Science and Research Information Report IR-13

Aquatic connectivity, fish introductions, and risk assessment for lakes in Algonquin Provincial Park

Ministry of Natural Resources and Forestry

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Cover photo: Louisa Lake Creek flowing from west (lower left corner) to east (upper right corner) with a smaller stream joining the creek at a confluence. The location of a waterfall barrier is indicated by white water. The waterfall serves as a limit to upstream movement of fish in this watershed. Photo: high resolution digital image.

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Summary

The aquatic connectivity of the lakes, rivers, and streams of Algonquin Provincial Park strongly influences the risk of fish introductions and the related risks to native fish species. The park's aquatic network is defined by watershed boundaries beginning on the Algonquin Dome in the park centre and draining towards the park boundaries. Other parts of the network begin as headwaters near or just beyond the park boundary and drain into and across the park landscape. The Petawawa River is such a watershed with over 80% of its area in the park. In total, the park's aquatic network comprises nearly 1300 lakes (with surface area larger than 5 ha) and nearly 7300 km of streams and rivers with approximately 3700 km of stream reaches being second order or greater.

Algonquin Provincial Park has many native fish species, and connectivity patterns define where they can move and live. Introduced fish disrupt native aquatic food webs and can lead to loss of key species such as brook trout as well as rare species such as blackfin cisco. Barriers such as waterfalls, dams, and steep slopes block movement in the aquatic network and limit where introduced fish can spread, depending on the introduction site. However, barriers do not limit downstream movements. While this report focuses on illegal introductions of unwanted fish as bait or game fish not native to the park landscape, the results also apply to invertebrates such as spiny waterflea and other organisms that alter lake food webs. The key difference is invertebrates have little or no ability to move upstream.

We developed an aquatic connectivity map for the park that includes data from the following sources:

- Maps showing aquatic barriers such waterfalls and dams
- Information on barriers not yet mapped (gleaned from local experts)
- High resolution photography
- Geographic information system slope models
- Field surveys of candidate sites

Through developing this map, we discovered that the park has natural protection from fish moving upstream towards it — a *fall line* or natural change in slope or elevation that produces a barrier. Remarkably, this fall line is similar to the park boundary.

This natural protection is not present when headwaters of watersheds are on or just outside the park boundary. In these locations, referred to as *thumbnail watersheds*, introduced fish can easily move downstream. With the Petawawa River, introductions

can extend across the park landscape from west to east. Due to flow from the western boundary east across the park, the headwater regions of the Petawawa River, the Nipissing River, and the upper Petawawa rivers (including the Tim River) have the greatest risk of effects from unwanted fish introductions. Rainbow smelt introduced in or near Tim Lake on the west boundary is an example of this risk. We highlight this introduction and present case studies on smallmouth bass and northern pike introductions. Thumbnail watersheds outside the northern park boundary (including headwater areas of the North and Hurdman rivers) are other locations where introduced fish will have downstream effects.

This downstream effect stemming from connectivity of the park's aquatic network shows that risk of fish introductions has a strong geographic component. Introductions to 1 lake results in invasions of other lakes downstream or upstream with limits to spread based only on barriers. Downstream lakes can be at greater risk because they get the accumulated effects of upstream events. The series of lakes from Cedar Lake to McManus Lake on the lower Petawawa River are at high risk of fish introductions from other lakes because so much of the park's lake and river system drains into this lake series.

Risk of fish introductions has a human driver based on campground use, access points to the park's interior and outdoor activity such as angling (recreational fishing). The highest ranked lake fishery based on angler use is Lake Opeongo, which gets 3 times the use of the second ranked one, Ralph Bice Lake. The watershed areas potentially affected by introductions in the top 5 fishery locations cover a large area of the park (in addition to Opeongo and Ralph Bice, Burnt Island, Pen, and Rock lakes). When summed across watersheds, based on angler use at watershed scales, the lakes most at risk from total fishing effort upstream are Cedar Lake and all its downstream lakes. Lake Opeongo and Ralph Bice Lake have larger targeted fisheries but little upstream area to contribute to risk.

The park's aquatic network does have some protection due to natural barriers and dams. Shirley Lake dam is a good example of biosecurity as it protects upstream native brook trout and lake trout lakes from walleye, northern pike, rock bass, and smallmouth bass — all introduced in the Opeongo River. A total of 376 Algonquin Park lakes >10 ha (47% of total lakes) are protected from fish introductions from access points or thumbnail watersheds. Among these are 71% of the park's brook trout lakes and 31% of lake trout lakes.

Résumé

La connectivité aquatique, l'introduction de poissons, et l'évaluation des risques dans les lacs du parc provincial Algonquin

La connectivité aquatique des lacs, des rivières et des cours d'eau du parc provincial Algonquin influence grandement les risques liés à l'introduction de poissons pour les espèces de poissons indigènes. Le réseau aquatique du parc comprend plusieurs bassins hydrographiques. Certains s'écoulent depuis le centre du parc, dans le massif Algonquin, vers l'extérieur du parc. D'autres prennent leur source à proximité, parfois immédiate, de la limite du parc, et s'écoulent dans le parc, ou même le traversent. La rivière Petawawa, dont plus de 80 % de la superficie est située à l'intérieur du parc, est l'un de ces bassins hydrographiques. Au total, le réseau aquatique du parc comprend presque 1 300 lacs, d'une superficie dépassant 5 hectares, et près de 7 300 kilomètres de cours d'eau et de rivières, dont environ 3 700 kilomètres de tronçons sont de deuxième ordre ou plus.

La connectivité aquatique définit les zones où peuvent vivre et se déplacer les nombreuses espèces de poissons indigènes peuplant le parc provincial Algonquin. L'introduction de poissons bouleverse les réseaux alimentaires aquatiques des poissons indigènes, et peut engendrer la disparition d'espèces importantes comme l'omble de fontaine et d'espèces rares comme le cisco à nageoires noires. Des obstacles comme les chutes d'eau, les barrages et les pentes raides limitent les zones où les poissons introduits peuvent se propager au sein du réseau aquatique à partir d'un site d'introduction. Toutefois, ces obstacles ne restreignent pas leurs déplacements vers l'aval. Bien que ce rapport se concentre sur l'introduction illégale sur le territoire du parc de poissons non indigènes indésirables qui servent d'appât ou de poisson gibier, ses conclusions s'appliquent également aux invertébrés comme le cladocère épineux et à d'autres organismes qui altèrent les réseaux alimentaires des lacs, à la différence notable près que les invertébrés sont quasiment incapables de se déplacer vers l'amont.

Nous avons conçu une carte de la connectivité aquatique du parc qui comprend des données provenant des sources suivantes :

- des cartes indiquant les obstacles aquatiques comme les chutes d'eau et les barrages;
- des renseignements sur les obstacles qui n'ont pas encore été cartographiés (recueillis auprès d'experts locaux);
- des photographies à haute résolution;
- des modèles de pentes provenant de systèmes d'information géographique;

- des études sur le terrain des sites candidats.

En concevant cette carte, nous avons découvert que le parc disposait d'une protection naturelle empêchant les poissons de se déplacer vers l'amont dans sa direction, sous la forme d'une *zone de chutes*, d'un changement de pente naturel ou d'une élévation constituant un obstacle. Étonnamment, la zone de chutes coïncide avec la limite du parc.

Cette protection naturelle est inexistante pour les bassins hydrographiques dont l'amont se trouve sur la limite du parc, ou juste à l'extérieur. Les poissons introduits dans ce que nous appellerons ces *zones d'amont limitrophes* peuvent facilement se déplacer vers l'aval. Sur la rivière Petawawa, les poissons introduits peuvent se propager à travers le territoire du parc, d'ouest en est. En raison de l'écoulement de ces rivières qui traversent le parc d'ouest en est, l'amont de la rivière Petawawa, de la rivière Nipissing et des affluents de la rivière Petawawa (y compris la rivière Tim) sont les zones où il est le plus risqué d'introduire des poissons indésirables. L'éperlan, qui a été introduit dans le lac Tim ou à proximité, à la limite ouest du parc, illustre bien ce risque. Nous mettons son introduction en lumière et présentons des études de cas portant sur l'introduction de l'achigan à petite bouche et du grand brochet. Les zones d'amont limitrophes au nord du parc (y compris l'amont de la rivière North et du lac Hurdman) figurent parmi celles où l'introduction de poissons aura des effets en aval.

Ces effets, découlant de la connectivité du réseau aquatique du parc, démontrent que le risque lié à l'introduction de poissons présente une composante géographique importante. L'introduction de poissons dans un seul lac entraîne l'invasion de l'amont ou de l'aval d'autres lacs, la propagation n'étant limitée que par des obstacles. Les lacs d'aval sont plus à risque, car ils subissent les effets cumulés de l'introduction de poissons en amont. La série de lacs s'étendant du lac Cedar au Lac McManus, sur le cours inférieur de la rivière Petawawa, est très menacée par l'introduction de poissons dans d'autres lacs, car une bonne partie du réseau des lacs et des rivières du parc s'y écoule.

Le risque de l'introduction de poissons comporte un facteur humain, à savoir les terrains de camping ainsi que les points d'accès pour profiter des activités d'intérieur et de plein air qu'offre le parc, comme la pêche à la ligne (pêche sportive). Le lac Opeongo est trois fois plus fréquenté par les pêcheurs à la ligne que le lac Ralph Bice, ce qui en fait le mieux classé pour la pêche. Les bassins hydrographiques pouvant être affectés par l'introduction de poissons dans les cinq meilleurs sites de pêche couvrent une grande superficie du parc (en plus des lacs Opeongo, Ralph Bice, Burnt Island, Pen et Rock). En tenant compte de tous les bassins hydrographiques fréquentés par les pêcheurs à la ligne, les lacs les plus menacés par l'effort total de pêche en amont sont le lac Cedar et tous ses lacs d’aval. Les pêches ciblées sur le lac Opeongo et le lac Ralph Bice sont importantes, mais les zone d’amont y sont limitées, ce qui réduit les risques.

Le réseau aquatique du parc dispose d’une certaine protection en raison de barrages et d’obstacles naturels. Le barrage du lac Shirley illustre bien le concept de biosécurité, car il protège les lacs d’amont, où l’omble de fontaine et le touladi sont indigènes, de l’introduction du doré jaune, du grand brochet, du crapet de roche et de l’achigan à petite bouche, des poissons qui sont introduits dans la rivière Opeongo. Au total, 47 % des lacs du parc Algonquin, soit 376 lacs sur plus de 10 hectares, sont ainsi protégés des poissons introduits à des points d’accès ou dans des zones d’amont limitrophes. Parmi ceux-ci, on trouve 71 % des lacs à omble de fontaine ainsi que 31 % des lacs à touladi du parc.

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Contents

Introduction to park aquatic connectivity

Algonquin Provincial Park contains over 3700 km of stream and river habitat distributed among 9 tertiary watersheds. When total lake surface area (over 710 km^2) is included, the park landscape can be viewed as a *waterscape*, which is where hydrology, water budgets, and drainage patterns define an aquatic ecosystem network.

Over millennia, this network was used by Indigenous people for travel and harvesting. Early inhabitants of the park area would have developed portage routes around natural barriers. The barriers present then and now stem from the post-glacial era when the park emerged from a long period of ice cover that at times was 2 km thick. Landforms such as deeply cut valleys and associated vertical drops that create natural barriers in watersheds have their origins far earlier in time, predating glaciers.

During forestry operations in the 19th and 20th centuries, this network was important as a transportation route. Dams were built to provide flow to move logs downstream to mills and export depots. During this period, park watersheds were viewed as utilitarian — they were needed to move a commodity to market.

Today, this aquatic ecosystem network is part of the outdoor experience for visitors from around the world as they move in and among the park’s watersheds. While some dams have been removed, remaining dams are used to manage water levels in a system of watersheds feeding hydroelectric facilities. Natural barriers remain and serve as sites for park visitors to take photos and reflect.

Barriers also limit upstream movement of aquatic organisms — but if sites where illegal introduction of aquatic organisms occur are upstream, barriers offer little protection. Fish and other aquatic organisms move over them easily when travelling downstream. Both introduction location and presence of barriers are key considerations when addressing effects in watersheds from illegal introductions of fish and other aquatic organisms.

This report describes an assessment of the risk that illegal fish introductions pose to park watersheds and aquatic food webs in lakes. Risk is based on human use of watersheds plus network connections that allow introductions to spread through the park’s network of lakes, streams, and rivers. The location of natural and human-built barriers provides the most obvious protection for native fish species and their food webs. Areas of relatively high slope also act as barriers. We combined information about the park’s aquatic network with that about lake-specific visitor use as a measure of the human footprint — where introductions could occur. We also combined landscape models of watershed boundaries and barriers with potential movement in the stream network to assess watershed risk to introduced species. One feature of risk of illegal introductions is proximity to access points with greater visitor traffic expected at those locations.

Illegal introductions of northern pike and rainbow smelt to Algonquin Park’s watersheds are useful case studies. For northern pike, introductions to the Opeongo River system and Victoria Lake outside the park boundary soon led to this species spreading into the park. After northern pike reached the Booth Lake dam, people introduced pike to Booth Lake, allowing this species to spread to the Annie Bay dam at the outlet of Lake Opeongo. Its further spread is curtailed for now by that dam. Northern pike are top predators and consume native fish living in relatively shallow waters.

Rainbow smelt were introduced to 2 tertiary watersheds in the park because of their illegal use as bait. In the mid-1980s, smelt were found in North Tea Lake, and they moved downstream through Lakes Manitou and Kioshkokwi. In 2009, smelt were found in Tim Lake on the western park boundary and in the headwaters of the Petawawa River. By 2016, a single specimen of this species was captured in Catfish Lake downstream of Tim Lake. It will continue to spread down the Petawawa River for years to come. Rainbow smelt eat larval stages of fish such as cisco and lake whitefish as well as any other fish species with larvae living in open water. Rainbow smelt’s future occupancy of Cedar and Radiant lakes also place this species in the food web with the extremely rare blackfin cisco.

These examples highlight that any fish introductions in Algonquin Park are illegal. This is reflected in the recreational fishing regulations prohibiting use of live baitfish and the prohibition on introducing non-native game fish.

Given these examples of fish introductions and spread, a thorough analysis of risk assessment stemming from fish introductions was needed. Many aquatic food webs and species assemblages are represented only within the park boundaries as introduced species have altered aquatic food webs outside the park. The landscape around the park has a homogenizing pattern of stocked game fish and baitfish introductions.

The global spread of species is extensive and likely to expand in this century. The role of people in the spread of species is aided by climate change, which will unfold more acutely in the years ahead. This report provides a set of mapped predictions of possible sites for fish introductions and spread for Algonquin Provincial Park. The connections among streams and rivers in watersheds are the underlying structure for determining how far introduced fish can travel upstream or downstream. These connections are referred to as *aquatic corridors,* reflecting their role in movement. These corridors may include barriers that prevent passage. We produced map predictions based on the park’s aquatic corridors, barriers, and spatial distribution of potential fish introductions.

This report focuses on introduced fish species because they can move up and downstream depending on barrier locations. Invertebrates (e.g., invasive zooplankton) arriving via trailered boats can spread only downstream; they can’t move against stream flow at watershed confluences. But they do share with fish the likelihood of moving over barriers to sites lower in watersheds.

Finally, the distribution of fish in the park is known primarily from fish occupancy in lakes (Ridgway et al. 2017). When combined with the corresponding stream and river connections in and among watersheds, movement in watersheds could be inferred based on the occurrence of fish in connected lakes rather than directly observing movement. Lakes and connecting streams accessible by unhindered movement can be highlighted for any watershed based on a map of fish movement barriers. This highlighting results in streams and lakes being identified as potential habitat for fish moving through watersheds. Whether illegal fish introductions will actually result in introduced species establishing depends on whether the right habitat is there and how each species responds to available space.

Park aquatic history

The park's watersheds are an interconnected network of lakes, rivers, and streams making up the aquatic ecosystems of this landscape. Fish and aquatic invertebrates living in this network make up native aquatic food webs, which are:

- Defined by differences in species composition that stem from re-colonization patterns after the Laurentide Ice Sheet retreated thousands of years ago
- Affected by recent species introductions that alter natural predator-prey patterns, reduce productivity, and cause loss of native species

For tens of thousands of years, the park had no aquatic food webs or even streams and lakes because it was covered by thick glacial ice. This pattern of ice cover and retreat has been repeated several times over the last 2 to 3 million years. Only in the last 14,000 years has flowing water and lake development returned to the park landscape, allowing fish and invertebrates to return (Ridgway et al. 2017).

Today's watershed connections likely did not exist when the glaciers retreated. Then streams and lakes were defined directly by glacial melt water with flow patterns reflecting the state of the landscape — depressed from the long period of ice coverage and then released to rebound in elevation (Table 1). Known as *isostatic rebound*, the period of rising landscape elevation has slowed but is still happening. Today's watershed boundaries are the current representation of a rebound that started over 13,000 years ago (Ridgway et al. 2017). In the past, watersheds now isolated from each other may have been connected in ways quite different from today's.

How fish are distributed in the park reveals some past connections. At the watershed scale, native fish distribution is defined by drainage patterns from the time of glacial retreat as well as persistent natural barriers, which limit distribution (Table 1; Ridgway et al. 2017). Waterfalls have likely existed for millennia, while smaller falls and rapids reflect drainage effects over thousands of years. Steep slopes can also create elevation changes that bar fish from moving upstream.

We can draw conclusions about fish re-colonizing the park landscape from current fish distribution. For example, brook trout are present in every fourth-order watershed and have been found in 444 lakes in the park (Ridgway et al. 2017). So we conclude that soon after ice retreat, this species used the stream and lake system of the day to occupy the park's entire post-glacial landscape. If brook trout had arrived late to this landscape, their distribution would been more limited due to barriers. Other native species such as lake trout and lake whitefish are also widely distributed in the park so were also likely on the landscape right after the last glaciers retreated, taking advantage of the watershed flow and connections of the time. All 3 of these species tolerate coldwater environments, which gave them an edge as the ice front retreated.

Less cold-tolerant species have more limited native distribution in the park so we conclude they arrived after glacial ice retreated north and water temperatures became more favourable. The native fish species of Lake Travers — smallmouth bass, rock bass, walleye, and muskellunge, to name a few — are example of less cold-tolerant fish that were late arrivals.

Non-native fish species have been introduced to the park for more than a century whether by accident or by design (Mitchell et al. 2017). Logging began in the park in the late 19th century, and it was soon followed by the building of railroads and lodges as well as camping. Two kinds of fish introductions resulted:

- **Game fish such as smallmouth bass** were introduced to satisfy a perceived need to provide fishing opportunities for park visitors. The food web outcome of introducing predatory fish has been to reduce native prey fish abundance, with local loss of some species, as well as reductions in other native species such as brook trout.

- **Small non-native fish such as rainbow smelt** were introduced through use as bait. Smelt consume larval fish stages in open water and can reduce abundance of native lake whitefish, lake cisco, and others.

Table 1. Algonquin Provincial Park's aquatic history over 4 periods based on dominant processes (Ridgway et al. 2017) as well as fish distribution and likely broad scale movements through watersheds.

Phase	Water	Fish species
Glacial	• All of Ontario, including Algonquin Provincial Park, locked under ≈2 km of ice • Water flowed at sub-glacial levels, eventually revealing as eskers/drumlins or as melt streams off the glacial surface during warm periods	• All Ontario fish species located beyond ice edge in lakes and watersheds in several glacial refugia • Watersheds defined by runoff from continental ice cover

Phase	Water	Fish species
Post-glacial	• ≈13,800 years ago, southern edge of retreating glacial ice reached southern tip of park • For 800+ years, glacial retreat moved north over park landscape reaching park's northern boundary • During Younger-Dryas event, retreat slowed during global temperature decline • For next 2,000 years, retreating ice slowly revealed Ottawa River valley • Algonquin Park flow network driven directly by melt water and early elevation (200 m lower than today) • Watersheds/connections differed greatly from today's as landscape continued to rebound • Lakes of varying sizes formed at melting edge of glacial ice • Glacial retreat not a single line but broken zone of melting ice; mature forests absent	• Coldwater species such lake trout, lake whitefish, and brook trout followed melting ice and recolonized park landscape from refugia • Warmwater species such as smallmouth bass arrived after cold melt water was gone; watersheds operated much as today • Inundation by glacial Lake Algonquin defined fish access to watersheds in northern part of park
Algonquin watersheds	• After forests, watersheds function much as today • Only natural barriers present	• All native fish species present; fish location among lakes and streams settled after flooding and inundation stopped

Phase	Water	Fish species
19th century–today	- Control structures built at lake outlets/rivers to transport logs and support hydroelectric power, restricting natural fish movement	- Humans introduced fish species into lakes to support recreational fishing; some sanctioned by resource agencies but others unauthorized - Where natural fish passage possible, fish species spread to other lakes

Park watersheds as aquatic ecosystems

Aquatic connectivity helps introduced fish spread throughout a watershed. Tracing water flow from a headwater area is a story of directional flow in a network of watersheds. In Algonquin Provincial Park, water flows overland and through shallow groundwater seepage to collect in small streams in small valley segments with each segment reflecting recent and long ago flow conditions. Water moves downslope in a system of stream segments eventually joining with water from other small valley systems at confluences. Along the way, it encounters lakes and wetland complexes resulting in both water flow and environmental conditions being altered. The water becomes defined by an expanding landscape contributing to flow conditions — higher up in the watershed, it was dispersed among several smaller valley systems. The flow increasingly aggregates into a larger network of streams and rivers. Eventually, stream or river volume increases greatly, reflecting the increase in runoff volume over a larger landscape. Intersecting lakes result in an increasing integration of flow from several valley systems that were at first far apart.

The above description focuses on watershed *hydrology* — the flow of water in a topographic environment. The hydrological view of watersheds is logical based on the simple idea of water flowing downhill. If hydrology were the sole criteria for understanding watersheds as aquatic ecosystems then their description and classification would be based on physics, soil conditions, and precipitation. This approach might result in a more general description of watersheds as aquatic ecosystems across different landscapes and watersheds. However, watersheds as aquatic ecosystems have much greater complexity above and beyond hydrology. Park watersheds such as the Nipissing and upper Petawawa River are excellent examples of the complexity of watersheds as aquatic ecosystems.

The Nipissing and upper Petawawa River systems

The Petawawa River watershed is the largest tertiary watershed in Algonquin Provincial Park (4191 km^2). Two of the largest sub-watersheds of the Petawawa River are the Nipissing River and upper Petawawa River (including the Tim River; Figure 1). Both have headwaters on the park's western boundary, and both drain to Cedar Lake. The 2 watersheds are next to each other with their entrance to Cedar Lake just over 1 kilometre apart on the south shore (Figure 1). Water from the 2 watersheds, along with other watersheds draining to Cedar Lake, is mixed in the lake producing the outflow of Cedar Lake as the Petawawa River to the east (Figure 1).

These 2 river systems reaching Cedar Lake have different histories so differ as ecosystems in important ways (Table 2). However, they share the same basic hydrological description as above, and they both end at Cedar Lake. Many differences between the Nipissing and upper Petawawa Rivers stem from the end of the park's glacial period over 13,000 years ago.

The Nipissing River basin is defined by extensive coverage of glacial-fluvial runoff — materials such as sand and gravel (Figure 1). Smaller watersheds to the north and south of the Nipissing River are defined by bedrock and glacial tills typical of Canadian Shield landscapes. In contrast, the upper Petawawa River landscape is typical for many areas of Ontario, having lots of bedrock and glacial tills.

The Nipissing River also differs from the upper Petawawa in its history of glacial inundation. The upper Petawawa River has a waterfall near its confluence with Cedar Lake that stops fish from moving upstream from Cedar Lake. This vertical drop isolated the upper Petawawa from centuries of inundation from glacial Lake Algonquin as it flowed through the upper region of the park including through Cedar Lake (Ridgway et al. 2017). During the Lake Algonquin period, the Nipissing River was effectively split into an upper river above High Falls and a large bay below these falls. Sedimentary history of the lower Nipissing is a combination of runoff and sediments from the glacial period as well as lake inundation and associated sediments from the Lake Algonquin period. Not so for the upper Petawawa due to that waterfall.

The Nipissing River has many small lakes as part of the headwaters network contributing to it (Figure 1; Table 2). This river never passes through a series of lakes that alter its flow and environment downstream — it is not influenced by lake ecosystems. It is a classic stream/river network that passes through Canadian Shield in its upper reaches then crosses into a sedimentary and wetland complex in its lower reaches before reaching Cedar Lake. The ecological boundary between the Nipissing River and Cedar Lake, referred to as an *ecotone*, occurs over a broad shallow bay reflecting sediment deposition from higher in the watershed to Cedar Lake and deposition from the bay formed during the Lake Algonquin period. The river-lake ecotone is a large and complex community of aquatic macrophytes (plants).

In contrast, the upper Petawawa River passes through a series of several large lakes including Longer, Burnt Island, and Catfish lakes (Figure 1; Table 2). This lake series alters watershed flow and environmental conditions such as water temperature of the upper Petawawa River (Jones 2010). The ecotone at the confluence of the upper Petawawa River to Cedar Lake is a small, relatively deep bay that reflects the strong flow from the waterfall near Cedar Lake.

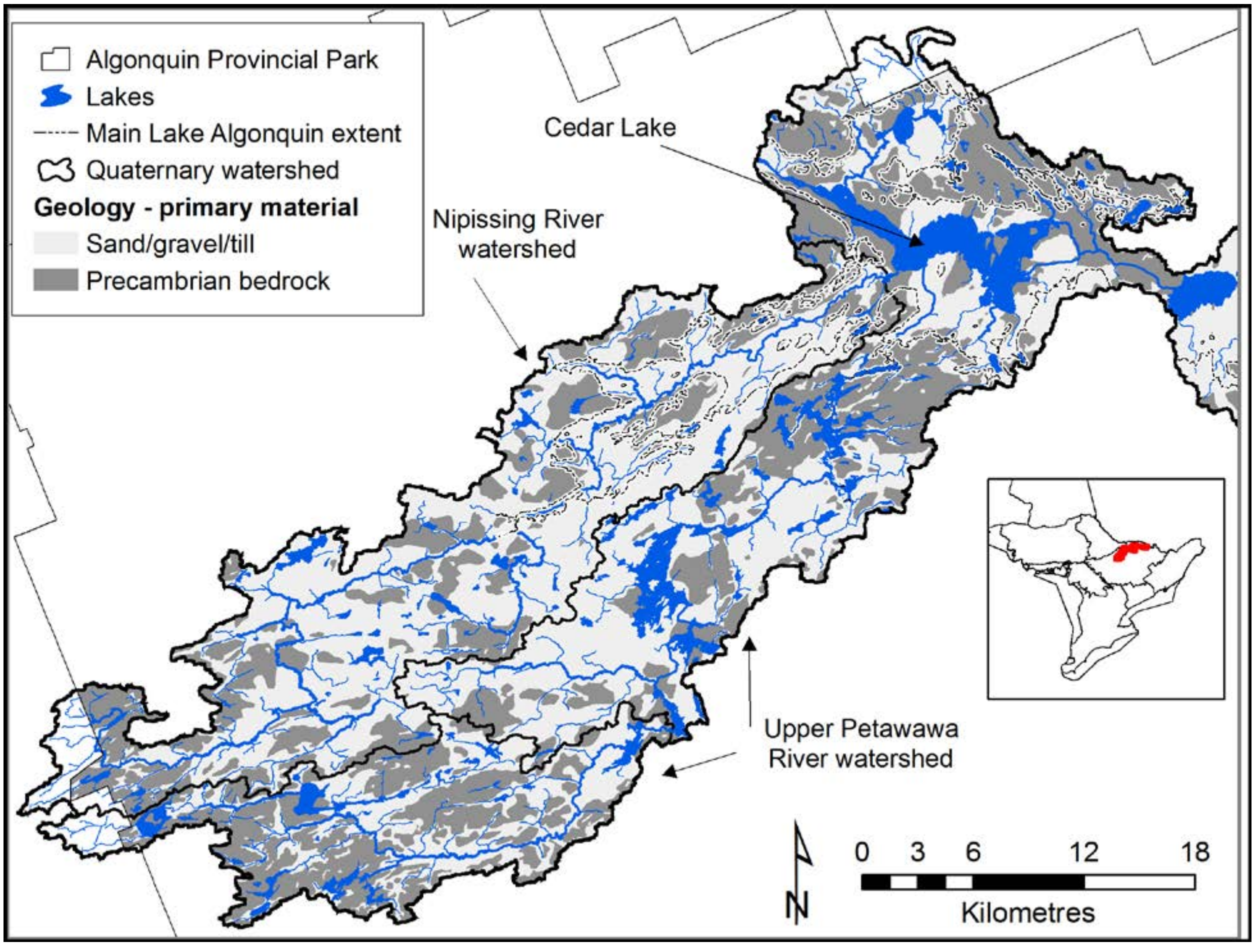

Figure 1. The Nipissing and upper Petawawa river watersheds (Tim and Petawawa rivers combined) both drain to Cedar Lake in Algonquin Provincial Park but have different histories. The Nipissing's lower reaches were flooded by glacial Lake Algonquin resulting in large areas of depositional mud, and no lakes intersect the main stem. The Upper Petawawa was not flooded, has more bedrock near the landscape surface, and has several lakes along its course.

These 2 river watersheds also have differing major fish species:

Nipissing: No lake trout or lake whitefish because the small headwater lakes lack deep cold water. Burbot occurs only in Osler Lake and the lower reaches of the Nipissing. Brook trout is the top predator in lake and river habitats in most of this watershed.

Upper Petawawa: Lake trout, lake whitefish, and burbot are common in all of this watershed's large lakes. Brook trout co-occur with lake trout in many lakes and occupy the river system. The result is a more complex, multi-predator food web than in the Nipissing River.

These 2 watersheds highlight how distinctive the park's aquatic biodiversity is. The history of glacial retreat and flow influenced the park landscape, in turn determining how fish were distributed in watersheds as they recolonized the region after glaciation

(Ridgway et al. 2017). Watersheds as aquatic ecosystems are defined by not just hydrology but also food webs, habitats, and organisms, including fish.

Table 2. A comparison of 2 neighbouring sub-watersheds of the Petawawa River that drain to Cedar Lake in Algonquin Provincial Park. The Nipissing and upper Petawawa have different histories so their surface geology, lake size and distribution, and fish species differ.

Feature	Nipissing River	Upper Petawawa River
Watershed area (km^2)	• 410 km^2	• 741 km^2
Glacial history	• Inundation by glacial Lake Algonquin to High Falls for centuries • Lower part was embayment of early Cedar Lake	• Lower reaches were at higher elevation, preventing inundation
Surface geology	• Large areas of sand and gravel indicate glacial water flow from higher to lower elevation areas	• Large areas of bedrock and glacial till (typical of Canadian Shield)
Forests and wetlands	• Large river wetlands from glacial flow deposits reflected as bog/wetland areas near river with forested areas upslope	• Forested to river edge in many areas; wetlands reflect deposition from river flow patterns including transition areas between lakes and river
Lake distribution	• Small lakes in headwater areas; no lakes on main river stem	• Many lakes throughout watershed with large lakes on main river stem
Fish	• Brook trout in lakes and streams	• Lake trout, lake whitefish, burbot, brook trout

Park streams and rivers as directional nested networks

The significance of aquatic connectivity when it comes to species introductions is fish can move through a network of streams and rivers within and among watersheds. Seeing streams and rivers as connected corridors is essential to understanding movement of introduced fish but does not capture their full complexity as aquatic ecosystems. Fish take up residence in streams and rivers, rather than just move through them, so these watercourses must also be viewed as habitat.

Agreeing on a definition of *stream ecosystem* has been a challenge for ecologists for over a century (Melles et al. 2012). At first, *organism zonation* in rivers and streams provided a unifying approach: Higher up, aquatic food webs in streams and rivers are represented by invertebrates and fish able to survive in small systems relying on the surrounding landscape for nutrients. Farther down, rivers are characterized by different invertebrates and fish relying on nutrients generated in the river and flowing down from the upper watershed. The repeatable pattern of different fish species occurring at different points along a watershed provided a way to view the structure of stream ecosystems: Lower reaches had 1 fish assemblage, and upper reaches had a different one, often with only 1 or 2 species. This repeatable pattern helped early stream ecologists to look for basic ecosystem patterns of production and input into streams and rivers based on where in the watershed a fish zone was. Fish species defining a zonation approach differ from one major watershed to another due to historical and geographic patterns of fish species distribution.

Later, stream ecologists incorporated the source of primary production as a function of where in the watershed a stream or river segment was located (Vannote et al. 1980). In other words, the “valley rules the stream” (Hynes 1975).

However, streams and rivers that make up a watershed network are not just corridors but also intersect lakes and wetlands in several locations (Jones 2010). Each intersect with other sub-watersheds, lakes, or wetlands changes the stream environment from upper to lower reaches of watersheds through a series of these intersects (Jones and Schmidt 2017). So the network’s directional, nested nature is now considered a defining feature of watershed streams and rivers (Melles et al. 2012, 2014) — they are more than the sum of their parts at any point along their course (Melles et al. 2012):

- Each stream in a sub-watershed contributes water from a small area to the larger watershed.
- As streams join and pass through lakes and wetlands they in turn join in larger networks; the stream ecosystem at any point cannot be partitioned into the smaller contributing streams that make up the network farther up. The nature of

primary production has changed along the course and organisms relying on primary production have changed as well — they are not based on the sum of small stream segments but as a property of their combined influence, including the ecosystem that emerges along streams and rivers that connect many landscapes.

A directional, nested network ecosystem is a more complete model of streams and rivers as aquatic ecosystems (Table 3).

Figure 2 shows a comparison of watershed ecosystems and terrestrial forest ecosystems in the park:

- Boxes A-C represent a watershed with water flowing from the lower to the upper part of the landscape image:
    - Each box covers part of the watershed in a directional, nested network beginning with Box A and continuing in increasing scale to Box C.
    - Moving Box A to another area of Box C signals a different part of the watershed with different characteristics (different ecosystem) depending on upstream and valley conditions.
- Boxes D-F show a forest ecosystem landscape:
    - Moving Box D to another area of Box F may result in different densities of conifer and hardwood tree species but **not** a different forest ecosystem.
    - The hierarchical nature of the box series D-F reflects the same ecosystem at different resolutions.
    - Moving boxes A and B similarly would not provide the same hierarchical view of the watershed ecosystem. Their nested nature prevents this freedom of movement while retaining the same watershed structure.

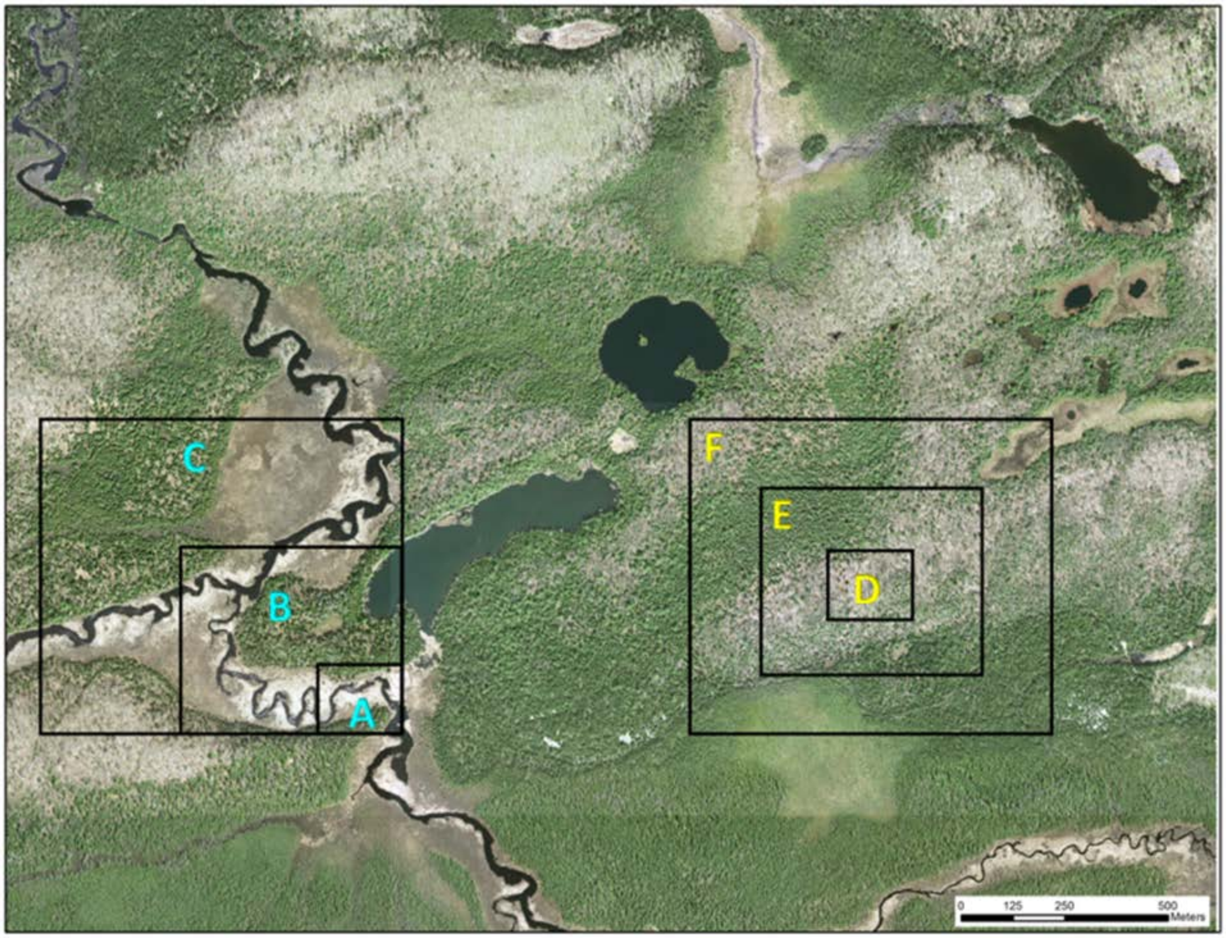

Figure 2. A comparison of Algonquin Provincial Park aquatic ecosystems (boxes A-C) and terrestrial ecosystems (boxes D-F). Box A includes a stream segment and likely input from the adjacent lake, with flow moving towards the confluence of streams in Box B. Box C includes all directional flow from boxes A and B as well the larger contributing area of the watershed. The ecosystem's direction is set — Box C contains the contribution of all areas equivalent to Box A (not just the sum of them), forming a stream network. The forested landscape in boxes D-F has some features of an aquatic ecosystem but lacks a direction (flow) and a network structure. Moving Box D to other locations in Box F would not change the ecosystem unless it were placed over the wetland in the upper right corner (directionality is imposed due to water flowing to the right).

Table 3. Characteristics of Algonquin Provincial Park stream and river ecosystems adapted from Melles et al. (2012, 2014).

Component	Description
Directional	• Flow goes one direction — lower reaches contain water representing combined flow of separate primary streams • Events in headwater systems can affect downstream ecology • River cannot be divided into different headwater streams
Nested	• Watershed begins as network of primary streams that eventually grows to higher order streams as smaller sub-watersheds join • Higher order rivers cannot exist without first starting in multiple locations as primary streams
Network	• Typically is a complex of lakes, rivers, and wetlands (not a singular river system) • Watershed position is important; contributing area to any stream in watershed increases as position shifts downstream • Greater areas of watershed become linked as flow moves from primary to higher order streams and rivers • Lakes, wetlands, and confluences among streams and rivers all contribute to stream network variation
Ecosystem	• Biological community of interacting organisms and their physical environment • As aquatic ecosystems, watersheds/streams have directional flow, are nested within the watershed boundaries, and are organized as a network (small streams join to make larger ones) • Patterns in faunal zonation and primary production depend on location — structure based on directional, nested network

The network view of the park's watersheds changes the perspective: The park becomes a *waterscape*, a highly complex aquatic ecosystem network. The park's watersheds are extensive and comprise all the streams, rivers, and lakes inside the park (Figure 3). This directional, nested network of aquatic ecosystems is one of the last parts southern Ontario to remain in a near-natural state. Even in the park, however, dams and road crossings create discontinuity in some watersheds. Natural barriers like falls, steep slopes, and impassible rapids help limit movement of introduced aquatic species. Since flow is directional, the effects of introduced aquatic species are directional and limited by barriers in other sub-watersheds. Introduced aquatic species move downhill in watersheds until they meet a barrier that limits their spread to the other linked watersheds.

