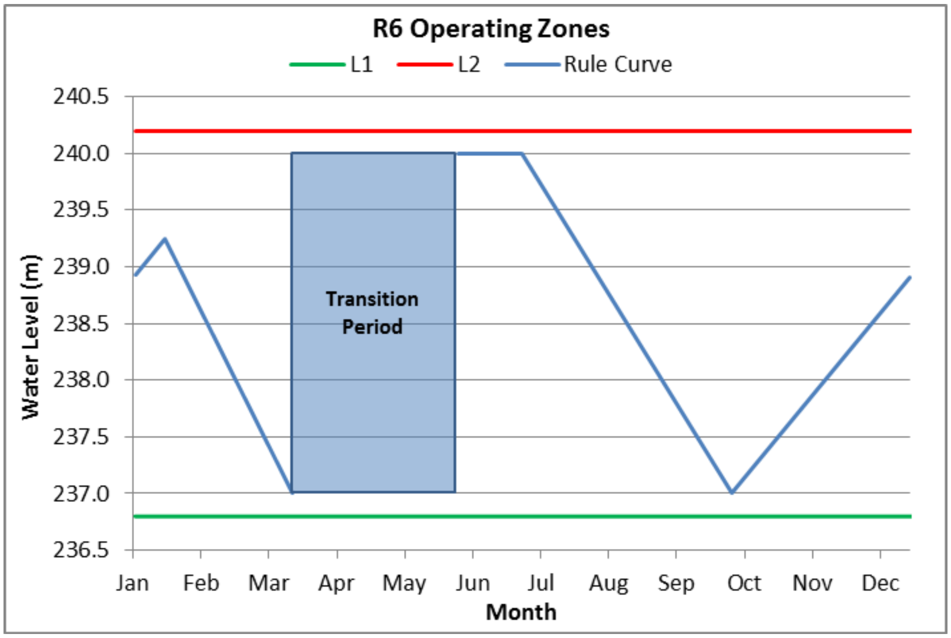


Figure 5:2. Reservoir 6 – Rule Curve



5.4 Baseline Operating Strategies

Variables considered in operating approach;

- rule curve Fig.5:1
- winter/spring transition changes not only from one year to the next but constantly within the timeframe table 5:2

- determination of onset/occurance of freshet
    - snowwater content decreases or
    - air temperatures of the previous 72 hours is above zero degrees Celcius

5.4.1 Strategies

Winter holding strategy (WMS1) – This strategy governs operation of the reservoir during the winter period when the reservoir is maintained at the low Winter Holding Level. This strategy is followed once the Winter Holding Level has been achieved until a predefined date (Date 1 - typically February 15th). Beyond Date 1, this strategy will continue to be followed until the snow water content (SWE) in the snowpack has been depleted in accordance with a trade-off function described in Table 5-3. This trade-off function relates the previous 30 day mean air temperature (°C) to the ratio (%) of the current snow water content/runoff volume required to fill all upstream reservoirs. The trade-off function is intended to balance the risk of failing to satisfy the Summer Holding Level due to a lack of available runoff versus creating potential damage to shoreline structures if reservoir levels are raised while an ice sheet still exists on the reservoir.

Table 5-3. Trade-off Function

Tav (°C)	R (%)
-10.0	0.00
-5.0	75.00
-3.0	100.00
-1.0	125.00
0.0	130.00

The trade-off function is user-defined for each reservoir and is a measure of risk tolerance. As indicated in Figure 5:3, while snow water content is not a particularly strong indicator of runoff potential it can provide a useful guide as to the risk of not receiving sufficient runoff to fill the reservoirs, which in the Mississippi River watershed is approximately 125 mm.

The 30 day mean air temperature is used as a measure of ice quality and has been applied in ice modeling studies[4].

Reservoir filling strategy (WMS2) – This strategy is initiated once the snow water content has been depleted in accordance with Table 5-3. During WMS2, the model will attempt to determine an inflow value, based on forecasted inflows within the period Fp2 which will achieve the reservoir storage requirements by transitioning from the current reservoir outflow to the inflow value Qfp as depicted in Figure 5:4. Should the model fail to determine an inflow match during the period Fp2, which will satisfy the reservoir storage requirements, reservoir outflow will be maintained at a rate Qlim based on the average inflow forecasted over period Fp2 as specified by the user-defined function in Table 5-4.

Figure 5:3. Runoff Depth vs Snow Water Content

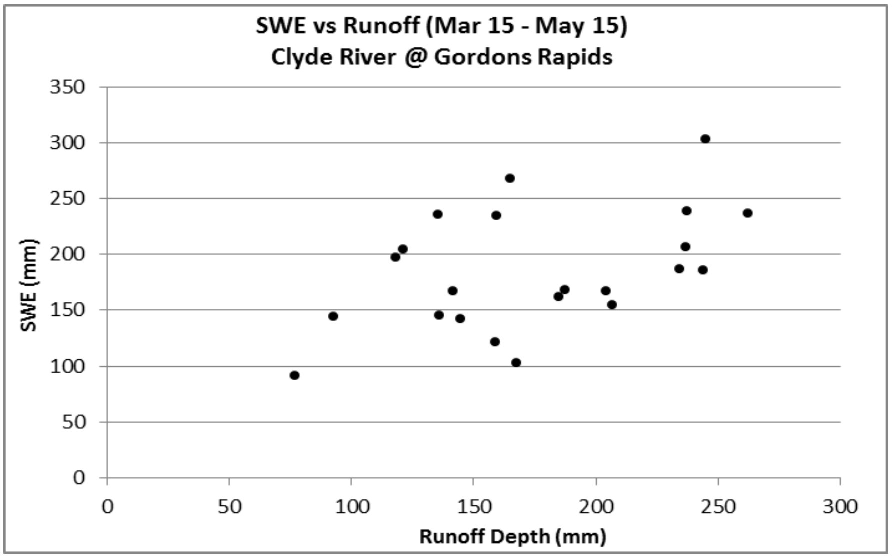
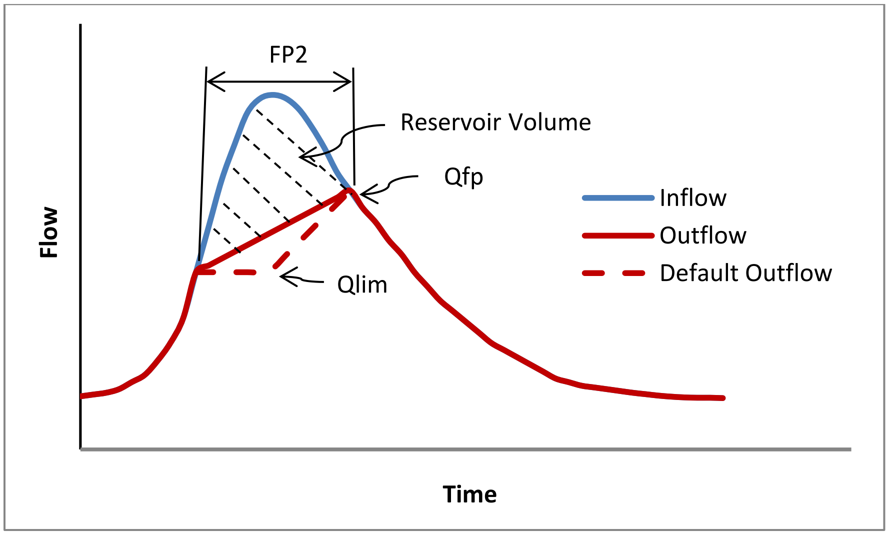


Figure 5:4. Reservoir Fill Methodology



Summer holding strategy (WMS3) – This strategy governs operation during the summer recreation period where the reservoir levels will be maintained at L3 in accordance with the basic outflow decision strategy.

Fall drawdown strategy (WMS4) - This strategy governs operation during the fall drawdown period once the simulation date reaches the reservoir drawdown date (*Date 2*). Reservoir levels will be drawn down in accordance with the *Rule Curve* until the reservoir level achieves the *Winter Holding Level*.

Table 5-4. Mean Inflow vs Minimum Reservoir Release Rate (WMS2)

Qmean	Qlim
0.00	0.00
2.00	0.29
4.00	0.57
6.00	0.86
8.00	1.14
10.00	1.43
12.00	1.71
14.00	2.00
16.00	2.00
18.00	2.00
20.00	2.00

5.4.1 Upstream Control Function

Between the *Inactive Zone* (L1) and the *Flood Zone* (L2) the reservoir level can be manipulated around the *Rule Curve* to moderate short term changes in reservoir inflow. A trade-off function as shown in Table 5-5 is used to allow the reservoir level to fluctuate by a specific amount of storage available between L2 and the *Rule Curve*, based on the average forecasted inflow (Iav) over a user-defined forecast period Fp1. Separate trade-off functions can be defined for each of the above operational strategies.

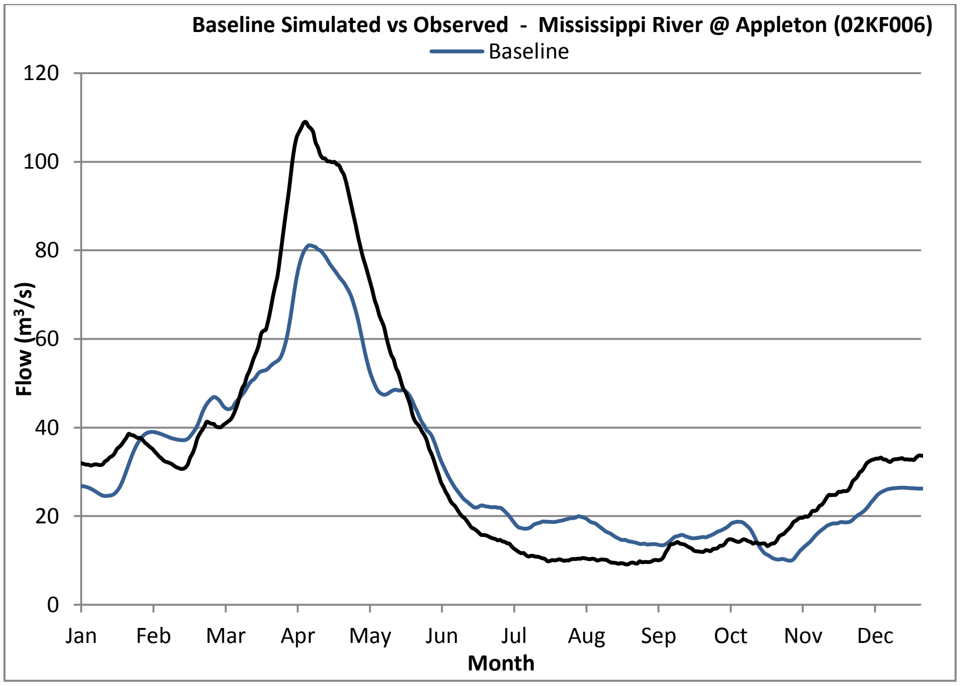
Table 5-5. Upstream Control Function

Iav(m3/s)	WMS1(%)	WMS2%)	WMS3(%)	WMS4(%)
0.0	0	0	-20	0
1.1	14	15	-5	14
2.2	19	30	10	19
3.3	23	40	25	23
4.4	28	50	40	28
5.6	32	60	55	32
6.7	37	70	70	37
7.8	41	80	85	41
8.9	46	90	100	46
10.0	50	100	100	50
11.1	57	100	100	57
12.2	64	100	100	64
13.3	71	100	100	71
14.4	79	100	100	79
15.6	86	100	100	86
16.7	93	100	100	93
17.8	100	100	100	100
18.9	100	100	100	100
20.0	100	100	100	100

5.5 Simulation Results

A comparison of the simulated baseline stream flow to the observed stream flow for the Mississippi River at Appleton stream gauge site, expressed as a mean annual hydrograph for the period 1971 - 2000 is shown in Figure 5:5. While there is good agreement in the timing of runoff between the simulation and the observed, the annual runoff volume of the simulated flow is 8% less than the observed flow. Furthermore, the simulated stream flow during the spring period is approximately 20% lower than observed and approximately 40% higher through the summer period. This discrepancy is attributed to two factors as discussed below.

Figure 5:5. Baseline Simulated vs Observed Stream Flow



Hydrologic simulation relies on a mathematical representation of many complex physical processes to describe a catchments response to hydrologic events. Due to limitations in understanding and representing these physical systems, a simplification of the processes is required in the mathematical simulation, which can introduce errors in the results. These errors can be minimized through a calibration process, where the parameters used in the simulation are adjusted until acceptable results are obtained compared to hydrologic observations. This process is described in Section 4.5, where the simulated annual runoff volume for the Clyde River at Gordons Rapids NAM model is within 0.25% of the observed for the 30 year baseline period and was considered acceptable for the purpose of this study.

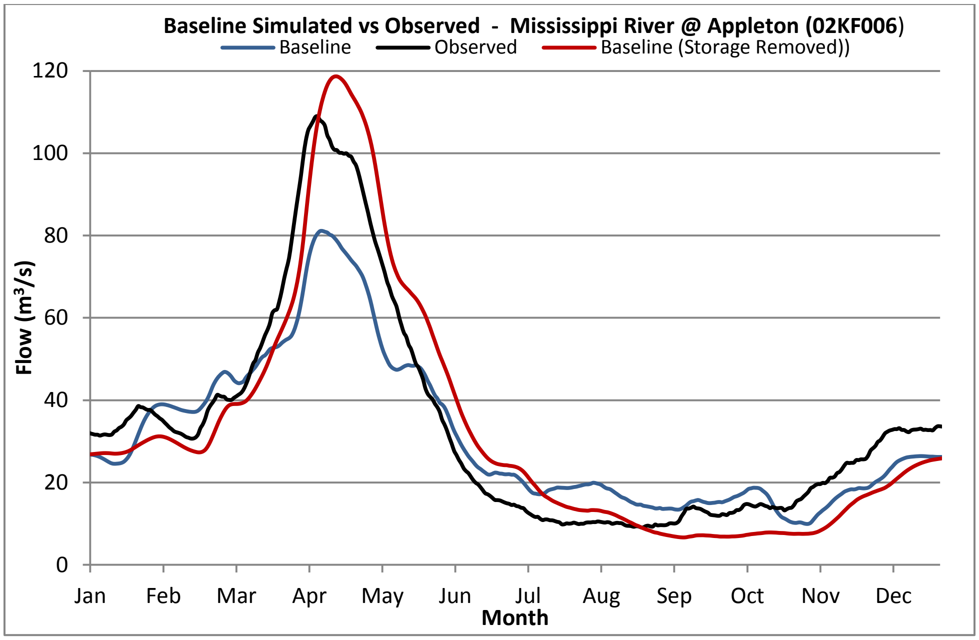
Due to a lack of available stream flow records with which to calibrate and verify the simulation of individual reservoir inflows, transposing the simulation results from the Clyde River at Gordon's Rapids NAM model on the basis of relative drainage area was selected as the best approach to determining reservoir inflows for use in the study. This approach does not capture the spatial variation in meteorological parameters such as precipitation and temperature which may occur as a result of using one climate station for the entire study area. As a means of comparison, total precipitation amounts for the baseline period at the Drummond Center climate station is approximately 3% less than the Ottawa CDA climate station. In addition, as described in Section 4.4, potential evapotranspiration estimated using the modified Penman-Monteith equation also relies on meteorological data from a single site and as such is susceptible to the same limitations in data availability. The 8% discrepancy between simulated and observed runoff volume at the Appleton gauge site is therefore attributed to spatial variation in meteorological conditions and is considered to be within acceptable limits.

