Effects of impoundment and drawdown amplitude on fish species and community structure

Raphaelle Thomas

Department of Natural Resource Sciences

McGill University, Montreal

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Abstract

Dams are present worldwide to satisfy diverse human needs. They are widespread in North America and create hydrological modifications, such as winter drawdown to control water levels and generate hydropower. In fact, alteration of hydrological regimes is considered one of the major stressors on aquatic biodiversity. Previous research has demonstrated that fish are affected by the alteration of the littoral zone resulting from winter drawdown. These modifications of the littoral habitat tend to impact their shelter habitat, food resource availability and quality of spawning grounds. Winter drawdown has also been shown to be responsible for differences in fish assemblages and abundance of fish species. However, synthetic multi-lake studies of impoundment and drawdown amplitude effects on fish communities are scarce. We used data from 205 impounded and non-impounded lakes in Québec and the Eastern United States to examine the relationship between impoundment and fish community metrics, fish assemblages, and individual fish species. In addition, we also investigated the effects of drawdown amplitude on the same parameters across a subset of 23 lakes. Redundancy analysis was used to test the effects of impoundment and drawdown amplitude on fish assemblages and generalised linear models were performed to investigate the effects of impoundment and drawdown amplitude on fish community metrics and abundance of individual fish species. We found similar fish assemblage between impounded and non-impounded lakes and failed to demonstrate significant impacts of drawdown amplitude on assemblage structure. Finally, we observed higher species richness in impounded lakes and across the drawdown gradient probably because of the positive correlation between fish species richness and lake surface area.

Key words: Dam, winter drawdown, impoundment, drawdown amplitude, littoral zone, fish assemblages, fish community metrics, fish species richness

Résumé

La modification du régime hydrique, comme dans le cas du marnage hivernal, pour la production d'hydroélectricité ou pour la prévention des inondations causées par les crues printanières sont considérés comme des facteurs de stress majeurs affectant la biodiversité aquatique. Des études antérieures ont démontrés que les effets de mise en eau d'un barrage ainsi que l'amplitude du marnage sont plus fortement ressentis dans la zone littorale des lacs. Les perturbations de la zone littorale auront des conséquences sur les poissons qui utilisent cet habitat pour se réfugier, se nourrir et se reproduire. Il a déjà été démontré que le marnage hivernal affecte les populations et la structure des communautés de poissons. Par contre, les études qui s'intéressent aux effets de mise en eau des barrages et de l'amplitude du marnage incluant plusieurs lacs se font rares. Nous avons utilisé une base de données de 205 lacs québécois et de l'est des États-Unis pourvus ou non de barrages pour examiner la relation entre la mise en eau des barrages et les communautés de poissons ainsi que l'abondance de différentes espèces de poisson. Nous avons aussi testé la relation entre l'amplitude du marnage et ces mêmes paramètres sur 23 lacs dont nous connaissons l'amplitude du marnage. Dans le but d'examiner les effets de la mise en eau des barrages et de l'amplitude du marnage sur la structure des communautés de poissons, nous avons utilisé des analyses de redondance. Ensuite, pour identifier les effets de la mise en eau des barrages et de l'amplitude du marnage sur la diversité, la richesse spécifique, l'uniformité, l'abondance relative des reproducteurs printaniers en zone littorale, la position trophique pondérée et l'abondance de différentes espèces de poissons, nous avons utilisé des modèles linéaires généralisés. Nous avons démontré que la structure des communautés de poissons des lacs avec et sans barrages sont similaires. Par ailleurs, nous n'avons pas décelé d'effets significatifs de l'amplitude du marnage sur la structure des communautés de poissons. Finalement, la richesse spécifique plus élevée dans les lacs pour lesquels il y a présence d'un barrage ainsi que ceux caractérisés par une importante amplitude de marnage sont le résultat de la corrélation positive entre la richesse spécifique de poisson et la surface des lacs.

Mots clées: Barrage, marnage hivernal, mise en eau d'un barrage, amplitude de marnage, zone littorale, structure de communauté de poissons, richesse spécifique,

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Preface and contribution of authors

Chapter 1 is a literature review that I conducted and wrote, with input from my advisor Christopher Solomon as well as from Katrine Turgeon. Chapter 2 is a manuscript that I intend to submit for publication. The contributions of the coauthors of that manuscript are listed below.

Raphaelle Thomas

I took on the lead for the writing of the manuscript as well as this masters thesis. I designed and conducted the fieldwork, and performed the statistical analysis.

Christopher Solomon

Chris provided guidance for the project design, fieldwork logistics, statistical analysis and writing of the manuscript and thesis. He provided critical reviews of the manuscript and thesis throughout the writing process.

Katrine Turgeon

Katrine provided advice on the statistical analysis and provided critical reviews of the manuscript and thesis throughout the writing process

Irene Gregory-Eaves

Rene also provided guidance for the project design and the fieldwork logistics.

Christian Nozais

Christian also provided guidance for the project design and the fieldwork logistics.

Chapter 1: Review of the effects of impoundment and drawdown amplitude on lakes and reservoirs

Dams are present worldwide to satisfy diverse human needs such as irrigation, water supply, navigation, flood control and hydropower, just to name a few. Canada and United States of America together have more than 100 000 dams, including some that are considered as large dams under the ICOD (International commission on large dams) definition (CDA http://www.imis100ca1.ca/cda, US Army Corps of Engineers http://nid.usace.army.mil/). Several of these Canadian and American structures are built to serve two main purposes: creating hydropower and controlling water levels. As a result, most northern reservoirs experience winter drawdown, meaning that they reach their minimum level during winter for hydroelectricity production, and prevention of spring floods. Since reservoirs are considered as one of the principal stressors and a major threat to the biodiversity of freshwater ecosystems (Strayer and Dudgeon 2010, Vörösmarty, McIntyre et al. 2010), we suspected that artificial regulation of water levels might impacts fisheries. We searched the published literature to learn about the known effects of winter drawdown on fish populations and found that several studies demonstrated that changes in fish populations result from the alterations of the littoral zone. The effects on fish are known to depend on the sediment composition, trophic status, macrophyte and food source abundance, composition of resident fish fauna, and available reproductive habitat of dominant species (Jansen 2000). Furthermore, we wanted to determine what were the impacts on fish populations for the different hydrological disturbances resulting from the construction of dams: water level manipulations and impoundment. Drawdown amplitude refers to the vertical changes in the water column as a result of flow manipulations, which are often repeated on an annual cycle. On the other hand, impoundment simply refers to the presence of a dam and often results in the flooding of terrestrial habitats upstream when the dam is erected. Even more, impoundment leads to the modification of the natural schedule of water level fluctuation. Under natural circumstances, lakes fluctuate to reach the maximum water level in spring, and minimum at the end of the summer (Zohary and Ostrovsky 2011). In contrast, the water level of many northern impounded lakes fluctuates and reaches a maximum from spring to summer and a minimum in winter. In addition, impounded lakes experience a lower peak in water level during spring than they would under natural circumstances. Because drawdown amplitude and impoundment modify hydrological regimes in different ways, we suspected that their impacts on fish populations could also be different. The goal of this literature review is to understand how drawdown amplitude and impoundment affect littoral zones of regulated lakes and so the fish populations that depend on it. We also aim to identify the potential impacts of impoundment and drawdown amplitude on fish assemblage structure of regulated lakes.

Impacts of winter drawdown on the littoral zone

Desiccation of the littoral zone caused by winter drawdown can potentially impacts macrophyte, macroinvertebrate as well as fish spawning habitat and may lead to particularly strong repercussions on fish and fisheries. Drawdown causes desiccation of the littoral zone as it is exposed when water levels decrease. The littoral zone is generally defined as the belt of shallow water around the shoreline of a lake to a maximum depth at which light can still reach the bottom sediments (Zohary and Ostrovsky 2011). Many fish species occupy the littoral zone for part of their life cycle, if not permanently, and so do macrophytes and macroinvertebrates, making the littoral zone an essential habitat that supports most of the diversity in a lake (Wetzel

2001). Fish may visit these shallow waters daily or seasonally to feed, hide from predators, and breed (Gafny, Gasith et al. 1992, Winfield 2004, Sutela, Aroviita et al. 2013). For instance, several studies demonstrated that drawdown led to modification of important littoral macroinvertebrates populations included in fish diets (Aroviita and Hämäläinen 2008), reduction of fish shelter availability due to decreasing abundance of littoral macrophytes (Hellsten 2000), and alteration of spawning grounds (Person, Bieri et al. 2013). Therefore, we suspect that winter drawdown affects fish population using the littoral zone extensively. Even more, some studies also found that the lost of shelter resulting from the modification of macrophyte populations tend to increase predation pressure on forage fish species inhabiting the littoral zone. However, piscivorous fish species only tend to benefit from the vulnerabitlity of their preys the first years of water drawdown, until the fish species they prey upon start to decline (Ploskey 1986). Although piscivorous species foraging in the littoral zone may benefit from artificial water fluctuation, their spawning habitat (if located in the littoral zone) could still be impaired by it. In all cases, alteration of the littoral zone has the potential to indirectly impact fish population dynamics through the availability of habitat and food resources (Yurk and Ney 1989).

Impacts of winter drawdown on substrates

Altered fluctuation of the water level can result in the modification of the substrate in the drawdown zone and increase the area of the frozen zone in the winter, potentially damaging fish spawing habitat. Wave action, in interaction with water level fluctuation, can act to transport small particles to deeper water, resulting in exposed larger substrates, such as boulders, and the accumulation of small particles (sand, clay and silt) at lower levels (Hofmann, Lorke et al. 2008, Evtimova and Donohue 2016). Since substrate composition plays a role in the quality of fish spawning habitat and is important to littoral vegetation for nutrient storage and diffusion (Wagner and Falter 2002), we conclude that alteration of the substrate in the drawdown zone could impact fish populations. Even more, increases or decreases in water level fluctuation and siltation rate potentially interfere with spawning and egg incubation (Winfield 2004). So not only spawning habitat can potentially be altered by the magnitude of drawdown but also reproduction success. In addition to the alteration of substrates, large variation in water levels can lead to increased areas of ice penetration and frozen zones (Hellsten 2000). Similarly, this leads to aquatic vegetation decline, reduced fish spawning habitat quality, and increased probability of fish egg mortality. These alterations of the littoral zone lead to poor habitat for macrophytes and fish spawning, both important to fish populations.

Impacts of winter drawdown on macrophytes

Larger and smaller drawdown than would be expected in nature tends to reduce diversity of macrophytes, an important component of the habitat for fish assemblages and the aquatic insects they feed upon. In deep stratified lakes, macrophytes are restricted to the shallow littoral zones. Abundance of macrophytes is determined by the length of the growing season, which is in turn determined by the initial water level and its rate of decline (Gafny and Gasith 1999). In other words, the length of the growing season depends on the depth of the water column, which is in itself controlled by the water level fluctuation. Knowing that northern impounded lakes are characterised by their lower peak in water level during spring and their relatively stable water level from late spring to summer, it is not surprising to observe disturbance in the macrophyte growing season of regulated lakes. Water drawdown, as well as altered timing of minimum and maximum water levels, leads to loss of macrophyte species and abundance as their physical capabilities are surpassed. For instance, lakes with high water level fluctuation were observed to have significantly reduced macrophyte coverage in littoral zones (Evtimova and Donohue 2016). Even more, reservoirs influenced by regular, large water level fluctuations have even been known to be completely devoid of littoral macrophytes (Smith, Maitland et al. 1987). Aquatic vegetation provides habitats with different food, cover, and structure for aquatic biota. Fish use macrophytes and woody debris as shelter from predators, spawning grounds, fry habitat, and feeding areas (Hellsten 2000, Santos, Agostinho et al. 2011). Not only fish requires macrophyte but also invertebrates, an important resource in fish diet. Invertebrates use macrophytes when seeking refuge from predation, as oviposition sites and as food supply (Wolcox and Meeker 1992). Therefore, by modifying macrophyte populations, winter drawdown indirectly affects fish species relying on these macrophytes as well as macroinvertebrates, a principal source of food for several fish species.

Impacts of winter drawdown on zooplankton

Impacts of artificial hydrological regimes on zooplankton assemblages are inconsistent between regulated lakes, making it hard to predict the possible repercussions on planktivorous fish. When artificial winter drawdown alters zooplankton community structure, it results from either zooplankton species sensitivity to water level fluctuations, or trophic cascades. Some studies have demonstrated that zooplankton communities can be significantly different in regulated water bodies (Jarvis, Hart et al. 1987, Ortega-Mayagoitia, Armengol et al. 2000), while others did not detect any significant effects (Crome and Carpenter 1988, Turner, Huebert et al. 2005). Different zooplankton groups have been observed to show different sensitivities to water level fluctuations and were distinctly affected by floods (Ortega-Mayagoitia, Armengol et al.

2000). Despite drastic water level fluctuations, zooplankton assemblages can demonstrate a basic annual cycling that can reestablish after drying and refilling (Crome and Carpenter 1988). However, zooplankton population could also be indirectly affected by water level regulation. Modification in zooplankton populations could result from altered phytoplankton, macrophyte, and fish populations, which are potential outcomes of winter drawdown. In other words, the hydrology of reservoirs can interact with the trophic processes in at least two different ways: via bottom-up processes, influencing phytoplankton dynamics on which zooplankton feeds; and via top-down processes, regulating zooplankton populations by the predation efficiency of planktivorous fish (Naselli-Flores and Barone 1997). We suspect that a low zooplankton population could be disseminated by predation of planktivourous fish, leading in a decrease of the planktivourous fish population itself but to our knowledge, no studies have observed this scenario in regulated lakes. The discrepancy in the results of the studies investigating the impacts of artificial drawdown on zooplankton populations makes it difficult to predict the indirect repercussions of altered water levels on planktivorous fish populations.

Impacts of winter drawdown on macroinvertebrates

The impoverishment of littoral macroinvertebrate community and the dominance of smaller sizes and lower energy content invertebrates species present in regulated lakes may lead to an increase foraging activity of fish species feeding on aquatic insects. Composition of littoral macroinvertebrate assemblages is strongly associated with drawdown amplitude (Jansen 2000, Baumgärtner, Mörtl et al. 2008) as taxon richness decreases with increasing amplitude of drawdown (White, Xenopoulos et al. 2008, Evtimova and Donohue 2016). Freezing and flushing of sediment in late winter seems to be the main factor causing impoverished littoral macroinvertebrate faunas (Aroviita and Hämäläinen 2008). Unfortunately for fish, aquatic insects with long life-cycles (for example: Ephemeroptera, Odonata), which are usually of bigger size and highly caloric (Cummins and Wuycheck 1971) tend to be more vulnerable to winter drawdown (Kaster and Jacobi 1978). They possibly cannot escape the disturbance events in time, and if they do, they have to experience them repeatedly in their lifetime (Aroviita and Hämäläinen 2008, Sutela, Aroviita et al. 2013). As a result, fish from regulated lakes are left with a higher ratio of macroinvertebrate species characterised by a short life cycles (for example: some chironomids), which also tend to be of smaller size and low in energy content (Kaster and Jacobi 1978). For that reason, we suspect that fish feeding on depleted macroinvertebrates communities resulting from winter drawdown may have to increase foraging activity to achieve their required energy needs.

Impacts of winter drawdown on fish reproductive success

Because of the altered timing of artificial drawdown, early spring and fall spawners might be confronted with inaccessible spawning grounds or desiccated eggs that will freeze and die (Gafny, Gasith et al. 1992). In early spring, if water levels are not high enough in time for spawning, mature fish cannot reach their spawning grounds. As an example, Gaboury (1984), showed that pike (*Esox lucius*) and walleye (*Sander vitreus*) were not able to access spawning areas when water levels were too low. Consequently, the fish recruitment of these years was almost null. Similarly, fall spawners risk to not be able to reach their spawning sites if water level started to decrease before spawning period. Moreover, if fish do reach their spawning sites but water levels starts decreasing after spawning, fertilised eggs might not be covered with water anymore and fertilised eggs are susceptible to dry and die (Sutela, Mutenia et al. 2002, Cott, Sibley et al. 2008, Sutela, Aroviita et al. 2013). For instance, intense overwinter drawdown had been seen to reduced the reproductive success of lake whitefish (*Coregonus clupeaformis*) and cisco (*Coregonus artedi*), both fall spawners species, due to egg desiccation and dewatering of spawning grounds (Gaboury 1984). Thus, the access to spawning sites and survival of the fertilised eggs depend on the amplitude and timing of water drawdown. If several fish of the same species fail to reproduce in the same year, we expect the fish recruitment to be low for this particular year. As a result, yearly variation in fish recruitment could lead to fluctuation in year-class abundance of that same fish species. In a scenario where several year-class abundance of a fish species are low, we suspect that the abundance of that fish population would also decrease. To sum up, artificial regulation of water levels can reduce spawning opportunities for spring and fall spawners, increase year-class fluctuations in major fish species, reduce abundance of fish and increase mortality of fish eggs and fry (Jansen 2000).

Impacts of winter drawdown on littoral piscivorous fish species

By altering the abundance and diversity of macrophytes, winter drawdown has the potential to favor growth and abundance of littoral piscivorous fish because their prey lose shelter habitat and can not hide properly from them. Previous studies demonstrated that drawdown amplitude concentrates and exposes forage fish species, which become more vulnerable to predation and lead to an increase in predator foraging (LeRoy Heman, Campbell et al. 1969, Noble 1981, Ploskey 1986). However, littoral predators might only benefit from drawdown until the fish species they prey upon start to decline (Ploskey 1986). One study even demonstrated growth disparity in a fish predator, largemouth bass, due to the lack of their prey species (Shelton, Davies et al. 1979). Similar scenario would be likely to occur in impounded lakes: piscivorous fish species abundance may expand with the increase availability of prey fish, until the prey fish abundance starts to decline and not be sufficient to feed the expanded population of piscivorous fish. As a result, growth disparity could be observed in littoral fish predators. To conclude, predators fish species might benefit from artificial drawdown, but this advantage is likely to only be ephemeral.

Impacts of impoundment on fish richness, diversity and assemblages

Modification of fish habitat, predation pressure, food resource availability and reproduction success resulting from artificial drawdown could lead to alterations of fish assemblages and decrease in fish richness and diversity. Studies investing the impacts of winter drawdown on fish communities tend to be divided into two categories. They either focus on the effects of impoundment on riverine fish assemblage or on the effects of drawdown amplitude on littoral fish assemblage. It becomes difficult to compare the results between these two categories because they investigate the effects of different variable on different fish ecosystem. Researches on riverine fish assemblages demonstrated that impoundment induces important changes in assemblage structure, but most of these modifications occur in the first years following impoundment (Patriarche and Campbell 1958, Quinn and Kwak 2003, Turgeon, Solomon et al. in review). Nonetheless, fish assemblage structure keep changing over time (Gido, Matthews et al. 2000, Quinn and Kwak 2003). These changes in fish community caused by the impoundment of a river can lead to decreased diversity and species richness (Quinn and Kwak 2003). Interestingly, all of these studies investigating the impacts of impoundment on riverine fish assemblage were conducted over time, before and after the impoundment of only one river (Patriarche and Campbell 1958, Gido, Matthews et al. 2000, Quinn and Kwak 2003). On the other hand, Sutela (2008) tested the effects of drawdown amplitude on the littoral fish community of regulated and non-regulated lakes. His results suggest that water-level regulation alters fish community structure. However, species richness of littoral lacustrine assemblages stayed unchanged across lakes characterised by different drawdown amplitude (Sutela 2008). Even though the two categories of studies are not necessarily comparable, they suggest that impoundment and drawdown amplitude can potentially impacts fish community structure.

Drawdown and fisheries management

Due to its success rates, artificial water level fluctuations have been part of fisheries management plans to either reduce undesirable fish species or to increase the abundance and growth of predators. Fisheries managers used summer drawdown to control unwanted fish species, such as common carp (Shields 1958). By reducing water levels, unwanted fish species became more exposed, thus more susceptible to predation. Therefore, this technique was only efficient for fish preyed-upon by littoral predators. Still, success rates as high as 45 percent was recorded (Meronek, Bouchard et al. 1996). Summer drawdown and its negative effects on forage fish species was also used to control predators of interest, like largemouth bass. By reducing the water levels, drawdown increased the exposition of prey fish and their nests (for nesting species), making these species more vulnerable to predation. It resulted in a reduction in the density of fry and intermediate forage fish size due to increased predation pressure. On the other hand, predators increased in abundance and average size (LeRoy Heman, Campbell et al. 1969). In summation, fisheries management plans used water level fluctuations to expose forage fish and increase predation risk either to reduce the prey fish abundance or to increase predator abundance and growth.