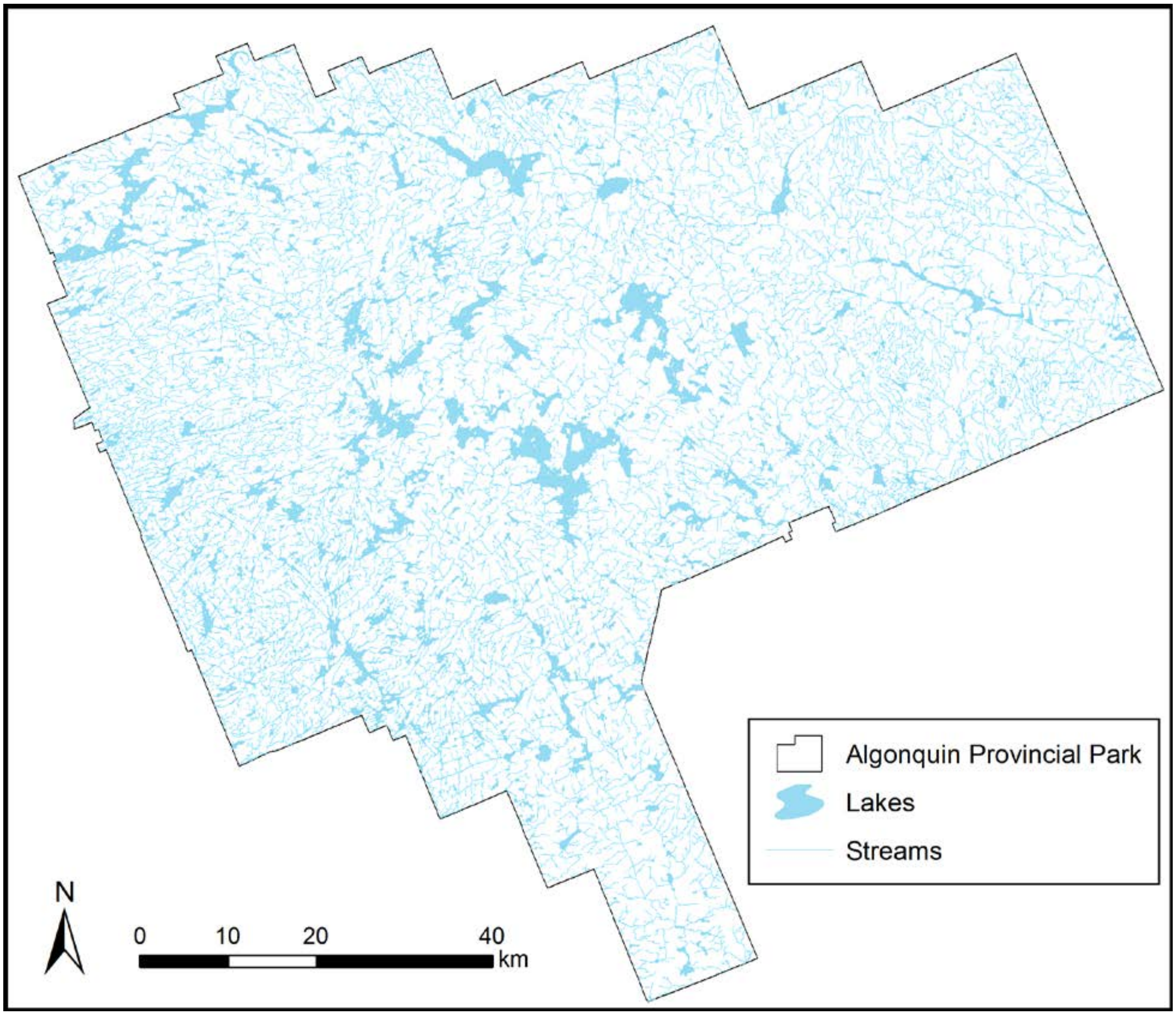

Figure 3. The lakes and streams of Algonquin Provincial Park, which is covered by aquatic ecosystems that make up a directional, nested network. *Confluences* (junctions) between streams or between streams and lakes add complexity as 2 flowing ecosystems form larger stream segments. Immediately after glaciation, the stream network would have been different from today's due to landscape rebound after the loss of 2 km of ice cover and shifting watershed boundaries stemming from those elevation changes. Some headwater areas extend beyond the park's boundaries.

Park stream order

Each stream or river is given a *stream order* number that reflects its place in the network. We used the Strahler method to calculate stream order:

- **First order:** Headwater stream or stream without upstream connections
- **Second order:** Stream resulting from 2 first-order streams merging
- **Third order:** Stream resulting from 2 second-order streams merging
- Etc.

Stream order does not increase when a smaller stream joins a higher-order one, for example a first order stream connects with a third-order stream (it remains third order).

Figure 4 shows the park's stream order. The Petawawa River has the highest stream order and the longest stream network of the park's watersheds, reaching the seventh-order stream category (Figure 4). The Muskoka, Upper Madawaska, Bonnechere and Kipawa rivers each exit the park as sixth-order streams. The remaining watersheds have much smaller areas and have lower stream orders: French River is fifth order; Magnetawan River, fifth order; Dumoine River, fourth order; and Gull River, third order.

First-order streams are the beginnings of watersheds, the smallest streams of the network. In the park, first-order streams comprise 3600 km of Algonquin Park's 7300 km (49% of the watershed length; Figure 5). They do not connect water bodies so were not included in connectivity estimates.

Some small lakes connected by first-order streams were lost from the network. The total number of lakes lost was 5387 (average size of 16 ha), most were unnamed, with 38 named and >20 ha. These lakes are all *terminal*, meaning they are headwater lakes and not contained within a network downstream allowing fish to travel to other lakes. These lakes were not included in the connectivity analysis for obvious reasons.

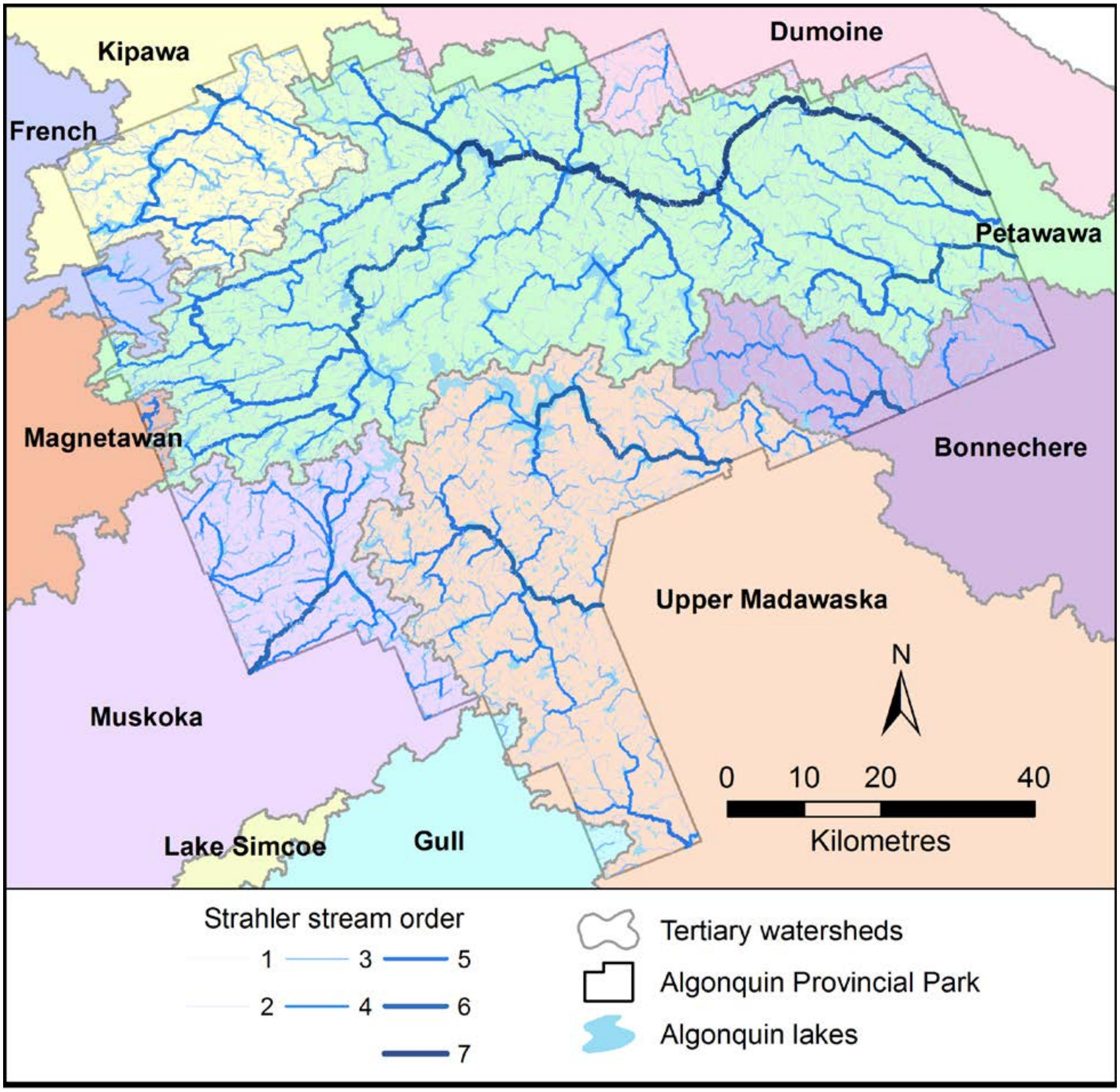

Figure 4. Algonquin Provincial Park watershed networks based on Strahler stream order (Dingman 2002). Darker, thicker stream lines indicate increasing stream order. Many first order (the smallest) streams are excluded for clarity. Streams run through lakes to emphasize watershed connectivity.

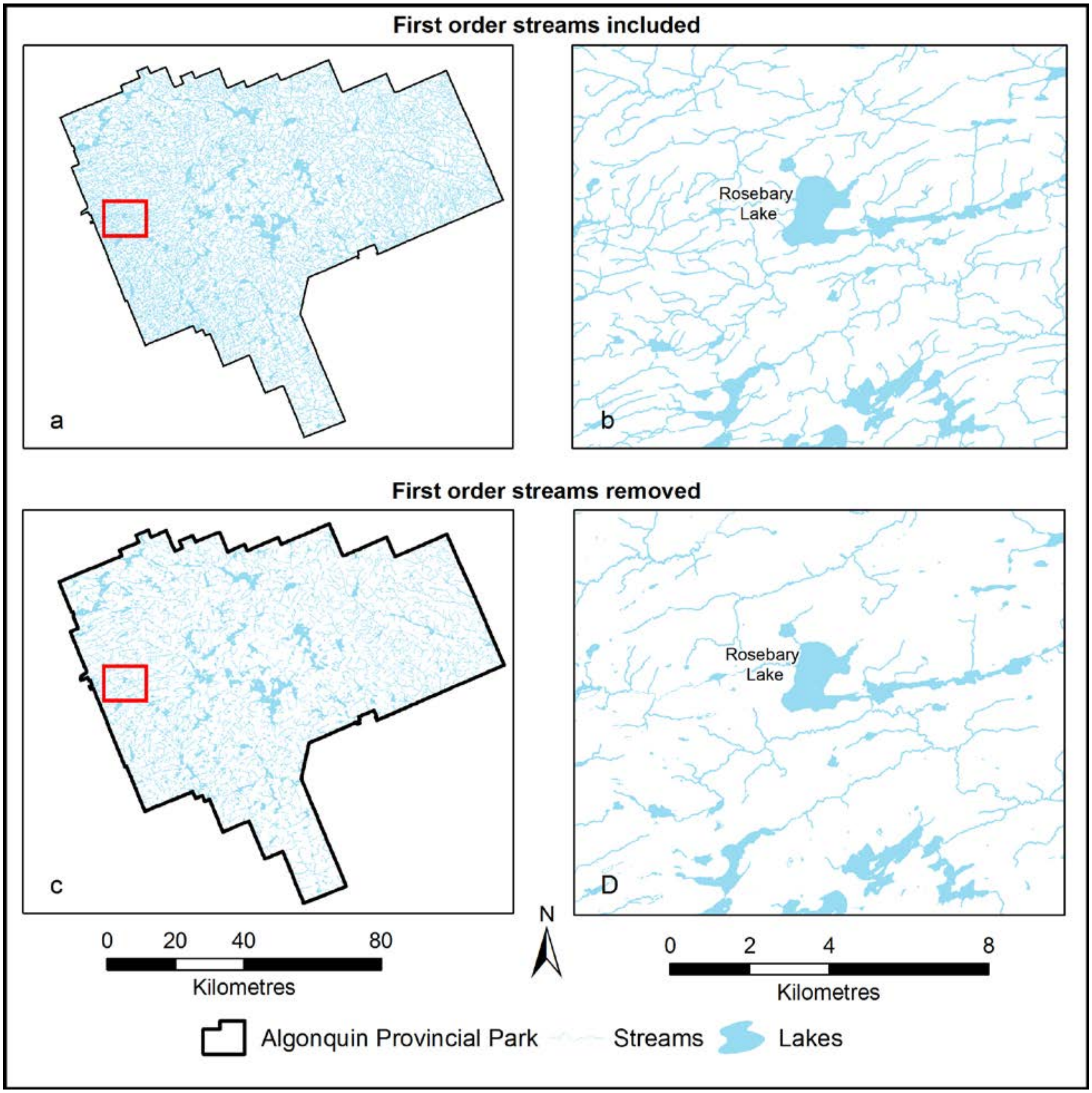

Figure 5. A) The full stream (including all first order streams) and lake map for Algonquin Provincial Park, B) closeup of watersheds in the Rosebary Lake area as an example of the full stream and lake network, C) Algonquin Park with primary streams removed to reduce network complexity, and D) the same closeup of watersheds in the Rosebary Lake area with primary streams removed.

The Algonquin Dome

A key feature of Algonquin Provincial Park is the higher elevation of the park landscape compared with surrounding areas. Tertiary watersheds flow off the Algonquin Dome to the surrounding landscapes with the Ottawa River and Georgian Bay at the end of the line (Ridgway et al. 2017). The park's highest elevation areas are on the west boundary and include headwaters for the largest park watershed, the Petawawa River. This river crosses the park landscape from west to east (Figure 6). As an aquatic network, this watershed system provides some protection from invasive fish and invertebrates due to the upstream approach to the park from all directions. On the other hand, fish or invertebrates introduced to the park can move downstream over large areas of the landscape within and beyond park boundaries. The only limits to the spread of introduced species are barriers such as dams and waterfalls.

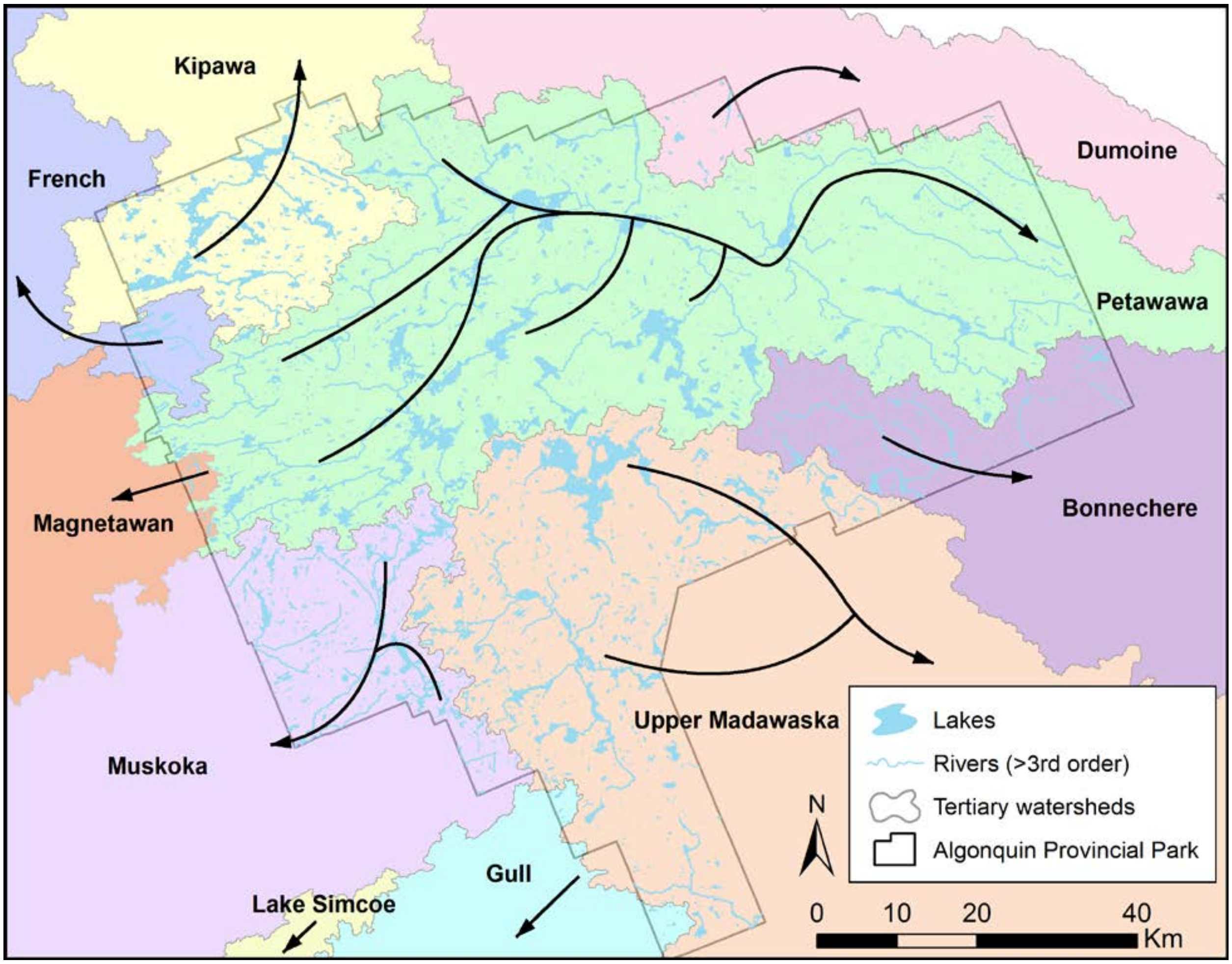

Figure 6. Tertiary watersheds of Algonquin Provincial Park and the flow direction of each watershed off the Algonquin Dome. Each watershed is named after its major river system.

Barriers to fish movement in park watersheds

Barriers are critical as they limit upstream movement of fish in the park's aquatic network, providing protection from invasive species. In Algonquin Provincial Park, watersheds with lots of variation in elevation tend to have more natural barriers in the form of steep slopes and waterfalls than watersheds with less variation. Dams, waterfalls, and steep slopes all present a barrier to fish moving upstream but not downstream. For our study, we did not consider fish movement downstream to be restricted by barriers, acknowledging that some species can cross over them.

Restricting fish from moving upstream has important ecological and geographic consequences. For natural barriers, restricting movement in a watershed produces different fish assemblages due to differences in the presence or absence of various predator and prey species. Over time, aquatic food webs develop, reflecting the mix of species in each habitat above or below barriers. Adding human-built barriers can restrict various species' access to spawning areas, productive rearing habitat, and corridors linking distant river ecosystems needed to complete a species' life cycle.

Two case studies in fish distribution in the park watersheds illustrate the importance of natural barriers in defining fish assemblages. For centuries, smallmouth bass, walleye, and muskellunge were restricted to Lake Travers due to a series of waterfalls and rapids upstream on the Petawawa River. This set of species arrived late to the park's post-glacial landscape compared with coldwater fish such as lake trout. Landscape rebound following loss of glacial ice and erosion from thousands of years of river flow produced a barrier to their moving farther into the park near the inlet to Lake Traverse.

Lake whitefish lives in most lakes in the upper reaches of the Petawawa River system, including lakes upstream of Big Trout Lake (except Timberwolf Lake). A barrier in the lower reaches of the Timberwolf Lake outlet stream has prevented lake whitefish from reaching the lake after glacial retreat. However, Misty and MacIntosh lakes to the north and south of Timberwolf Lake, respectively, have lake whitefish. The lack of lake whitefish in Timberwolf Lake has resulted in smaller lake trout with shorter lifespans and different productivity compared with lakes in this watershed that have lake whitefish. This absence of a species beyond a barrier has resulted in an abrupt change in food web structure known as a *faunal break*. Understanding faunal breaks helps us understand how the presence or absence of barriers affects fish ecology and diversity.

A series of repeating barriers in the same location in a series of watersheds is called a *fall line.* This geological feature marks the border between an upland region and a coastal plain, and different species are found above and below this line. A fall line can occur at smaller scales: The Algonquin Dome has created one where watersheds draining off the dome reach lower elevation areas with less relief. This fall line is an important boundary because it limits fish access to the park landscape. Its role in providing natural protection for the park landscape has eroded with the introduction of non-native fish predators above the fall line (e.g., Trumpickas et al. 2011).

Another fall line occurs in the park’s north. The draining of glacial Lake Algonquin through the Fossmill outlet and into the valley system including North Tea Lake in the west through to Grand Lake in the east resulted in this area being flooded to an elevation of 385 m (Martin and Chapman 1965, Ridgway et al. 2017). This event lasted nearly a thousand years and resulted in different aquatic food webs above and below 385 m.

Other structures such as culverts and road crossings can limit fish movement in streams and rivers. In some areas, culverts that are perched or have a vertical drop at the downstream end can bar upstream movement. Road crossings with intermediate or low probabilities of fish passage result in clear differences in brook trout density upstream and downstream of the road (Pepino et al. 2012). Algonquin Provincial Park has culverts and road crossing structures, but their effectiveness in fish passage has not been fully assessed so they were not included in our analysis.

Dams’ effect on the ecology of streams and river systems has been well documented (Olden 2016). Dams fragment watersheds in ways that alter productivity, help species invade by forming reservoirs or lake-like ecosystems, and disrupt fish life cycles by preventing access to spawning or rearing habitat. However, dams can also play a role in conservation by barring invasive species from threatening native fish assemblages upstream (Saunders et al. 2002, Novinger and Rahel 2003, Rahel 2013, Hermoso et al. 2015). For our study, we summarized the biosecurity that park dams have provided.

Park barrier map

We created a barrier map for Algonquin Provincial Park that includes dams, vertical barriers and high slope sites (Figure 7). We based the map on known dam locations, maps of waterfall location, high resolution digital photography, digital elevation models of the park landscape converted to slope maps, and watershed field surveys (see Appendix 1 for information about our methods and Appendix 2 for an example of a digital region of the park landscape and corresponding slope map). We used the barrier map to determine accessibility and limitations to fish moving among and within watersheds.

The park has 2277 barriers to fish movement: 27 dams, 190 vertical barriers >20 cm, and 2,060 high slope sites (>10%; 10-15% is considered high enough to deter fish movement, depending on the fish species).

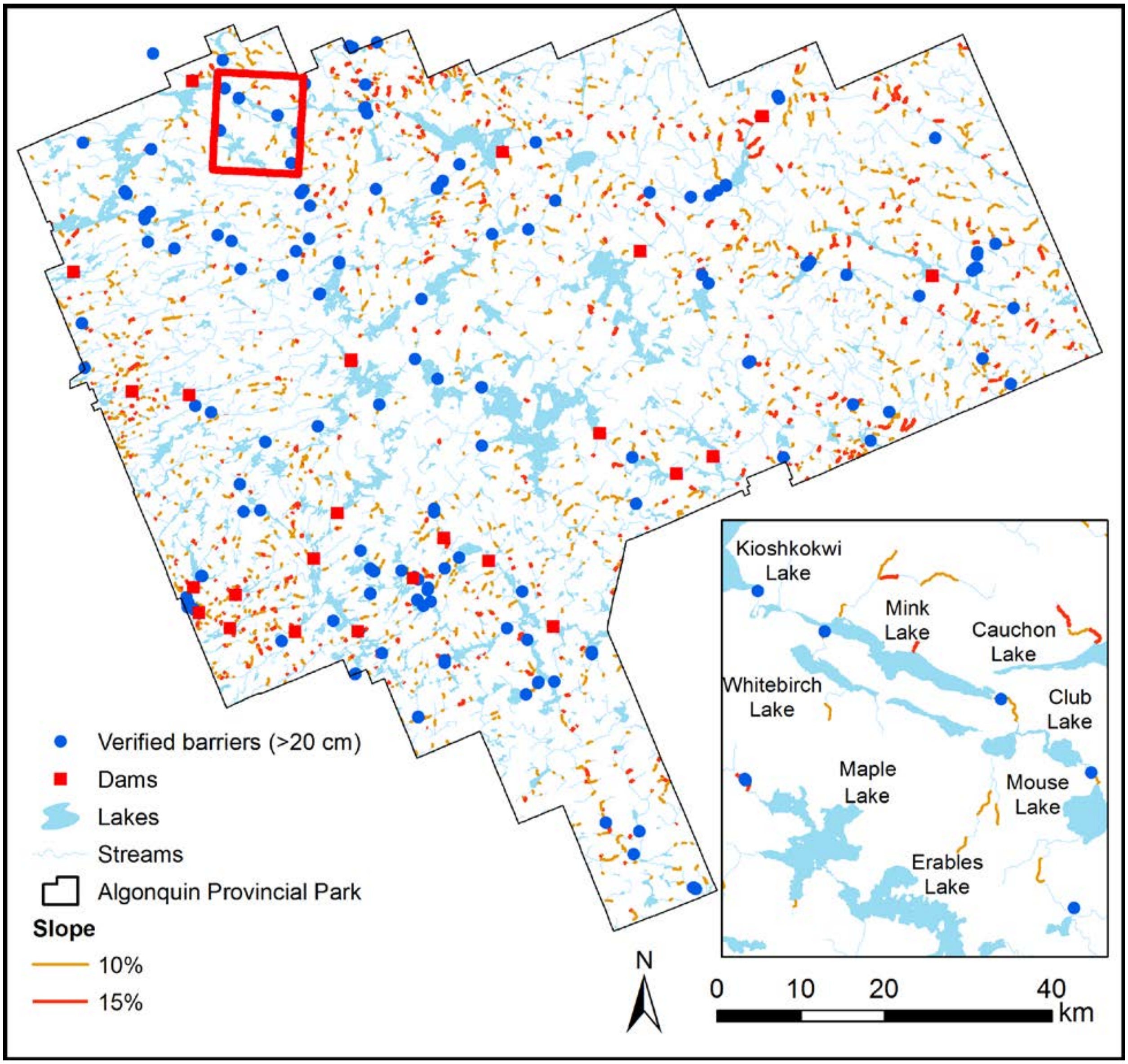

Figure 7. Map of barriers to fish movement in Algonquin Provincial Park, including dams, vertical barriers, and stream high slope segments (orange indicates slope greater than 10% and red indicates slope greater than 15%; 10-15% is considered an effective deterrent depending on the species). Insert highlights an area near Cache and Head lakes. Known barriers (blue circles) are often found on or adjacent to high slope segments.

Aquatic connectivity and park boundaries

Aquatic connectivity along the park's boundary reveals which watersheds flow into and out of the park landscape. Two kinds of boundary crossings occur around the park's boundary, and they have different levels of invasion risk:

1) **Outflow streams and rivers:** Headwaters are in the park interior and flow off the Algonquin Dome to the surrounding landscape. Invasion is limited by barriers that stop fish from moving upstream onto the dome.

2) **Inflow streams and rivers (*thumbnail* headwaters):** The top of the watershed sits outside the park boundary but flows into the park. The upper Petawawa River (see Figure 1) is an example of a thumbnail headwater that extends just beyond the west park boundary.

Figure 8 shows very limited access to the park landscape for fish moving upstream after introduction outside the park but within a watershed originating inside the park. Within the Madawaska River watershed, only sections along the Opeongo River are at slight risk from introductions from outside the park.

The park boundary has 32 sites where water flows into the park (Figure 9; Table 4). Fish introduced into these streams or lakes in these headwater areas could swim downstream into the park. Once in the park landscape, fish moving through these watersheds could be prevented from accessing other watersheds if barriers are present.

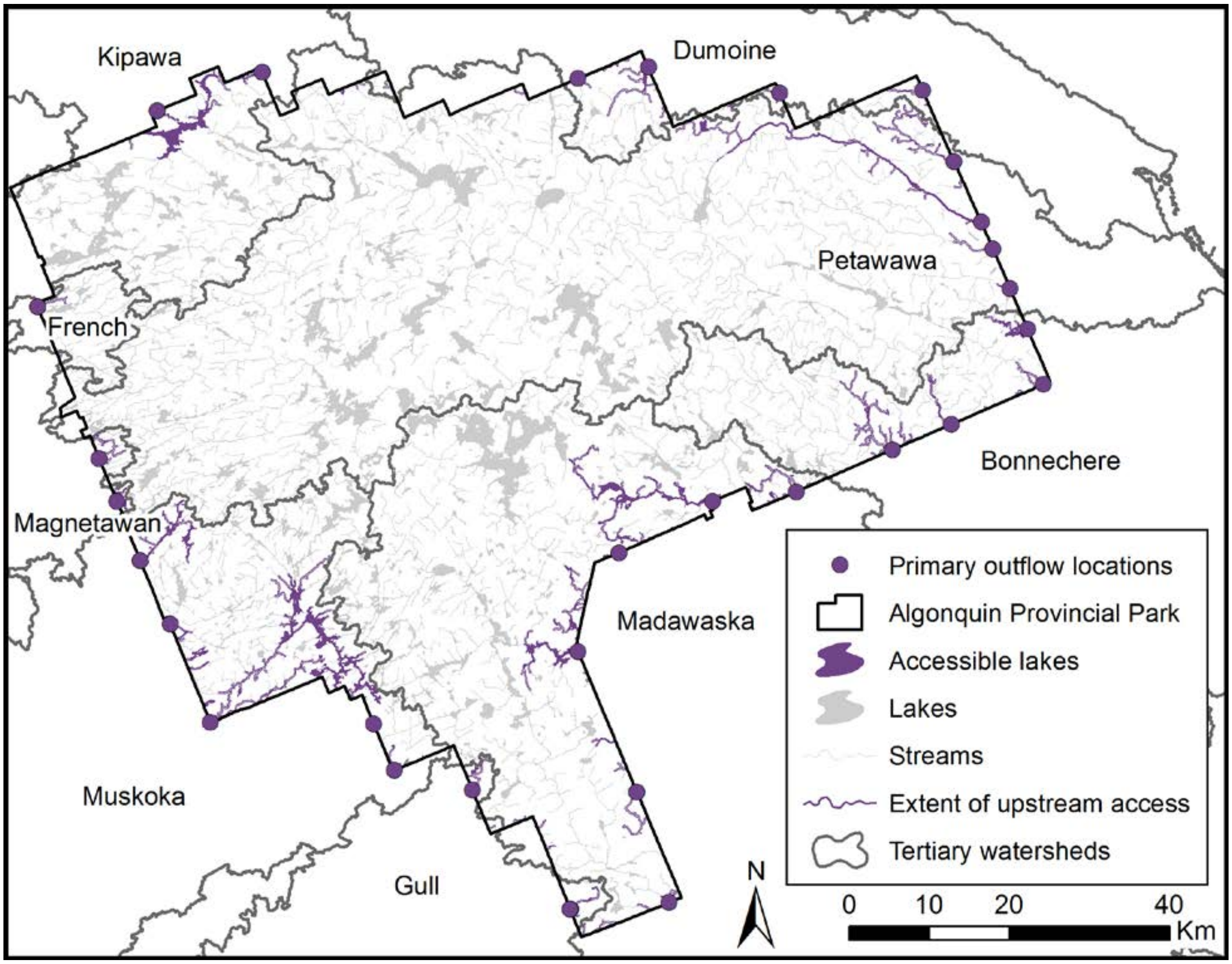

Figure 8. The extent of maximum upstream access for fish entering from outside Algonquin Provincial Park. Fish moving into the park would have to swim upstream to reach these areas, and their access is prevented by vertical barriers of >20 cm or stream slope >10%.

Figure 9 highlights the headwaters of the Petawawa River (Nipissing River tributary and Upper Petawawa River tributary; see Figure 1) as at highest risk among the thumbnail watersheds. Fish introductions in these headwaters can result in fish moving down the entire Petawawa River watershed from west to east across the park landscape. Other at risk areas are the park's northwest corner in the Kawawaymog Lake area and along the north boundary where headwaters drain south through the Hurdman River and North River (Figure 9). The thumbnail headwaters along the north boundary eventually joins the Petawawa River in Cedar Lake or Radiant Lake. From this map, the Petawawa River and the Amable du Fond River in the Kipawa watershed are the 2 watershed sections at highest risk from fish introductions in their respective thumbnail headwaters.

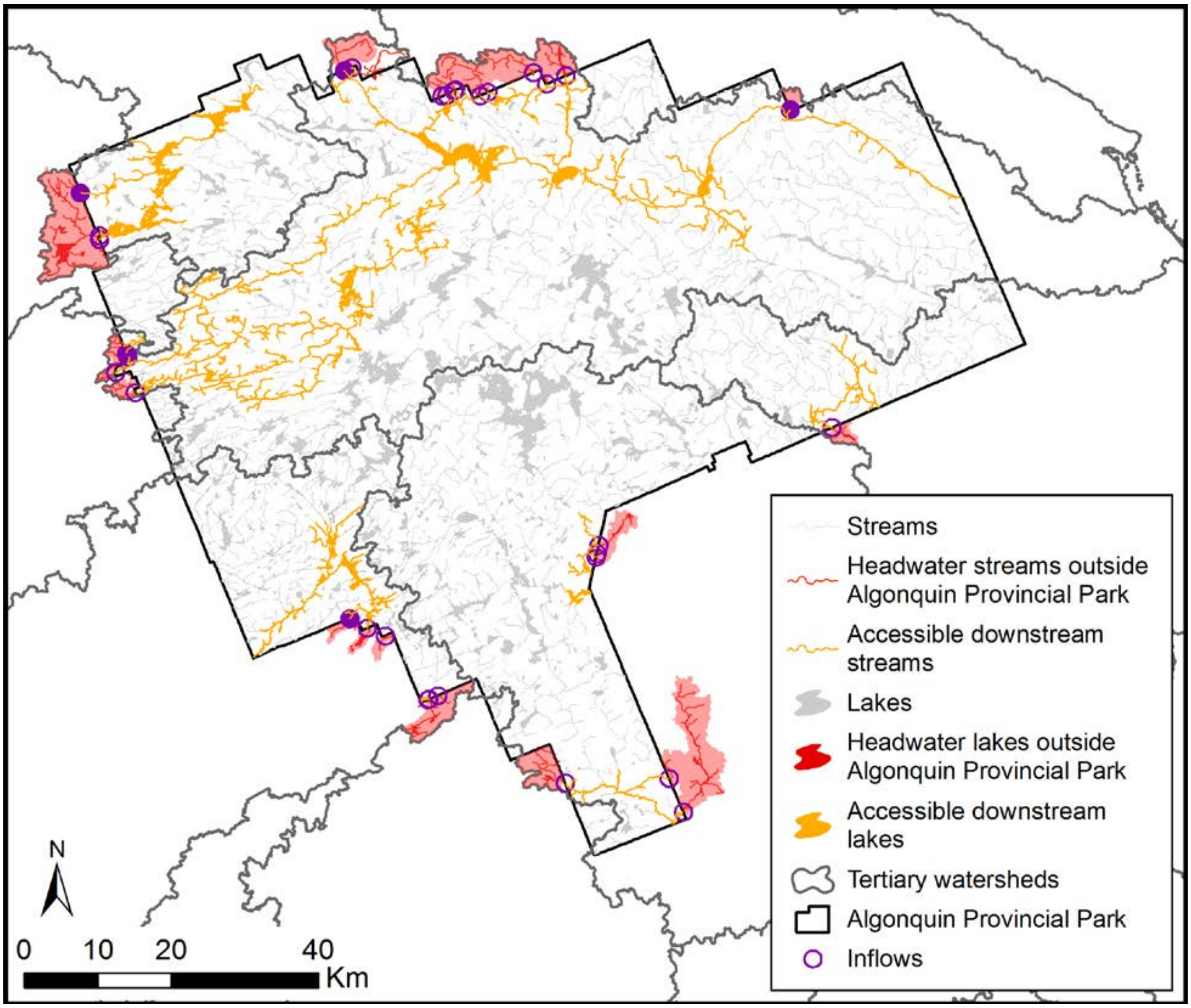

Figure 9. Maximum downstream extent of access for fish entering Algonquin Provincial Park in watersheds with thumbnail headwaters (tertiary watershed boundaries are in grey). These streams flow into the park so fish accessing these streams from outside the boundary would swim downstream into the park. Barriers do not stop fish from moving downstream. In connected adjacent waterways, fish can't move upstream where barriers are >20 cm or stream slope is >10%.

Other thumbnail headwaters also present some risk of introductions (Figure 9). Streams and lakes draining to Ragged Lake in the Muskoka watershed eventually lead to the Smoke/Canoe Lake system. Introductions occurring in this thumbnail headwater would travel over the Ragged Lake dam and into a lake system that gets lots of visitors.

In the southeast corner of the park panhandle, the Madawaska watershed lakes and streams in the Mink Lake system just outside the park boundary represent one of the longest thumbnail watersheds. The Mink Creek system provides access to the York River system and associated lakes in the park. Recently, largemouth bass was detected in lakes joined by the York River in the park.

Table 4. Watersheds with thumbnail headwaters beginning outside the Algonquin Provincial Park boundary and flowing into the park. These thumbnail headwaters are small relative to the total park watershed area yet could affect many lakes and streams.

Tertiary watershed	Combined area of thumbnail catchments (outside park boundary; km^2)	Watershed area in park (km^2)	Affected downstream lakes >5 ha in park (n/ total lake area in ha)	Affected downstream streams in park (km)
Bonnechere	8.3	525	7/275	117
Kipawa	85.2	639	8/4131	179
Muskoka	42.8	656	9/1895	175
Petawawa-west	17.9	3672	81/9235	1388
Petawawa-north	108.1			
Upper Madawaska	128.3	1780	11/713	85
Total	390.6	1936	116/16,218	1936

The areas of third-order park watersheds that fall into the thumbnail are small relative to the area of the total park watershed but can affect many lakes and kilometres of streams (Table 4). The Petawawa River watershed encompasses 48.1% of the park area with only 4.5% of its thumbnail watershed beyond the park boundary. Overall, 5.8% of the third-order watershed area covering the park is beyond the park boundary (the thumbnail watersheds).

When mapped, the size of the thumbnail watersheds relative to the overall park area is small (Figure 9; Table 4). Each watershed originating outside the park is an area of conservation concern as aquatic invasive species could spread to much larger areas downstream and in the park. The Petawawa and Kipawa watershed systems include large areas of the park landscape relative to the area of their thumbnail watershed areas (Figure 9).

Headwater lakes in the park — real and assigned

Headwater lakes are the uppermost reaches of watersheds; most are very small and not visited by many anglers. Lakes adjacent to headwater lakes can be large and popular with anglers so are assigned as headwaters (Figure 10 insert). The park has 845 headwater lakes larger than 5 ha (real or assigned) and many smaller ones, which may or may not be connected via intermittent streams.

Lakes assigned as headwater lakes in Figure 10 (insert) include Merchant, Happy Isle and Redrock lakes — all destinations for anglers. Other notable lakes include La Muir, Kingscote, McKaskill, Ralph Bice (and vicinity), Tim, and Lauder. Ralph Bice and Tim lakes occupy headwaters for the Petawawa River.