The resulting stream flow simulation at the Appleton stream gauge is also influenced by the reservoir simulation as described in Sections 5.3 to 5.4. While the reservoir simulation procedures endeavoured to approximate management practices employed in the watershed, the simulation methodology utilizes a process which assumes reservoir inflow is accurately known for selected forecast periods. This allows for an idealized staging of reservoir outflows to minimize downstream flood risk during the spring freshet and augment stream flow over the summer period more efficiently. In reality, reservoir inflows are not known to this degree of accuracy and reservoir operations must rely on changes in reservoir level and stream flow response in other areas of the watershed to estimate inflow volumes. Due to incomplete historic operating records it is not possible to accurately reflect historic operation decisions in a simulation setting over a period of 30 years.

To examine the degree of influence that reservoir operations could potentially exert on stream flow conditions, another simulation was conducted for the baseline period without any reservoir storage. Figure 5:6 illustrates the results which the manipulation of reservoir storage, as defined in the baseline simulation, could exert on stream flows at the Appleton gauge site. On the basis of the simulation, it was determined that stream flow in the spring could be reduced by as much as 23% while stream flow in the summer months could be augmented by up to 39% through effective use of reservoir storage in the six upstream reservoirs.

Given the uncertainties associated with simulating a complex reservoir system over multiple years, it was concluded that the simulation methodology provided a reasonable representation of both the physical system as well as the management strategies currently in place for the Mississippi River watershed. As such, the application of this methodology in assessing the impact of future climate scenarios and potential adaptation measures is considered reasonable. It should be recognized however, that comparisons between the simulation results and historic observations may be skewed as a result the factors discussed above.

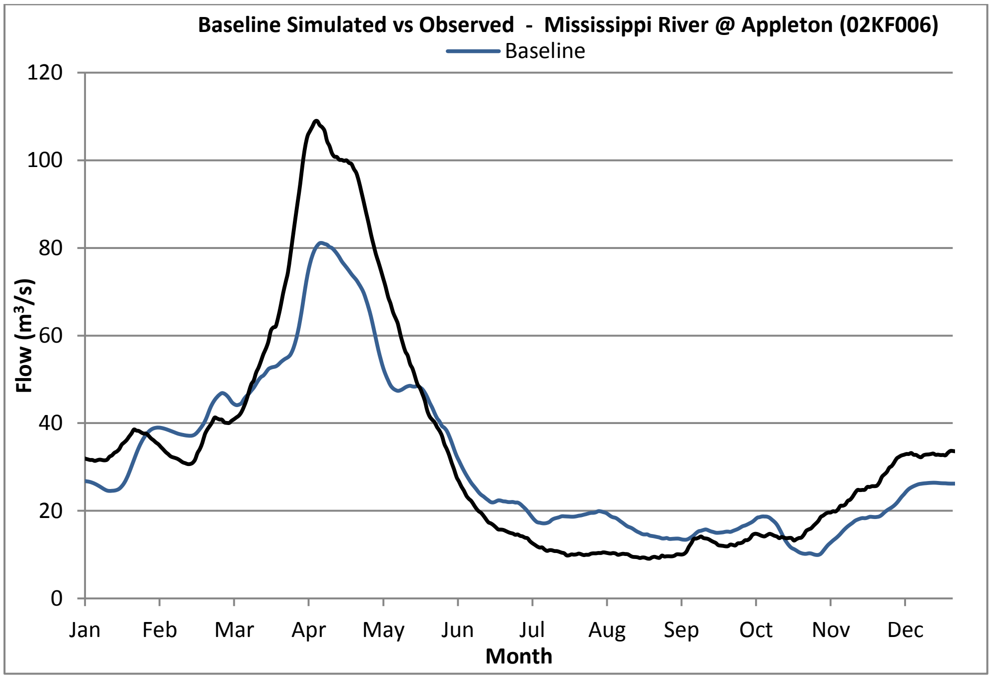
Figure 5:6. Baseline Simulated (w/wo Storage) vs Observed Stream Flow



6. Climate Change Impacts and Adaptation Options

Reservoir regulation involves the strategic storage and release of water over varying time periods to achieve a range of water management objectives. These objectives are established to address a variety of social, environmental and economic interests within the constraints imposed by the physical characteristics of the watershed and reservoir system under consideration. Reservoir operation policies are typically defined to achieve a number of objectives by capitalizing on the basin's expected range of hydrologic characteristics while mitigating the impact of extreme events. Over time, stakeholders develop perceptions of a "normal" condition within an anticipated range of variability. Changes in either the perceived "normal" condition or the range in variability can negatively impact individual users, creating the potential for conflicts to arise.

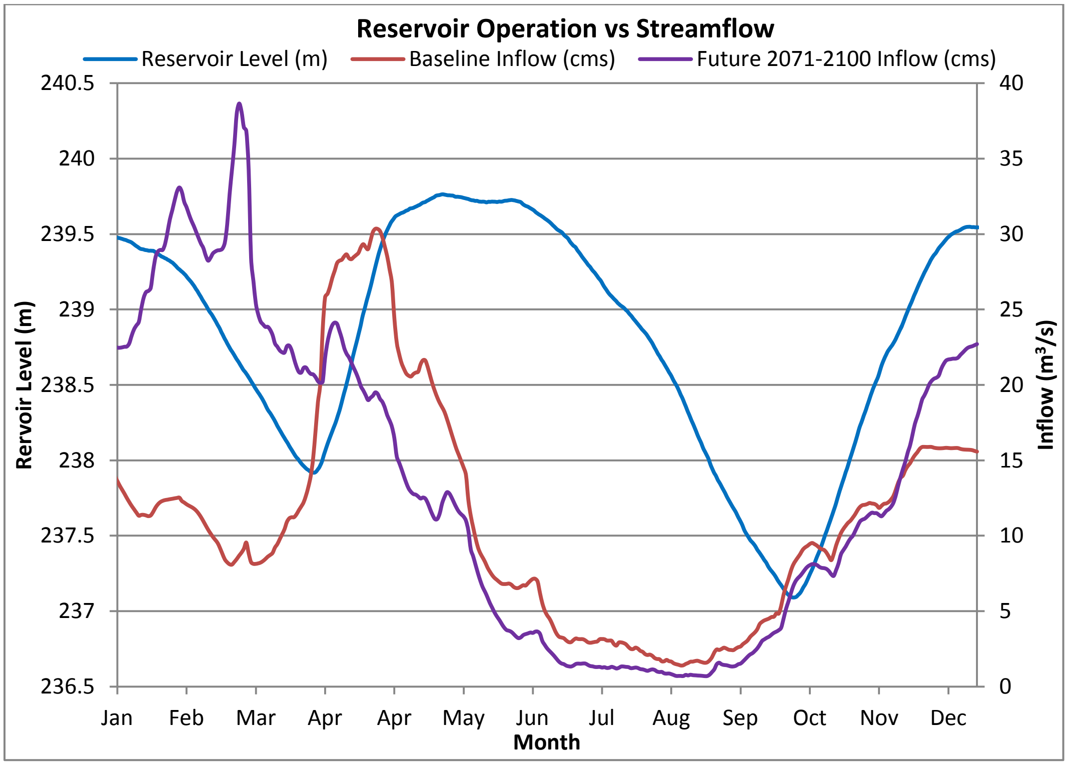
Figure 6:1. Baseline Simulated vs Observed Streamflow



As described earlier, the management regime of the Mississippi River has been largely successful in exploiting the historic runoff patterns to regulate stream flow over the year to reduce flood risk in the spring and to augment stream flow during periods of low runoff. Projected changes in climate will alter the runoff patterns and hydrologic characteristics under which stakeholder expectations and the resulting water management objectives have been established. As a result current operating policies will no longer be compatible with projected runoff patterns as demonstrated in Figure 6:2.

A variety of metrics are used to describe the hydrologic conditions under future climate scenarios for the Mississippi River @ Appleton (02KF006) and the Mississippi River @ Dalhousie Lake (02KF019) gauges. Reservoir inflows were routed through reservoirs R1 through R6, the High Falls Generating Station and Mississippi Lake based on current operating strategies as defined in the Mississippi River Water Management Plan[2] for the baseline and future climate scenarios. This operating regime is referred to as Option 1 in the following discussion and is used to describe the future hydrologic conditions for the 2011-2040, 2041-2070 and 2071-2100 periods under both Dry and Wet climate scenarios relative to the baseline period of 1972-2000.

Figure 6:2. Reservoir Operation vs Streamflow



In addition to Option 1, three additional reservoir operation strategies were developed and assessed for their feasibility in addressing the impact of future climate projections. These adaptation measures are presented solely to assess their potential effectiveness at mitigating future stream flow conditions and should not be construed as a preferred alternative. Each adaptation measure will have both positive and negative consequences which will require further study and consultation before selecting a preferred course of action. The adaptation options considered include the following measures which are discussed in more detail in the following Sections.

Option 1 – Current operating strategy as defined by the Mississippi River Water Management Plan

Option 2 – Removal of artificial reservoir storage

Option 3 – Revised reservoir operations within physical constraints of existing water control structures

Option 4 – Increased reservoir storage

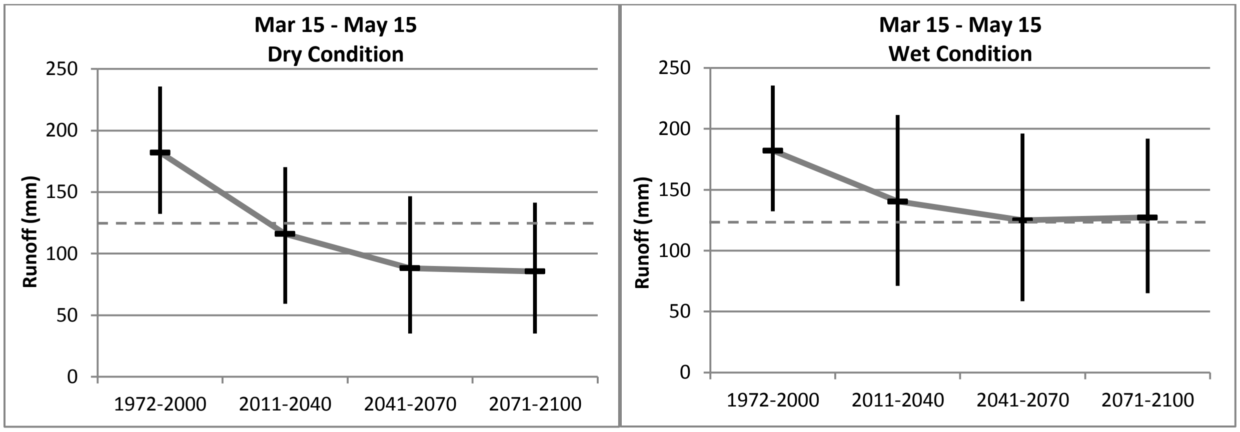
6.1 Option 1 - Baseline Management Strategy Assessment

6.1.1 Runoff

Runoff is the predominant factor affecting stream flow while the ability of reservoirs to regulate stream flow is largely dependent on when runoff occurs and the storage capacity of the reservoir. Figure 6:3 shows the range in total runoff depth (20th percentileto 80th percentile) occurring between March 15th and May 15th for the baseline period and the three future periods and climate scenarios. The March 15th to May 15th period corresponds to the typical periods in which the Mississippi River reservoirs are filled. The six reservoirs control a maximum storage volume of 12,160 ha-m. This volume requires approximately 125 mm of runoff to fill all reservoirs with as much as 160 mm required for individual reservoirs which have limited contributing drainage areas.

As indicated in Figure 6:3, while the baseline period was able to satisfy the runoff requirements, the future periods under both Dry and Wet scenarios will frequently fail to generate sufficient runoff to fill the reservoirs.

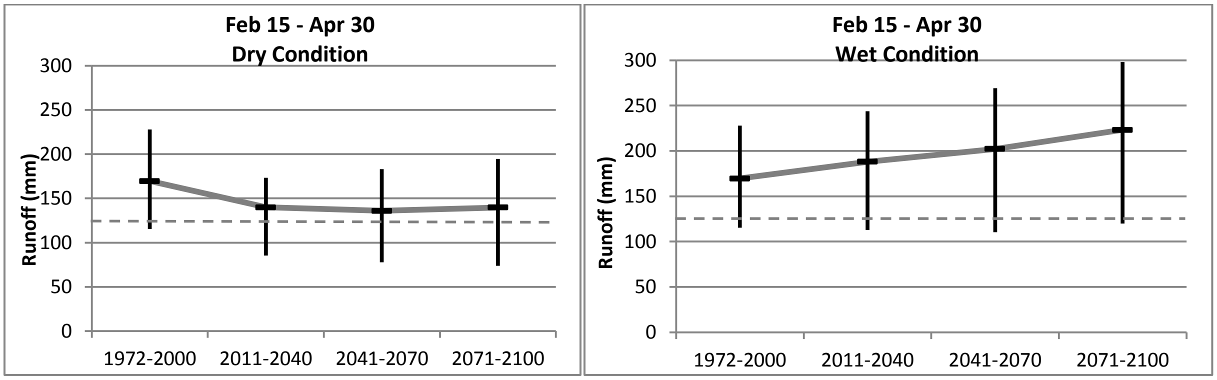
Figure 6:3. Runoff Depth Comparison (Mar 15 – May 15)



Considering the projected shift in timing of the spring freshet, the runoff depths from February 15th to April 30th were assessed to determine if a change in reservoir operation timing would be an effective response. Figure 6:4 provides an indication of runoff depth over this period.

The runoff volume from February 15th to April 30th indicates a much improved ability for reservoir operations to capture the necessary runoff to fill the reservoirs.

