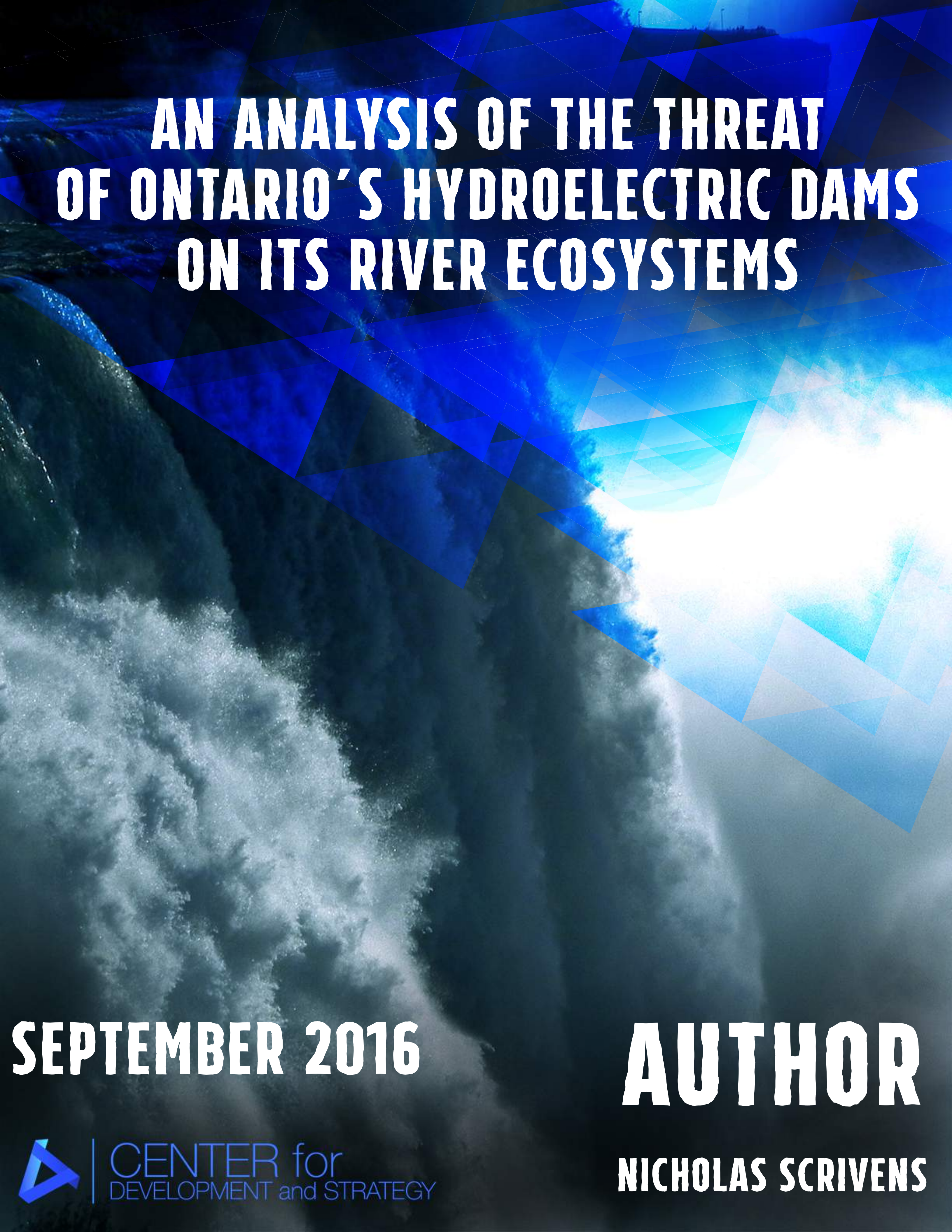

AN ANALYSIS OF THE THREAT OF ONTARIO'S HYDROELECTRIC DAMS ON ITS RIVER ECOSYSTEMS

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An analysis of the threat of Ontario’s hydroelectric dams on its river ecosystems

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Abstract

Dams have been used for centuries to assist with the development of human civilization. Access to drinking water, flood control and agricultural irrigation are historical reasons for the development of dams and river impoundments. The abundance of large rivers in Ontario has enabled 22% of the province's power generation to be based on renewable hydroelectric power. The composition of Ontario's energy portfolio is shifting away from carbon intensive energy production and towards hydroelectric power, which presents a threat to Ontario's rivers. What is the extent of the threat of storage and hydroelectric dams on the Ontario's river ecosystems given the growing hydroelectric capacity, and how might these effects be mitigated? Storage dams with large hydraulic head volumes and those with power generating capabilities are developed to serve and meet the needs of human civilization but also affect the naturally occurring ecosystem function. Dam development often results in a debate regarding the balance between civilization and the surrounding ecosystem. An analysis of previous research suggests that Ontario's extensive network of dams and river impoundment can alter the naturally occurring thermal regime, river flow, sediment and nutrient transport, fish communities and riparian zones of rivers. The continuous development of large hydroelectric dams and the use of hydropeaking to meet Ontario's electricity demand could further impair abiotic and biotic elements of the river ecosystem without the implementation of progressive mitigation strategies.

Keywords: hydroelectric dams, hydropeaking, Ontario, river, ecosystem

Introduction

Water storage, irrigation, power generation, flood mitigation and access to recreation are among the most common reasons for the development of dams globally, and this is no different in Ontario. There are more than 2600 dams in Ontario, which are concentrated in southern Ontario, where the majority of the population resides (Ontario, 2010). The majority of Ontario's dams are located in the watersheds of Ontario's Great Lakes Basin. The provincial government maintains an inventory of dams in Ontario, but because this is a recent undertaking not all dams in Ontario have been inventoried. Many of the dams are unmanaged in rural areas, and this contributes to the difficulty of maintaining an accurate inventory of Ontario's dams (Ontario, 2015). Figure 1 shows the location of Ontario's dams that are registered in the provincial inventory (Ontario, 2015). Dams are either considered storage or run-of-river dams. Run-of-river dams have short retention times, low head volume, very little control of flow and are generally small in scale. Storage dams have large hydraulic head volumes, long retention times, and control over water release (Poff & Hart, 2002; Chen *et al*., 2011a). There is a combination of run-of-river and storage dams in Ontario, and both affect their associated river ecosystems (Smokorowski *et al*., 2011).

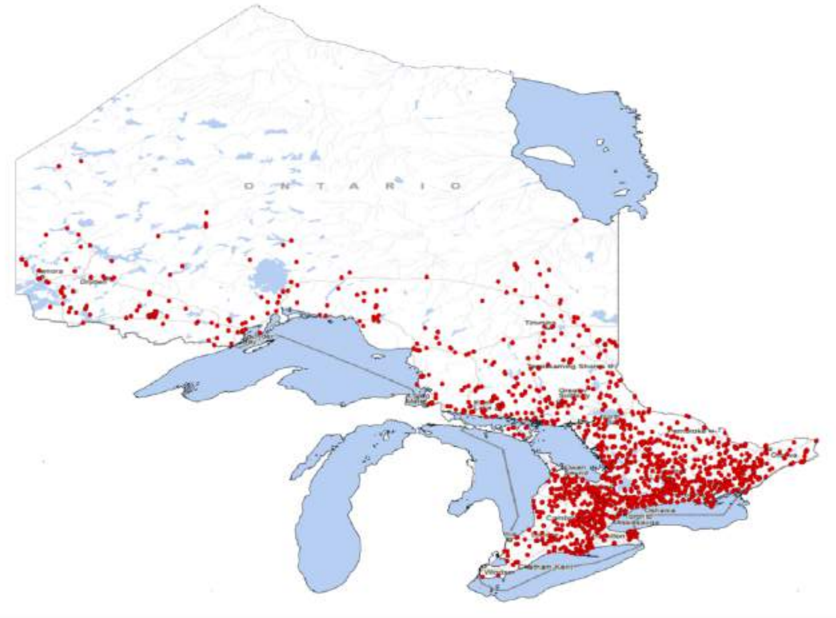

Figure 1. Map of dams in Ontario that are registered in the Ontario Dam Inventory. Dams are represented by red marks (Ontario, 2015).

