UNIVERSITÉ DU QUÉBEC EN OUTAOUAIS

CARACTÉRISATION DES INFRASTRUCTURES DE VOIRIE DANS LES FORÊTS PUBLIQUES ET PRIVÉES DE L'OUTAOUAIS, QUÉBEC

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DÉDICACE

Dedicated to my niblings.

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CHZ : Controlled Harvesting Zone

PRLR : Percentage of running lane revegetation

IRLW : Initial running lane width

CRLW : Current running lane width

LQE : Loi sur la qualité de l'environnement

RADF: Règlement sur l'aménagement durable des forêts du domaine de l'État

RÉSUMÉ

La forêt québécoise est sillonnée par un important réseau de routes forestières qui sont le résultat d'activités d'extraction et qui constituent souvent la voie d'accès à des environnements éloignés. Différents travaux ont montré que ce réseau comprend de nombreuses routes abandonnées et des ponceaux peu entretenus qui peuvent perturber la connectivité de l'habitat aquatique et avoir un impact sur l'intégrité de l'écosystème. Les déterminants de l'état des ponceaux demeurent peu documentés et étant donné l'absence d'un recensement précis et à jour des infrastructures routières forestières, une telle information est cruciale pour informer les efforts de restauration. Les objectifs de ce projet de mémoire sont de i) documenter l'état des ponceaux forestiers et les déficiences rencontrées et ii) identifier les déterminants de l'état des ponceaux forestiers et plus particulièrement comprendre l'influence de la tenure des terres ainsi que de l'état et le niveau d'entretien des routes adjacentes. Notre étude s'est déroulée sur les terres forestières publiques et privées de l'Outaouais (Québec, Canada) et a évalué l'état de 121 ponceaux et des routes qui leur sont directement adjacentes. L'état des ponceaux a été évalué de « Bon » à « Non fonctionnel », à partir d'un recensement des déficiences (déformation, aplatissement, corrosion ou abrasion, perforation ou fissuration, séparation structurelle, pourriture, obstruction). Afin d'évaluer le niveau d'entretien des routes, la revégétalisation de la surface des routes a été quantifiée sur une échelle de 0 à 100%, 100% indiquant une couverture végétale complète. L'état des routes a également été évalué de « Bon » à « Non fonctionnel » en évaluant la présence d'érosion ou de différents types de déficiences (nids-de-poule, ornières, roulières, érosion, émergence de la sous-fondation, ondulations, bris partiel, bris complet).

Notre étude a révélé que l'état des ponceaux est influencé par l'état du chemin et la tenure des terres mais pas par le niveau de revégétalisation du chemin. La majorité (63 %) des ponceaux recensés étaient en mauvais état (« Médiocre » ou « Critique »). Dans l'ensemble, 52 % des ponceaux sur les terres privées étaient dans un état critique, comparativement à 34 % sur les terres publiques. Les déficiences les plus fréquemment observées pour les ponceaux en mauvais état sont l'obstruction, la perforation et la corrosion. Nos résultats indiquent que la tenure privée et le mauvais état des chemins sont associés au mauvais état des ponceaux. Cependant, nos résultats concernant l'influence de la tenure privée doivent être interprétés avec une certaine prudence, car nous disposions d'un jeu de données relativement restreint (n = 121). Somme toute, de précédents travaux ont permis de documenter le piètre état des ponceaux sur les terres publiques québécoises et les résultats de ce mémoire permettent d’étendre ce constat aux terres privées, qui n’avaient jusqu’à maintenant été peu documentées.

Dans le cadre du projet, nous avons également recueilli des données sur le nombre de ponceaux suspendus, car ils représentent une menace importante pour la connectivité aquatique. Sur l'ensemble des ponceaux inventoriés en terres publiques et privées, 57 % étaient suspendus, avec une hauteur moyenne de suspension de 27 cm. De plus, on constate que près d'un quart (24 %) des ponceaux sont à la fois suspendus et en mauvais état. Si l'on tient compte à la fois de l'état des ponceaux et de leur suspension, cela signifie qu'en moyenne, à chaque 10,1 km du réseau hydrographique, on retrouve un ponceau qui pourrait constituer une menace pour la biodiversité aquatique et/ou la connectivité de l'habitat.

La localisation, l’entretien et la réfection des ponceaux doivent être considérés comme une priorité d'action, étant donné l'ampleur du problème, à la fois dans les forêts publiques et privées du Québec. Cette étude met en évidence le besoin de poursuivre les recherches sur les facteurs déterminants de l'état des ponceaux, ainsi que le besoin d’avoir des inventaires à jour de l’état de la voirie forestière produits à partir de protocoles standardisés.

Mots clés : Ponceau, chemin forestier, tenure des terres, connectivité aquatique, infrastructure

ABSTRACT

Forests in Quebec are criss-crossed by a vast road network, which is the result of extractive activity that oftentimes is the first heavily-used access into remote areas. Previous studies have shown that this network includes many abandoned roads and deteriorated culverts, which can disrupt aquatic connectivity and impact ecosystem integrity. There is still little known about the drivers of culvert condition. Given the absence of accurate and up-to-date surveys of the forestry road infrastructure, information regarding what is associated with or causes culvert condition is integral to informing restoration efforts. The two main objectives of this project were to i) document the defects and condition of forestry road culverts and ii) identify the drivers of culvert condition, and more specifically, to understand the impact of land tenure, as well as the condition and maintenance level of adjacent forestry roads, on culvert condition. Our study evaluated and compared the condition of 121 culverts and the roads directly adjacent to them in public and private forests in the Outaouais (Quebec, Canada). Culvert condition was rated from 'Good' to 'Non-functional' using a protocol evaluating the presence and extent of defects (deformation, ovalisation, corrosion or abrasion, perforation or cracking, wood rot, obstruction). To evaluate the level of road maintenance, the road surface revegetation was quantified on a scale from 0 to 100%, with 100% indicating complete vegetative cover. Road condition was also evaluated from 'Good' to 'Non-functional' using erosion type and extent, as well as degradation type (pot-holes, ruts, furrows, erosion, sub-grade emergence, wash-boarding, partial road failure, complete road failure) as metrics.

Our study revealed that culvert condition is influenced by road condition and land tenure but not by road lane re-vegetation. The majority (63%) of the culverts inventoried were in poor condition ('Mediocre' or 'Critical'). Overall, 52% of culverts on private lands were in critical condition compared to 34% on public lands. The defects most frequently observed in poor condition culverts were: obstruction, perforation, and corrosion. Our results indicate that private land tenure and poor road condition are associated with poor culvert condition. However, our results regarding the impact of private land tenure should be interpreted cautiously, as we had a relatively small dataset (n = 121). In sum, previous studies have documented the poor condition of culverts in public forests within Quebec, and our results permit us to extend this observation to what is occurring in private forests, which until now, has been little documented.

We additionally collected data on the number of hanging culverts, as this poses an important threat to aquatic connectivity. Of all the culverts inventoried across both land tenures, 57 % were hanging, with a hang height of 27 cm on average. When crossed with data regarding culvert condition, this resulted in almost a quarter (24%) of all culverts being both hanging and in poor condition. When taking both culvert condition and culvert hang into consideration, this translates to one culvert in every 10.1 kilometres of stream potentially posing a threat to aquatic biodiversity and/or habitat connectivity.

The location, maintenance and repair of culverts must be considered a priority for action, given the scale of the problem in both public and private forests in Quebec. The results of our study highlight the importance of further research regarding the factors which determine culvert condition, as well as the necessity for standardised protocols and continued forestry infrastructure inventories.

Keywords : Culvert, forestry roads, land tenure, aquatic connectivity, infrastructure

CHAPITRE 1

INTRODUCTION

Un important réseau de routes forestières parsème le territoire québécois et différentes études ont montré l'absence d'entretien des routes et traverses de cours d'eau. En forêt publique, le réseau de routes forestières est cartographié et mis à jour par le biais des inventaires écoforestiers. Depuis 1981, il y a eu cinq inventaires écoforestiers, le plus récent ayant été publié en juin 2022. Environ 5000 km de routes forestières sont ajoutés au réseau chaque année (MRNF, 2010), mais les cartes disponibles sont souvent incomplètes ou imprécises (Paradis-Lacombe, 2018). Il s'avère ainsi difficile de dresser un portrait clair du réseau de routes forestières au Québec et cela est d'autant plus vrai dans la forêt privée pour laquelle peu de données sur la voirie forestière sont disponibles.

Outre le manque de données sur la localisation des routes forestières, il n'y a pas d'informations complètes, consolidées et à jour concernant le niveau d'entretien et l'abandon des routes forestières dans les forêts publiques ou privées. L'historique de la réglementation des routes forestières publiques ainsi que la responsabilité d'entretien des routes sont complexes. Lorsque des routes forestières sont construites sur les terres publiques, elles sont ouvertes à l'utilisation publique. Alors que le Règlement sur l'aménagement durable des forêts du domaine de l'État (RADF) encadre la construction des routes forestières en terre publique, il y a peu d'encadrement au niveau de l'entretien lorsque les compagnies forestières y cessent leurs activités (Jutras, 2022). En terre privée, il n'existe généralement aucune réglementation pour l'entretien des routes forestières, mais il existe des guides de bonnes pratiques qui conseillent un entretien régulier des routes et des ponceaux (FDPFQ, 2022; Trottier, 2021). Pour encourager de telles pratiques, il existe un remboursement des taxes foncières des producteurs forestiers, mais les coûts et exigences associés peuvent s'avérer dissuasifs pour certains gestionnaires forestiers. En théorie, toutes les routes forestières sont soumises aux conditions du Règlement sur l'encadrement d'activités en fonction de leur impact sur l'environnement, qui a été mis en place par la Loi sur la qualité de l'environnement (LQE). Cependant, dans la pratique, lorsque des plaintes ont été déposées concernant le mauvais entretien des routes forestières, elles ont été souvent largement ignorées (Plamondon Lalancelette et Movilla, 2022).

Une étude de 2018 évaluant 528 km de routes forestières sous tenure publique a révélé qu'une partie importante des routes forestières et des ponceaux étaient en mauvais état (Paradis-Lacombe, 2018). Les jonctions où les routes forestières traversent les cours d'eau constituent un point d'entrée direct pour des sédiments dans le système aquatique et ont été identifiées comme des sources problématiques d'érosion et de sédimentation accrues (Lane et Sheridan, 2002). Pour réduire cet impact, les routes forestières sont initialement construites avec des infrastructures (ex., ponceaux, des fossés de drainage et des digues) pour atténuer l'érosion. Dans certaines régions du Québec, on compte en moyenne quatre ponceaux par kilomètre de cours d'eau (Trottier, 2021).