Figure 6:4. Runoff Depth Comparison (Feb 15 – Apr 30)



6.1.2 Stream flow

The resulting stream flows are presented based on current reservoir operating policies. Simulated hydrographs are provided at two locations; Mississippi River @ Appleton (02KF006) and Mississippi River @ Dalhousie Lake (02KF019).Figures 6:5 and 6:6 show projections for the Appleton gauge for the baseline period (1972 – 2000) and the three future periods (2011 – 2040, 2041 – 2070 and 2071 – 2100) under both Dry and Wet climate scenarios. Similarly, Figures 6:7 and 6:8 show hydrographs for the Dalhousie Lake site.

Relative to the baseline condition, the future periods consistently demonstrate earlier spring freshets. Under the Dry climate scenario future stream flow rates are consistently lower than the baseline rates throughout the year. Under the Wet climate scenario, future stream flow rates are considerably higher in the late fall and winter and comparable to the baseline conditions for the late spring and summer periods.

Stream flow variability was found to increase substantially particularly in the November through April period as shown in Figures 6:9 and 6:10. Table 6-1 provides the relative change in stream flow variability between the 20th percentile and 80th percentile flows for the future periods at Appleton.

6.1.3 Flow Duration

A *Flow-duration Curve* (FDC)is the cumulative frequency curve which shows the percentage of time a specified stream flow rate is expected to be exceeded at a given site. It describes the stream flow characteristics across the entire range of stream flows experienced without regard to the sequence of occurrence and can provide an important measure of a site's hydro-electric energy potential. The resulting flow duration curves at Appleton are shown in Figures 6:11 and 6:12,and at Dalhousie Lake are shown in 6:13 and 6:14, for both Dry and Wet scenarios,. The flow duration curves at both sites indicate that flow rates below 25 m^3/s will become considerably more prevalent under both Dry and Wet scenarios, while flow rates above 25 m^3/s will become more prevalent during future periods under the Wet climate scenario.

At Dalhousie Lake, the total time at which flow rates between 3 m^3/s and 15 m^3/s (the range in which existing hydroelectric facilities operate within)will be available will decrease by 30% under the Dry scenario and 6% under the Wet scenario. At Appleton, the total time at which flow rates between 5 m^3/s and 30 m^3/s will be available will decrease by 20% under the Dry scenario and 7% under the Wet scenario. As this is a measure of potential waterpower capacity, these flow-duration curves will be used to evaluate potential changes in hydro-electric generation based on site characteristics at the four existing waterpower facilities.

Table 6-1. Stream flow variability (20th – 80th Percentile)

	Annual Range (m^3/s) 20% - 80%	% Change from Baseline	Nov - Apr Range (m^3/s) 20% - 80%	% Change from Baseline
Baseline	21.56		26.08	
2011-2040 Dry Scenario	24.10	11.8%	30.35	16.4%
2011-2040 Wet Scenario	30.21	40.1%	39.91	53.0%
2041-2070 Dry Scenario	24.42	13.3%	33.92	30.0%
2041-2070 Wet Scenario	33.05	53.3%	47.59	82.4%
2071-2100 Dry Scenario	27.56	27.8%	39.65	52.0%
2071-2100 Wet Scenario	35.23	63.4%	51.74	98.4%

Figure 6:5. Mean Hydrograph Comparison @ Appleton (Dry Scenario)

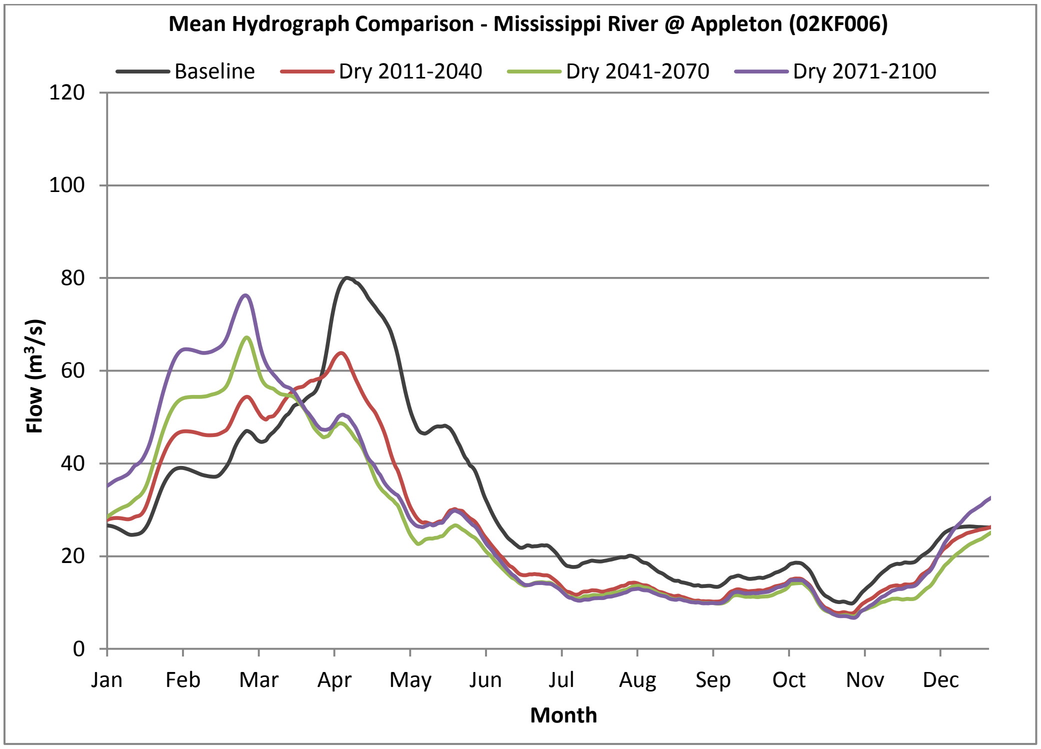


Figure 6:6. Mean Hydrograph Comparison @ Appleton (Wet Scenario)

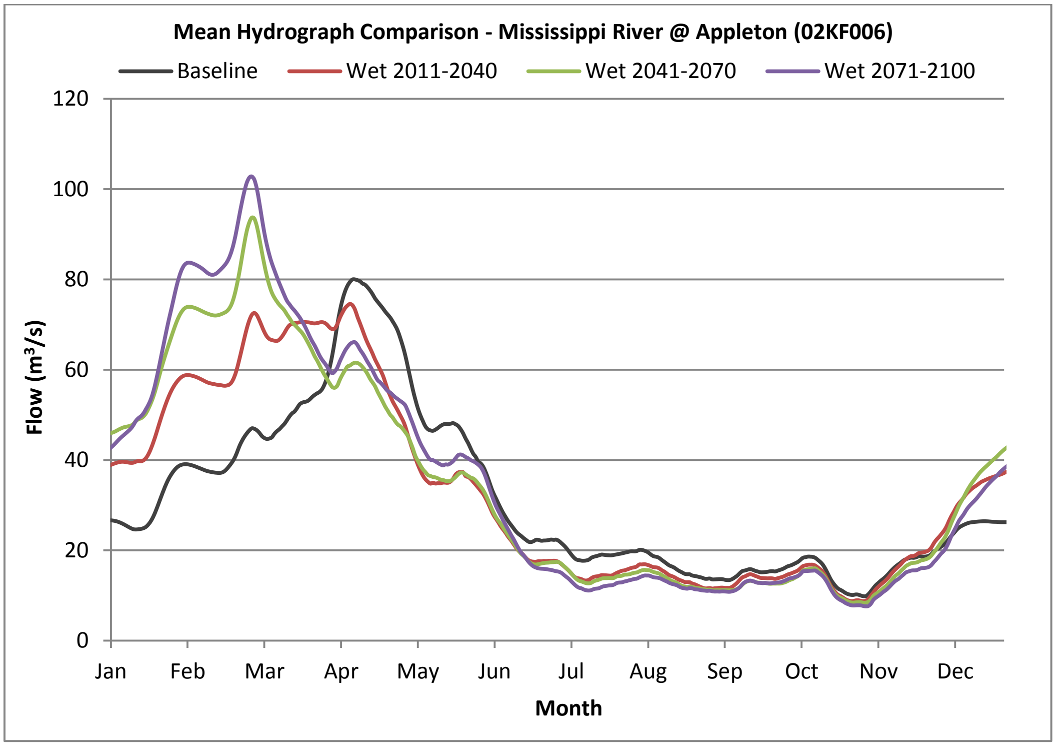


Figure 6:7. Mean Hydrograph Comparison @ Dalhousie Lake (Dry Scenario)

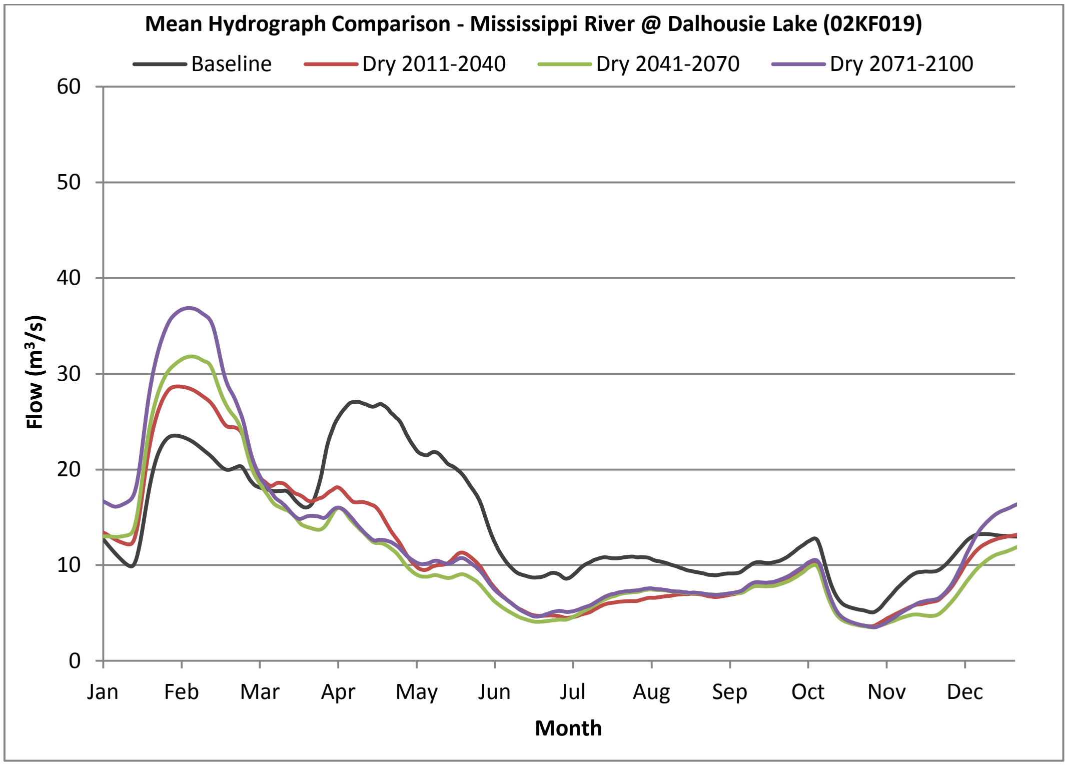


Figure 6:8. Mean Hydrograph Comparison @ Dalhousie Lake (Wet Scenario)