While dams and water impoundments were initially used for water access and irrigation, they were later used for power generation through waterwheels before the use of hydroelectric generators (Baxter 1977). The large hydraulic head volumes and controlled rate of release of storage dams enable their use for power generation. Access to freshwater river systems gives Ontario the opportunity to utilize hydroelectric dams as a renewable, and cost efficient contributor to power generation (Ontario Ministry of Energy, 2013). In 2013, 22% of Ontario's electricity was a result of hydroelectric sources and by 2025, this figure is projected to grow to 29%, which can be seen in Figure 2 (Ontario Ministry of Energy, 2013).

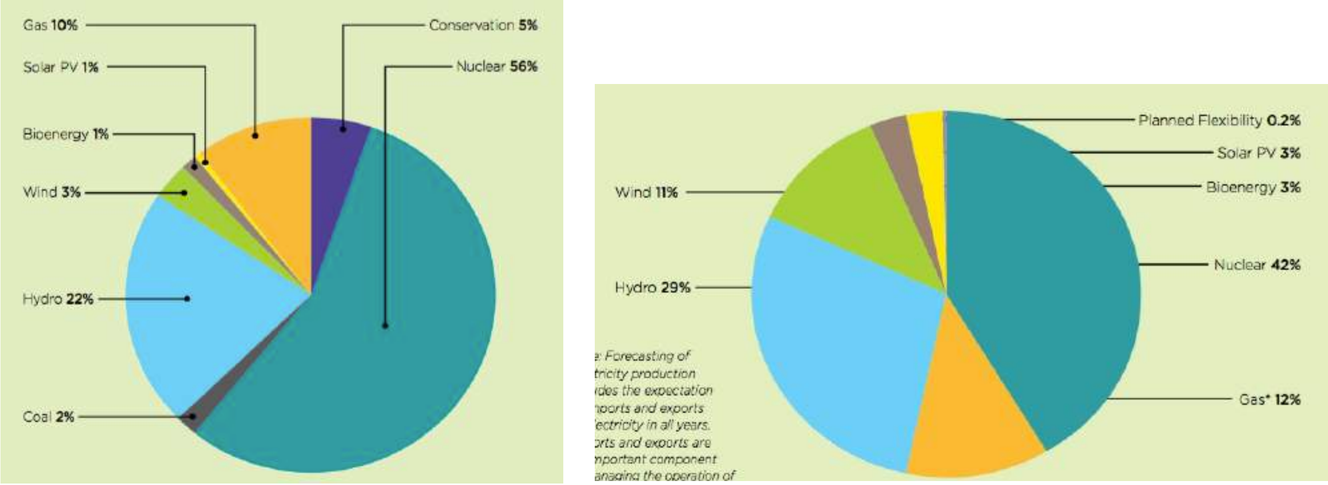

Figure 2. Composition of the sources of Ontario's energy production in 2013 (left) and projection for 2025 (right) (Ontario Ministry of Energy, 2013).

Hydro contributes to more than half of Ontario's renewable energy portfolio, and it is their lowest cost power generator (Ontario Ministry of Energy, 2013). There are 250 operating water power facilities in Ontario, some of which are privately owned, but the majority are owned and operated by Ontario Power Generation, a corporation that is owned by the province (Ontario Ministry of Energy, 2013). In 2007, there were 60 sites that were proposed for hydroelectric dams in Ontario's Great Lakes Basin, further emphasising hydropower as a growing power generation source in Ontario for the future (Melles *et al.,* 2015). Hydroelectric dams will release water through their turbines selectively, depending on the changing demand for electricity in a process called hydropeaking. Hydropeaking is cost efficient for the power generating companies, however it generates negative externalities for the surrounding river ecosystem because of the constantly changing water flows (Chen *et al*., 2015). The rate of change of water flow in a hydropeaking dam is referred to as the ramping rate. Since 2001, provincial law has required dam operators to develop an operating plan that identifies minimum and maximum flows and ramping rate restrictions for each dam (Chen *et al.,* 2015; Metcalfe *et al.,* 2005). These Water Management Plans are agreements or contracts that are made between power generating companies and the Ministry of Natural Resources. The aim of this contract is to balance the economic incentive of water power generation with the environmental and societal protection of the river ecosystem. There is a Water Management Planning Guideline, which is an aid for the development of the management plans (Metcalfe *et al.*, 2005). However, the environmental component of this guide is an appendix, which illustrates the limited inclusion of the environment in the development of the province's Water Management Plans. A map of Ontario's hydroelectric dams in 2005 that undertook a Water Management Plans can be seen in Figure 3 (Metcalfe *et al*., 2005). On a global scale, these water restrictions and management plans are ineffective in maintaining natural ecosystem function (Chen *et al.,* 2015).

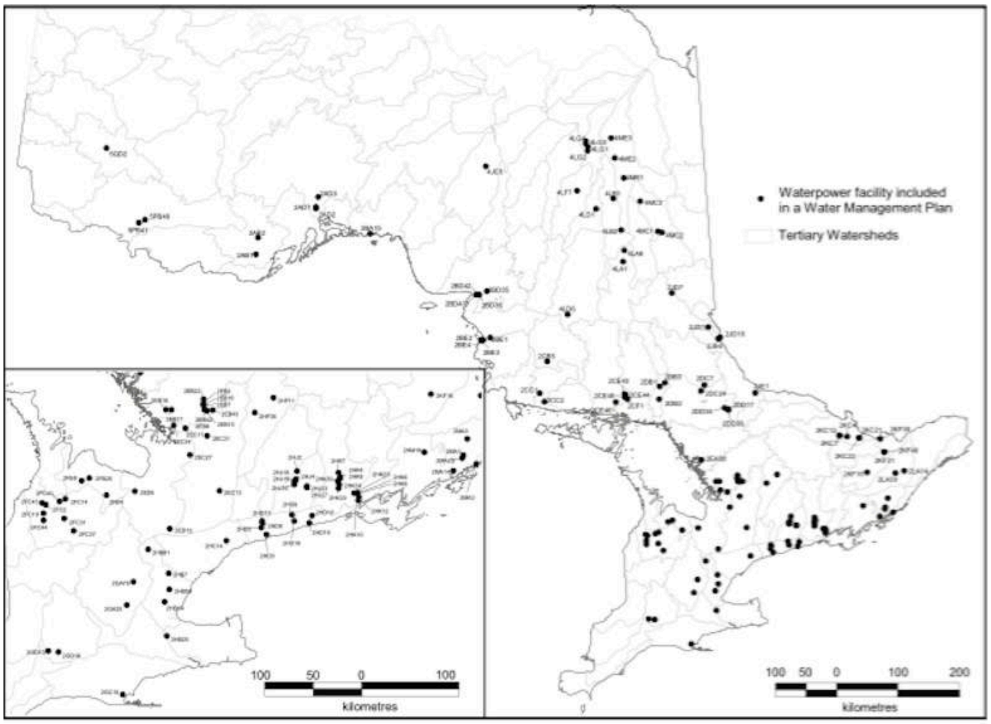

Figure 3. Map of the hydroelectric dams in Ontario that are currently included in a Water Management Plan (Metcalfe *et al.,* 2005).

