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REVIEW

Implications of linear developments on northern fishes

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Abstract: Canada's Northwest Territories (NWT) is currently the focus of significant exploration and development activity. In particular, increased global demand for oil and gas resources has resulted in an escalation in the search for hydrocarbon deposits. Canada's north is a landscape defined by water where large numbers of pristine water bodies still exist in remote areas. Northern development activities conducted in these areas will affect these sensitive aquatic ecosystems that support important fish and fish habitat. Fishes in low productivity northern systems grow slowly and mature late, making them particularly sensitive to environmental perturbations. The fishery resources of the NWT are an integral component of our northern ecosystems, and are of significant economic and cultural importance to northern people. By necessity, linear developments constructed in the NWT, such as roads, seismic lines, and pipelines, intersect lakes, rivers, and streams. This paper discusses linear development activities and their impacts on northern fishes, with a focus on oil and gas developments. Once a target area is identified, the development of northern oil and gas reserves typically follows a predictable sequence of events: (*i*) construction of temporary access roads into the exploration area to conduct seismic surveys to delineate reserves; (*ii*) exploration well(s) are drilled to assess the potential of the deposit; (*iii*) if the deposit is of economic interest, then production wells are developed and gathering systems constructed, often coupled with additional transportation infrastructure; (*iv*) a pipeline is then built to move the hydrocarbons southward to processing facilities; and (*v*) after the reserve is depleted, closure of all associated infrastructure is conducted and the site is remediated. The main stressors from these activities that may impact fish and aquatic ecosystems include sediment transport to water bodies, noise and pressure impacts from the use of explosives, water withdrawal, obstructions to flow and fish passage, removal of in-stream structure and riparian vegetation, enhanced access and fisheries exploitation, and contaminant spills. These stressors can adversely affect fish directly (e.g., through direct toxicity associated with exposure to elevated contaminants) or indirectly (e.g., through habitat degradation). Such impacts on fish can vary in severity, and on temporal and spatial scales, depending on the nature and extent of the disturbance. These activities can have cumulative impacts and can be exacerbated by natural or indirect stressors, such as a changing climate or forest fires. Appropriate baseline monitoring needs to be conducted, prior to development, to allow for appropriate mitigation to be employed and sound and responsible resource management decisions to be made within an adaptive management framework.

Key words: pipeline, oil and gas, freshwater fishes, northern environment, Northwest Territories, cumulative impacts, linear developments.

Résumé : Les Territoires du Nord-Ouest (TNO) au Canada font présentement l'objet d'importantes activités d'exploration et de développement. En particulier, la demande en augmentation pour les ressources gazières et pétrolières engendre une escalade dans la recherche de dépôts d'hydrocarbures. Le Nord canadien est un paysage défini par l'eau où de grandes étendues d'eau vierge existent toujours dans des endroits éloignés. Les activités de développement nordique conduites dans ces régions affecteront des écosystèmes aquatiques fragiles supportant une importante quantité de poissons et de leurs habitats. Les poissons vivants dans des systèmes nordiques à faible productivité croissent lentement et arrivent tardivement à maturité, ce qui les rend particulièrement sensibles aux perturbations de l'environnement. Les ressources piscicoles des TNO constituent une composante intégrale de nos écosystèmes nordiques et sont d'importance sociale et économique pour les communautés du Nord. Par nécessité, les développements linéaires construits dans les TNO, tels que les routes, les lignes sismiques et les pipelines, traversent les lacs, les rivières et les ruisseaux. Les auteurs discutent les activités de développement linéaire et leurs impacts sur les poissons nordiques, avec accent sur les développements gaziers et pétroliers. Suite à l'identification d'une cible, le développement des réserves de gaz et de pétrole se fait typiquement selon une suite d'évènements prévisibles : (*i*) construction de routes d'accès temporaires dans la zone d'exploration, pour conduire des suivis sismiques et déterminer les réserves; (*ii*) forage de puits exploratoire(s) pour évaluer le potentiel du dépôt; (*iii*) si le dépôt présente un intérêt économique, on développe alors des puits de production et on construit les systèmes de conduits, souvent couplés avec des infrastructures de transport additionnelles; (*iv*) on construit un pipeline pour déplacer le pétrole vers le sud aux usines de transformation; et, (*v*) une fois les réserves épuisées, on procède à la fermeture de toutes les infrastructures associées et à la réhabilitation du site. Les principaux agents stressants de ces activités, pouvant exercer des effets néfastes sur les poissons et les écosystèmes aquatiques, incluent le transport de sédiments vers les milieux aquatiques, le bruit et la pression provenant de l'utilisation des explosifs, l'élimination