La dégradation des routes forestières est due à de nombreux facteurs tels que le niveau d'entretien, le drainage approprié, et la pente (Dobias, 2004; Ryan et al, 2004; Girardin et al, 2022). Sans entretien régulier, les routes forestières et les ponceaux peuvent devenir des causes importantes de dépôt de sédiments dans les cours d'eau environnants (Elliot et al, 1996). Le manque d'entretien des routes entraîne une détérioration et une efficacité compromise de ces infrastructures. Les dépressions de la surface des routes, lorsqu'elles ne sont pas nivelées, peuvent exacerber l'érosion causée par le ruissellement de surface (Dobias, 2004). Le temps écoulé depuis le dernier entretien influence l'état des routes forestières et le niveau de dégradation observé augmente de façon exponentielle lorsqu'au moins cinq années se sont écoulées sans entretien (Girardin et al, 2022). Les routes forestières sans entretien régulier peuvent devenir des sources importantes de dépôt de sédiments dans les cours d'eau environnants. Pour cette raison, l'entretien régulier des routes et des ponceaux est recommandé par de nombreux manuels de saines pratiques (Jetté, 1998; RAPPEL, 2015; FDPFQ, 2022). À titre d'exemple, la revégétalisation d'une surface de route est associée au manque d'entretien ou à l'abandon d'une route (Ryan et al, 2004; Paradis-Lacombe, 2018; Girardin et al, 2022). Cependant, la revégétalisation est également un moyen possible pour atténuer l'érosion. En effet, le couvert végétal permet de réduire l'érosion hydrique et de favoriser la stabilité des sols (Grace, 2000). Ainsi, l'absence de végétation dans les routes fortement utilisés peut conduire à l'érosion de surface et le dépôt de sédiments dans les cours d'eau (Swantson et Swanson, 1976), ce qui a un impact négatif sur la biodiversité et la densité des macroinvertébrés aquatiques, et peut modifier les assemblages des communautés (Chatzinikolaou et al, 2006; Kaller et Hartman, 2004; Couceiro et al, 2010; Wood et Armitage, 1997).

En plus des problématiques de sécurité publique, les routes forestières et ponceaux en mauvais état peuvent également avoir un impact non négligeable sur les écosystèmes environnants. Les ponceaux non entretenus peuvent être enfouis par l'action des castors ou par d'autres débris suivant les crues, se dégrader et devenir des sources de sédiments dans les cours d'eau, perturber les berges et changer le régime d'écoulement de cours d'eau (Elliot et al, 1996; MPO, 2022; Frankiewicz et al, 2021; Vaughan, 2002). Par exemple, les ponceaux présentent une quantité plus importante d'érosion et de sédimentation en comparaison aux ponts (Wellman et al, 2000; Aust et al, 2011). Les sédiments en suspension provenant de l'érosion ont un impact sur les communautés de macroinvertébrés, entraînant une diminution de la richesse taxonomique des espèces sensibles (Angradi, 1999) et une absence d'espèces intolérantes aux sédiments (Wood et Armitage, 1997).

Les ponceaux en mauvais état peuvent aussi entraîner des problèmes de connectivité aquatique (Khan et Colbo, 2008; Maitland et al, 2016; Torterotot et al, 2014; Peterson, 2010). Une traverse en mauvais état peut entraîner un bris de connectivité et une entrave au libre mouvement de l'eau et des organismes (Anderson et al, 2014; Park et al, 2008; Macpherson et al, 2012). L'âge depuis l'installation, une installation inadéquate et l'érosion du lit du substrat du cours d'eau sont des facteurs qui contribuent à la formation de ponceaux suspendus (Park et al, 2008). Les ponceaux suspendus contribuent de manière significative à la fragmentation de l'habitat et aux ruptures de connectivité, car les poissons et autres organismes aquatiques ne peuvent plus se déplacer vers l'amont de ces cours d'eau (Park et al, 2008; Anderson et al, 2014). Les ponceaux obstrués sont également associés à la perte de connectivité génétique (Torterotot et al, 2014). L'impact des traverses sur les populations de poissons (St-Onge et al, 2001) est particulièrement préoccupant au Québec, où la pêche récréative a une contribution économique importante (MPO, 2010). Par exemple, la présence de ponceaux endommagés a été associée à une diminution de la diversité génétique (Torterotot et al, 2014) et des changements de composition dans les communautés de poissons (Maitland et al, 2016).

Malgré ce constat du piètre état de la voirie forestière québécoise et des impacts potentiels sur les écosystèmes aquatiques, les déterminants de l'état des ponceaux demeurent peu documentés et étant donné l'absence d'un recensement précis et à jour des infrastructures routières forestières, une telle information est cruciale pour guider les efforts de restauration. Les objectifs de ce projet de mémoire sont de i) documenter l'état des ponceaux forestiers et les déficiences rencontrées dans les forêts publiques et privées de l'Outaouais et ii) identifier les déterminants de l'état des ponceaux forestiers et plus particulièrement comprendre l'influence de la tenure ainsi que de l'état et le niveau de maintenance des routes adjacentes.

Pour répondre à ces objectifs, cette étude a évalué l’état de 121 ponceaux ainsi que l’état des tronçons de chemins forestiers qui leur sont directement adjacents dans trois bassins versants de troisième ordre de la rivière des Outaouais, dans les régions du Pontiac et de la Petite Nation, dans le sud-ouest du Québec. Les sites ont été choisis dans des forêts privées et publiques, avec environ 60 ponceaux par type de tenure. L'état des ponceaux et des routes a été évalué de « Bon » à « Non fonctionnel ». Les ponceaux ont été évalués à l'aide d'une méthode d'évaluation existante (Paradis-Lacombe, 2018). Un protocole d'évaluation de l'état des routes a été développé, évaluant le type et l'étendue de l'érosion, ainsi que les types de dégradation présents. La revégétalisation de la surface des routes a également été évaluée sur une échelle de 0 % à 100 %, 100 % indiquant une couverture complète.

CHAPITRE 2

CARACTÉRISATION DE L'ÉTAT DES INFRASTRUCTURES ROUTIÈRES DANS LES FORÊTS PUBLIQUES ET PRIVÉES

Dans ce chapitre, nous présenterons un article présentant la méthodologie et résultats du projet qui fait l'objet de ce mémoire. Dans cet article, nous présentons l'état des infrastructures forestières au Québec et le situons dans un contexte international. Nous interprétons et discutons également de nos résultats concernant les facteurs qui influencent l'état des ponceaux, et nous abordons les orientations futures de la recherche. Il est prévu de soumettre l'article pour publication dans un journal révisé par les pairs avec un lectorat international, comme Journal of Environmental Management.

Tragedy of the culverts? Characterizing the state of road infrastructure in public and private forests

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ABSTRACT

Forests in Québec are criss-crossed by a vast road network, which is the result of extractive activity that oftentimes is the first heavily used access into remote environments. Previous studies have shown that this network includes many abandoned roads and deteriorated culverts, which can disrupt aquatic habitat connectivity and impact ecosystem integrity. There is still little known about the drivers of culvert condition. Given the absence of accurate and up-to-date surveys of the forestry road infrastructure, information regarding what is associated with or causes culvert condition is integral in informing restoration efforts. Our study evaluated and compared the condition of 121 culverts and the roads directly adjacent to them in public and private forests in the Outaouais (Quebec, Canada). The majority (63%) of the culverts inventoried were in poor condition ('Mediocre' or 'Critical'). Overall, 52% of culverts on private lands were in critical condition compared to 34% on public lands. The defects most frequently observed in poor condition culverts were: obstruction, perforation, and corrosion. When taking both culvert condition and culvert hang into consideration, this translates to one culvert in every 10.1 kilometres of stream potentially posing a threat to aquatic biodiversity and/or habitat connectivity. Land tenure and road condition were drivers of poor culvert condition. Culverts should be considered an action priority, given the magnitude of their impact on aquatic ecosystems and the dearth of information regarding their location and overall condition. The results of our study highlight the importance of further research regarding the factors which determine culvert condition, as well as the necessity for standardised protocols and continued forestry infrastructure inventories.

HIGHLIGHTS:

- The majority (63%) of culverts assessed along forest roads were in poor condition.
- Land tenure and road condition were drivers of culvert condition.
- Obstruction, perforation, and corrosion were the main defects associated with poor condition culverts.

KEYWORDS : Culvert, forestry road, land tenure, aquatic connectivity, infrastructure

2.1 Introduction

In 1217, Henry the III, King of England, sealed the Charter of the Forest, the lesser-known companion to the Magna Carta. While the Magna Carta primarily enshrined the rights of the wealthier barons, the Charter of the Forest was designed to protect the commoners. Throughout the reigns of Kings Richard and John, commoners witnessed the monarchy gradually encroach upon and privatise their access to forests and other communal lands, which they relied upon for food, fuel, and shelter. The Charter of the Forest's intent was the inauguration of rights safeguarding these commons from monopolisation by the monarchy, ensuring equal and fair access to those who depended upon them. It defined terms for the responsible use and stewardship of public lands and forests for everyone; ''...these liberties of the forest we have granted to all'', it states in the concluding article (Coke, 1680). As united British colonies, the Dominion of Canada was once held to the standard of this preliminary version of land stewardship. Although its original intent and purpose have eroded since its inception, its enduring legacy within colonialist Canada is the creation of public forests, known as Crown land, and the corresponding laws governing their management.

Forests cover 362 million hectares of land in Canada, constituting 9% of all forests worldwide (Ministry of Natural Resources, 2022). Canada represents its ownership of 90.1% of these forests as public; of this, 88.4% of forests are owned by the provinces and territories, and 1.7% are federally-owned[1]. The remaining 6.7% of forests are privately-owned, and 2.1% are Indigenous-owned (Government of Canada, 2022). Within the province of Quebec, 92% of the forests are public and managed by the provincial government (MRNF, 2024). Schlager and Ostrom (1992), and DiGiano et al (2013) have previously differentiated between public and private tenure in terms of which body (public or private) upholds the rights within a forest. The rights can be divided into the right to control access and use of the land, resource management, and the right to sell or lease the resource, access, or management. This definition is applicable throughout Quebec, wherein these rights are either controlled by a municipal, provincial, or federal government (public), or a forestry company or individual (private).

Although all public forests are subject to the same regulation regarding management (MFFP, 2017), different types of land use influence harvesting practices, infrastructure maintenance and access, and long-term management goals. Controlled Harvesting Zones (CHZ), outfitters, wildlife reserves, and unorganised territories are four primary types of land use in public forests. In Controlled Harvesting Zones, the access and activities are managed by a non-profit organisation, whereas outfitters are private companies which have exclusive rights to the hunting and fishing management of public lands. Wildlife reserves are public lands managed by the provincial Ministry of Environment. Unorganised territories are public lands where there is no specific land manager, although sometimes specific land use is in part managed by the regional county municipalities. There is active forest management within all public forests, which falls under provincial jurisdiction. Private forestry lots are owned and managed

[1] Currently, there are multiple land claims, treaties, and ancestral right disputes between Canada and several Indigenous and Métis nations. Matters of this nature are beyond the purview of this article, and the expertise of its authors. As such, when we make reference to land ownership in terms of 'public' or 'private', we are referring solely to how its ownership is represented by the Canadian government. This is not to be interpreted as an erasure of these disputes.

by large-scale forestry companies, smaller operations, or individuals. While timber extraction represents a significant proportion of lot use, private forests can also simply be owned by an individual for other purposes, such as recreation. Within Quebec, around 134 000 property owners are responsible for 70 000 km^2 of private forests, accounting for 21% of all timber harvested in Quebec, and revenues of $4.3 billion (Gouvernement du Québec, 2024; FDPFQ, 2020). Although timber harvest and infrastructure are controlled by the private lot owners, it is still subject to certain provincial rules and regulations that also oversee management within public forests. Previous studies focused on public forests have demonstrated that the level of forestry infrastructure degradation varies depending on type of land use, with marked differences in the condition of road and water crossings found in CHZs, outfitters, and wildlife reserves (Paradis-Lacombe, 2018).