Restrictions to minimum and maximum flows and ramping rates address the quantity of water traversing the dam. These restrictions do not however, place an emphasis on the water quality, which can cause many abiotic and biotic changes to the river ecosystem (Olden & Naiman, 2010). The effects of river impoundment have been well studied and is not a novel field for ecologists and environmental scientists (Baxter 1977; Poff & Hart, 2002). A considerable amount of time and resources have been devoted to understanding how fish communities and distribution of populations is affected by the imposition of physical barriers (Haxton & Findlay, 2009; Smokorowski *et al.,* 2011). Depending on the size of the dam and the nature of the fish community, dams can become barriers to migration creating fragmented habitats (Yellen & Boutt 2015). The effects of dams on river ecosystems are more far reaching than immediate habitat destruction and the creation of a physical barrier. There is expanding literature on the water quality changes as a result of dam development and the associated implications for the river ecosystem (Olden & Naiman, 2010; Cassie *et al.,* 2006). Naturally occurring thermal fluctuation can be both daily and seasonal, depending on solar radiation, geothermal and groundwater interactions (Olden & Naiman, 2010). Dams and river impoundments are an anthropocentric cause of thermal pollution that depends on the mechanism of water release and the size of the reservoir (Cassie, 2006). Selective water release from reservoirs can deviate from the natural flow regime of the river. This deviation is magnified in rivers where hydropeaking operations are in place (Olden & Naiman, 2010). Changes to the natural flow patterns have been shown to affect the life cycle of many species of fish and invertebrates (Chen et al., 2015). Natural periods of high and low flows are also important for creating natural disturbances, and maintaining riparian zone habitats (Nadon *et al.*, 2015; Graf, 2006). Furthermore, research has focused on the the transport of nutrients and sediment through river systems and how this can be affected by impoundment (Smokorowski et al., 2011; Chen *et al.,* 2011a; Chen *et al.,* 2011b). All of these implications are not isolated and can function synergistically or antagonistically, but often generate cumulative negative effects for the ecosystem.

Every river has a unique set of biotic and abiotic factors, and dams will affect river ecosystems differently depending on the type of dam and particular environmental characteristics. Although the amount of research on the effects of hydroelectric dams in Ontario's rivers is not extensive, it can be used in combination with global research to assist in predicting how Ontario river ecosystems are and will be affected by future hydroelectric power generation. As a result, some of the analysis and conclusions made about the effects of hydroelectric dams in Ontario is based on research from other jurisdictions. An analysis of previously published research on the effects of large storage dams and hydropeaking on river ecosystems, as well as the mitigation strategies, will help in evaluating the threat of Ontario's growing hydroelectric capacity its rivers.

Analysis and Discussion

Hydroelectric dams have proven to be a cost effective strategy for energy generation in Ontario, but the environmental costs associated with the operation of these dams must also be taken into consideration. An analysis of the effects of hydroelectric dams on the thermal regime, river flow, and sediment and nutrients, in addition to the effects of hydropeaking on riparian ecology, fish communities, and hyporheic water exchange will expose these environmental externalities. The subsequent evaluation of mitigation strategies will provide methods in which the environmental costs of hydropower generation in Ontario can be reduced.

Thermal Regime

The thermal regime is important to any river because it can be the primary driver of many ecosystems energy flows. Water temperature dictates overall ecosystem health by influencing productivity and species growth (Caissie *et al*., 2006). The optimal growth for flora and fauna occurs within a specific temperature range. Species however, must adapt to daily fluctuations in water temperatures, and Ontario's climate leads to seasonal fluctuation. Water temperature is influenced by interactions at the surface and at the riverbed (Olden & Naiman, 2010). At the surface, solar radiation, precipitation, evaporation and runoff all contribute to the temperature of the water (Olden & Naiman, 2010). Geothermal energy and groundwater intrusion affect the thermal energy of a river from the riverbed (Olden & Naiman, 2010). A representation of the energy sources that naturally contribute to the river's thermal regime can be seen in Figure 4. The temperature of river water however, is not only dictated by the energy fluxes. Water's high heat capacity means that the volume of water and the rate of water flow can influence water temperature in rivers. Water temperature not only influences primary production and species growth, but it also affects the solubility and transport of pollution, organic matter, nutrients, sediment and dissolved oxygen in the river (Olden & Naiman, 2010). Water temperature can dictate the reproduction, growth, distribution and life history events of many species (Olden & Naiman, 2010). It is evident that water temperature and the thermal regime are important for the functioning of a river from a species and ecosystem level. Large artificial reservoirs that are created for hydroelectric potential are subject to the same thermal fluxes outlined above. The release of water from these artificial reservoirs can therefore change the thermal regime of a river.

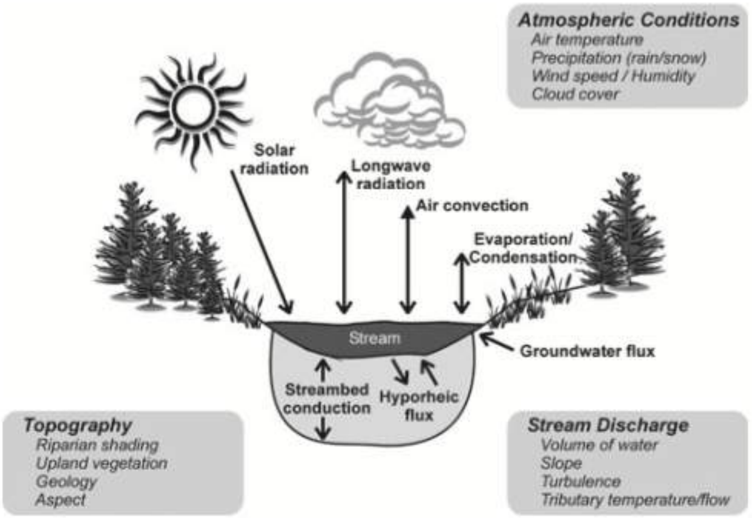

Figure 4. Factors affecting the thermal properties of a river or stream (Olden et al. 2010).

The long residence time of water in large reservoirs leads to the water being exposed to thermal energy, for example solar radiation and geothermal energy, for a longer period of time.

If the reservoir is relatively deep, which is true for most hydroelectric dams, the possibility of thermal energy leading to reservoir stratification is increased (Olden & Naiman, 2010). The climate in Ontario and its seasons means that the majority of large reservoirs would be dimictic, resulting in stratification with two periods of mixing (Melles *et al.,* 2015). In the summer, the epilimnetic layer at the surface of the reservoir is warmer than the hypolimnetic water. The reverse would occur in the winter, where warmer water, close to 4°C, would be found at the bottom, while water that is close to freezing temperature would be found at the surface. The release mechanism of the reservoir can influence the downstream thermal regime due to this stratification process (Olden & Naiman, 2010). In the summer, cold hypolimnetic water is often released from dams in order to maintain productive recreational fisheries upstream of the dam (Olden & Naiman, 2010). When cold hypolimnetic water is released it depresses downstream river temperatures in Ontario's summer months and increases river temperatures in the winter, compared to natural conditions (Olden & Naiman, 2010). The changes to a river's thermal regime as a result of hypolimnetic release can be seen in Figure 5. While this dam is in the United States, it represents the potential influences of hypolimnetic release on Ontario's rivers. When epilimnetic water is released from reservoirs in the summer, this leads to an increased downstream water temperature (Olden & Naiman, 2010). Six separate studies of the thermal depression of rivers as a result of hypolimnetic release show temperature depression ranging from 3 to 12 degrees Celsius during the summer months compared to similar unregulated rivers (Olden & Naiman, 2010). While these studies were not conducted in Ontario, it does show the significant effect of water release on the river's thermal regime.