Conclusion

Available literature demonstrated that fish communities are indirectly affected by artificial water level fluctuation through impacts on the littoral zone. Alteration of spawning habitat, reproductive success, food resource and shelter habitat were demonstrated to occur in regulated lakes. Repercussions from these modifications could lead to alteration in fish assemblages. These variations in fish community structure can be driven by both impoundment and drawdown amplitude. Studies testing the effects of impoundment tend to focus on the riverine fish assemblage of only one reservoir through time. On the other hand, most researches focusing on the impacts of drawdown amplitude compared littoral fish assemblage between regulated and non-regulated lakes and across drawdown gradient. However, to our knowledge no studies involve a large set of lakes that test the effects of impoundment and drawdown amplitude on lacustrine fish communities. There is a need for future studies considering the impacts of winter drawdown on the whole fish communities of lakes. We need to acquire a better knowledge of the impacts of impoundment and drawdown amplitude on fish assemblages to properly manage fish populations in the increasing number of reservoirs globally.

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Chapter 2: The effects of impoundment and drawdown amplitude on fish community structure and assemblage

Thomas R., C. Solomon, K. Turgeon , I. Gregory-Eaves and C. Nozais

Abstract

Dams are present worldwide to satisfy diverse human needs. They are widespread in North America and create hydrological modifications, such as winter drawdown to control water levels and generate hydropower. Alteration of the hydrological regime is considered as one of the major stressors on aquatic biodiversity. Previous research has demonstrated important effects of impoundment and drawdown amplitude on littoral zones of lakes, which, in turn, may impact fish communities by altering refuge, habitat, prey resources, and spawning grounds. However, synthetic multi-lake studies quantifying the effects associated with impoundment and drawdown amplitude effects on fish communities are rare. We used data from 205 impounded and non-impounded lakes in Québec and the Eastern United States to assess relationships between impoundment and fish community (i.e. diversity and community composition) or population metrics. We also investigated the effects of drawdown amplitude on the same parameters across a subset of 23 lakes. We used redundancy analysis to quantify the effects of impoundment or drawdown amplitude on fish assemblages whereas we used generalized linear models for our univariate response variables. We found that impoundment significantly explained 0.6% of the variation in fish assemblage but drawdown amplitude was not a significant variable. Finally, we observed there was higher species richness in impounded lakes compared to non-impounded ones and across a drawdown gradient, likely due to the positive correlation between fish species richness and lake surface area.

Key words: Dam, reservoir, water level fluctuation

Introduction

Dams are used internationally to satisfy diverse purposes such as irrigation, water supply, navigation, flood prevention and production of hydropower to only name a few. More than 100 000 dams are present in Canada and United States of America, including some large dams according to ICOLD (International commission on large dams) definition (CDA http://www.imis100ca1.ca/cda, US Army Corps of Engineers http://nid.usace.army.mil/). Many of these boreal and temperature structures are built to serve two main purposes: creating hydropower and controlling water levels. Presence of dams results in the alteration of the hydrological regime of regulated lakes and reservoirs, which is considered a principal stressor and a major threat to the biodiversity of freshwater ecosystems (Strayer and Dudgeon 2010, Vörösmarty, McIntyre et al. 2010). Most northern reservoirs experience winter drawdown, meaning the lake water level is at a minimum during winter for hydroelectricity production and prevention of spring flooding. Variation in the schedule of water fluctuation as well as the amplitude of the drawdown can occur. The potential impacts of winter drawdown are broad and may have particularly strong repercussions on the littoral zone of stratified lakes (Wetzel 2001). Changes in sediment composition, abundance and diversity of macrophytes and macroinvertebrates have already been observed in the littoral zone of boreal and temperate regulated lakes (Sutela, Vehanen et al. 2011). These effects have particularly strong repercussions on fish and fisheries through the reduction of shelter due to changes in littoral macrophytes (Hellsten 2000), effects on littoral macroinvertebrates populations that are an important source of food for fish (Aroviita and Hämäläinen 2008) and the alteration of spawning ground (Person, Bieri et al. 2013).

With the construction of dams, there can be more than one form of hydrological disturbance that occurs upstream: impoundment and water level manipulations. Impoundment simply refers to the presence of a dam and often results in the flooding of terrestrial habitats upstream when the dam is erected. The drawdown amplitude refers to the vertical changes in the water column as a result of flow manipulations, which are often repeated on an annual cycle. Under natural circumstances, lake levels are at a maximum in spring and a minimum at the end of summer (Zohary and Ostrovsky 2011). In contrast, the water level of many northern impounded lakes fluctuates and reaches a maximum from spring to summer and a minimum in winter. In fall and winter, water levels of most boreal and temperate reservoirs are lower than non-impounded lakes. In spring, impounded lakes also experience a lower peak in water level than they would under natural circumstances. Given that these hydrological manipulations are fairly widespread in northern impounded lakes, it is important to determine what are the potential effects on fish populations and assemblage, so that the management of these systems is grounded in science.

Impoundment and drawdown amplitude may have significant repercussions on fish populations and assemblages, particularly for taxa relying on the littoral zone for spawning and feeding. As mentioned previously, alteration in the schedule of water fluctuation and amplitude of drawdown can potentially impacts the littoral zone. For instance, spring and fall fish spawners that reproduce in the shallow water of the littoral zone might not be able to reach their spawning ground if water levels are not high enough in time for spawning (Gaboury 1984, Gafny, Gasith et al. 1992). Furthermore, fertilised eggs deposited in fall risk desiccation if water levels decrease after spawning (Sutela, Mutenia et al. 2002, Cott, Sibley et al. 2008, Sutela, Aroviita et al. 2013). Previous studies have also demonstrated that littoral predators benefit temporarily from impoundment and drawdown amplitude due to increased exploitation of their prey, until the prey populations are overexploited and littoral predators begin to decline (LeRoy Heman, Campbell et al. 1969, Noble 1981, Ploskey 1986). Overall, the indirect effects of winter drawdown on littoral fish populations are well understood and documented.

Previous studies suggest that impoundment and drawdown amplitude potentially modify fish community and assemblage but they either focus on the effects of impoundment on riverine fish assemblage or on the effects of drawdown amplitude on littoral fish assemblage. It becomes difficult to compare the results between these two types of studies because they investigate the effects of different variable on different fish ecosystem. Researches on riverine fish assemblages demonstrated that impoundment induces important changes in assemblage structure, but most of these modifications occur in the first years following impoundment (Patriarche and Campbell 1958, Quinn and Kwak 2003, Turgeon, Solomon et al. in review). These early changes are due to the increase availability of space and food resources derived from the flooded land (Patriarche and Campbell 1958, Gido, Matthews et al. 2000, Quinn and Kwak 2003). Nonetheless, fish assemblage structure keep changing over time (Gido, Matthews et al. 2000, Quinn and Kwak 2003). These alterations in fish community caused by the impoundment of a river can lead to significant variation in fish assemblage as well as decreased diversity and species richness (Quinn and Kwak 2003). Interestingly, all of these studies investigating the impacts of impoundment on riverine fish assemblage were conducted over time, before and after the impoundment of only one river (Patriarche and Campbell 1958, Gido, Matthews et al. 2000, Quinn and Kwak 2003). On the other hand, studies investigating the effects of drawdown amplitude on fish communities tend to focus on littoral fish communities of shallow lakes within a region, except for Sutela's (2013) research that investigated the impacts of water level fluctuation on thirty regulated and non-regulated stratified lakes on central Finland. His results suggest that water-level regulation alters fish community structure. However, species richness of littoral lacustrine assemblages stayed unchanged across lakes characterised by different drawdown amplitude (Sutela 2008). In conclusion, previous work on the impacts of drawdown amplitude showed variation in the littoral fish assemblage of stratified regulated lakes. Similarly, researches looking at the effects of impoundment on riverine fish communities also demonstrated modification in fish assemblage. To our knowledge, no studies have investigated the impacts of impoundment and drawdown amplitude on the whole fish communities and the same fish ecosystem.

Our research project is a large scale study comparing the impacts of impoundment and drawdown amplitude on lacustrine fish communities and populations between regulated and non-regulated lakes and across drawdown gradient. Previous studies already demonstrated that impoundment lead to alteration in fish assemblages structure (Patriarche and Campbell 1958, Gido, Matthews et al. 2000) as well as reduction of fish diversity and richness (Quinn and Kwak 2003). On the other hand, drawdown amplitude was only shown to cause variation in fish assemblage structure (Sutela 2008). However, the small amount of literature interested by the impacts of drawdown amplitude on fish assemblage let us believe that more support is needed to rely on this finding. We suspect that modifications of the littoral zone resulting from drawdown amplitude and impoundment could lead to variation in fish assemblages. In other words, reduced reproductive success of littoral spawnering species as well as alteration of littoral food resource availability could have repercussions on the whole fish communities of regulated lakes. Only piscivorous species foraging in the littoral zone were shown to benefit from artificial water fluctuations due to their increased predation efficiency (LeRoy Heman, Campbell et al. 1969, Noble 1981, Ploskey 1986), until the species they prey upon start to decline (Ploskey 1986). We hypothesised that impoundment and drawdown amplitude are responsible for variation in fish assemblage structure, decrease in fish diversity and richness as well as reduction in the abundance of littoral spring spawnering species. We also expect to detect a raised in the abundance of predators. To test our hypotheses, we conducted analyses of fish community (composition and diversity) and populations metrics from 206 non-impounded and impounded lakes, as well as a subset of 23 impounded lakes that were exposed to various drawdown amplitudes. We sought to demonstrate the impacts of impoundment and drawdown amplitude on fish assemblage structure using constrained ordination. We also determined the effects of impoundment and drawdown amplitude on fish species richness, diversity, evenness, abundance of spring spawning littoral fish, weighted trophic position, and abundance of individual fish species using generalized linear models.

Methods

Data sources

To investigate the impacts of impoundment and drawdown amplitude on fish assemblage and individual species abundance, we used a database from three sources (Appendix 3). The first dataset consisted of a field survey performed by R.T. in 2013 in five lakes located in Southern Québec (Appendix 1 and 2). We selected the other datasets based on the compatibility with the fishing gear and technique of this first dataset. Only two datasets that fit our requirements were available: a large scale survey of 167 lakes performed by the Environmental monitoring and assessment program (EMAP; data accessed on November 2014) and environmental monitoring survey reports from Hydro-Québec. All lakes comprised in these three datasets are temperate or boreal and vary in size. Dams regulating reservoirs also vary in type and size.

Southern Québec field survey dataset

Five lakes were sampled that differed in drawdown amplitudes but were similar in their surface area, shore index, maximum depth, and latitude (Appendix 1). In each lake, five to nine littoral and one pelagic sampling sites were randomly selected. Each sampling site was sampled once during July and August 2013 with a gill net of various mesh sizes (Appendix 4). Gill nets were deployed overnight (between 12-16 hours), they were set before twilight and collected at dawn. At each site, four to seven nets were set perpendicular to shore with the smallest mesh near shore. One net was set on the bottom of the pelagic area of every lake. Every fish caught was identified to the species level.

EMAP dataset

The public EMAP dataset is a large dataset of lakes within the United States that were sampled to monitor and assess the status and trends of national ecological resources. We selected the Northeast lakes 1991-1994 dataset because fish assemblage data was available. The 167 lakes included in this study were located in the states of Maine, New Hampshire, New York, Vermont, Connecticut and Massachusetts (US Environmental Protection Agency https://archive.epa.gov/emap/archive-emap/web/html/nelakes.html). To compare data to those sampled by R.T. (2013) in Southern Québec, we only used the fish data collected with gillnets. The number of gillnets deployed depended on the size of the lake. For lakes smaller than 29 ha, they used only one gillnet was used in the pelagic area. When lakes were bigger than 29 ha, nets were deployed in the littoral and pelagic areas. Gillnets were set in the early evening (two to three hours before sunset) and retrieved the following morning (Appendix 4).

Hydro-Quebec dataset

We extracted thirty-three natural lakes and reservoirs from the Hydro-Quebec dataset (Gendron 1990, Faucher and Gilbert 1992, Doyon and Belzile 1998, Lacasse 1999), based on their fish sampling methods and gear used. We selected lakes and reservoirs for which the sampling was similar to the Québec field survey conducted by R.T. (2013). Gillnets were set overnight, between 16 to 24 hours (depending on the study). The sampling technique and size of the nets differed slightly between surveys (Appendix 4).

Databases

From the combined database, we ran one set of analyses to determine the impacts of impoundment (comparing impounded and non-impounded ecosystems) and one set of analyses to determine the impacts of drawdown amplitude on community and population metrics. The first database consisted of fish relative abundance in impounded (N=99) and non-impounded aquatic ecosystems (N=106; total N =205). The second database consisted of presence-absence data in impounded (N=99) and non-impounded aquatic ecosystems (N=106; total N =205). The third database examined fish relative abundance in relation to drawdown amplitude (N=23) and the fourth database consisted of presence-absence data in relation to drawdown amplitude (N=23). Because our databases had many zero inflated values, we used the Delta method to determine the potential impacts of impoundment and drawdown amplitude on individual fish species. The Delta method is one of the most common methods used in fisheries (Carlson, Hale et al. 2012) and consists of modelling the effects of predictors on presence-absence data (0 and 1) and on relative abundance using occurences only. This method was only used to investigate the effects of impoundment and drawdown amplitude on individual fish species but not for community metrics and fish assemblages.

Impoundment database

In this database, when a dam was present directly on a water body or on one of its adjacent tributaries or rivers, it was classified as impounded. The presence of dams on a given lake was determined based on dam coordinates from reports and from public governmental lists (Engineers. http://nid.usace.army.mil/cm_apex/f?p=838:12, MDDEFP http://www.cehq.gouv.qc.ca/suivihydro/graphique.asp?NoStation=030201, Gendron 1990, Faucher and Gilbert 1992, Doyon and Belzile 1998, Lacasse 1999). A total of 71 fish species were included in this database (Table 1). However, to reduce noise in the analysis on fish assemblages (RDA), we only included fish species that were present in at least five percent of the lakes (i.e. a total of 29 fish species; see Table 2). Five environmental variables were used to predict community metrics, fish assemblage and species presence-absence and relative abundance. These variables included three continuous variables: surface area (ha), latitude and longitude as well as two discrete variables: impoundment (impounded or not) and six fish basin ecoregions (FEOW http://www.feow.org/globalmap).

Drawdown amplitude database

This database included 23 lakes for which we had information about the maximum annual drawdown amplitude (Figure 1B). A total of 38 fish species were included in this database (Table 1), but we used the same dominant fish species list as developed from the impoundment database to allow us to compare the two analyses (Table 2; RDA). Five environmental variables were used to predict fish diversity metrics, fish assemblage, and species presence/absence or relative abundance. These variables consisted of four continuous variables: surface area (ha), latitude, longitude, and drawdown amplitude (m) and one discrete variable, fish basin ecoregions (Appendix 3).

Calculation of the fish community metrics

We used five different fish community metrics: species richness, the Shannon Wiener index, evenness, the relative abundance of spring spawning littoral fish and the weighted trophic position. To calculate these metrics, we used all fish species from the databases, not just the dominant (i.e. there was a total of 71 species in the impoundment database and 38 fish species in the drawdown amplitude database (Table 1)). We calculated species total richness which is defined as the total number of species present per lake (Krebs 1999) and the Shannon Wiener index (diversity) following this equation: -SUM[(pi) * ln(pi)], where pi represents the relative abundance of species i divided by the total relative abundance of the lake (sum of the relative abundance of all fish species=100; (Krebs 1999)). Evenness was calculated as (diversity/ln(richness); (Krebs 1999)). The fish species that were identified as spawning in littoral zones in the spring are summarized in Table 3. Finally, the weighted trophic position was calculated by summing the product of the trophic level position (FishBase http://www.fishbase.ca/) of each fish species with its relative abundance in a given lake.

Data analysis

For our univariate response indicators, we used Generalized linear models to quantify the relationships with environmental predictors. Generalized linear models were also used to evaluate the impacts of impoundment and drawdown amplitude on a limited set of fish species. To examine the effects of impoundment and drawdown amplitude on fish assemblage, we used constrained ordinations (redundancy analysis; RDA).

Generalized linear model (GLM)

GLM estimates parameters using maximum likelihood (McCullagh and Nelder 1989). We used a normal Gaussian distribution and an identity link function to generate candidate models examining the effects of our predictor variables on diversity, richness, evenness, relative abundance of spring spawning littoral fish, and weighted trophic position. For the drawdown amplitude database, we used a Gamma distribution and a log link function to model richness. In the modelling process, all the single terms (impoundment or drawdown amplitude, surface area, latitude, longitude, and fish basin ecoregions) and plausible interactions with either impoundment or drawdown amplitude were included (Tables 4-5). GLMs were used to compare the relative abundance of X to both impoundment and drawdown amplitude. Since the environmental predictors of the databases are expressed in different units, all the predictors were centered and standardised. For surface area, the data were log transformed prior to standardizing them.

To select the best subset of models, we used the Akaike's information criterion (AICc) modified for small samples sizes (Burnham and Anderson 2003). The AICc value for each model quantifies its parsimony (based on the trade-off between the model fit and the number of parameters included) relative to other models considered. Candidate models were ranked using delta AICc (AICc of model i – AICc minimum, where AICc minimum represents AICc of the best model in the model subset). Only models with a delta AICc of two and less were included in the best models subset. We also performed model averaging to obtain unconditional model variance and parameter estimates for each predictor. To assess the reliability of the parameter estimates from averaging, the 95% confidence interval (CI) was calculated based on weighted unconditional standard error. To determine the relative importance of each explanatory variable, the sum of Akaike weight values (W_{imp}) for each model that contains the parameter of interest were computed (Burnham and Anderson 2003).

The effects of drawdown amplitude and impoundment on fish assemblages

RDA (redundancy analysis)

Redundancy analysis (RDA) was used to test the effects of impoundment, drawdown amplitude, surface area, latitude, longitude and fish basin ecoregions on fish assemblages. We performed RDA on each of the four databases 1) presence-absence data of the impoundment dataset, 2) fish relative abundance of the impoundment database, 3) presence-absence data of the drawdown amplitude database and 4) fish relative abundance of the drawdown amplitude database. RDA is a constrained ordination procedure using asymmetrical methods and combines regression and principal component analysis (Aggus and Elliot 1975, Borcard, Gillet et al. 2011). Before performing RDA, the environmental predictors were standardized and the species data were transformed. We used the Hellinger transformation of the relative abundance of fish species to ensure that the species data were treated according to their specificity, i.e. without undue importance being given to double zeros (Borcard, Gillet et al. 2011).

The statistical significance of an RDA (global model) and of individual canonical axes were tested by permutations (Borcard, Gillet et al. 2011). We also tested for potential multicollinearity in the predictors by calculating the variance inflation factor (VIF). VIF measures the proportion by which the variance of a regression coefficient is inflated in the presence of other explanatory variables. Ideally, VIFs above 10 should be examined and avoided if possible (Borcard, Gillet et al. 2011). VIFs were above 10 for Northeast US and Southeast Canada Atlantic drainages (impoundment databases, VIF=13.30; drawdown amplitude databases, VIF=13.55) and St-Lawrence (impoundment database, VIF=10.44; drawdown amplitude database, VIF=12.39) ecoregions, but they were still kept in the environmental matrix because they were one predictor with six categories without collinearity with the other predictors. Forward stepwise model selection using permutation tests (ordistep function) was performed to select significant explanatory variables (Oksanen, Blanchet et al. 2013). Non-significant predictors were discarded from the final RDA (Legendre and Gallagher 2001, Borcard, Gillet et al. 2011).