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de l'eau, les obstructions au passage de l'eau et des poissons, l'altération des structures dans les ruisseaux et de la végétation riveraine, l'augmentation de l'accès pour l'exploitation des poissons, et le déversement de contaminants. Ces agents stressants peuvent nuire aux poissons directement (p. ex., par la toxicité directe associée avec l'exposition à des doses élevées de contaminants) ou indirectement (p. ex., via la dégradation des habitats). La sévérité des impacts subis par les poissons peut varier, et aux échelles spatio-temporelles, selon la nature et l'envergure de la perturbation. Ces activités peuvent engendrer des impacts cumulatifs et peuvent être exacerbées par des agents stressants naturels ou indirects, tels le changement climatique et les incendies de forêt. On doit conduire un suivi selon une ligne de base appropriée, avant le développement, afin de déterminer les mesures de mitigation appropriées ainsi que la prise de décisions d'aménagement sensées et responsables à l'intérieur d'un cadre d'aménagement adaptatif. [Traduit par la Rédaction]

Mots-clés : pipeline, huile et gaz, poissons d'eau douce, environnement nordique, Territoires du Nord-Ouest, impacts cumulatifs, développements linéaires.

Introduction

The Northwest Territories (NWT) is a vast (1 143 793 km^2), natural, resource-rich region of northern Canada (Sibley et al. 2008, AANDC 2014). Situated above the 60th parallel, north of the western provinces of British Columbia, Alberta, and Saskatchewan, between the Yukon and Nunavut territories, and extending its portion of the Arctic Archipelago into the Beaufort Sea, the NWT is remote. The low population of approximately 43 000 (0.04 people per km^2) (StatsNWT 2013), with few urban centres and limited transportation infrastructure, makes the majority of the NWT inaccessible and relatively pristine.

Ecologically the NWT is diverse; with 45 ecoregions ranging from the taiga plains to the northern Arctic islands (NWTPAS 2013). It is a landscape defined by water. Retreat of the last glacial maximum left behind major river drainages, such as the Mackenzie, Liard, Peel, and Slave, two of the world's largest lakes — Great Bear and Great Slave — and thousands of smaller lakes, ponds, rivers, and streams. The NWT supports over 50 species of freshwater and anadromous fish (WGNWTS 2011). In austere, low productivity systems, fish often mature late, grow slowly (Healey 1978; Sullivan 2003), and reproduce less frequently than in productive areas where energetic demands are greater (e.g., Cott et al. 2013). Such energy-conserving life history strategies make northern fishes particularly sensitive to perturbations of their environments, making them especially vulnerable to impacts from northern resource development (Reist et al. 2006).

Increasing global demand for natural resources, such as oil and gas, has renewed interest in northern areas and accelerated exploration and production activities. These resources have historically been gold and other base metals, but more recently they have been eclipsed by diamonds. Hydrocarbon resources have always been important to the NWT economy, with a worldwide increase in demand for oil resulting in expansion of associated exploration and development activities. The economic potential of oil and gas resources in the NWT has long been recognized; beginning in 1920 with Imperial Oil developing oil deposits in what has become the town of Norman Wells (Bott 1999). In the 1970s, high oil demand instigated exploration throughout the Mackenzie Valley, Mackenzie Delta, the Beaufort Sea, and the Arctic Archipelago. This exploration yielded many significant discoveries, including the Taglu, Parson's Lake, and Niglintgak reserves in the Mackenzie Delta, collectively comprising 5.8 trillion cubic feet of natural gas (MGP 2004*a*). The three Mackenzie Delta "anchor fields" were the impetus for the previously proposed Mackenzie Gas Project (MGP) — a 1220 km pipeline to take the stranded onshore natural gas reserves from the Mackenzie Delta down the Mackenzie Valley to southern markets (MGP 2004*a*). Large infrastructure projects, like pipelines, facilitate smaller projects that would otherwise not be economically viable to develop. For example, between 1996 and 2006, as a result of the MGP proposal, 56 exploration licences were issued and 192 wells were drilled in the NWT, including 101 exploratory wells (INAC 2007*a*). In recent years the Sahtu Region in the central NWT has experienced increased oil and gas exploration activity since the discovery of shale oil reserves. It is estimated that Canada's north holds 38% of Canada's remaining marketable natural gas, and 35% of remaining light crude (AANDC 2013).