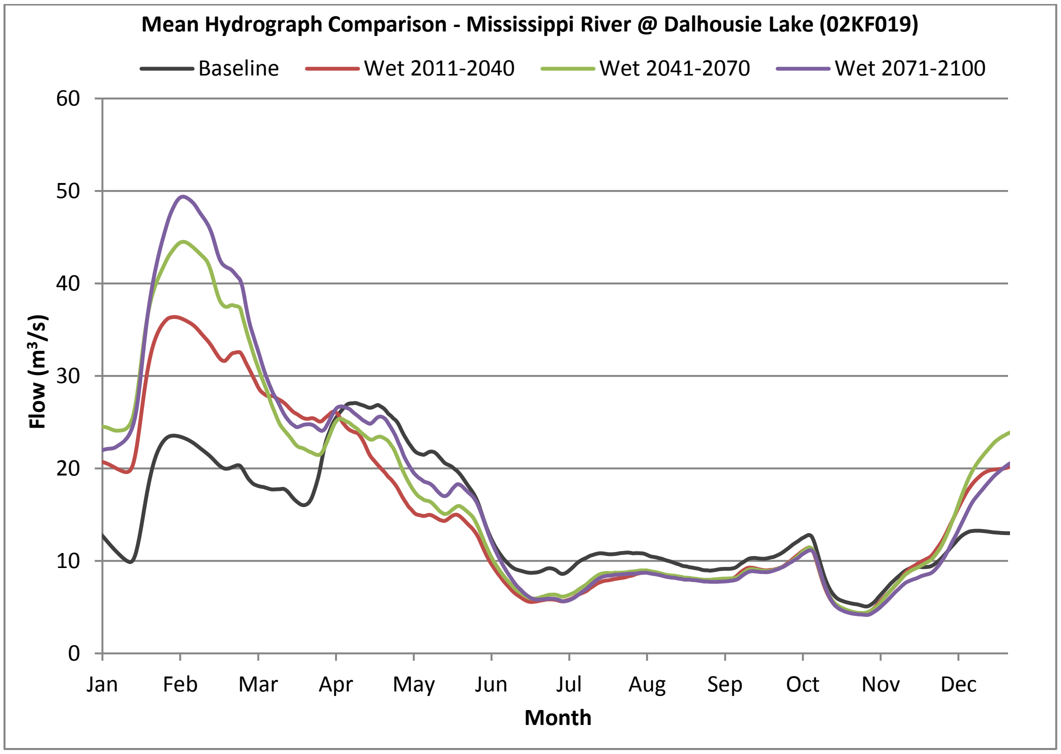


Figure 6:9. Baseline Stream Flow Variability

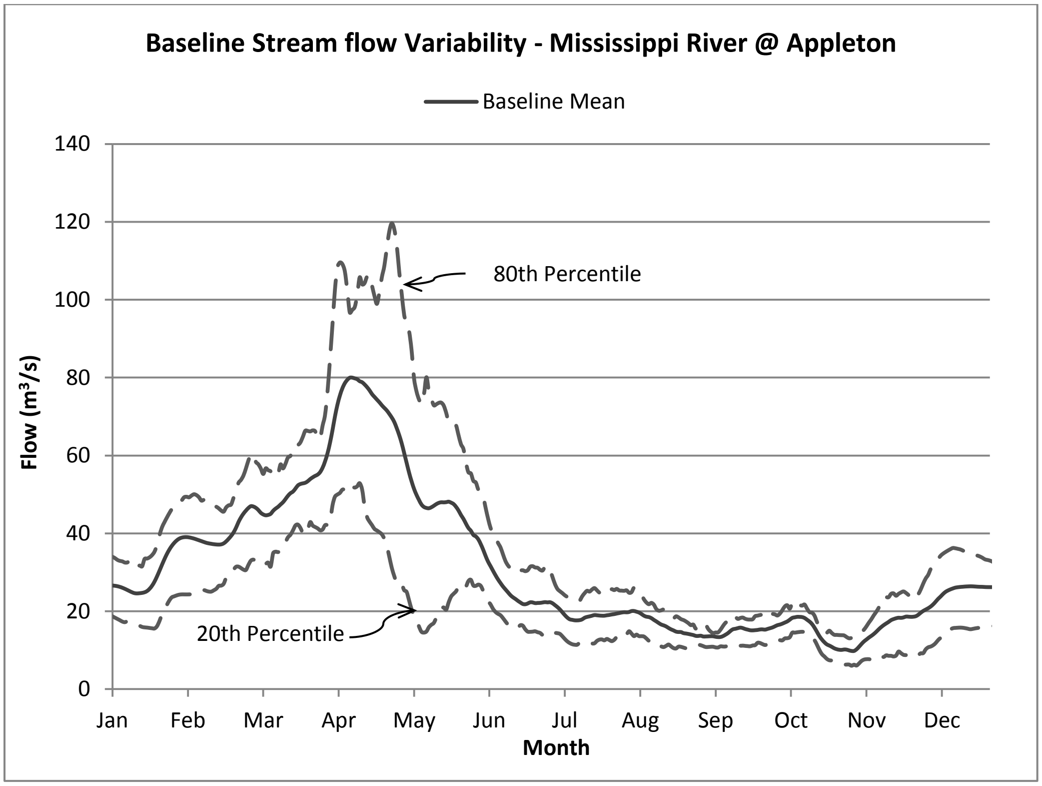


Figure 6:10. Future Stream Flow Variability

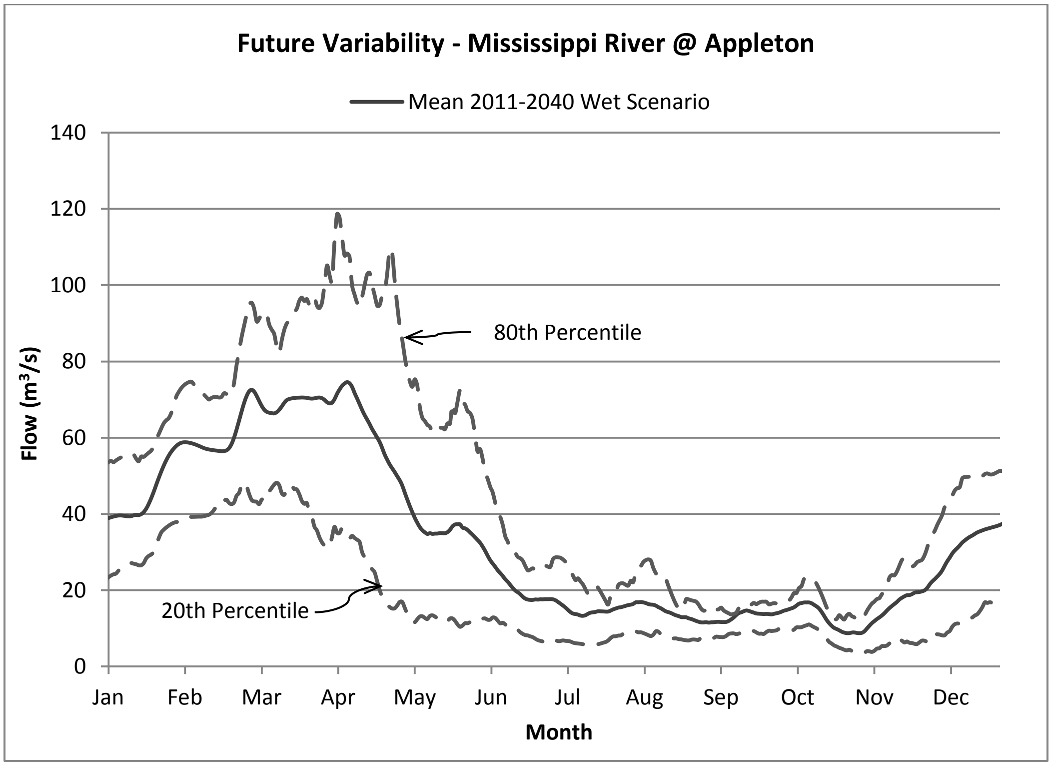


Figure 6:11. Flow Duration Curve @ Appleton (Dry Scenario)

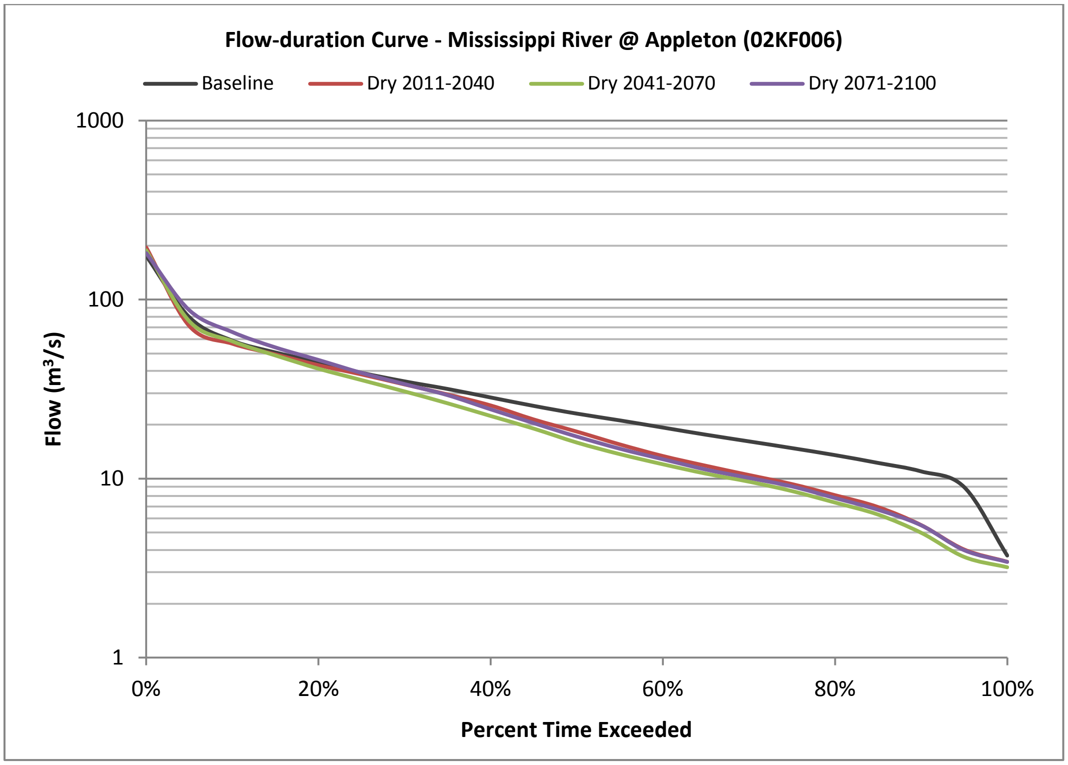


Figure 6:12. Flow Duration Curve @ Appleton (Wet Scenario)

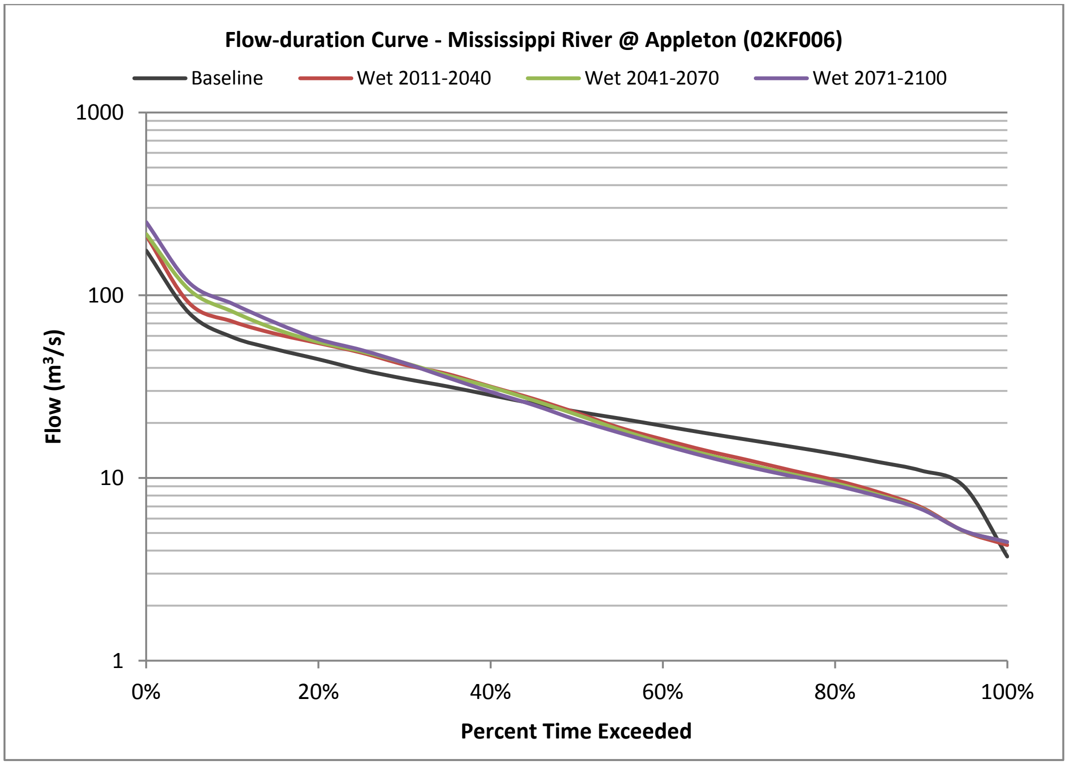


Figure 6:13. Flow Duration Curve @ Dalhousie Lake (Dry Scenario)

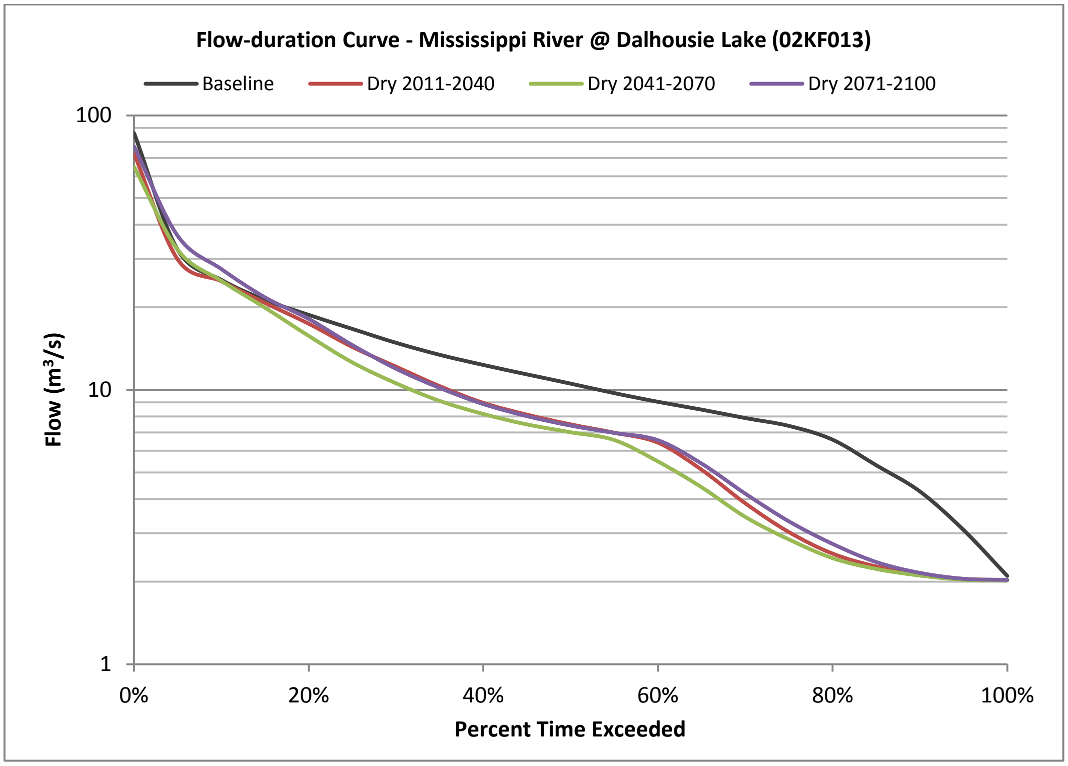
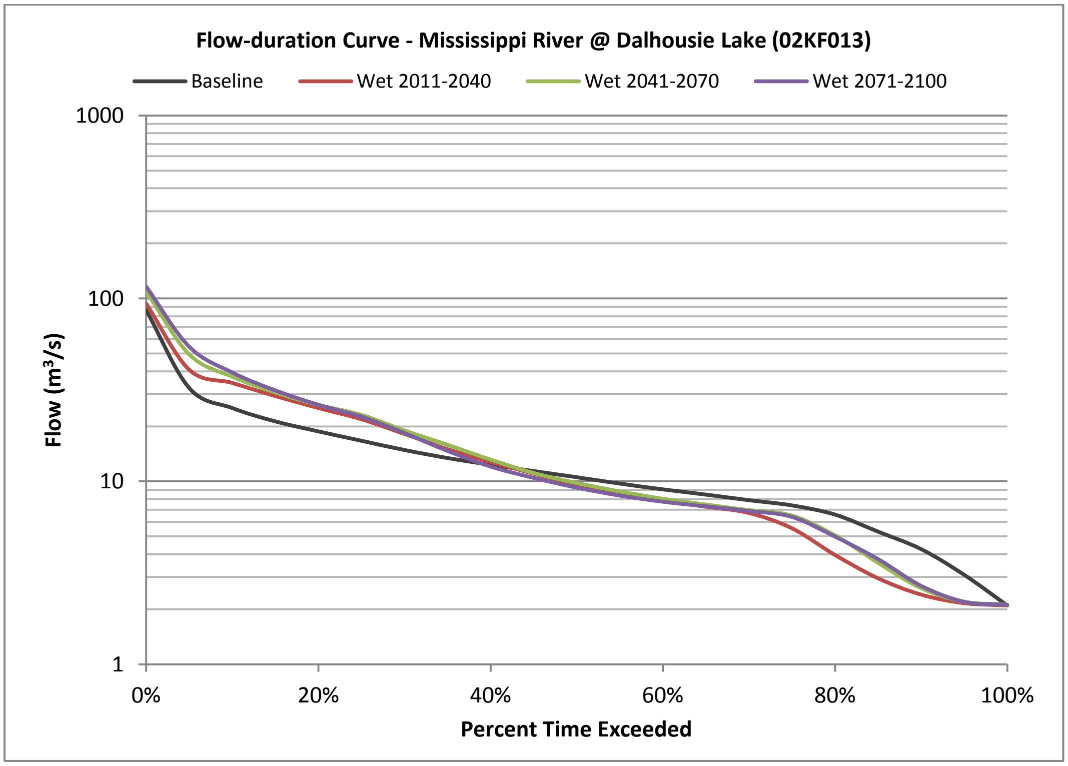


Figure 6:14. Flow Duration Curve @ Dalhousie Lake (Dry Scenario)



6.1.4 Flood Risk

Flood mitigation is an important consideration in reservoir management on the Mississippi River. While the current study does not specifically address extreme events, reservoir performance under high flow conditions was assessed to evaluate potential changes in reservoir operation to mitigate flood risk arising from projected changes in climate. Table xxx provides projected changes in mean annual maximum flows (Qmax) for the Mississippi River at Appleton and Dalhousie Lake under the baseline and future climate conditions for both Dry and Wet climate scenarios. For Dalhousie Lake the critical flood threshold is above 55 m^3/s while at Appleton the flood threshold is above 150 m^3/s.