Variation partitioning of the impoundment redundancy analysis

When impoundment and (or) drawdown amplitude variables were significant, a variation partitioning was also run to determine how much of the variation was explained by significant environmental variables: the spatial variables matrix (latitude, longitude and ecoregions) and a matrix of variables related to regulation (impounded lakes versus not impounded lakes). We used variation partitioning to quantify the variation in fish assemblage explained by all subsets of predictors when controlling for the effect of other subsets (Legendre and Legendre 2012). Since the matrices are generally not orthogonal to one another, some amount of variation is explained jointly by the two (Legendre and Gallagher 2001). Variation partitioning was performed on two matrices of explanatory variables. The significance of all fractions: a (spatial matrix only), c (impoundment matrix only), a + b (spatial matrix), c + b (impoundment matrix) and a+ b + c was tested. Since drawdown amplitude was shown as non-significant when the RDAs were performed, no variation partitioning was computed on drawdown amplitude database.

Relationship between drawdown amplitude and individual fish species (GLM)

Different environmental predictors (impoundment or drawdown amplitude, lake surface area, latitude and longitude) were tested as potential predictors to explain variation in the presence-absence and the relative abundance of a subset of fish species. We selected species that were present in at least 40 lakes of the impoundment database or the species that are of interest for recreational fishing (Table 6). Since the environmental predictors of the databases were expressed in different units, all the predictors were centered and standardised. They were also standardized to remove the non-essential collinearity when we included interactions in the model. For lake surface area, the data were log transformed prior to centering and standardised them. Fish basin ecoregions were excluded from the analyses because the VIF was above ten for

NUSCA (impoundment databases, VIF=13.30; drawdown amplitude databases, VIF=13.55) and SL (impoundment database, VIF=10.44; drawdown amplitude database, VIF=12.39) ecoregions and because there was low power for most relative abundance analyses (relative abundance of fish species and drawdown amplitude databases). Our sample size did not provide enough degrees of freedom to support a categorical predictor of six categories like fish basin ecoregions. Latitude and longitude predictors provided spatial information that complemented ecoregion information.

For relative abundance, analyses were performed for species that were present in at least 10 lakes (Table 6). Few cases showed a better fit using normal distribution of the data (family=Gaussian) and an identity link function (impoundment database, relative abundance of largemouth bass, burbot and brook trout; drawdown amplitude database, relative abundance of lake whitefish). For each species, all the single terms (impoundment or drawdown amplitude, surface area, latitude and longitude) and plausible interactions with either impoundment or drawdown amplitude were included in the models. Akaike's information criterion was also used to select the best model subset. Model averaging was performed to obtain unconditional model variance and parameter estimates for each predictor (Burnham and Anderson 2003).

Results

Characteristics of impounded and non-impounded ecosystems

The 205 non-impounded and impounded lakes included in this study varied widely in size (range: < 1 to 300 000 ha) and were distributed throughout Québec and Eastern United States (Figure 1). For the 23 lakes on which we had drawdown information, the amplitude ranged from

0 to 12 m. Despite important variation in ecosystem size and drawdown amplitude, the majority of the lakes were smaller than 10 000 ha (mean ± SD: 4528 ± 1876, median: 43 ha) and had drawdown amplitude smaller than four meters (mean ± SD: 3.30 ±0.67, median: 3.30m). Impounded lakes were significantly bigger than natural lakes (ANOVA; f-value = 4.983; p = 0.027). From the total of 71 fish species that were present in the databases, 66 in non-impounded and 54 species in impounded ecosystems.

Relationship between impoundment, drawdown amplitude and fish community metrics

Impoundment and drawdown amplitude both showed a significant relationship with richness, but not with the other fish community metrics (diversity, evenness, relative abundance of spring spawning littoral fish, and weighted trophic position; Tables 4 and 5). Species richness was positively related to drawdown amplitude (p= 0.009) and was also positively related to the interaction of impoundment and lake surface area (Figure 2; Table 4). Only the small impounded lakes (< 1000 ha) had a higher richness than the non-impounded lakes. Species richness of impounded lakes increased in larger lakes but there was a tendency for richness to be greater in non-impounded lakes (Figure 2).

The effects of impoundment on fish assemblages (RDA)

Variation in fish assemblages were significantly related to impoundment, ecoregion, latitude and longitude, but the effect of impoundment was negligible (Figure 3). Predictors from the relative abundance impoundment database explained 20.39% of the variation in the fish assemblage. The RDA showed that latitude and longitude were mainly responsible for dispersion of the sites along both axes (Figure 3). White perch (MOAM), pearl dace (MAMA), and brook trout (SAFO) were correlated to higher longitudes whereas white sucker (CACO), walleye (SAVI), northern pike (ESLU), and lake whitefish (COCL) were related to higher latitudes (Figure 3). The position of the centroids representing fish basin ecoregions GSLC and EHB-U suggest that these fish assemblages were distinct from the other group because they were distributed relatively far from the center of the ordination. However, there were no fish species particularly associated to these groups of sites (Figure 3). Most other fish species were clustered around the middle of the ordination. Variation partitioning of the relative abundance database showed that impoundment only explained 0.6% of the variation in the fish assemblage. In contrast, spatial predictors (latitude, longitude and fish basin ecoregions) explained 15.5% of the variation. The variation explained jointly by the two sets of predictors was minimal (1.1%).

The results from the constrained ordination of the presence-absence impoundment database were similar to those from the relative abundance impoundment database, except for a few minor differences. For example, the grouping of species to the significant environmental predictors differed: high longitude values were associated with rainbow smelt (OSMO), atlantic salmon (SASA), common shiner (LUCO) and lake chub (COPL) in addition to the other taxa detected in the relative abundance database. On the other hand, few fish species were positively correlated to high latitude values but none were strongly associated with it. Variation partitioning of the RDA from the presence-absence database was similar to the the variation partitioning from the the relative abundance database.

The effects of drawdown amplitude on fish assemblage

Fish assemblages were not significantly related to drawdown amplitude but only to spatial predictors (Figure 4). RDA of the relative abundance drawdown amplitude database explained 42.04% of the variation in the fish assemblage. Ecoregion and latitude were the only significant environmental predictors (R^2_{adj} = 0.29). An RDA triplot showed that latitude and fish basin ecoregion EHB-U were mainly responsible for site dispersion along the first axis (Figure 4). A correlation triplot determined 3 groups of fish species correlated to different environmental predictors: yellow perch (PEFL), walleye (SAVI) and lake cisco (COAR) were positively correlated to the centroid representing fish basin ecoregion SL (Figure 4). White perch (MOAM) were related to fish basin ecoregion NUSCA and longnose sucker (CACA), lake whitefish (COCL), and northern pike (ESLU) were correlated to high latitude values as well as EHB-U ecoregion (Figure 4). The other fish species clustered around the middle of the ordination indicated that they were either present in most of the lakes or related to intermediate ecological conditions.

The results from the constrained ordination of the presence-absence drawdown amplitude database were similar to those from the relative abundance impoundment database except for burbot (LOLO) and lake trout (SANA) that were also associated with higher latitude. No species were associated with NUSCA and EHB-U ecoregions and yellow perch (PEFL) did not correlate to SL ecoregion.

Relationship between impoundment, drawdown amplitude and individual fish species

The presence or relative abundance of 59% of the individual fish species subset (total of 17 fish species that were present in at least 40 lakes of the impoundment database or the species that are of interest for recreational fishing, (Table 6)) was significantly related to impoundment. There were no significant effects of drawdown amplitude on the presence or relative abundance of any of the individual fish species analysed (Appendix 6). More specifically, in impounded lakes, northern pike and smallmouth bass had a higher probability of being present, whereas lake whitefish and lake trout had a lower probability of being present. (Appendix 5).

With some of the taxa considered and using the presence-absence dataset, we found some significant interactions between impoundment and area as well as between impoundment and latitude. For example, white sucker (CACO) had a higher probability of being present in large impounded lakes. However, impounded lakes tended to be bigger than non-impounded lakes. Fallfish (SECO) had a higher probability of being present in higher latitude impounded lakes whereas largemouth bass (MISA) had a higher probability of occurence in lower latitude impounded lakes. For many of the taxa, the confidence intervals of the regression lines predicting species presence to area from impounded and non-impounded lakes overlapped for most of the area range. There were no significant interactions involving drawdown amplitude on the presence or relative abundance of any of the individual fish species (Appendix 6).

We found a significant interaction between impoundment and longitude and impoundment and latitude in relation to relative abundance of species (Apendix 3). Fallfish and lake trout showed lower relative abundance in impounded lakes when compared to non-impounded lakes of similar longitude (Appendix 5). Fallfish also showed lower relative abundance in impounded lakes when compared to non-impounded lakes of similar latitude

(Appendix 5). However, walleye showed higher relative abundance in impounded lakes when compared to non-impounded lakes of similar latitude (Appendix 5).

Discussion

Our findings are contradictory to previous studies and suggest that the fish assemblages in regulated and non-regulated lakes are similar. Investigations on the long-term changes in reservoir fish assemblages demonstrated that they change with time (Patriarche and Campbell 1958, Gido, Matthews et al. 2000, Quinn and Kwak 2003), implying that impoundment leads to alterations of assemblage structure (Patriarche and Campbell 1958, Gido, Matthews et al. 2000, Quinn and Kwak 2003). Similarly, Sutela (2008) looked at the differences in littoral fish assemblages between non-impounded and impounded lakes of different drawdown amplitude and found significant modifications in fish assemblage structure. His results also demonstrated that impoundment causes changes in fish assemblage structure. Because previous research does not support our results, we concluded that fish assemblage structure between regulated and non-regulated lakes do not differ as much as we expected. However, alteration of fish assemblage structure was observed in studies comparing the pre-impounded and impounded fish assemblage of the same reservoir (Patriarche and Campbell 1958, Quinn and Kwak 2003). We suspect the drastic changes in fish assemblage were related to the metamorphose of the initial river system into reservoir after the building of dams. It has been demonstrated that fish communities between rivers and reservoirs were more different than the fish communities between natural lakes and reservoirs (Irz, Odion et al. 2006). Previous studies that found important alterations in fish assemblage structure following impoundment were conducted between pre-impounded and impounded rivers. In other words, these studies were conducted between rivers and reservoirs.

However, Sutela (2008) compared littoral fish assemblage between lakes of different water level fluctuations and found alterations in fish assemblage structure. Contradictory to our study, Sutela (2008) showed modifications in the fish assemblage even tho he did not include riverine ecosystems in his data.

We failed to demonstrate significant impacts of drawdown amplitude on fish assemblage structure, probably because our databases only included a small set of lakes and because we did not control for shoreline steepness and annual magnitude of drawdown. Previous studies demonstrated that drawdown amplitude directly effects macrophytes and macroinvertebrates in the littoral zone (Wolcox and Meeker 1992, Palomäki and Koskenniemi 1993, Gafny and Gasith 1999, Aroviita and Hämäläinen 2008). Knowing that several fish species use the littoral to spawn, macrophytes to hide from predators and macroinvertebrates to feed, we expected that fish communities would be affected by the modifications in the littoral zone of reservoirs (LeRoy Heman, Campbell et al. 1969, Gaboury 1984, Palomäki and Koskenniemi 1993, Gafny and Gasith 1999, Sutela, Aroviita et al. 2013). Our results differ from the findings of Sutela (2008), which could be attributed to the different fish assemblage investigated. We analysed the fish assemblage from whole reservoirs and Sutela (2008) only investigated the littoral fish assemblage. The small set of lakes of our databases (23 lakes) could be another reason why we did not detect any impacts of drawdown amplitude on fish assemblage structure. However, Sutela also used a small set of lakes (13 lakes) composed of five natural reference lakes and eight regulated lakes in Northern Finland, ranging from 1.54 to 6.75 meters average winter drawdown, suggesting that it is possible to detect the effects of the amplitude of drawdown on assemblage structure with a small sample size. Maybe our results simply mean that drawdown amplitude does not affect the fish assemblage of regulated lakes. An alternative explanation for the lack of impact from drawdown amplitude on fish assemblage structure could be that we did not control for shoreline steepness and annual magnitude of drawdown. When the water level decreases, regulated lakes with low shoreline steepness loose much more littoral habitat area than regulated lakes with a steep shoreline. We suspect that a greater loss in littoral habitat could have stronger impacts on fish populations relying on this essential habitat which could result in an alteration of the fish assemblage (Dolson, McCann et al. 2009). There is also yearly variation in the magnitude of drawdown. Years characterised by higher drawdown (low water levels) mean less space in the littoral zone for shelter, spawning and feeding. Consequently, these years potentially impact fish assemblage more than years of lower drawdown. Since we did not control for these two environmental variables, we may have failed to detect potential effects of drawdown amplitude on fish assemblage structure.

Contrarily to previous studies investigating the effects of impoundment and drawdown amplitude on fish species richness, we found higher fish species richness in regulated lakes than in non-regulated lakes, which could be explained by their large surface area. Sutela (2008) did not find changes in the lacustrine fish species richness of regulated lakes. Even though the effect was not significant, he observed higher fish species richness at higher drawdown amplitude, suggesting that drawdown amplitude could potentially lead to an increase in the number of fish species present in regulated lakes. Previous studies also demonstrated that fish species richness tends to increase with lake surface area (Matuszek and Beggs 1988). Similarly, our results showed that fish species richness of impounded lakes increased with lake surface area. However, the fish species richness of impounded lakes was only higher than the species richness of non-impounded lakes in small reservoirs. The majority of the big reservoirs happened to be located at higher latitude than the small impounded lakes and it already has been shown that fish species richness decreases when latitude increases (Amarasinghe and Welcomme 2002). In other words, lakes tend to have less fish species as latitude increases, which could explain why species richness in large, northern impounded lakes was lower than fish species richness in non-impounded systems. Overall, we showed that fish species richness increased with lake surface area and was higher in impounded than non-impounded lakes, except passed a certain latitude. Similarly, we found that fish species richness increased with drawdown amplitude. The majority of the regulated lakes characterised by high drawdown amplitude are some of the largest reservoirs in our databases. This finding is also consistent with Matuszek and Beggs (1988) research demonstrating that species richness tends to be correlated with lake surface area.

Against all expectations, the abundance of spring spawning littoral fish was unchanged in impounded lakes and reservoirs of high drawdown amplitude, probably because we failed to detect years of low recruitment by these fish. However, we demonstrated that abundance of lake trout, a littoral fall spawner, decreased in impounded lakes. Previous studies demonstrated that fish species relying on the littoral zone for spawning in spring are negatively affected by artificial water level fluctuations (Gaboury 1984, Gafny, Gasith et al. 1992). Both impoundment and drawdown amplitude are important for these fish species. The occurence of a dam could alter the timing as well as the amplitude of the spring flood, which is critical for fish to reach their spawning grounds (Gafny, Gasith et al. 1992). Consequently, the recruitment of littoral spring spawners is low if not almost null in years when the water level does not reach a high enough level for the fish to reach their spawning grounds (Jansen 2000). Our result could be the outcome of not controlling for the annual amplitude of drawdown. We may have failed to detect the years of low recruitment in littoral spring spawners which could explain why we did not find significant effects from impoundment and drawdown amplitude on the abundance of littoral spring spawners. Littoral fall spawners are also threatened by impoundment and increased drawdown amplitude. Potential spawners might not be able to reach their spawning grounds because of low water levels or fertilised eggs could dry if water levels decrease too much (Sutela, Mutenia et al. 2002, Cott, Sibley et al. 2008, Sutela, Aroviita et al. 2013). We found that the abundance of lake trout, a littoral fall spawner, decreased in impounded lakes. This result is supported by previous findings of negative effects of artificial water fluctuation on the abundance of littoral fall spawners.

Our results suggest that weighted trophic positions do not increase in regulated lakes but the abundance of few littoral predators do, most likely because the average trophic level of the littoral zone was not high enough to increase the weighted trophic position. Previous studies demonstrated that drawdown concentrated and exposed prey fish, which became more vulnerable to predation and led to an increase in predator foraging (LeRoy Heman, Campbell et al. 1969, Noble 1981, Ploskey 1986). However, littoral predators might only benefit from drawdown until the fish species they prey upon start to decline (Ploskey 1986). We probably did not detect an increased weighted trophic position of the impounded lakes or across lakes of different drawdown amplitude because the regulated lakes were impounded for long enough that the abundance of forage species had time to decrease. We did not control for time since impoundment but we suspect that none of the regulated lakes in our databases were newly impounded. This could explain why we did not detect an increased weighted trophic position in regulated lakes. Nonetheless, weighted trophic position only indicates the average trophic level of a lake. The fact that there were no significant changes in weighted trophic position between lakes does not mean that the abundance of littoral predators species does not differ. Our results demonstrated that the abundance of littoral piscivorous species such as smallmouth bass and walleye increased in impounded lakes. Our finding supports previous research demonstrating higher abundance of littoral predators in impounded lakes when compared to non-impounded ones (LeRoy Heman, Campbell et al. 1969, Noble 1981, Ploskey 1986) .

Given the widespread distribution of dams, the lack of information about its impacts on lacustrine fish assemblage is striking. Our results contradict most research on fish community and assemblage structure, indicating the need to better understand the effects of winter drawdown on lacustrine fish populations and assemblages. Further studies of the impacts of impoundment and artificial water level fluctuations on fish body conditions would be a great complement to research on fish populations and assemblages. Previous studies already demonstrated that impoundment caused drastic decreases in the growth rate of fish (Milbrink, Vrede et al. 2011). A better understanding of the fish diet in regulated lakes would be a great asset to understand if the reduced growth rate arises from changes in food resources. Fatty acids profiles and composition has be shown to be a promising method to determine the diet and also the changes in the metabolism of freshwater organisms (Bell, Ghioni et al. 1994, Arts 1999). Identification of the fatty acid profiles and composition of fish experiencing winter drawdown would allow the investigation of their diet and body conditions. More detailed information on fish feeding habits could also lead to more realistic bioenergetics models. A better knowledge on fish body condition, diet, feeding behaviour and assemblage structure would be useful to understand fish population dynamics and eventually, manage reservoirs adequately.

Our study failed to demonstrate significant impacts of drawdown amplitude on fish assemblage structure and only showed negligible differences between fish community of impounded and non-impounded lakes. Dams are widespread as they are needed to sustain human activities. The increasing number of dams leads to freshwater habitat fragmentation of the freshwater habitats and is considered a worldwide major threat to the biodiversity of freshwater ecosystems (Strayer and Dudgeon 2010, Vörösmarty, McIntyre et al. 2010). Even more, artificial water regulation has effects from the genetic of freshwater organisms to the individual freshwater ecosystem up to the global freshwater system (Rosenberg, McCully et al. 2000). It is imperative to understand the effects of dams on freshwater ecosystems to responsibly guide human development.

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Table 1. List of the 71 fish species included in the impoundment databases and the 34 included in the drawdown amplitude databases

Common name, latin name, and fish code are listed for the 71 fish species included in the GLM analysis of the fish community metrics, impoundment databases. The 34 species also included in the drawdown amplitude databases are identified by a check mark.