Canada is the country with the largest net benefit as a result of forestry trade (Government of Canada, 2022), and is the second-largest exporter of forestry products (Government of Canada, 2020). Within Canada, Quebec is the second-largest employer in the industry, representing 27.8% of all total hires within forestry and logging (LMAD, 2023). The forestry and logging industry relies on building extensive road infrastructure within the forests themselves, for timber harvest and transport to processing facilities. In the province of Quebec, there are over 476 700 kilometres of public logging roads mapped, a distance which exceeds that between the earth and our moon. As they have never been fully mapped or quantified, the estimated distance portraying the amplitude of private forestry roads networks within Quebec remains unknown. Forests in southern Quebec are traversed by many permanent and ephemeral streams, and watersheds typically have a high drainage density (0.3-0.5 km^2; Assani et al, 2021). As a result, forest roads involve many stream crossings. It is estimated that on logging roads in certain regions of Quebec, there is an average of four culverts per kilometre of stream (Trottier, 2021).

Logging roads in public forests, once built, are open to multiple users. While there is considerable oversight governing their construction, there is scant legislation regarding their upkeep once forestry companies have ceased their operations (Jutras, 2022). On private land, there are no regulations governing logging road maintenance. Forestry infrastructure maintenance in private forests is encouraged by best management manuals targeted to lot owners (AFBF, 2021; FDPFQ, 2022), and incentivized through property tax reimbursements. In theory, all logging roads in both public and private forests are subject to the conditions of the *Regulation respecting the regulatory scheme applying to activities on the basis of their environmental impact*. However, in practice, when complaints have been lodged about poor forest road maintenance, they have been largely ignored (Plamondon Lalancelette and Movilla, 2022).

Despite this vast network's importance, we have little information on the size, condition, or maintenance level of at least 42% of the roads (Delisle, 2021), and no compiled data regarding the location or state of culverts. The lack of information is also significant on private lands, where there is no compiled information on the construction, condition or location of culverts and forestry roads. This represents a significant gap in our knowledge of public and private logging road networks. Over the past five years, efforts have been made to build a base of information about the forest road network in Quebec. A 2018 study assessing 528 km of roads and culverts in public forests revealed a concerning proportion of them were infrequently maintained and abandoned (Paradis-Lacombe, 2018). There have been no previous studies with compiled data regarding the number, condition, or location of culverts in private forests in the province.

In addition to creating public safety hazards, logging roads and culverts in poor condition have negative repercussions on surrounding aquatic ecosystems (Bérubé et al, 2010). The existence of logging roads is predicated on being the first means of high volume access to previously remote ecosystems, with the associated environmental repercussions (Daigle, 2010). Even those in good condition can negatively impact aquatic and terrestrial wildlife and habitat (Robinson et al, 2010). Lack of maintenance leads to road deterioration and can compromise the effectiveness of infrastructures. A study published in 2022 on 103.5 km of forest roads in Quebec revealed that after five years without maintenance, forest road degradation increased exponentially (Girardin et al, 2022). Abandoned roads, or those wherein a significant amount of time has passed since last maintenance, are generally associated with a high level of surface revegetation (Ryan et al, 2004; Paradis-Lacombe, 2018; Girardin et al, 2022). The absence of vegetation on heavily used roads can lead to surface erosion and sediment deposition in waterways (Swantson and Swanson, 1976). Unlevelled surface depressions can exacerbate erosion caused by runoff (Dobias, 2004). In extreme cases, erosion can create deep gullies several metres deep and long which can join hydrological systems and become major sources of sediment (Jetté et al, 1998). Increased erosion and sedimentation due to unmaintained roads can lead to a decline in water quality (Kidd et al, 2014), which in turn impact aquatic communities. High levels of suspended sediment due to erosion lead to a reduction in the taxonomic richness of sensitive species (Angradi, 1999) and an absence of sediment-intolerant species (Wood and Armitage, 1997).

When considering infrastructure impacts on aquatic ecosystems, culverts are of particular concern, given that they are often direct entry-points for pollutants and sediments in waterways (Vaughan, 2002). Culverts can be problematic sources of increased erosion and sedimentation (Lane and Sheridan, 2002), especially when unmaintained (Elliot et al, 1996). Culverts which are neglected or abandoned can become blocked by beavers or other debris, alter channel size and streamflow, and exacerbate retaining bank erosion and sedimentation (Langill and Zamora, 2002; FOC, 2015). Blocked or hanging culverts can obstruct waterflow and impede aquatic organism movement, leading to reduced genetic diversity, habitat fragmentation, and changes in community composition (Anderson et al, 2014; Park et al, 2008; Macpherson et al, 2012; Torterotot et al, 2014; Maitland et al, 2016). Poorly-installed and unmaintained culverts can also disrupt fish migratory routes (Makrakis et al, 2012). Despite the significant ecological risk created by poorly-maintained culverts, we still lack a standardised protocol which assesses the state of culverts by clearly identifying the defects leading to their deteriorated condition.

Within Canada, climate change and continued warming are predicted to impact and modify the flow regime. Streams in southern Quebec are projected to have increased mean annual streamflow (Guay et al, 2015; Nalley et al, 2012; Assani et al, 2012) and increased extreme precipitation events (Zhang et al, 2019). Increased streamflow can compromise the structural integrity of the culvert or alter geomorphic processes in streams, especially for culverts with reduced drainage area due to deformation or obstructions (Frankiewicz et al, 2021). Given this expected increase in extreme precipitation events, climate change could exacerbate the deterioration of culverts and thus their efficiency. Presently, we do not have clear information about either the number and condition of roads and culverts within the forestry network, or the circumstances that favour preservation of good condition in some, and deterioration into poor condition of others. Within the Ottawa River Watershed in southern Quebec and Ontario, the lack of data on connectivity barriers presented by stream crossings and culverts has been identified as a major gap (Ottawa Riverkeeper, 2019). Previous forestry network management recommendations have emphasised the importance of taking a structured assessment approach, informed by field visits, and with follow-up monitoring (Daigle 2010). The objectives of this study were to: i) assess and develop standardised protocols to determine culvert and road condition, and precisely identify defects leading to poor condition and, ii) identify drivers of poor culvert condition including land tenure, neighbouring road condition and their maintenance level. This knowledge can help decision-makers take informed and effective preventative actions to mitigate the impact of forestry infrastructure on public safety and the surrounding aquatic ecosystem.

2.2 Methods

2.2.1 Study area

Study sites were located in three third Strahler order catchments of the Ottawa River in the southwestern portion of the province of Quebec: the Petite Nation River (2250 km^2; N 45°59'13.55, W 75°4'33.24), the Saumon River (also called Kinonge River, 280 km^2; N 45°44'53.62, W 74°50'08.7) and the Noire River (2645 km^2; N 46°20'33.93, W 77°6'16.30). Catchments were selected on the basis of the presence of private and public lands, as well as the presence of Controlled Harvesting Zones (CHZ), outfitters, wildlife reserves, and unorganised territory on public lands. In all three catchments, the surface deposit is largely uniform till glacial deposit and forests are the dominant land cover type (OBV RPNS, 2013; Government of Canada, 2019; MRNF 2023). Over the study area, the climate is classified as Dfb according to the Köppen-Geiger classification (Beck et al, 2018), with a humid continental climate with warm summers and year-round precipitation. Mean annual air temperature was 4.5 °C and mean annual precipitation was 901 mm at the Noire river catchment and 1054 mm at the Petite Nation and Saumon river catchments (1981-2010, McKenney et al, 2011).

2.2.2 Site selection

Within each of the three studied catchments, we selected subwatersheds where we performed a systematic assessment of culvert condition at all potential locations, that is all intersections between roads and streams. The number of subwatersheds was chosen in order to reach the targeted number of culverts, that is ~60 culverts per land tenure type (private and public). The subwatersheds selected from the Petite Nation River watershed were: Ernest (166 km^2), Preston (237 km^2), Doré (27 km^2), and Rouge (528 km^2). Due to the smaller relative size of the Saumon watershed, we selected the watershed in its entirety (281 km^2). The subwatersheds selected in the Noire River watershed were: Chanceux (131 km^2), McGillivray (165 km^2), and a small unnamed watershed directly adjacent to McGillivray (14 km^2) (Fig. 2.1). Within each subwatershed, we selected permanent streams with a drainage area ranging from 0.7 to 10.0 km^2 from the LiDAR-derived dataset of potential waterways (MRNF, 2020). The selection of the 0.7 km^2 threshold was informed by on-site assessments, which determined that this size represented a permanent stream likely to require infrastructural water crossings. The upper limit of 10 km^2 was chosen to ensure a sufficient number of intersections with forestry roads while maintaining a focus on smaller streams. Using these filters, the total kilometres of permanent stream within each subwatershed is as follows: 191.1 km in Saumon; 356 km in Rouge; 13.5 km in Doré; 84.1 km in Ernest; 114.5 km in Preston; 79.2 km in Chanceux; 75.4 km in McGillivray; and 10.9 km in the small unnamed watershed directly adjacent to McGillivray. Additionally, we selected forestry roads classified as passable by vehicles (classes 2, 3, 4, 5) as well as those considered Unclassed and Unknown using the AQRéseau+ dataset (MRNF, 2018), which inventories roads on public lands. Roads classified as Non-Standard and 1 have larger widths (>8.5m) and did not appear within our selected sub-watersheds. As the AQRéseau+ dataset is not regularly updated for forestry roads, we additionally selected roads that appeared in the technical and financial activity reports from the years 2013-2020 (MRNF, 2023). Forestry roads in the private sector that did not appear in the AQRéseau+ dataset were located using maps provided by the lot owners. Using these datasets, we identified all potential culvert sites by intersecting selected forestry roads and potential waterways.