Table 6-2. Mississippi River @ Appleton (Option 1)

Scenario	Mean Annual Maximum Flow (m^3/s)	20th Percentile (m^3/s)	80th Percentile (m^3/s)	Threshold Exceedance (#)
Baseline	108.8	71.4	137.7	4
2011-2040 XDry	101.4	63.2	137.4	5
2041-2070 XDry	92.4	58.5	124.1	4
2071-2100 XDry	100.7	63.7	140.8	4
2011-2040 Wet	120.8	81.6	166.5	9
2041-2070 Wet	125.6	81.6	170.8	9
2071-2100 Wet	134.8	87.9	189.0	11
Note: Flood threshold = 150 m^3/s				

Table 6-3. Mississippi River @ Dalhousie Lake (Option 1)

Scenario	Mean Annual Maximum Flow (m^3/s)	20th Percentile (m^3/s)	80th Percentile (m^3/s)	Threshold Exceedance (#)
Baseline	43.8	29.4	58.3	7
2011-2040 XDry	36.2	25.7	44.5	5
2041-2070 XDry	37.0	25.0	45.6	4
2071-2100 XDry	40.9	27.2	54.9	6
2011-2040 Wet	50.0	38.5	59.4	8
2041-2070 Wet	55.4	34.7	76.6	15
2071-2100 Wet	61.0	34.1	84.8	16
Note: Flood threshold = 55 m^3/s				

Changes in the mean annual maximum flow are projected to range from a decrease of 7% to an increase of 24% at Appleton and 40% at Dalhousie Lake relative to Baseline conditions. The frequency of breaching the flood threshold at both Appleton and Dalhousie Lake is also expected to increase under the Wet climate scenario.

6.1.5 Low Flow

Low flow conditions for all future periods and climate scenarios at both Appleton and Dalhousie Lake consistently demonstrate a reduction in the minimum annual 7-day stream flow rate. At Appleton the low flow rate with a 20 year return period defined as 7Q20 is approximately 62% lower than the baseline and 28% at Dalhousie Lake for the 2011 – 2040 period under the Dry scenario (Figures 6:15 and 6:16).

Figure 6:15. Low Flow Frequency @ Appleton (Dry Scenario)

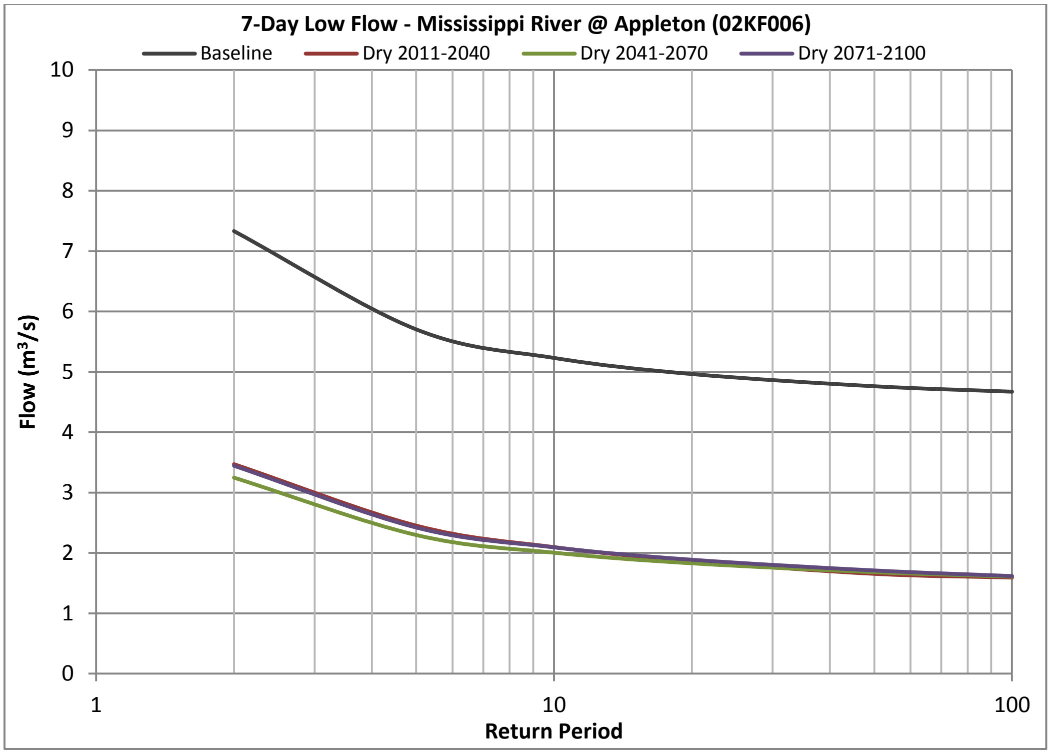
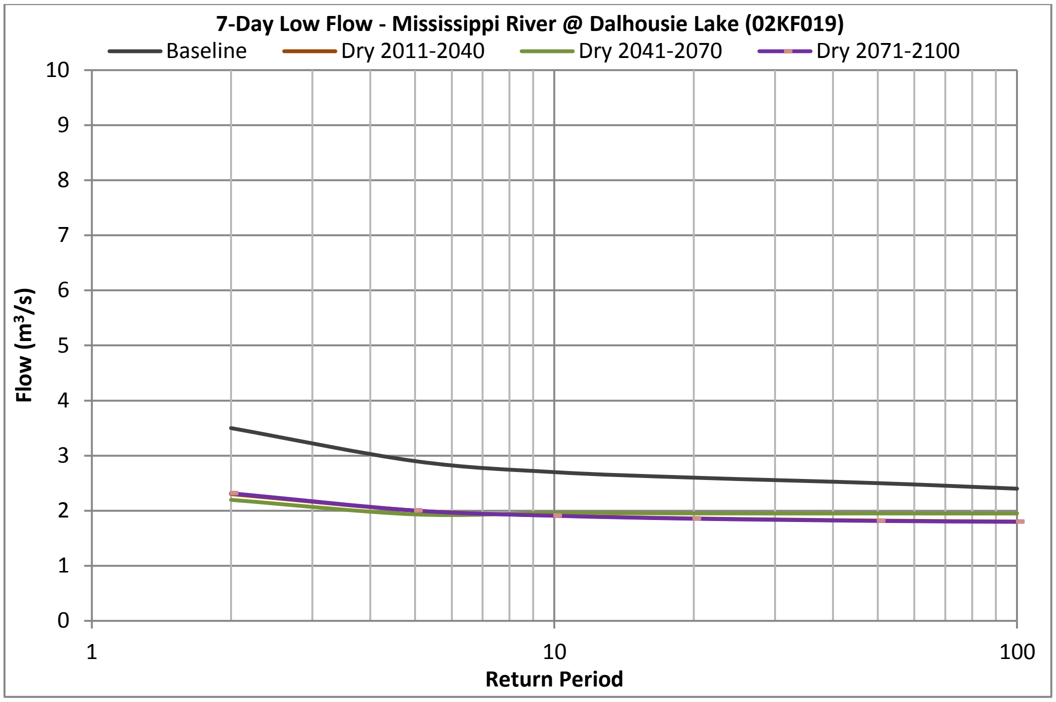


Figure 6:16. Low Flow Frequency @ Dalhousie Lake (Dry Scenario)



6.1.6 Reservoir Performance

As presented in Section 2.4, Reservoirs R1 – R5 support a variety of recreational and tourism objectives which rely on the reservoirs achieving a *Summer Holding Level* by mid-May and maintaining those reservoir levels until early-fall. Table 6-4 describes the performance of these reservoirs in achieving the reservoir water level objectives under the current operating strategy and future runoff conditions relative to the baseline.

Table 6-4. Reservoir Performance

Scenario	Failed	Achieved	Success Rate
Baseline	6	24	80.0%
2011 -2040 (Dry)	20	10	33.3%
2041 -2070 (Dry)	20	10	33.3%
2071 -2100 (Dry)	18	12	40.0%
2011 -2040 (Wet)	14	16	53.3%
2041 -2070 (Wet)	10	20	66.7%
2071 -2100 (Wet)	10	20	66.7%

The reservoirs most susceptible to projected changes in runoff are those with a limited upstream drainage area which require a greater total runoff depth relative to reservoir volume with which to fill the reservoir, specifically R1, R4, and R5.

6.1.7 Hydro-electric Generation

In assessing the impact of projected changes in stream flow at individual hydro-electric facilities, it is necessary to consider the minimum flow rates at which a generating station can operate, the maximum flow rate capacity of the station and the efficiency of the mechanical equipment across these range of flows. To assist in this analysis, RETScreen Analysis Sofware[5] was used to assess the hydro-electric production at three existing waterpower sites under the baseline and future periods and various climate scenarios. Collectively the three generating stations are projected to experience a reduction in energy production of 23% and 9.3% under the Dry and Wet scenarios respectively, as seen in Table 6-4.

6.2 Assessment of Options 2 through 4

For ease of comparison, the implications of the four options considered are presented for the future 2011-2040 period relative to the baseline period according to the metrics previously described for the Dry and Wet climate scenarios. While the 2071-2100 impacts are found to be more severe than those for the 2011-2040 or 2041-2070 periods, the implications do not significantly affect the resulting conclusions and the 2011-2040 period results are considered to be more applicable to the study’s objectives. Watershed runoff is not affected by reservoir operations and is not specifically addressed.

6.2.1 Option 2 - Removal of Artificial Storage

While this option was expected to result in unacceptable impacts to recreation and tourism, it was considered important to evaluate potential adaptation measures relative to the natural flow regime. Natural stream flow or mimicking the natural flow regime to the extent possible was a preferred objective of the Mississippi River Water Management Plan (2006) and was considered worthy of assessing under future climate conditions.

This option was assessed by routing reservoir inflows through the six reservoirs with the water control structures removed. It was assumed that the reservoir outflow rating curve would be equal to twice that of the maximum rating curve for the existing structure in a fully open condition. According to the Aquatic Ecosystem Assessments for Rivers[6], the natural flow regime is preferable to artificial stream flow regulation for sustaining ecosystem function. Comparison to alternative reservoir operating policies provides insight into the potential impact which reservoir operation policies may have on both ecosystem function and the risks posed by extreme events such as floods and drought.

In general, Option 2 results in less short-term variability in stream flows than Option 1 as the effects of artificial regulation have been eliminated. This is the preferred condition for ecosystem sustainability as it reflects a natural stream response to weather variation. However, as seen in Figures 6:18 to 6:21, stream flows in the spring are projected to be higher while lower through the summer and fall periods at both Appleton and Dalhousie Lake.

As indicated in Tables 6-2 and 6-3, mean annual maximum flows would remain relatively unchanged from Option 1, except for lower runoff events where the reservoirs have greater influence and the mean annual maximum flow could increase at Dalhousie Lake by up to 9%. Low flows (7Q20) in the future periods were found to decrease at Appleton by 85% and at Dalhousie Lake by 80% under the dry scenario. Figures 6:22 and 6:25 demonstrate the low flow frequency analyses results.

Aside from the implications to tourism and recreation as a result of the loss of stable reservoir levels in the summer, Option 2 would result in modest increases in flood risk and significantly lower stream flows in downstream communities.

As a result of generally lower stream flows in the future periods, the combined hydropower output from the four generating stations is projected to decrease by 23.2% to 12.8% for the Dry and Wet scenarios respectively under Option 2.

6.2.2 Option 3 - Revised Reservoir Operations

Revising reservoir operation within the physical limitations of the reservoirs' existing water control structures was assessed to determine the current capacity of existing infrastructure to address projected changes in stream flow without structural modification.

This option included the following measures:

1) The drawdown regime on reservoirs R1, R4 and R5 were reduced by 0.3 m from their current drawdown extent of 1.5, 0.6 and 0.8 m respectively. This option was intended to improve the ability of these reservoirs to achieve their *Summer Holding Level* by the required date. As shown in Table 6-5, the reservoirs' performance in achieving the *Summer Holding Level* is improved considerably.
   Under Option 3, 1005 ha-m of reservoir storage is unused which represents approximately 8% of the total storage available.

Table 6-5. Reservoir Performance Success

	Current Operation			Option 3		
	Failed	Achieved	Rate	Failed	Achieved	Rate
Baseline	6	24	80.0%	6	24	80.0%
2011 -2040 (Dry)	20	10	33.3%	13	17	56.7%
2041 -2070 (Dry)	20	10	33.3%	10	20	66.7%
2071 -2100 (Dry)	18	12	40.0%	9	21	70.0%
2011 -2040 (Wet)	14	16	53.3%	12	18	60.0%
2041 -2070 (Wet)	10	20	66.7%	5	25	83.3%
2071 -2100 (Wet)	10	20	66.7%	6	24	80.0%

2) Advancing reservoir operations for R6 from mid-February to mid-January was introduced to capture the winter/spring runoff which was occurring earlier in the year. With the shift in timing of reservoir operation, refilling of Reservoir R6 in the fall becomes redundant and the level to which the reservoir is filled in the fall was reduced from 2.25 m to 0.5 m (Figure 6:17). In addition, under this option the minimum reservoir outflow was increased from 2 m^3/s to 3 m^3/s.

Under this option, stream flow regulation over the fall and winter periods are improved as the requirement to refill and subsequently draw down Reservoir R6 over the winter is eliminated. As stream flows are found to increase over this period, the need to augment winter stream flow is reduced.

As indicated in Tables 6-7 and 6-8, mean annual maximum flows are generally increased by 5% – 9% relative to Option 1 at Appleton and Dalhousie Lake respectively. Low flows are found to improve marginally from Option1, primarily due to eliminating the need to refill Reservoir R6 in the fall period.