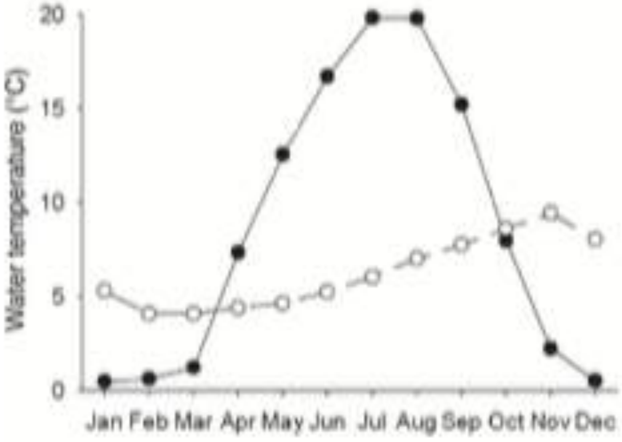

Figure 5. The temperature of the Green River, USA, below the hypolimnetic releasing dam (open symbols) and of the river prior to regulation (filled symbols) over an entire year (Olden & Naiman, 2010).

Water temperature is an important component for river ecosystems because many aquatic species rely on temperature for suitable habitat and for driving life history events. Thermal habitats are necessary for certain species of fish, invertebrates and other ectotherms (Olden & Naiman, 2010). Warmer water in the winter can be particularly harmful for some insect fauna that rely on prolonged exposure to near freezing water. The warm water can cause early insect emergence which can interfere with the natural period of growth that generally occurs in the spring and the summer. Premature insect emergence can be lethal or can impede mating, devastating insect populations (Olden & Naiman, 2010). Some species of freshwater insects rely on varying thermal conditions for different life processes. Life history events, such as spawning, are often timed with the natural fluctuation in the river's thermal regime for some insects and fish (Olden & Naiman, 2010). When hypolimnetic release from reservoirs dampens the natural fluctuation in river temperature it can reduce the reproduction and spawning ability of fish populations. There is a natural temperature window and threshold for fish spawning and changes to the river's thermal regime could cause reproductive complications (Olden & Naiman, 2010). Delayed spawning because of a shift in the temperature dependent spawning window combined with cold water that limits the growth of the juvenile could reduce the survival of the fish population (Olden & Naiman, 2010).

Flow Regimes

One of the most obvious implications of dams and river impoundments is the resulting change to the flow of water through the river system. In most cases the intended purpose of dams is to divert water, whether it be for flood control or power generation. Run-of-river dams affect the flow regimes of a river to a lesser extent than storage dams, because generally in run-of river dams the inflows are equal to the outflows (Metcalfe *et al.,* 2005). In contrast, the outflow in large storage dams can be controlled. This is particularly noticeable in peaking hydroelectric dams that regulate the rate of flow from the storage reservoir to match demands in electricity.

The control of flow through a large storage dam is based on several factors including: reservoir inflows, the storage of water, and the downstream release of water (Metcalfe et al., 2005). This regulation of river flows can change properties of the river ecosystem and the magnitude of this affect can depend on the type of the dam and the size of the water power generating facility (Metcalfe *et al.,* 2005). The natural flow regime of a river, which is the flow characteristics of an unregulated river, is considered to be one of the most important elements of the ecosystem and alterations to this natural flow through rivers is a global concern (Bond & Jones, 2015). Large storage dams and water power facilities can disrupt the natural flow regime by changing the magnitude, duration, rate of change and the frequency of flows through a river system. Academic research was originally focused on the upstream effects of dam construction, but this quickly shifted to the study of the downstream implications of altered flow regimes on the health of rivers (Metcalfe *et al.,* 2005). The natural flow of rivers can be highly variable in Ontario because of seasonal differences in precipitation and the physical state of the precipitation. Seasonally, the river flows are lowest in the winter months because large volumes precipitation and water in the form of either snow or ice and are restricted from entering the river systems. River flows are most consistently high in the spring when the snow and ice melt and enter rivers through groundwater or runoff. In the summer and fall, river flows are maintained though direct rainfall, runoff, or groundwater contributions (Bond & Jones, 2015) The unpredictable element of river flows in Ontario is attributed to climate patterns, which can bring short or extended periods of rainfall and periods of drought as well (Bond & Jones, 2015; Metcalfe *et al.,* 2005).

This natural variation in river flows, which is an important element of maintaining ecosystem health is affected by large storage dams. A study by Graf (2006) of the effects of dams on the flows of rivers in the United States documented several significant alterations in flow regimes. The study evaluated river flows of reaches downstream of 36 large storage dams, with storage capacity greater than 1.2 km^3, compared to similar unregulated reaches on the same river or nearby similar rivers. In the regulated reaches annual peak discharge was reduced by 67% (Graf, 2006). The ratio of maximum flow to minimum flow decreased by 60%, the range of daily discharges decreased by 64% and the timing of seasonal high and low flows periods changed by up to half a year (Graf, 2006). The size of downstream water channels is also significantly affected by large dam regulation. Low flow channels are generally larger and high flow channels are smaller in regulated reaches (Graf, 2006). The unregulated variation and fluctuation in flows is dampened by the presence of upstream large storage dams and this can affect the downstream fish communities and riparian zone ecology, which will be discussed later. These findings are shared with a study by Smokorowski *et al.,* of regulated river flows in a river in Ontario (2011). The Magpie River in Wawa, Ontario, was regulated by a hydroelectric dam in 1990 and now experiences attenuated flows as a result (Smokorowski *et al*., 2011). Figure 6 shows how the unregulated river had a seasonal cycle of high flow and low flow periods, while the regulated river experiences attenuated flows (Smokorowski *et al.,* 2011).