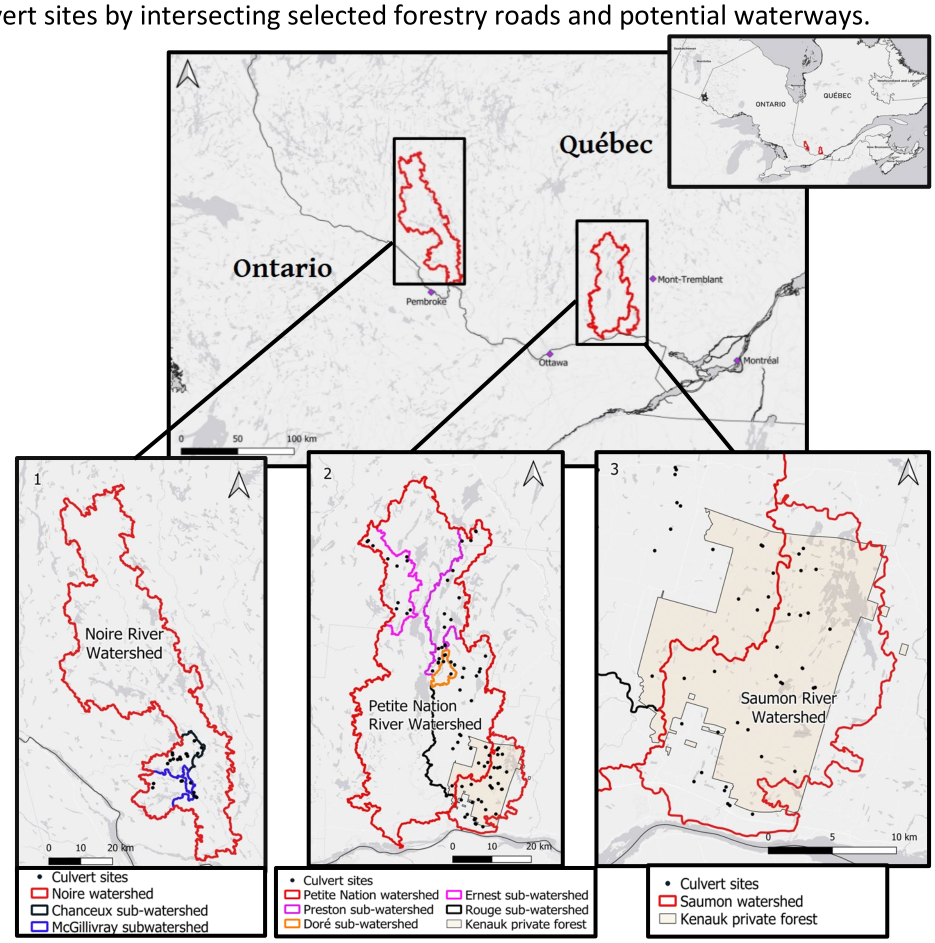

FIGURE 2.1: A) GENERAL LOCATION OF THE THREE CATCHMENTS WHERE CULVERT CONDITION WAS ASSESSED: B) NOIRE RIVER C) PETITE NATION RIVER D) SAUMON RIVER

Over the course of June-September 2022, and July 2023, potential culvert sites were visited and evaluated. Sites were considered ineligible and excluded if they were inaccessible, the watercourse was dried up, or if the watercourse in upstream and downstream direction was a marsh, lake, or pond. Culverts with dried up watercourses or where the watercourse was a marsh or lake were excluded because the culverts would not have been subject to the stressor of continuous water running through the conduit. Accessibility was defined as less than a 2 km hike-in, and without evident safety concerns. Of the potential culvert sites that were identified using geospatial datasets and that met our criteria in terms of being accessible and a culvert for a river or stream, we evaluated 98% and 100% of all eligible sites under public tenure within selected Petite Nation and Saumon catchments, respectively. In the Noire River catchments, 82% of eligible sites were assessed in the Chanceux sub-watersheds and 57% in the McGillivray and the adjacent unnamed sub-watershed. Fewer eligible sites were visited in the McGillivray sub-watershed due to the closing of forestry roads caused by the forest fires in the summer of 2023.

Sites located on private land required property owner consent for evaluation. We obtained consent to evaluate sites on Kenauk Nature, which is a 265 km^2 mixed-use private reserve, in the Saumon and Petite Nation catchments. It is under unified management, and sites found within the reserve share management practices. This differs from sites located in private forests under varied management, where for the most part, each culvert site corresponds to an independent management practice. Private property owners from sites other than within Kenauk Nature were located either through the municipal land registry or through in-person consultation. As a result, sites within the private forests were selected in a semi-random fashion, given that we were unable to obtain consent for certain sites.

2.2.3 Culvert condition evaluation

Culverts were evaluated in terms of their degradation condition and physical characteristics. In terms of physical characteristics, we assessed the number of conduits, their height, width and length and the construction material (metal, corrugated metal, plastic, corrugated plastic, concrete, wood). We also noted the condition, material, and height of the embankment. Data regarding hanging culverts was collected by noting the presence and height of a waterfall in the downstream conduit outlet. Table S1 outlines the data collected regarding the physical characteristics of the culvert. The level of degradation and overall condition of culverts were determined using a slightly modified protocol developed by Paradis-

Lacombe (2018). In the original protocol, the category of 'Structural separation' referred only to culverts where there were two conduits, whereas our protocol expanded this defect to include culverts with single conduits with disconnected sections. Using the modified protocol, the overall condition was determined based on the type and extent of each defect observed. Possible defect categories were: lengthwise pipe deformation; pipe deformation resulting in extremity deformation; pipe flattening or ovalisation; presence of corrosion, rust, abrasion; presence of perforation or cracking; structural separation with a disconnection between pipe sections; wood rot; fallen logs when culverts are made up of wood material; and obstruction causing a reduction of the drainage surface area and blockage within the pipe. Each category was given a grade of: 'Good', 'Acceptable', 'Mediocre', 'Critical', or 'Non-functional' based on criteria in Table 2.1. The overall condition of the culvert was determined based on the lowest grade received among all observed defects. For example, if a culvert received a grade of 'Acceptable' for the defect categories of 'Pipe deformation: Lengthwise', 'Pipe deformation: Extremity', 'Pipe flattening/ovalisation', and 'Corrosion/rust/abrasion'; a grade of 'Good' for 'Perforation or cracking' and 'Structural separation'; a grade of 'Mediocre' for 'Wood rot' and 'Fallen logs'; and a grade of 'Critical' for 'Obstruction'; the overall condition of the culvert is considered 'Critical', despite the majority of the defects being graded 'Acceptable'.

When exploring the data related to culvert defect distribution, we merged defect categories 'Deformation lengthwise' and 'Deformation at extremity' (as defined in Table 2.1) into 'Pipe deformation' due to their common impact on pipe deformations. We equally grouped the categories of 'Wood rot' and 'Fallen logs' into 'Wood degradation', due to their common impact on wood structure integrity. When exploring the data related to defects determining overall culvert condition, a defect occurrence determining overall condition was counted when a culvert received a mark in that category which corresponded to its overall condition category, as outlined in Table 2.1.

TABLE 2.1 CRITERIA TO ASSESS CULVERT DEFECTS AND TO DETERMINE OVERALL CULVERT CONDITION. THE PROTOCOL WAS ADAPTED FROM PARADIS-LACOMBE (2018)

Defect	Good	Acceptable	Mediocre	Critical	Non-functional
Pipe deformation: Lengthwise	No defect noted.	The pipe has a lengthwise deformation, but this does not cause a deformation or blockage at either extremity.	The pipe has a significant lengthwise deformation which causes a deformation at either extremity, decreasing the drainage area.	The pipe has a major lengthwise deformation which causes a deformation at either extremity, leading to perforation or cracking.	The culvert is in a severely degraded condition, such that the primary causes of degradation are not always identifiable. In certain cases, the cause of this degradation is related to the natural environment (ie: beaver dam blockage), and not the degradation of the culvert structure.
Pipe deformation: Extremity	No defect noted.	The pipe has one or several small bumps, but these do not decrease the drainage area by more than 10%.	The pipe has one or several bumps which decreases its drainage area by between 11-25%.	The pipe has one or several bumps which decrease its drainage area by over 26%.	
Pipe flattening/ ovalisation	No defect noted.	The pipe is ovalised, but this does not reduce its drainage area by more than 10%.	The pipe is ovalised, which decreases its drainage area by 11-25%.	The pipe is ovalised, which decreases its drainage area by over 26%.	
Corrosion/rust/abrasion	No defect noted.	The pipe is rusted or has abrasion, but it is not punctured.	The pipe has significant signs of rust or abrasion, and is punctured in one contained area.	The pipe has severe signs of rust or abrasion. It is punctured in several areas, which spread over a significant surface area.	
Perforation or cracking	No defect noted.	N/A	The pipe has one or several small cracks or perforations, which are not large enough for embankment material to seep into the culvert.	The pipe has one or several large cracks or perforations, which could lead to embankment material seeping into the culvert.	

Structural separation	No defect noted.	N/A	N/A	Culvert and pipe sections are disconnected. There is a seepage of embankment material into the culvert, or water seepage into the foundation.	
Wood rot	No defect noted.	Some pieces of wood are rotted in a small and contained area. This rot does not	One or several pieces of wood are significantly rotted, which impacts the structural integrity.	Most of the pieces of wood are heavily rotted, some of which are broken, significantly impacting the structural integrity.	
Fallen logs (only applicable for culverts made up of wood material)	No defect noted.	N/A	One or several logs constituting the culvert have fallen at either end of the pipe extremity.	One or several logs constituting the culvert have fallen at the extremity or inside of the culvert, causing seepage of embankment material into the culvert, or blocking the drainage area.	
Obstruction	No defect noted.	Blockage of less than 15% of the diameter of the pipe. Type of blockage include: substrate, organic material, rocks, beaver dam.	Blockage of 16-25% of the diameter of the pipe. Type of blockage include: substrate, organic material, rocks, beaver dam.	Blockage of over 26% of the diameter of the pipe. Type of blockage include: substrate, organic material, rocks, beaver dam.	

2.2.4 Road condition evaluation

We evaluated road conditions over a 20-metre road section on either side of the culvert, for a total section of 40 metres. Measurements were taken in five locations: at the 20-metre extremity on either side of the culvert, at a 10-metre mark on either side of the culvert, and directly above the culvert. In terms of physical characteristics, we assessed road surface type (gravel, earth, sand, mixture of gravel and earth, other), width of running lane and right-of-way (m), slope (%), presence of drainage ditches and additional infrastructure, and whether or not the vegetation on the shoulders and embankments of the right-of-way was cleared. On a forestry road, the 'running-lane' is the centre of the road where vehicles pass, while the 'right-of-way' includes the running-lane, shoulders, embankments, and ditches.

The level of degradation and overall condition of roads was determined based on the type and extent of each defect observed. Possible defect categories were: erosion on the running lane in a transversal or longitudinal direction, erosion on right-of-way and presence and types of road degradation such as pot-holes, ruts, furrows, erosion, sub-grade emergence, wash-boarding, and partial or complete road collapse. Table S2 describes each type of road degradation which were defined according to Girardin et al (2022), Paradis-Lacombe (2018), and OBVMR (2020). When evaluating overall road condition, each defect category was given a grade of 'Good', 'Acceptable', 'Mediocre', 'Critical', or 'Non-functional' based on criteria in Table 2.2. The overall condition of the road was determined based on the defect category in which it had the majority of characteristics. In cases of an equal distribution of grading, the median category was chosen. For example, if two defect categories were graded 'Good' while two other defect categories were graded 'Mediocre', the overall road condition was 'Acceptable'. If two possible medians existed, the worst one was selected. For example, if two defect categories were graded 'Good' while two other defect categories were graded 'Critical', the overall road condition was 'Mediocre'. If the defect category of 'Number and types of road degradation' was graded 'Critical' or 'Non-functional', the overall road condition was determined solely on these categories as this defect leads to potential or complete road failure. The defect category 'Erosion on right-of-way, excluding running lane' was graded less severely than defects on the running lane because running lane erosion significantly hinders road usability for vehicles, while erosion outside it does not directly impede vehicle use. Unlike our methodology to assess overall culvert condition, the overall road condition was determined by its grading in the majority of defect categories rather than the worst category because, except for defects causing partial or complete road collapse, no single defect category can render the road completely unusable.