As shown in Table 6-6, energy production under this Option would improve 4% over Option 1.

6.2.3 Option 4 - Increased Reservoir Storage with Option 3

Previous studies[3], suggested that to maintain the minimum stream flow objective as cited in the Mississippi River Water Management Plan[2], additional reservoir storage of 2,000 ha-m to 3,000 ha-m would be required, which had been based on the average projected runoff in the future periods. To assess this option, the maximum operating level for Reservoir R6 was increased by 1.0 m, providing additional reservoir storage of approximately 2,000 ha-m, representing an increase of 16% in existing reservoir storage or 8% over Option 3.

As indicated in Figures 6:22 to 6:25, Option 4 resembles Option 3 with the exception that low flow conditions throughout the summer are improved approximately 25% to 30% over Option 3 and actually achieves Baseline conditions at Dalhousie Lake. Flood risk at both Appleton and Dalhousie Lake were found to be marginally improved but by less than 5% over Option 3.

Energy production under Option 4 is marginally improved by approximately 3% under the Dry scenario from Option 3. Energy production for Option 4 improves by approximately 4% and 9% over Option 1 for Wet and Dry scenarios, respectively.

It should be noted that this Option could result in significant adverse impacts to upstream spawning habitat and shoreline conditions and would require further in-depth investigation. Further, the cost associated with this Option would be considerable as it would likely require complete reconstruction of the Crotch Lake dam (Reservoir R6).

Figure 6:17. Revised Operating Rule Curve (Reservoir R6)

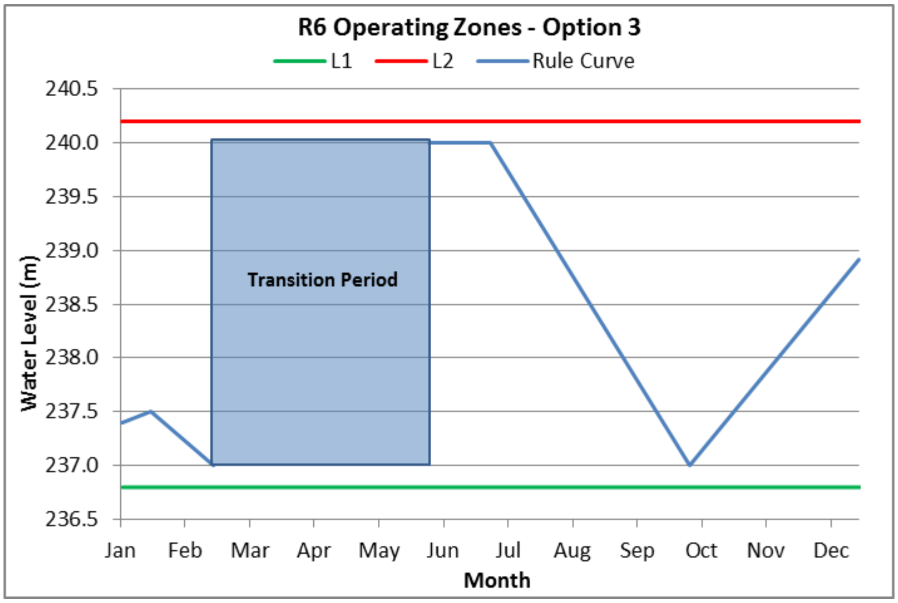


Table 6-6. Hydro-electric Generation Impacts

Scenario	Total Energy (MWh)	% Change
Baseline (1971-2000)	45,300	
Option 1		
2011-2040 Dry	36,900	-18.5%
2041-2070 Dry	34,900	-23.0%
2071-2100 Dry	36,600	-19.2%
2011-2040 Wet	41,700	-7.9%
2041-2070 Wet	41,800	-7.7%
2071-2100 Wet	41,100	-9.3%
Option 2		
2011-2040 Dry	34,800	-23.2%
2011-2040 Wet	39,500	-12.8%
Option 3		
2011-2040 Dry	38,900	-14.1%
2011-2040 Wet	43,800	-3.3%
Option 4		
2011-2040 Dry	40,300	-11.0%
2011-2040 Wet	43,400	-4.2%

Figure 6:18. Stream Flow Hydrograph Comparison @ Appleton (Dry Scenario)

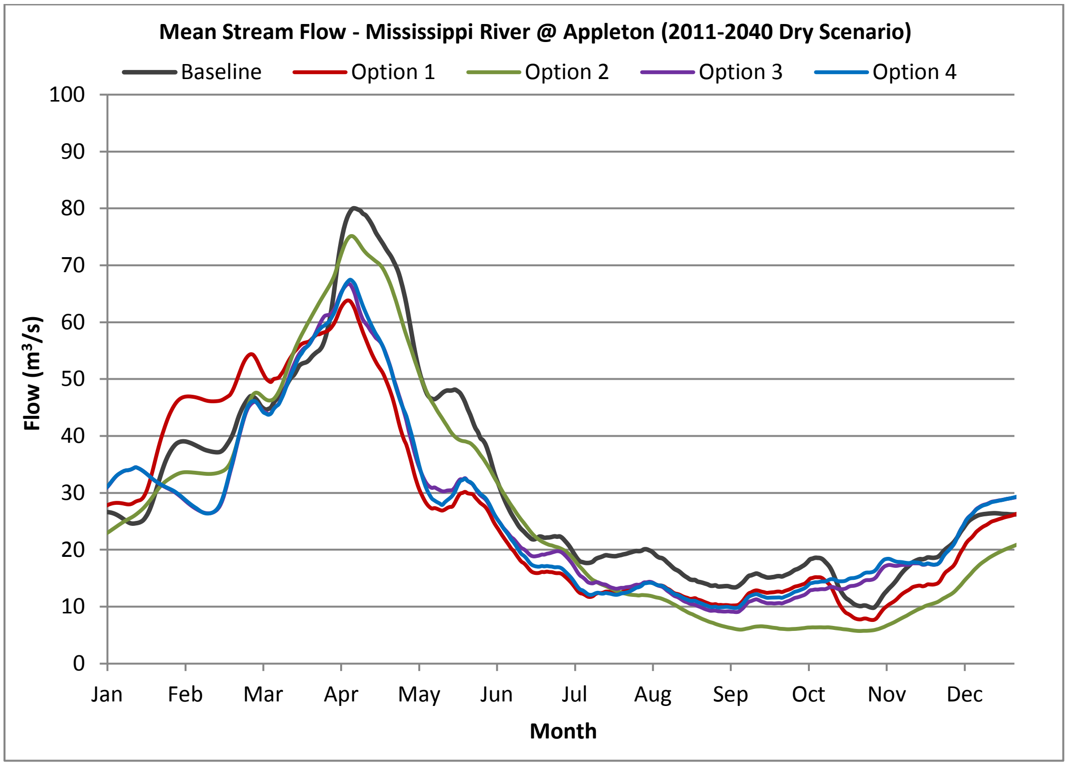


Figure 6:19 Stream Flow Hydrograph Comparison @ Appleton (Wet Scenario)

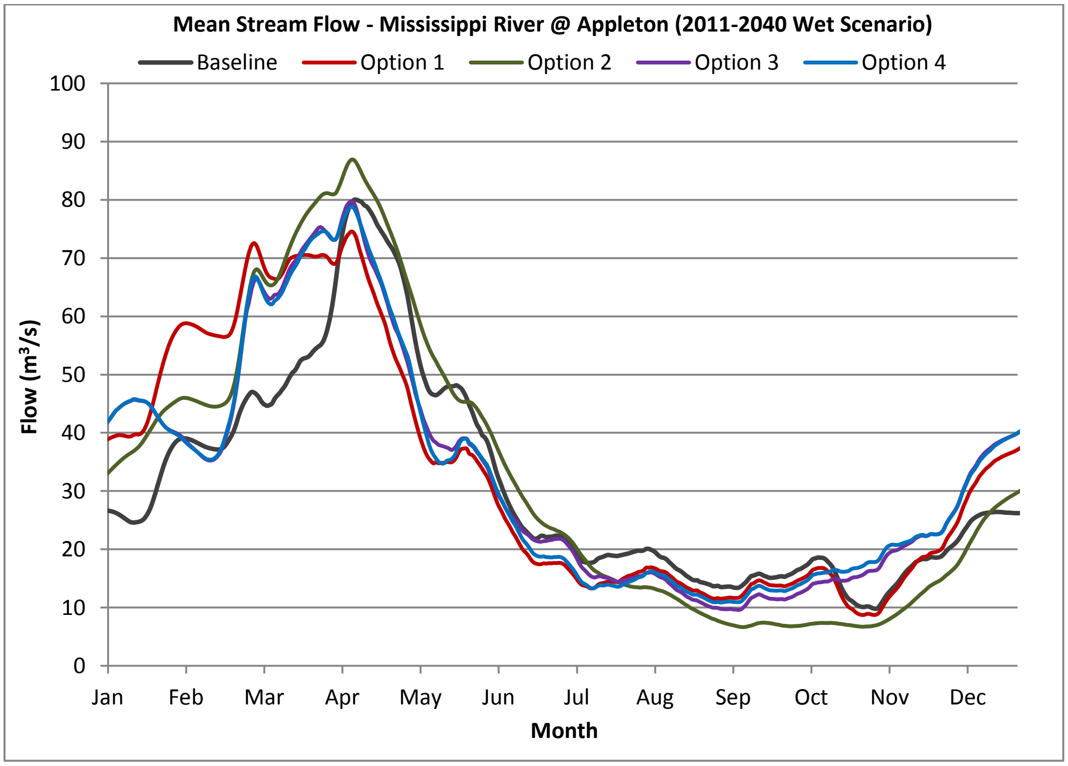


Figure 6:20 Stream Flow Hydrograph Comparison @ Dalhousie Lake (Dry Scenario)

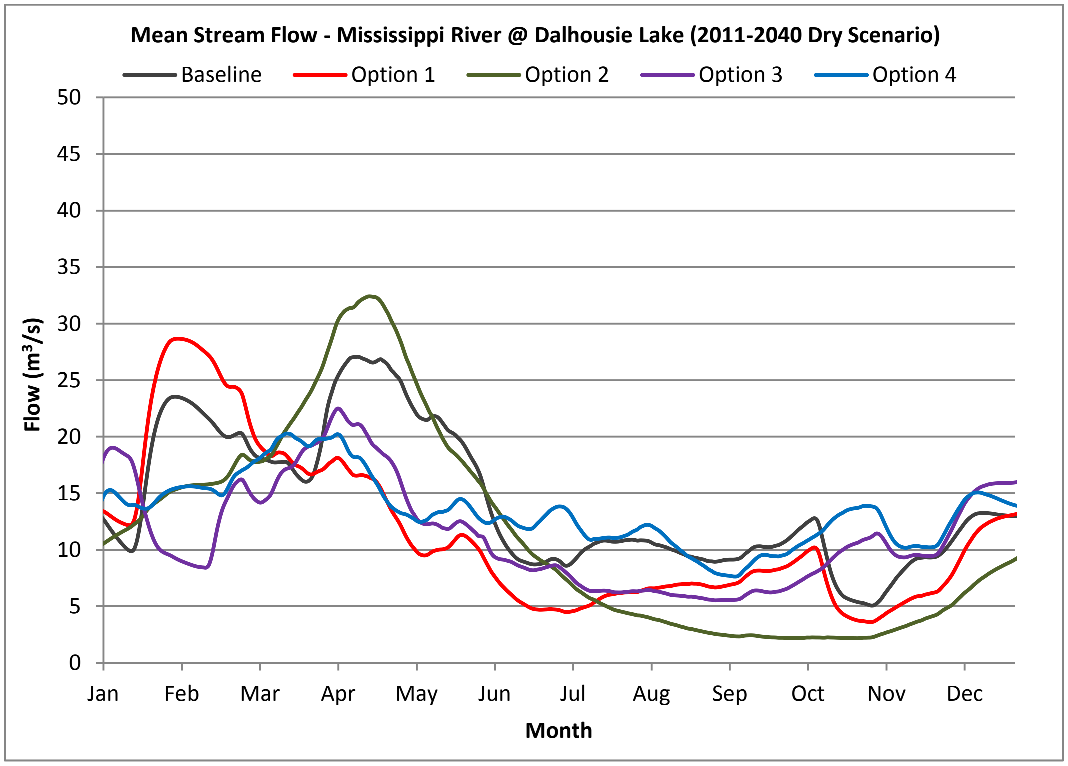


Figure 6:21 Stream Flow Hydrograph Comparison @ Dalhousie Lake (Wet Scenario)

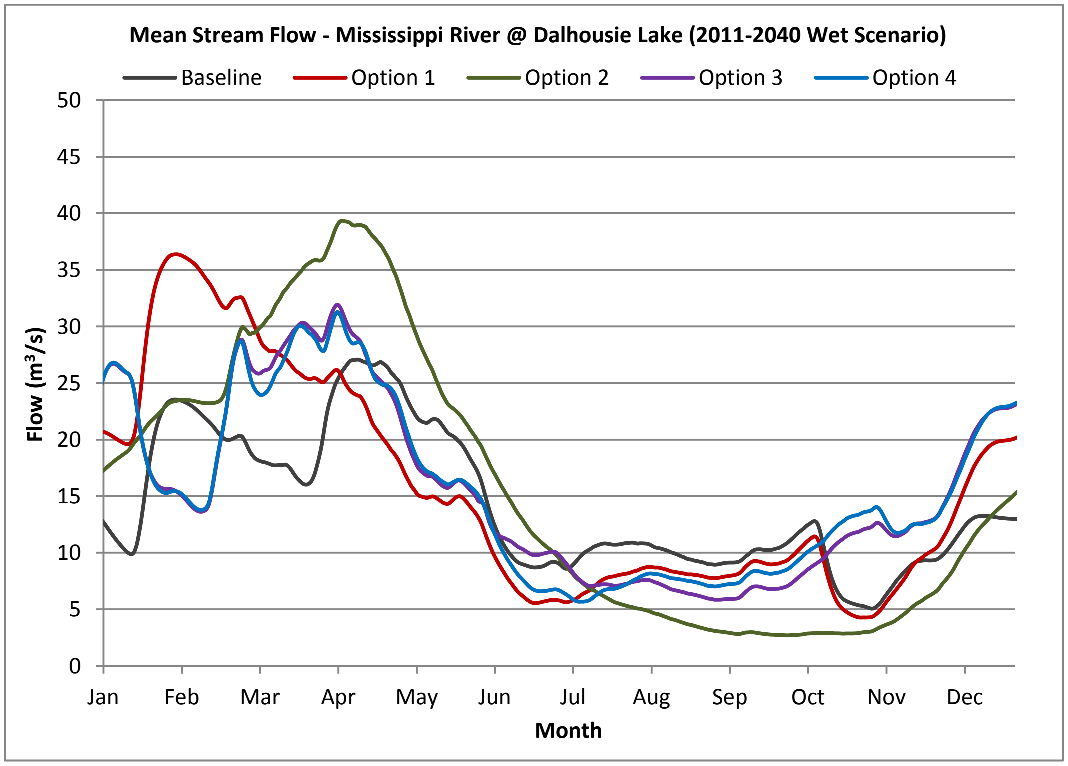


Table 6-7. Mean Annual Maximum Flow (Mississippi River @ Appleton)