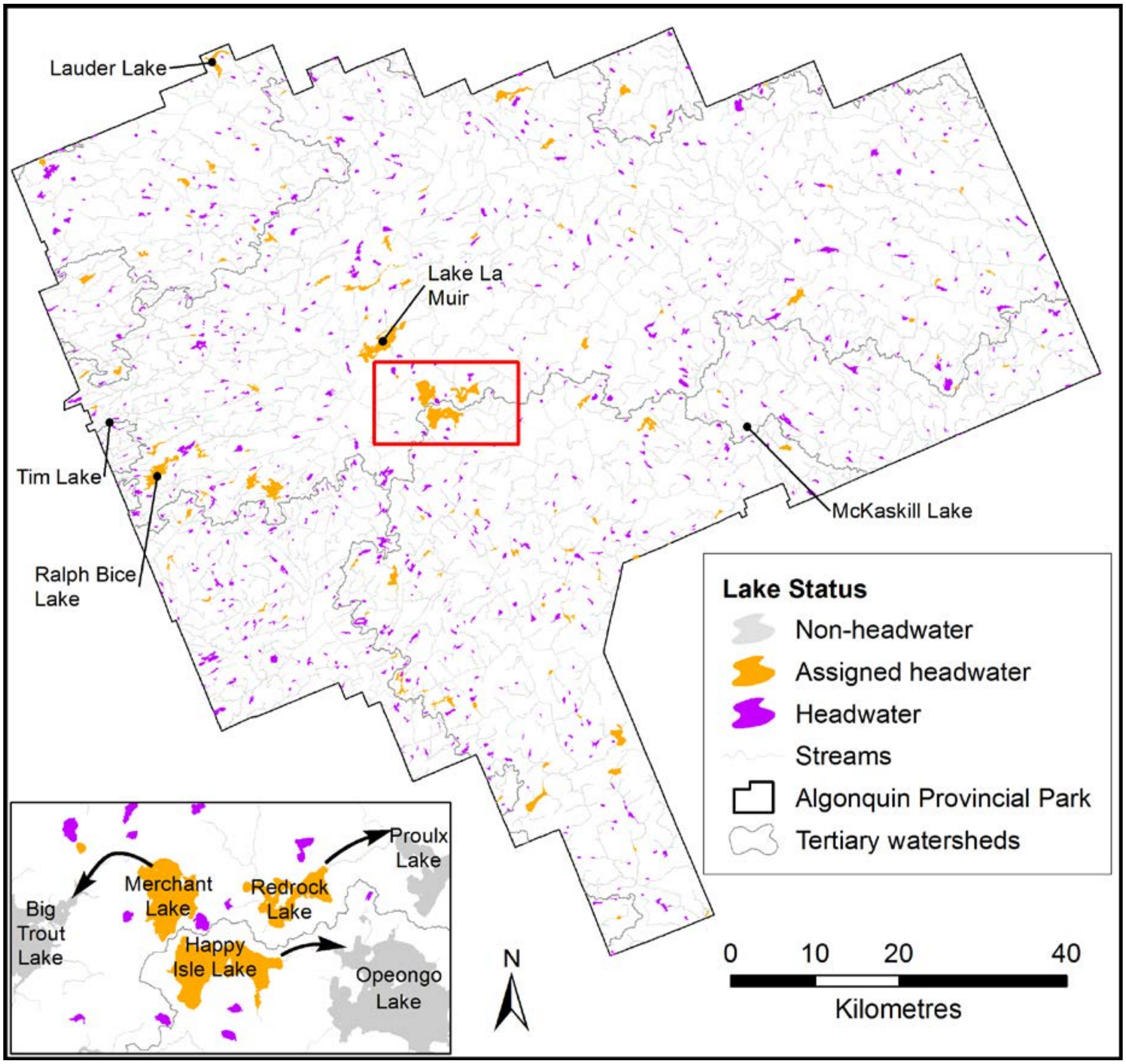

Figure 10. Headwater lakes in Algonquin Provincial Park may be true headwaters or assigned. Assigned headwaters are lakes directly connected to true headwater lakes. Flow directions in the insert map are indicated by black arrows.

Park dams as watershed security

In many parts of the world, the loss of native fish species and assemblages has led to the recognition that barriers can play an important role in conserving freshwater fish. For example, in western North America, introduced fish have severely compromised native trout assemblages, leading some to highlight dams as watershed security for sustaining native fish populations (Fausch et al. 2002, Rahel 2013). However, dams on rivers can also prevent proper ecosystem functioning including making it difficult or impossible for some species to complete their life cycle, for example, by barring access to spawning habitat (Olden 2016).

The 24 dams in Algonquin Provincial Park protect parts of the landscape from upstream invasion (Figure 11). The Petawawa watershed has a series of nested catchments, each layer adding protection in the upstream direction. For example, Big Trout Lake is protected by the remnants of Big Trout Dam, Cedar Dam, and Lake Travers Dam.

The Shirley Lake dam is a useful example of how park dams can provide biosecurity (Figure 12). The Opeongo River below this dam has several introduced predators including smallmouth bass, rock bass, northern pike, and most recently, largemouth bass (Ridgway et al. 2017). The watershed above the Shirley Lake dam includes brook trout populations and Type 1 (small body, plankton-eating) lake trout populations in Round Island Lake and Shirley Lake. Introduced non-native predators would put this lake trout food web at risk as they could dominate the inshore component of the food web as well as prey on small lake trout (Vander Zanden et al. 1999). The dam stops introduced fish predators from spreading further upstream and reaching more populations. If predators do establish above the current dam location, brook trout and lake trout populations will fall.

Other park dams also bar non-native fish predators. Annie Bay dam stops northern pike and rock bass from establishing in Lake Opeongo. Booth Lake dam prevents largemouth bass from establishing in that lake, but unsanctioned introductions of northern pike and rock bass into Booth Lake (over the dam) show how dams as conservation barriers can be breached.

For more about dams protecting park watersheds, see Appendix 2.

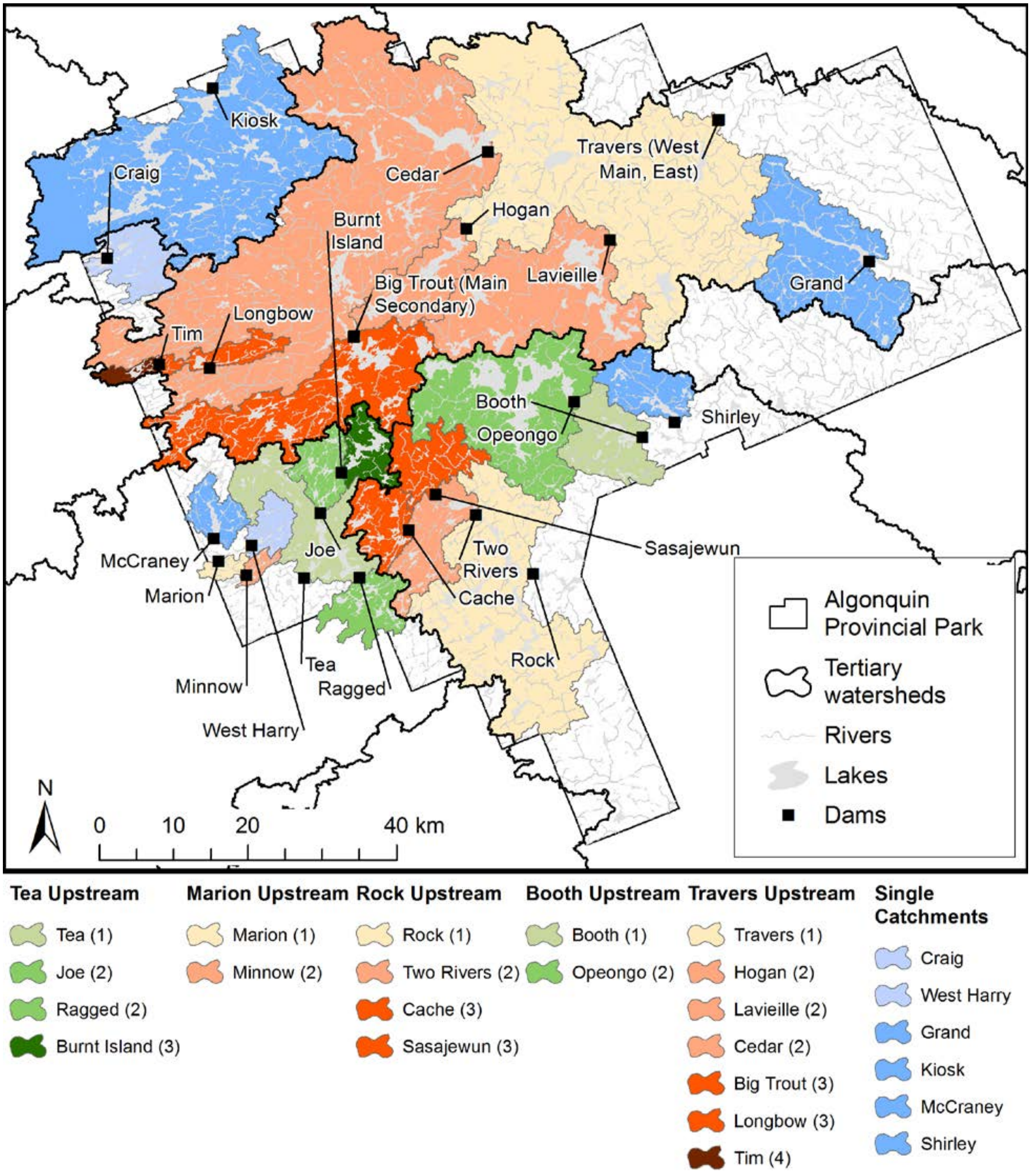

Figure 11. Upstream catchment of each dam in Algonquin Provincial Park. They range from 30 cm to a few metres tall. Dams not passable to fish protect the catchment. Some watersheds have multiple dams along the same river system, which means more isolation for areas upstream of all dams. For example, in the Madawaska watershed, Opeongo Lake is upstream of both the dam at Booth Lake and the dam on the east arm of Opeongo.

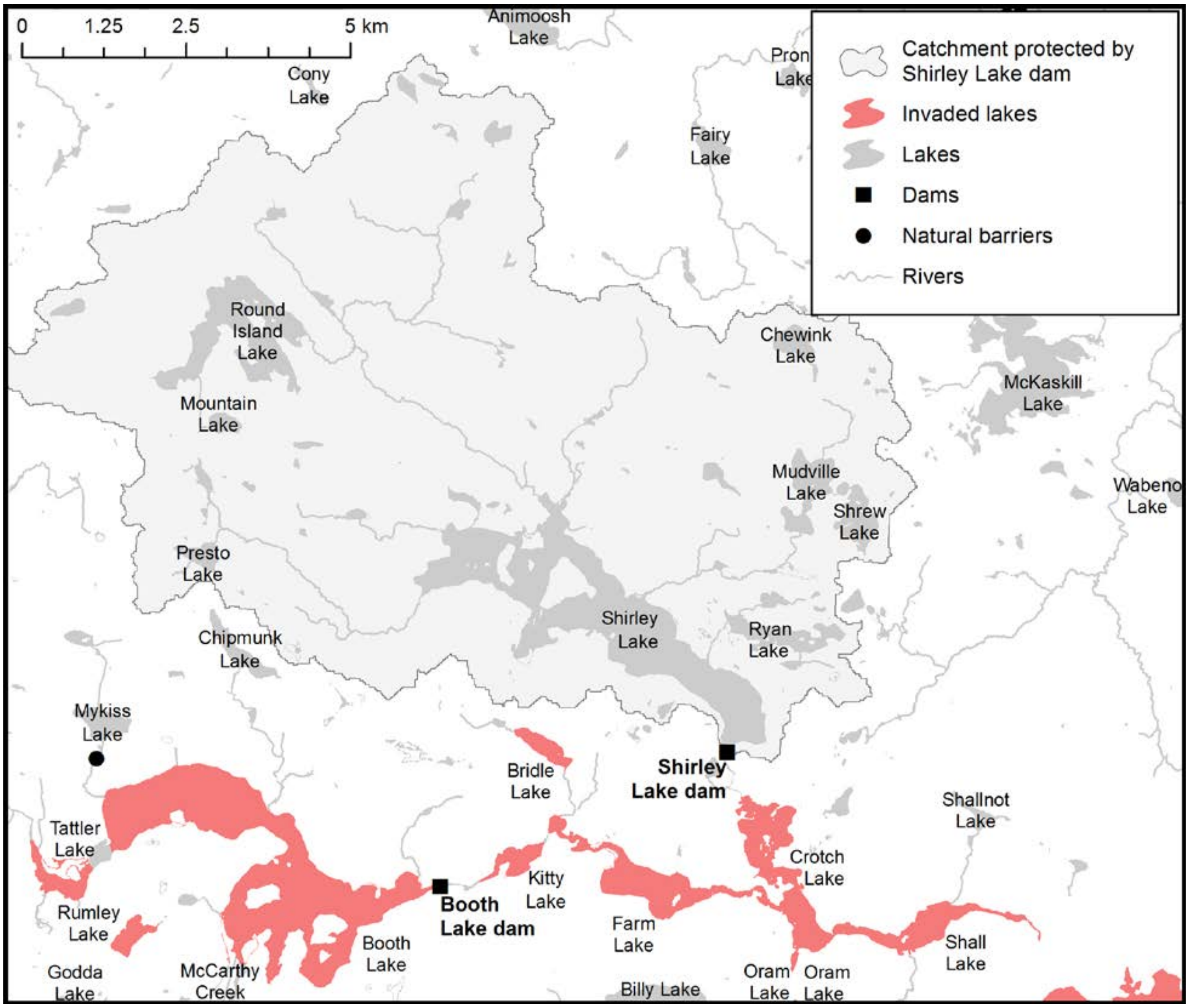

Figure 12. An example of a dam upstream catchment in Algonquin Provincial Park. This watershed is upstream of the Shirley Lake dam, including Round Island, Presto, Ryan and Shrew lakes (all brook trout lakes).

Annie Bay dam

The Annie Bay dam at the outlet of Lake Opeongo has been in place in one form or another for a century. Early in the 20th century, a log structure was used to control lake levels and generate lake height to help move logs downstream (figures 13 A,B). In 1955, the dam was replaced with a stop-log structure as part of a water management system supporting hydroelectric generation downstream (figures 13 C-F). In 2011, an *ogee* (s-shaped) dam replaced the previous structure, allowing for continued spillover.

A survey of the plunge pool below the dam revealed a species list that included warm and cold water species (Table 5). Four species introduced to the Opeongo River watershed over several decades are below the dam with rock bass and northern pike captured close to the dam's base. These two were not present in Lake Opeongo as of 2016 — the Annie Dam bars their spread into the larger watershed.

The distribution of dams and illegally introduced fish in the Opeongo River below Annie Bay Dam is a case study on the issue of dams providing biosecurity for watersheds and aquatic ecosystems. The Booth Lake dam was sufficient to stop the spread of northern pike and rock bass but individuals that illegally moved those species from the river below the dam to Booth Lake resulted in additional spread of these species further towards the park's centre — and closer to watersheds with abundant populations of brook trout and lake trout. If pike, rock bass and smallmouth bass were to spread to central areas of the park then many native aquatic food webs would be deeply affected.

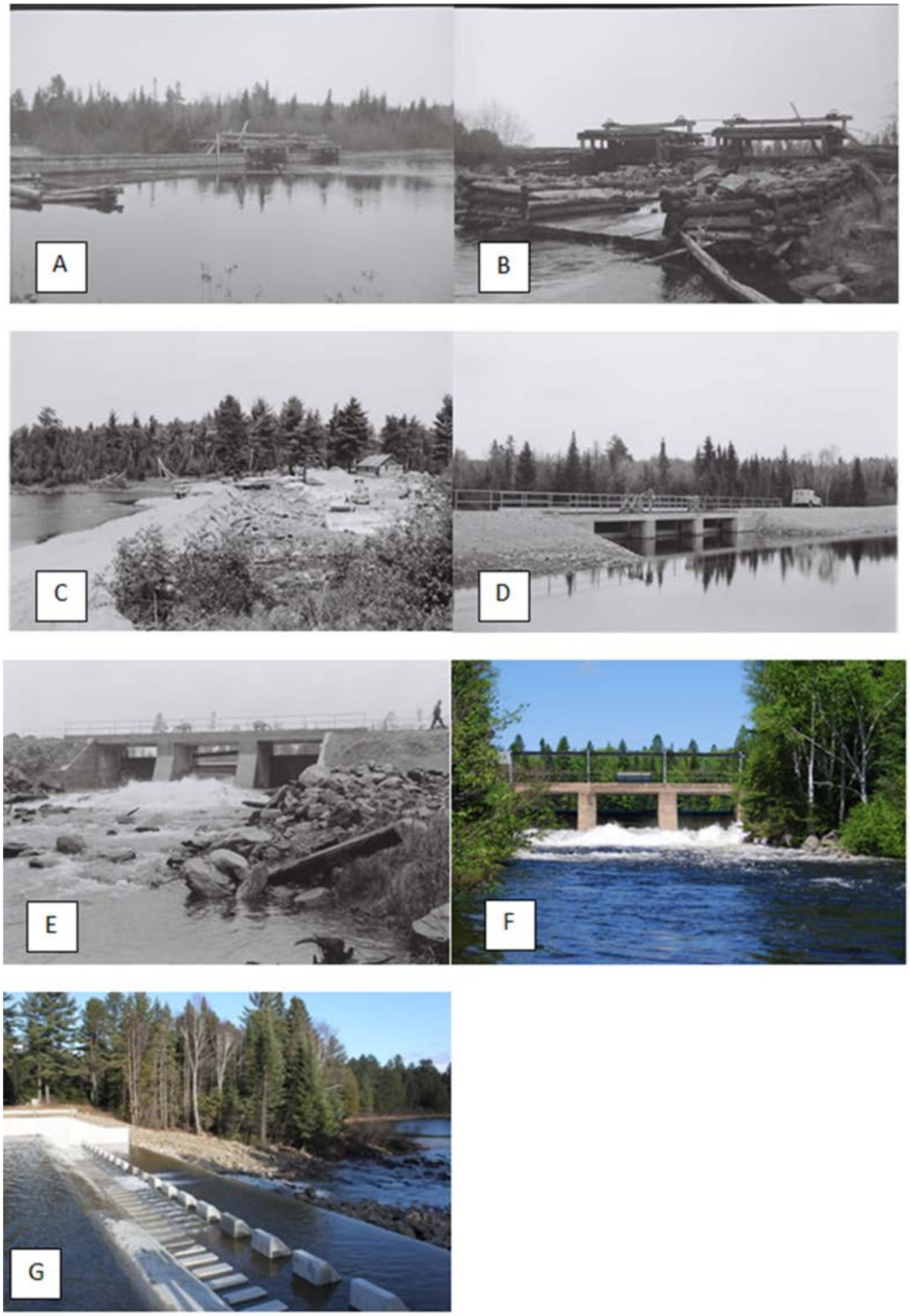

Figure 13. The Annie Bay dam on Lake Opeongo in Algonquin Provincial Park over time: A-B) First dam being used for log transport in the early 20th century; C) second dam being built in 1955; D-E) second dam operating in 1955; F) second dam in 2011; and G) third *ogee* (s-shaped) dam operating after construction in 2011. Images C and G have the same perspective.

Table 5. Fish species list for seasonal sampling in Tip-Up Lake, the plunge pool below the Annie Bay Dam on Lake Opeongo in Algonquin Provincial Park. Sampling occurred from May to August 2011 using bait traps. Fall sampling was in 2004 using gillnets; ** indicates a species not native to the Opeongo River and Lake Opeongo/Booth Lake. These species (**) were introduced in the 20th century.

Species	May	June	July	August	Fall
Lake trout	●	●	●	●	Yes
Round whitefish	●	●	●	●	Yes
Cisco**	Yes	●	●	●	●
Northern pike**	●	Yes	Yes	●	Yes
Central mudminnow	●	●	Yes	Yes	●
Brassy minnow	Yes	●	●	●	●
Creek chub	Yes	Yes	Yes	Yes	●
Golden shiner	●	●	Yes	Yes	●
Bluntnose minnow	Yes	Yes	Yes	Yes	●
White sucker	●	Yes	●	Yes	●
Burbot	Yes	Yes	Yes	Yes	●
Brown bullhead	●	●	Yes	Yes	●
Pumpkinseed sunfish	Yes	Yes	Yes	Yes	●
Rock bass**	Yes	Yes	Yes	Yes	●
Smallmouth bass**	Yes	Yes	Yes	Yes	●
Brook stickleback	Yes	Yes	Yes	●	●
Yellow perch	Yes	Yes	Yes	Yes	●
Iowa darter	●	●	●	Yes	●
Mottled sculpin	Yes	●	●	●	●

Risk assessment of fish introductions in the park

Risk is the probability of something happening and its consequences. For aquatic ecosystems in the park, risk includes the probability of illegally introducing non-native species, the locations they could travel to, and the outcomes of their establishing in lakes that haven't had new species since the last ice age ended. Two components of risk are important for fish introductions in the park:

1) Risk of introductions includes **people and their use of different areas** as a measure of potential occurrence.
2) Risk has a **geographic element through aquatic connectivity** — fishes' ability to move among lakes and rivers.

Fish introductions disrupt native fish assemblages that have defined the park landscape since glaciation. This disruption can happen several ways; examples include:

- **Rainbow smelt:** Example of a bait fish introduction with potential effects on native species (smelt are illegal to use as bait in the park, alive or dead)
- **Northern pike and smallmouth bass:** Examples of predator introduction with potential effects starting at the top of a food web and moving down

To capture the effects of fish introductions on lake food webs, consequences must be assessed lake by lake, which was outside the scope of our study.

Spread of introduced fish from park access points

Visitor access points in the park and near the park boundary are sites where fish introductions could occur and includes access at campgrounds and sites with major outfitting operations (Canoe Lake and Lake Opeongo). The hierarchical, directional network of park lakes and streams can lead to the spread of introduced fish species from these points. Table 6 summarizes the extent of lakes and streams that introduced fish species could occupy via watersheds that cross boundaries (thumbnail watersheds and upstream into park) or visitor access points.

The number of stream kilometres at risk from access point introductions (981 km) is about the same as the stream kilometres at risk from introductions in thumbnail headwaters (979 km). The number of lakes potentially invaded from access points is lower (N=171) compared with thumbnail headwaters (N=252). Overall, 12% of the park's stream length is at risk of fish introductions from visitor access points or introductions in thumbnail headwaters. Angling effort in thumbnail watersheds is unknown, but since these have small headwater ponds and streams, the scale of angling in the headwaters is likely far lower than at access point lakes with recreational fisheries.

Table 6. Algonquin Provincial Park stream kilometres, number of lakes at risk of fish introductions at the park boundary (thumbnail headwaters upstream movement across the boundary), and public access points. The park has about 3700 km of streams (Strahler second order and larger; Dingman 2002).

Introduction locations (barriers and 10% slope)	Lakes affected (>10 ha) (n)	Lakes affected (>10 ha) (%)	Stream kilometres affected (n)	Stream kilometres affected (%)
Park boundary — downstream from thumbnail headwaters	252	31	979	26.5
Park boundary — upstream	119	15	602	16.3
Visitor access points	171	21	981	26.5

A look at park visitor access points reveals several watersheds and sets of lakes at risk of fish introductions based on human use patterns (Figure 14):

- The Tim River access point is at high risk due to its position as a headwater area for the Upper Petawawa River system.

- The Magnetawan Lake site, adjacent to Ralph Bice Lake, has a relatively small area of immediate risk from fish introductions because at the access point, the watershed flows out of the park. This access point could have an effect equivalent to the Tim River access point due to the proximity to a headwater position of Ralph Bice Lake in the Upper Petawawa River system.

- Highway 60 corridor access points linked with camping areas are at risk due to high levels of human use regardless of whether they are used as departure points for interior camping. At Lake Opeongo and Canoe Lake, the combination of outfitting operations and a departure point for interior camping makes these lakes at higher risk of fish introductions.

- At the Brent access point, on Cedar Lake, fish introductions would disperse downstream in the Petawawa River system but not upstream into the Upper Petawawa due to vertical barriers downstream of Catfish Lake and in the Nipissing River.

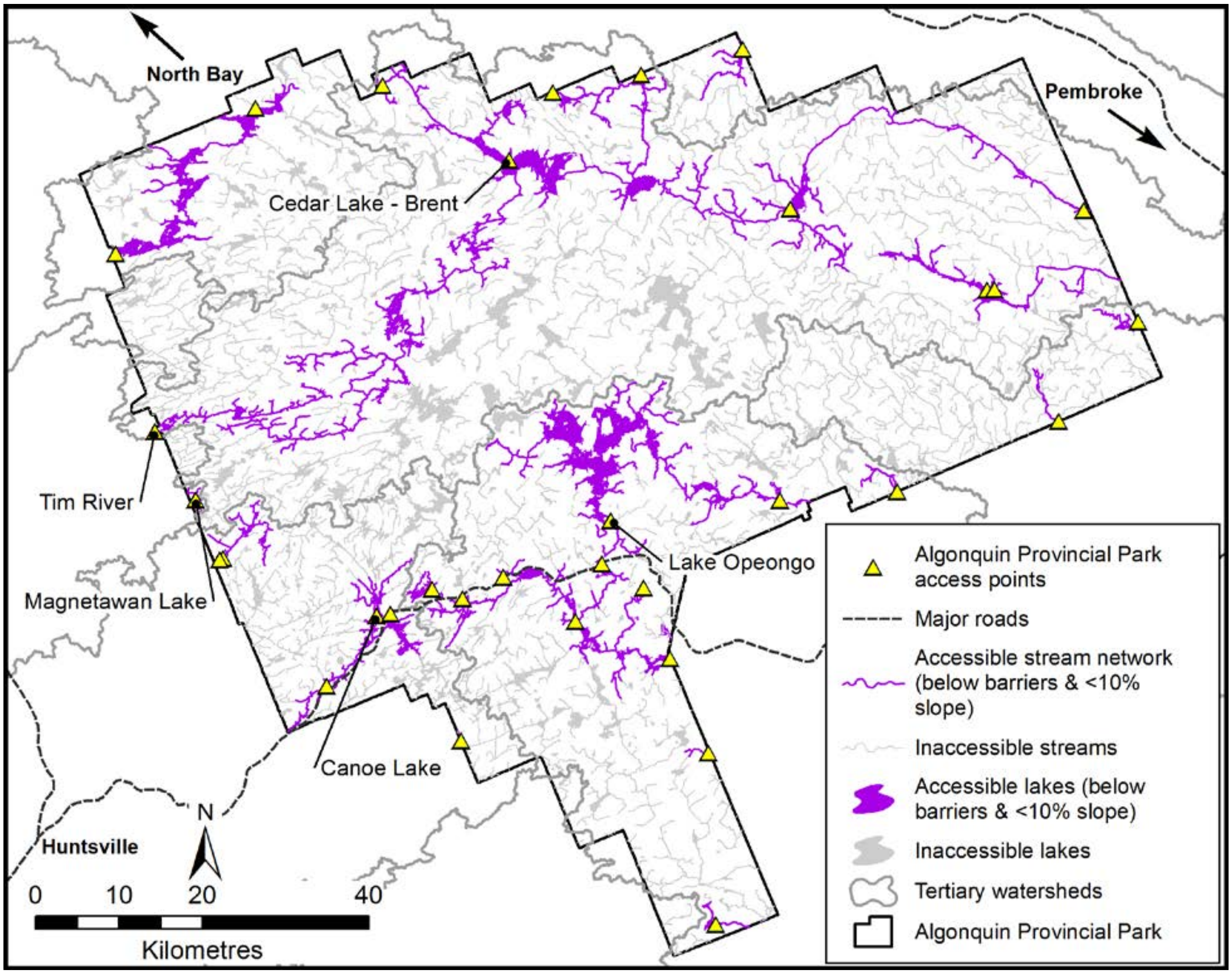

Figure 14. Algonquin Provincial Park lakes and streams potentially vulnerable to illegal fish introductions directly or through nested directional flow from official park access points. This includes vehicle-based campgrounds, outfitting store locations, departure points for back country hiking/camping, and canoeing locations. Angling is permitted at all access points.

Campgrounds are a subset of park access points (Figure 15). The use patterns of campers differs from those of non-campers (e.g., at Canoe Lake and Lake Opeongo). At campgrounds, visitors spend several days at a fixed location, but at sites without camping, visitors are day users or use the point to start several days of interior camping. The map of campground access sites and corresponding risk of introduction is a subset of the total access map (Figure 15):

- In the park's northwest, risk of fish introductions is confined to the Amable du Fond watershed especially Kioshkokwi and Manitou lakes.

- The lower Petawawa River from Cedar Lake to the park's east boundary is at risk of fish introductions from the Cedar Lake campground.

- From the Achray campground, fish introductions are largely confined to the Grand Lake watershed. As well, along the Highway 60 corridor, campgrounds at Cannisbay, Mew, Pog, and Rock lakes and Lake of Two Rivers have high use. Barriers limit the spread of fish introductions to these and several other lakes (Figure 15 insert).

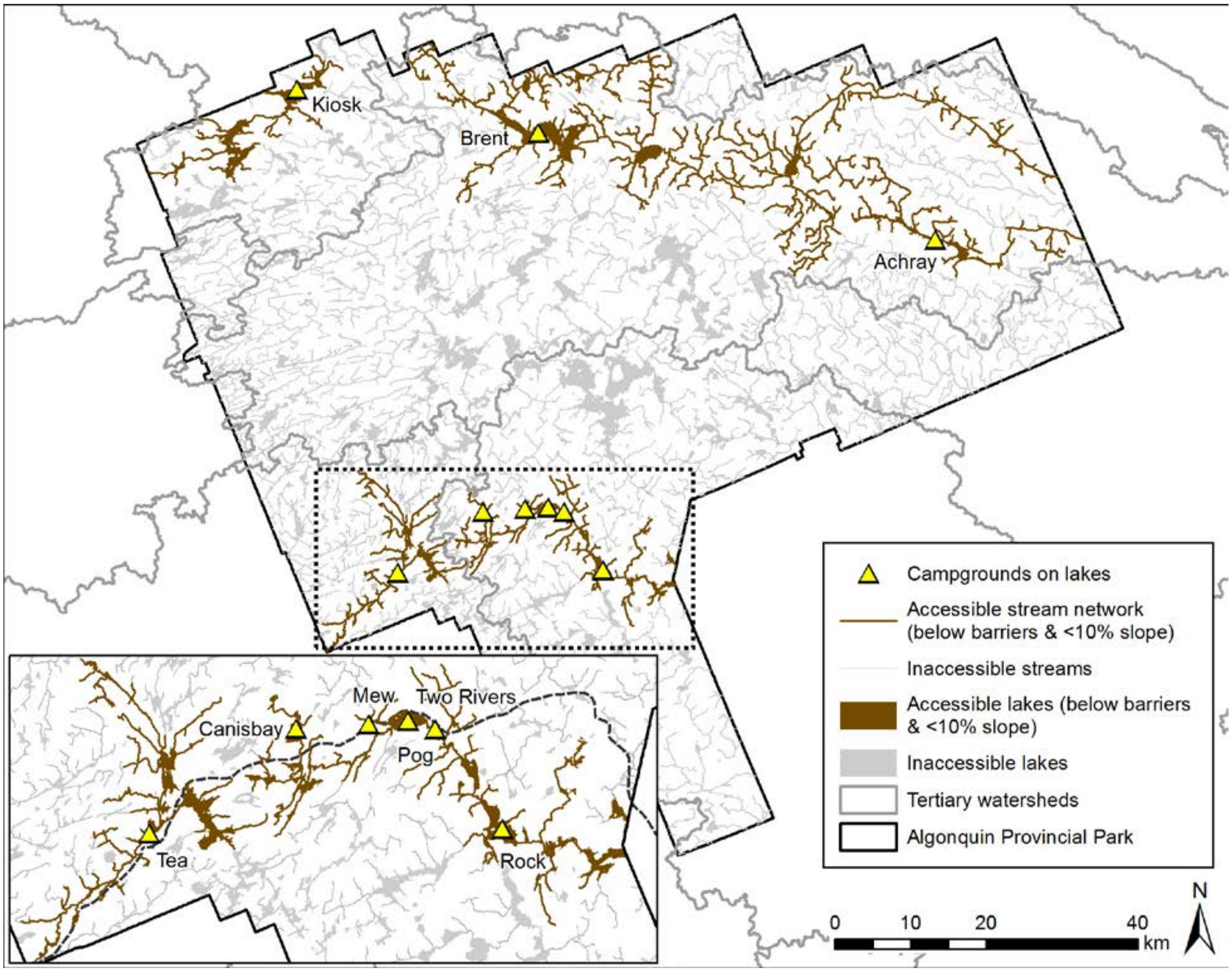

Figure 15. A map of vehicle-accessible campgrounds in Algonquin Provincial Park. Watersheds and lakes are highlighted where fish introductions could spread from campgrounds. Insert shows the Highway 60 corridor campgrounds.

Table 7 provides a ranking of access points used by interior campers in 2015 — it is an index of public use as well as jumping-off points for camping. Canoe Lake is the highest ranked departure point. The west gate rank shows visitors arriving at the park, acquiring an interior camping permit, and moving to a potential departure point. The rankings listed in Table 6 provide a list of lakes most vulnerable to species introductions based on level of public use.

Table 7. Ranking of popularity of visitor access sites used in 2015 as departure points for interior camping in Algonquin Provincial Park (includes all campers, whether fishing or not).

Lake	Ranking
Canoe	1
Opeongo	2
Rock	3
Grand	4
Smoke	5
Magnetawan	6
Kawawaymog	7
Shall	8
Rain	9
Kioshkokwi	10
Cedar	11
West Gate	12
Cache	13
Travers	14

Figure 16 shows the distribution of fish introductions (predators and prey fish; thickened black lake boundary) and their proximity to access points:

- Twenty of 31 lakes with access points (65%) have introduced fish species.
- Eleven lakes immediately downstream of the 20 access point lakes with introduced fish species also have confirmed introduced species. This demonstrates spread from access point introductions.
- Ten lakes isolated from access point lakes by barriers have introduced fish species through historic stocking and/or spread from lakes with historic stocking.

Mink, Burnt Island, and Happy Isle lakes stand out as they are isolated from access point introductions yet have an introduced predator — smallmouth bass. Bass may have been introduced above barriers that normally protect these lakes (Figure 16).

The Figure 15 insert focuses in on the lake set in the Highway 60 corridor. This area has several lakes with some of the oldest fish introductions in the park (Mitchell et al. 2017) and includes lakes where fish (almost exclusively smallmouth bass) were transported over natural barriers that protect lakes from access point introductions. Generally, a good indicator of lakes with introduced fish is the lake set associated with park access points.

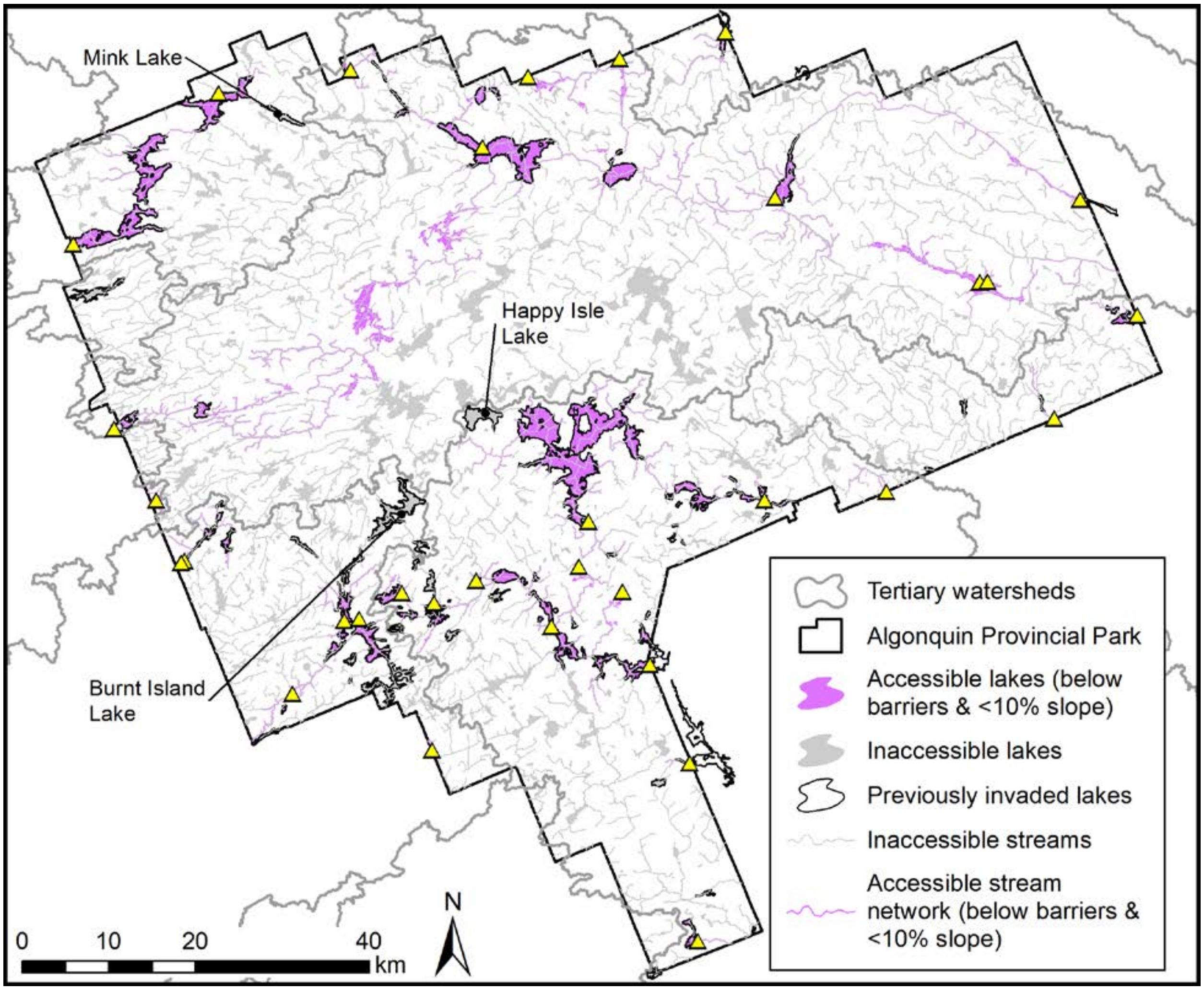

Figure 16. Fish introductions in Algonquin Provincial Park lakes and streams that can be reached directly or through nested directional flow from official access points (purple). Lakes without detected fish introductions are purple. Lakes that have introduced fish species and can be reached from access points are outlined in black. Sixty-five per cent of access point lakes have introduced fish species.

Spread of 3 introduced fish species in the park

Introducing fish species into new areas beyond their original habitat leads to *homogenization of fish fauna* (Rahel 2000, 2007, 2013). Introduced predator or prey fish alter natural food webs established over long periods of time and extirpate small fish species, generating a pattern of sameness across geographic areas. The loss of diversity (food webs, species) reflects historical patterns of fish spread in watersheds. Three species of introduced fish exemplify this trend, and we have data on the timing of introductions and later spread of 2 of them.

Smallmouth bass

George Bartlett, an early superintendent of Algonquin Provincial Park, noted in 1907: “The small-mouthed bass introduced into a few of these lakes some years ago have abundantly stocked the streams for 50 miles to the east of the Park, and splendid bass fishing is now had where a few years this gamiest of fish was unknown.”

Smallmouth bass was introduced to a small number of park lakes in 1899 (Mitchell et al. 2017). Stocking continued well into the 20th century (ending in the mid-1960s) and was followed by spread through aquatic corridors in the park or unauthorized introductions (Figure 17). This species’ distribution can be mapped from fish stocking history, anecdotal reconstructions, and later findings in other lakes. If smallmouth bass is in lakes connected to stocked lakes, bass likely spread through the watershed to the lakes. If a barrier separates lakes in a watershed, then bass in lakes with no recorded stocking history points to arrival due to unrecorded introductions, sanctioned or not. Bass stopped spreading due to barriers or watershed limits (e.g., Burnt Island Lake and the upper reach of the Muskoka River watershed; Figure 17). The occurrence of this species in several park watersheds outside its native location in Lake Travers has led to the loss of small fish species and increased the homogenenization of the fish fauna in those lakes through loss of species diversity (MacRae and Jackson 2002; Trumpickas et al. 2011).

This pattern of smallmouth bass stocking and spread has been repeated across Ontario and other regions with resulting loss of small native fish species (Whittier et al. 1997, Findlay et al. 2000, Jackson 2002). Smallmouth bass preying on smaller native fish species is the ecological mechanism predicted to occur in Ontario (Vander Zanden et al. 2004, Sharma et al. 2009). This species also alters lake food web structure, leading to lake trout declining in lake size and number (Vander Zanden et al. 1999).