TABLE 2.2 CRITERIA TO ASSESS ROAD DEFECTS AND TO DETERMINE OVERALL ROAD CONDITION, BASED ON TYPE AND EXTENT OF DEFECTS PRESENT

Defect	Good	Acceptable	Mediocre	Critical	Non-functional
Erosion on running lane in transversal direction	No erosion	Presence of light erosion	Presence of moderate erosion	Presence of heavy erosion	N/A
Erosion on running lane in longitudinal direction	No erosion	Presence of light erosion	Presence of moderate erosion	Presence of heavy erosion	N/A
Erosion on right-of-way, excluding running lane	No erosion; or light erosion	Presence of moderate erosion	Presence of heavy erosion	N/A	N/A
Number and type of degradation	No degradation type noted	Up to two degradation types noted	Three degradation types noted	Degradation that leads to a partial road collapse or failure	Degradation that leads to a complete road collapse or failure

2.2.5 Road maintenance level

Running lane revegetation was used as a proxy for the level of maintenance of the road (Ryan et al, 2004; Paradis-Lacombe, 2018; Girardin et al, 2022). We used a modified version of the protocol developed by Girardin et al (2022) to quantify the percentage of running lane revegetation (PRLR, equation 1). In this protocol, initial running lane width (IRLW) corresponds to the width of the running lane at the time of construction, and current running lane width (CRLW) corresponds to the width of the running lane without any woody or herbaceous vegetation ≥ 5 cm. The general type of vegetation (small herbaceous, shrubs or saplings, trees) was noted. We modified the Girardin et al (2022) protocol to perform an additional measurement of the vegetation in the middle of the running lane when calculating the current running lane surface width. Running lane revegetation was measured at five equidistant locations within the 40-meter section of road evaluation and the final value of a site corresponds to the average of the five values.

$$PRLR = [(IRLW - CRLW)/IRLW] * 100 \quad \textbf{(1)}$$

2.2.6 Statistical analyses

Using package 'ordinal' (v. 2023.12-4; Christensen, 2023) in R, a cumulative link model was constructed with the categorical ordinal response variable of *Overall culvert condition* (ordinal categorical with three levels), with the explanatory variables of *Overall road condition* (ordinal categorical with five levels), *Land tenure* (categorical discrete with two levels, private or public), and *Running lane re-vegetation percentage* (continuous numeric). In the model, we merged categories 'Good' and 'Acceptable' as well as categories 'Critical', and 'Non-functional' to describe *Overall culvert condition* to facilitate analysis and interpretation.

2.3 Results

2.3.1 Characteristics of culverts

We assessed the state of 121 culverts: 59 culverts were located in public lands, and 62 were in private lands (32 in Kenauk Nature private forest and 30 in private forests under varied management; Fig. 2.2). Public lands have diversified management, which we were able to capture in our distribution of culverts evaluated within these varied land use types (Fig. 2.2). In terms of distribution throughout watersheds, 34 culverts were within the Saumon River catchment, 65 culverts within the Petite Nation River catchment, and 22 culverts within the Noire River catchment. Culverts assessed were between 25-270 cm in diameter and 25-243 cm in height, with an average of 106 cm for diameter, and 104 cm for height. The length ranged between 2.80 m and 23.1 m, with an average of 8.8 m. Culvert conduit material was distributed as follows: 67 of corrugated metal, 32 of corrugated plastic, 1 of smooth metal, 6 of wood, 7 of concrete, and 8 of mixed materials (any two or more of the materials outlined above). Within the three studied catchments, a total of 45 culverts were found in 'Acceptable' condition, 24 in 'Mediocre' condition, and 52 in 'Critical' condition. In terms of proportion, the three catchments had similar distributions of culvert conditions. We found little difference in the proportion of sites within each overall culvert condition category between those sites found under various landowners, and the sites found within Kenauk Nature private forest. The largest discrepancy occurred within the category of culverts found 'Acceptable', where there were proportionally 11% more culverts in 'Acceptable' condition in sites under private tenure managed by

Kenauk Nature as compared to the sites under private tenure managed by other property owners (Table S3). As such, we did not make a distinction between sites under sole (Kenauk Nature) vs varied management, and land tenure for all these sites was simply defined as private.

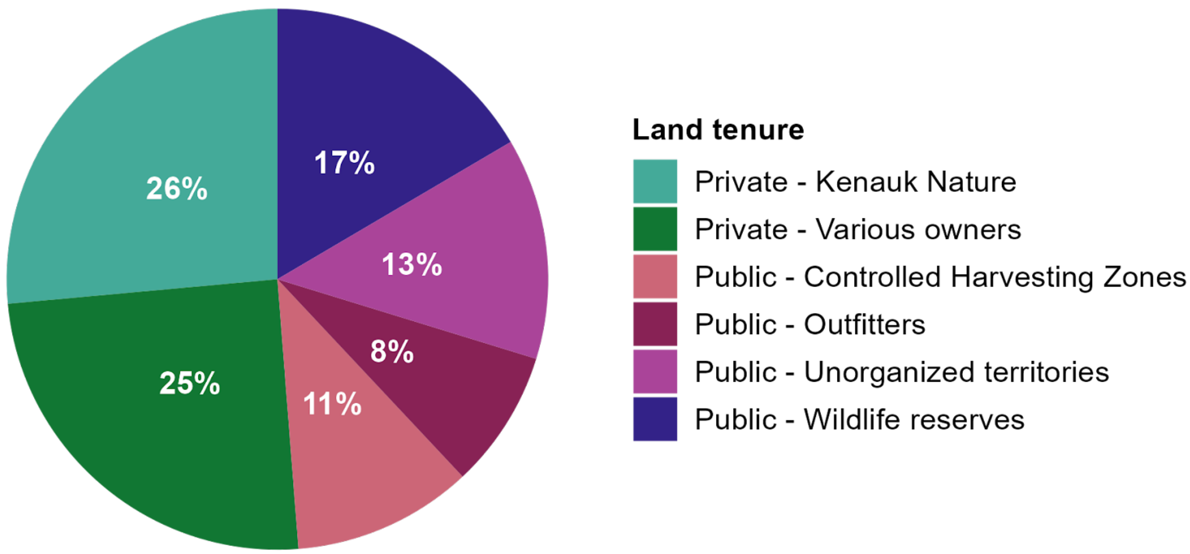

FIGURE 2.2 THE DISTRIBUTION OF THE EVALUATED CULVERT SITES IN TERMS OF LAND TENURE (PRIVATE UNDER SOLE MANAGEMENT OF KENAUK NATURE; PRIVATE UNDER VARIOUS LAND MANAGERS; PUBLIC MANAGED BY OUTFITTERS; PUBLIC UNDER UNORGANISED TERRITORIES CLASSIFICATION; PUBLIC MANAGED BY WILDLIFE RESERVES)

2.3.2 Culvert condition is influenced by road condition and land tenure but not by lane revegetation

We found a positive relationship between road condition and culvert condition (Table 2.3). As the road condition improves and moves from a higher category (ex: Non-functional) to a lower category (ex: Critical), there was corresponding improvement in overall culvert condition. The majority (78%) of culverts associated with non-functional road conditions were in a critical condition and conversely, culverts in acceptable conditions were predominantly associated with roads in good (41%) or acceptable (50%) conditions (Fig. 2.3a). We also found that land tenure significantly influenced the overall condition of culverts, with culverts on public lands more likely to be found in good condition than those found on private lands (Table 2.3). Overall, 52% of culverts on private lands were in critical condition compared to 34% on public lands (Fig. 2.3b), suggesting important issues with culvert maintenance under both land tenures. The percentage of running lane revegetation was not related to culvert condition and was similar for culverts in ‘Critical’ or ‘Acceptable’ condition. In the ‘Mediocre’ culverts, there are three points with high values, which indicate that culverts in this condition could be associated with higher levels of lane revegetation. However, the overall data distribution in Figure 2.4 suggests that culverts in all conditions can be found on roads with varying levels of maintenance, as represented by lane revegetation. This finding is further supported by the fact that in constructing the final model, the variable *Running lane revegetation* contributed little to the explained variance of the model.

We first fitted a model to assess the influence of the three targeted explanatory variables (*Overall road condition*, *Land tenure*, *Running lane revegetation*) on overall culvert condition. However, the condition number of the Hessian (5.3 x 10^4) suggested the model may be ill-fitted, as Christensen (2023) indicated that values should be below 1 x 10^1. Then, we compared the condition number of the Hessian of models when removing one variable at a time from the model and found that only the model with *Land tenur*e and *Overall road condition* as explanatory variables led to an acceptable fit (4.5 x 10^1, Table S4). We performed a likelihood ratio test between the full model (*Overall road condition*, *Land tenure*, *Running lane revegetation*) and a reduced model (*Overall road condition*, *Land tenure*) and found no statistical evidence to include Running lane revegetation in the model (likelihood ratio statistic = 1.59, p-value = 0.21). The final model with the two included explanatory variables is described in Table 2.3.

TABLE 2.3 SUMMARY OF MODEL DESCRIBING OVERALL CULVERT CONDITION AS A FUNCTION OF OVERALL ROAD CONDITION AND LAND TENURE

Variable	Estimate	Standard error	z-value	p-value	Odds ratio	Confidence intervals at 95%
Overall road condition: Linear term	1.57	0.60	2.59	**0.009**	4.82	(0.38; 2.76)
Land tenure: Public	-0.74	0.35	-2.07	**0.038**	0.47	(-1.44; -0.04)