Scenario	**Mean Annual Maximum Flow**			
	Option 1 (m^3/s)	**Option 2 (m^3/s)**	**Option 3 (m^3/s)**	**Option 4 (m^3/s)**
Baseline	108.8			
2011-2040 XDry	101.4	103.9	104.7	102.3
2041-2070 XDry	92.4	94.4	93.6	91.3
2071-2100 XDry	100.7	102.7	103.1	101.1
2011-2040 Wet	120.8	122.9	126.4	124.6
2041-2070 Wet	125.6	126.9	132.0	129.2
2071-2100 Wet	134.8	135.5	139.6	137.1

Table 6-8. Mean Annual Maximum Flow (Mississippi River @ Dalhousie Lake)

Scenario	**Mean Annual Maximum Flow**			
	Option 1 (m^3/s)	**Option 2 (m^3/s)**	**Option 3 (m^3/s)**	**Option 4 (m^3/s)**
Baseline	43.8			
2011-2040 XDry	36.2	39.4	37.9	38.8
2041-2070 XDry	37.0	36.6	34.5	37.9
2071-2100 XDry	40.9	39.3	38.6	34.1
2011-2040 Wet	50.0	50.7	54.5	53.8
2041-2070 Wet	55.4	53.1	59.6	58.1
2071-2100 Wet	61.0	58.4	63.4	62.5

Figure 6:22. Low Flow Frequency Comparison @ Appleton (Dry Scenario)

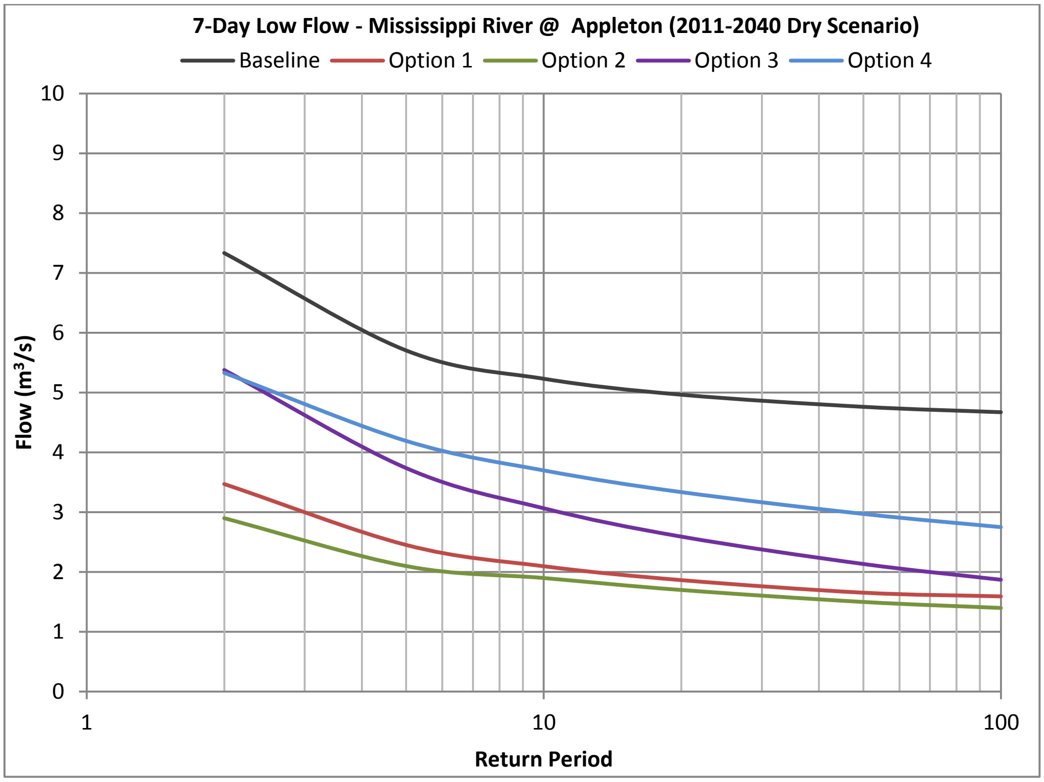


Figure 6:23 Low Flow Frequency Comparison @ Appleton (Wet Scenario)

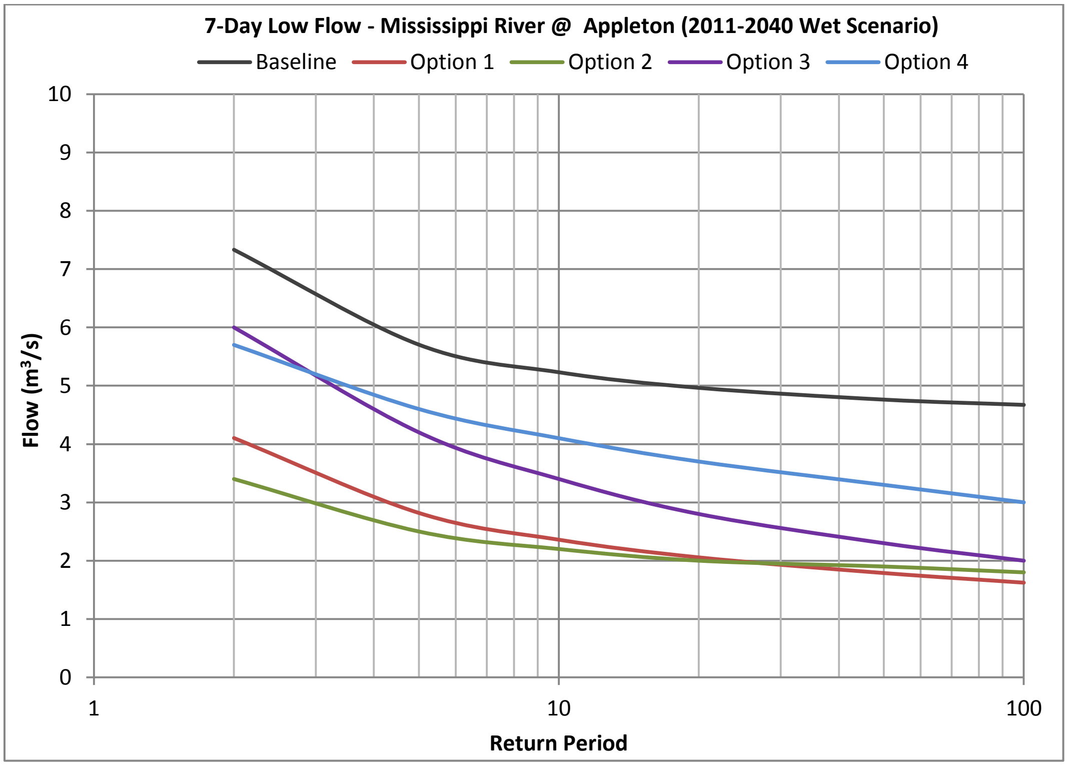


Figure 6:24 Low Flow Frequency Comparison @ Dalhousie Lake (Dry Scenario)

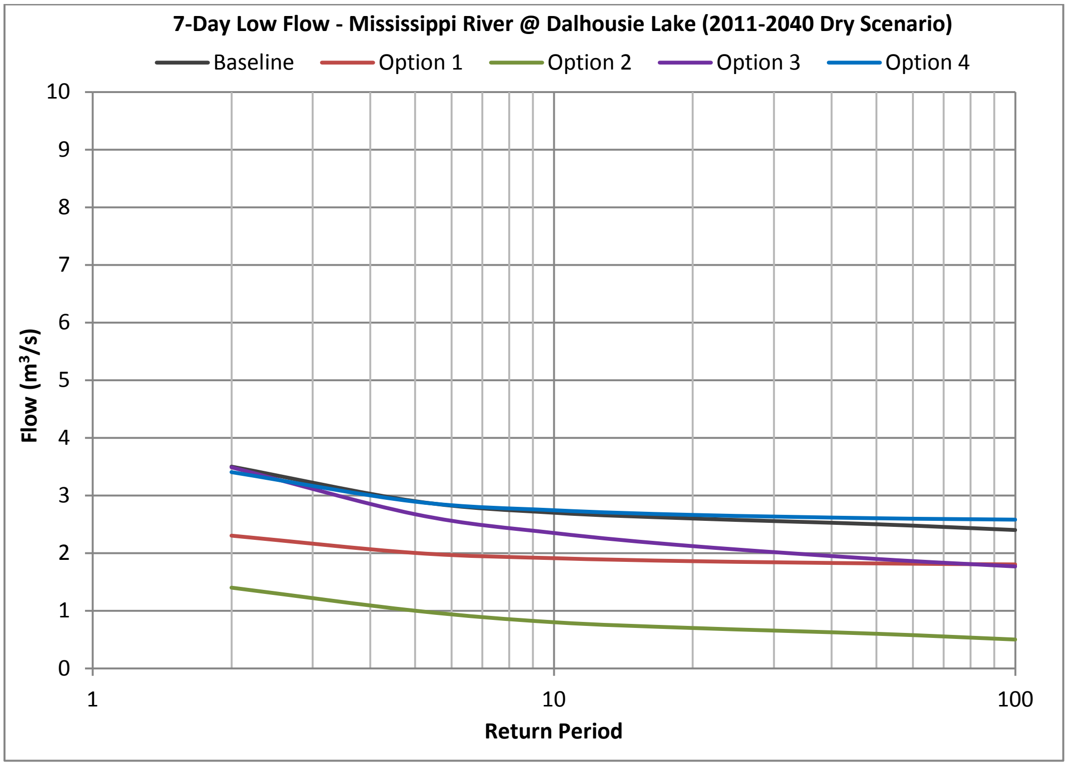
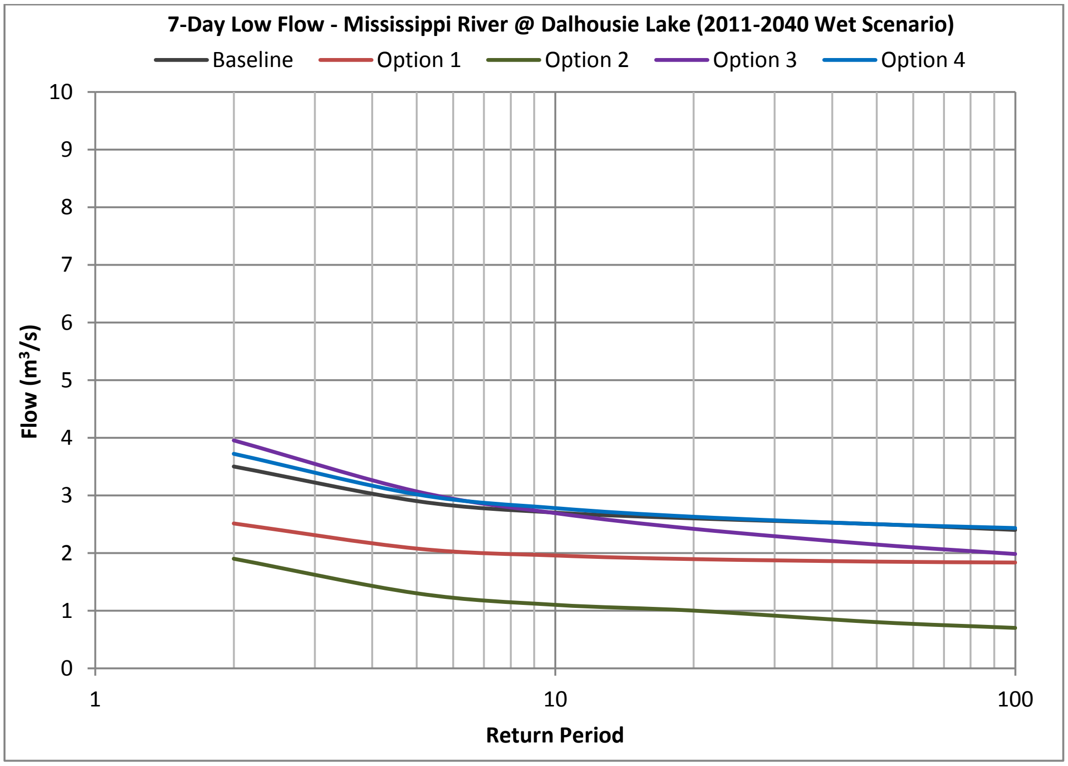


Figure 6:25 Low Flow Frequency Comparison @ Dalhousie Lake (Wet Scenario)



6.3 Inclusion of Other Factors When Determining Best Options

Though this study focuses on changes in water quantity, including stream flows and waterlevels, and how they may impact hydrogeneration it must be remembered that this is only one variable to be managed within the river system. This subsection indentifies some of the numerous factors to be included in the water management decision-making process.

6.3.1 Water Quality

Water quality in particular is directly related to water quantity.The impact of climate change on water quality is complex and highly uncertain. The IPCC's Fourth Assessment report did not consider the impacts of climate change on water quality in great detail[16]. It is observed that the increased frequency and severity of flooding can mobilize erosion, sedimentation, and other contaminants to the system, while droughts may reduce pollutant dilution thereby potentially increasing toxicity. The projected changes in air temperature and rainfall will affect stream flow and therefore the mobility and dilution of contaminants.

In 2014 and 2015 blue-green algae blooms were reported in the Mississippi River watershed. Nutrient loads are expected to increase under climate change[8], however this has not been determined in the Mississippi River watershed to date. Eutrophication occurs as a result of the complex interplay between nutrient availability, light conditions, temperature, residence time and flow conditions[15], hence it is hard to determine a specific cause for these occurrences. The increase in temperature is suspected to be a factor as the condition favours accelerated growth rates of algae, especially cyanobacteria [26]. By 2100, a 4.1°C increase in temperature is projected for the Mississippi River watershed[17]. In the Netherlands, a laboratory study where a 4°C increase in the temperature and salinity conditions were introduced, showed increased risk of harmful algae blooms even with restrictions on the uncertainties in climate projections and its effects on the ecosystem[23].