*Common name	*Latin name	Code	Drawdown amplitude
Lake sturgeon	*Acipenser fulvescens*	ACFU	✓
Mud sunfish	*Acantharchus pomotis*	ACPO	
Alewife	*Alosa pseudoharengus*	ALPS	
Bowfin	*Amia calva*	AMCA	
Yellow bullhead	*Ameiurus natalis*	AMNA	✓
Brown bullhead	*Ameiurus nebulosus*	AMNE	✓
Rock bass	*Ambloplites rupestris*	AMRU	✓
American eel	*Anguilla rostrata*	ANRO	
Freshwater drum	*Aplodinotus grunniens*	APGR	
Pirate perch	*Aphredoderus sayanus*	APSA	
Longnose sucker	*Catostomus catostomus*	CACA	✓
White sucker	*Catostomus commersonii*	CACO	✓
Quillback	*Carpiodes cyprinus*	CACY	
Northern redbelly	*Chrosomus eos*	CHEO	
Finescale dace	*Chrosomus neogaeus*	CHNE	
Cisco	*Coregonus artedi*	COAR	✓
Lake whitefish	*Coregonus clupeaformis*	COCL	✓
Slimy sculpin	*Cottus cognatus*	COCO	
Lake chub	*Couesius plumbeus*	COPL	✓
Brook stickleback	*Culaea inconstans*	CUIN	
Common carp	*Cyprinus carpio*	CYCA	
Gizzard shad	*Dorosoma cepedianum*	DOCE	
Blackbanded sunfish	*Enneacanthus chaetodon*	ENCH	
Bluespotted sunfish	*Enneacanthus gloriosus*	ENGL	
Banded sunfish	*Enneacanthus obesus*	ENOB	
Northern pike	*Esox lucius*	ESLU	✓
Chain pickerel	*Esox niger*	ESNI	✓
Tessellated darter	*Etheostoma olmstedi*	ETOL	
Cutlip minnow	*Exoglossum maxillingua*	EXMA	
Banded killifish	*Fundulus diaphanus*	FUDI	✓
Mummichog	*Fundulus heteroclitus*	FUHE	
Threespine	*Gasterosteus aculeatus*	GAAC	
Mooneye	*Hiodon tergisus*	HITE	✓
Channel catfish	*Ictalurus punctatus*	ICPU	

Redbreast sunfish	*Lepomis auritus*	LEAU	
Pumpkinseed	*Lepomis gibbosus*	LEGI	✓
Bluegill	*Lepomis macrochirus*	LEMA	✓
Longnose gar	*Lepisosteus osseus*	LEOS	
Burbot	*Lota lota*	LOLO	✓
Common shiner	*Luxilus cornutus*	LUCO	✓
Pearl dace	*Margariscus margarita*	MAM	✓
Smallmouth bass	*Micropterus dolomieu*	MIDO	✓
Largemouth bass	*Micropterus salmoides*	MISA	✓
White perch	*Morone americana*	MOA	✓
Shorthead redhorse	*Moxostoma*	MOM	✓
Bridle shiner	*Notropis bifrenatus*	NOBI	
Golden shiner	*Notemigonus crysoleucas*	NOCR	✓
Blacknose shiner	*Notropis heterolepis*	NOHE	
Spottail shiner	*Notropis hudsonius*	NOHU	✓
Rosyface shiner	*Notropis rubellus*	NORU	
Rainbow trout	*Oncorhynchus mykiss*	ONMY	✓
Rainbow smelt	*Osmerus mordax*	OSMO	✓
Logperch	*Percina caprodes*	PECA	
Yellow perch	*Perca flavescens*	PEFL	✓
Trout-perch	*Percopsis omiscomaycus*	PEOM	✓
Northern redbelly	*Phoxinus eos*	PHEO	✓
Bluntnose minnow	*Pimephales notatus*	PINO	
Fathead minnow	*Pimephales promelas*	PIPR	✓
White crappie	*Pomoxis annularis*	POAN	
Black crappie	*Pomoxis nigromaculatus*	PONI	
Round whitefish	*Prosopium cylindraceum*	PRCY	✓
Ninespine	*Pungitius pungitius*	PUPU	
Eastern blacknose	*Rhinichthys atratulus*	RHAT	
Sauger	*Sander canadensis*	SACA	✓
Brook trout	*Salvelinus fontinalis*	SAFO	✓
Lake trout	*Salvelinus namaycush*	SANA	✓
Atlantic salmon	*Salmo salar*	SASA	✓
Brown trout	*Salmo trutta*	SATR	✓
Creek chub	*Semotilus atromaculatus*	SEAT	
Fallfish	*Semotilus corporalis*	SECO	✓
Walleye	*Sander vitreus*	SAVI	✓

*(FishBase http://www.fishbase.ca/)

Table 2. List of the 29 fish species selected for the redundancy analysis (RDA)
Common and latin names, as well as the fish code (first two letter of the genus followed by the first two letters of the species latin name) of the 29 species selected for the redundancy analysis are listed. See footnote of Table 1 for details about data source.

Fish species		
Common name	Latin name	Code
Alewife	*Alosa pseudoharengus*	ALPS
Yellow bullhead	*Ameiurus natalis*	AMNA
Brown bullhead	*Ameiurus nebulosus*	AMNE
Rock bass	*Ambloplites rupestris*	AMRU
Longnose sucker	*Catostomus catostomus*	CACA
White sucker	*Catostomus commersonii*	CACO
Cisco	*Coregonus artedi*	COAR
Lake whitefish	*Coregonus clupeaformis*	COCL
Lake chub	*Couesius plumbeus*	COPL
Northern pike	*Esox lucius*	ESLU
Chain pickerel	*Esox niger*	ESNI
Pumpkinseed	*Lepomis gibbosus*	LEGI
Bluegill	*Lepomis macrochirus*	LEMA
Burbot	*Lota lota*	LOLO
Common shiner	*Luxilus cornutus*	LUCO
Pearl dace	*Margariscus margarita*	MAMA
Smallmouth bass	*Micropterus dolomieu*	MIDO
Largemouth bass	*Micropterus salmoides*	MISA
White perch	*Morone americana*	MOAM
Golden shiner	*Notemigonus crysoleucas*	NOCR
Rainbow trout	*Oncorhynchus mykiss*	ONMY
Rainbow smelt	*Osmerus mordax*	OSMO
Yellow perch	*Perca flavescens*	PEFL

Black crappie	*Pomoxis nigromaculatus*	PONI
Brook trout	*Salvelinus fontinalis*	SAFO
Lake trout	*Salvelinus namaycush*	SANA
Atlantic salmon	*Salmo salar*	SASA
Fallfish	*Semotilus corporalis*	SECO
Walleye	*Sander vitreus*	SAVI

Table 3. List of littoral spring spawning species
Common name, latin name, and fish code are listed for all the littoral spring spawning species included in the GLM analysis of the impoundment database. Species also included in the drawdown amplitude database are identified by a check mark. See footnote of Table 1 for details about data source.

Fish species			
Common name	**Latin name**	**Code**	**Drawdown**
Mud sunfish	*Acantharchus pomotis*	ACPO	
Alewife	*Alosa pseudoharengus*	AMNA	✔
Pirate perch	*Aphredoderus sayanus*	APSA	
Longnose sucker	*Catostomus catostomus*	CACA	✔
White sucker	*Catostomus commersonii*	CACO	✔
Quillback	*Carpiodes cyprinus*	CACY	
Slimy sculpin	*Cottus cognatus*	COCO	
Blackbanded sunfish	*Enneacanthus chaetodon*	ENCH	
Northern pike	*Esox lucius*	ESLU	✔
Chain pickerel	*Esox niger*	ESNI	✔
tessellated darter	*Etheostoma olmstedi*	ETOL	
redbreast sunfish	*Lepomis auritus*	LEAU	
Pearl dace	*Margariscus margarita*	MAMA	✔
Rainbow smelt	*Osmerus mordax*	OSMO	✔
Yellow perch	*Perca flavescens*	PEFL	✔
Trout-perch	*Percopsis omiscomaycus*	PEOM	✔
Sauger	*Sander canadensis*	SACA	✔
Walleye	*Sander vitreus*	SAVI	✔

Table 4. Predictors and interactions comprised in the best models explaining the variation in diversity, richness, evenness, relative abundance of littoral spring spawners, and weighted trophic position of non-impounded and impounded lakes
For each response variable, predictors included in models with AICc between 2 AICc units of the best model are incorporated in the table. For each predictor or interaction between predictors, the estimate, standard error (std. Error), 95% confidence interval (C.I.), and normalised Akaike weights ($W_{im.}$) are shown. Bold numbers and grey shadowing identify the significant predictor or interaction.

Response	Predictor	Impoundment			
		Relative abundance			
		Estimate	Std. Error	C.I.	W imp.
Diversity	Intercept	***1.170***	***0.036***	***1.100, 1.240***	***1.000***
	Impoundment	0.039	0.036	-0.033, 0.110	0.906
	Area	***0.268***	***0.042***	***0.187, 0.350***	***1.000***
	Latitude	***-0.107***	***0.042***	***-0.189, -0.024***	***1.000***
	Longitude	-0.055	0.031	-0.116, 0.006	0.769
	Fish basin ecoregions	-	-	-	-
	Impoundment * Area	-0.057	0.038	-0.131, 0.016	0.441
	Impoundment * Latitude	-0.066	0.036	-0.136, 0.005	0.568
	Impoundment * Longitude	-0.030	0.032	-0.092, 0.032	0.202
	Impoundment * fish basin ecoregions	-	-	-	-
Richness	Intercept	***7.062***	***0.762***	***5.569, 8.556***	***1.000***
	Impoundment	-0.133	0.197	-0.519, 0.254	1.000
	Area	***2.824***	***0.229***	***2.375, 3.272***	***1.000***
	Latitude	***-1.637***	***0.295***	***-2.216, -1.058***	***1.000***
	Longitude	***-0.398***	***0.166***	***-0.724, -0.072***	***0.602***
	Fish basin ecoregion: EHB-U	3.369	1.890	-0.335, 7.074	0.400
	Fish basin ecoregion: GSLC	-2.072	1.756	-5.513, 1.369	0.400
	Fish basin ecoregion: LGL	0.639	1.423	-2.149, 3.427	0.400
	Fish basin ecoregion: NUSCA	0.105	1.178	-2.203, 2.413	0.400
	Fish basin ecoregion: SL	0.615	1.262	-1.858, 3.089	0.400

	Impoundment * Area	***-0.453***	***0.177***	***-0.799, -0.107***	***1.000***
	Impoundment * Latitude	-	-	-	-
	Impoundment * Longitude	-0.176	0.168	-0.506, 0.153	0.225
	Impoundment * fish basin ecoregions	-	-	-	-
Evenness	Intercept	***0.473***	***0.109***	***0.259, 0.688***	***1.000***
	Impoundment	0.016	0.016	-0.015, 0.047	0.276
	Area	0.014	0.018	-0.021, 0.048	0.230
	Latitude	-	-	-	-
	Longitude	***-0.044***	***0.020***	***-0.084, -0.004***	***1.000***
	Fish basin ecoregion: EHB-U	0.156	0.145	-0.127, 0.440	1.000
	Fish basin ecoregion: GSLC	***0.305***	***0.154***	***0.003, 0.608***	***1.000***
	Fish basin ecoregion: LGL	-0.104	0.129	-0.357, 0.150	1.000
	Fish basin ecoregion: NUSCA	0.151	0.113	-0.070, 0.372	1.000
	Fish basin ecoregion: SL	0.162	0.112	-0.057, 0.381	1.000
	Impoundment * Area	-	-	-	-
	Impoundment * Latitude	-	-	-	-
	Impoundment * Longitude	-	-	-	-
	Impoundment * fish basin ecoregions	-	-	-	-
Littoral spring spawners	Intercept	***3.357***	***0.017***	***3.324, 3.390***	***1.000***
	Impoundment	0.022	0.020	-0.017, 0.062	0.526
	Area	***0.078***	***0.022***	***0.035, 0.122***	***1.000***
	Latitude	***-0.052***	***0.023***	***-0.096, -0.007***	***1.000***
	Longitude	***-0.085***	***0.017***	***-0.118, -0.051***	***1.000***
	Fish basin ecoregions	-	-	-	-
	Impoundment * Area	-	-	-	-
	Impoundment * Latitude	-	-	-	-
	Impoundment * Longitude	0.020	0.017	-0.014, 0.054	0.216
	Impoundment * fish basin ecoregions	-	-	-	-

Weighted trophic postion	Intercept	***46.885***	***2.045***	***42.877, 50.892***	***1.000***
	Impoundment	0.915	2.432	-3.851, 5.682	0.142
	Area	***6.432***	***2.553***	***1.428, 11.435***	***1.000***
	Latitude	3.824	2.512	-1.100, 8.748	0.670
	Longitude	-1.060	2.063	-5.105, 2.984	0.151
	Fish basin ecoregions	-	-	-	-
	Impoundment * Area	-	-	-	-
	Impoundment * Latitude	-	-	-	-
	Impoundment * Longitude	-	-	-	-
	Impoundment * fish basin ecoregions	-	-	-	-

Table 5. Predictors and interactions comprised in the best models explaining the variation in diversity, richness, evenness, relative abundance of littoral spring spawners, and weighted trophic position of lakes for which drawdown is known
For each response variable, predictors included in models with AICc between 2 AICc units of the best model are incorporated in the table. For each predictor or interaction between predictors, the estimate, standard error (std. Error), 95% confidence interval (C.I.), and normalised Akaike weights ($W_{im.}$) are shown. Bold numbers and grey shadowing identify the significant predictor or interaction.

Response	Predictor	Drawdown amplitude			
		Relative abundance			
		Estimate	Std. Error	C.I.	W imp.
Diversity	Intercept	***1.448***	***0.064***	***1.322, 1.574***	***1.000***
	Drawdown amplitude	0.065	0.069	-0.071, 0.201	0.210
	Area	0.072	0.071	-0.067, 0.211	0.228
	Latitude	-	-	-	-
	Longitude	***-0.203***	***0.069***	***-0.337, -0.068***	***1.000***
	Fish basin ecoregions	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-
	Drawdown amplitude * Latitude	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-
	Drawdown amplitude * fish basin ecoregions	-	-	-	-
Richness	Intercept	***2.177***	***0.048***	***2.084, 2.270***	***1.000***
	Drawdown amplitude	***0.101***	***0.051***	***0.001, 0.201***	***0.659***
	Area	***0.150***	***0.073***	***0.007, 0.292***	***0.858***
	Latitude	***-0.148***	***0.057***	***-0.258, -0.037***	***0.858***
	Longitude	***-0.182***	***0.048***	***-0.277, -0.087***	***1.000***
	Fish basin ecoregions	-	-	-	-
	Drawdown amplitude * Area	-0.113	0.063	-0.236, 0.009	0.249
	Drawdown amplitude * Latitude	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-

	Drawdown amplitude * fish basin ecoregions	-	-	-	-
Evenness	Intercept	***0.674***	***0.027***	***0.620, 0.727***	***1.000***
	Drawdown amplitude	-	-	-	-
	Area	-	-	-	-
	Latitude	-	-	-	-
	Longitude	-0.024	0.028	-0.079, 0.031	0.283
	Fish basin ecoregions	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-
	Drawdown amplitude * Latitude	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-
	Drawdown amplitude * fish basin ecoregions	-	-	-	-
Littoral spring spawners	Intercept	***3.405***	***0.056***	***3.294, 3.515***	***1.000***
	Drawdown amplitude	-	-	-	-
	Area	***0.234***	***0.074***	***0.089, 0.379***	***1.000***
	Latitude	-0.105	0.074	-0.250, 0.040	0.398
	Longitude	-0.088	0.062	-0.208, 0.033	0.399
	Fish basin ecoregions	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-
	Drawdown amplitude * Latitude	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-
	Drawdown amplitude * fish basin ecoregions	-	-	-	-
Weighted trophic postion	Intercept	***61.378***	***3.553***	***54.414, 68.342***	***1.000***
	Drawdown amplitude	-	-	-	-
	Area	-	-	-	-
	Latitude	-	-	-	-
	Longitude	-6.725	3.554	-13.692, 0.241	0.617
	Fish basin ecoregions	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-

	Drawdown amplitude * Latitude	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-
	Drawdown amplitude * fish basin ecoregions	-	-	-	-

Table 6. Number of lakes included in the individual fish species analysis for the four different databases
Each fish species involved in the individual fish species analysis are listed. For all of these species, the number of lakes involved in the analysis are registered for the four databases. For the relative abundance impoundment database, the fish species included in the analysis because they are present in at least 40 lakes are shown. Species included in the analysis because of their recreational fishing interest are also indicated. For the relative abundance drawdown amplitude database, the species for which the number of lakes involved in the analysis is lower than ten are signaled. See footnote of Table 1 for details about data sources.

Fish species			Sample size (number of lakes)						
			Impoundment				Drawdown amplitude		
Common	Latin name	Code	Presence-absence	Relative abundance	Present in at least 40	Species of interest for	Presence-absence	Relative abundance	N<10
Brown	*Ameiurus*	AMNE	205	97	✔		23	6	✔
White sucker	*Catostomus*	CACO	205	130	✔		23	21	
Lake	*Coregonus*	COCL	205	28		✔	23	13	
Northern	*Esox lucius*	ESLU	205	34		✔	23	14	
Chain	*Esox niger*	ESNI	205	60	✔		23	4	✔
Pumpkinseed	*Lepomis*	LEGI	205	92	✔		23	5	✔
Bluegill	*Lepomis*	LEMA	205	44	✔		23	1	✔
Burbot	*Lota lota*	LOLO	205	24		✔	23	11	
Smallmouth	*Micropterus*	MIDO	205	49	✔		23	11	
Largemouth	*Micropterus*	MISA	205	78	✔		23	2	✔
Golden	*Notemigonus*	NOCR	205	108	✔		23	8	✔
Rainbow	*Osmerus*	OSMO	205	33		✔	23	6	✔
Yellow	*Perca*	PEFL	205	143	✔		23	18	
Brook trout	*Salvelinus*	SAFO	205	43	✔		23	5	✔
Lake trout	*Salvelinus*	SANA	205	20		✔	23	8	✔
Fallfish	*Semotilus*	SECO	205	43	✔		23	7	✔
Walleye	*Sander*	SAVI	205	27		✔	23	10	

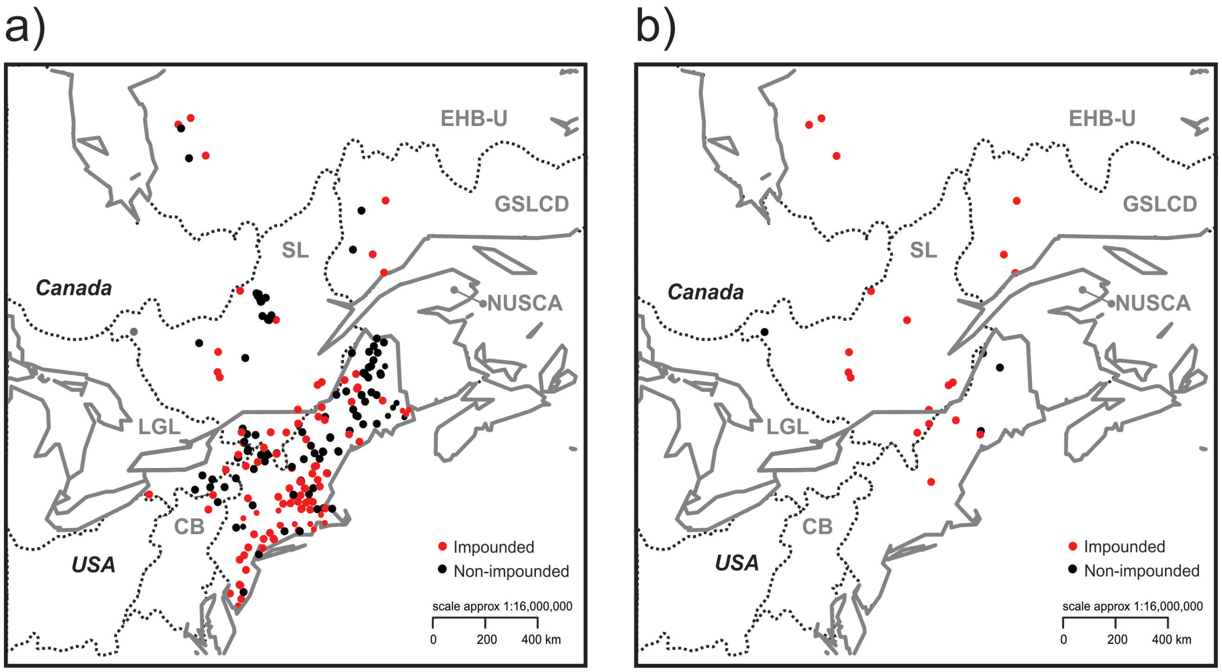


Figure 1. Maps of the lakes included in the impoundment and drawdown amplitude databases

(a) Non-impounded and impounded lakes used in the "impoundment" databases. **(b)** Subset of lakes for which drawdown amplitude was known, used in the "drawdown amplitude" databases. Abbreviations indicate fish basin ecoregions (US Army Corps of Engineers http://nid.usace.army.mil/): CB=Chesapeake Bay drainage, EHB-U=Eastern Hudson Bay-Ungava, GSLCD=Gulf St. Lawrence coastal drainage, LGL=Laurentian Great lakes, NUSCA=Northeast US and Southeast Canada Atlantic drainages, SL=St-Lawrence drainage.