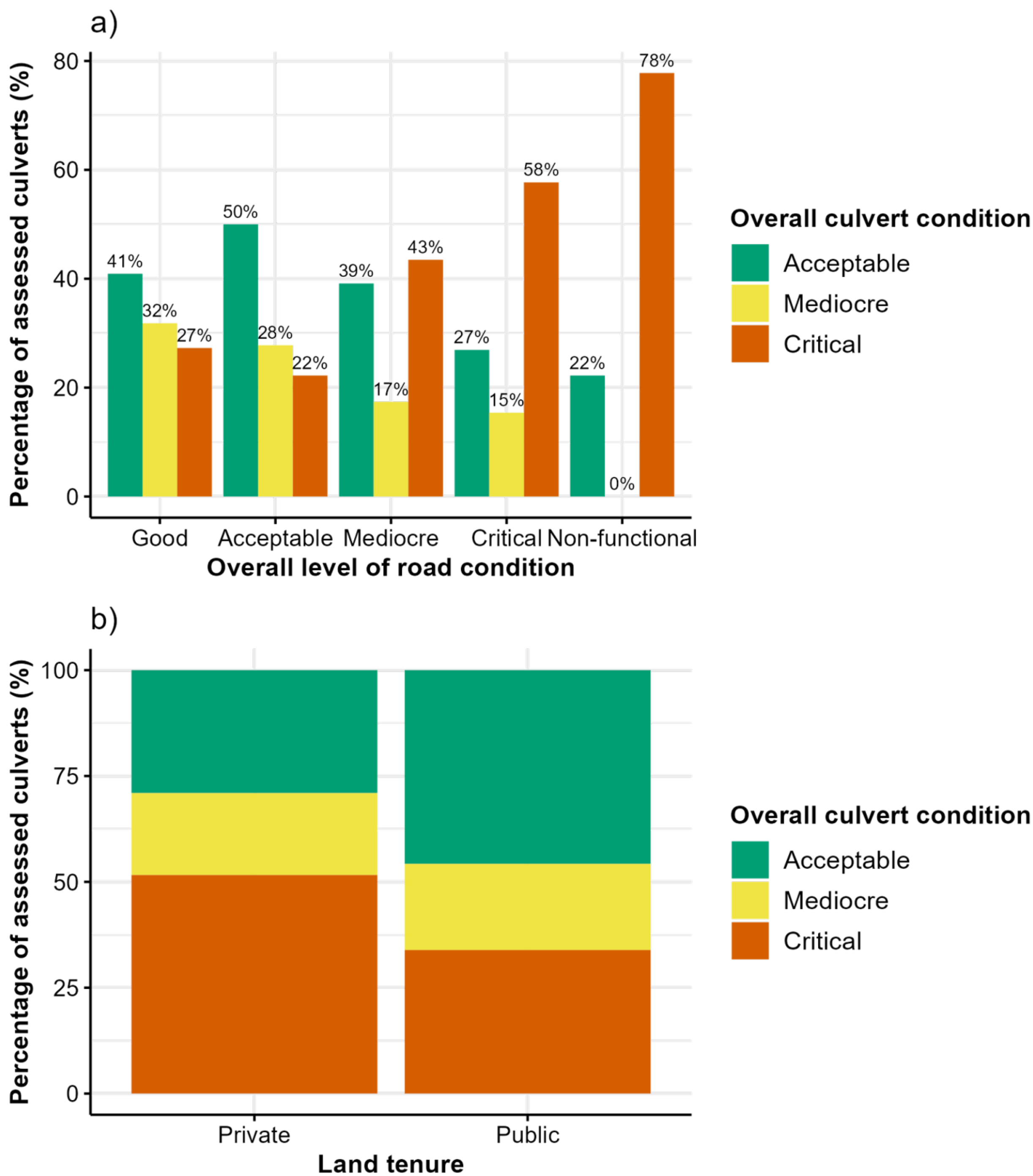

FIGURE 2.3 PROPORTION OF OBSERVED CULVERT CONDITION ('ACCEPTABLE', 'MEDIOCRE', AND 'CRITICAL') FOUND A) WITHIN LAND TENURE TYPE ('PUBLIC', 'PRIVATE') AND B) WITHIN LEVEL OF OVERALL ROAD DEGRADATION ('GOOD', 'ACCEPTABLE', 'MEDIOCRE', 'CRITICAL', 'NON-FUNCTIONAL')

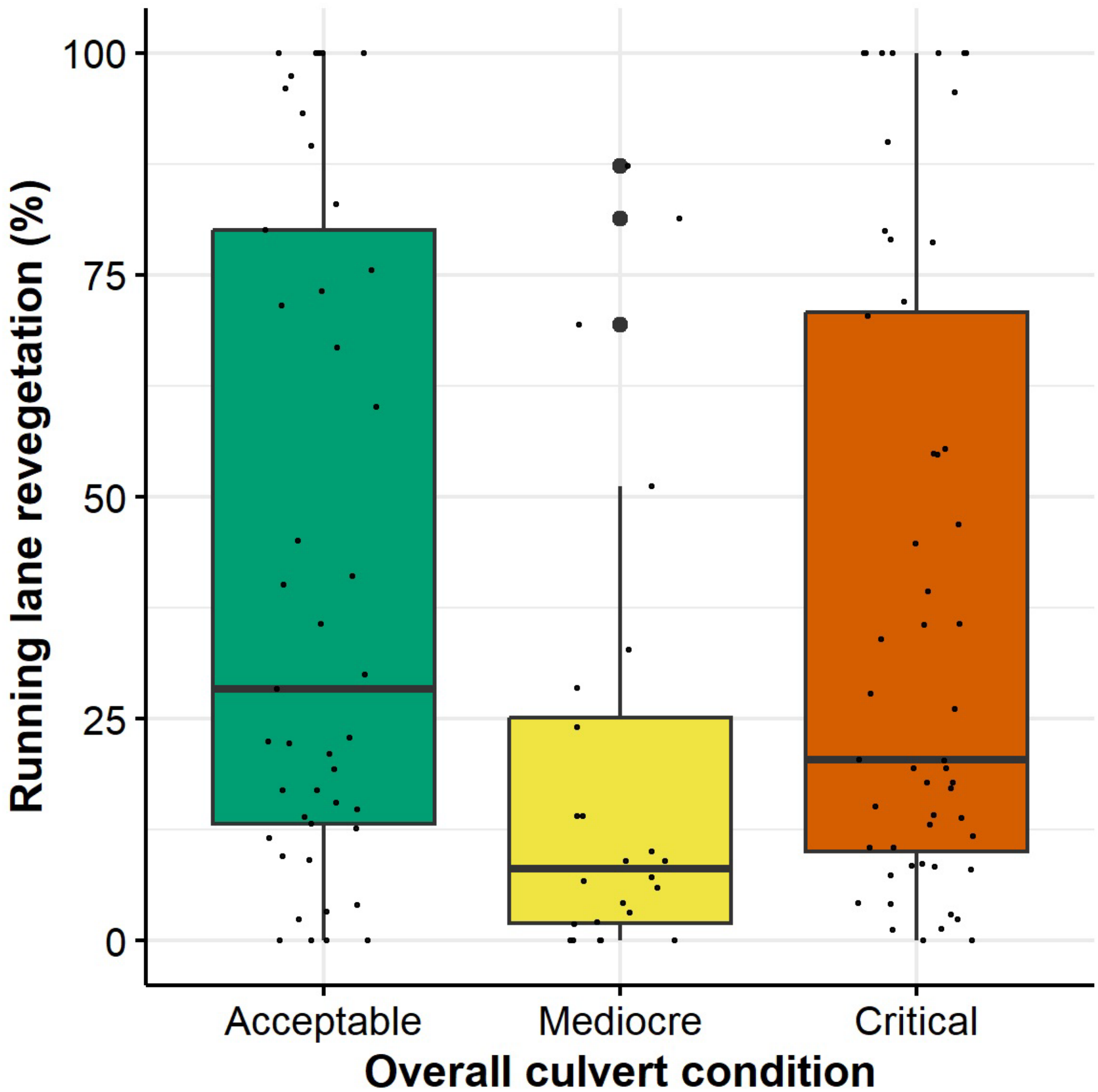

Figure 2.4 Relationship between running lane revegetation percentage and the overall culvert condition (‘Acceptable’, ‘Mediocre’, ‘Critical’)

2.3.3 Defects associated with mediocre and critical condition culverts

Culvert defects which determined overall culvert condition were counted in the ‘Mediocre’ and ‘Critical’ condition categories, across the public and private land tenures (Table 2.4). The top three defects which determined overall culvert condition under both land tenures were ‘Obstruction’, ‘Corrosion’, and ‘Perforation’. In public forests, ‘Wood degradation’ also had an important impact on culvert degradation. For example, ‘Wood degradation’ was observed in equal proportion to ‘Perforation’, both representing

16% of the total defects determining 'Mediocre' culvert condition. For 27% of culverts assessed (n = 33), there was a single defect determinant for overall culvert condition. Under both land tenures, 'Obstruction', 'Corrosion', and 'Perforation' were again the top three sole defects determining culvert condition. 'Obstruction', represented 58% of these cases, while 'Corrosion' and 'Perforation' each represented 18% of these cases. This indicates that, for 16% of the culverts assessed (n = 19), were the defect leading to the 'Obstruction', 'Corrosion', or 'Perforation' classification resolved, the culvert would immediately be reclassified in a better overall condition.

Aside from the overall assessment of culvert condition based on criteria defined in Table 2.1, we found that 57% (n=69) of all culverts had a waterfall in the downstream conduit outlet and would be considered hanging or suspended. The height of the waterfall ranged from 1 to 206 cm, with an average of 27 cm. Of the hanging culverts, 42% (n = 29) were in 'Critical' condition, 41% (n = 28) were in 'Acceptable' condition, and 17% (n = 12) were in 'Mediocre' condition. 58% (n = 40) of the hanging culverts were found in private forests, and 42% (n = 29) were found in public forests.

TABLE 2.4 FREQUENCY AND DISTRIBUTION OF DEFECTS DETERMINING OVERALL CULVERT CONDITION IN 'MEDIOCRE' AND 'CRITICAL' CULVERTS IN PUBLIC AND PRIVATE FORESTS

Forest type	**Culvert state**	**Count of defect occurrence determining overall culvert condition**						
		Obstruction	**Perforation**	**Corrosion**	Pipe deformation	Ovalisation	Wood degradation	Structure separation
Private	Mediocre	15.8%	36.8%	21.1%	10.5%	10.5%	5.3%	0.0%
	Critical	33.7%	19.8%	17.4%	12.8%	8.1%	1.2%	7.0%
Public	Mediocre	31.6%	15.8%	26.3%	10.5%	0.0%	15.8%	0.0%
	Critical	30.2%	15.1%	11.3%	15.1%	9.4%	11.3%	7.6%

2.3.4 Discrepancies between road representation in databases vs field assessments

In our efforts to locate culverts admissible to our study using primarily the GIS road and waterway intersections, we traversed several hundreds of kilometres of forestry roads and hundreds of water-crossings that were not surveyed, due to their not meeting our inclusion requirements. Of the road networks, we documented 60 inconsistencies in road representation in the provincial database of logging road access and condition. Inconsistencies included: the road as mapped is non-existent (n = 12); the road is incorrectly represented in the database, ie: represented as accessible by a car when it is in actuality accessible only by an all-terrain vehicle (n = 40); the road has a degradation which renders it impassable (n = 8).

2.4 Discussion

2.4.1 Culverts are often in poor condition on forestry roads

Although culverts were developed as the infrastructural solution to habitat fragmentation caused by roads, they in turn can jeopardize aquatic connectivity and biodiversity (Frankiewicz et al, 2021; Price et al, 2010; Park et al, 2008; Vaughan, 2002; Kreutzweiser et al, 2013). Our study revealed that the majority (63%) of the culverts inventoried were in poor condition ('Mediocre' or 'Critical'), which could pose a risk to aquatic ecosystem integrity.

In terms of condition, the three most common defects observed in poor-condition culverts ('Obstruction', 'Corrosion', 'Perforation'), can directly impact aquatic connectivity and sediment transport into waterways. First, conduit obstructions are physical barriers which can impede aquatic organisms' migration and movement (Anderson et al, 2014; Park et al, 2008; Makrakis et al, 2012). Increased flow velocity at culvert sites has been shown to reduce aquatic organism movement across the culvert (Warren and Pardew, 1998; Jackson 2003), as well as favour more tolerant invasive species distribution (Foster and Keller, 2011). The existing increase in flow velocity at culvert sites can also be exacerbated by the reduced drainage area caused by partial conduit obstructions. Second, perforations and corrosion are structural defects which cause sediment from the backfill and embankment surrounding the conduit to be deposited into the waterway. Increased fine sediment in the waterways can reduce water quality, rearing habitat, and organism survival (Kidd et al, 2014; Lachance et al, 2008; Honeycutt et al, 2016).