Cyanobacterial species are highly competitive for low concentrations of inorganic phosphorus (P) and able to acquire organic phosphorus compounds. Both Nitrogen (N) - fixing and non-nitrogen fixing cyanobacteria shows great flexibility in the nitrogen sources for their bloom. Therefore, even though some cyanobacterial blooms are associated with eutrophication, several other species bloom under a low concentrations of inorganic N and P[25]. A study which examined the relationships between eutrophication, climate change and representative cyanobacterial species, suggests that climate change and eutrophication will likely enhance the magnitude and frequency of harmful cyanobacterial blooms[25].Recent studies show climatic change may benefit some harmful cyanobacteria species by increasing their growth rates, dominance, persistence, geographic distributions[12].

In the world's current climate, some cyanobacterial species form massive blooms that produce toxins, deplete oxygen and alter food webs, pose threat to drinking and irrigation water supplies, fishing and recreational use of surface waters[12]. Higher temperatures will reduce the saturation levels and higher nutrient levels will enhance respiration, and thereby deplete oxygen concentrations. Future projections suggest a decline in oxygen levels and extensive blooms in cyanobacteria blooms may become more extensive[27].

It is also projected that low flows will become more severe during the summer in the Mississippi River watershed[17] which could increase the residence time of water in river reaches which could increase algae growth potential, and enhance sediment settling. This in turn reduces turbidity and improves light penetration which could enhance algae growth. Lake ecosystems respond to changes in inflow volumes, water quality and water temperature, as well as to changes in thermocline behaviour and residence times[11]. Higher wind speeds could reduce lake stability, and enhance mixing of nutrients[11]. Conversely, higher temperatures lengthen the period of thermal stratification and deepen the thermocline[13]. Nitrate concentrations increase over time as higher temperatures increase soil mineralization and is significant under high flow conditions following a drought[27]. This may be more important for nutrient-poor rivers and lakes that ultimately receive additional nutrients through an increased frequency of flushing events which is expected from climate projections and which could enhance the eutrophication in receiving water bodies[27].

In another study, it has been noted that algae bloom in the Lake Maggiore, Italy, always occurred in summer time and at a certain epilimnetic temperature range. The bloom was at the peak after a sudden increase in lake level following a high rainfall event[28]. They also studied the desiccation and wetting pattern using an artificial substrate and confirmed distinct seasonal changes with the highest Carbon (C) and N amounts observed in the spring and highest P in the fall. The bloom corresponded to the release of material with a low C:P ratio and a high percentage of P release from the shore. It has been found that desiccation and rewetting increase P availability in the littoral zone and trigger algae blooms even in oligotrophic systems[28].

It has seen worldwide and in the Mississippi River watershed that climate change has triggered drought-driven decreases in lake levels which is frequently followed by heavy rainfall events. Therefore, the contribution of P from the shore due to drying and rewetting cannot be ignored; the fluctuations in water levels enhance the nutrient release from the littoral zone and may assist algae growth in lake ecosystems[24].

Climate scenarios project a rise in temperature, enhanced vertical stratification of aquatic ecosystems, and changes in seasonal and inter-annual climate and hydrologic patterns (droughts, storms, floods etc.) in the future. Combined, these changes will favour cyanobacterial blooms in eutrophic and/or oligotrophic waters. The mechanisms relating water level fluctuations with nutrient pulses from the shore and associated cyanobacterial blooms require improved understanding to assist in identifying possible mitigation measures in an effort to limit the spread of cyanobacterial blooms in our freshwater ecosystems.

6.3.2 Natural Systems and Cultural Factors

As noted in Sections 2.4 and 2.5 there are, and always have been, a number of competing interests throughout the Mississippi River system for a finite amount of water. They include;

1. Aquatic ecosystems,
2. Riparian and terrestrial ecosystems,
3. Residential properties,
4. Shoreline structures, public and private, and
5. Cultural values.

The Mississippi Water Management Plan (2006) has a stated goal, “To develop a water level and flow management plan for the Mississippi River that builds on the current operating regime for the system and integrates environmental and socio-economic values and considerations.” As such all factors require consideration during the process of choosing best management options.

Ecosystems

Ecosystem management and protection of habitat and diversity within the system must, among other things, include protection of Provinically Significant Wetlands, protection of Species at Risk (SAR) habitat (both aquatic and terrestrial) as well as the species themselves, with the goal of retaining overall ecosystem diversity.

A recent report titled Climate Change Vulnerability Assessment for Aquatic Ecosystems in the Mississippi and Rideau Conservation Authority Watersheds[29] discusses changing vulnerabilities of aquatic habitats within the Mississippi Rideau region and provides information on some of the vulnerabilities in these systems associated with a changing climate.

A previous report on projected changes in fisheries in the watershed[3] indicates that increasing water temperatures will affect fish community composition.

Waterfront Properties

Location and characteristics of residential properties throughout the system may be affected by high water levels and flows and/or erosion as well as damage associated with low water levels.

Shoreline Structures

Shoreline structures, public and private may be damaged by changing water levels, water flows, and ice shifting.

Cultural Values

Cultural values such as the wild rice found in parts of the system may be impacted by increased or decreased water levels.

Other Factors

As a point of interest, a previous study conducted by the University of Guelph[7], demonstrated that the Mississippi River @ Appleton (02KF006) stream flow record is cyclic in nature with 3-year and 12-year periods which may be affected by the ENSO (El-Nino Southern Oscillation) phenomena. This connection with larger global weather patterns should be considered when assessing options.

Though this study focuses on impacts to hydro-electric facilities associated with a changing climate, associated hydrologic changes and options for revising management strategies specific to hydrogeneration, it should be noted that all factors will be considered when determining best options for future water management strategies.

7. Conclusions and Recommendations

A number of conclusions may be reached which can assist in identifying further actions and information which may be need to support the decision process. Following is a list of conclusions followed by associated recommendations.

1. Conclusion

Hydro-electric Generation – Hydro-electric production in the Mississippi River watershed is expected to be reduced by 14 to 23% due to projected changes in stream flow. This impact might be mitigated by 9% through the introduction of revised reservoir operation policies which will provide additional benefits in terms of low flow augmentation. This Option however, may result in increased flood risk to downstream communities as reservoir storage is reduced. Other impacts on environmental, cultural, economic, and other factors are not known at this time. Potential improvements to runoff forecasts may assist in mitigating the potential increase in flood risk by providing the ability to revise reservoir operating policies based on projected runoff potential.

Increasing upstream reservoir storage was found to further mitigate the reduction in hydro-electric production by an additional 3%. This Option would provide marginal improvements to flood risk however it would improve low flow conditions by up to 30%. Augmenting low flow conditions may become an increasingly important consideration in protecting water quality conditions in the river system.

As shown in the flow duration curves in Section 6, projected future stream flows above 25 m^3/s at Appleton will occur more frequently than present while stream flows below 25 m^3/s will occur less frequently. An increase in the design flow of 20% at the three generating stations will result in an increase in energy production of approximately 12%.

Recommendations

a. Future refurbishment or reconstruction of hydro-electric facilities on the Mississippi Rier should include an analysis as to whether the additional energy value is cost beneficial.

b. Further analysis is required to determine overall impacts and benefits of each option to stakeholders in the system.

2. Conclusion

Stream flow – Future stream flow projections indicate that stream flow will become considerably more variable and erratic specifically in the spring and summer low flow seasons which may result in increased flood risk and more severe low flow conditions.

Recommendations

a. Determine if additional streamflow monitoring stations are required and identify the optimum spatial distribution.

b. Determine if additional meteorological stations, especially in the upper watershed, are required and identify the optimum spatial distribution.

c. Identify opportunities to retain runoff on the landscape to encourage infiltration and increase soil moisture conditions.

d. Retention of wetlands, natural stream corridors and the use of Low Impact Development measures should be given strong consideration and utilized through municipal Official Plan policies and other regulatory instruments wherever appropriate.

3. Conclusion

Reservoir Operations – Due to the variability and uncertainty in projected runoff volumes, the current reservoir drawdown regime will create challenges to ensuring reservoir levels can achieve *Summer Holding Levels*. Reservoirs with a limited catchment area will be the most susceptible to low runoff conditions.

Reducing the extent of drawdown on these reservoirs can improve recreational/tourism interests, however, doing so may result in increased flood risk in downstream communities.

Recommendations

a. Further determine the amount of increase in flood risk to downstream communities under proposed options.

b. Determine impacts on other stakeholders and cumulative impacts under proposed options.

4. Conclusion

Reservoir Inflow Forecasts - The accuracy of both short-term (3-day) and long-range (14-Day) forecasts of reservoir inflow can have a significant bearing on the effectiveness of reservoir operations in mitigating flood risk. Short-term forecasting requires real-time precipitation, temperature and snow cover data across broad geographic areas coupled with stream flow and reservoir levels to assist in reservoir inflow simulation.

Recommendation

Identify opportunities to access real-time climate data. Use of weather radar to provide aerial coverage of catchment areas would provide a significant improvement in forecast capability.

5. Conclusion

Confidence and Uncertainty - Based on the present study, the uncertainty associated with available climate projections (AR4) on watershed hydrology will be an important consideration in water management policy and infrastructure decisions.

Recommendation

As necessary, further identify where additional study is required to increase confidence in outcomes to the level where preliminary adaptation measures to water management planning (and eventual implementation) may be initiated. An example may be in using RCM regional climate data rather than change field method.

6. Conclusion

ENSO influences on stream flows - As noted in Section 6.3.2, a previous study conducted by the University of Guelph[7], demonstrated that the Mississippi River @ Appleton (02KF006) stream flow record is cyclic in nature with 3-year and 12-year periods which may be affected by the ENSO (El-Nino Southern Oscillation) phenomena. Use of the ENSO index to provide forecasts of potential dry and wet periods could assist operators in assessing the potential risk associated with reducing the drawdown regime of susceptible reservoirs.

Recommendation

The relationship between stream flow and ENSO should be analysed further and if feasible the chosen option(s) should include monitoring of these forecasts as potential management indicators.

7. Conclusion

Extreme events and their (changing) frequency have not been included in the climate projection analysis.

Recommendation

A study should be conducted to analyze climate data for extreme events and estimate frequency and probability of extreme events such as floods and droughts. This will help in understanding and quantifying the uncertainties connected with the estimation of the design storms, which is very important for a sound watershed management at plan.

8. Conclusion

Current water management policies were not developed to consider impacts of a changing climate. Future projections indicate that runoff and the resulting stream flow will increase substantially during the late fall/early winter with corresponding reductions during the spring periods and significant reductions over the summer and early fall. These general trends will be interspersed with highly variable conditions throughout the year.

As a result of these highly variable and uncertain runoff conditions, maintaining reservoir storage and resiliency of shoreline structures to water level fluctuations and ice damage will provide the best opportunities to mitigate potential impacts. While a natural flow regime is acknowledged as being preferable to sustaining ecosystem function, future runoff projections indicate that reservoir storage can aid in maintaining aquatic quality.

Recommendation

a. Water management policy should be reassessed relative to future projections of temporal changes in runoff patterns.

b. The Mississippi River Water Management Plan should be reviewed taking into consideration the results of this study and previous studies[3] to assist in rebalancing the competing interests for the basins water resource.

9. Conclusion

Water Quality, Nutrients and Eutrophication - The impact of climate change on water quality is complex and highly uncertain. The IPCC's Fourth Assessment report did not consider the impacts of climate change on water quality in great detail (Kundzewicz et al. 2007). It is observed that the increased frequency and severity of flooding can mobilize erosion, sedimentation, and other contaminants to the system, while droughts may reduce pollutant dilution thereby potentially increasing toxicity. The projected changes in air temperature and rainfall will affect stream flow and therefore the mobility and dilution of contaminants.

Climate scenarios project a rise in temperature, enhanced vertical stratification of aquatic ecosystems, and changes in seasonal and inter-annual climate and hydrologic patterns (droughts, storms, floods etc.) in the future. Combined, these changes will favour cyanobacterial blooms in eutrophic and/or oligotrophic waters. The mechanisms relating water level fluctuations with nutrient pulses from the shore and associated cyanobacterial blooms require improved understanding to assist in identifying possible mitigation measures in an effort to limit the spread of cyanobacterial blooms in our freshwater ecosystems.

Recommendation

Further study is required to fully understand the mechanisms relating water level fluctuations with nutrient pulses from the shore and associated cyanobacterial blooms and to utilize climate projection data to project trends in distribution and quantity.

10. Conclusion

Natural Systems Function and Diversity – Water is obviously a large component of both aquatic and terrestrial natural systems. Modifying stream flow may affect both in-line and adjacent wetlands, water temperatures, dissolved oxygen, and a number of other key factors in aquatic systems. Terrestrial systems, especially riparian, are often dependent on soil moisture being replenished by groundwater supplied by adjacent surface water, and wildlife dependencies on having reliable, clean sources of water is also an obvious necessity.

Healthy, diverse ecosystems have developed over long periods of time to address and buffer local climate variabilities and resulting habitat changes and it is to our advantage to protect these systems.

Recommendations

a. Develop a further understanding of optimum conditions for the local natural systems which may be affected by changes in stream flow and water levels. Building on that information we can determine how these systems may respond to changing conditions, as per Chu's (2014) aquatic habitats study.

b. Take into account cumulative effects of changing conditions under climate change scenarios and changes to streamflow under the proposed options for modification of water management strategies.

11. Conclusion

Retention of Cultural Values – Wild rice has been identified as being important to the local indigenous community and may be adversely affected by changing water levels.

American Eel also occurs in the river system and is of great importance to local Algonquins.

Recommendation

Determine what impacts the identified options may have on wild rice distribution, eel migration and distribution, and other species of cultural value within the system.

12. Conclusion

Recreational values in the system - Water levels associated with reservoir lakes subject to a drawdown regime will become highly variable and unreliable relative to historic conditions. This may restrict abilities to retain water levels in recreational areas at their historic and expected levels.

Recommendations

a. Where feasible, based on considerations for fish habitat and potential damage to shoreline structures, moderately reduced drawdown regimes should be explored to assist in addressing recreational interests.

b. Despite these adaptation measures, land use policies should restrict encroachment of susceptible structures below the maximum reservoir operating level.

13. Conclusion

Shoreline Structures on the system – As noted, reservoir levels will become highly variable and unpredictable with respect to ice conditions.

Adapting shoreline structures to accommodate these variable conditions by promoting conversion of permanent to floating/removable docks which will be less susceptible to damage is suggested. The unreliability of achieving summer target levels will also necessitate recreational and tourism use to adapt to these conditions.

This will require the Conservation Authority and area municipalities to provide effective information regarding potential risks and regulation of shoreline activities.

Recommendation

The MVCA, municipalities, and other identified stakeholders should develop and distribute information regarding potential (changing) risks to shoreline structures, suggestions for reducing the risk, and details regarding regulation of shoreline activities.

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