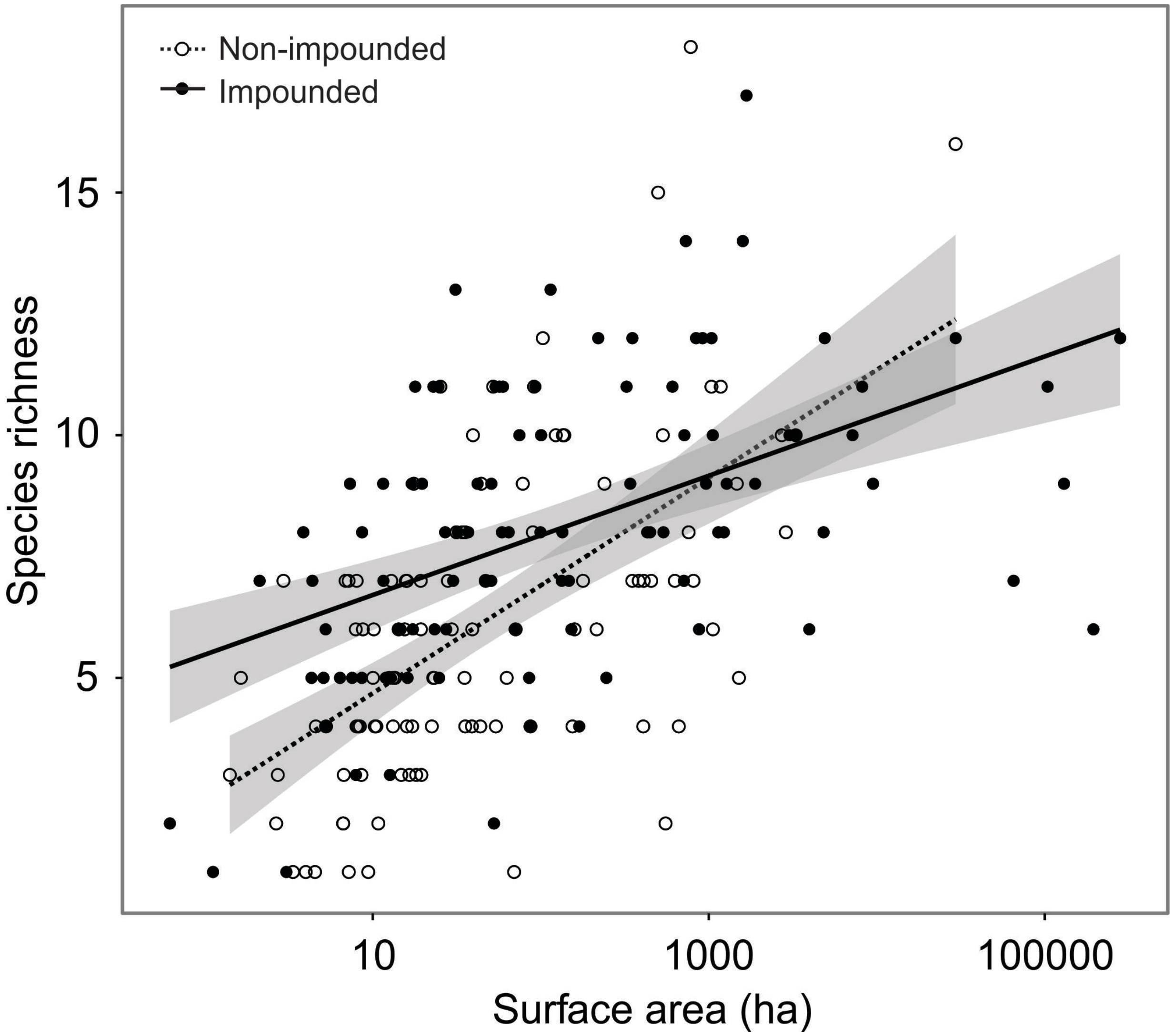
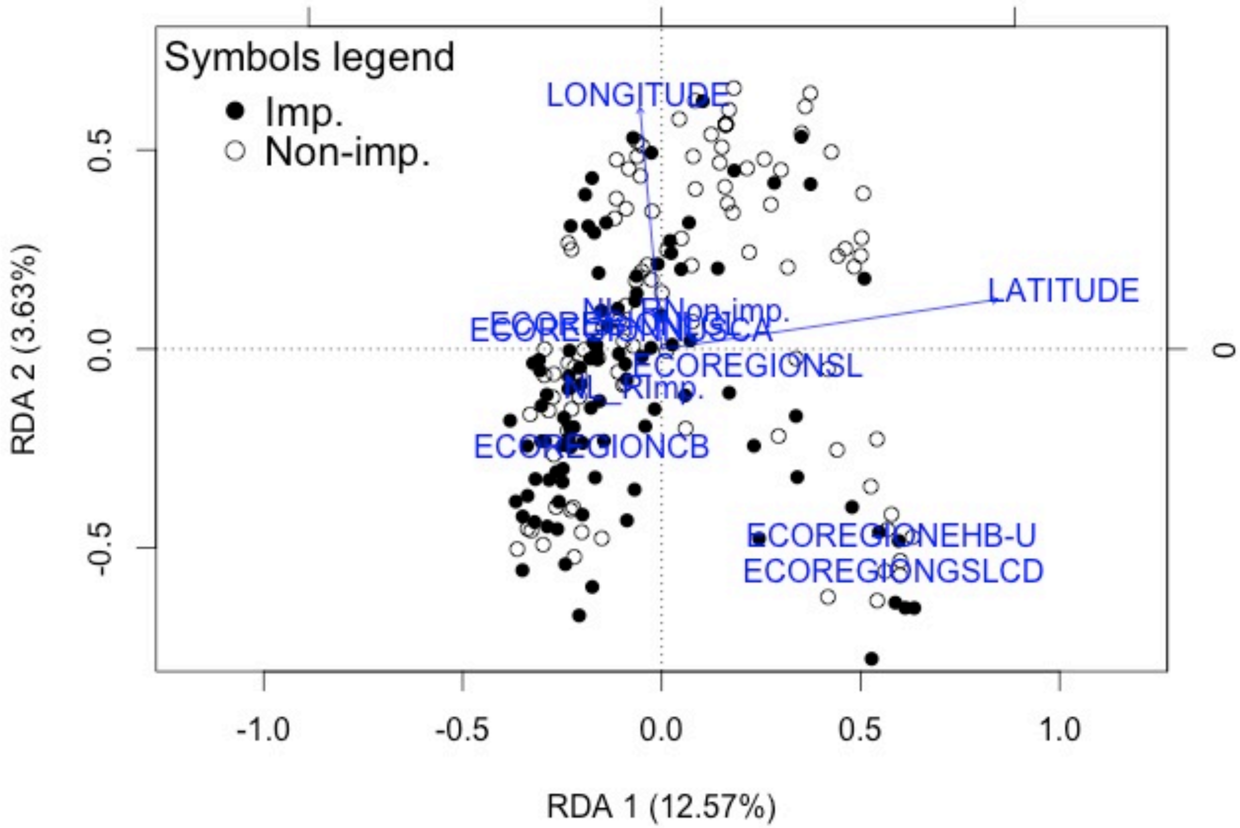


Figure 2. Fish species richness plotted against lake area for 205 non-impounded and impounded lakes

Fitted regression lines from a regression of richness on area and impoundment and 95% confidence bands are indicated for both lake types. Small impounded lakes have higher richness than small natural lakes, but this difference disappears at larger lake areas.

a)


Symbols legend
Imp.
Non-imp.
LONGITUDE
LATITUDE
ECOREGIONSL
ECOREGIONCB
ECOREGIONEHB-U
ECOREGIONGSLCD
RDA 2 (3.63%)
RDA 1 (12.57%)
0.5
0.0
-0.5
-1.0
1.0
0

b)

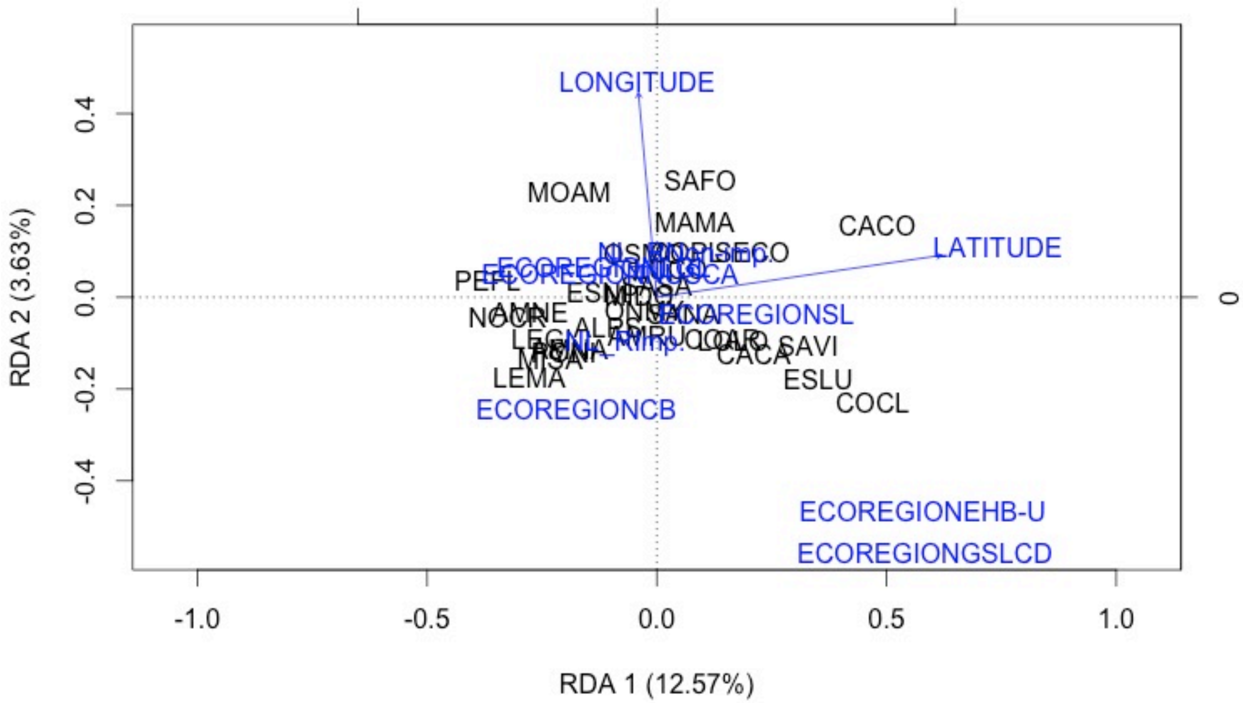
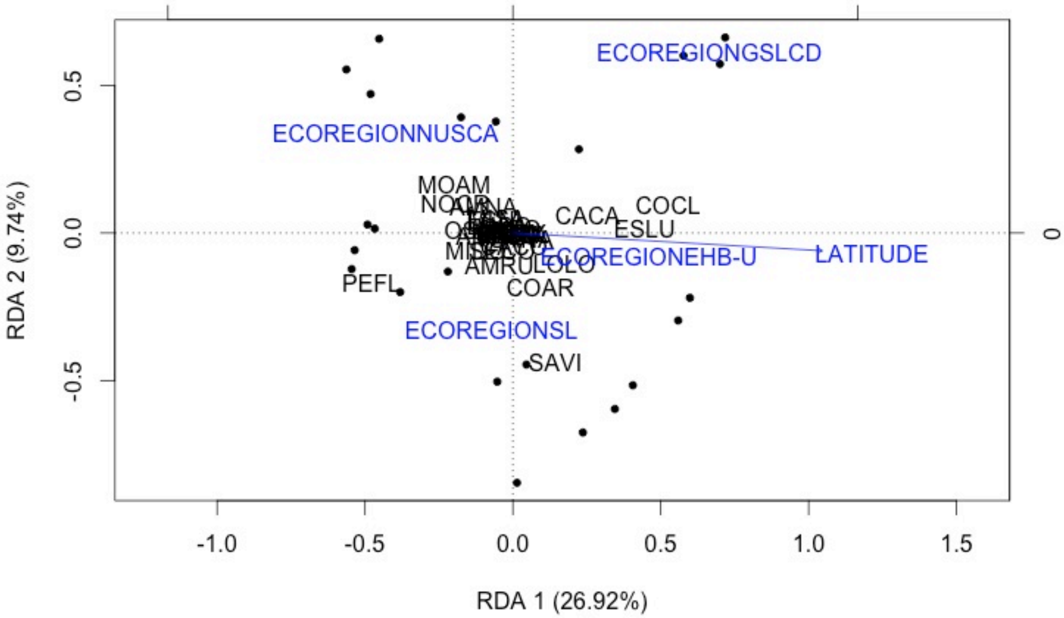


Figure 3. Correlation biplots showing the relationship among environmental predictors and impounded and non-impounded lakes and between environmental predictors and fish species
Relative abundance of fish species are Hellinger-transformed, Fish species are represented by the first two letters of the genus followed by the first two letters of the species latin name (Table 2). Abbreviations indicating fish basin ecoregions (US Army Corps of Engineers http://nid.usace.army.mil/): CB=Chesapeake Bay drainage, EHB-U=Eastern Hudson Bay-Ungava, GSLCD=Gulf St. Lawrence coastal drainage, LGL=Laurentian Great lakes, NUSCA=Northeast US and Southeast Canada Atlantic drainages, SL=St-Lawrence drainage. **(a)** Biplot representing the relationship between lakes (impounded and non-impounded lakes) and environmental predictors. **(b)** Biplot representing the relationship between fish species and environmental predictors.

a)


ECOREGIONGSLCD
ECOREGIONNUSCA
MOAM
CACA
COCL
ESLU
LATITUDE
ECOREGIONEHB-U
PEFL
COAR
ECOREGIONSL
SAVI
RDA 1 (26.92%)
RDA 2 (9.74%)

b)

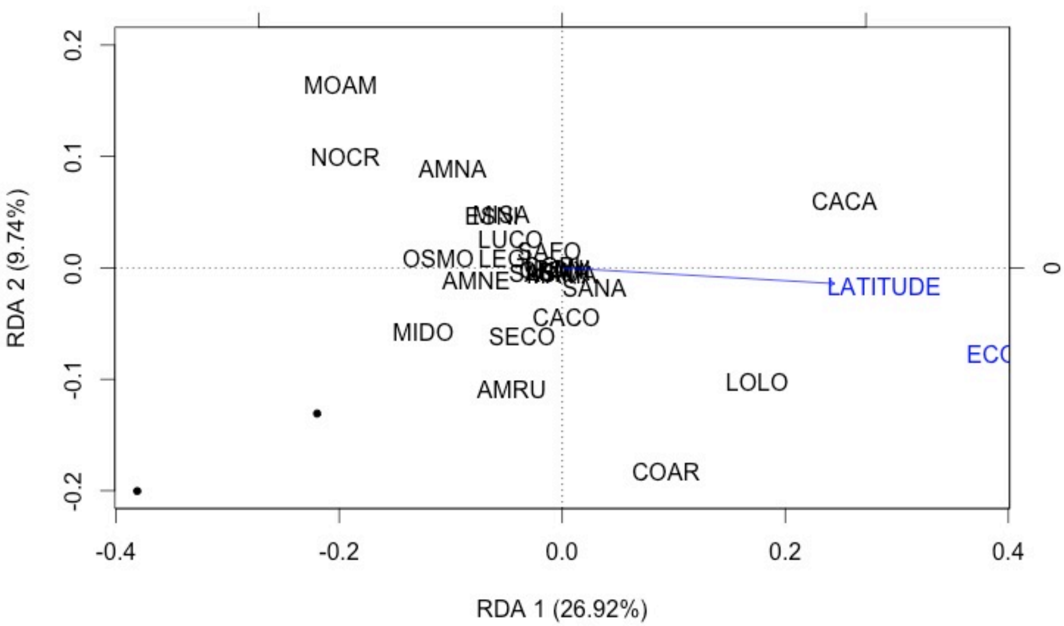

MOAM
NOCR
AMNA
CACA
LUCO
OSMO
AMNE
SANA
LATITUDE
CACO
MIDO
SECO
LOLO
AMRU
COAR
RDA 1 (26.92%)
RDA 2 (9.74%)

Figure 4. Correlation triplots showing the relationship among environmental predictors, fish species and lakes for which drawdown amplitude is known
Relative abundance of fish species are Hellinger-transformed, environmental predictors are centered and standardised except for surface area that was log transformed prior to being centered and standardised. Latitude and fish basin ecoregions are significant predictors explaining the variation in fish communities. Fish species are represented by the first two letters of the genus followed by the first two letters of the species latin name (Table 2). Abbreviations indicating fish basin ecoregions (US Army Corps of Engineers http://nid.usace.army.mil/): CB=Chesapeake Bay drainage, EHB-U=Eastern Hudson Bay-Ungava, GSLCD=Gulf St. Lawrence coastal drainage, LGL=Laurentian Great lakes, NUSCA=Northeast US and Southeast Canada Atlantic drainages, SL=St-Lawrence drainage. **(a)** Correlation triplot showing the relationship among environmental predictors, fish species and lakes for which drawdown amplitude is known **(b)** Zoomed in correlation triplot showing the relationship among environmental predictors, fish species and lakes for which drawdown amplitude is known

Final conclusion

Previous studies demonstrated the important effects of impoundment and drawdown amplitude on the littoral zones of lakes (Sutela, Aroviita et al. 2013). Because of littoral habitat modification, impoundment and drawdown amplitude could indirectly affect fish species using the littoral zone for shelter, feeding and reproduction. We performed a synthetic multi-lake study of impoundment and drawdown amplitude effects on lacustrine fish communities. Our study failed to demonstrate that winter drawdown is a significant threat for fish populations and assemblages inhabiting regulated lakes. Even though we found similarity between fish assemblage of impounded and non-impounded boreal and temperate lakes, impoundment could have stronger impacts on different ecosystems such as tropical rivers and lakes. Dams are widespread globally to satisfy diverse human activities. This important and increasing number of dams leads to global habitat fragmentation of freshwater habitats and is considered a worldwide major threat on the biodiversity of freshwater ecosystems (Strayer and Dudgeon 2010, Vörösmarty, McIntyre et al. 2010). Even more, artificial water regulation has impacts on genetic, ecosystem and global levels (Rosenberg, McCully et al. 2000). It is imperative to understand the impacts of dams at every different level in order to demystify the potential suite of interrelated environmental impacts and manage freshwater ecosystems consequently.

References

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Sutela, T., et al. (2013). "Assessing ecological status of regulated lakes with littoral macrophyte, macroinvertebrate and fish assemblages." Ecological Indicators **24**: 185-192.

Vörösmarty, C. J., et al. (2010). "Global threats to human water security and river biodiversity." Nature **467**(7315): 555-561.

Appendices

Appendix 1. Parameters of the lake sampled in R.T. field surveys 2013 and 2014

The parameters of the 13 lakes sampled by R.T. field surveys 2013 and 2014 are listed below. When available, these parameters are indicated for every lake: latitude, longitude, surface area (km2), perimeter (km), shore index, maximum drawdown (m), year of impoundment, drainage area (km2), max depth (m), mean depth (m), volume (m3), pH, conductivity (uS), mean chlorohyll a (ug/L), mean total phosphorus (ug/L), mean color and mean secchi (m). Lakes are indicated by abbreviation: TRE=Trente-et-Un-Milles (Quebec, Canada), MEM=Memphremagog (Quebec, Canada), RAN=Rangeley (Maine, US), AYL=Aylmer (Quebec, Canada), MOO=Mooselookmeguntic (Maine, US), KEN=Kennebago (Maine, US), Ric=Richardson (Maine, US), UMB=Umbagog (Maine and New Hampshire, US), GLSF=Grand Lac Saint-François (Quebec, Canada), FRA=Francis (New Hampshire, US), Poi=Poisson Blanc (Quebec, Canada), FLA=Flagstaff (Maine, US) and AZI=Aziscohos (Maine, US).