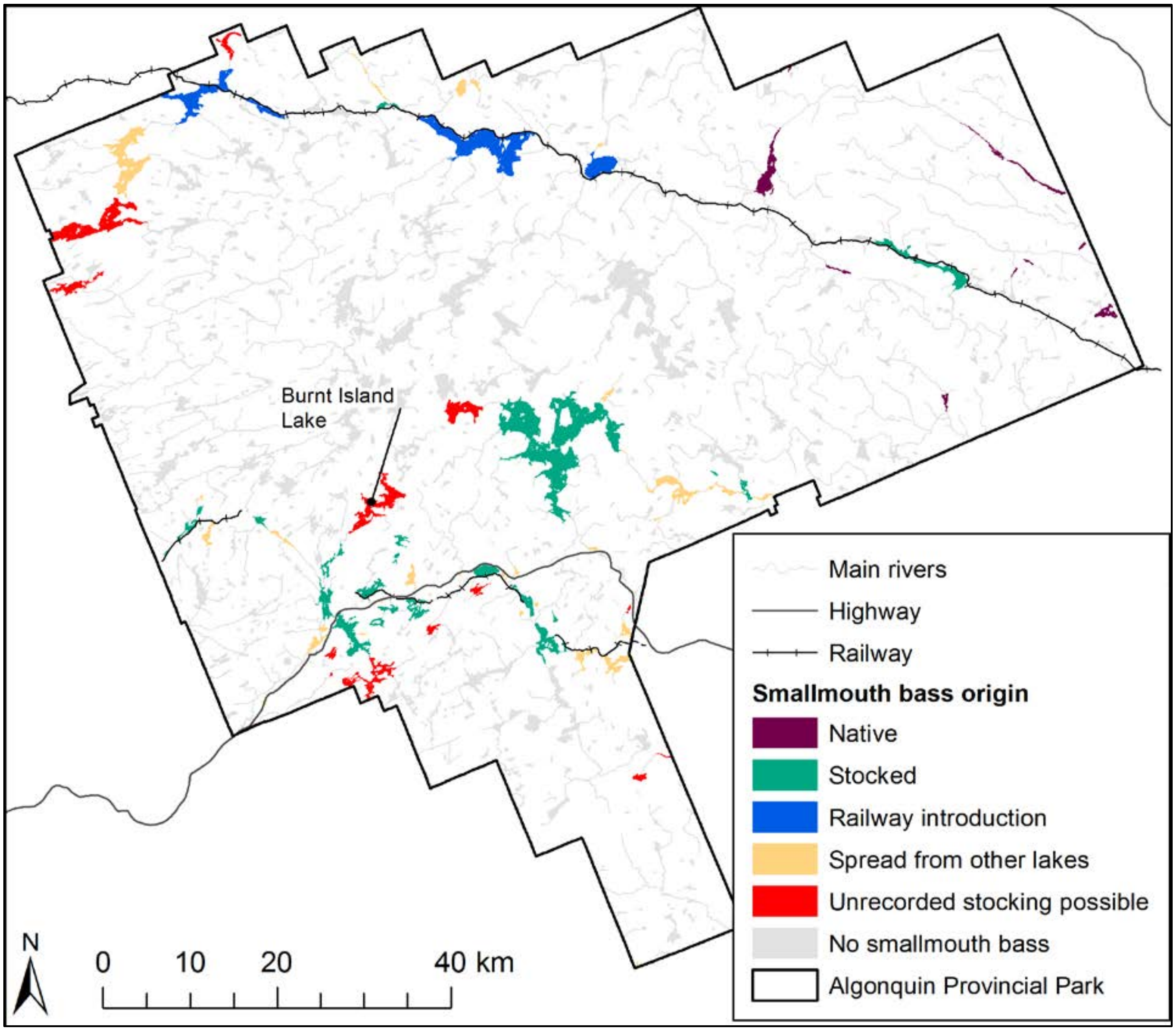

Figure 17. Past smallmouth bass stocking locations and spread in Algonquin Provincial Park. Smallmouth bass are native to low elevation lakes in the park's eastern area (dark purple). Starting in 1899 through to the mid-1960s, bass were stocked in several lakes in the park including along the rail line (green and dark blue). Other lakes with smallmouth bass had previous introductions (peach) or unauthorized stocking where barriers prevented direct spread.

Rainbow smelt

In the past, rainbow smelt was illegally used as a baitfish and has been introduced into the headwaters of 2 park river systems, spreading into the park following those introductions. First, this species was introduced into the upper reaches of the Amables du Fond River (Kipawa watershed) outside the park. First detected in North Tea Lake in 1985, it then spread to Manitou (1990) and Kioshkokwi lakes (1993) within a decade of its discovery in the park (Figure 18). Upstream barriers and high slope areas have limited the spread of rainbow smelt to the 3 large lakes. This introduction should be contained given the limits to natural movement in the Amables du Fond River in this area of the park.

A second introduction was in Tim Lake in 2009, in the uppermost reach of the Petawawa River system (Figure 18). It’s unclear whether rainbow smelt were introduced directly to this lake or in the small stream and pond system upstream of Tim Lake. Regardless, the outcome has been the same as in the Amables du Fond River over 20 years earlier: Tim Lake was a Type 1 lake trout lake defined by lack of open water prey fish and small-bodied lake trout, and now its lake trout are piscivorous and larger. It is transforming to a Type 2 lake trout lake — a direct consequence of a fundamental change in the food web due to rainbow smelt introduction.

In 2011, rainbow smelt were detected in the next lake downstream, Rosebary Lake (Figure 18). Then in 2016, 1 rainbow smelt was captured farther downstream in a lake survey of Catfish Lake. This finding could be a separate introduction, but this lake is farther into the park and away from access points. So rainbow smelt have likely spread downstream from Roseberry Lake, with passage through Longer and Burntroot lakes (or these lakes already have rainbow smelt).

Uncertainty about smelt presence in Longer and Burntroot lakes reflects how difficult it is to track dispersal of fish introductions. Lake surveys of Longer Lake in 2015 as well as Burntroot and Catfish lakes in 2013 failed to detect this smelt species. It was either missed or absent from the lakes at that time. If absent, then the detection in Catfish Lake was a recent dispersal from Roseberry Lake. Lake surveys of Cedar Lake in 2011 and Radiant Lake in 2010 and 2016 showed no rainbow smelt. Whether present or absent from lakes in the Petawawa River watershed, rainbow smelt will occur in Algonquin Park lakes within the Petawawa River system as shown in Figure 18. This species prefers cold water so their establishing in lakes such as Travers and McManus will depend on whether they have the right habitat. Cedar and Radiant lakes have the extremely rare blackfin cisco, along with other fish whose larval stages are vulnerable to smelt, so rainbow smelt could pose a serious threat.

The use of live baitfish is prohibited in Algonquin Park. Use of rainbow smelt as live or dead bait is prohibited in the park.

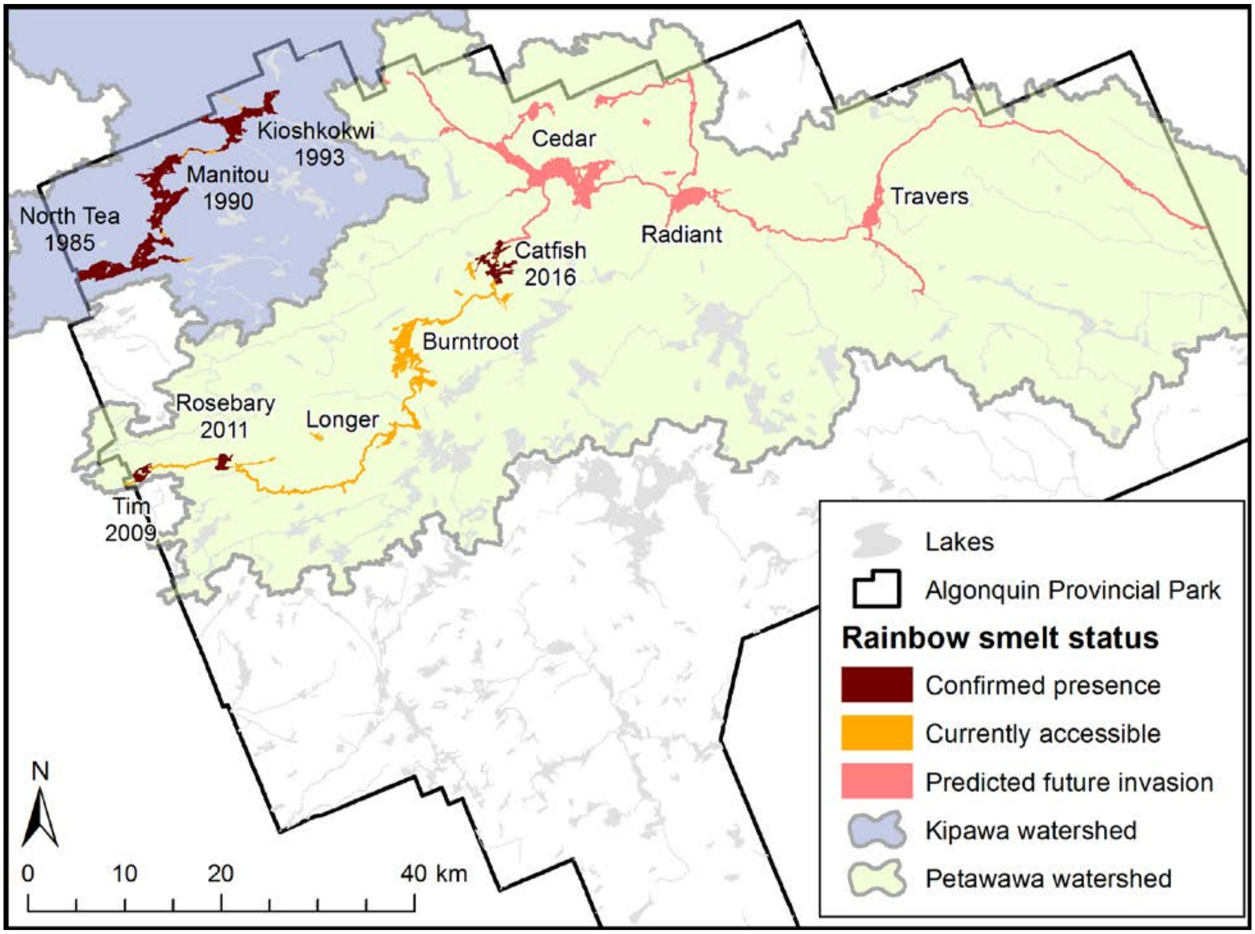

Figure 18. Rainbow smelt current and predicted distribution in Algonquin Provincial Park with year of detection shown for some lakes. Lakes with confirmed rainbow smelt are dark red; aquatic corridors between lakes with rainbow smelt are orange. Predicted future occurrence of rainbow smelt in lakes and streams connected to occupied lakes is pink.

The rainbow smelt case study offers an excellent example of the speed and certainty with which fish introductions into headwater lakes can spread downstream in hierarchical, networked aquatic corridors. No matter what the protection levels for native fish populations in lakes, upstream introductions will eventually have a watershed-wide distribution (depending on barriers).

Northern pike

Northern pike is a top predator in lake and river ecosystems in Ontario. In 1982, this species was illegally introduced to Victoria Lake just outside the park boundary (Figure 19). Since that introduction, this species has moved into the park with a first appearance in the Shall Lake area in 1989, including Crotch Lake below the Shirley Lake dam. In 1992, northern pike were found in Farm Lake upstream of Shall Lake. The Victoria Lake to Farm Lake dispersal consisted of this species moving through a lake-river system ending at the foot of the Booth Lake dam. The Booth Lake dam produces an approximate 1 m difference in water levels above and below the dam, more than enough to block natural movement of pike (Figure 20).

However, an illegal introduction occurred over the Booth Lake dam, resulting in pike being detected in the Booth Lake ecosystem in 1994. Northern pike have now spread to other accessible lakes in the area (Figure 19), including to the foot of the Annie Bay dam on Lake Opeongo.

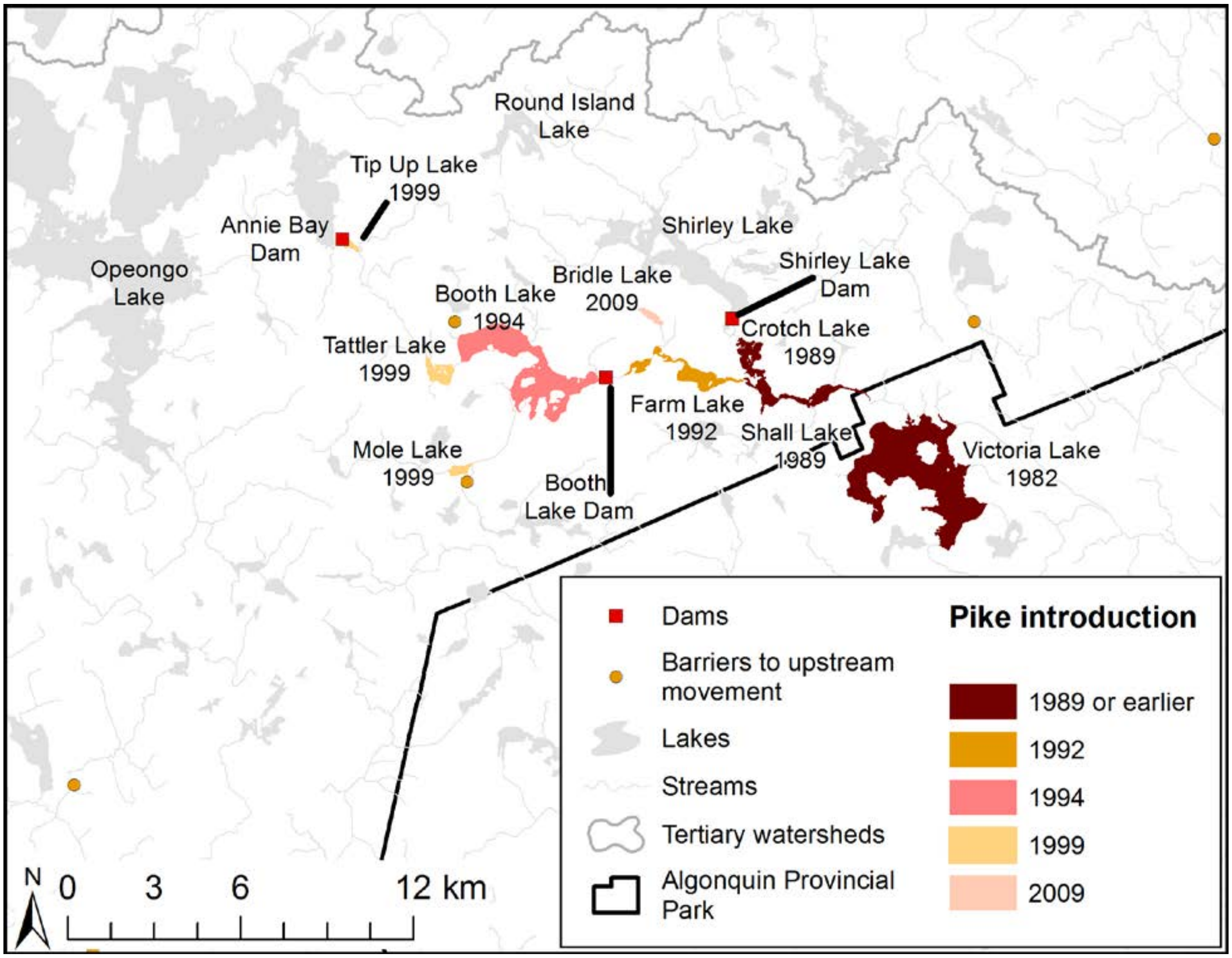

Figure 19. Movement of northern pike from Victoria Lake into Algonquin Provincial Park including year of the first reported northern pike in each lake. Pike have expanded upstream from Victoria Lake to the edge of Annie Bay dam on Lake Opeongo and the Shirley Lake dam.

The spread of northern pike in this section of the Opeongo River is an example of upstream movement with no barriers. Three dams (Annie Bay, Booth Lake, and Shirley Lake) stopped this species from spreading farther into the park. Being helped over the Booth Lake dam has given northern pike access to a watershed area that matches or exceeds the park watershed area they previously occupied. Most of the current distribution of northern pike in the Opeongo River unfolded in less than 15 years.

Figure 20. Booth Lake dam in 2013. This dam causes a 1 m water level difference between the lake and the downstream river so bars natural movement of large predator fish.

Invertebrate introductions in the park

The transport and use of boats and outboard motors in the park poses a risk of introducing non-native invertebrates, some of which can be highly disruptive to native lake food webs. Different life stages can hide in small, wet spaces of boat trailers, boats, and engines. Signs at park access points highlight the risks and places where invertebrates could hide, and for many years, park staff have been advocating for proper washing of boats, engines, and trailers. Figure 21 illustrates the lakes in Algonquin Park that allow boats with motors.

If a non-native invertebrate such as a zooplankton species were to be introduced in a park lake, it would spread downstream only from the introduction point. Unlike fish, invertebrates like zooplankton cannot swim upstream so flow direction (rather than vertical barriers and steep slopes) defines vulnerable lakes.

Figure 21 shows the difference among lakes in access and motor allowance:

- Interior lakes that allow a 6 hp engine in spring are difficult to get to and require at least 1 foot portage to reach.
- A 20 hp limit is allowed on several lakes, with a subset along Highway 60.
- Other lakes such as Galeairy and Opeongo have no horsepower limits, get boats with a range of engine sizes, and are easy to access.

Thus, interior lakes with a 6 hp engine limit are at lower risk of invertebrate introductions than easier-to-access lakes with higher or no horsepower limits. Generally, motor allowances occur on lakes known for recreational fishing as well as pleasure boating.

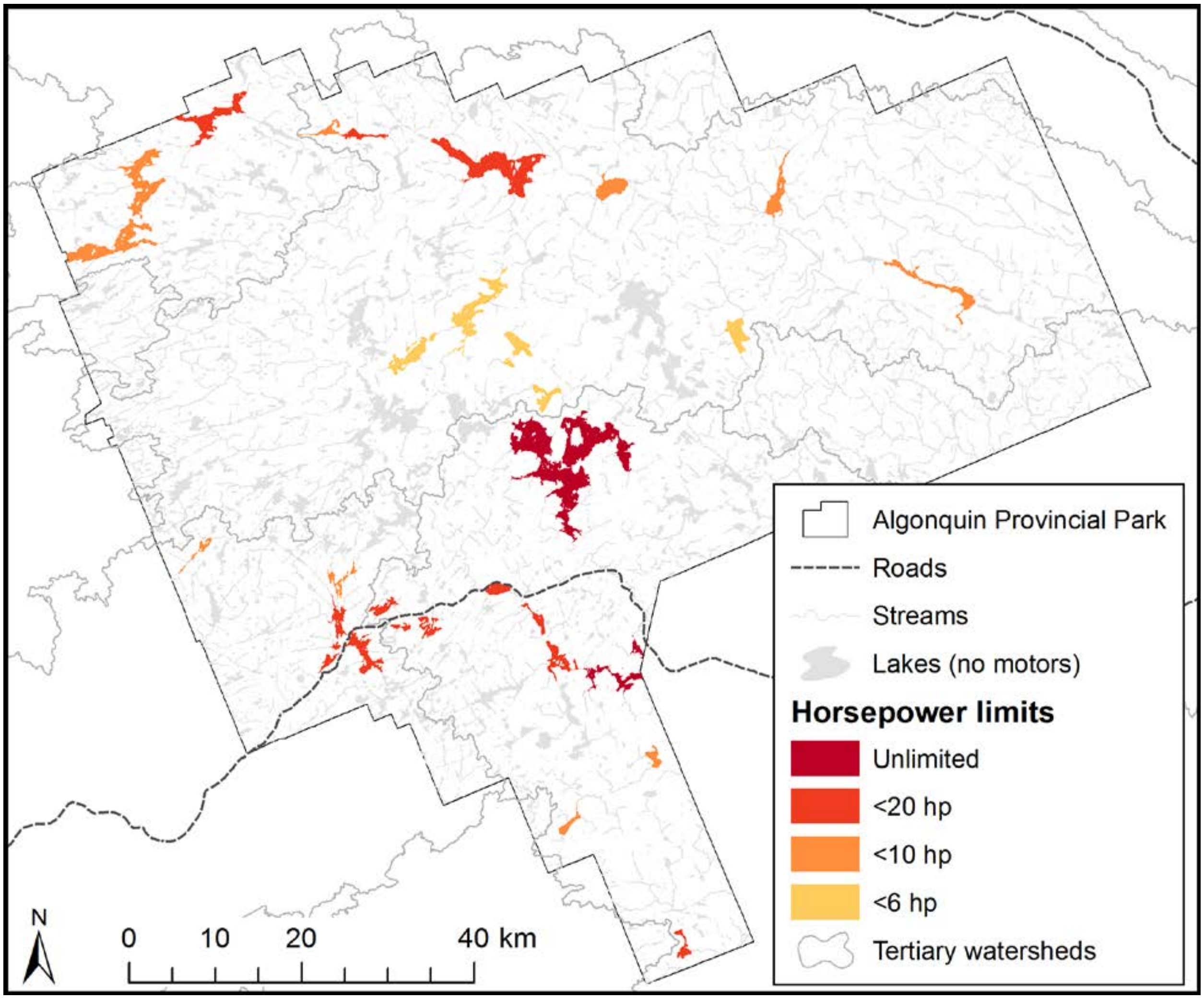

Figure 21. Boat motor limits on lakes in Algonquin Provincial Park. Invertebrate introductions can occur if boats, motors, and trailers are not properly washed after visits to lakes outside the park, with easier to access lakes being more at risk.

Invertebrates moving among lakes via boats and trailers accounts for the spread of invasive dreissenid mussels (*Dreissena spp.*) and spiny water flea (*Bythotrephes longimanus*) in North America. These species have not yet been detected in the park, but their spread outside park boundaries is a lesson in human-assisted gravity models of spread — that is, downstream and landscape spread from introduction sites such as boat ramps at lakes. Gravity models begin with identifying the method of transporting invasive species (= boat trailering), movement routes (= road system), and the probability that wet spaces in boats or trailers contain 1 of the invertebrates (= probability of seeding lakes with invasive species). This approach has been successful in mapping the spread of spiny waterflea (MacIsaac et al. 2004). As with bait movement, only a small per cent of boats or trailers will have an invasive species. The likelihood a site is a recipient of an introduced species is based on how much that site is used — more use means greater risk.

Barrier protection of park lakes

The park has 376 lakes (>10 ha) that cannot be reached by introduced fish species from any access point lake or thumbnail headwaters. These lakes make up 47% of all of the park's lakes over 10 ha (total = 802). This protection level is due to watershed barriers that break aquatic connectivity. However, fish sometimes get help to overcome barriers (see lakes in orange in Figure 22).

Some lakes shown in Figure 22 have a natural barrier but have introduced species due to past stocking or unauthorized introductions. Lakes such as Happy Isle, Burnt Island, Provoking, and Cannisbay are protected by barriers from fish spreading to them after introductions in downstream lakes. Instead they have smallmouth bass introduced through stocking (legal or illegal) many decades ago.

Brook trout are listed as present in 71% of the protected lakes, and lake trout are listed as present in 31% of these lakes. Due to this protection level, the park will continue to be important for sustaining these coldwater species from homogenization due to fish introductions at access points or in thumbnail headwaters.

Figure 22 shows that areas in the park's interior are not protected from introductions at access point or boundary watersheds because some watersheds such as the Petawawa River begin just beyond the park boundary and flow east across the park.

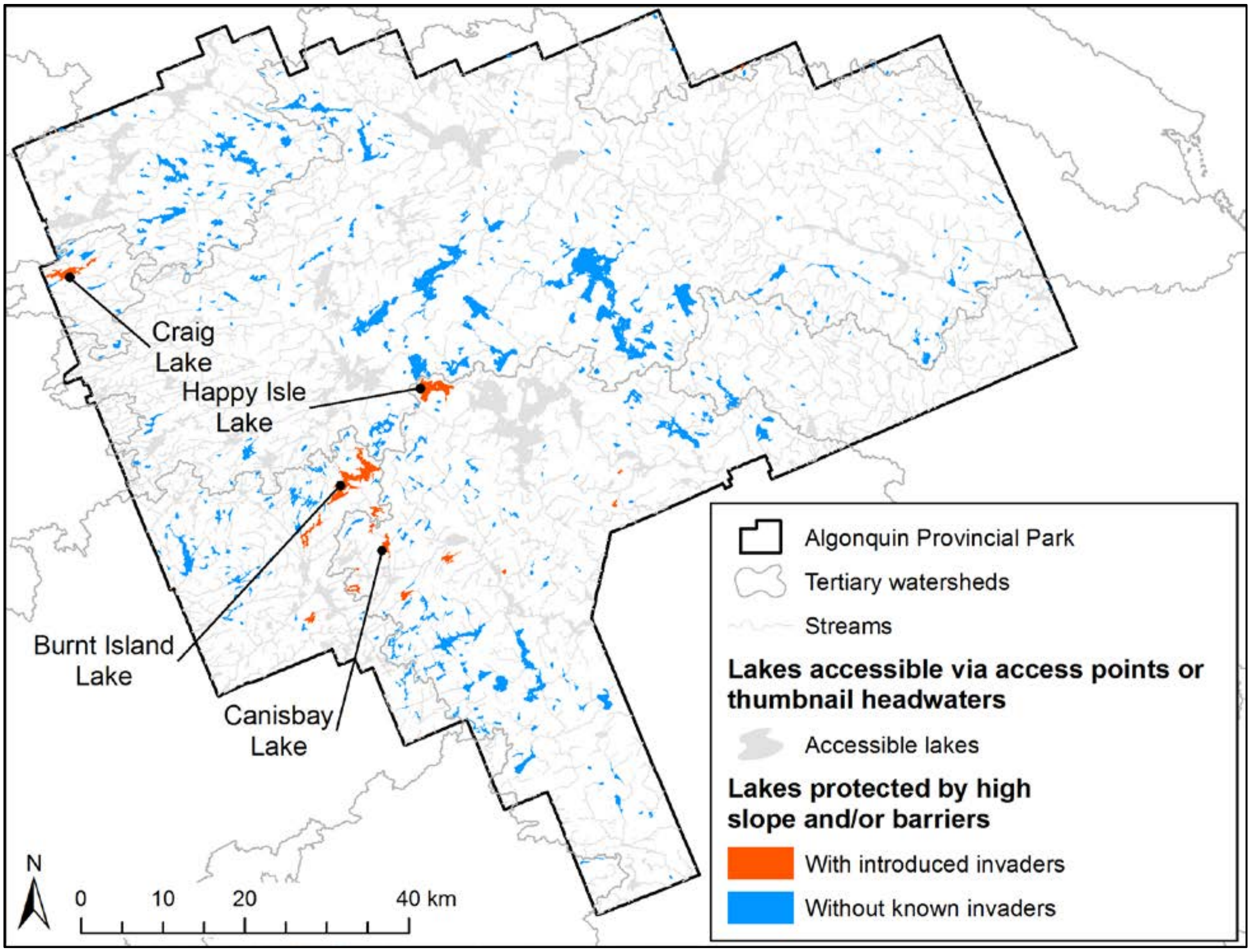

Figure 22. Algonquin Provincial Park lakes that are protected by natural barriers and high slopes in aquatic corridors, as well as fish introductions from access points and locations in thumbnail headwaters outside the park. Some inaccessible lakes (e.g., Burnt Island, Canisbay, Happy Isle, and Craig) have introduced smallmouth bass due to historic stocking or unrecorded introductions.

Populations of special interest in the park

All fish populations are of interest since each has its own story of how it recolonized the park landscape after the glaciers retreated at the end of the last ice age, how they fit in a larger fish assemblage in each lake, and how their predator/prey relationships affect productivity and sustainable harvest levels. However, the lakes highlighted in Figure 23 are unique due to evolution and current fisheries management. Dickson Lake, for example, is a source population for a native strain of brook trout used in the provincial hatchery system. This strain is used for stocking lakes in the park for population recovery efforts or for put-grow-take fisheries in the Highway 60 corridor. It’s also used for stocking in other parts of central and southern Ontario.

Figure 23 highlights other lakes that are cases of relatively rare *ecological speciation* — the island-like evolution of multiple forms of a single species in a lake. In these cases, lakes act as islands with fish species colonizing lakes after glaciation followed by a partitioning into different populations based on availability of different feeding niches. For example:

- White Partridge Lake has at least 2 forms of cisco (*Corgeonus artedi*) with one occupying the whitefish niche (lake whitefish are absent from White Partridge Lake) and the other occupying the open water plankton feeding niche typical of cisco (Turgeon et al. 2016).
- Mink, Cedar, Radiant, and Hogan lakes have the extremely rare blackfin cisco as well as regular cisco (except for Mink) — a form of cisco that is a glacial refuge of a now-extinct Great Lakes species or a new example of island evolution.
- Big Trout Lake has the normal form of lake whitefish feeding on bottom organisms as well as a form that is a cisco mimic and feeds on zooplankton in the open water. The absence of cisco has allowed lake whitefish to develop bottom feeding and plankton-feeding forms. Canada has seen few such cases in lake whitefish (Mee et al. 2015).
- Lake Opeongo has 2 forms of lake whitefish but not in the pattern found in Big Trout Lake: Its normal form is long lived, but the other is much smaller and short lived and it does not occupy open water as in Big Trout Lake but rather bottom habitat (Kennedy 1943).
- La Muir Lake does not have a bottom form of lake whitefish (common across Canada) but rather a plankton-feeding form occupying open water — effectively a cisco mimic. This lake whitefish population may be the only of its kind in Canada. La Muir Lake does not have a deepwater oxygen deficit so the lack of bottom-feeding lake whitefish can’t be attributed to degraded habitat.
- McManus Lake on the eastern park boundary has had 1 sighting of a dead lake sturgeon. Since this species’ distribution in this part of Ontario has been greatly reduced, this sighting is of great interest.

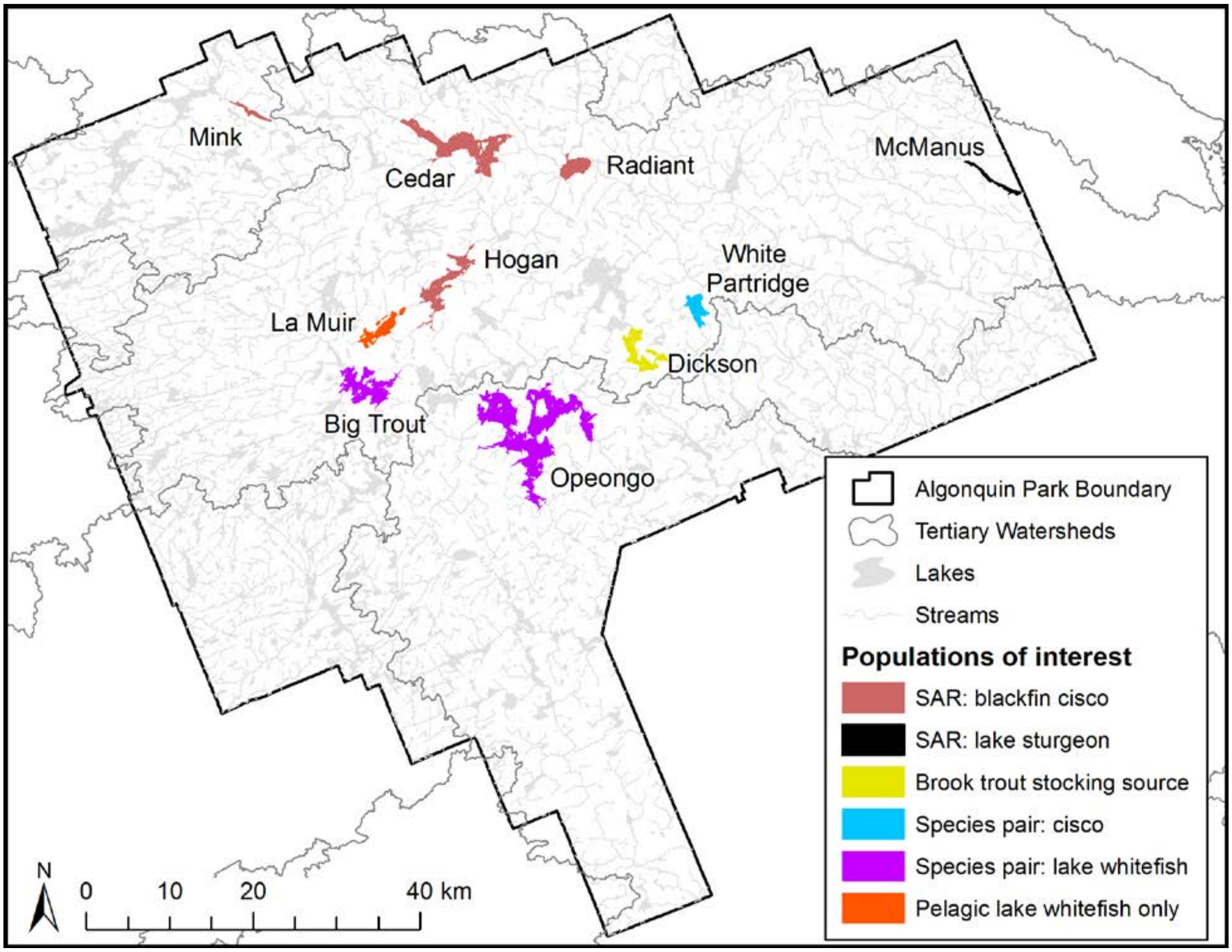

Figure 23. Algonquin Provincial Park fish populations of special interest based on species status, ecological speciation, and hatchery source.

Cumulative risk of fish introductions in the park

Three factors to consider when thinking about species introductions in directional nested networks:

- Any given lake is at risk of non-native species being introduced directly.
- If a given lake is without an introduced species, its risk of getting one is heavily influenced by its position in the network (up- or downstream) and the presence of barriers such as dams in connecting stream and river systems.
- An introduction in a given lake can disrupt native food webs downstream and far away from that lake. So a lake downstream from lakes and streams higher in the watershed has cumulative risk.

Table 8 lists Algonquin Provincial Park lakes with the most upstream lakes. McManus Lake (#2) to Cedar Lake (#11) is on the Petawawa River, and Narrowbag Lake is on the Petawawa River below Catfish Lake. Galeairy and Rock lakes are in the Madawaska River watershed. The lower Petawawa River (from Cedar Lake to the park's eastern border) has more upstream lakes than any other third-order park watershed because the Petawawa headwaters is just beyond the western park boundary and flows east across most of the park (Figure 4). Eighty-seven per cent of the Petawawa River watershed lies within the park.

Table 8. Algonquin Provincial Park lakes that have the highest risk of fish invading from other lakes due to watershed position.

Lake	Contributing upstream lakes
Montgomery Lake	413
McManus Lake	412
Smith Lake	410
Whitson Lake	409
Coveo Lake	402
Lake Travers	383
Kildeer Lake	294
Francis Lake	293
Mudcat Lake	286
Radiant Lake	281
Cedar Lake	232
Galeairy Lake	177
Rock Lake	152
Narrowbag Lake	127
Catfish Lake	124

Lakes and streams are directional nested networks so lake-specific introductions can quickly expand to watershed scales. Lake position determines the number of lakes upstream. For example, Cedar Lake is at the confluence of 2 sixth-order streams and 2 fifth-order streams. If an introduction occurred in any upstream lake, the introduced species would eventually spread to Cedar Lake.

Figure 24 shows a map of the cumulative number of lakes upstream from any given lake (>5 ha in surface area) in the park (≈1260 lakes). Most lakes have relatively few upstream lakes due to the park's many headwater areas: 738 lakes have 1 or no upstream lakes (59% of total lakes) and 1090 lakes (87% of total lakes) have less than 5 or fewer upstream lakes. The Petawawa River system from Big Trout Lake (59 upstream lakes) through Burntroot, Catfish, Cedar (232 upstream lakes; Table 8), and Radiant lakes and onto McManus on the eastern park boundary is the watershed with the most upstream lakes. The Madawaska River system from Lake of Two Rivers to Galeairy Lake is the second ranked area for upstream lakes. Only 20 lakes (1.6% or total lakes) have 100 or more upstream connections.

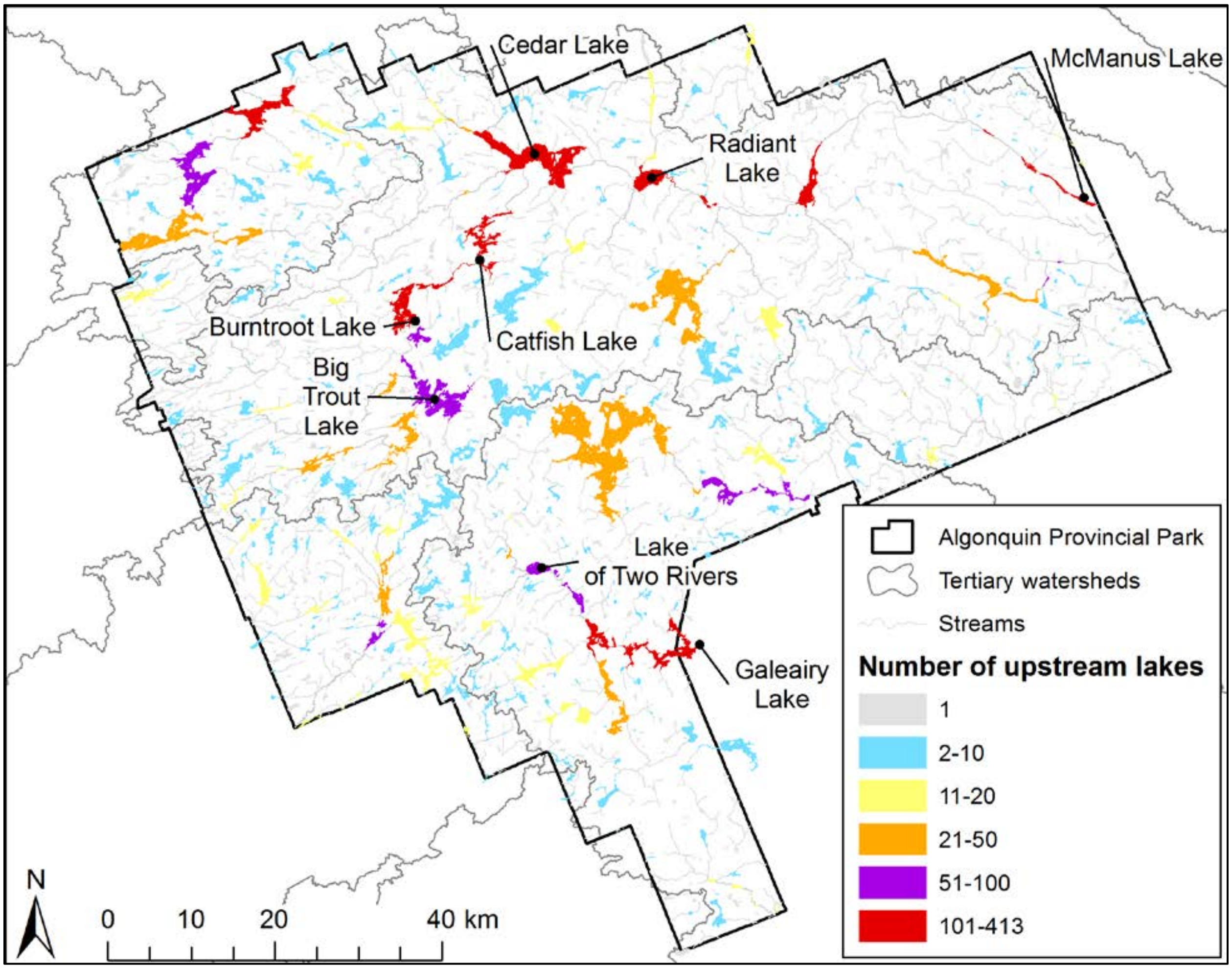

Figure 24. Upstream lakes in Algonquin Provincial Park. The more upstream lake connections, the higher the risk of introduced species.

How an introduction in a lake affects the downstream network of accessible lakes can be measured by counting the accessible downstream lakes connected to it, including those without apparent upstream barriers. Figure 25 shows a map of this measure for most lakes in the park. Headwater lakes in the far west of the Petawawa watershed show the highest effect downstream with lakes upstream of White Trout Lake (including Misty, Timberwolf, Ralph Bice, and Salvelinus lakes) having 70+ accessible downstream connections. La Muir and Hogan lakes have a smaller downstream effect despite their central location and proximity to more affected lakes such as Burntroot. They are isolated in a fourth-order watershed within the Petawawa watershed, which drains farther downstream via the Little Madawaska River into Radiant Lake.