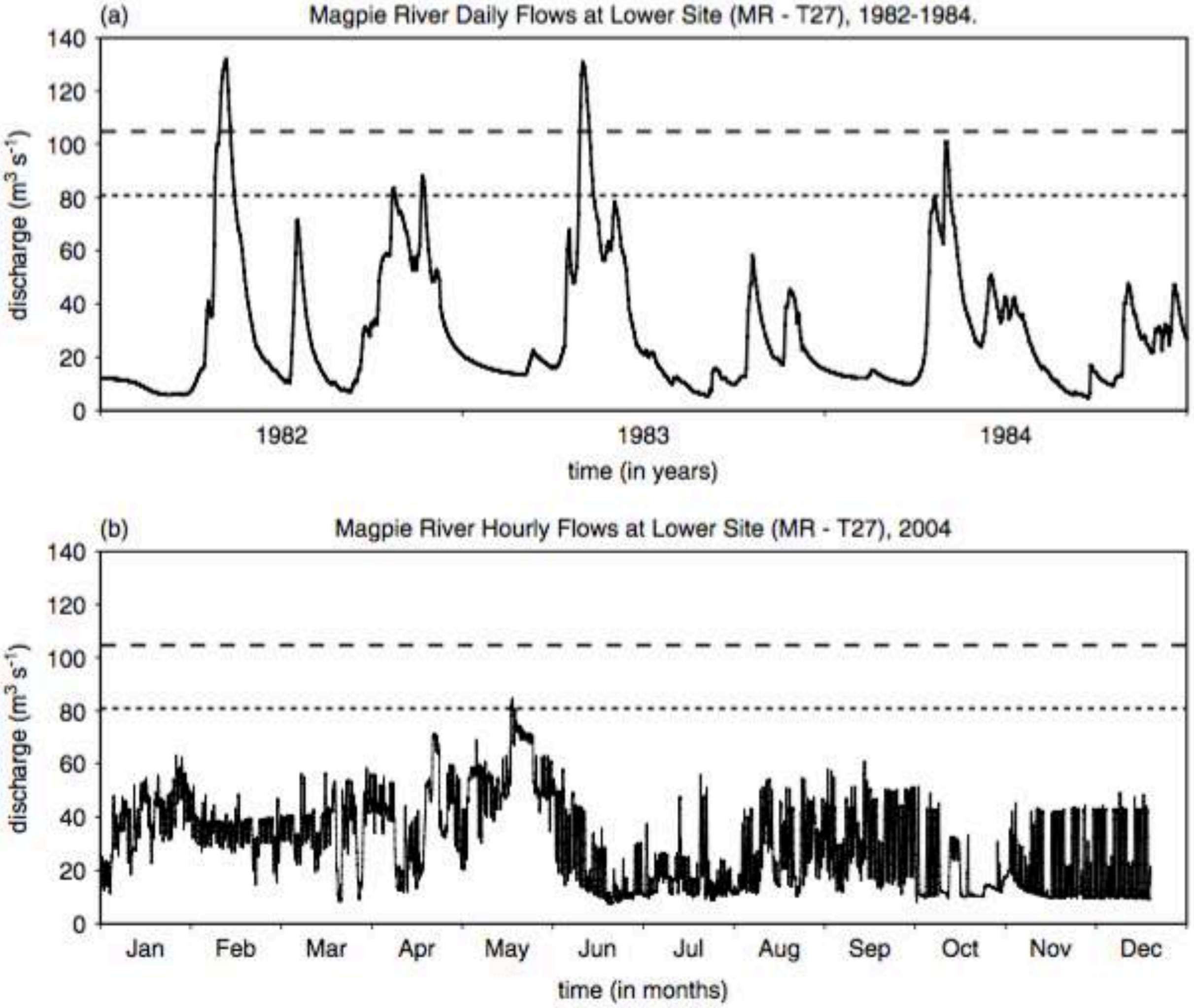

Figure 6. The flows of the Magpie River in Wawa, Ontario, before (a) and after (b) regulation by Steephills Water Power Facility (Smokorowski *et al.,* 2011).

Sediment and Nutrients

Dams and river impoundments alter the abiotic environment by disrupting the flow of sediment and nutrients through the river ecosystem. As water flows in a river system it carries sediment and nutrients such as organic matter, carbon, nitrogen and phosphorus. These organic and inorganic elements can be used as aquatic ecosystem indicators because their chemical composition varies depending on various environmental factors (Nadon *et al.,* 2015). Sediment that is suspended within the water column will eventually accumulate in the riparian zone, at the bottom of a stagnant basin and underneath waterfall features, among other regions of the river (Nadon *et al.,* 2015). These areas of sediment accumulation are naturally occurring and can erode in a similar way to terrestrial erosion (Chen *et al.,* 2011a). When a large storage dam is constructed in the river, it creates a fragmented flow of water and stagnant reservoirs. As the water spends an increased amount of time in the reservoir, the sediment is subjected to the force of gravity, which leads to its accumulation at the bottom of the reservoir (Chen *et al.,* 2011a). This leads to an increase of sediment build up in the upstream reservoir compared to the downstream riverbed. Furthermore, the dams can influence the downstream transport of sediment through the changes to river flow patterns. Sediment that has accumulated on the riverbed can be eroded and transported downstream with the water current, depending on the rate of flow in the river and the sediment transport threshold (Chen *et al.,* 2011a). If the rate of flow is less than the sediment transport threshold, sediment will remain accumulated on the riverbed and will not become suspended in the water column. Sediment dispersal and erosion is an important element of benthic diversity. Disturbances to the riverbed are a critical element of benthic community dynamics and the lack of sediment transport and erosion from the riverbed can lead to a reduction of benthic diversity (Smokorowski *et al.,* 2011). Sediment accumulation and transportation can be influenced both upstream and downstream of dams. This influence can be based on the size and residence time of the reservoir as well as the downstream rate of flow. The further development of large hydroelectric dams in Ontario and the control of flow rates will likely have an effect on the sediment and benthic diversity in the newly regulated rivers.

Through the fragmentation of river flows and attenuation of water level fluctuations, dams can disturb the flow of nutrients through the ecosystem. Dissolved organic matter is an important element of the river ecosystem as it represents the metabolic foundation of much of the food web (Smokorowski *et al.,* 2011). Much of the organic matter that becomes dissolved in a river is from vegetation and other sources on the shorelines (Smokorowski *et al.,* 2011). Water current carries the dissolved organic matter through the river system providing a metabolic source for the base of the ecosystems food web. Dam regulated rivers generally have attenuated flows, which reduces the variability in water levels and the frequency of shoreline flooding periods (Metcalfe *et al.,* 2005). The rapid fluctuations in water level which occur in the natural flow regime of a river are essential for flushing organic matter from the shoreline into the river reach (Smokorowski *et al.,* 2011). In the absence of these river level fluctuations, organic matter builds up on the shorelines and is less accessible as a nutrient source for the river community. In rivers regulated by large storage dams, the shoreline and riparian zone is flooded less frequently. This long term disconnect from the riparian zone reduces the nutrient and organic matter inputs into the river. There are however constant fluctuations in water level of the wetted perimeter, which is expected to increase the flushing of nutrients and organic matter into the river reach (Nadon *et al.,* 2015). A study of 34 rivers in northern Ontario showed that there was a non-significant difference in the distribution of nutrients in a regulated river compared to unregulated rivers (Nadon *et al.,* 2015). The rivers included in the study were in areas of low agricultural activity and had similar watershed characteristics. The results from this study in northern Ontario are consistent with previously published research and suggest that the influence of dams on dissolved organic matter are either negligible or they are short-term and rapidly attenuated downstream (Nadon *et al.,* 2015; Ellis & Jones 2013). While research on effects of river regulation on the longitudinal distribution of dissolved organic matter is limited, and some studies identify a non-significant influence, this could be different in rivers that are more anthropocentrically disturbed (Nadon *et al*., 2015; Ellis & Jones 2013). A different study has shown that a course particulate organic matter gradient exists downstream of dams, which decreases with distance from the dam (Bond, 2015). The distribution of organic matter downstream of large storage dams is likely dependent on a number of factors that are unique to each river and dam.

There are several other nutrients which can be affected as a result of large storage dams in Ontario. Carbon and nitrogen are often studied as indicators in most ecosystems, while phosphorus is an important element in aquatic ecosystems because of its influence on eutrophication. There is often concern related to the inconsistent distribution of nutrients as a result of disrupted river flow (Smokorowski *et al.,* 2011). Large reservoirs are known to affect the carbon cycle by reducing the amount of carbon through respiration, oxidation and photolysis that occurs within the river impoundment (Smokorowski *et al.,* 2011). This however does not necessarily translate to a change in the carbon signature in the upstream and downstream river reaches when compared to unregulated rivers. This suggests that carbon, from detritus and prey, are still entering the river reach. The carbon signatures are variable as a result of the selective consumption and feeding (Smokorowski *et al.,* 2011). The study of 34 northern Ontario rivers by Nadon *et al*., reported a higher concentration of nitrogen and phosphorus in unregulated rivers (2015). This is consistent with other research and could be a result of the smaller rivers, characterized by channel size, having increased nutrient retention (Nadon *et al.,* 2015). The low flow channels are larger in regulated rivers which could reduce the nutrient retention of nitrogen and phosphorus, among other nutrients that are important for river community dynamics.

Downstream effects of hydropeaking

Hydropeaking has become a cost effective strategy for hydroelectric managers to supply electricity to a growing population in Ontario (Ontario Ministry of Energy, 2013). As discussed above, large storage dams have downstream consequences because of flow alterations. Hydropeaking further modifies the flow regime by creating a highly unnatural, flow patterns. Demand for energy in Ontario fluctuates throughout the day and on a seasonal time scale (Ontario Waterpower Association, 2014). Demand is minimal overnight and gradually increases throughout the daytime, and this trend is consistent for the entire year. In the winter however, there are generally two peaks of electricity demand, the first is from 8-11 AM and the second is in the evening at roughly 6 PM. In the summer months, energy demand increases gradually throughout the day and begins to decrease around 4 PM. The trends of electricity demand in Ontario during the summer and winter months and the flexibility of Ontario's hydroelectric dams is shown in Figure 6 (Ontario Waterpower Association, 2014). This demand for electricity could be sustained throughout the day in the summer because of the use of air conditioning systems. There may not be a peak demand in the evening because of prolonged sunlight hours. The demand for electricity is not consistent throughout the day and as a result it is more efficient for hydroelectric dams to regulate their flow and power generation to match the population's demand for electricity.