Parameters	TRE	MEM	RAN	AYL	MOO	KEN	RIC
Latitude	46.2011	45.0859	44.9454	45.8167	44.9162	45.0935	44.831
Longitude	-75.8087	-72.2352	-70.694	-71.3604	-70.8045	-70.7188	-70.886
Surface area (km2)	48.24	95.07	25.5	30.23	65.73	7.14	31.37
Perimeter (km)	226.26	168.41	52.45	64.03	116.51	21.53	87.11
Shore index	9.19	4.87	2.93	3.29	4.05	2.27	4.39
Maximum drawdown (m)	0.31	0.41	1	1.34	1.83	2	3.05
Year of impoundment	1978	1920	1836	1953	1853	1883	1853
Drainage area (km2)	337	1779	256	1719	989	290	1222
Max depth (m)	88	107	45.42	35.65	40.23	35.36	32.92
Mean depth (m)	24	15.5	18.288	8.6	18.288	20.72	13.41
Volume (m3)	274696722	16104338871	359008300.1	227000000	693376100.5	126402997.4	181442348.8
pH	8.2	NA	7.01	7.48	7.03	7.13	6.92
Conductivity (uS)	114.5	135.1	57.5	77.77	28	26	27.5
Mean chlorohyll a (ug/L)	1.12	NA	2	5.87	4.3	2.65	3.75

Mean total phosporus (ug/L)	0	NA	4.5	0.01	6	6.5	5.5
Mean color	3	NA	15	50.67	21	33	18.5
Mean secchi (m)	7.4	NA	6.5	1.98	5.55	5.3	5.8

Continuity Appendix 1

Parameters	UMB	GLSF	FRA	POI	FLA	AZI
Latitude	44.7629	45.9026	45.0424	46.0445	45.1978	45.0173
Longitude	-71.0427	-71.1707	-71.3307	-75.7114	-70.3067	-70.9986
Surface area (km2)	30.86	49.02	7.83	71.77	70.28	27.99
Perimeter (km)	104.95	122.65	26.15	311.85	236.84	104.38
Shore index	5.33	4.94	2.64	10.38	7.97	5.57
Maximum drawdown (m)	4.57	4.97	6.18	7.18	10.97	16.76
Year of impoundment	1853	1917	1940	1930	1950	1911
Drainage area (km2)	2707	1217	442	7613	1336	554
Max depth (m)	14.63	34.77	19.81	124	15.24	18.29
Mean depth (m)	4.267	15.6	12.2	32	5.486	9.45
Volume (m3)	93982832.73	709281723	102676000	1706673794	322393443.9	194825256.3
pH	7.01	7.8	6.57	NA	NA	7.01
Conductivity (uS)	24	63	36.87	NA	40.5	28.5
Mean chlorohyll a (ug/L)	3.5	5.46	NA	NA	NA	4

Mean total phosporus (ug/L)	15	0.01	NA	NA	NA	6.5
Mean color	20	44.67	NA	NA	NA	25
Mean secchi (m)	3.65	2.42	NA	NA	NA	4.27

Appendix 2. Abundance of fish species and other animals captured by R.T. field survey 2013 and 2014

The abundance of fish species and other animals captured by R.T. field surveys 2013 and 2014 are listed below. Common name, latin name, and fish code are indicated for every fish species caught (see footnote of table 1 for details about data source). Lakes are indicated by abbreviation: TRE=Trente-et-Un-Milles (Quebec, Canada), MEM=Memphremagog (Quebec, Canada), RAN=Rangeley (Maine, US), AYL=Aylmer (Quebec, Canada), MOO=Mooselookmeguntic (Maine, US), KEN=Kennebago (Maine, US), Ric=Richardson (Maine, US), UMB=Umbagog (Maine and New Hampshire, US), GLSF=Grand Lac Saint-François (Quebec, Canada), FRA=Francis (New Hampshire, US), Poi=Poisson Blanc (Quebec, Canada), FLA=Flagstaff (Maine, US) and AZI=Aziscohos (Maine, US).

Common name	Latin name	Code	AYL	AZI	FIR	FLA	FRA	GSF	MEM	MOO
Alewife	*Alosa pseudoharengus*	ALPS								28
Atlantic salmon	*Salmo salar*	SASA			10		5	6	2	
Banded killifish	*Fundulus diaphanus*	FUDI		1				1		2
Bluegill	*Lepomis macrochirus*	LEMA	4					5	29	
Brook trout	*Salvelinus fontinalis*	SAFO		1						
Brown bullhead	*Ameiurus nebulosus*	AMNE	11	134	107		33	29		14
Burbot	*Lota lota*	LOLO			3		1			
Chain pickerel	*Esox niger*	ESNI					41		3	
Cisco	*Coregonus artedi*	COAR								
Common shiner	*Luxilus cornutus*	LUCO		68	245		6	3		2
Fallfish	*Semotilus corporalis*	SECO		19	35		134	9		75
Fallfish or common shiner	*Semotilus corporalis or luxilus cornutus*	SECO or LUCO			19			109		
Golden shiner	*Notemigonus crysoleucas*	NOCR	1			9		204	2	
Lake chub	*Couesius plumbeus*	COPL		3	31					
Lake trout	*Salvelinus namaycush*	SANA			2					
Lake whitefish	*Coregonus clupeaformis*	COCL	15							

Largemouth bass	*Micropterus salmoides*	MISA							2	
Logperch	*Percina caprodes*	PECA	7							
Longnose sucker	*Catostomus catostomus*	CACA		2			3	3		6
Northern pike	*Esox lucius*	ESLU	9			15		11		
Pearl dace	*Margariscus margarita*	MAMA						1		4
Pumpkinseed	*Lepomis gibbosus*	LEGI	12					26	13	
Rainbow smelt	*Osmerus mordax*	OSMO								
Rainbow trout	*Oncorhynchus mykiss*	ONMY					1			
Rock bass	*Ambloplites rupestris*	AMRU	20					78	78	
Round whitefish	Prosopium cylindraceum	PRCY								
Smallmouth bass	*Micropterus dolomieu*	MIDO	15					2	76	
spottail shiner	*Notropis hudsonius*	NOHU	9							
Walleye	*Sander vitreus*	SAVI	28					18		
White sucker	*Catostomus commersonii*	CACO	5	153	75	6	52	34	19	194
Yellow perch	*Perca flavescens*	PEFL	103			221		183	306	49
Fish not identified to the species level										
NA	Family: Catostomidae	NA						1		
NA	Family: centrarchidae	NA						925		
NA	Family: Cyprinidae	NA	21					1339		
NA	Genus: *Etheostoma*	NA						11		
NA	Genus: *Notropis*	NA						4	1	
NA	Genus: *Percina*	NA							3	
Not fish species										
Crayfish					69		12			1
Frog										1

LOON					1					
Mussel										
Tadpole										
Turtle										

Continuity Appendix 2

Common name	Latin name	Code	POI	RAN	RIC	TRE	UMB
Alewife	*Alosa pseudoharengus*	ALPS			37		
Atlantic salmon	*Salmo salar*	SASA			2		
Banded killifish	*Fundulus diaphanus*	FUDI		2	1		
Bluegill	*Lepomis macrochirus*	LEMA				27	
Brook trout	*Salvelinus fontinalis*	SAFO		1			
Brown bullhead	*Ameiurus nebulosus*	AMNE		1	20		21
Burbot	*Lota lota*	LOLO	18				
Chain pickerel	*Esox niger*	ESNI					8
Cisco	*Coregonus artedi*	COAR	9			12	
Common shiner	*Luxilus cornutus*	LUCO		30	66		
Fallfish	*Semotilus corporalis*	SECO	3	68	30		2
Fallfish or common shiner	*Semotilus corporalis or luxilus cornutus*	SECO or LUCO					
Golden shiner	*Notemigonus crysoleucas*	NOCR		8	8		1
Lake chub	*Couesius plumbeus*	COPL					
Lake trout	*Salvelinus namaycush*	SANA	1			3	
Lake whitefish	*Coregonus clupeaformis*	COCL	2			6	

Largemouth bass	*Micropterus salmoides*	MISA				5	
Logperch	*Percina caprodes*	PECA					
Longnose sucker	*Catostomus catostomus*	CACA	3	2			
Northern pike	*Esox lucius*	ESLU				4	
Pearl dace	*Margariscus margarita*	MAMA		35			
Pumpkinseed	*Lepomis gibbosus*	LEGI				7	2
Rainbow smelt	*Osmerus mordax*	OSMO		1			
Rainbow trout	*Oncorhynchus mykiss*	ONMY					
Rock bass	*Ambloplites rupestris*	AMRU					
Round whitefish	Prosopium cylindraceum	PRCY				1	
Smallmouth bass	*Micropterus dolomieu*	MIDO	8			22	13
spottail shiner	*Notropis hudsonius*	NOHU					
Walleye	*Sander vitreus*	SAVI	37				
White sucker	*Catostomus commersonii*	CACO	3	108	229	15	12
Yellow perch	*Perca flavescens*	PEFL	392	46	125	68	29
Fish not identified to the species level							
NA	Family: Catostomidae	NA	4				
NA	Family: centrarchidae	NA					
NA	Family: Cyprinidae	NA	25				
NA	Genus: *Etheostoma*	NA					
NA	Genus: *Notropis*	NA					
NA	Genus: *Percina*	NA					
Not fish species							
Crayfish				24	3		
Frog							

LOON								
Mussel				1				
Tadpole				1	4			
Turtle								1

Appendix 3. Lake characteristics of the 206 impounded lakes and the subset of 23 lakes for which we know the drawdown amplitude

The 206 lakes included in the impoundment databases are listed below. The drawdown (m) amplitude is indicated for the 23 lakes involved in the drawdown amplitude databases. For every lake, impoundment, drawdown amplitude (when available), area (ha), latitude, longitude, fish basin ecoregion, and data source are indicated. Fish basin ecoregions are designated with abbreviations: CB=Chesapeake Bay drainage, EHB-U=Eastern Hudson Bay-Ungava, GSLCD=Gulf St. Lawrence coastal drainage, LGL=Laurentian Great lakes, NUSCA=Northeast US and Southeast Canada Atlantic drainages, SL=St-Lawrence drainage. Data source are also identified with abbreviations: EMAP=Environmental monitoring assessment program, HQ=Hydro-Québec and R.T. 2013=R.T. field surveys 2013.

Lake id	Impoundment	Drawdown (m)	Area (ha)	Latitude	Longitude	*Fish basin ecoregion	Data source
CT500L	Impounded		64.49	41.48780	-72.20150	NUSCA	**EMAP
CT501L	Non-impoundment		39.49	41.46370	-72.14890	NUSCA	EMAP
CT502L	Non-impoundment		2.94	41.46450	-72.82900	NUSCA	EMAP
CT504L	Impounded		3.06	41.41580	-73.47890	NUSCA	EMAP
CT750L	Impounded		26.98	41.67700	-72.37590	NUSCA	EMAP
CT751L	Impounded		7.32	41.62640	-73.03340	NUSCA	EMAP
CT752L	Impounded		11.53	41.64750	-72.98820	NUSCA	EMAP
CT753L	Impounded		17.89	41.65200	-73.04760	NUSCA	EMAP
CT754L	Impounded		169.43	41.21870	-73.29190	NUSCA	EMAP
CT755L	Impounded		24.61	41.24110	-73.31900	NUSCA	EMAP
MA004L	Impounded		5.22	42.29583	-72.56639	NUSCA	EMAP
MA006L	Impounded		52.66	42.31139	-71.87889	NUSCA	EMAP
MA252L	Impounded		56.74	42.53417	-72.11528	NUSCA	EMAP
MA254L	Non-impoundment		6.89	42.15194	-71.08889	NUSCA	EMAP
MA255L	Impounded		14.65	42.14417	-71.02028	NUSCA	EMAP
MA258L	Impounded		92.92	42.10944	-71.68861	NUSCA	EMAP
MA260L	Impounded		7.94	42.07806	-73.09639	NUSCA	EMAP
MA500L	Impounded		27.36	42.33880	-71.56840	NUSCA	EMAP
MA501L	Impounded		5.24	42.34330	-72.23170	NUSCA	EMAP

MA502L	Impounded		100.47	42.28270	-72.89030	NUSCA	EMAP
MA504L	Impounded		17.06	41.951900	-71.20650	NUSCA	EMAP
MA506L	Impounded		1594.45	42.37420	-71.73320	NUSCA	EMAP
MA750L	Non-impoundment		39.12	42.57340	-71.74120	NUSCA	EMAP
MA751L	Impounded		50.83	42.50140	-72.43100	NUSCA	EMAP
MA752L	Non-impoundment		12.49	42.55110	-72.43160	NUSCA	EMAP
MA753L	Non-impoundment		8.56	42.12230	-71.37390	NUSCA	EMAP
MA754L	Non-impoundment		1.64	42.13420	-70.71060	NUSCA	EMAP
MA755L	Impounded		245.83	41.71030	-71.03650	NUSCA	EMAP
MA757L	Impounded		59.60	42.12390	-72.08860	NUSCA	EMAP
MA758L	Impounded		42.05	42.13800	-72.06120	NUSCA	EMAP
MA759L	Impounded		30.10	42.48630	-73.10670	NUSCA	EMAP
ME006L	Impounded		537.38	46.14500	-69.64806	NUSCA	EMAP
ME013L	Non-impoundment		3.35	46.97389	-68.85222	NUSCA	EMAP
ME251L	Non-impoundment		8.17	46.77778	-68.68472	NUSCA	EMAP
ME252L	Non-impoundment		663.65	46.37667	-68.97722	NUSCA	EMAP
ME253L	Non-impoundment		22.89	46.37389	-68.35806	NUSCA	EMAP
ME255L	Non-impoundment	0.00	10.29	46.34194	-69.08111	NUSCA	EMAP
ME256L	Impounded		324.10	45.96278	-70.15694	NUSCA	EMAP
ME259L	Non-impoundment		758.93	45.59972	-68.96167	NUSCA	EMAP
ME261L	Non-impoundment		35.53	45.52333	-70.52417	NUSCA	EMAP
ME263L	Non-impoundment		628.23	45.14361	-68.00139	NUSCA	EMAP
ME264L	Impounded		17.32	45.07528	-67.30111	NUSCA	EMAP
ME271L	Non-impoundment		8.02	44.26139	-70.79750	NUSCA	EMAP
ME272L	Non-impoundment		13.53	44.24333	-70.79722	NUSCA	EMAP
ME274L	Non-impoundment		5.27	43.84833	-70.44361	NUSCA	EMAP
ME275L	Non-impoundment		15.74	43.83167	-70.42583	NUSCA	EMAP
ME500L	Non-impoundment		29.53	46.55550	-68.87080	NUSCA	EMAP
ME502L	Non-impoundment		27.99	46.16280	-68.56610	NUSCA	EMAP

ME503L	Non-impoundment		31.46	46.13770	-69.24200	NUSCA	EMAP
ME504L	Non-impoundment		239.41	46.11970	-68.54210	NUSCA	EMAP
ME505L	Non-impoundment		14.78	45.32220	-69.24470	NUSCA	EMAP
ME506L	Impounded		87.44	45.70640	-69.60770	NUSCA	EMAP
ME507L	Impounded		430.13	45.74700	-69.56860	NUSCA	EMAP
ME508L	Non-impoundment		10.50	44.88550	-69.57480	NUSCA	EMAP
ME509L	Non-impoundment	0.00	15.98	44.45420	-69.92790	NUSCA	EMAP
ME510L	Non-impoundment		44.24	44.90720	-69.63450	NUSCA	EMAP
ME511L	Non-impoundment		215.07	44.86680	-71.02070	NUSCA	EMAP
ME512L	Non-impoundment		138.18	45.28100	-67.84500	NUSCA	EMAP
ME513L	Non-impoundment		122.85	44.85820	-67.49430	NUSCA	EMAP
ME514L	Non-impoundment		178.51	44.89590	-68.22820	NUSCA	EMAP
ME517L	Impounded		1278.44	44.95170	-67.40860	NUSCA	EMAP
ME519L	Non-impoundment		3292.89	47.08240	-68.40690	NUSCA	EMAP
ME520L	Impounded		341.10	45.35320	-68.46700	NUSCA	EMAP
ME521L	Non-impoundment		533.02	46.17780	-69.31620	NUSCA	EMAP
ME522L	Impounded		1888.91	44.13100	-69.49660	NUSCA	EMAP
ME524L	Impounded		875.84	45.31900	-69.84570	NUSCA	EMAP
ME525L	Impounded	0.91	711.72	44.34910	-69.95570	NUSCA	EMAP
ME526L	Impounded	4.60	3305.80	44.77410	-71.03680	NUSCA	EMAP
ME750L	Non-impoundment		46.97	47.19980	-68.72180	NUSCA	EMAP
ME751L	Non-impoundment	0.00	350.85	46.77040	-69.83290	NUSCA	EMAP
ME753L	Non-impoundment		2.72	46.80500	-69.06810	NUSCA	EMAP
ME754L	Non-impoundment		69.42	45.50890	-69.40400	NUSCA	EMAP
ME755L	Non-impoundment		9.40	45.52250	-69.40040	NUSCA	EMAP
ME756L	Non-impoundment		454.48	45.51880	-68.73400	NUSCA	EMAP
ME757L	Non-impoundment		52.10	44.66320	-68.72370	NUSCA	EMAP
ME759L	Non-impoundment		7.20	45.08660	-69.77450	NUSCA	EMAP
ME761L	Non-impoundment		553.32	46.03790	-69.09810	NUSCA	EMAP

ME762L	Non-impoundment		1178.71	45.62680	-70.08340	NUSCA	EMAP
ME763L	Non-impoundment		1037.11	44.64930	-69.33050	NUSCA	EMAP
ME764L	Impounded		715.94	45.04940	-67.57470	NUSCA	EMAP
NH006L	Non-impoundment		17.54	42.74750	-71.55056	NUSCA	EMAP
NH007L	Impounded		1.12	44.87250	-71.32028	NUSCA	EMAP
NH250L	Non-impoundment		8.38	43.84056	-71.12778	NUSCA	EMAP
NH251L	Non-impoundment		35.41	43.82389	-71.10472	NUSCA	EMAP
NH253L	Impounded		58.74	43.40833	-71.42028	NUSCA	EMAP
NH254L	Impounded		0.62	43.39083	-71.49083	NUSCA	EMAP
NH500L	Non-impoundment		6.72	43.19010	-70.93300	NUSCA	EMAP
NH501L	Impounded		147.09	43.19260	-70.95380	NUSCA	EMAP
NH502L	Non-impoundment		19.34	43.60920	-71.97010	NUSCA	EMAP
NH503L	Non-impoundment		16.52	44.00910	-71.65380	NUSCA	EMAP
NH504L	Impounded		134.51	43.18130	-71.59260	NUSCA	EMAP
NH505L	Non-impoundment		135.34	43.62240	-71.26590	NUSCA	EMAP
NH506L	Impounded		152.30	42.79590	-71.25850	NUSCA	EMAP
NH507L	Impounded		14.19	42.73940	-71.90740	NUSCA	EMAP
NH508L	Impounded		12.81	42.73950	-71.93450	NUSCA	EMAP
NH751L	Non-impoundment		22.47	43.78700	-71.49390	NUSCA	EMAP
NH752L	Impounded		74.64	42.93750	-72.07700	NUSCA	EMAP
NH753L	Non-impoundment		15.84	42.97490	-72.10480	NUSCA	EMAP
NH754L	Impounded		24.83	44.19970	-71.86710	NUSCA	EMAP
NH755L	Impounded	0.91	37.01	42.93880	-72.13520	NUSCA	EMAP
NH756L	Impounded		16.11	42.94360	-72.12810	NUSCA	EMAP
NH757L	Impounded		47.11	42.95720	-72.12270	NUSCA	EMAP
NH758L	Impounded		1039.22	42.99370	-71.35490	NUSCA	EMAP
NH759L	Impounded		447.97	45.15510	-71.17150	NUSCA	EMAP
NJ250L	Impounded		5.09	40.75111	-74.62361	NUSCA	EMAP
NJ252L	Impounded		4.32	39.45083	-74.75528	NUSCA	EMAP