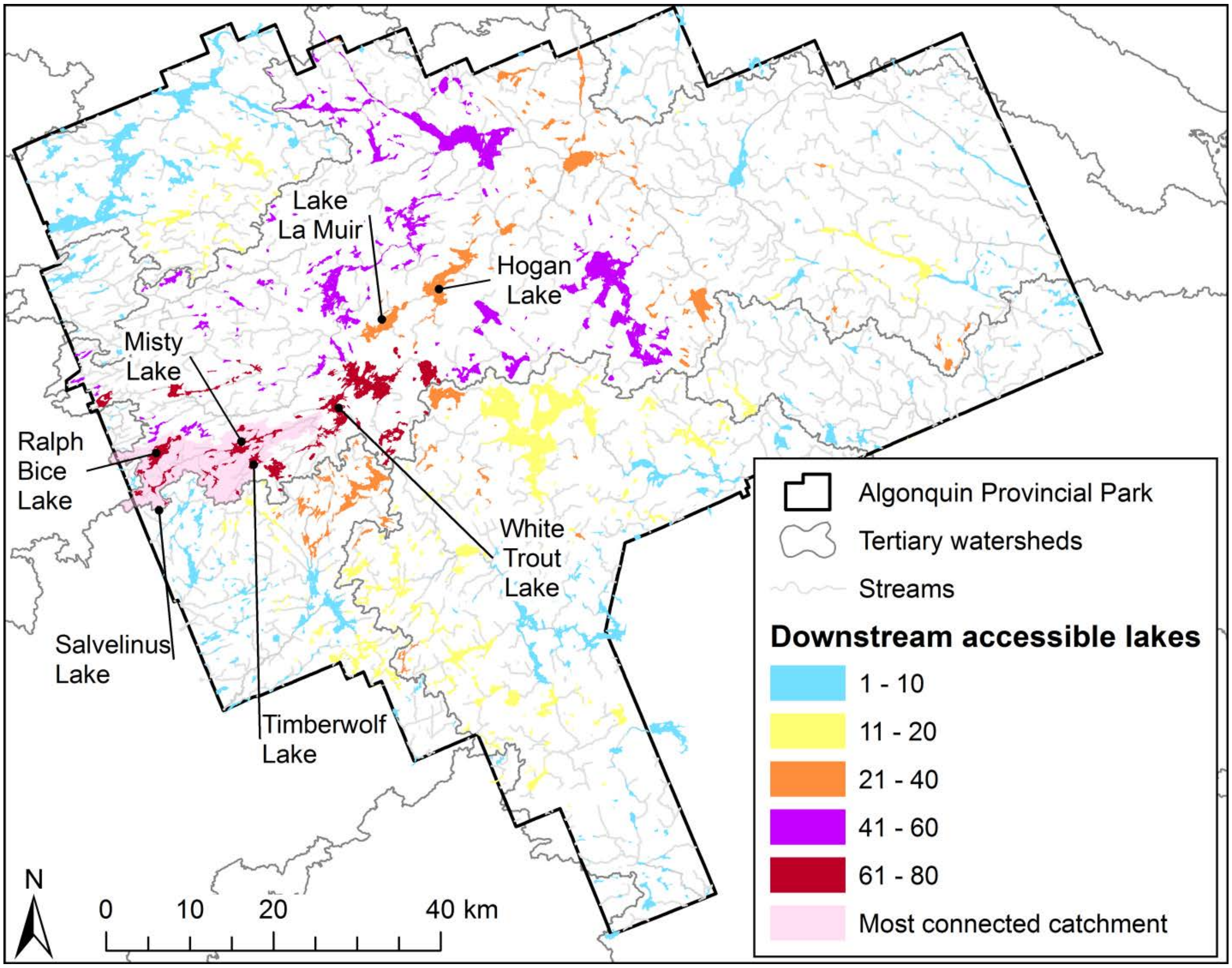

Figure 25. Downstream accessible lakes in Algonquin Provincial Park with the most connected catchment in the park, Misty Lake and upstream, highlighted. The more accessible connections a lake has downstream, the more widespread the effect of fish introductions.

Angling effort in the park

While nearly all anglers have good intentions and follow park fishing regulations, some do not. In the past, bait fish such as rainbow smelt and top predators have been introduced illegally. Use of bait fish is widespread outside the park with a very low but persistent probability of introduction (Drake and Mandrak 2014). This probability is no different in Algonquin Provincial Park. We used angler use of lakes as a criterion for risk of introduction recognizing that only a few people are likely to be responsible.

Angling effort in the park is equivalent to visitation rate by boaters to different lakes while possibly carrying invasive invertebrates such as spiny waterflea. More visitation means greater probability that bait fish or unwanted game fish will be released.

Since *risk* is the probability an event will occur plus its consequences, the probability of any fish species being introduced depends on the amount of angler visitation to a lake. We assumed that anglers, rather than non-anglers, are potentially introducing fish. One measure of use is the number of days anglers spend on a lake, referred to as *angler days*. A potential *consequence* of a fish introduction is an established population of non-native bait fish or a predator species that was not present when the glacial era ended. Another consequence is the introduced species spreading downstream to other lake ecosystems and other watersheds depending on whether barriers are present. Rainbow smelt in the Petawawa River watershed is an example of an introduced fish species on the move, and northern pike and smallmouth bass are examples of predators whose movement has been limited by barriers.

The park’s camping registration system provides information on trip itinerary and destination. When asked whether or not groups intend to fish, this system allows for assigning lakes targeted by anglers during their trip based on the itinerary. The accumulated number of anglers per lake for a season represents the angler days for each lake and is a measure of the human footprint on a lake or watershed. Our summary represented those camping overnight in the park interior and not Highway 60 corridor campgrounds and did not include day trips to the park for fishing or day trips by those staying in campgrounds. However, Highway 60 corridor campgrounds are still potential sites of fish introduction with spread from relevant campgrounds shown in Figure 15.

Table 9 lists the top-ranked access points for angler entry to the park. All but 2 have lakes associated with the access point — Magnetewan and Kawawaymog refer to access points associated with Ralph Bice and North Tea lakes, respectively. For some access points, such as Lake Opeongo and Grand Lake, anglers may spend part of or their entire trip on the access point lake, while for others with no camp sites, such Canoe and Smoke lakes, anglers use these locations to access the park interior.

Table 9. Ranking of angler use of Algonquin Park access points in 2015 based on interior camping permits (not angler days on each lake; rather, interior fishing using these lakes as a park entry point).

Lake	Rank
Opeongo	1
Canoe	2
Magnetewan	3
Rock	4
Kawawaymog	5
Smoke	6
Rain	7
Cedar	8
Grand	9
Tim R	10
Galeairy	11
Cache	12
Kioskokwi	13
Travers	14

There was a total of 37,000 angler days of fishing in the park in 2015. Lake Opeongo had the most angler days by overnight campers (over 10%; Table 10). Other lakes with high angler days included Ralph Bice, Burnt Island, Pen, and Rock Lakes. Lake Opeongo had approximately 3 times more angler days (greater than 3700 angler days) than the second-ranked lake, Ralph Bice (greater than 1000 angler days).

Rock and Pen Lakes are in close proximity with a relatively easy portage between them. When considered as a unit, the Rock/Pen lake system received over 1600 angler days making it the second ranked lake fishery in the park.

The largest river-based fishery is the Petawawa River with 1.6% of total angler days in the park. This represents nearly 600 angler days and with a rank of 8th on the list of recreational fisheries in the park.

Table 10. Algonquin Park lakes ranked by angler days, a measure of use of lakes for recreational fishing. Rankings are based on the interior camping permit system for 2015.

Lake name	Percent of all angling days
Opeongo	10.4
Ralph Bice	2.8
Burnt Island	2.4
Pen	2.3
Rock	2.2
North Tea	2.2
Ragged	2.2
Petawawa River	1.6
Big Trout	1.5
Louisa	1.5
Galeairy	1.4
Happy Isle	1.4
Rain	1.4
Proulx	1.2
Tom Thomson	1.2
Big Crow	1.2
Little Trout	1.1
Big Porcupine	1.1
Booth	1.1

The map of angler days for the park provides an index for the probability of introduction for a specific lake (Figure 26). All lakes receiving recreational fishing were scaled to the Lake Opeongo proportion of angling effort (10.4% = 1.0; Table 10) and can be interpreted as the percentage of angling effort relative to that lake. All other lakes in the park have less than a third of the effort targeting Opeongo (Figure 26). The distribution of angler days shows greater use of lakes near access points or lakes that are a single portage beyond any given access point. For example, access to North Tea Lake is just outside the park boundary at the Kawawaymog Lake access point, and North Tea gets more angler days than any other of the northern tier of lakes in the park. A set of lakes south of Smoke Lake (including Big Porcupine and Ragged) are also targeted by anglers as are a set of lakes through the Rock Lake access point (including Louisa, Rock, Pen, and Galeairy). Most interior lakes’ angler days are far less than top ranked fishery of Lake Opeongo.

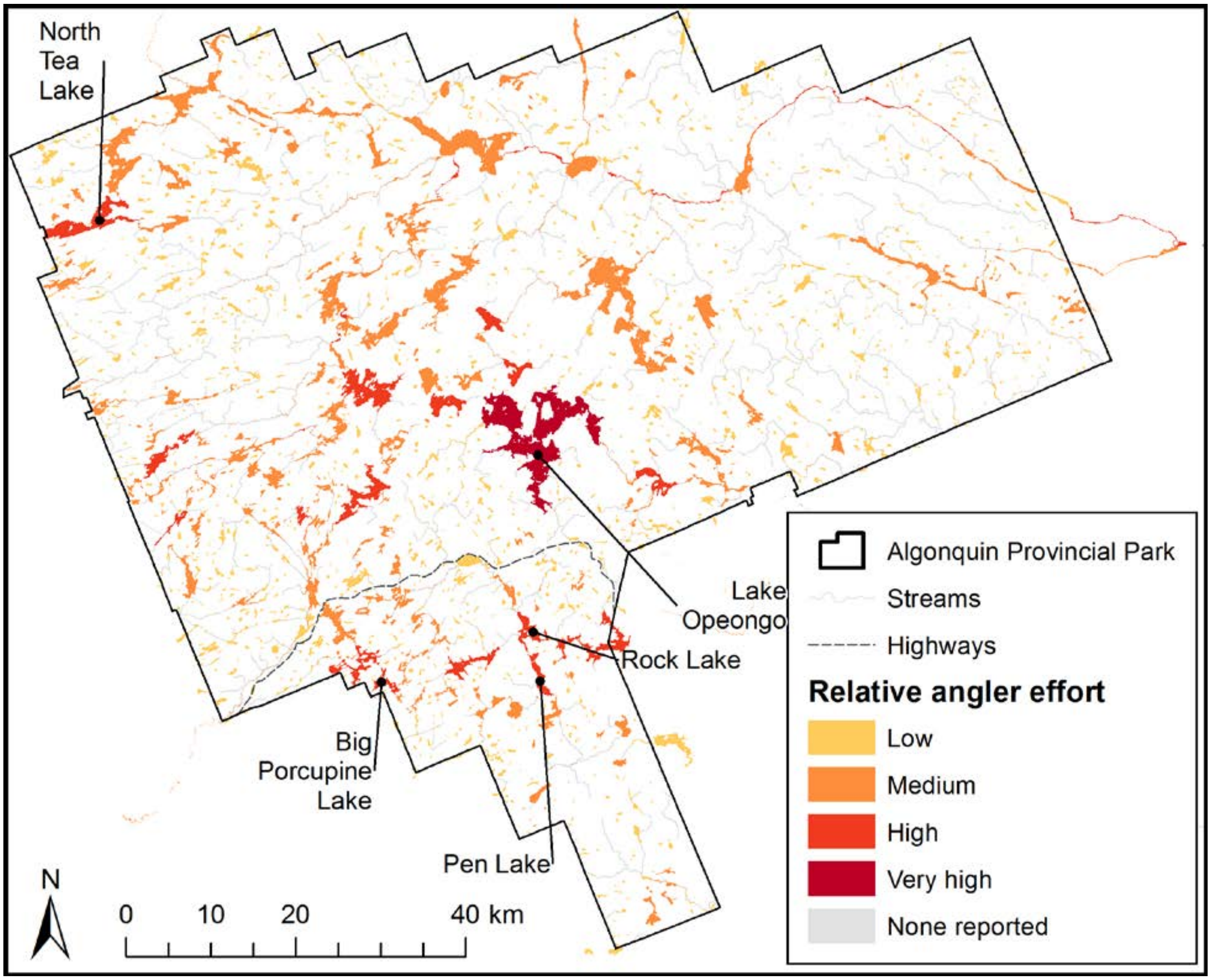

Figure 26. Angler days per lake for Algonquin Park in 2015, based on the camp registration system for overnight trips and angler itineraries. Data for campers using Highway 60 corridor campgrounds and those making day trips were not included. Lake-specific data were scaled as a proportion of Lake Opeongo (10.4% of all angler days =1.0; see Table 10), the largest park fishery.

Lakes can be assigned cumulative total angler days they accumulate from lakes upstream to identify those that increasingly bear the brunt of the fish introductions aspect of the human footprint in watersheds (Figure 27). Lakes with the highest cumulative angler days were Radiant, Travers, and McManus and other sites in that section of the Petawawa River. Cedar Lake gets cumulative angler days from large lakes such as Big Trout, Burntroot, and Catfish, which collectively contribute many angler days (Figure 27). While Lake Opeongo has the most angler days, it has relatively few cumulative angler days. Booth Lake, downstream of Lake Opeongo, gets the large angling effort expended on Opeongo.

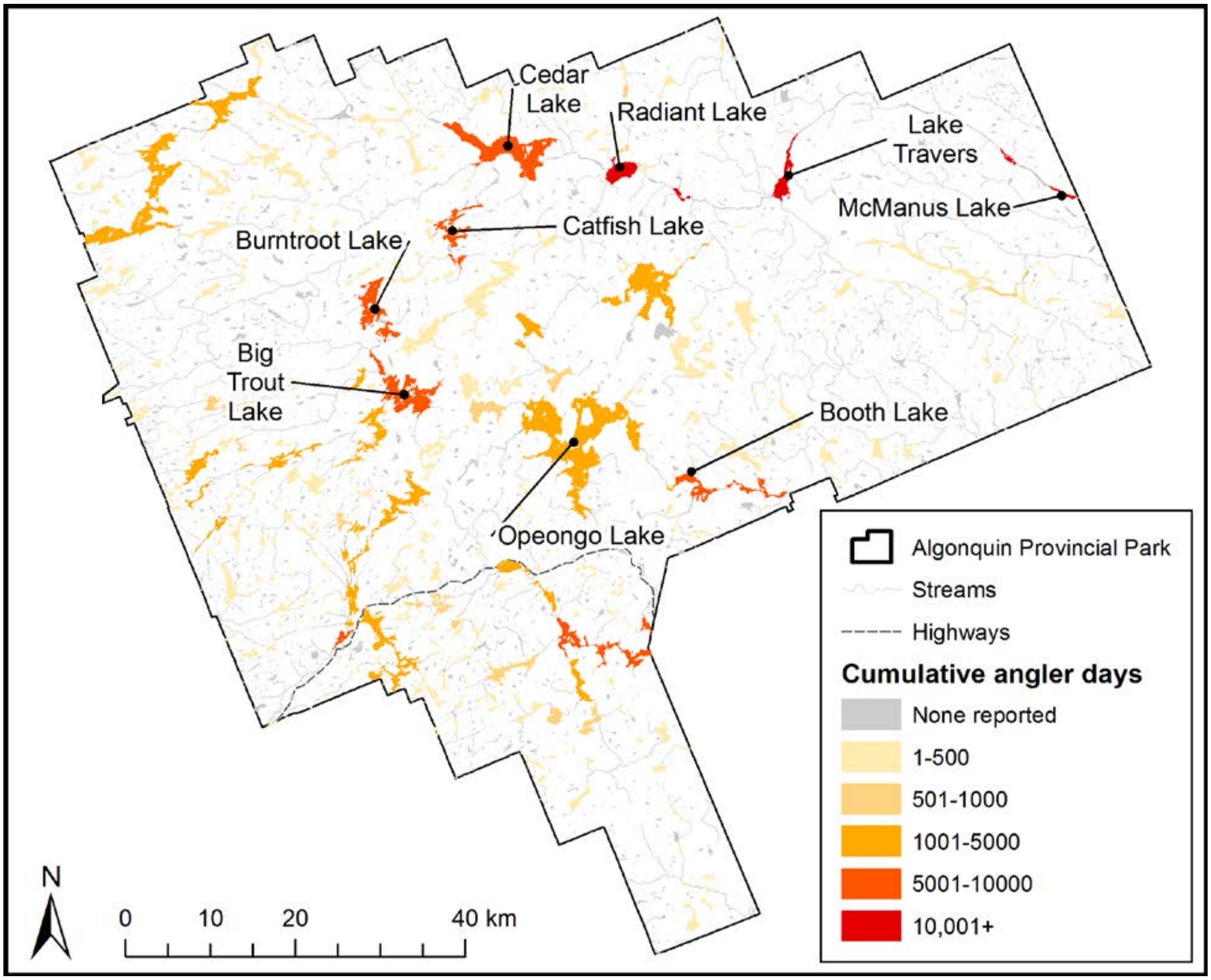

Figure 27. Cumulative angling pressure from on-lake and upstream angling in Algonquin Provincial Park. Colours represent the total angling days on that lake plus those for all upstream lakes that flow into it. This map shows that angling pressure is a function of the watershed placement of a lake: Headwater lakes have lower cumulative pressure than park outflow lakes.

Finally, the top 6 lakes for angler days show the watershed distribution of fish introductions stemming from introductions at those lakes (Figure 28). Large areas of the park are vulnerable to introductions at lakes with highest use, and introductions in any park lake have potential downstream effects. Appendix 4 outlines a set of scenarios for fish introductions and potential spread in other watersheds.

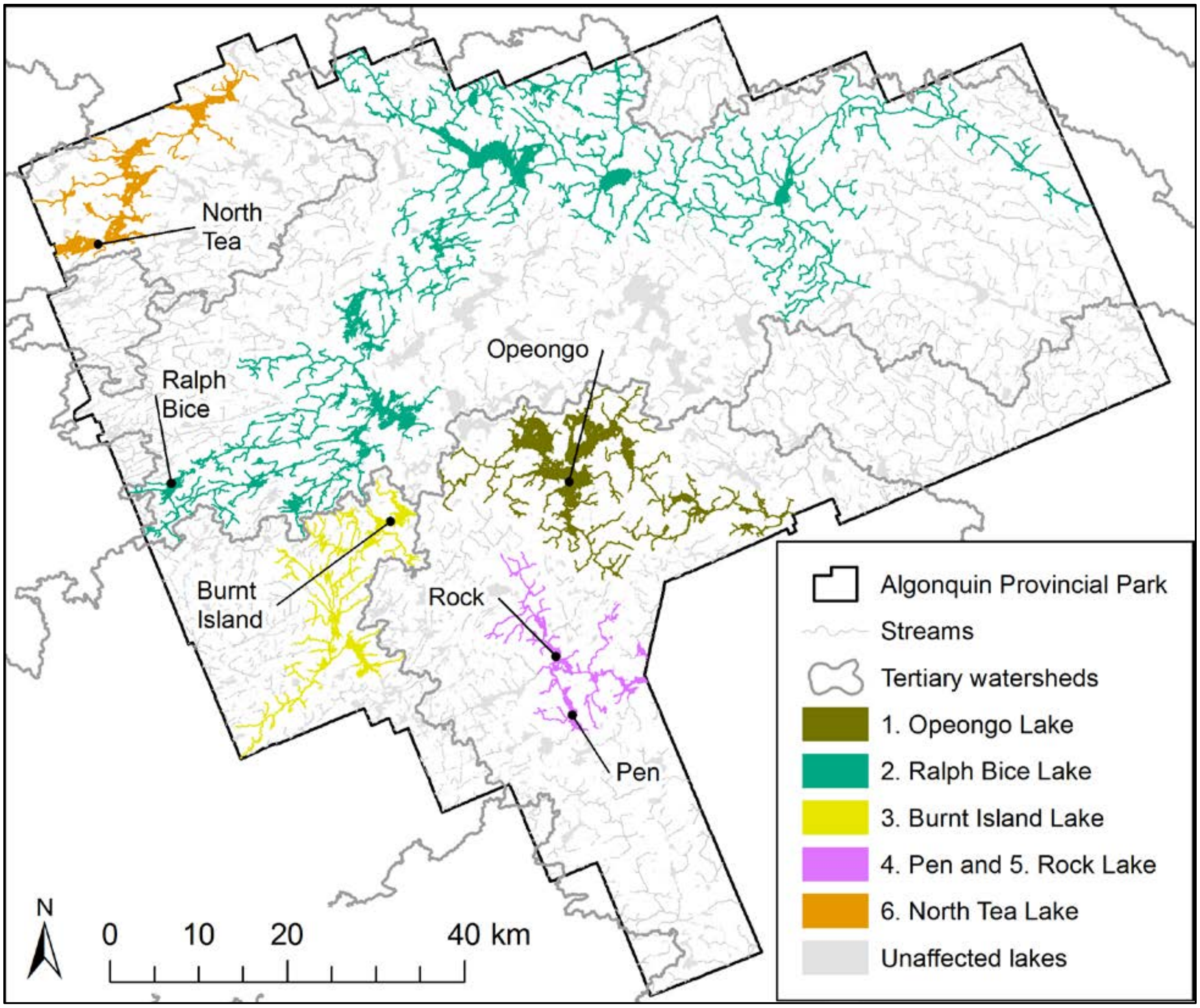

Figure 28. Connected invasion pathways from the 6 most fished backcountry lakes in Algonquin Provincial Park in 2016: 1) Opeongo, 2) Ralph Bice, 3) Burnt Island, 4) Pen, 5) Rock, and 6) North Tea.

Conclusions

Algonquin Provincial Park’s streams, rivers, and lakes are complex ecosystems because they are directional nested networks due to flow and connectivity. This connectivity also makes streams and lakes vulnerable to human activity and introductions in other parts of the watershed.

This park is important due to its glacial history, fish distribution, and headwater areas, as well as its cultural significance to Indigenous peoples and its enormous popularity with the public including recreational anglers and other park visitors. Coldwater fish such as lake and brook trout help define the park’s character. Although the park’s geography affords protection from fish introductions based on its own fall line, fish species introductions have occurred due to authorized and unauthorized, illegal activities. Yet large areas of the park are protected from further introductions due to natural and human-built barriers as well as watershed boundaries in headwater areas.

The risk associated with fish introductions can be defined in several ways. It is associated with:

- Thumbnail watersheds whose headwaters extend slightly beyond the park boundaries so get no park protection
- Human use of access points and potential downstream spread
- Possible illegal bait use by a small number of anglers, with increased risk on lakes with high angler use

Risk is also cumulative:

- Species introductions in 1 lake flow downstream and barriers to movement are the only feature limiting spread in tributaries.
- Human use in upstream lakes can aggregate to affect many lakes downstream.
- A single fish introduction in a lake that is relatively high up in a watershed can lead to undesirable changes in many more lakes downstream.

The park retains many assemblages of native fish species from the time of glacial retreat. Protecting this aquatic heritage relies on:

- Utilizing barriers to fish movements, both human built and natural
- Understanding the headwater nature of the park landscape (what happens at the top can cause dramatic effects farther down in the watershed)

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Appendix 1. Mapping barriers to fish movement in Algonquin Provincial Park

Algonquin Provincial Park is a landscape with major changes in elevation, watersheds covering different landforms of glacial origin, and a history of human activity such as dam building. So it has a diversity of barriers to upstream fish movement, with some (e.g., dams) well recorded in databases and others (e.g., waterfalls) less well represented. Locations of other barrier types — largely stream sections with a steep slope >10-15% providing 1 or more small vertical drops over a stream length or fast water flow — are poorly represented in databases or have been missed in park surveys.

We used high resolution digital photography and digital slope maps for the park to locate, visit, and map many areas of the park's watersheds. We also inspected watershed sections that had steep slopes or appeared to be vertical barriers based on digital photography. Following is a description of the steps we took to generate a final stream barrier map for the park.

Data sources

Data was collected from a range of sources to complete the barrier map (Table A1.1). Existing digital map data (geographic information systems/GIS) came from Land Information Ontario (LIO), including the park boundary, lakes, streams, dams, access points, and roads. LIO was also the source of topological data and high quality aerial images. Recognized waterfalls were obtained from digital and hard copy maps.

We expanded this data by using local knowledge of other waterfalls as well as examining current fish distribution patterns. Ontario Parks wardens and rangers, as well as Ministry of Natural Resources and Forestry technicians and youth workers working at Harkness Laboratory of Fisheries Research, were interviewed (see Acknowledgements for a list of those interviewed). Interviewees were shown a park map and asked to locate waterfalls considered large enough to prevent fish passage. The approximate height and location were recorded. The current distribution of fish species in the park can indicate the presence of barriers. Breaks in fish distribution in otherwise connected lakes point to a barrier producing such a faunal break. In a small number of cases, connected lakes with faunal breaks were considered to have a functional barrier at locations with high slope (see below).

Table A1.1. Data/information sources and descriptions used for building the barrier map for Algonquin Provincial Park.

Data	Description	Source	File name
Algonquin Provincial Park Boundary	Extent of boundary	Land Information Ontario	Provincial Park Regulated
Stream network	Stream network including Strahler Stream Order and flow direction	Land Information Ontario	Ontario Hydro Network Watercourse
Watersheds	Tertiary and quaternary watersheds	Land Information Ontario	Watershed, Tertiary Watershed, Quaternary
Lakes	Lakes	Land Information Ontario	Ontario Hydro Network Waterbody
Roads	Highways around and across the park	Land Information Ontario	MNR Road Network
Railways	Railway locations	Land Information Ontario	Railway
Access points	Digitized access point locations from Algonquin Zone staff	Land Information Ontario	Recreation Point
Dams	Ontario Hydro Network provincial dams and status of park dams (2015)	Land Information Ontario	Ontario Hydro Network Dam and Barrier
Aerial images	South Central Ontario Orthophotography Project 2013 Digital Raster Acquisition Project Eastern Ontario 2014 Algonquin 2015	Land Information Ontario	SCOOP2013 DRAPE2014 Algonquin2015
Digital elevation model	South Central Ontario Orthophotography Project 2013 Digital Raster Acquisition Project Eastern Ontario 2014 Algonquin 2015 Digital Elevation Model	Land Information Ontario	SCOOP2013 DRAPE2014 Algonquin2015

Motor restrictions	Lakes that allow motor boats in Algonquin Park	Algonquin Park website	n/a
Recognized waterfalls	Algonquin Park Canoe Route Map, 2015-2016, Jeff's Map	Friends of Algonquin Canoe Route Map 2015;Jeff's Map	n/a
Observed waterfalls	Interviews with MNRF staff (including Ontario Parks)	Local knowledge	n/a
Algonquin species distribution database	A database of species presence in lakes in Algonquin; year of first and most recent confirmation	Aquatic Ecology, History and Diversity of Algonquin Provincial Park (Ridgway et al. 2017)	n/a
Upstream catchments	A web based tool that calculates area upstream of a point, or catchment.	Ontario Flow Assessment Tool	n/a

Dams

Dams fragment fish populations at watershed scales but also stop upstream movement of introduced species. The park has 27 permanent dams on 24 lakes (Figure A1.1). Lake Travers and Big Trout Lake both have multiple dams at the same site, blocking either side of islands. These dams serve several purposes: raising water levels, maintaining water levels on canoe routes, and providing water for downstream hydro power. Ontario Parks manages 26 of the dams, with Ontario Power Generation owning and maintaining one. Dams range from 3 m concrete stop-log dams to 30 cm rock-filled timber weirs (Figure A1.1). No park dam contains a fish ladder or fish passage system. Figure A1.2 provides 2 examples of park dams. Most of the park landscape is behind one or several dams (see Figure 11).

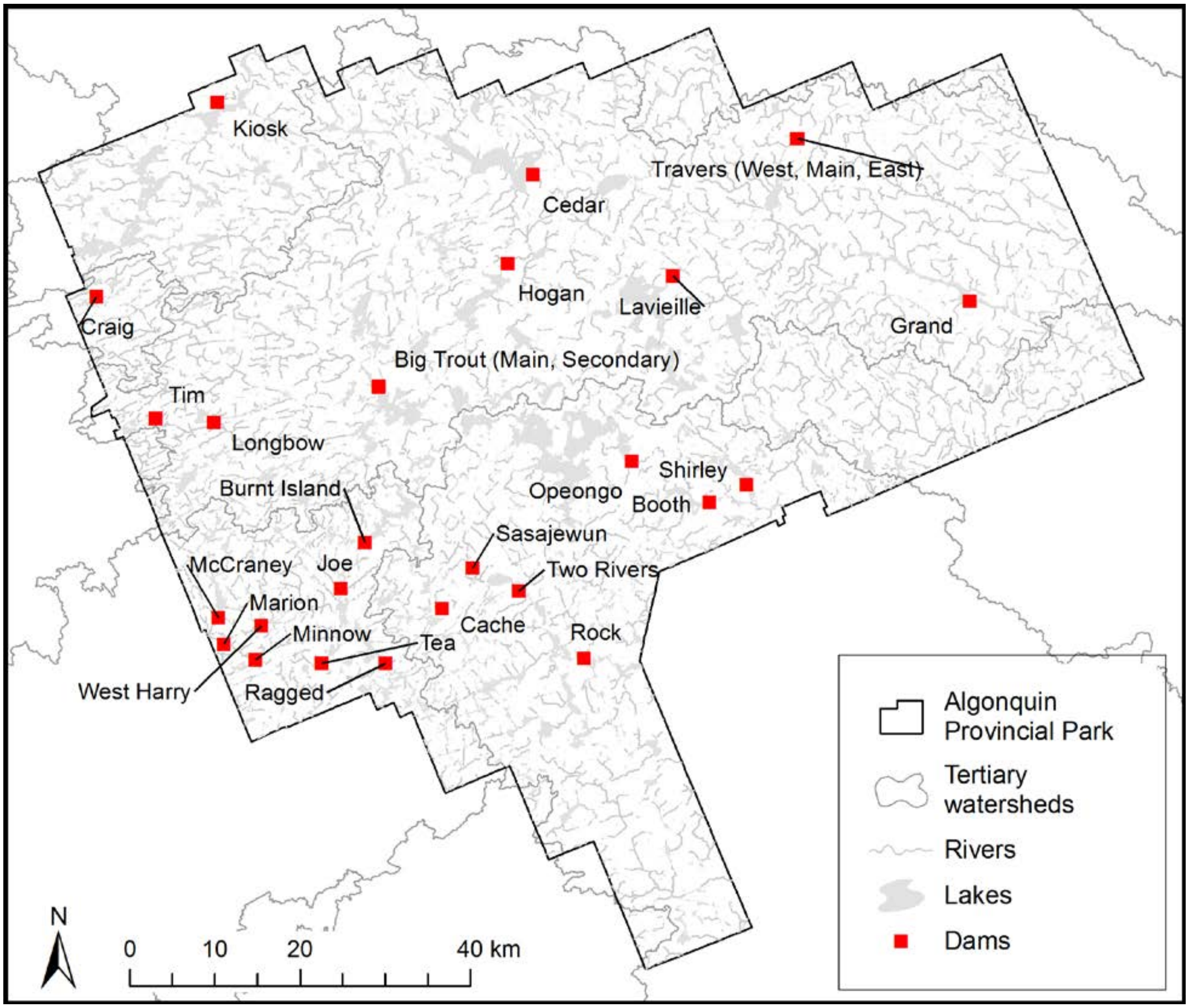

Figure A1.1. The dams and water control structures of Algonquin Provincial Park. Two sites (Lake Traverse and Big Trout Lake) have multiple structures close together, shown here as a single dam. The Hogan Lake Dam is a log and rock structure and not maintained.

Figure A1.2. Two Algonquin Provincial Park dams — a small dam on Cedar Lake that has with a timber weir about 30 cm tall (above left; photo taken in 1999) and a large 2.5 m high concrete stop log dam on Joe Lake (above right).

The digital landscape

Digital elevation models (DEMs) map the topography of the landscape in 3 dimensions (Figure A1.3). On Canadian Shield landscapes, including Algonquin Provincial Park, a DEM generally reflects underlying bedrock structure due to relatively thin soil. Province-wide DEMs have existed for many decades, but change as technology and precision improves.

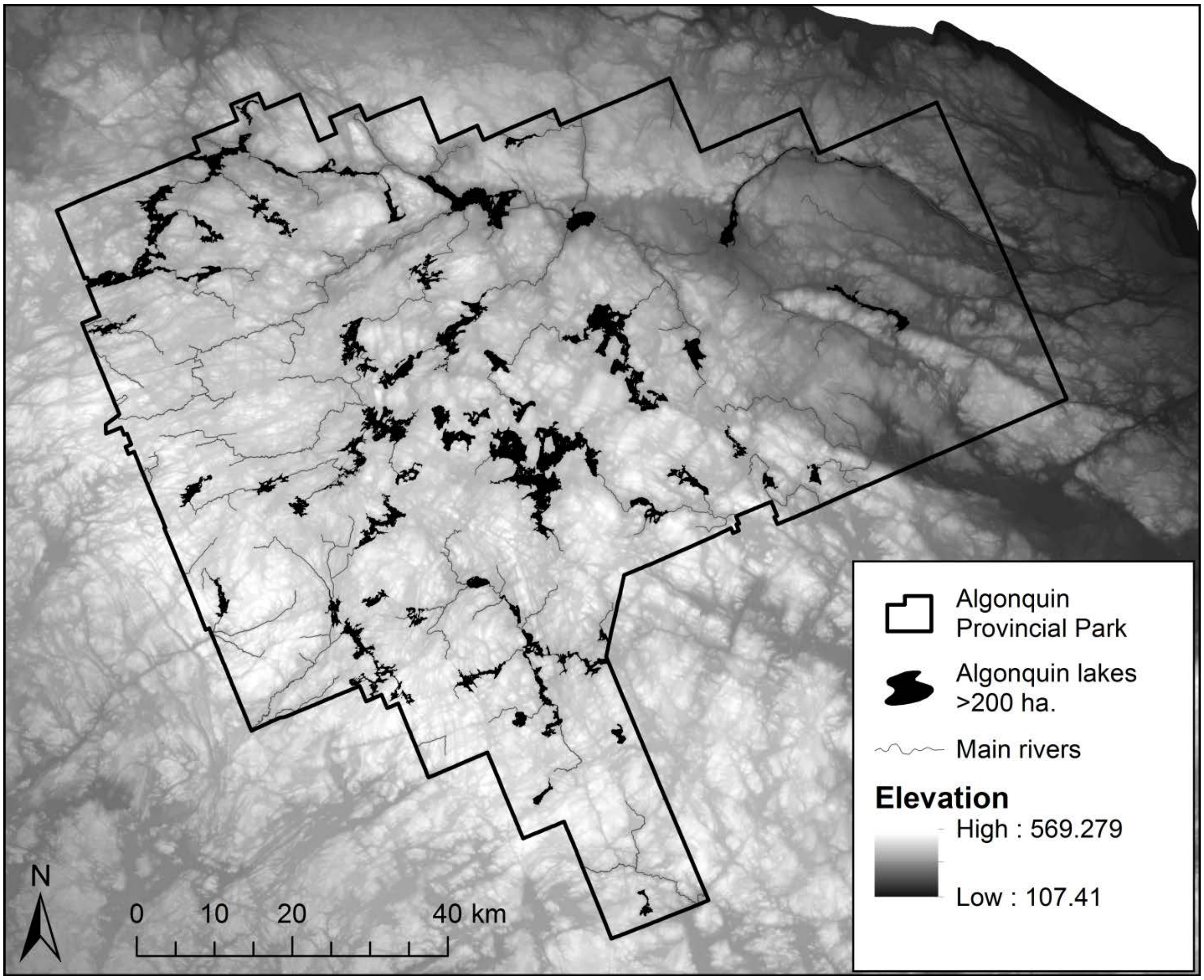

Figure A1.3. Digital elevation model of Algonquin Provincial Park, showing landscape peaks and valleys.

DEMs show elevation data derived from high resolution aerial photography and ground measurements, and more recently, remotely recorded elevation data from satellites. For Ontario, several digital elevation products exist, varying in spatial extent, resolution, and data source. We used the Provincial Digital Elevation Model v.3.0 (Spatial Data Infrastructure 2013, Ontario Ministry of Natural Resources 2013), which provides seamless provincial scale elevation data at 30 m resolution. For the park area, the underlying elevation data come from a combination of Ontario Base Map (OBM) Digital

Terrain Model and OBM contour data. Both data sets have been validated to produce a reliable elevation model for the province that is suitable for various uses including generating slope and aspect products (Ontario Ministry of Natural Resources 2013).

In addition to the Ontario DEM, we used high resolution aerial photography (resolution = 20 cm) for the park to allow us to inspect many areas of its watersheds. The SCOOP2014, DRAPE2014, and Algonquin2015 aerial imagery acquisition projects provide complete coverage of this park. Features such as whitewater and vertical barriers were inspected to confirm presence/absence of barriers. All images were taken in early spring before hardwood trees leafed out, allowing for a clear view of the ground. Most large waterfalls remain visible in these images, although dense conifers limited visibility in some places.

Slope is important to understanding fish passage and formation of barriers. We calculated each cell's slope as the maximum change in elevation over the distance between the cell and its 8 neighbours (ESRI 2012). The example in Figure A1.4 illustrates our method. On the left is the park DEM with the Heron Lake area near the west gate highlighted in the red box. The centre image is a finer scale view of the DEM around Heron Lake. For every 30 m grid cell in the centre image, a slope was calculated from the elevation data. The right panel of Figure A1.4 shows a map of the grid cells — slopes greater than 10% are in red with darker shades representing higher slopes. This map captures the steep slopes on the southern shore of Heron Lake, as well as the valley system where streams are located or begin as first-order streams (Strahler index; Dingman 2002) from shallow groundwater runoff.

Slope for the park landscape was derived from digital elevation using this method and helped us identify candidate sites for barriers to fish movement.

Abrupt changes in elevation or high slope areas may indicate waterfalls especially if these slope areas run perpendicular to stream flow. Flow rate and obstruction or constriction of valley systems also contribute to barrier formation. We overlaid the digital stream system for the park with the 30 m grid cell system to locate stream segments that align with steep slopes in each grid cell (>10%). These locations have potential barriers through the presence of waterfalls/stone steps that develop in high slope stream systems or due to slope itself.

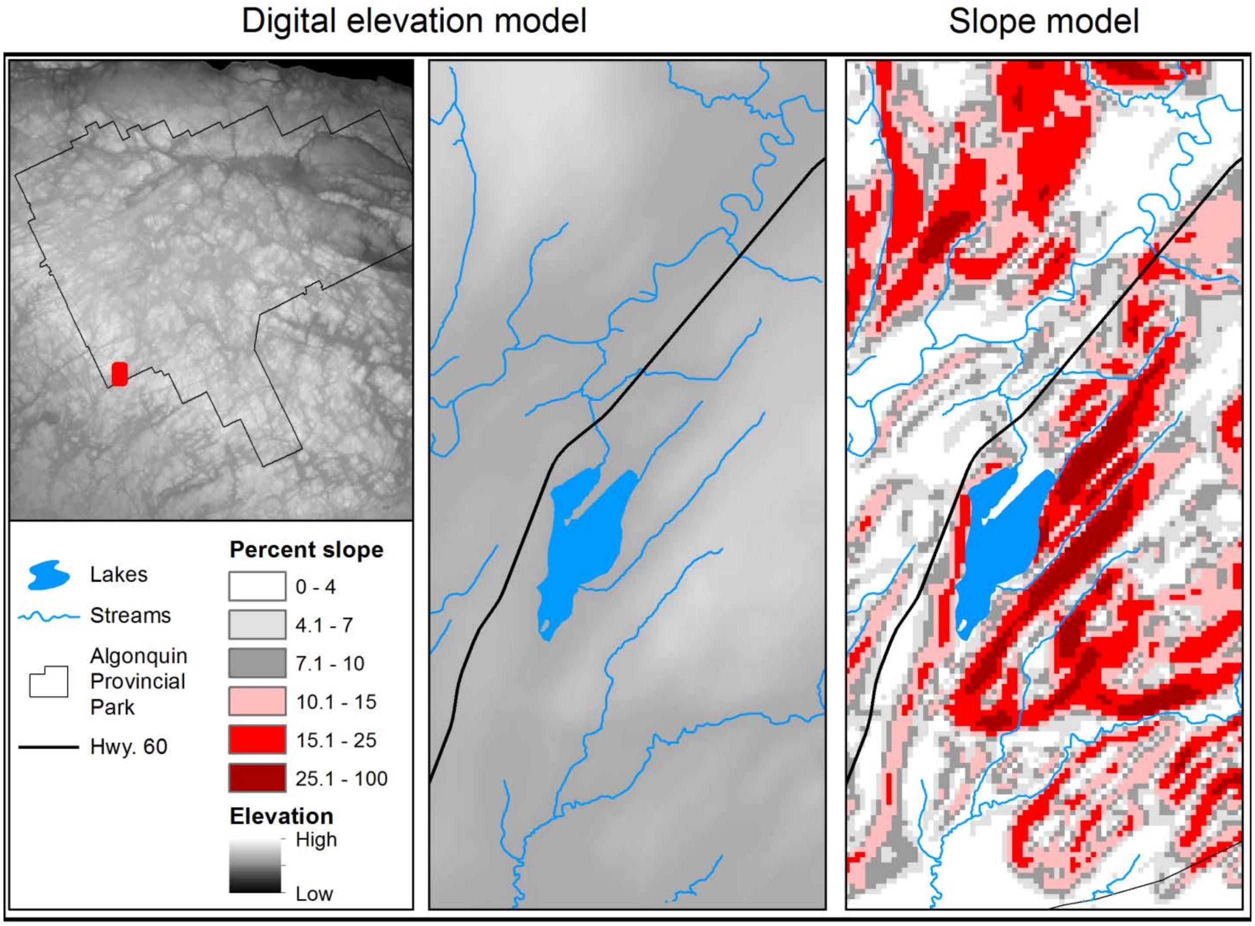

Figure A1.4. An example of transforming Algonquin Provincial Park elevation data into percent slope: At above left, the digital elevation model shows lower elevation in dark grey and higher elevation in light grey. The river and stream network is visible as relatively low elevation areas. The above middle image shows the digital elevation model of the landscape around Heron Lake (near the west gate; Highway 60 is the black line north of Heron Lake). And the image at above right shows the per cent slope (rise over run) calculated for each 30 x 30 m grid cell in the area of Heron Lake. Slopes >10% are in red with darker red being steeper slopes (darkest red is slopes ≥25%).