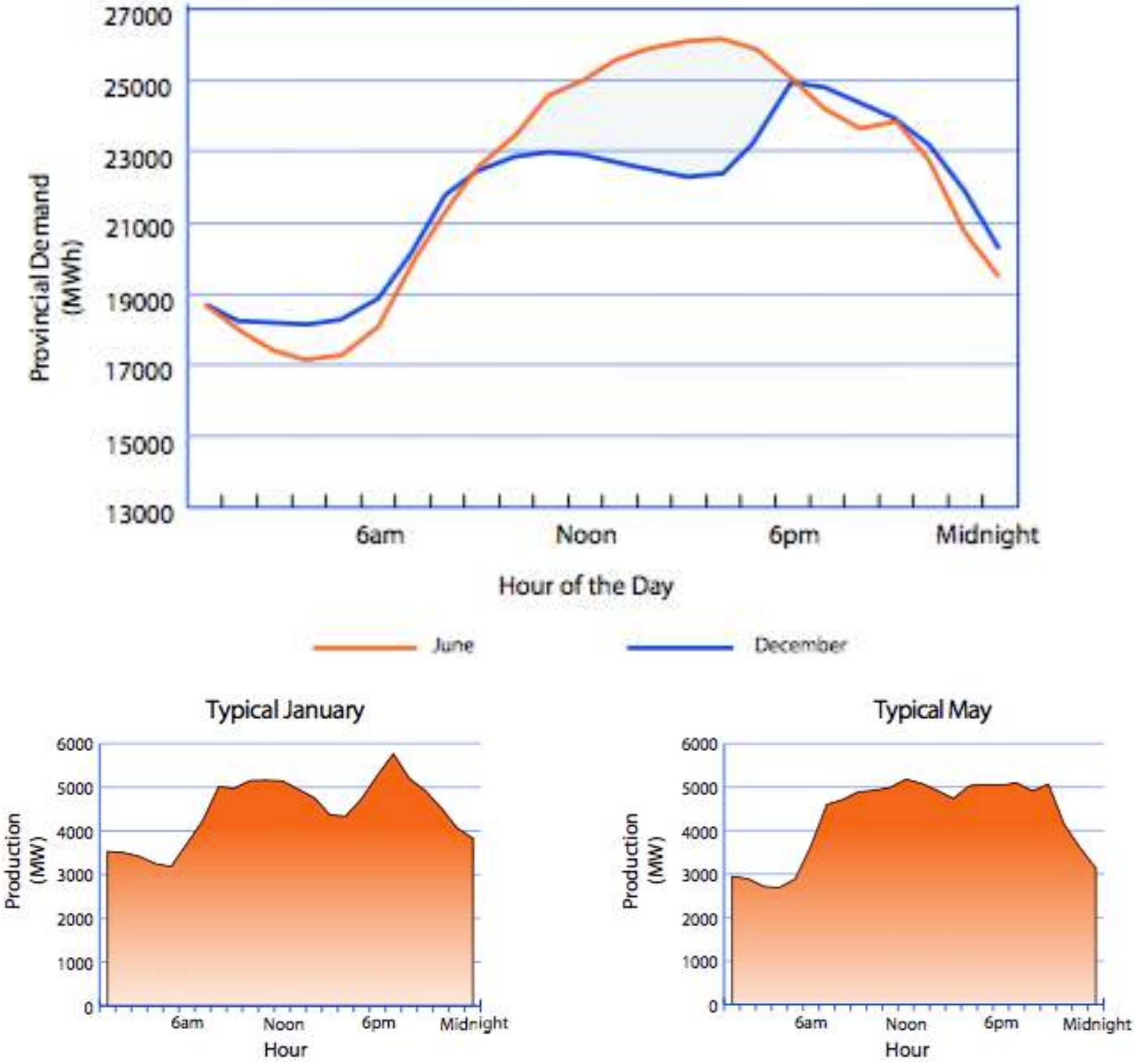

Figure 6. The average demand for electricity during a summer and winter month in Ontario throughout the day (Top). The power generation from hydroelectric dams throughout the day to match the

electricity demand in an average day in January and May (Bottom) (Ontario Waterpower Association, 2014).

The fluctuating flow through the turbines of a hydropeaking dam considerably affects the downstream current and water level, in many of Ontario's rivers. The water level upstream and downstream of a hydropeaking dam on the Magpie River in Ontario can be seen in Figure 7 (Nadon *et al.,* 2015). The upstream variation in water level is negligible, while downstream of the dam there are noticeable fluctuations in water level because of the changing flow through the dam to match energy demand. This unnatural fluctuation constrains riparian zones, fish communities and affects the hyporheic water exchange of the river (Nadon et al., 2015; Chen *et al.,* 2011b).

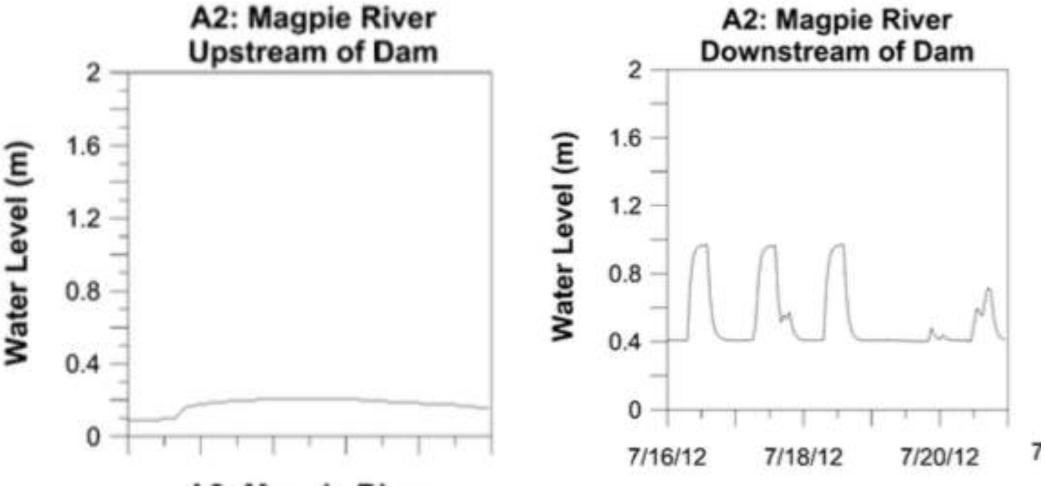

Figure 7. The water level upstream (left) and downstream (right) of the the hydropeaking dam in the Magpie River. The time scale, shown on the downstream and upstream hydrographs is the same (Nadon *et al.,* 2015).

Fish Community

Fish community dynamics upstream and downstream of dams is largely dependent on the nature of the dam and the species within the community (Dauffresne *et al.,* 2015). There are difficulties in attempting to assess fish communities' response to flow regimes because of the need for long-term data, the issues in quantifying fish communities in large rivers and the local and global variables that influence community dynamics (Dauffresne *et al.,* 2015). Despite these difficulties, the effect of dams on fish communities has been well studied and fish diversity is often less in a dam regulated river (Smokorowski *et al.,* 2011; Jackson et al., 2001).