NJ500L	Impounded		219.88	40.98240	-74.44020	NUSCA	EMAP
NJ503L	Non-impoundment		25.26	39.65340	-74.65340	NUSCA	EMAP
NJ504L	Impounded		8.64	39.61170	-75.25380	NUSCA	EMAP
NJ505L	Impounded		22.96	39.22620	-74.88460	NUSCA	EMAP
NJ751L	Impounded		3.86	40.31210	-74.54490	NUSCA	EMAP
NJ752L	Impounded		32.06	39.85370	-74.79280	NUSCA	EMAP
NJ753L	Impounded		11.57	39.87300	-74.83410	NUSCA	EMAP
NJ755L	Impounded		918.37	40.61620	-74.82910	NUSCA	EMAP
NY024L	Non-impoundment		3.99	43.00639	-76.04167	LGL	EMAP
NY031L	Non-impoundment		34.14	44.35333	-74.49833	SL	EMAP
NY042L	Non-impoundment		102.89	43.54222	-73.70333	SL	EMAP
NY250L	Non-impoundment		6.67	44.51972	-74.69333	SL	EMAP
NY254L	Impounded		1677.01	43.78472	-73.77722	NUSCA	EMAP
NY255L	Non-impoundment		13.20	43.73444	-73.87833	NUSCA	EMAP
NY256L	Non-impoundment		15.97	43.31528	-74.19444	NUSCA	EMAP
NY257L	Impounded		963.51	43.29167	-75.44306	NUSCA	EMAP
NY266L	Non-impoundment		7.92	41.59917	-74.67111	NUSCA	EMAP
NY268L	Impounded		730.89	41.23500	-73.75972	NUSCA	EMAP
NY273L	Non-impoundment		7.18	40.77583	-73.97167	NUSCA	EMAP
NY500L	Impounded		50.71	44.40980	-73.44430	SL	EMAP
NY501L	Non-impoundment		10.14	44.32910	-74.11880	SL	EMAP
NY502L	Impounded		11.94	43.95180	-73.74680	NUSCA	EMAP
NY503L	Impounded		133.34	43.52530	-74.02240	NUSCA	EMAP
NY506L	Non-impoundment		8.73	43.03980	-74.99320	NUSCA	EMAP
NY508L	Non-impoundment		2.66	42.23690	-74.24810	NUSCA	EMAP
NY509L	Impounded		2.12	41.37350	-74.18580	NUSCA	EMAP
NY510L	Impounded		23.34	40.96020	-73.80410	NUSCA	EMAP
NY511L	Impounded		7.54	42.54360	-76.01180	CB	EMAP
NY516L	Non-impoundment		38.93	43.89910	-74.44960	SL	EMAP

NY517L	Impounded		4.37	42.11120	-76.21870	CB	EMAP
NY520L	Non-impoundment		499.83	43.85190	-74.47140	SL	EMAP
NY521L	Impounded		608.15	41.85090	-74.66260	NUSCA	EMAP
NY522L	Impounded		1229.66	44.41190	-74.74040	SL	EMAP
NY750L	Non-impoundment		13.57	43.73930	-73.57830	SL	EMAP
NY752L	Impounded		114.40	42.44300	-74.45520	NUSCA	EMAP
NY754L	Impounded		8.61	42.01080	-74.07320	NUSCA	EMAP
NY757L	Non-impoundment		19.29	41.57240	-74.9820	NUSCA	EMAP
NY758L	Non-impoundment		15.47	42.77660	-75.49610	CB	EMAP
NY759	Non-impoundment		91.22	42.77460	-76.13550	LGL	EMAP
NY760L	Non-impoundment		10.03	42.33170	-75.79900	CB	EMAP
NY761L	Impounded		19.66	42.56150	-78.85190	LGL	EMAP
NY763L	Non-impoundment		4.58	42.69880	-76.81210	LGL	EMAP
NY764L	Non-impoundment		10.79	43.65040	-74.91030	LGL	EMAP
NY765L	Non-impoundment		4.53	43.65900	-74.88370	LGL	EMAP
NY767L	Non-impoundment		62.70	44.09420	-74.64270	SL	EMAP
NY768L	Impounded		99.58	44.11440	-74.65480	SL	EMAP
NY769L	Non-impoundment		158.95	44.13190	-74.61900	SL	EMAP
NY775L	Impounded		1057.30	43.408400	-74.55260	NUSCA	EMAP
NY776L	Non-impoundment		781.13	43.12520	-76.48230	LGL	EMAP
NY778L	Impounded		840.51	43.74090	-74.88160	LGL	EMAP
RI500L	Impounded		6.38	41.52240	-71.52260	NUSCA	EMAP
RI750L	Impounded		69.95	41.68000	-71.68200	NUSCA	EMAP
VT252L	Non-impoundment		6.66	43.78500	-73.18056	SL	EMAP
VT253L	Impounded		31.06	43.76528	-73.18389	SL	EMAP
VT500L	Non-impoundment		1.41	44.41370	-72.04080	NUSCA	EMAP
VT501L	Impounded		12.66	42.74270	-72.61140	NUSCA	EMAP
VT502L	Impounded	6.40	351.13	44.40380	-72.74990	SL	EMAP
VT750L	Impounded		53.78	43.34680	-72.50650	NUSCA	EMAP

VT751L	Non-impoundment		23.23	43.38100	-72.50100	NUSCA	EMAP
VT752L	Non-impoundment		13.18	44.64400	-72.20430	SL	EMAP
VT753L	Impounded	0.30	85.26	44.66870	-72.22500	SL	EMAP
TEM	Non-impoundment	3.96	29485.00	47.401667	-79.53306	SL	***HQ
OPI	Impounded	3.60	104000.00	52.643603	-76.33530	EHB-U	HQ
RON	Non-impoundment		1470.37	52.565115	-77.07933	EHB-U	HQ
ROB	Impounded	3.30	281500.00	53.763339	-77.00484	EHB-U	HQ
DES	Impounded	4.50	1140.00	53.567966	-77.55692	EHB-U	HQ
DET	Non-impoundment		811.36	53.454393	-77.43035	EHB-U	HQ
BLA	Impounded	7.90	8200.00	47.754339	-73.20577	SL	HQ
LEO	Non-impoundment		54.06	47.797222	-73.51944	SL	HQ
MAR	Non-impoundment		89.72	48.294444	-73.88611	SL	HQ
AO5	Non-impoundment		12.89	48.305556	-73.85833	SL	HQ
BRE	Non-impoundment		78.17	47.86936	-73.81162	SL	HQ
SEA	Non-impoundment		19.47	47.779167	-73.53750	SL	HQ
FRA	Non-impoundment		17.17	47.797432	-73.54016	SL	HQ
MAX	Non-impoundment		18.13	47.786667	-73.50556	SL	HQ
DIN	Non-impoundment		70.87	47.763611	-73.56889	SL	HQ
REJ	Non-impoundment		35.17	48.413889	-73.95417	SL	HQ
MIG	Non-impoundment		14.25	48.37000	-73.91944	SL	HQ
DEV	Non-impoundment		43.66	48.521667	-73.97500	SL	HQ
BOB	Non-impoundment		409.99	47.748611	-73.51944	SL	HQ
LIE	Non-impoundment		86.86	47.778372	-73.52055	SL	HQ
RHE	Non-impoundment		407.65	47.890278	-73.41278	SL	HQ
GOU	Impounded	1.50	130276.00	48.621639	-74.80583	SL	HQ
CEC	Non-impoundment		8.00	46.619722	-74.57639	SL	HQ
FAG	Non-impoundment		382.75	48.545558	-74.08050	SL	HQ
LEV	Non-impoundment		1059.05	48.470496	-74.02255	SL	HQ
RIN	Non-impoundment		154.49	48.41199	-73.66265	SL	HQ

BAS	Impounded	12.00	29500.00	46.801944	-75.78417	SL	HQ
DIS	Non-impoundment		1513.34	49.845006	-69.78594	GSLCD	HQ
JEA	Non-impoundment		2719.00	47.063611	-76.62694	SL	HQ
TET	Non-impoundment		2879.30	51.00624	-69.40761	GSLCD	HQ
MAN	Impounded	4.80	195000.00	51.306407	-68.33326	GSLCD	HQ
OUT2	Impounded	0.30	3969.00	49.16040	-68.40070	GSLCD	HQ
OUT4	Impounded	6.80	65300.00	49.705616	-68.90581	GSLCD	HQ
TRE	Impounded	0.31	4824.00	46.20110	-75.80870	SL	R.T. 2013
MEM	Impounded	0.41	9507.00	45.08590	-72.23520	SL	R.T. 2013
AYL	Impounded	1.34	3023.00	45.81670	-71.36040	SL	R.T. 2013
GSF	Impounded	4.97	4902.00	45.90260	-71.17070	SL	R.T. 2013
POI	Impounded	7.18	7177.00	46.04450	-75.71140	SL	R.T. 2013

* US Army Corps of Engineers http://nid.usace.army.mil/

** US Environmental Protection Agency https://archive.epa.gov/emap/archive-emap/web/html/nelakes.html

*** Gendron 1990, Faucher and Gilbert 1992, Doyon and Belzile 1998, Lacasse 1999

Appendix 4. Fishing gear and sampling techniques from the three different data sources

For the three different sources of data (Hydro Québec, Environmental monitoring and assessment program, and R.T. 2013 field surveys), the year and season of sampling, the fishing gear used, and the sampling techniques are registered. Because the year and season of sampling, the fishing gear, as well as the fishing technique differ between the lakes from Hydro Quebec surveys, the information is registered for every lake included in our databases. For EMAP and R.T. 2013, the information registered applies for all lakes included in our databases. See footnotes of Appendix 3 for details about data sources.

<table>
<tr><th>Lake id</th><th>Source of data</th><th>Year</th><th>Season</th><th>Fishing gear</th><th>Sampling technique</th></tr>
<tr><td>ROB</td><td>HQ</td><td rowspan="5">1977-1984, 1988, 1992, 1996</td><td rowspan="5">Summer and fall, 1996 (summer only)</td><td rowspan="10">2 nets of uniform mesh sizes (76mm and 102mm), 45.7m long and 2.4m height; experimental gillnet of 6 pannels (stretched mesh from 25mm to 102mm), 45.7m long and 2.4 m height</td><td rowspan="5">Experimental gillnet coupled to a uniform mesh size net, the pair of nets is set perpendicular to shore, one begining at the end of the previous one:
102 mm uniform mesh size net towards shore, smallest mesh of experimental gillnet further offshore;
Smallest mesh of the experimental gillnet towards shore, 76mm uniform further offshore</td></tr>
<tr><td>OPI</td><td>HQ</td></tr>
<tr><td>DES</td><td>HQ</td></tr>
<tr><td>RON</td><td>HQ</td></tr>
<tr><td>DET</td><td>HQ</td></tr>
<tr><td>GOU</td><td>HQ</td><td>1990</td><td>Summer and fall</td><td rowspan="5">Experimental gillnet coupled to a uniform mesh size net, the pair of nets is set perpendicular to shore, one beginning at the end of the previous one:
76 mm uniform mesh size net towards shore, largest mesh of experimental gillnet further offshore;</td></tr>
<tr><td>RHE</td><td>HQ</td><td>1990</td><td>Summer and fall</td></tr>
<tr><td>LEV</td><td>HQ</td><td>1990</td><td>Summer and fall</td></tr>
<tr><td>FAG</td><td>HQ</td><td>1990</td><td>Summer and fall</td></tr>
<tr><td>RIN</td><td>HQ</td><td>1990</td><td>Summer and fall</td></tr>
</table>

CEC	HQ	1990	Summer and fall		Smallest mesh of the experimental gillnet towards shore, 102mm uniform further offshore
BOB	HQ	1990-1991	Summer and fall		
BRE	HQ	1990-1991	Summer and fall		
LIE	HQ	1990-1991	Summer and fall		
MAR	HQ	1990-1991	Summer and fall		
LEO	HQ	1991	Summer and fall		
AO5	HQ	1991	Summer and fall		
SEA	HQ	1991	Summer and fall		
FRA	HQ	1991	Summer and fall		
MAX	HQ	1991	Summer and fall		
DIN	HQ	1991	Summer and fall		
REJ	HQ	1991	Summer and fall		
MIG	HQ	1991	Summer and fall		
DEV	HQ	1991	Summer and fall		
BLA	HQ	1991	Summer and fall	2 experimental gillnets of 8 panels (stretched mesh of 25mm to 153mm),	Nets are set perpendicular to shore

				60.9m long and 1.8m height	
OUT2	HQ	1982-1983	Summer (only 1982) and fall (only 1983)	Experimental gillnet of 6 panels (stretched mesh from 25mm to 102mm), 45.7m long and 2.4 m height	NA
MAN	HQ	1989	Summer and fall	Experimental gillnets of 8 panels (stretched mesh of 25mm to 153mm), 60.9m long and 1.8m height Net of uniform mesh sizes (102mm)	NA
TET	HQ	1989	Summer and fall	NA	NA
DIS	HQ	1989	Summer and fall	NA	Nets are set perpendicular to shore
OUT4	HQ	1989	Summer and fall	NA	NA
JEA	HQ	1988-1989	Fall	NA	NA
BAS	HQ	1989	Fall	NA	NA

TEM	HQ	1987-1988, 1996, 1998	Summer	Net of uniform mesh sizes (127mm) (1987); experimental gillnet of 8 panels (stretched mesh from 25mm to 152mm), 60.9m long (1987-1988, 1998); experimental gillnet of 6 panels (stretched mesh from 25mm to 102mm), 45.7m long and 2.4 m height (1996, 1998)	
All 167 lakes	EMAP	1991-1994	NA	Gillnet , 1.5m height	When deployed in the littoral zone, gillnets are set parallel to shore.
5 lakes	R.T. 2013	2013	Summer	Experimental gillnets of 6 panels (stretched mesh of 1, 1.5, 2, 2.5, 3 and 3.5 inches), 7m long and 2m height; Experimental gillnet of 6 panels (stretched mesh of 1, 1.5, 2, 2.5, 3 and 4 inches), 7m long and 2m height; Experimental gillnet of 8 panels (stretched mesh of 1, 1.5, 2, 2.5, 3, 4, 5, and 6 inches), 7m long and 2 m height.	The 6 panel experimental gillnets were set in the littoral zone, perpendicular to shore and smallest mesh size towards shore; The 8 panel experimental gillnet was randomly set in the bottom of the pelagic zone.

Appendix 5. Predictors and interactions comprised in the best models explaining the variation in the presence-absence, and relative abundance of individual fish species from non-impounded and impounded lakes

For each fish species and database (presence-absence and relative abundance), predictors included in models with AICc between 2 AICc units of the best model are incorporated in the table. For each predictor or interaction between predictors, the estimate, standard error (std. Error), 95% confidence interval (C.I.), and normalised Akaike weights ($W_{im.}$) are shown. Bold numbers and grey shadowing identify the significant predictor or interaction.

Fish species	Predictor	Impoundment							
		Presence-absence				Relative abundance (of presence only)			
		Estimate	Std. Error	C.I.	W imp.	Estimate	Std. Error	C.I.	W imp.
AMNE	Intercept	-0.481	0.262	-0.995, 0.033	1.000	***2.242***	***0.154***	***1.939, 2.544***	***1.000***
	Impoundment	0.562	0.415	-0.25, 1.37	0.698	-	-	-	-
	Area	0.396	0.281	-0.15, 0.95	0.806	-0.727	0.171	-1.06, -0.39	1.000
	Latitude	***-1.889***	***0.428***	***-2.73, -1.05***	***1.000***	0.383	0.207	-0.02, 0.79	0.664
	Longitude	***0.531***	***0.197***	***0.14, 0.92***	***1.000***	-	-	-	-
	Impoundment * Area	0.482	0.402	-0.31, 1.27	0.124	-	-	-	-
	Impoundment * Latitude	0.881	0.525	-0.15, 1.91	0.404	-	-	-	-
	Impoundment * Longitude	-	-	-	-	-	-	-	-
CACO	Intercept	***1.436***	***0.466***	***0.522, 2.350***	***1.000***	***2.420***	***0.123***	***2.179, 2.660***	***1.000***
	Impoundment	-0.606	0.553	-1.690, 0.478	0.790	0.267	0.185	-0.096, 0.630	0.456
	Area	***2.025***	***0.687***	***0.678, 3.373***	***1.000***	***-0.553***	***0.105***	***-0.758, -0.347***	***1.000***
	Latitude	***0.891***	***0.308***	***0.287, 1.494***	***1.000***	***0.743***	***0.107***	***0.534, 0.953***	***1.000***
	Longitude	-0.090	0.224	-0.530, 0.350	0.168	0.079	0.076	-0.069, 0.227	0.342
	Impoundment * Area	***-1.482***	***0.672***	***-2.800, -0.164***	***0.790***	-	-	-	-
	Impoundment * Latitude	0.301	0.602	-0.880, 1.481	0.175	-	-	-	-

	Impoundment * Longitude	-	-	-	-	-	-	-	-
COCL	Intercept	***-5.556***	***1.495***	***-8.487, -2.625***	***1.000***	***3.811***	***0.264***	***3.293, 4.329***	***1.000***
	Impoundment	1.636	1.648	-1.594, 4.866	0.389	***-3.587***	***0.607***	***-4.777, -2.396***	***1.000***
	Area	***2.216***	***0.737***	***0.772, 3.660***	***1.000***	-0.120	0.235	-0.580, 0.339	1.000
	Latitude	***3.203***	***0.930***	***1.380, 5.026***	***1.000***	-	-	-	-
	Longitude	***-2.237***	***0.778***	***-3.762, -0.712***	***1.000***	***0.469***	***0.119***	***0.235, 0.702***	***1.000***
	Impoundment * Area	-	-	-	-	***1.225***	***0.340***	***0.558, 1.892***	***1.000***
	Impoundment * Latitude	-	-	-	-	-	-	-	-
	Impoundment * Longitude	-	-	-	-	-	-	-	-
ESLU	Intercept	***-3.419***	***0.655***	***-4.703, -2.135***	***1.000***	***1.649***	***0.328***	***1.006, 2.292***	***1.000***
	Impoundment	***1.722***	***0.777***	***0.199, 3.244***	***1.000***	-0.800	0.471	-1.724, 0.124	0.611
	Area	0.243	0.366	-0.475, 0.961	0.158	-0.499	0.266	-1.020, 0.023	1.000
	Latitude	***2.250***	***0.504***	***1.261, 3.239***	***1.000***	***0.775***	***0.205***	***0.374, 1.176***	***1.000***
	Longitude	***-1.252***	***0.353***	***-1.944, -0.560***	***1.000***	0.196	0.146	-0.090, 0.483	0.368
	Impoundment * Area	-	-	-	-	***0.729***	***0.282***	***0.175, 1.282***	***0.611***
	Impoundment * Latitude	1.234	0.924	-0.576, 3.045	0.482	-	-	-	-
	Impoundment * Longitude	-0.358	0.700	-1.729, 1.014	0.137	-	-	-	-
ESNI	Intercept	***-1.483***	***0.295***	***-2.061, -0.905***	***1.000***	***0.734***	***0.317***	***0.112, 1.355***	***1.000***
	Impoundment	-0.063	0.498	-1.039, 0.912	0.480	0.486	0.295	-0.091, 1.064	0.461
	Area	0.399	0.256	-0.103, 0.901	0.604	***-1.371***	***0.488***	***-2.328, -0.415***	***1.000***
	Latitude	***-2.225***	***0.593***	***-3.388, -1.062***	***1.000***	0.357	0.246	-0.126, 0.839	0.319
	Longitude	***1.083***	***0.277***	***0.540, 1.626***	***1.000***	0.281	0.157	-0.027, 0.589	0.543