The majority (57%) of inventoried culverts were hanging, with a hang height of 27 cm on average. Hanging culverts can equally compromise the biological integrity of stream ecosystems. The average overhang height found within our dataset exceeds the ≥10 cm threshold for passability by salamanders (Anderson et al, 2014). Previous studies which assessed only the impact of hanging culverts, independent of overall culvert condition, found that watersheds wherein half the culverts were hanging resulted in levels of between 5-20% fragmentation (Park et al, 2008). Overall, our findings were that the largest proportion of culverts were in poor condition, and over half of all culverts were hanging. Almost a quarter (24%) of all culverts were affected twofold, as they were hanging culverts in poor condition. The total length of streams within our selected watersheds which met our size and permanence criteria was 925 km. When considering hanging culverts in 'Acceptable' or 'Mediocre' condition which pose a threat to connectivity via their condition of being hanging (n = 40), and 'Critical' culverts which pose a threat to aquatic integrity through their poor condition (n = 52), this translates to one culvert in every 10.1 kilometres of stream potentially posing a threat to aquatic biodiversity and/or habitat connectivity. This is a conservative estimate of the density of these problematic culverts, given that we were unable to perform a complete survey of the catchments.

Our study reveals a concerning level of infrastructural degradation within our forestry road network, which may have severe repercussions on aquatic ecosystems. This wide-spread infrastructure degradation is consistent with what has been previously observed, both regionally and farther-afield (Paradis-Lacombe, 2018; Girardin et al, 2022; Macpherson et al, 2013; Park et al, 2008; Januchowski-Hartley et al, 2013). Ageing forestry infrastructure will only continue to contribute to habitat fragmentation and degradation. The age of culverts and associated infrastructures would have been an interesting criterion to consider in our analysis and might have explained certain differences in culvert condition. However, given that there is little to no compiled data from standardised surveys on the location or state of culverts within forests in Quebec, this information was unavailable, and we were unable to incorporate it into our analysis. This highlights the need for thorough inventories, additional research into understanding the drivers of poor infrastructure condition, and informed rehabilitation and mitigation strategies.

2.4.2 Overall road condition as a driver of culvert condition

Our two main findings were that overall road condition, as evaluated through the lens of erosion and degradation type, as well as land tenure, were predictors of overall culvert condition. Road surface erosion is a possible explanation for the association between poor road condition and poor culvert condition. As the road deteriorates and surface material is lost, the integrity of the stabilizing material surrounding the culvert is compromised. This leaves the culvert conduit more directly susceptible to environmental stressors, and load from passing vehicles. Our findings also indicated that road surface revegetation, as a proxy for time since last road maintenance, was not a good predictor of overall culvert condition.

Future inventorying efforts can be rendered more efficient given our finding that poor culvert condition is associated with poor road condition. Evaluating culvert condition through field visits can be time-consuming and costly (Hendrickson, et al. 2008, Daigle 2010), and requires practitioners who are familiar with a specialized protocol. Road condition and location can be assessed by remote sensing, with increasingly accurate methodologies (Waga et al, 2020; Morley et al, 2024). While there are gains being made in regard to locating culverts using remote sensing (Lessard et al, 2023), it is still an imprecise process. Given our findings, results from remote-sensing road condition could be used to then inform where the more specialized, costly, and time-consuming culvert evaluation efforts should be concentrated within the road network.

2.4.3 Land tenure as a driver of culvert condition

There are numerous previous studies evaluating land tenure as a driver of forest cover change (Robinson et al, 2013, DiGiano et al, 2013; Paneque-Gálvez et al, 2013). In Central and South America, forests with higher levels of privatized rights correspond to higher rates of deforestation (DiGiano et al, 2013), and loss of old-growth forest (Paneque-Gálvez et al 2013). While many studies have evaluated the impact of land tenure on resource management via canopy cover change, they generally do not address forestry infrastructure management. Overall, infrastructure condition can give us an indication of not only management practices, but how these practices impact the surrounding ecosystem. Our study has contributed to filling this gap in knowledge regarding how different infrastructure management practices, such as land tenure, could have ecological impacts. Our finding regarding culvert condition and land tenure is tempered by our relatively small dataset (n= 121 culverts). Foremost, we can conclude that the ubiquity of culverts in poor condition, their far-reaching impact on the aquatic ecosystem, is not a problem confined to public forests, and is of similar magnitude in public and private lands.

Land tenure is one of the many overlapping and complex mechanisms that impact forest management. Land security, culture, and politico-economic context all influence forest management (Robinson et al 2013; Barsimantov et al 2011; Singleton and Taylor, 1992). Our study only distinguished between 'public' and 'private' land tenure and did not evaluate the influence of land use. Given previous findings that infrastructure condition varied according to land use type on public lands (Paradis-Lacombe, 2018), we believe there is value in further sub-categorizing land use in any future studies evaluating land-tenure as a driver of infrastructure condition. For example, previous studies evaluating forest cover change have included the categories ‘communal’, ‘protected’, and ‘customary’, in addition to ‘public’ and ‘private’ (Robinson et al, 2013; Paneque-Gálvez et al, 2013). Land use distinctions would help parse-out the relative contributions of the mechanisms which impact forest management. In sum, additional research with larger datasets capturing the influence of land use would be required to expand upon our finding of land tenure as a predictor of overall culvert condition.

2.4.4 Addressing defects in poor culvert condition

Standardised protocols are important to facilitate data sharing and analysis, and allow for larger datasets to fill research gaps in future studies. We used a detailed culvert evaluation protocol which assessed characteristics related to both erosion and connectivity impacts. This protocol allowed us to precisely diagnose culvert defects, which can guide rehabilitation and restoration efforts.

We identified the defects most frequently observed in poor condition culverts: obstruction, perforation, and corrosion. Culvert obstructions are not always due to conduit deformation, and as such, can be resolved through removal of the blockage during regular maintenance. Obstructions can be mitigated by installing culverts with a diameter that takes into account increases in flooding events, and peak flow velocity predicted by climate change (Gillespie et al, 2014). Entrance screens can also be used to prevent debris from accumulating within the culvert but require regular maintenance lest they themselves become the obstruction (Streftaris et al, 2013). Corrosion and perforation, which lead to sediment deposition in the waterway, require replacement of the conduit material, or culvert itself (Jutras et al, 2022). Restoration cases which involve culvert replacement are more resource intensive. As such, either upgrading the culvert to address connectivity and flow regime changes, or road decommissioning, should be considered.

Hanging culverts are caused by aging, improper installation, and/or stream bed erosion (Cocchiglia et al, 2012; Park et al, 2008). In these cases, the stream is not properly channelled through the conduit, or the culvert opening is elevated above the stream bed. The evident solutions to hanging culverts are to correctly install passable culverts, with a conduit of appropriate diameter and embedded to the correct depth within the streambed, as well as streambed erosion mitigation measures (Barnard et al, 2013; Bates et al, 2003; Gillespie et al. 2014; Cenderelli et al, 2011). In lieu of replacing the incorrectly-installed culverts, researchers have also proposed species-specific remediation measures, such as adding baffles, providing streambed substrate, or placing mussel spat ropes on the interior of conduits (Anderson et al, 2014; Duguay and Lacey, 2016; David and Hamer, 2012).

In many cases, replacing and upgrading culverts is a necessary, but costly, process. Further, we cannot use a 'one-size-fits-all' approach when addressing connectivity concerns through culvert upgrades, as different target species require specialized solutions (Frankiewicz et al, 2021). This highlights the need for cooperation between conservation organisations and infrastructure management bodies. To more equally distribute the financial burden between conservation organisations and infrastructure management bodies, Neeson, et al (2018) has suggested a strategy of collaboration and cost-sharing. Culverts which have already been flagged as safety hazards would undergo assessment by aquatic connectivity specialists, and the cost of replacing the culvert in poor condition with one that meets connectivity standards would be shared between the conservation and infrastructure management bodies. It should also be noted that while certain upgrades in the short-term are more expensive, they reduce maintenance costs in the long-term (Gillespie et al, 2014).

2.4.5 Mapping forestry infrastructure

The importance of a thorough forestry infrastructure inventory, to inform mitigation and management plans, is a suggested practice regionally, nationally, and internationally (Ottawa Riverkeeper, 2019; CNC, 2021; Mazany-Wright, 2021; Hendrickson, et al, 2008; Januchowski-Hartley et al, 2013). However, a lack of up-to-date inventories and accurate maps of forestry infrastructure is a common problem (Davis et al, 2020; Kantartzis et al, 2021). In public forests in Quebec, the network of forest roads is mapped and updated through forest inventories performed every ~10 years and these data are compiled in a provincial database (AQRéseau+). However, the available maps do not always reflect the reality on the ground. Some roads appear in the first provincial inventories but disappear from later versions. Some roads were never mapped, and others do not appear on the maps because they were too recently built (Paradis-Lacombe, 2018). In private forests, and this information is not publicly available. In total, we assessed the physical characteristics and condition of 121 culverts, as well as the forestry road section adjacent to them. Overall, we documented 60 inconsistencies in representation in the provincial database of forestry road access and condition. While there is extensive work being done regarding remote sensing to identify and assess road condition (Waga et al, 2020; Morley et al, 2024), simply identifying culvert locations via remote-sensing is still imprecise or impossible in certain circumstances (Li et al, 2013; Lessard et al, 2023). Continued in-person field inventories are necessary for identifying culvert location and condition. They also contribute to and correct existing online databases. Additionally, they provide a dataset that can be used in validating remote-sensing culvert detection methodologies. Accurate maps and information regarding infrastructure condition are an essential part of any future studies resulting from our findings that the majority of forestry infrastructure is in poor condition, and poses a threat to aquatic connectivity, biodiversity, and ecosystem integrity.

2.5 Conclusion

Ecologists, land managers, and policy-makers have recognized the importance of collaboration in order to understand the impact of the intensive forestry operations from over the last century, and develop effective restoration and mitigation protocols. Our findings demonstrated that culverts in poor condition are dominant in both private and public forests in southern Quebec (Canada), and that land tenure and road condition are drivers of culvert condition. Culverts should be considered an action priority, given the magnitude of their impact on aquatic ecosystems and the dearth of information regarding their location and overall condition. The identified drivers of culvert condition (i.e. land tenure, road condition) could be used to inform inventory protocols, and avenues for future research into the causes of poor culvert condition.

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CHAPITRE 3

CONCLUSION

3.1 Résumé du travail sur le terrain et des résultats

Au total, nous avons évalué 121 ponceaux et les tronçons de route de 40 mètres qui leur sont directement adjacents. Nos principales conclusions sont que la tenure des terres et l'état de la route sont des facteurs déterminants de l'état global des ponceaux. La revégétalisation de la route, en tant qu'indicateur du temps depuis le dernier entretien de la route, n'était pas un facteur déterminant de l'état des ponceaux. Nous avons également constaté que les ponceaux situés dans les forêts publiques étaient globalement en meilleur état que ceux situés dans les forêts privées. Ce résultat doit être interprété avec précaution car notre ensemble de données était relativement restreint et des études supplémentaires sont nécessaires pour confirmer la relation entre l'état des ponceaux et la tenure des terres. Il faut aussi considérer que les forêts situées dans les bassins versants de nos sites d'étude sont représentatives des régions forestières du sud du Québec avec des tenures mixtes. L'Outaouais est recouvert de 20 % des forêts productives régionales de tenure privées, et se distingue en effet des régions qui sont largement dominées par les terres forestières publiques comme Abitibi-Témiscamingue, Côte-Nord, et Saguenay-Lac-Saint-Jean, qui ne sont couvertes que par 2 à 9 % des forêts productives régionales de tenure privée (FDPFQ, 2023). L'Outaouais est plus semblable à des régions comme les Laurentides et Lanaudière, qui ont 27 % et 24 % des forêts productives régionales de tenure privée, et de nombreux propriétaires privés (FDPFQ, 2023). Somme toute, de précédents travaux (Paradis-Lacombe, 2018) ont permis de documenter le piètre état des ponceaux sur les terres publiques québécoises et les résultats de ce mémoire permettent d'étendre ce constat aux terres privées, qui n'avaient jusqu'à maintenant été peu documentées.