Dams create a physical barrier that prevents the migration of fish, but there are other factors associated with dams that influence fish communities. Phytoplankton provides the metabolic base for many fish communities and therefore if there is a change in plankton biomass as a result of altered river flow, fish communities can be affected (Smokorowski *et al.,* 2011). The reservoir that is developed from the construction of large hydropeaking dams often contains high quantities of plankton which can result in a favourable source of food for fish immediately downstream of the reservoir (Smokorowski *et al.,* 2011). A gradient exists where there is a higher fish density and biomass closer to the dam and this decreases further downstream (Bond & Jones, 2015). The daily fluctuations also create a vertical gradient in water column (Bond & Jones, 2015). The fluctuating water level downstream of hydropeaking dams lead to a decrease in fish density in the varial zones that alternate between being submerged and exposed (Bond & Jones, 2015). The mean fish density in the areas of the river that are consistently submerged is four times greater than the density within the varial zones of the downstream river reaches (Bond & Jones, 2015). Fluctuations in flow and the reduced shallow water habitat because of the low flow periods can threaten fish communities by limiting the suitable habitat for juveniles. This is especially threatening for the juveniles of less dominant fish species that must compete for habitat space (Smokorowski *et al.*, 2011). A study of two rivers in Ontario, the Magpie (altered by hydropeaking dam) and Batchawana (unregulated) rivers, showed a reduction of fish diversity in the altered river (Smokorowski *et al.,* 2011). The reduced habitat availability for juveniles of non-dominant species could be a contributing factor to this reduced diversity, as these non-dominant species could be outcompeted and forced to find habitat elsewhere. There is evidence that the effects of dam construction on fish community dynamics is not persistent and can be reversed with river flow restoration (Dauffresne *et al.,* 2015).

Riparian Zone

The riparian zone is the interface between the aquatic and terrestrial components of a river reach. The riparian zone plays an important role in the river ecosystem as they regulate water quality, provide habitat for some species, they are a source of primary production and can act as a buffer for flooding (Graf, 2006). The ecosystem goods and services that are inextricably linked to riparian zones are closely interconnected with dams. The unnatural river flow and water level created by hydropeaking dams have direct impacts on riparian ecology (Chen *et al.,* 2015). The periods of low flow, during non-peak energy demand periods places an increased amount of stress on the riparian zones (Chen *et al.,* 2015). The vegetation in riparian zones may be adapted to succeed in a habitat with prolonged flooding events, and when hydropeaking dams are in operation, downstream floods are less common (Chen *et al.,* 2015). Furthermore, the frequent low flow periods decrease the water level, reducing water saturation of the riparian zone. This provides an opportunity for the recruitment of new riparian plants (Chen *et al.,* 2015). When riparian zones are used less frequently as flood plains because of hydropeaking river regulation, the productivity and geomorphic complexity of these habitats is reduced (Graf, 2006). The geomorphic complexity is a measurement of functional surfaces within a habitat per unit of distance (Graf, 2006). The added stress created by the flow changes in riparian habitat has been shown to reduce the diversity, survival and reproductive success of riparian flora and fauna (Chen *et al*., 2015). The riparian zone acts as a filter for the river by acting as a trap for sediment and nutrients. When riparian zones are flooded less frequently because of river regulation there may be a reduction in the amount of sediment that is returned to the river (Nadon *et al.,* 2015). The riparian zones are important and productive river habitats as they provide numerous ecosystems goods and services, which are directly affected and will continue to be affected by the increasing use of hydropeaking dams in Ontario to meet power demands.

Hyporheic Water Exchange

The hydrological characteristics of a river are often dependent on the flow of water and the surrounding groundwater. A river is typically in a constant state of gaining or losing water volume, especially within the same season (Yellen & Boutt, 2015). This is a direct result of the groundwater and river flows dynamics in the hyporheic region (Yellen & Boutt, 2015). In the summer months in Ontario, evapotranspiration is high leading to the water table being lower. In these situations, water can be lost from the river to the surrounding groundwater. At peak times of evapotranspiration up to 10% of the water in a river can be lost every 20 km as a result of a river losing water in the hyporheic region (Yellen & Boutt, 2015). Alternatively, in periods of low flow, water can move from the groundwater to the river creating a gaining situation (Yellen & Boutt, 2015). When a hydropeaking dam results in the continuous fluctuation of water level and flows, the river can be losing water when the water table is lower than the river level, and gaining water when river flow is lower than the water table. The seasonal relationship between the river water and the groundwater in the hyporheic region is represented in Figure 8. Depending on the hydropeaking dam operation the alternating between a gaining and losing river situation can occur several times in one day. This not only affects the volume of water within the river but can disturb many important processes, such as elements of the nitrogen, phosphorus and carbon cycles (Yellen & Boutt, 2015). These cycles are mediated and housed within the hyporheic region of the river (Yellen & Boutt, 2015).

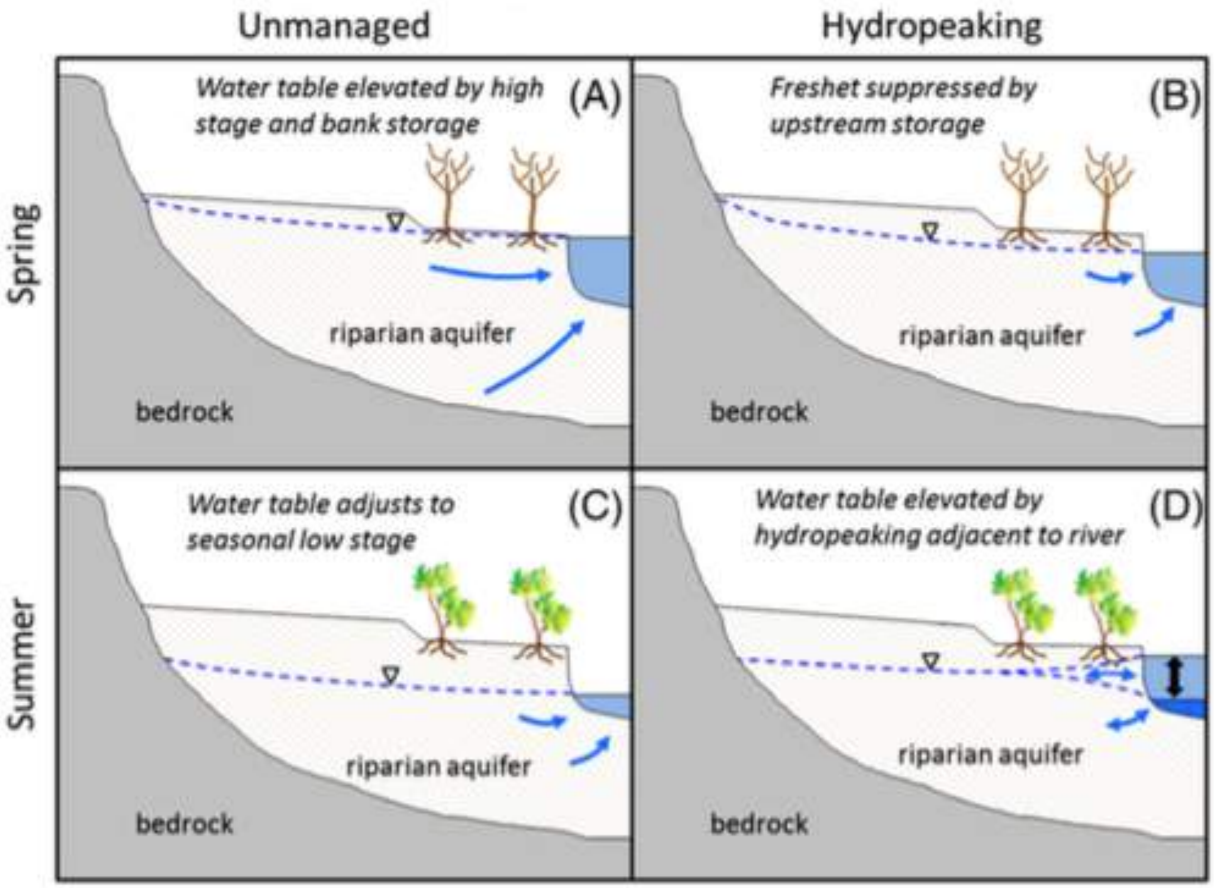

Figure 8. The seasonal hyporheic exchange of a regulated and unregulated river. In the unregulated river (on the left), the water table drops in the summer and low flows result in groundwater flowing into

the river. In the regulated river (on the right), unnatural high flows cause some water to be lost to the groundwater from the river (Yellen & Boutt, 2015).