Digital streams and messy slopes: Limits of precision for watershed maps

The park landscape was mapped using the Provincial DEM v.3.0 with a resolution of 30 m and via a derived slope, identified candidate sites that may function as fish barriers. Digital elevation products are available for the park at finer spatial resolutions — the 2 m resolution SCOOP 2013, DRAPE 2014, and Algonquin 2015 DEMs, derived from high resolution aerial photography, cover the entire park. We looked at whether these higher resolution products would help us to better identify candidate barrier locations, such as abrupt changes in elevation over a short distance. For our purposes, however, the digital stream network needs to be of a similar precision to match slope. Streams and rivers flow through valleys often bordered by high slope topography. If the digital stream network varies from the true stream course, the calculated stream slope would be incorrect.

Aerial photography taken across the park (DRAPE 2014,Algonquin 2015) was used to inspect streams and barriers. The imagery was orthorectified — corrected for tilt of the camera's perspective and for landscape relief in the photo. An orthorectified photo presents a flat (*planimetric*) image corrected for these 2 elements of high resolution photography. Many of the bends/meanders in streams did not line up with the imagery and were projected to be on highly sloped edges rather than in the valley.

To demonstrate this point, Figure A1.5 shows 2 park stream sections. On the left near Bouillon Lake, the meandering stream in the high resolution photo is well represented by the digital blue line inserted in the database to show stream location. On the right near Whitebirch Lake, the digital blue line is off the true stream in several places. If the digital stream intersects hill slopes (upper arrow in Figure A1.5), then that stream segment would indicate a high slope location when it was not. In general, we found that the digitized stream network did not fit well with the 2 m slope model — in many cases, it deviated enough from the true stream location to result in slope calculation errors. The 30 m DEM produced much better results.

Also of concern was elevation accuracy of the high resolution DEMs. The SCOOP, DRAPE, and Algonquin DEMs are photogrammetry-derived DEMs to which a steam rolling algorithm has been applied to reduce the elevation of surface features such as forest stands and buildings. As mentioned in the documentation for each, the products do not represent a full bare-earth elevation surface so many features such as larger forest stands and larger buildings were still raised above ground (OMNRF 2013).

We found many of these features, typically adjacent to wetlands, where high slopes resulted from elevation abruptly changing from surface (i.e., treetops) to terrain (Figure A1.6). This error occurred at both the 2 m and 30 m resolutions but was much more common at the 2 m grid cell resolution. With the 2 m slope model, 36% of high slope areas (>15% slope) were found within 50 m of known wetlands or wide meandering rivers with no obvious slope gradient based on high resolution aerial photography. This result supports the use of the 30 m resolution for mapping barriers.

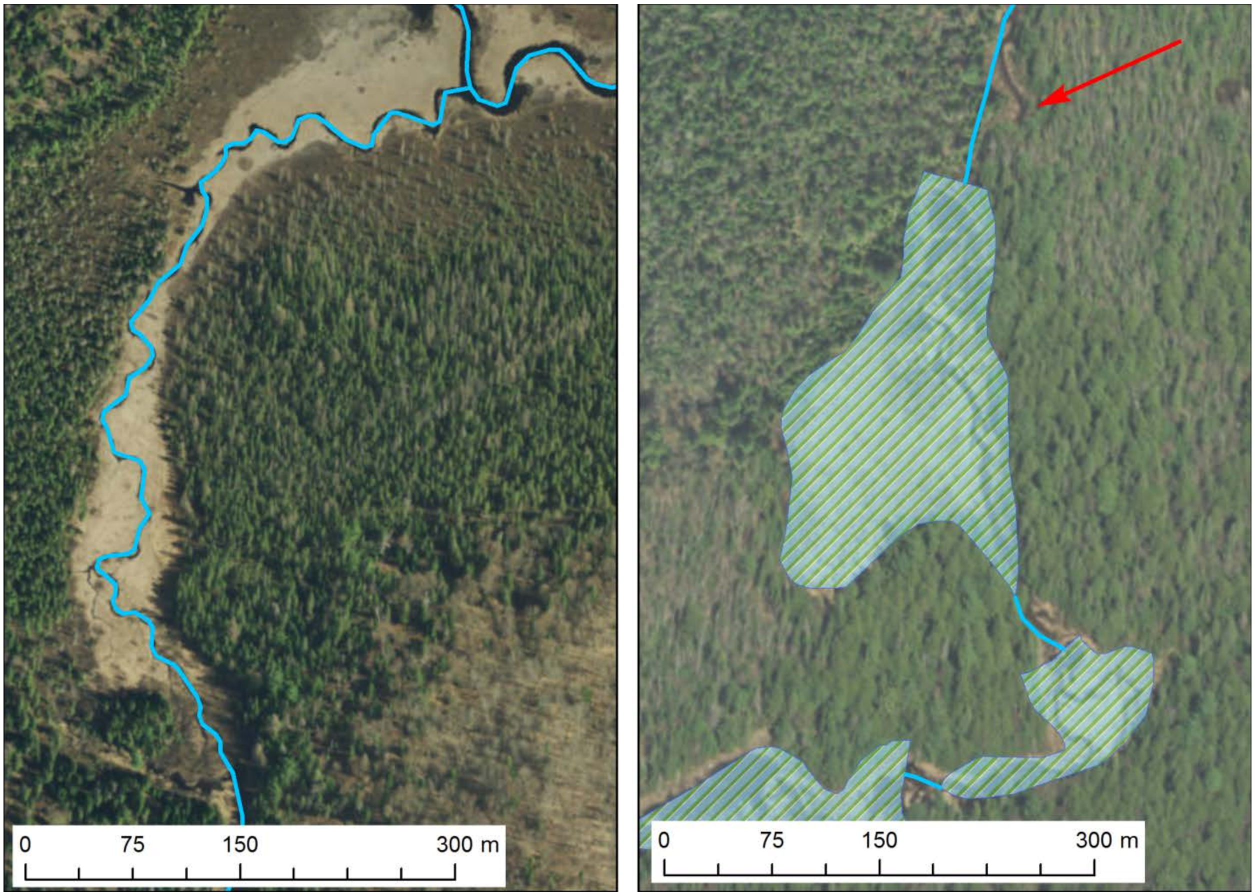

Figure A1.5. The blue line overlain on stream location shows that stream digitization is accurate in the left image above (east of Bouillon Lake in Algonquin Provincial Park) but inaccurate in the right image (north of Whitebirch Lake). This digital stream is an approximate location. Lack of accuracy in location can generate slope maps adjacent to streams that are based on land form that is not actually adjacent to the digitized stream.

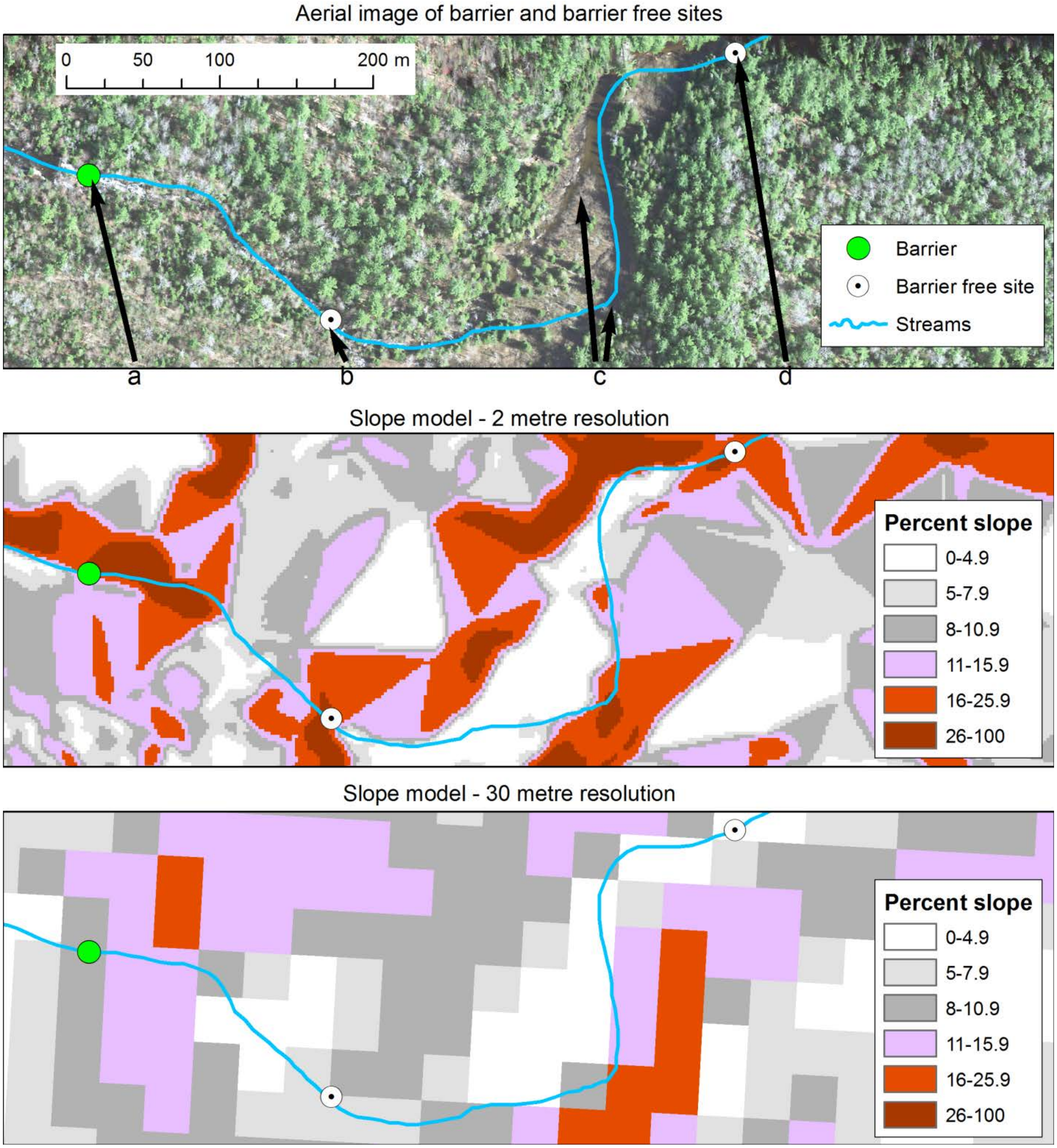

Figure A1.6. Comparison of barrier and non-barrier sites on the Little Madawaska River in Algonquin Provincial Park. In the aerial image (top panel), a waterfall is visible at Site a. At sites b, c, and d, no falls or rapids are visible. Site B and D show more than 25% slope in the 2 m slope model (middle panel) but less than 7% slope in the 30 m model (lower panel). The 2 m slope model is precise, but the 30 m model is more accurate when compared with aerial images. Site C is an unavoidable error because the stream outline (blue line) does not follow the stream.

A literature review showed that non-trout species were unable to overcome slopes greater than 12% (Table A1.2). Slope limits are most often calculated from a variant on the mark and recapture studies or presence/absence above natural or artificial barriers so we used a threshold of 15% to account for exceptional cases. A second threshold of 10% was also denoted as it presents a barrier to some species (e.g., northern pike). The maximum slope for high and mid slope regions was calculated from the 30 m slope model and assigned to each stream reach.

The maximum slope for high- and mid-slope regions was calculated from the 30 m slope model and the values assigned to each stream segment. Stream segments greater than 15% were considered high slope areas and those greater than 10% but less than 15% were considered mid-slope regions (Figures A1.4 and A1.7). Stream segments with high slope can be used as one-way barriers; a gradient of >15% was used as barriers to all species, while a >10% slope was used for some smaller species like rainbow smelt. At the 2 m scale, sections >15% were highlighted but remained unconnected to the stream segment.

Table A1.2. Literature review of observed slope barriers for fish species.

Species	Slope limit (%)	Literature source
Round goby	0.5	Kornis and Vander Zanden 2010
Large-scale sucker, Bridgelip sucker	1.3	Porter et al. 2005
Prickly sculpin	1.4	Porter et al. 2005
Northern pike	7	Spens et al. 2007
Chum, pink, coho, sockeye, chinook salmon	7–16	Washington Department of Fish and Wildlife 2009
Anadromous salmonid	>8	California Department of Fish and Game (TCC 2004)
Cutthroat trout	10	Kruse et al. (1997)
Australian smelt, redfin perch	11	Mallen-Cooper and Brand 2007
Mountain whitefish	12	Platts 1974
Channel catfish, bullheads, creek chub	>12	Larson et al. 2004 and Thomas et al. 2013 Citing: Litvan et al. 2008

Species	Slope limit (%)	Literature source
Sculpin	12	Platts 1974
Rainbow trout	12.5	Larson and Moore 1985
Brook trout	>17	Adams 2000 citing Maret et al. 1997, Schroeter 1998

Park barrier locations

Locating barriers began with known waterfalls and rapids from the Ontario Hydrographic Network (Figure A1.7). This list was expanded as follows:

1. Key local experts among Algonquin Provincial Park and Harkness staff were interviewed for information on locations of unmapped waterfalls and potential fish barriers.
2. A barrier between lakes was assumed for every *faunal break* — location where a fish species was present downstream but absent upstream (or vice versa) in adjacent lakes in a watershed. The slope map was used to determine where a reasonable break in a stream might occur.
3. Site visits were made to candidate sites based on information from local experts or digital photography.
4. High resolution digital imagery of high slope landscapes was inspected.

High resolution aerial imagery was used to verify the remaining candidate barrier sites. Between 2013 and 2015, MNRF and partners collected orthophotography of the entire park. The images have a resolution of 20 cm and were taken in early spring so deciduous leaves and snow did not obstruct the view. Only areas surrounding high slope areas were examined. High slope areas were cross-referenced with existing maps and local expert knowledge of waterfalls. Some candidate areas were selected for field inspection and measurement (Figure A1.8). The remaining sites were verified based on high resolution orthophotography.

The inspected sites were chosen for ease of access, concentration of barriers per visit, and unverified status. Crews were instructed to measure or approximate the height of the vertical drop and to take pictures with objects or people for relative scale (Figure A1.9). Vertical drop was measured at the smallest point, representing the barrier that fish would attempt to pass. If no barrier was found or the barrier was found at a different location, this information was recorded.

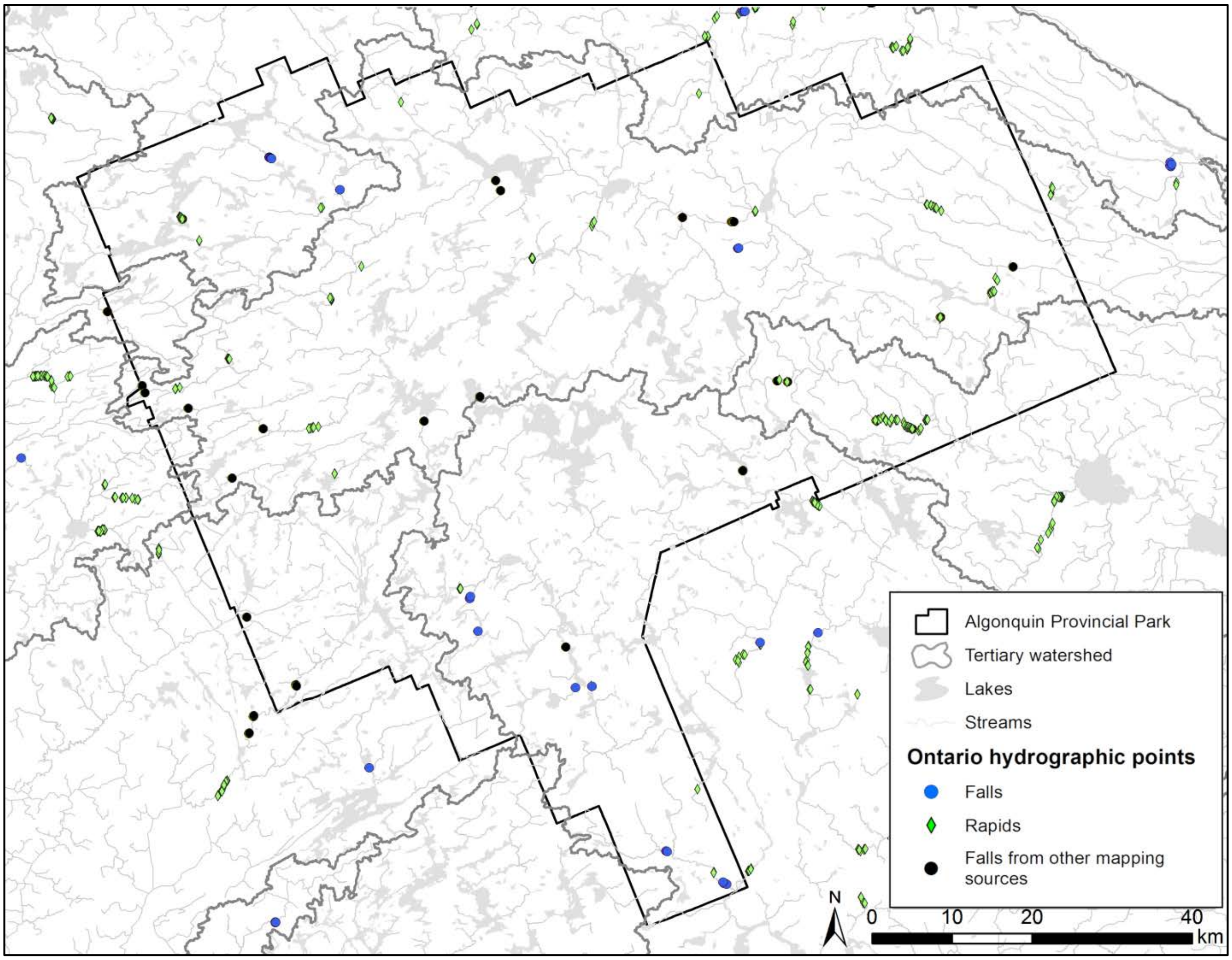

Figure A1.7. Locations of waterfalls and rapids in Algonquin Provincial Park. The park has 19 waterfalls (according to the Ontario Hydrographic Network) with 36 more found on other maps.

Beaver dams were excluded from our study because they can break at any time, making them unreliable barriers. Also, their construction dates are unknown so they are not good predictors of past barriers to fish movement.

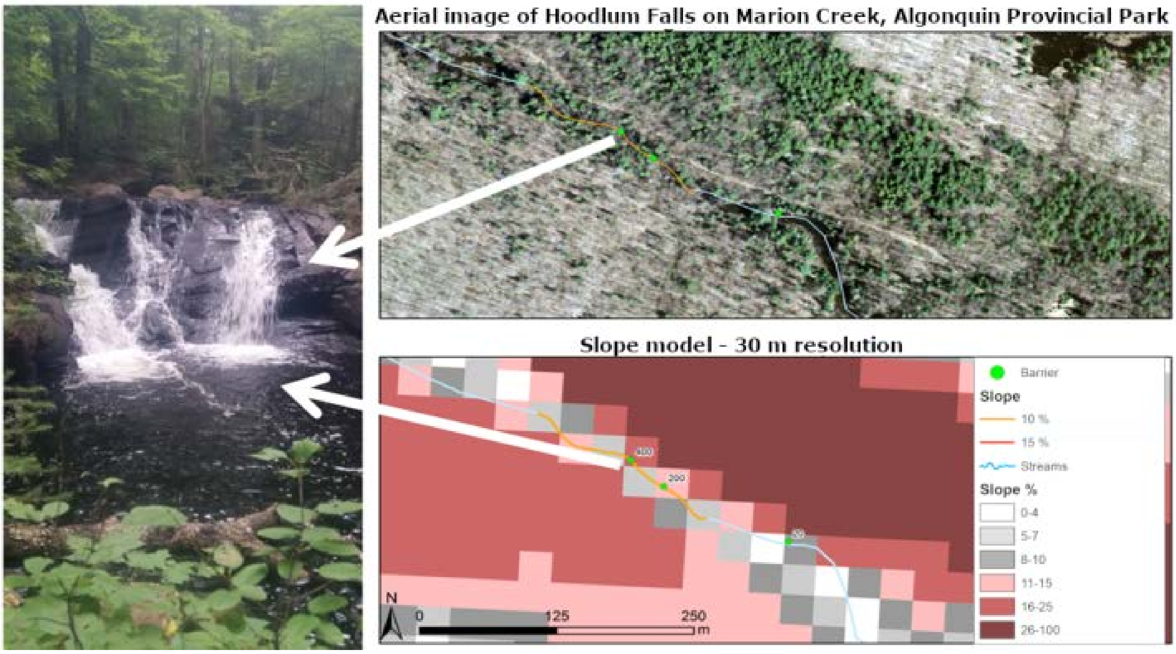

Figure A1.8. Hoodlum Falls on Marion Creek in Algonquin Provincial Park: Site visit photo of the 400 cm tall waterfall (above left), aerial image (top right), and slope model (bottom right).

Figure A1.9. Algonquin Provincial Park barriers were verified through site visits. Above left: Aerial imagery of the west part of Louisa Lake with high slope areas highlighted. Centre: Barrier on the top stream from North Lemon Lake is a 1.2 m seep. Right: a 2 m fall from the lower stream to North Grace Lake (not visible in aerial image).

Newly recorded park dams and waterfalls

A total of 783 sites were inspected using 1 or a combination of the 4 methods outlined above. Most sites did not provide an adequate obstacle to be a vertical barrier. Aerial images and site visits showed 393 of the sites have flat water slowly flowing downstream with 203 having rapids with very small vertical drops. Rapids, small cascades, or partial falls less than 20 cm were not included as vertical barriers. The remaining 187 inspected sites were barriers higher than 20 cm. Of these barriers, 111 were between 20 cm and 60 cm while 76 sites ranged from 60 to 600 cm tall (Figure A1.10).

Figure A1.10. Field inspection of a barrier in the Grand Lake watershed in Algonquin Provincial Park.

Streams that are fourth order or higher are the main arteries of the hydrological network. Each was inspected for at least 1 barrier per stream segment. One barrier along a stream segment functions the same as multiple barriers with respect to blocking fish movement so long as it is between either 2 confluences or source waters and the first tributary. Two decisions were made to increase field search efficiency if an adequate barrier was found:

1. The rest of the stream segment was not thoroughly inspected.
2. Any further searching was based on close inspection of the 1 km^2 orthophoto for that stream segment and any remaining stream segments.

Many second- and third-order streams were also checked, especially if they connected to lakes >20 ha.

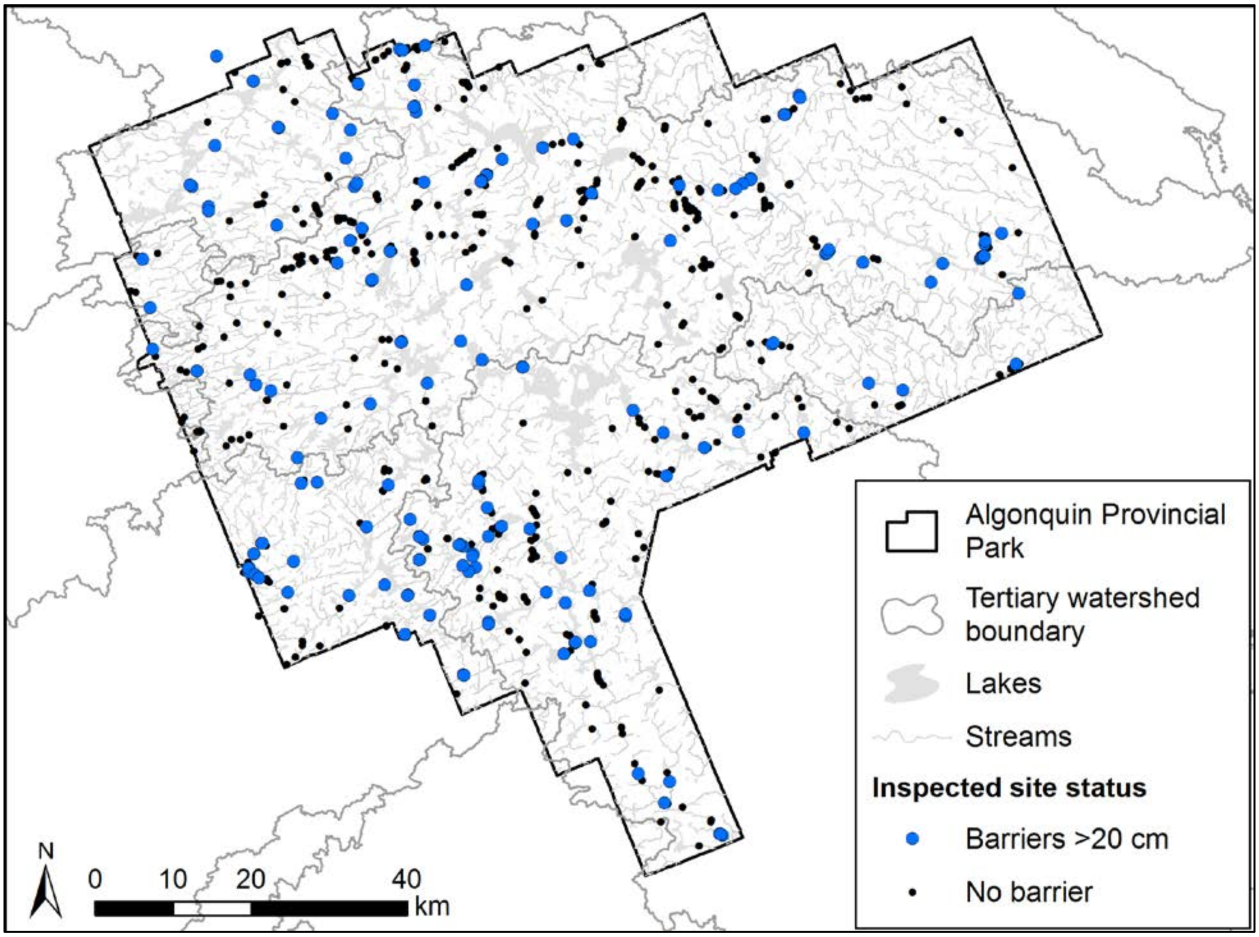

Figure A1.11. Results of inspection of candidate barrier sites — vertical barriers are falls >20 cm (large blue circles) and non-barriers are <20 cm or flat water (small black circles).

Breaks in the distribution of fish species between lakes in a watershed served as a test to ensure the barrier map was functionally correct. Stream systems with faunal breaks (between lakes) but without detected barriers indicated a missed barrier (waterfalls, steep slopes etc.). These faunal breaks were investigated using the orthophoto images, which led to a few more barriers identified at what appeared to be steep slope sites according to slope maps (see Figure A1.9). For a few faunal breaks, we could not confirm barriers using the orthophotos due to obstructed views. We mapped these barriers as small functional ones at steep slope locations. The remaining ones were also accepted as barriers even if rapids or very small falls were observed. Figure A1.11 summarizes the distribution of our site inspections across the park, including sites with no barrier that may have appeared to have one based on map and digital imagery.

In summary, we detected 178 vertical barriers >20 cm tall relying on previously mapped waterfalls, knowledge collected from local experts, and verification through field visits and aerial imagery (Figure A1.12). Sites shown in Figure A1.12 represent the best available information on barriers to fish movement in Algonquin Provincial Park. The combination of methods we used added many sites to the list of known barriers, with many of the missed barriers in watersheds that have at least 1 functional barrier. The suite of methods used to locate barriers could still have resulted in some barriers that remain unmapped. The barrier map could be further developed with additional digital and field inspection.

We did not include road culverts used in forestry operations because they can be removed or replaced; information on locations of perched culverts is not available.

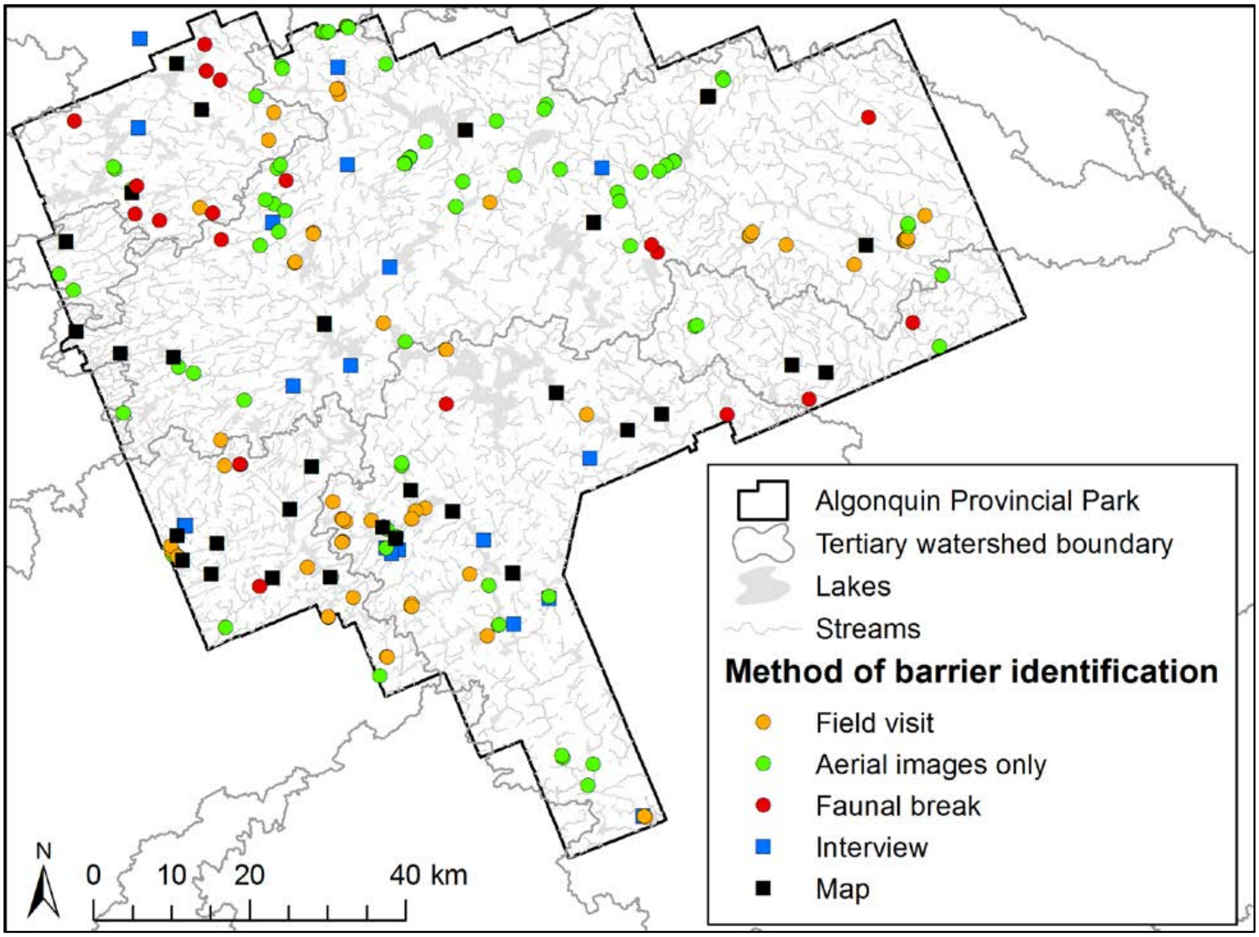

Figure A1.12. Methods used to identify and map verified barriers. Faunal breaks, sites identified by local experts, and mapped barriers were all verified using orthophotos.

Figure A1.13 shows the mapped distribution of vertical stream barriers used in this study. Figure A1.14 shows the distribution of vertical barriers by height category. Most vertical barriers are <40 cm tall, but a few are almost 600 cm.

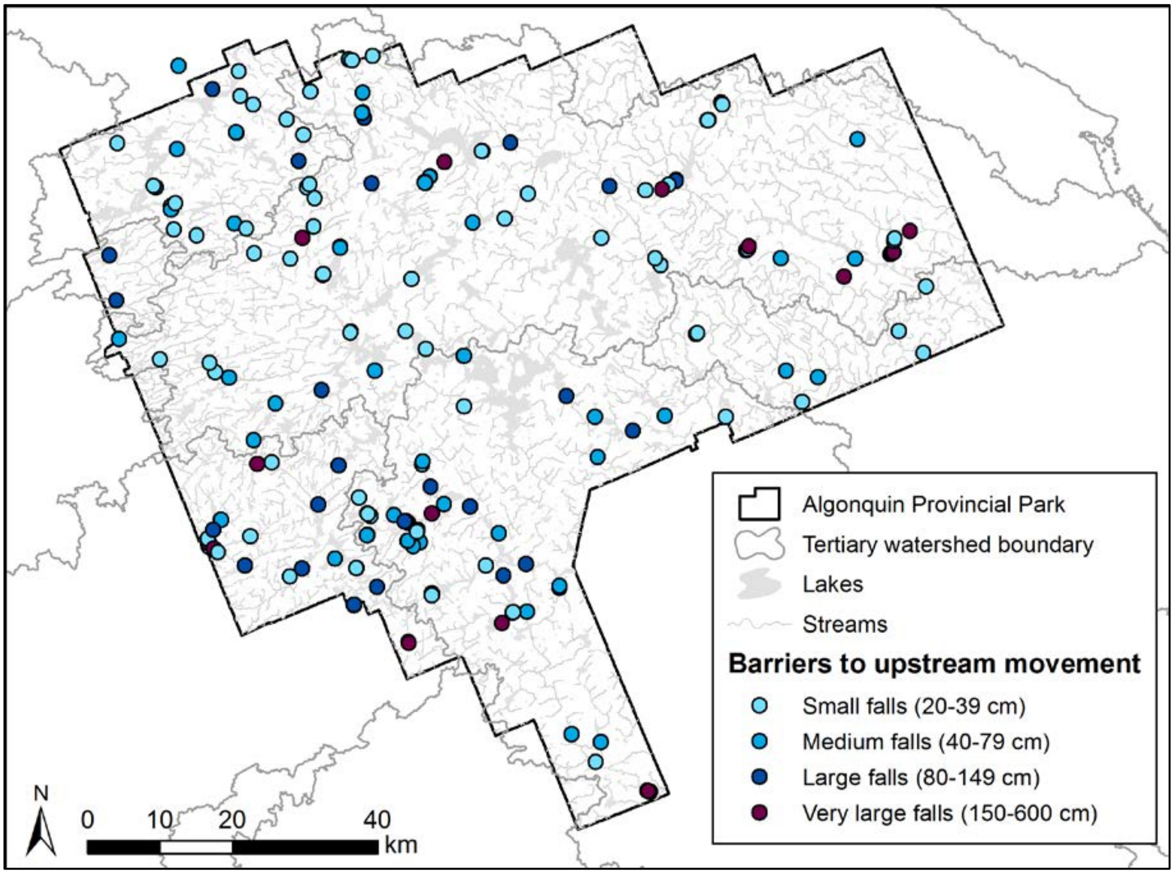

Figure A1.13. Results of inspection of candidate barrier sites. Vertical barriers are falls >20 cm tall; of the 178 barriers, 78 are >60 cm.

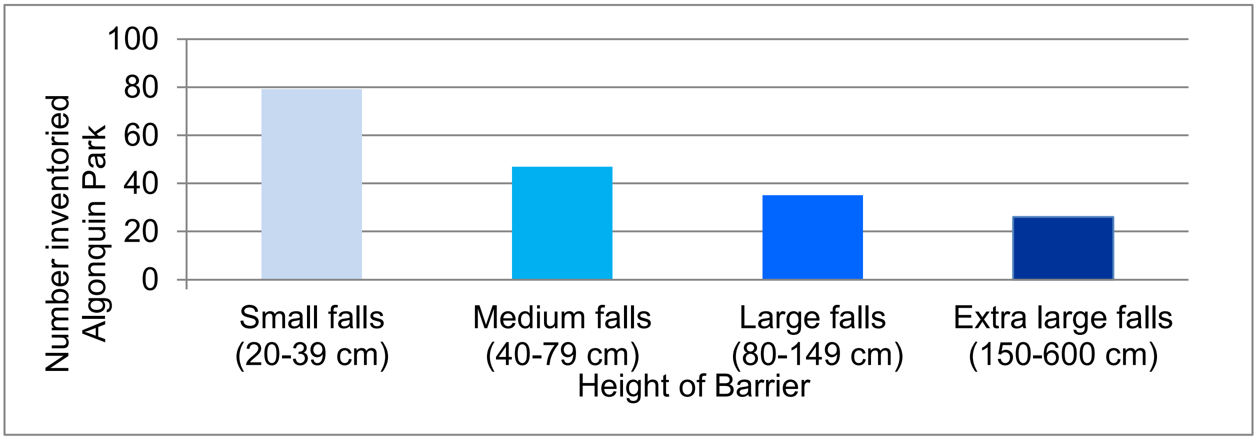

Figure A1.14. The frequency of 4 barrier sizes in Algonquin Provincial Park for 178 vertical barrier sites.

High slope sites in the park

Data provided by Land Information Ontario (LIO) was at a 30 m scale (cells = 30 m x 30 m). This resolution was used to calculate slope across the park landscape using ArcGIS 10.1. Figure A1.15 shows the steps used to estimate slope for the park:

1. A digital elevation model was developed based on the 30 m resolution data for the park landscape (left image, Figure A1.15).

2. The elevation map was used to calculate slope ranging from no slope to steep slope areas (middle image, Figure A1.15).

3. Stream segments in high slope areas were identified as either greater that 10% or greater than 15% (right image, Figure A1.15).

4. The set of verified barriers shown as green points in the right image of Figure A1.15 demonstrates they are associated with steep slope stream segments.

Some verified vertical barriers overlap or are adjacent to high slope areas as shown in Figure A1.15 (right image). Of the total vertical barriers shown in Figure A1.14, 18% of were found within 50 m of high slope segments, while 52% were found within 50 m moderately sloped segments. More than half (16/27) of the dam sites do not occur on areas of naturally high gradient.