	Impoundment * Area	1.001	0.611	-0.198, 2.199	0.335	***0.893***	***0.442***	***0.026, 1.759***	***0.461***
	Impoundment * Latitude	-	-	-	-	-	-	-	-
	Impoundment * Longitude	-	-	-	-	-	-	-	-
LEGI	Intercept	***-0.655***	***0.279***	***-1.201, -0.109***	***1.000***	***1.386***	***0.230***	***0.936, 1.837***	***1.000***
	Impoundment	0.617	0.434	-0.234, 1.468	0.700	0.271	0.256	-0.230, 0.773	0.700
	Area	0.467	0.245	-0.014, 0.948	0.819	***-1.171***	***0.320***	***-1.798, -0.543***	***1.000***
	Latitude	***-2.195***	***0.540***	***-3.254, -1.137***	***1.000***	-	-	-	-
	Longitude	***0.541***	***0.229***	***0.092, 0.991***	***1.000***	-0.164	0.166	-0.490, 0.161	0.849
	Impoundment * Area	-	-	-	-	0.603	0.326	-0.037, 1.243	0.700
	Impoundment * Latitude	1.061	0.607	-0.128, 2.251	0.542	-	-	-	-
	Impoundment * Longitude	-0.317	0.426	-1.151, 0.518	0.113	-0.333	0.235	-0.794, 0.127	0.274
LEMA	Intercept	-4.176	2.205	-8.498, 0.146	1.000	***2.422***	***0.336***	***1.765, 3.080***	***1.000***
	Impoundment	0.790	0.928	-1.029, 2.609	0.307	-0.494	0.379	-1.237, 0.249	0.401
	Area	0.225	0.315	-0.392, 0.842	0.172	***-0.871***	***0.222***	***-1.306, -0.436***	***1.000***
	Latitude	***-3.230***	***0.792***	***-4.782, -1.677***	***1.000***	-	-	-	-
	Longitude	0.137	0.310	-0.469, 0.744	0.147	-0.330	0.232	-0.785, 0.124	0.392
	Impoundment * Area	-	-	-	-	-	-	-	-
	Impoundment * Latitude	1.775	1.300	-0.774, 4.323	0.157	-	-	-	-
	Impoundment * Longitude	-	-	-	-	-	-	-	-
LOLO	Intercept	***-5.288***	***1.109***	***-7.462, -3.113***	***1.000***	***4.679***	***1.791***	***1.169, 8.189***	***1.000***
	Impoundment	0.528	1.163	-1.752, 2.807	0.222	-	-	-	-
	Area	***1.793***	***0.526***	***0.761, 2.825***	***1.000***	-	-	-	-

	Latitude	***3.092***	***0.886***	***1.355, 4.829***	***1.000***	-	-	-	-
	Longitude	-0.130	0.398	-0.911, 0.651	0.211	-2.116	1.198	-4.464, 0.232	0.569
	Impoundment * Area	-	-	-	-	-	-	-	-
	Impoundment * Latitude	-	-	-	-	-	-	-	-
	Impoundment * Longitude	-	-	-	-	-	-	-	-
MIDO	Intercept	***-1.625***	***0.236***	***-2.088, -1.163***	***1.000***	***0.594***	***0.284***	***0.038, 1.149***	***1.000***
	Impoundment	-	-	-	-	***1.120***	***0.340***	***0.453, 1.786***	***1.000***
	Area	***1.643***	***0.284***	***1.087, 2.199***	***1.000***	-	-	-	-
	Latitude	***-1.391***	***0.318***	***-2.013, -0.769***	***1.000***	-	-	-	-
	Longitude	0.327	0.201	-0.067, 0.720	0.583	-0.282	0.200	-0.673, 0.109	0.308
	Impoundment * Area	-	-	-	-	-	-	-	-
	Impoundment * Latitude	-	-	-	-	-	-	-	-
	Impoundment * Longitude	-	-	-	-	0.501	0.288	-0.064, 1.065	0.308
MISA	Intercept	***-1.790***	***0.477***	***-2.724, -0.855***	***1.000***	***5.554***	***1.941***	***1.750, 9.358***	***1.000***
	Impoundment	1.131	0.578	-0.001, 2.263	1.000	-2.956	3.756	-10.317, 4.406	0.460
	Area	0.772	0.722	-0.644, 2.187	0.431	-1.672	1.122	-3.872, 0.528	0.429
	Latitude	***-4.773***	***1.189***	***-7.103, -2.442***	***1.000***	3.748	3.676	-3.456, 10.952	0.384
	Longitude	0.189	0.255	-0.311, 0.689	0.180	-0.478	1.029	-2.494, 1.538	0.075
	Impoundment * Area	-1.271	0.720	-2.681, 0.140	0.280	-	-	-	-
	Impoundment * Latitude	***2.884***	***1.293***	***0.350, 5.418***	***1.000***	***-8.448***	***3.559***	***-15.424, -1.471***	***0.303***
	Impoundment * Longitude	-	-	-	-	-	-	-	-
NOCR	Intercept	-0.022	0.233	-0.478, 0.434	1.000	***2.607***	***0.181***	***2.253, 2.961***	***1.000***

	Impoundment	0.186	0.401	-0.600, 0.972	0.609	-0.161	0.298	-0.745, 0.422	0.190
	Area	0.439	0.274	-0.098, 0.975	0.781	***-1.255***	***0.191***	***-1.629, -0.880***	***1.000***
	Latitude	***-2.029***	***0.501***	***-3.010, -1.048***	***1.000***	***0.841***	***0.283***	***0.287, 1.395***	***1.000***
	Longitude	***0.631***	***0.197***	***0.244, 1.018***	***1.000***	-0.224	0.184	-0.584, 0.136	0.347
	Impoundment * Area	-0.510	0.479	-1.448, 0.428	0.147	-	-	-	-
	Impoundment * Latitude	1.047	0.563	-0.055, 2.150	0.609	-	-	-	-
	Impoundment * Longitude	-	-	-	-	-	-	-	-
OSMO	Intercept	***-1.997***	***0.390***	***-2.761, -1.232***	***1.000***	***2.908***	***0.336***	***2.251, 3.566***	***1.000***
	Impoundment	-1.006	0.560	-2.104, 0.092	0.801	0.825	0.628	-0.406, 2.056	0.479
	Area	***1.844***	***0.424***	***1.013, 2.674***	***1.000***	***-0.818***	***0.365***	***-1.532, -0.103***	***1.000***
	Latitude	***-1.398***	***0.467***	***-2.313, -0.483***	***1.000***	-	-	-	-
	Longitude	***0.939***	***0.253***	***0.444, 1.435***	***1.000***	-	-	-	-
	Impoundment * Area	-0.284	0.524	-1.312, 0.744	0.177	***-1.150***	***0.519***	***-2.167, -0.132***	***0.278***
	Impoundment * Latitude	0.322	0.554	-0.765, 1.408	0.181	-	-	-	-
	Impoundment * Longitude	-	-	-	-	-	-	-	-
PEFL	Intercept	***1.104***	***0.219***	***0.675, 1.534***	***1.000***	***3.577***	***0.080***	***3.419, 3.734***	***1.000***
	Impoundment	-0.195	0.410	-0.999, 0.609	0.282	-0.142	0.135	-0.406, 0.122	0.246
	Area	***1.218***	***0.259***	***0.710, 1.726***	***1.000***	-0.101	0.080	-0.258, 0.056	0.284
	Latitude	***-1.048***	***0.230***	***-1.499, -0.597***	***1.000***	***-0.310***	***0.078***	***-0.463, -0.158***	***1.000***
	Longitude	***-0.465***	***0.182***	***-0.820, -0.109***	***1.000***	***0.197***	***0.065***	***0.069, 0.325***	***1.000***
	Impoundment * Area	-	-	-	-	-	-	-	-
	Impoundment * Latitude	-	-	-	-	-	-	-	-

	Impoundment * Longitude	-	-	-	-	-	-	-	-
SAFO	Intercept	***-1.295***	***0.297***	***-1.876, -0.713***	***1.000***	***25.152***	***6.336***	***12.733, 37.571***	***1.000***
	Impoundment	-0.710	0.478	-1.647, 0.227	0.767	-18.840	13.209	-44.729, 7.050	0.525
	Area	-0.488	0.253	-0.985, 0.008	0.789	***-15.576***	***7.002***	***-29.300, -1.851***	***1.000***
	Latitude	***0.790***	***0.281***	***0.239, 1.340***	***1.000***	5.378	7.219	-8.771, 19.527	0.135
	Longitude	0.329	0.207	-0.078, 0.735	0.647	-	-	-	-
	Impoundment * Area	-	-	-	-	18.863	10.957	-2.614, 40.340	0.301
	Impoundment * Latitude	0.502	0.389	-0.260, 1.264	0.250	-	-	-	-
	Impoundment * Longitude	-0.531	0.393	-1.300, 0.238	0.240	-	-	-	-
SANA	Intercept	***-3.077***	***0.410***	***-3.880, -2.273***	***1.000***	***2.785***	***0.289***	***2.219, 3.351***	***1.000***
	Impoundment	0.181	0.593	-0.981, 1.343	0.156	***-0.719***	***0.337***	***-1.380, -0.057***	***1.000***
	Area	***1.504***	***0.308***	***0.899, 2.108***	***1.000***	***-0.749***	***0.135***	***-1.014, -0.484***	***1.000***
	Latitude	-0.119	0.308	-0.723, 0.485	0.160	-	-	-	-
	Longitude	-0.262	0.243	-0.739, 0.215	0.269	***0.763***	***0.197***	***0.377, 1.150***	***1.000***
	Impoundment * Area	-	-	-	-	-	-	-	-
	Impoundment * Latitude	-	-	-	-	-	-	-	-
	Impoundment * Longitude	-	-	-	-	***-0.888***	***0.235***	***-1.349, -0.427***	***1.000***
SECO	Intercept	***-1.488***	***0.326***	***-2.126, -0.850***	***1.000***	***1.744***	***0.756***	***0.261, 3.226***	***1.000***
	Impoundment	-0.814	0.593	-1.977, 0.349	1.000	-1.103	0.806	-2.683, 0.476	0.742
	Area	0.586	0.354	-0.109, 1.280	1.000	0.126	0.405	-0.668, 0.921	0.292
	Latitude	***0.860***	***0.347***	***0.180, 1.541***	***1.000***	***1.152***	***0.570***	***0.035, 2.269***	***0.613***
	Longitude	0.196	0.182	-0.160, 0.552	0.382	***-0.852***	***0.236***	***-1.314, -0.390***	***0.601***
	Impoundment * Area	0.949	0.566	-0.160, 2.059	0.605	-	-	-	-

	Impoundment * Latitude	***-1.316***	***0.590***	***-2.473, -0.159***	***1.000***	***-1.173***	***0.562***	***-2.274, -0.072***	***0.141***
	Impoundment * Longitude	-	-	-	-	***1.330***	***0.413***	***0.519, 2.140***	***0.601***
SAVI	Intercept	***-3.610***	***0.644***	***-4.872, -2.347***	***1.000***	***1.736***	***0.583***	***0.594, 2.878***	***1.000***
	Impoundment	-0.507	0.964	-2.396, 1.382	0.287	-0.998	0.663	-2.298, 0.301	0.717
	Area	***0.898***	***0.395***	***0.123, 1.673***	***1.000***	0.157	0.205	-0.244, 0.559	1.000
	Latitude	***1.781***	***0.435***	***0.927, 2.634***	***1.000***	***0.816***	***0.201***	***0.422, 1.209***	***0.717***
	Longitude	***-2.166***	***0.510***	***-3.166, -1.166***	***1.000***	-	-	-	-
	Impoundment * Area	-	-	-	-	***1.957***	***0.389***	***1.195, 2.719***	***0.717***
	Impoundment * Latitude	-	-	-	-	***-2.133***	***0.281***	***-2.684, -1.582***	***0.717***
	Impoundment * Longitude	-	-	-	-	-	-	-	-

Appendix 6. Predictors and interactions comprised in the best models explaining the variation in the presence-absence and relative abundance of individual fish species from lakes of known drawdown amplitude

For each fish species and database (presence-absence and relative abundance), predictors included in models with AICc between 2 AICc units of the best model are incorporated in the table. For each predictor or interaction between predictors, the estimate, standard error (std. Error), 95% confidence interval (C.I.), and normalised Akaike weights ($W_{im.}$) are shown. Bold numbers and grey shadowing identify the significant predictor or interaction.

Fish species	Predictor	Drawdown amplitude							
		Presence-absence				Relative abundance (of presence only)			
		Estimate	Std. Error	C.I.	W imp.	Estimate	Std. Error	C.I.	W imp.
AMNE	Intercept	-12.901	8.239	-29.049, 3.247	1.000	-	-	-	-
	Drawdown amplitude	-12.531	8.586	-29.360, 4.298	1.000	-	-	-	-
	Area	-	-	-	-	-	-	-	-
	Latitude	-27.342	17.982	-62.587, 7.903	1.000	-	-	-	-
	Longitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-
	Drawdown amplitude * Latitude	-31.018	20.636	-71.465, 9.429	1.000	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
CACO	Intercept	14.228	19.771	-24.523, 52.979	-	***2.471***	***0.108***	***2.258, 2.683***	***1.000***
	Drawdown amplitude	16.329	17.379	-17.734, 50.392	0.413	-	-	-	-
	Area	-16.932	16.176	-48.637, 14.773	0.413	***-0.602***	***0.149***	***-0.894, -0.311***	***1.000***
	Latitude	-	-	-	-	***0.503***	***0.138***	***0.232, 0.774***	***1.000***
	Longitude	-3.366	2.563	-8.389, 1.657	0.587	-	-	-	-

	Drawdown amplitude * Area	-22.126	19.919	-61.168, 16.916	0.413	-	-	-	-
	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
COCL	Intercept	6.070	5.038	-3.804, 15.944	1.000	***12.682***	***3.828***	***5.179, 20.185***	***1.000***
	Drawdown amplitude	-	-	-	-	-	-	-	-
	Area	6.862	5.025	-2.987, 16.711	1.000	***15.232***	***4.647***	***6.124, 24.341***	***1.000***
	Latitude	13.831	10.980	-7.690, 35.352	1.000	5.397	2.776	-0.043, 10.837	0.376
	Longitude	-	-	-	-	***11.159***	***2.269***	***6.712, 15.605***	***1.000***
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-
	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
ESLU	Intercept	1.643	0.977	-0.271, 3.557	1.000	***1.776***	***0.214***	***1.356, 2.196***	***1.000***
	Drawdown amplitude	-	-	-	-	-	-	-	-
	Area	-	-	-	-	0.349	0.274	-0.189, 0.886	0.165
	Latitude	***3.572***	***1.652***	***0.334, 6.810***	***1.000***	***0.917***	***0.216***	***0.493, 1.341***	***1.000***
	Longitude	-	-	-	-	0.282	0.152	-0.016, 0.580	0.446
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-

	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
ESNI	Intercept	-5.064	2.671	-10.299, 0.171	1.000	-	-	-	-
	Drawdown amplitude	-	-	-	-	-	-	-	-
	Area	-	-	-	-	-	-	-	-
	Latitude	-5.521	3.158	-11.711, 0.669	1.000	-	-	-	-
	Longitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-
	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
LEGI	Intercept	-4.176	2.205	-8.498, 0.146	1.000	-	-	-	-
	Drawdown amplitude	-1.736	1.585	-4.842, 1.370	0.328	-	-	-	-
	Area	3.223	2.132	-0.955, 7.401	0.820	-	-	-	-
	Latitude	-6.078	3.567	-13.069, 0.912	1.000	-	-	-	-
	Longitude	2.573	2.077	-1.499, 6.644	0.362	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-

	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
LEMA	Intercept	-3.876	2.938	-9.634, 1.882	1.000	-	-	-	-
	Drawdown amplitude	-3.238	5.067	-13.168, 6.693	0.308	-	-	-	-
	Area	-	-	-	-	-	-	-	-
	Latitude	-1.464	2.035	-5.452, 2.524	0.216	-	-	-	-
	Longitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-
	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
LOLO	Intercept	1.786	2.466	-3.047, 6.619	1.000	***1.609***	***0.279***	***1.062, 2.156***	***1.000***
	Drawdown amplitude	-	-	-	-	-	-	-	-
	Area	-	-	-	-	***1.182***	***0.286***	***0.620, 1.743***	***1.000***
	Latitude	11.386	8.835	-5.930, 28.702	1.000	***-1.334***	***0.192***	***-1.711, -0.957***	***1.000***
	Longitude	-3.466	3.351	-10.034, 3.101	0.731	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-

	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
MIDO	Intercept	-0.899	0.866	-2.596, 0.799	1.000	-	-	-	-
	Drawdown amplitude	-0.736	0.682	-2.072, 0.600	0.157	-	-	-	-
	Area	1.808	1.200	-0.544, 4.160	0.521	-	-	-	-
	Latitude	-3.852	2.067	-7.903, 0.198	1.000	-	-	-	-
	Longitude	-0.973	0.742	-2.429, 0.482	0.206	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-
	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
MISA	Intercept	***-2.723***	***1.105***	***-4.888, -0.558***	***1.000***	-	-	-	-
	Drawdown amplitude	-1.623	1.652	-4.862, 1.615	0.235	-	-	-	-
	Area	-1.214	0.876	-2.930, 0.503	0.311	-	-	-	-
	Latitude	-	-	-	-	-	-	-	-
	Longitude	0.720	0.945	-1.132, 2.572	0.135	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-

	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
NOCR	Intercept	-1.821	0.993	-3.767, 0.125	1.000	-	-	-	-
	Drawdown amplitude	-	-	-	-	-	-	-	-
	Area	-	-	-	-	-	-	-	-
	Latitude	***-3.053***	***1.453***	***-5.900, -0.205***	***1.000***	-	-	-	-
	Longitude	1.111	0.965	-0.779, 3.002	0.382	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-
	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
OSMO	Intercept	-1.762	1.154	-4.024, 0.501	1.000	-	-	-	-
	Drawdown amplitude	1.092	0.917	-0.706, 2.889	0.152	-	-	-	-
	Area	-	-	-	-	-	-	-	-
	Latitude	-1.529	1.114	-3.712, 0.655	0.618	-	-	-	-
	Longitude	1.762	1.383	-0.947, 4.472	0.704	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-

	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
PEFL	Intercept	3.122	1.599	-0.012, 6.256	1.000	***2.946***	***0.239***	***2.478, 3.414***	***1.000***
	Drawdown amplitude	-	-	-	-	-	-	-	-
	Area	-	-	-	-	0.542	0.354	-0.152, 1.235	0.175
	Latitude	-1.248	1.080	-3.364, 0.869	0.336	***-1.250***	***0.287***	***-1.813, -0.687***	***1.000***
	Longitude	***-3.400***	***1.704***	***-6.741, -0.060***	***1.000***	0.609	0.356	-0.088, 1.306	0.525
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-
	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
SAFO	Intercept	***-1.881***	***0.786***	***-3.422, -0.340***	***1.000***	-	-	-	-
	Drawdown amplitude	-	-	-	-	-	-	-	-
	Area	-2.008	1.060	-4.086, 0.070	1.000	-	-	-	-
	Latitude	***2.528***	***1.184***	***0.207, 4.849***	***1.000***	-	-	-	-
	Longitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-

	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
SANA	Intercept	-1.245	1.052	-3.306, 0.816	1.000	-	-	-	-
	Drawdown amplitude	-0.329	1.224	-2.729, 2.070	0.257	-	-	-	-
	Area	1.372	0.855	-0.304, 3.048	0.846	-	-	-	-
	Latitude	0.898	0.506	-0.095, 1.890	0.154	-	-	-	-
	Longitude	-1.841	1.716	-5.205, 1.523	0.430	-	-	-	-
	Drawdown amplitude * Area	4.380	2.280	-0.089, 8.848	0.257	-	-	-	-
	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	3.893	2.386	-0.784, 8.570	0.257	-	-	-	-
SECO	Intercept	-0.663	1.380	-3.368, 2.042	1.000	-	-	-	-
	Drawdown amplitude	3.100	2.146	-1.105, 7.305	1.000	-	-	-	-
	Area	-	-	-	-	-	-	-	-
	Latitude	-1.459	2.210	-5.791, 2.874	1.000	-	-	-	-
	Longitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Area	-	-	-	-	-	-	-	-

	Drawdown amplitude * Latitude	-7.063	5.076	-17.011, 2.885	1.000	-	-	-	-
	Drawdown amplitude * Longitude	-	-	-	-	-	-	-	-
SAVI	Intercept	0.830	5.154	-9.272, 10.932	1.000	***2.510***	***0.637***	***1.263, 3.758***	***1.000***
	Drawdown amplitude	3.699	7.952	-11.886, 19.284	0.532	-	-	-	-
	Area	5.326	10.970	-16.175, 26.826	0.461	***2.559***	***0.432***	***1.712, 3.405***	***0.526***
	Latitude	1.125	0.951	-0.739, 2.989	0.193	***-1.351***	***0.249***	***-1.839, -0.862***	***0.526***
	Longitude	-4.645	11.387	-26.963, 17.674	1.000	-	-	-	-
	Drawdown amplitude * Area	21.075	17.211	-12.658, 54.809	0.077	-	-	-	-
	Drawdown amplitude * Latitude	-	-	-	-	-	-	-	-
	Drawdown amplitude * Longitude	-17.532	25.243	-67.008, 31.945	0.183	-	-	-	-