Mitigation Strategies

The considerable amount of research that has been devoted to the effects of large storage dams and hydroelectric dams on river ecosystems points to several biotic and abiotic consequences. As Ontario shifts away from a carbon intensive energy portfolio, there will be continued consideration for the construction of water power facilities and the regulation of Ontario's rivers. Energy providers and the provincial governments should work towards developing and implementing strategies to reduce the negative effects of dam operations on the river ecosystems. Much of the research on mitigation strategies concern the restoration of natural river flows, the implementation of minimum flows and ramping rate restrictions.

The effects of dam operation on rivers are not isolated and there can be ecosystem wide implications. When assessing the value of mitigation strategies, an Ecological Network Analysis (ENA) should be used to more accurately model the flow of materials through the entire ecosystem (Chen *et al*, 2010; Chen *et al*., 2011b). Risk can be incorporated within the ENA and be treated as a material flow, this allows for the modeling of how risks associated with dams can be transferred within the entire ecosystem. Risks and materials that are accumulated within the ecosystem can be classified into the five levels of the ENA model which can be seen in Figure 9 (Chen *et al.,* 2010). The cumulative effects of dam operation on the river can be visualized and represented using the ENA, which makes it a valuable tool for dam management (Chen *et al*., 2010).

Ontario's provincial government requires that a minimum flow be incorporated into the management plan of every dam. There has been a movement towards increasing the minimum flow requirements in an attempt to reduce the negative environmental effects of dam operation. Minimum flows improve the habitat conditions for invertebrates by increasing the heterogeneity of the habitat (Smokorowski *et al.,* 2011). Many of the negative effects of hydroelectric dam operation can be attributed to the changes made to the flow regime of the river (Smokorowski *et al.,* 2011). For this reason, dam management has begun shifting towards a natural flow state. This management strategy is not based on minimum flows, but tries to mimic the natural variability of the river flow (Smokorowski *et al.,* 2011). The problems relating to ramping rates are specific to hydropeaking dams. The up-ramping periods leading up to peak demand create unnatural changes in rates of flow. Limitations to the ramping rate can reduce the scouring of the riverbed and preserve the physical environment (Smokorowski *et al.,* 2011).

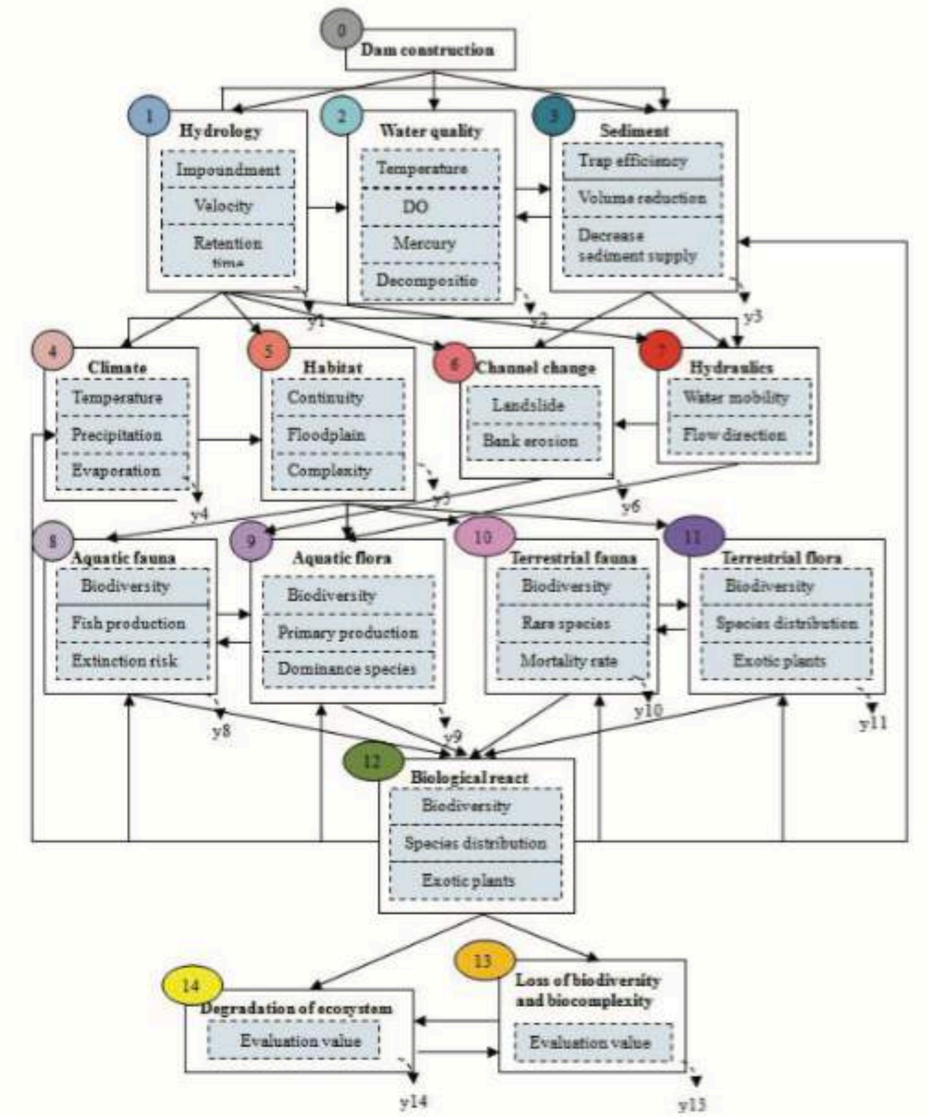

Figure 9. The Ecological Network Analysis framework for dam operation that includes risk flows (Chen *et al*., 2010).

Increasing minimum flow, reducing ramping rates, and restoring natural flow systems have proven to be effective mitigation strategies (Smokorowski *et al.,* 2011; Dauffresne *et al*., 2015).

Constrained dam operations have been used in Ontario and have proven to be successful at mitigating some of the risks associated with hydropower dam operation. The Magpie River's hydrograph is dissimilar to an unregulated river's hydrograph, but several of the biotic factors, including fish biomass, fish condition, invertebrate density and food web length, remained unchanged (Smokorowski *et al.,* 2011). Furthermore, there is evidence that flow restoration can reverse the original negative effects of hydroelectric dam operation on the dynamics of fish communities (Dauffresne *et al.,* 2015). This research on mitigation strategies provides hope that the negative effects of increasing hydroelectric energy capacity on Ontario's river ecosystems can be minimized.

Conclusion and Future Directions

An increasing population and energy intensive economy in Ontario has led to the exploitation of rivers for the generation of hydroelectric power. Hydropeaking has been used in water power facilities to more efficiently meet Ontario's fluctuating energy demand. The regulation of river flows leads to unnatural changes to the thermal and flow regimes. Furthermore, hydropeaking dams affect the nutrient and sediment dispersal, fish community dynamics and riparian zone ecology. The effects of hydroelectric dams and hydropeaking on river ecosystems should not be ignored as research of the negative implications discussed above is convincing. Flow restoration and the Ecological Network Analysis models used as mitigation strategies for the negative effects of dam operation are promising however, there is a need for the development of more precautionary dam management strategies. Further research should be devoted to the effect of differing ramping rates on the downstream river ecosystem because there will be an increasing pressure for the use of aggressive ramping rates to meet energy demands in hydropeaking dams. Research should also focus on the effectiveness of flow restrictions in dam operation as mitigation strategies. The effects of hydropeaking dams on river ecosystems in Ontario will continue to be a topic of controversy because of the province's desire to shift more towards "green" energy. If dam management uses an ecosystems based approach and research is focused on the evaluation of mitigation strategies, there is a possibility of striking a balance between the river ecosystems and Ontario's power demand.

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