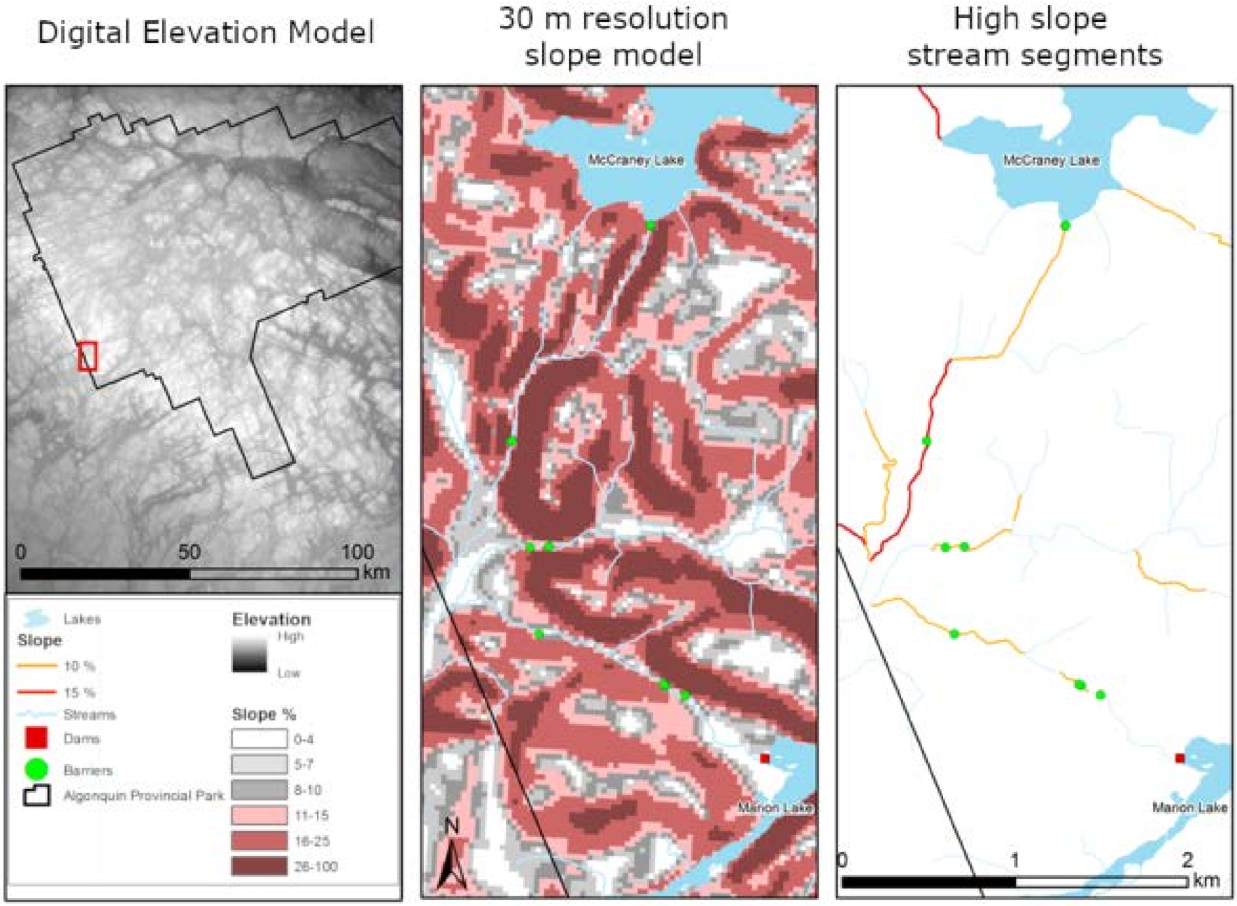

Figure A1.15. The process of identifying high slope areas beginning with 30 m elevation data for Algonquin Provincial Park. Above left: The park digital elevation model with darker shades indicating lower elevations. Middle: The calculated slope model at a resolution of 30 m for the McCraney and Marion Lake area. Above right: The highest slope has been assigned to the stream segment so areas that cross >10% slope can be easily identified. See Appendix 2 for an example of slope for a region of the park derived from a digital elevation model.

Appendix 2. Detailed digital elevation and slope maps for Algonquin Provincial Park

The slope maps for Algonquin Provincial Park show areas of high and low slope across the landscape. They are derived from the 30 m x 30 m digital elevation data for the park and expressed as percent slope. This is the rise-over-run change in elevation in a 30 x 30 m grid cell. Figure A2.1 shows an example of an elevation map, while Figure A2.2 shows how the corresponding slope map based on elevation changes for this section of the park.

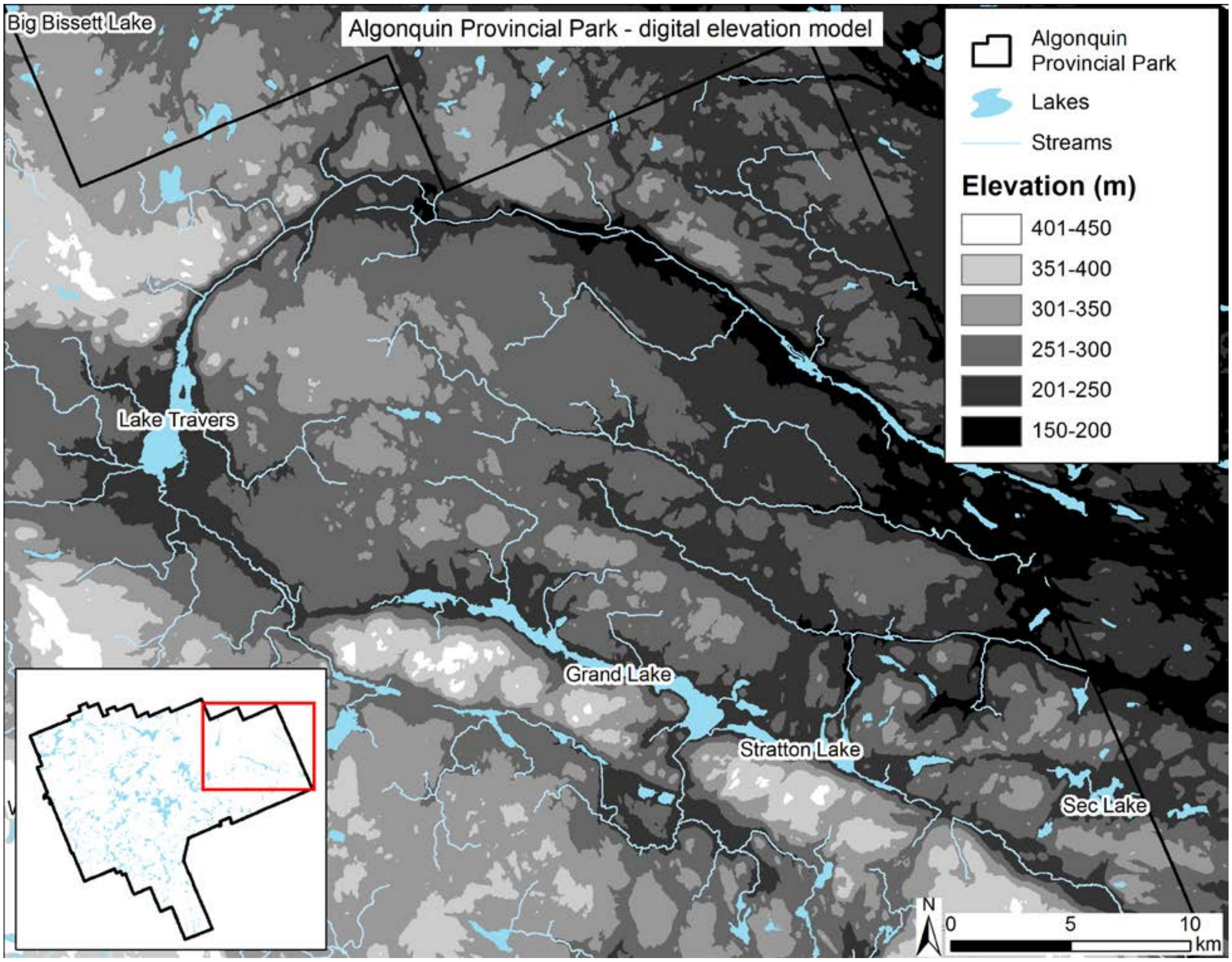

Figure A2.1. Digital elevation model of the northeast corner of Algonquin Provincial Park (Grand Lake area) with elevation shown as shades of grey (black indicates highest elevation).

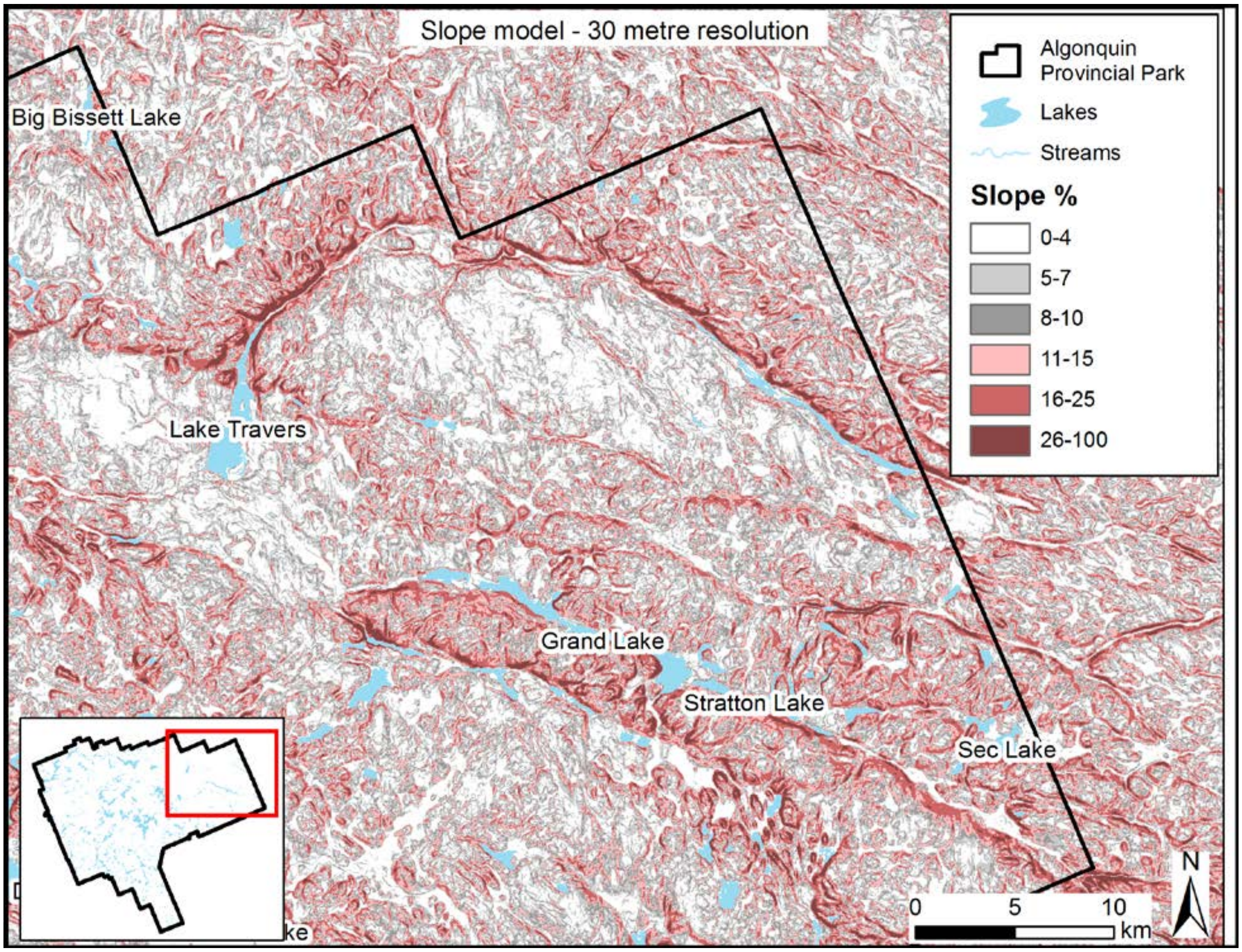

Figure A2.2. A 30 m resolution slope model of the northeast corner of Algonquin Provincial Park (Grand Lake area).

Appendix 3. Upstream catchment of dams in Algonquin Provincial Park

Dams protect upstream catchments by barring fish movement. In Algonquin Provincial park, they range from 30 cm to several metres tall. We grouped dam catchments by watershed for clarity, including the areas above dams in the Madawaska River watershed (Figure A3.1), Muskoka River watershed (Figure A3.2), Petawawa River watershed (Figure A3.3) and Kipawa/French River watershed (Figure A3.4).

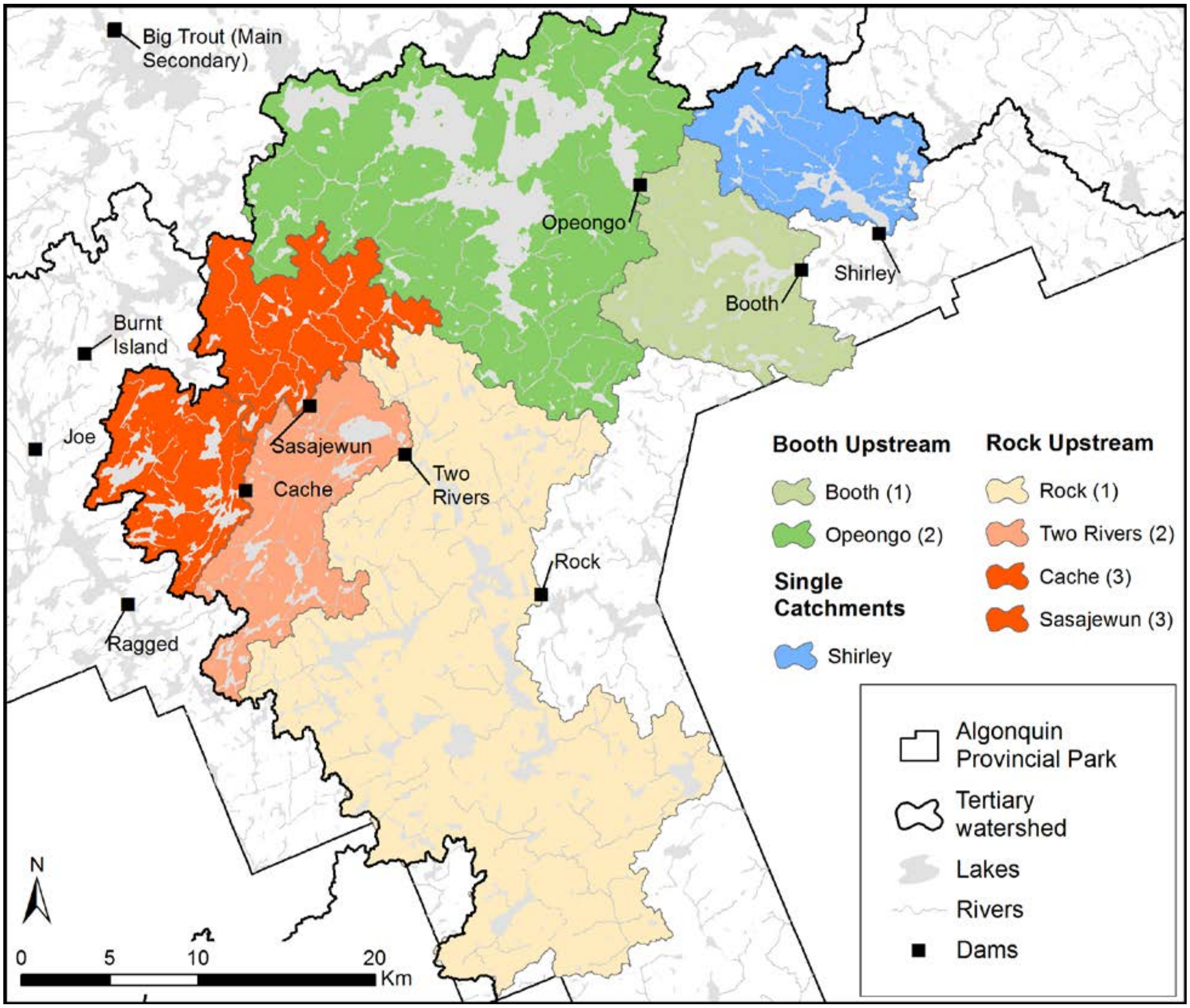

Figure A3.1. Upstream dam catchments in the Madawaska River watersheds in Algonquin Provincial Park.

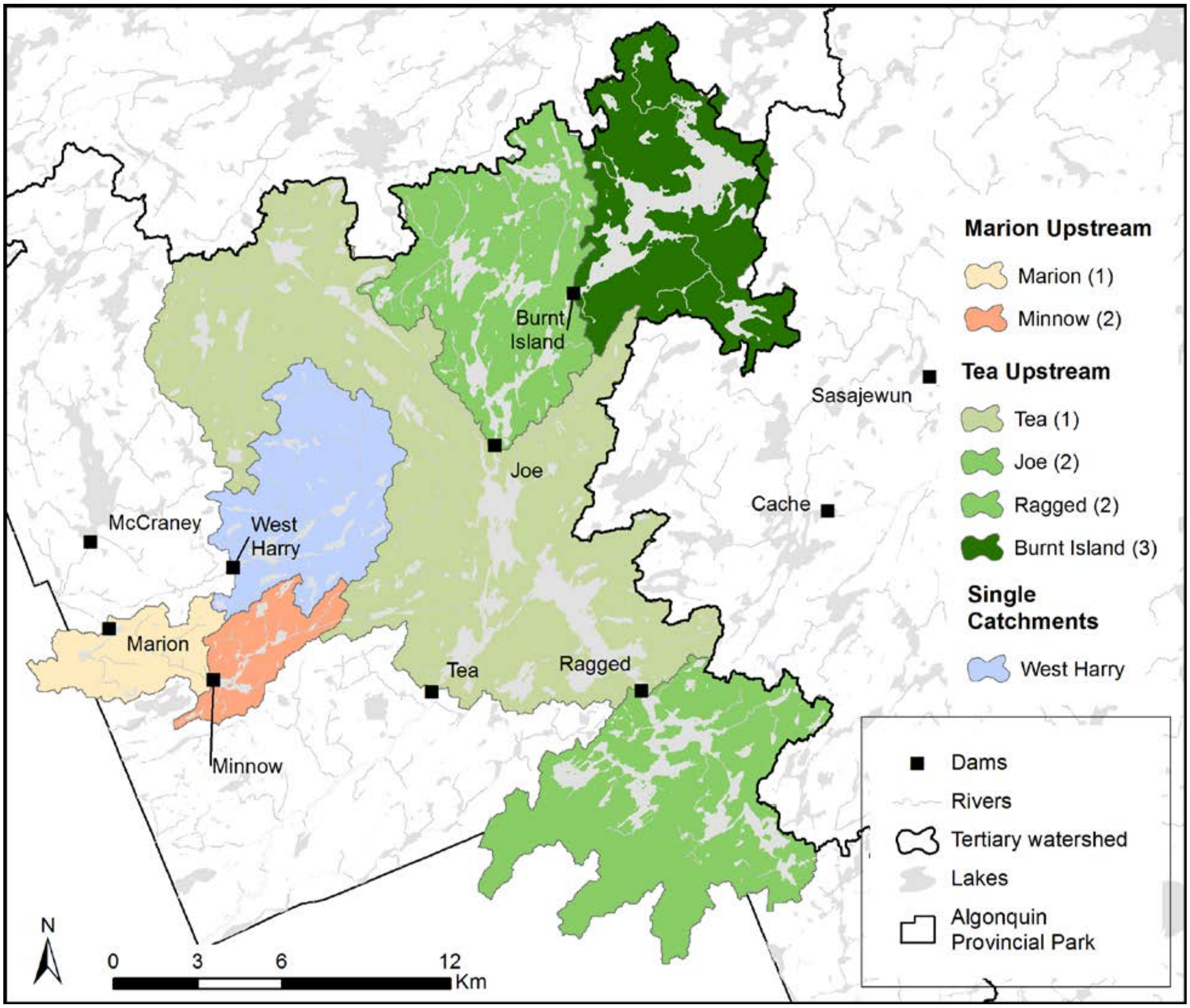

Figure A3.2. Upstream dam catchments in the Muskoka River watersheds in Algonquin Provincial Park.

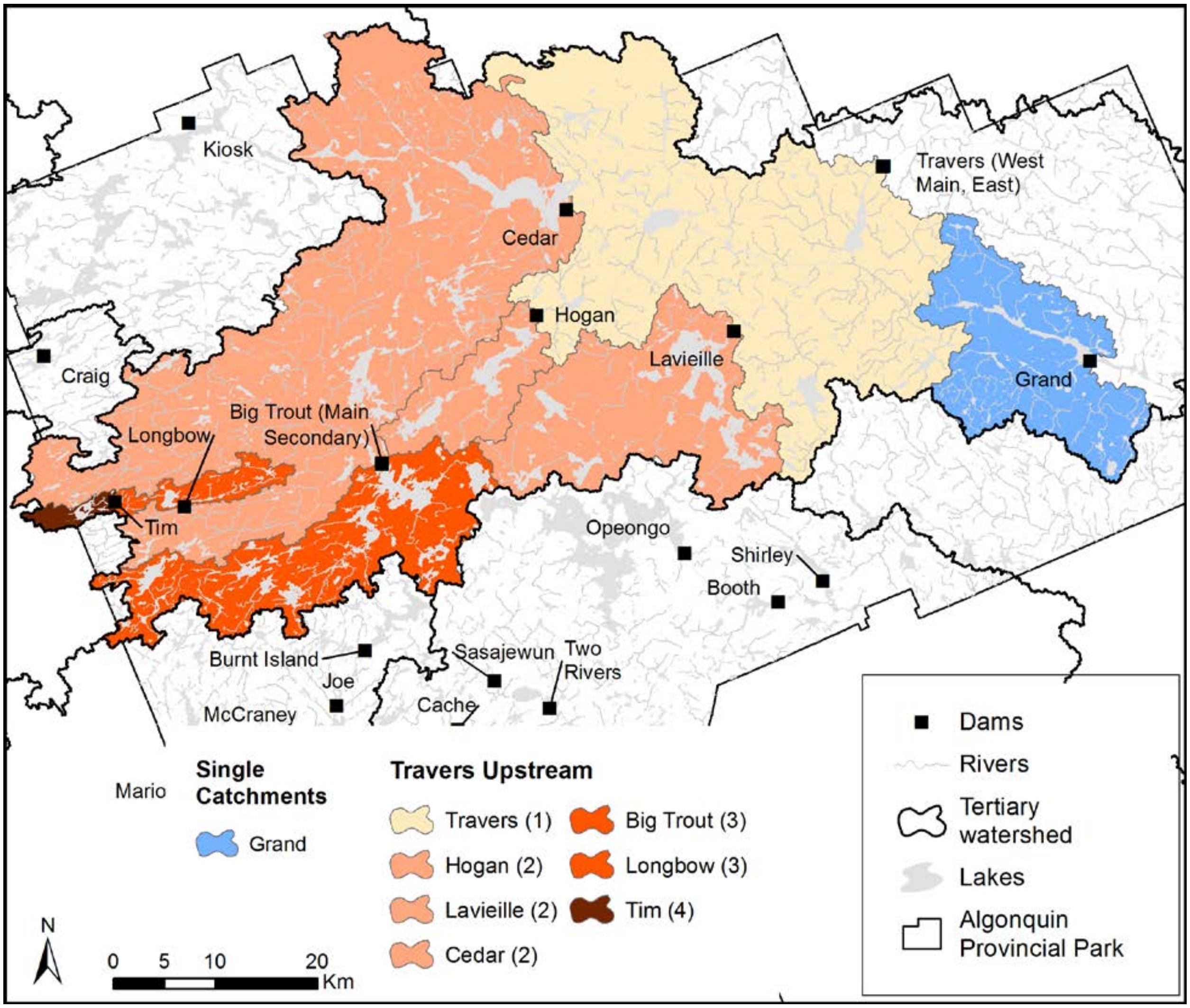

Figure A3.3. Upstream dam catchments in the Petawawa River watersheds in Algonquin Provincial Park.

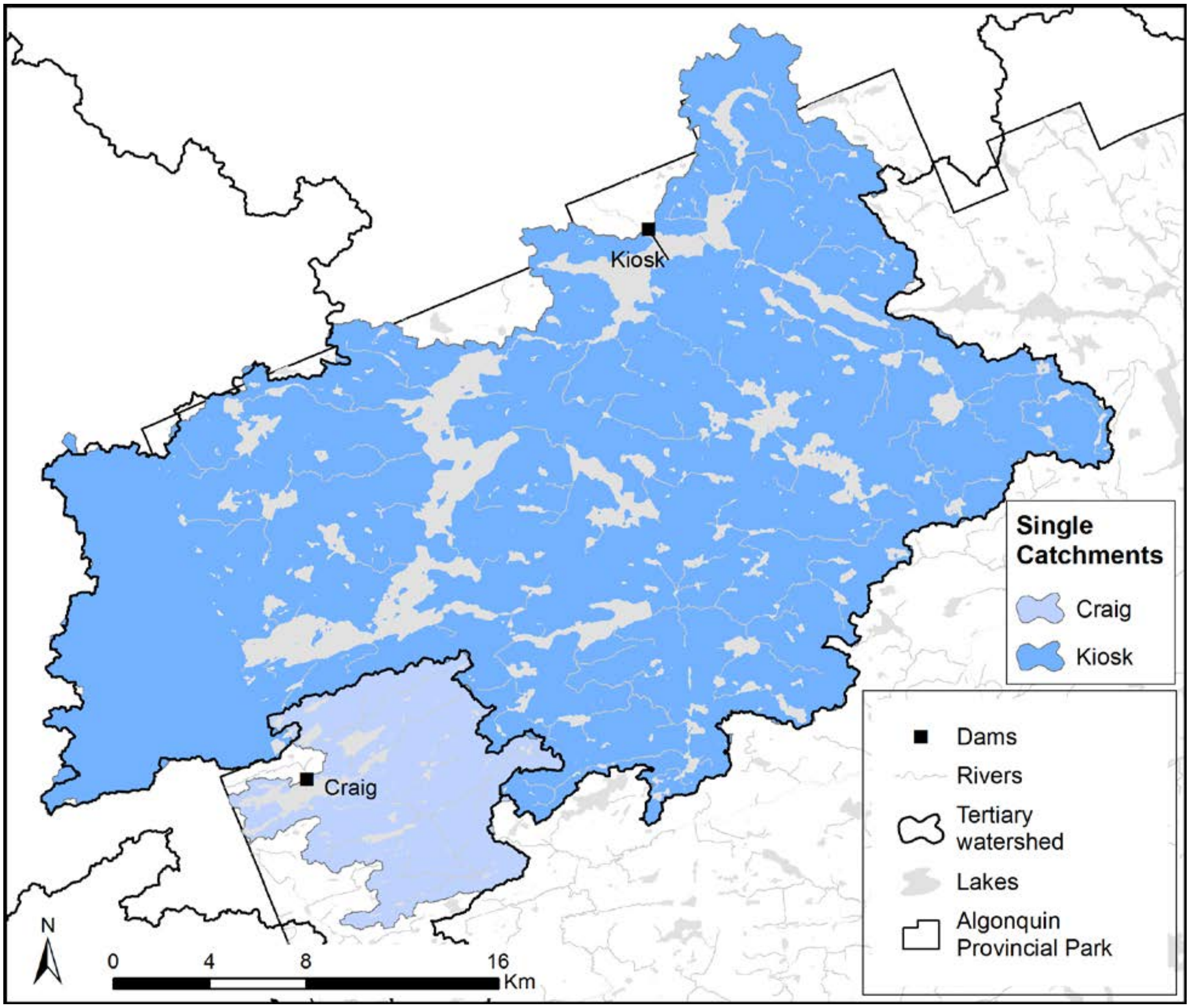

Figure A3.4. Upstream dam catchments in the Kipawa and French River watersheds in Algonquin Provincial Park.

Appendix 4. Scenarios of secondary spread from single lake introductions

Figures A4.1 to A4.14 show how illegal fish introductions to a single lake in Algonquin Provincial Park could spread. These scenarios provide a finer scale illustration of likely dispersal downstream. Stream locations are possible sites of spread based on the park barrier map — actual occupancy will depend on introduced species' habitat preferences.

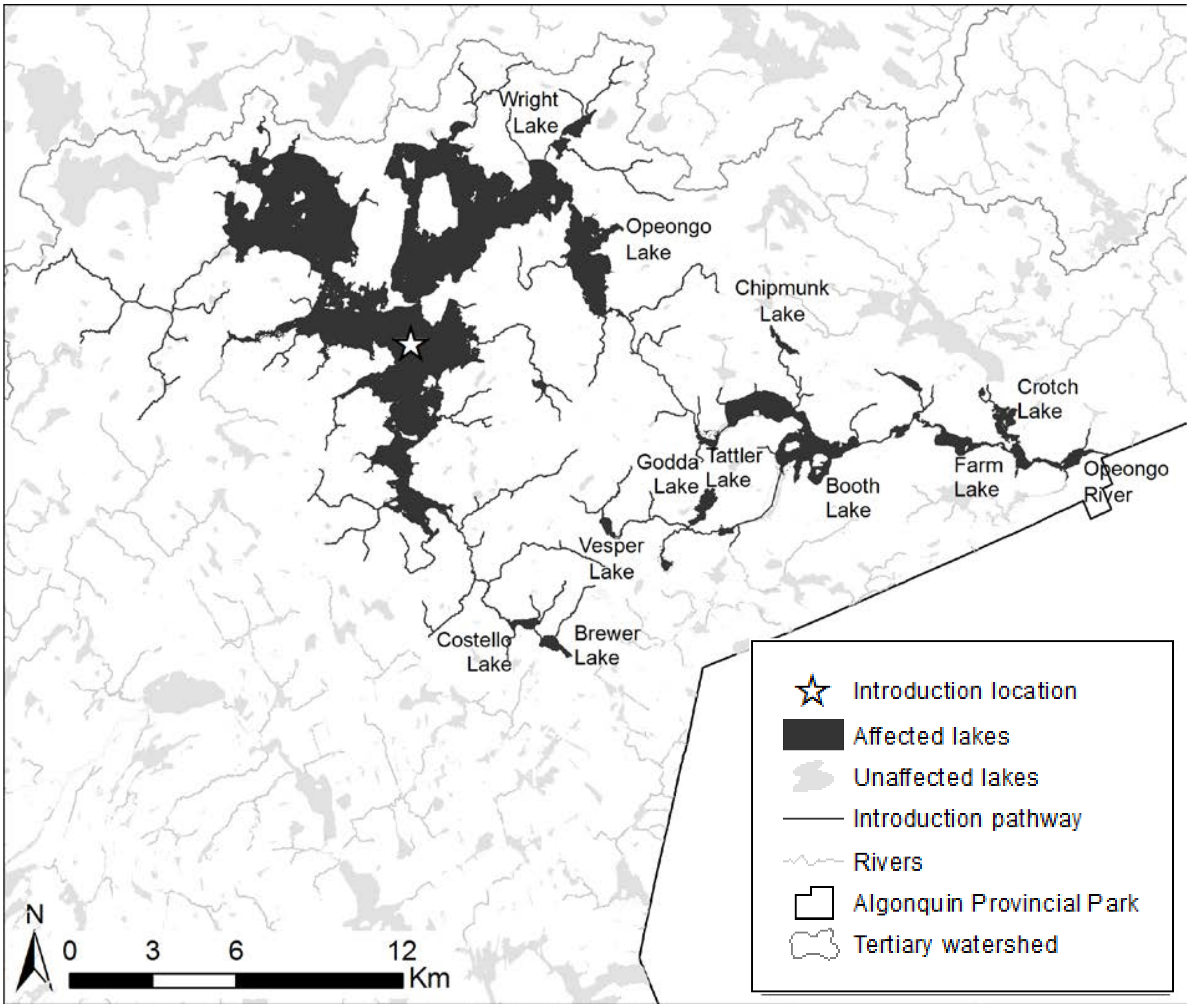

Figure A4.1. Potential smallmouth bass and cisco distribution after being introduced to Lake Opeongo in Algonquin Provincial Park decades ago and then spreading downstream.

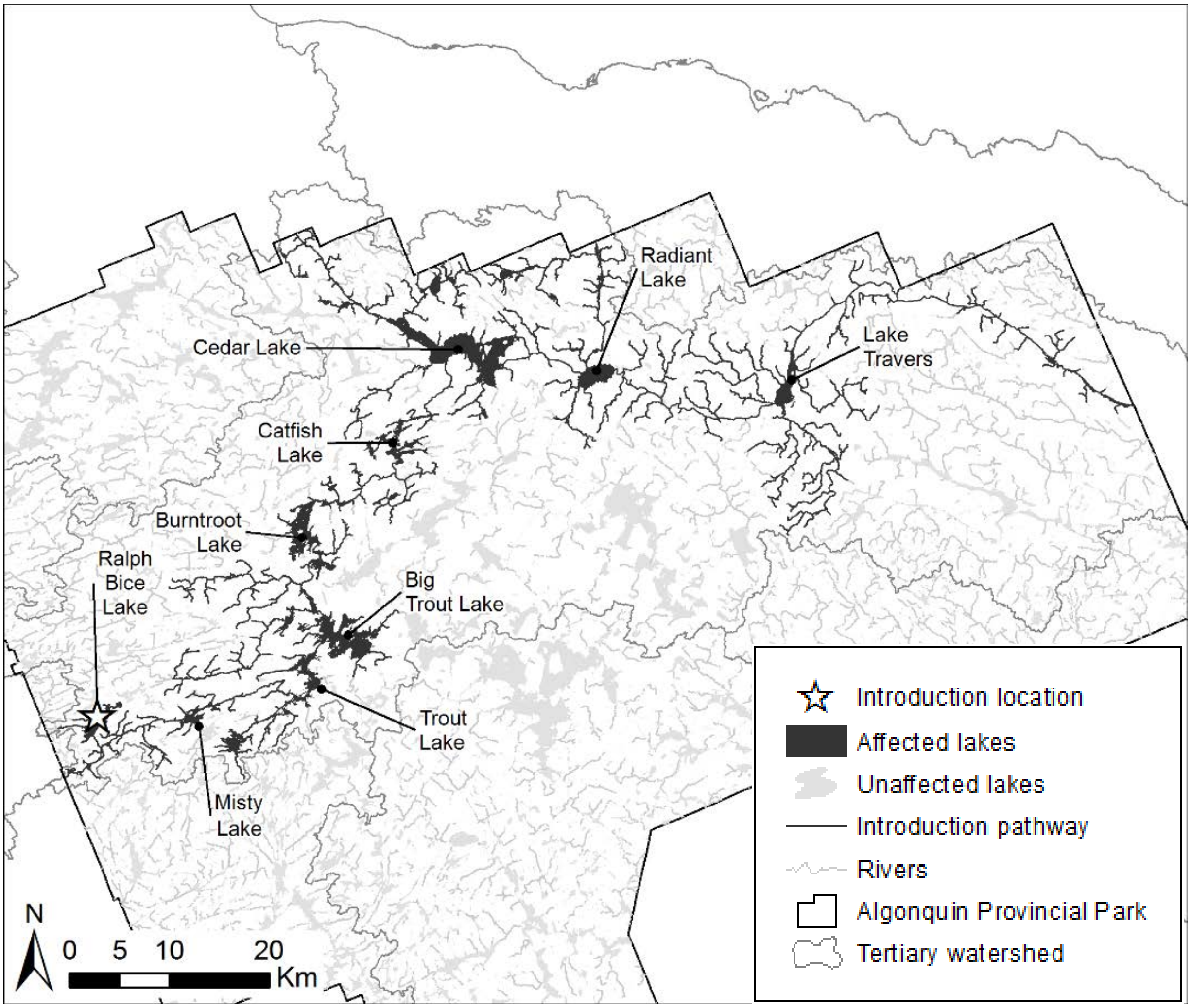

Figure A4.2. Potential fish distribution following illegal introduction to Ralph Bice Lake in Algonquin Provincial Park and then spreading downstream.

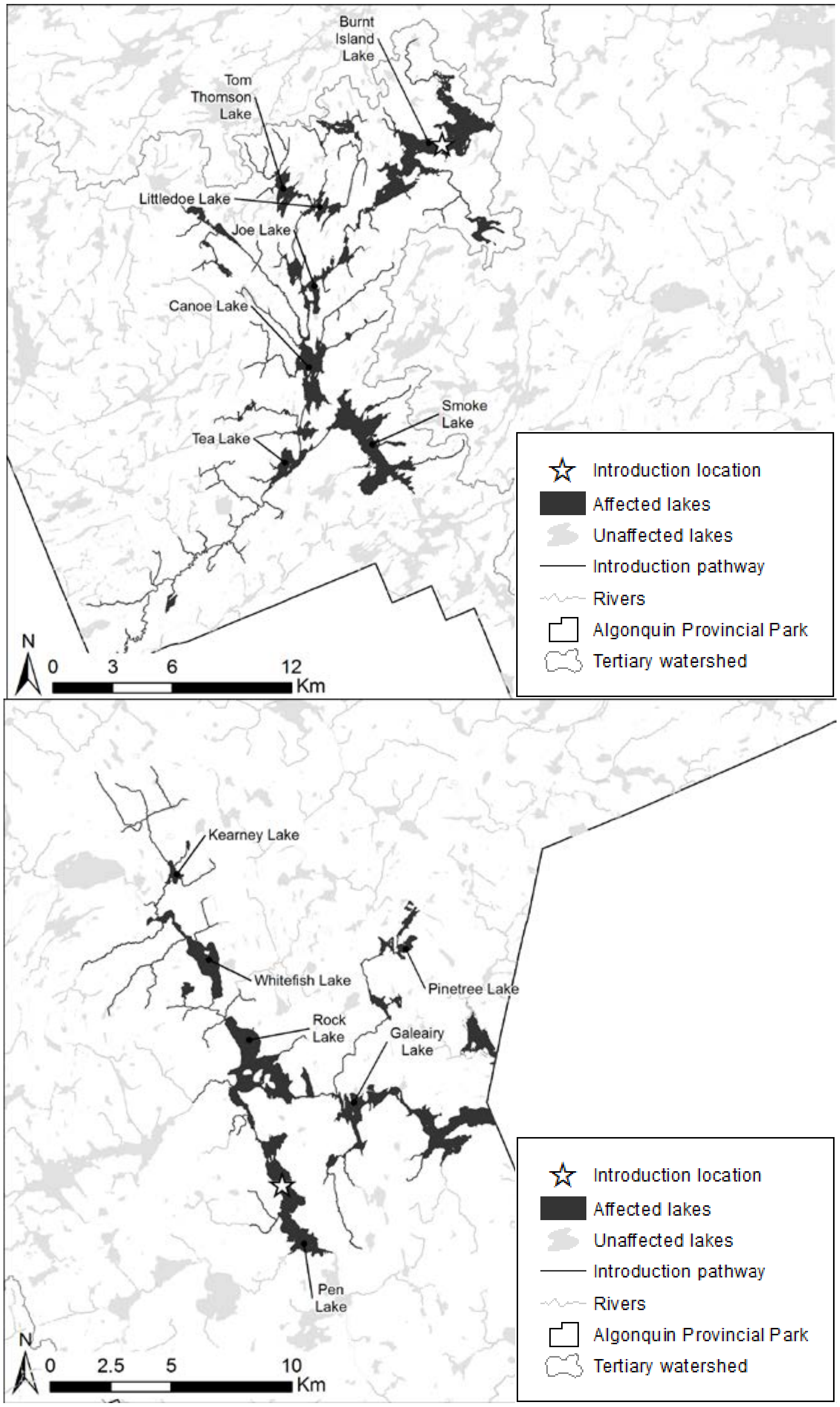

Figure A4.3. Potential fish distribution following illegal introduction to Burnt Island (upper map) and Pen lakes (lower map) in Algonquin Provincial Park and then spreading downstream.