3.2 Développement et mise en oeuvre du protocole d'évaluation de l'état des ponceaux

Lors de l'élaboration de la méthodologie de ce projet, nous avons rencontré de nombreux protocoles d'inventaire et d'évaluation de l'état des routes et des ponceaux en Amérique du Nord. Réconcilier ces différents protocoles s'est avéré un défi, car chaque méthodologie comporte des critères et des définitions spécifiques, qui varient d'un protocole à l'autre. Certains protocoles sur les ponceaux se concentrent sur l'impact sur la connectivité aquatique (Abbott et al, 2019; CNC, 2021), tandis que d'autres se concentrent sur le niveau d’érosion et de sédimentation (Gouvernement de l’Alberta, 2015) ou s'intéresse uniquement à l'état du ponceau du point de vue de la sécurité publique pour les usagers de la route. Ce manque de standardisation entre les protocoles empêche de regrouper et d’analyser facilement les données, et la standardisation dans la méthode de caractérisation de l’état des ponceaux est une recommandation de plusieurs organismes (Sentinelle Outaouais, 2019; Mazany-Wright, 2021).

Dans le cadre de nos travaux, nous avons cherché à créer un protocole qui traite des questions de connectivité, d'érosion et d'intégrité structurelle. Notre protocole d'inventaire s'inspire de protocoles régionaux (Latrémouille 2014, OBVMR 2020) et nationaux (CNC 2021) préexistants, et inclut une version de la méthode d'évaluation de l'état des ponceaux suggérée par Paradis-Lacombe (2018). Pour déterminer l'état des routes, nous avons simplifié la méthodologie proposée par Girardin et al. (2022), et ajouté la précision du type et de l'étendue de l'érosion, comme le proposent l'OBVMR (2022) et Latrémouille (2014). Notre protocole était réalisable par une seule personne et ne nécessite pas d'équipement spécialisé. De plus, nos protocoles ne sont pas basés sur des normes réglementaires et peuvent donc être utilisés dans une variété de contextes. Notre protocole pourrait être utilisé dans n'importe quelle région où les conditions environnementales et les facteurs de stress sont semblables à ceux des forêts tempérées du sud du Québec. Un élément qui n'a pas été abordé dans notre protocole est la pente du ponceau. Cette mesure aurait nécessité l'utilisation d'un outil spécialisé (Ziplevel), et il peut être difficile d'obtenir des mesures précises dans les ponceaux bloqués.

3.3 Importance de se rendre sur le terrain pour la collecte des données

Nous avons rencontré plusieurs cas de ponceaux sur des routes qui avaient été abandonnées depuis longtemps, d'après l'étendue et le type de végétation. En raison de la hauteur de la végétation, la localisation de ces routes et des intersections de ponceaux n'aurait pas été possible en utilisant uniquement la télédétection. De nombreux ponceaux persistent bien au-delà de la durée de vie et de l'utilisation des chemins, et restent une menace potentielle pour l'intégrité du système aquatique. Une prospection en personne a été nécessaire pour localiser et identifier les ponceaux sur les chemins abandonnés, et devrait être considérée comme une partie cruciale de tout effort d'inventaire à l'avenir.

3.4 Limites et défis de l'étude

L'une des principales limites de l'étude était l'accès aux lots de forêts privées. Nous avons utilisé plusieurs approches pour tenter de recruter des participants, notamment en contactant les associations de producteurs de forêts privées et le Ministère des Ressources naturelles et des Forêts. Au final, nous avons eu le plus de succès en localisant simplement les lots de forêt privée dans les registres municipaux, et en contactant les propriétaires par téléphone ou par courriel, ou en nous rendant sur place et en demandant la permission en personne. Il convient également de noter que la recherche de ponceaux, en particulier ceux qui se trouvent sur des chemins forestiers abandonnés, peut prendre beaucoup de temps. Au cours de la seule saison 2022, nous avons visité 193 sites potentiels de ponceaux. De ce nombre, seulement 40 % répondaient à nos critères et ont été évalués. Bien que cet effort semble chronophage, les résultats de ce travail significatif sont importants, car ils contribuent à combler le manque d'informations compilées concernant le nombre ou l'emplacement des ponceaux dans les forêts privées ou publiques. Même les informations concernant l'absence de ponceaux aux intersections entre les chemins et les cours d'eau sont importantes, car elles peuvent aider à optimiser les efforts d'inventaire à l'avenir.

3.5 Pistes de recherche pour l'avenir

L'interprétation et la mise en application de nos résultats sont limitées par notre petit jeu de données. De futures études, utilisant un protocole similaire, permettraient de compiler les données entre les études. Nous pourrons tirer des conclusions plus significatives et applicables à partir d'ensembles de données plus importants. Des études antérieures ont démontré que l'état des infrastructures dans les forêts publiques variait en fonction du type d'utilisation des terres (Paradis-Lacombe, 2018). Des ensembles de données plus importants nous permettent également de déterminer si les infrastructures forestières suivent ou non des résultats similaires à ceux observés pour le couvert forestier (Robinson et al, 2013 ; Paneque-Gálvez et al, 2013).

3.6 Collaboration multidisciplinaire

Lorsque des routes forestières sont construites sur les terres publiques, elles sont ouvertes à l'utilisation publique. Par exemple, ils peuvent être réappropriés par d'autres entreprises d'extraction de ressources et utilisés par les membres du public. Pour représenter cela, les routes forestières sont parfois appelées « chemins multiressources ». Outre le partage des données et des protocoles entre les organismes de conservation et les chercheurs en sciences aquatiques, il convient de mettre l'accent sur la collaboration avec les usagers des chemins forestiers. La science suscite de plus en plus de méfiance et de rejet idéologique, ainsi qu'une polarisation scientifique selon des lignes partisanes (Rekker, 2021). La collaboration avec des personnes ne faisant pas partie du milieu universitaire traditionnel peut créer un espace à partir duquel nous pouvons combattre les perceptions erronées et la politisation de la science. Lorsqu'il s'agit de préserver la connectivité aquatique, les usagers des routes forestières pourraient être certains de nos meilleurs alliés. Les chasseurs, les trappeurs, les propriétaires de ZEC et de pourvoiries sont ceux qui connaissent le mieux les réseaux des routes forestières et qui s'investissent dans le maintien d'un écosystème forestier en bonne santé. De plus, l'application de politiques ou d'outils visant à atténuer l'impact de l'utilisation des routes forestières sur l'écosystème environnant nécessitera probablement un changement de paradigme en ce qui concerne l'utilisation des chemins forestiers. Les décisions concernant les tronçons de routes à déclasser ou les changements d'accès aux routes et aux ponceaux ont moins de chances d'être contestées si elles sont élaborées avec les usagers des routes forestières plutôt qu'imposées à ces derniers. La collaboration entre les organismes de conservation et les associations d'usagers de la voirie forestière nous permet de développer des liens et un partage des connaissances entre les différents secteurs de la société, et de développer des outils d'enseignement et d'apprentissage efficaces et à long terme.

ANNEXE A

Matériel supplémentaire pour Chapitre 2

TABLE S1 CHARACTERISTICS AND POSSIBLE VALUES ASSIGNED DURING CULVERT ASSESSMENT

Characteristic	Units and/or Possible values
Number of conduits	
Diameter	cm
Height	cm
Length	m
Pipe material	Metal; corrugated metal; plastic; corrugated plastic; concrete; wood
Presence of embankment	Yes; No
Embankment material	Gravel; earth; rock; other
Presence of geotextile material	Yes; No
Height of embankment above conduit	cm
Presence of erosion of embankment material	Yes; No; moderate; heavy
Vegetative covering of embankment	0%; 1-25%; 26-50%; 51-75%; 76-100%
Waterfall at conduit outlet	Yes, No
Height of waterfall at conduit outlet	cm

TABLE S2 THE DIFFERENT TYPES OF DEGRADATION WHICH COULD BE OBSERVED ON THE RUNNING LANE SURFACE WITH DESCRIPTIONS INFORMED BY GIRARDIN ET AL (2022), OBVMR (2020), AND AUTHORS

Degradation type	Description	Image
Pot-holes	Potholes are deep and often circular depressions in the road surface.	

Ruts	Ruts are deep depressions in the road surface caused by water erosion and the transport of sediment away from the road surface. Ruts are distinct from furrows in that they consist of multiple rivets over the width of the road surface, and in the direction of vehicle travel.	 Source: Girardin et al, 2022
Furrows	Furrows are deep, parallel rivets which are caused by the repeated passage of vehicles. They are usually on the outermost left and right of the running lane surface and are the same width and distance apart as vehicle wheels.	 Source: Girardin et al, 2022
Erosion	In this case, erosion is defined as the transport of earth or surface material caused by the erosive action of water. This results in the repeated transport of sediment, even in small quantities, from the road surface to the nearby waterbody. It is represented by several deep or shallow channels, either in the longitudinal or transversal direction, distributed along the whole road surface.	
Sub-grade emergence	Sub-grade emergence refers to severe erosion, wherein the surface and base layer of the running lane are eroded, and foundation material is revealed. This is represented by exposed rocks on the running lane surface.	

Wash-boarding	Wash-boarding consists of many small parallel bumps, which are perpendicular to one another along the running lane surface.	
Complete road failure	Any degradation which leads to a complete break in road access. It could consist of the loss or collapse of a large portion of the road, such that it is no longer accessible.	
Partial road failure	Any degradation which leads to a partial break in road access. It could consist of the loss or collapse of a portion of the road, such that access is severely restricted or limited.	

TABLE S3 DISTRIBUTION OF CULVERT SITES UNDER PRIVATE TENURE MANAGED BY KENAUK NATURE VERSUS THE SITES UNDER PRIVATE TENURE MANAGED BY VARIED OWNERS

Private land tenure management type	Number of culverts in 'Acceptable' condition	Number of culverts in 'Mediocre' condition	Number of culverts in 'Critical' condition	Total number of culverts
Sole management (Kenauk Nature)	11	6	15	32

Varied management	7	6	17	30

TABLE S4 CONDITION NUMBER OF THE HESSIAN FOR THE FULL MODEL AND NESTED MODELS

Model	Explanatory variables included	Condition number of the Hessian
Full model	1. Land tenure 2. Overall road condition 3. Running lane re-vegetation percentage	5.3×10^4
Nested model 1	1. Land tenure 2. Overall road condition	4.5×10^1
Nested model 2	1. Running lane re-vegetation percentage 2. Overall road condition	5.3×10^4
Nested model 3	1. Running lane re-vegetation percentage 2. Land tenure	1.8×10^4

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