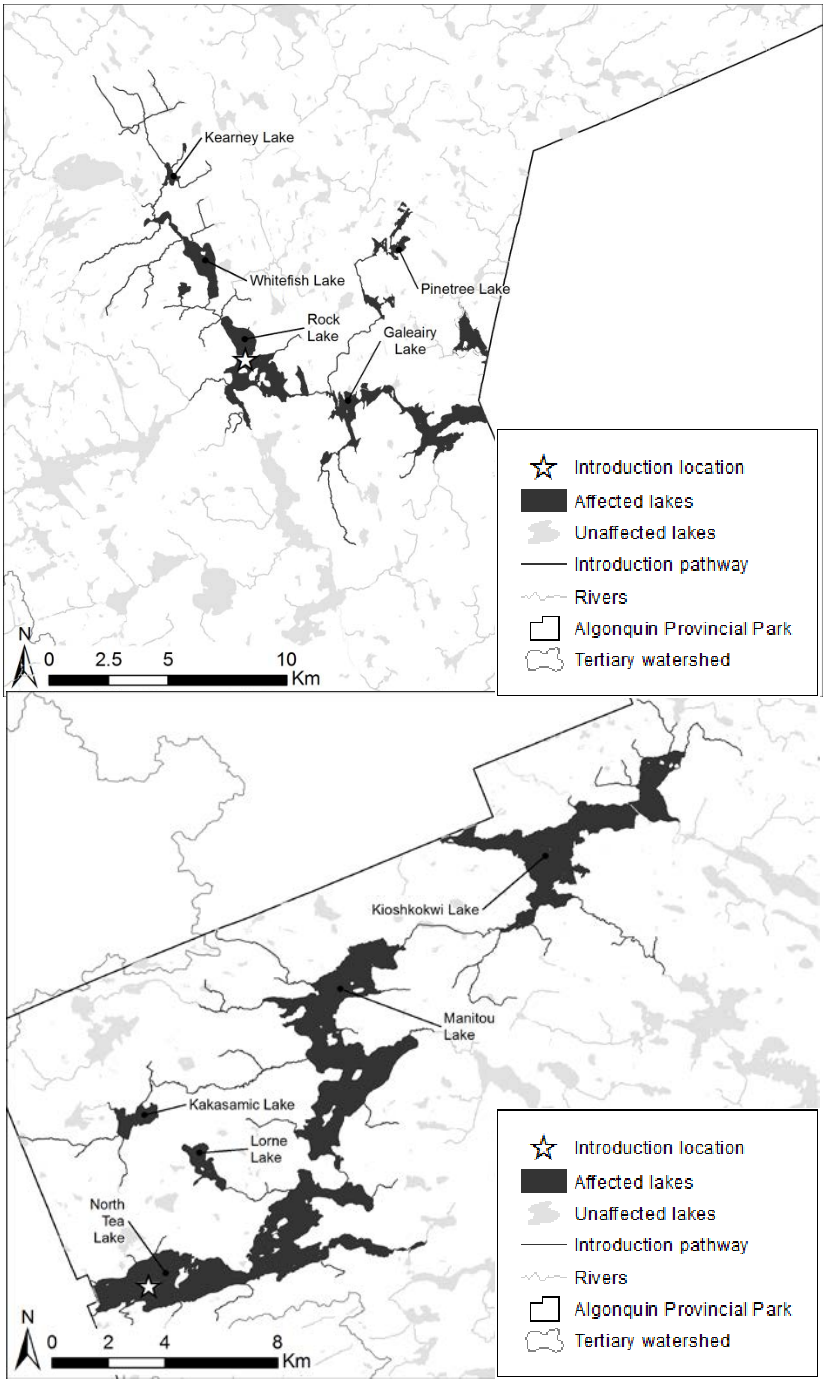

Figure A4.4. Potential fish distribution following illegal introduction to Rock (upper map) and North Tea lakes (lower map) in Algonquin Provincial Park and then spreading downstream.

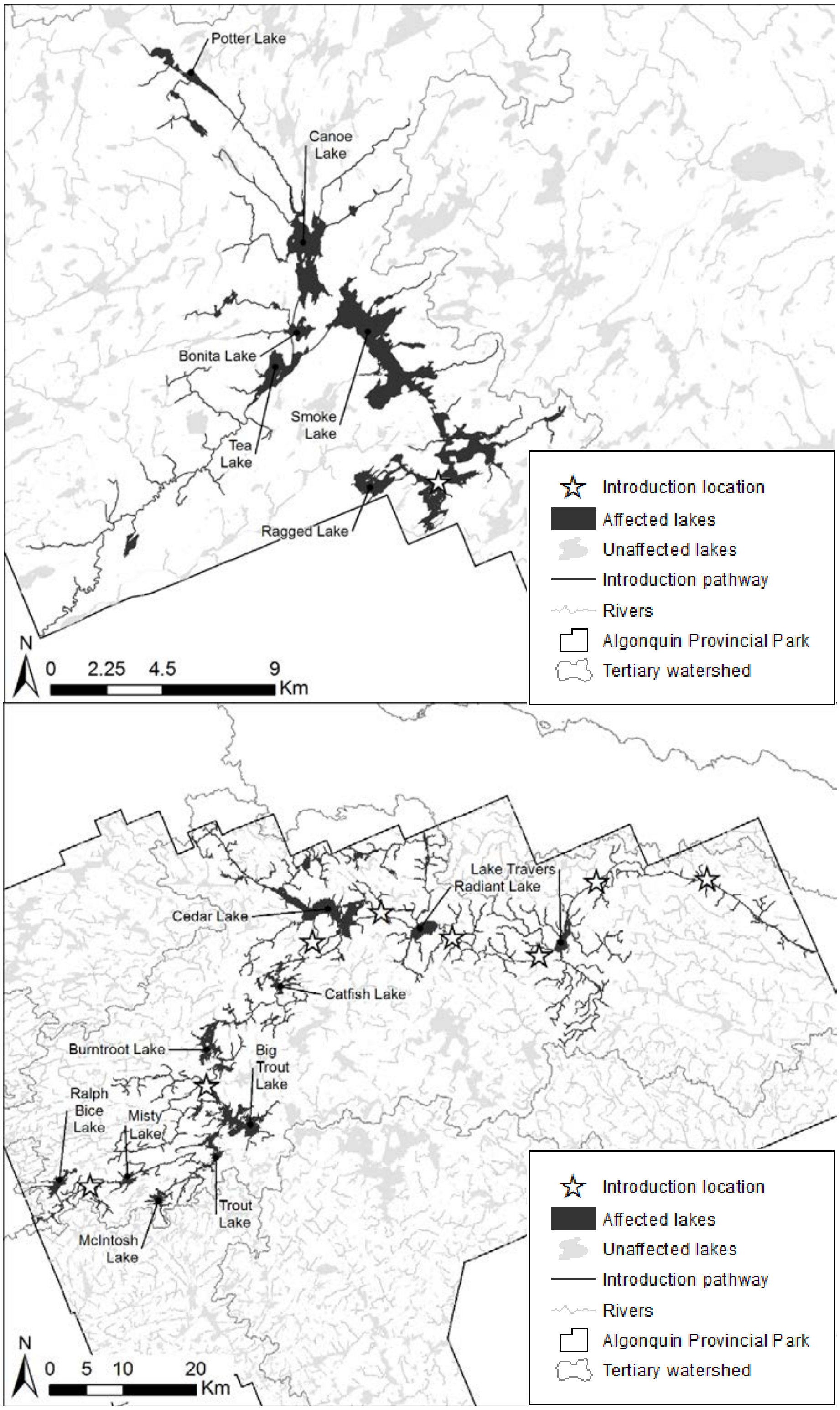

Figure A4.5. Potential fish distribution following illegal introduction to Ragged Lake (upper map) and the upper Petawawa River (lower map) in Algonquin Provincial Park and then spreading downstream.

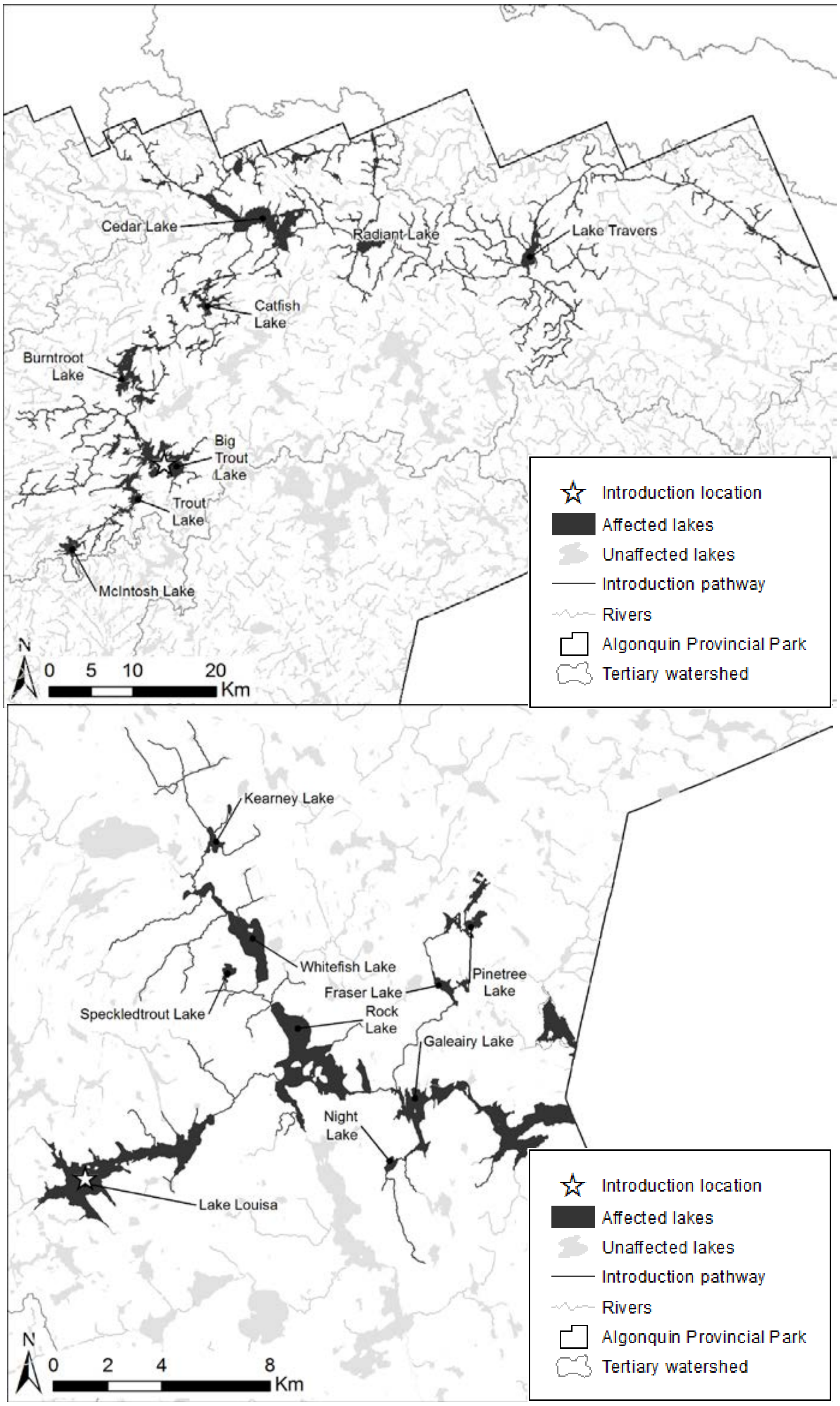

Figure A4.6. Potential fish distribution following illegal introduction to Big Trout (upper map) and Louisa lakes (lower map) in Algonquin Provincial Park and then spreading downstream.

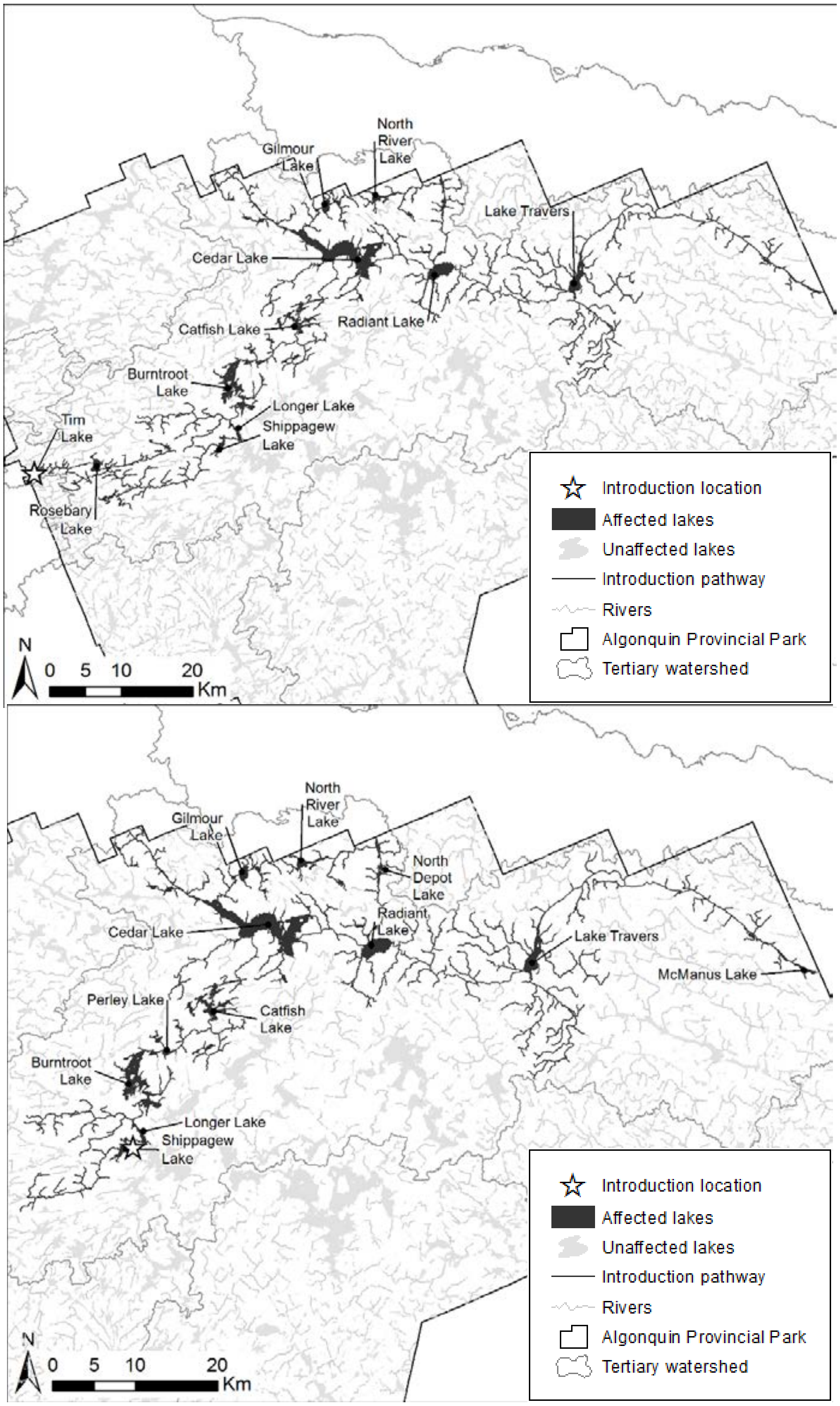

Figure A4.7. Potential fish distribution following illegal introduction to Tim (upper map) and Burnt Root lakes (lower map) in Algonquin Provincial Park and then spreading downstream.

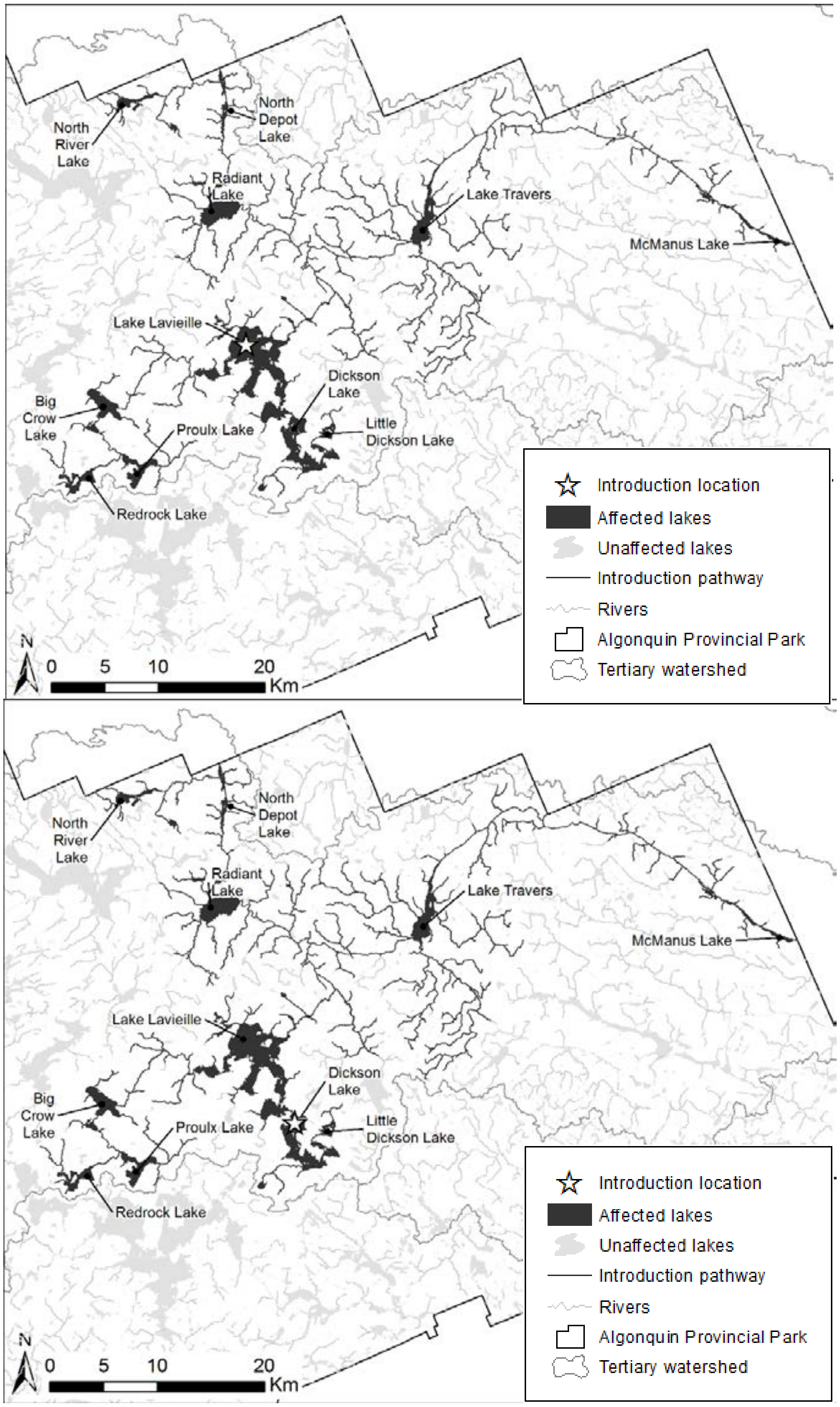

Figure A4.8. Potential fish distribution following illegal introduction to Lavieille (upper map) and Dickson lakes (lower map) in Algonquin Provincial Park and then spreading downstream.

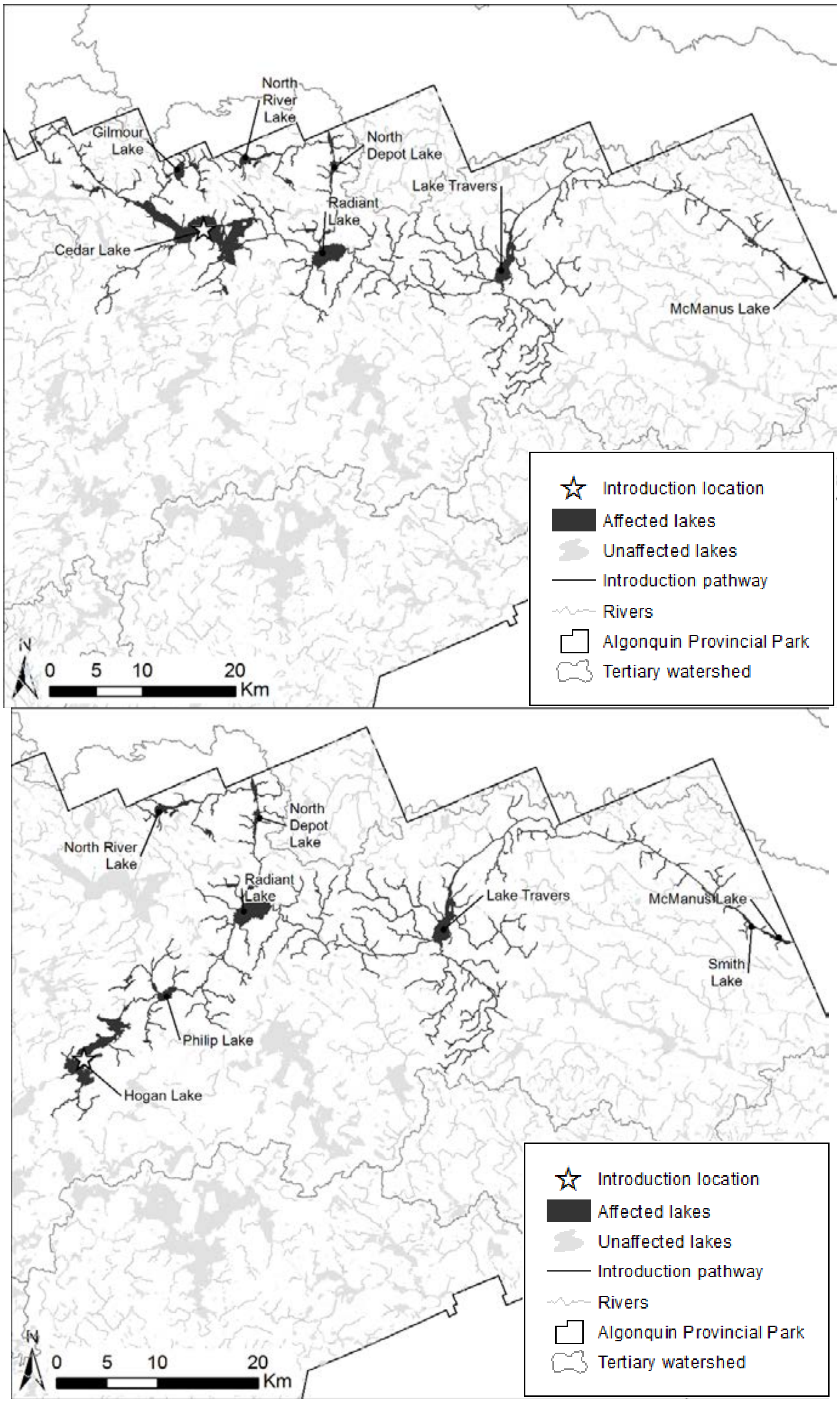

Figure A4.9. Potential fish distribution following illegal introduction to Cedar Lake (upper map) and Hogan Lake (lower map) in Algonquin Provincial Park and then spreading downstream.

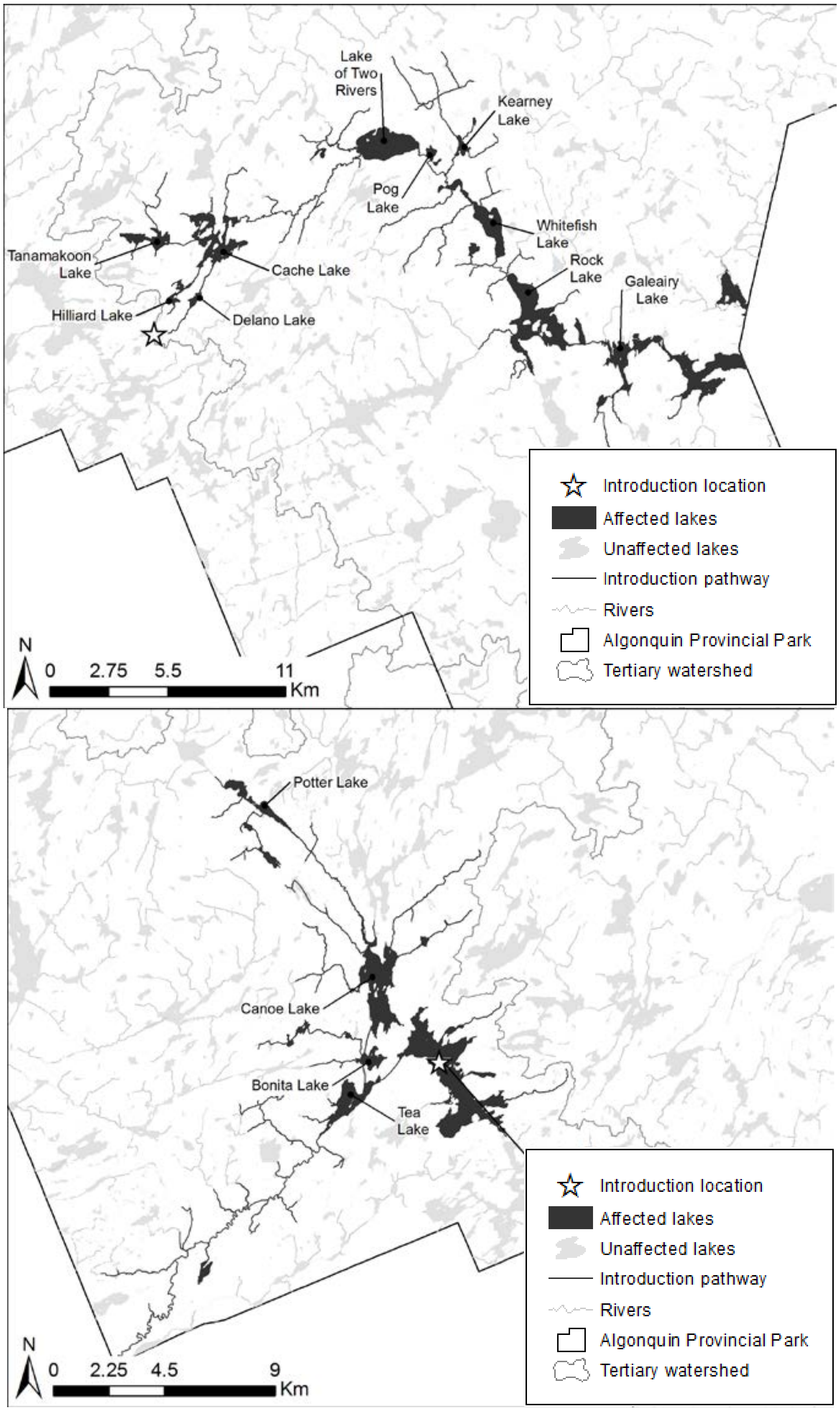

Figure A4.10. Potential fish distribution following illegal introduction to Cache (upper map) and Smoke lakes (lower map) in Algonquin Provincial Park and then spreading downstream.

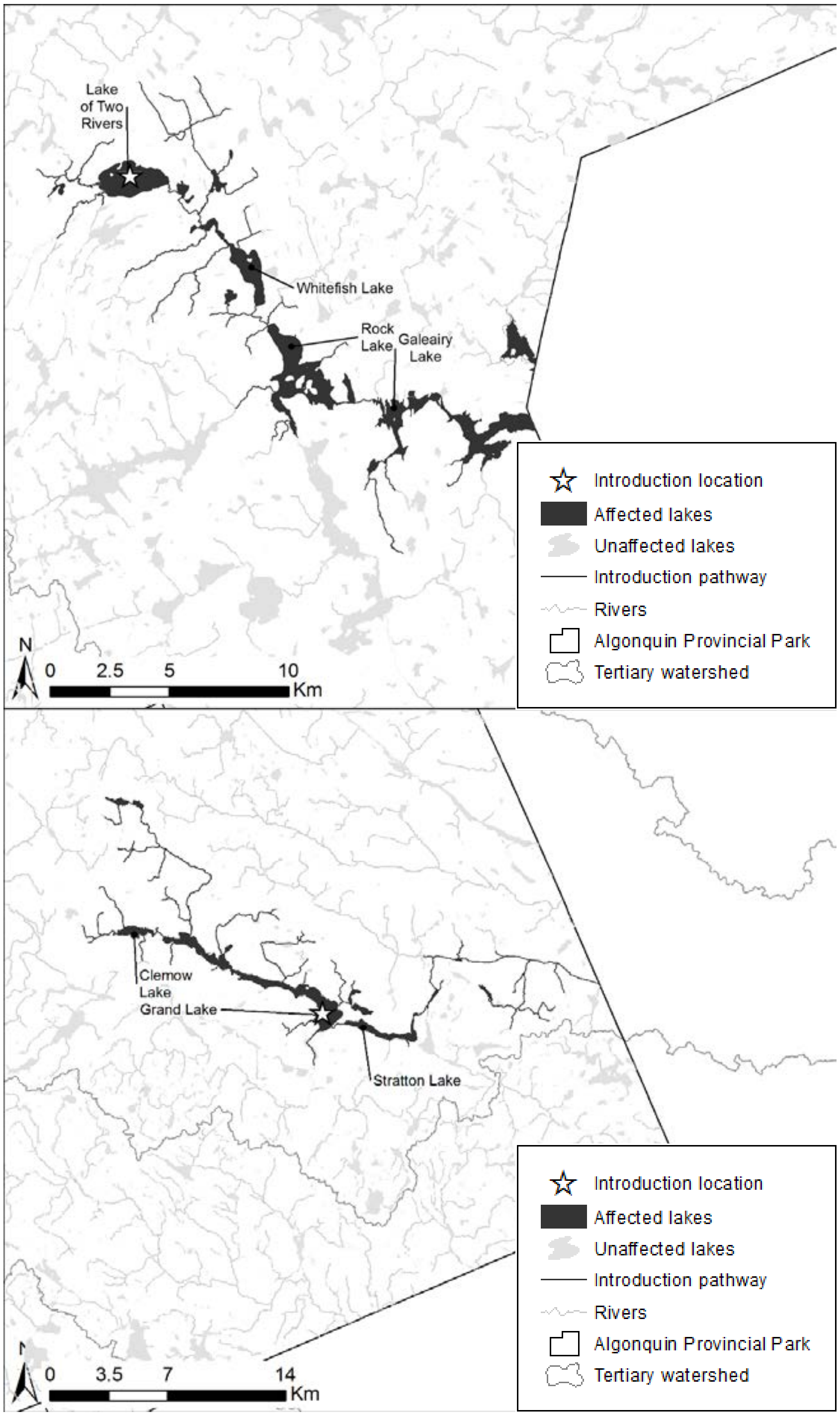

Figure A4.11. Potential fish distribution following illegal introduction to Lake of Two Rivers (upper map) and Grand Lake (lower map) in Algonquin Provincial Park and then spreading downstream.

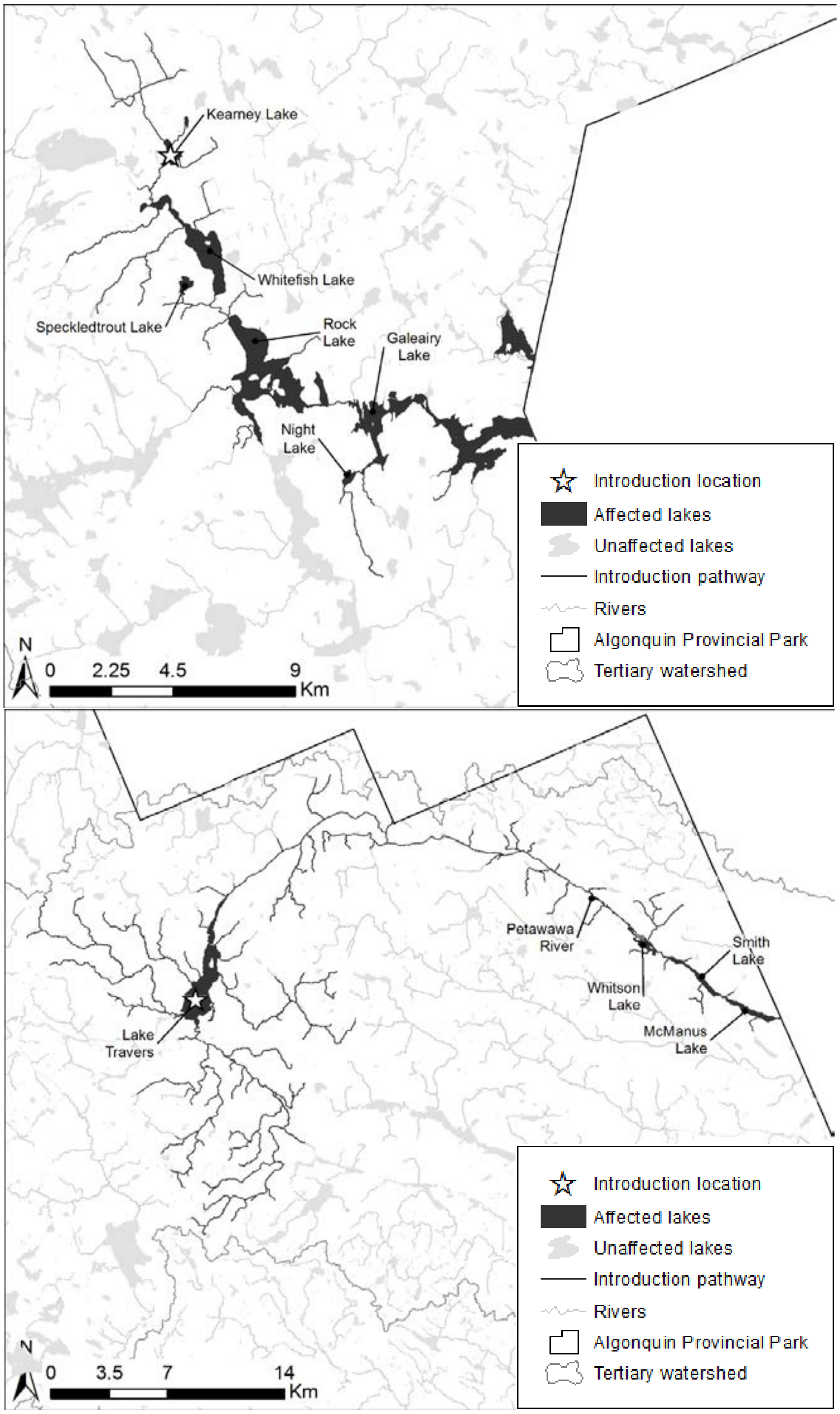

Figure A4.12. Potential fish distribution following illegal introduction to Kearney (upper map) and Travers lakes (lower map) in Algonquin Provincial Park and then spreading downstream.

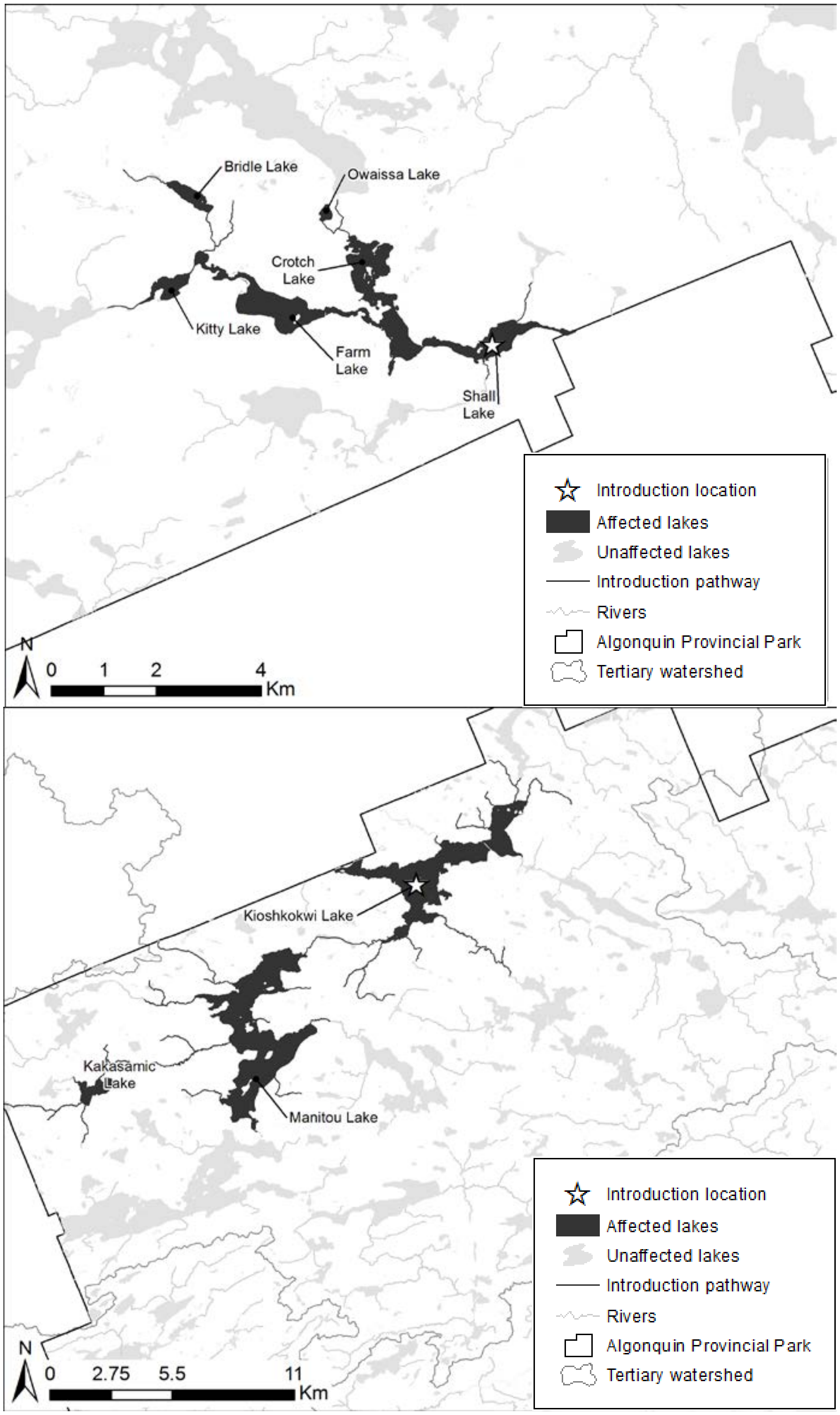

Figure A4.13. Potential fish distribution following illegal introduction to Shall (upper map) and Kioshkokwi lakes (lower map) in Algonquin Provincial Park and then spreading downstream.

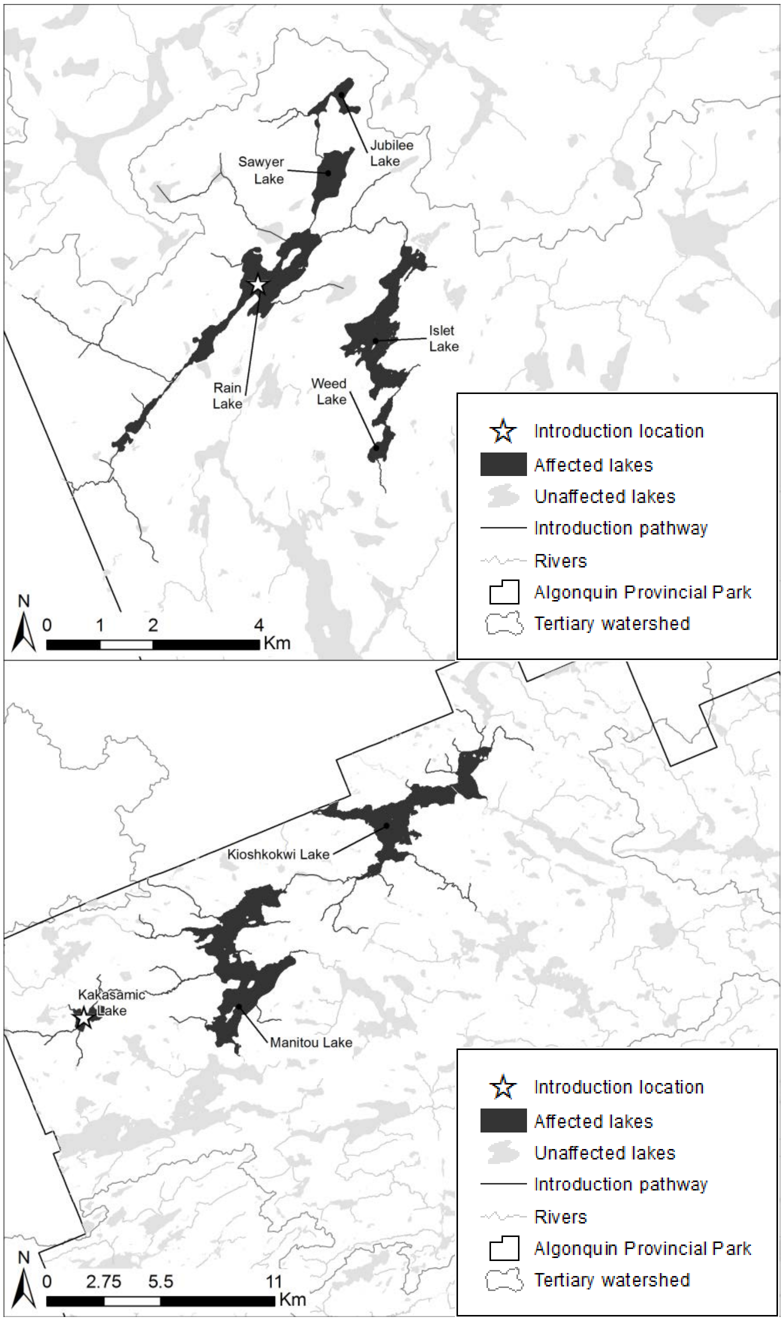

Figure A4.14. Potential fish distribution following illegal introduction to Rain (upper map) and Kakasamic lakes (lower map) in Algonquin Provincial Park and then spreading downstream.

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