As exploration for new hydrocarbon reserves or mineral deposits advances, transportation infrastructure is also expanded. A current example of this is the Inuvik to Tuktoyaktuk Highway, an all-weather road being developed to provide an artery between southern Canada (via the Dempster Highway to the town of Inuvik) to the Hamlet of Tuktoyaktuk on the Beaufort Sea coast (Hamlet of Tuktoyaktuk, Town of Inuvik, and Government of the Northwest Territories 2010). The purpose of this project is to provide year-round ground access to the Beaufort Sea and the considerable hydrocarbon reserves it holds. Many of these activities are conducted in or around water and therefore have the potential to impact fishes and their habitats (Pembina Institute 2004*a*). In particular, linear developments developed in the NWT, such as roads, seismic lines, and pipelines, will cross waterbodies and watercourses, often into areas that have not been accessed previously. For instance, the 138 km Inuvik to Tuktoyaktuk Highway crosses approximately 40 ephemeral and permanent streams (GNWT 2010), and the previously proposed MGP was slated to cross over 400 watercourses.

It has long been acknowledged that linear developments, and roads in particular, have negative impacts on the environment, including: physical loss of habitat, habitat fragmentation, wildlife mortality from collisions, ease in the transmission of exotic species, and increased human activity in areas previously inaccessible (Trombulak and Frissel 2000; Laurance et al. 2009). Such impacts can be dramatic and pronounced in remote and sensitive areas, as they are often the only visible anthropogenic impact in otherwise pristine areas. For example, road dust from the Dalton Highway, which cuts through Alaskan tundra to the Prudhoe Bay oil fields, has increased the melting of snow and permafrost in a wide swath (30–100 m) along the road. This early melting has altered the plant communities, and has also increased ponding adjacent to the road that then attracts wildlife (Walker and Everett 1987). Remote areas often harbour sensitive, often ecologically specialized, species that are vulnerable to habitat disturbances, fragmentation, and loss. The access afforded by linear developments facilitates predation, including by humans, to species unaccustomed to such pressure (Laurance et al. 2009). Perhaps because linear developments are primarily a terrestrial disturbance, the impacts that linear developments have on fishes have often been overlooked.

The oil and gas industry builds various types of linear developments; therefore, it is a good example to illustrate the potential implications of linear developments on northern fishes. For context, this paper describes the activities and possible stressors associated with linear developments in the north, and their potential direct and indirect effects on freshwater fish and aquatic habitats (Table 1).

Table 1. Stressors and potential impacts to freshwater fishes from activities associated with linear developments common in the NWT, Canada.

Stressor	Associated development activity	Potential impact to fish	Potential duration	Potential severity
Sediment mobilization and deposition	All-season road construction and maintenance, winter road construction, culvert and bridge installation, fording, open-trench pipeline crossing, right-of-way clearing, ancillary activities	Altered behaviour, reduced food availability (smothering of feeding areas, reduced primary production), reduced visual foraging ability, gill abrasion, altered blood chemistry, increased stress, inhibiting visual mate-selection and courtship, smothering spawning areas, smothering incubating eggs	Short- to long-term	Minor (e.g., behavioural changes) to severe (e.g., loss of spawning habitat)
Fish passage restriction	Ice-bridge construction, culvert installation, water withdrawal, open-trench pipeline crossings	Access prevented to key habitats (e.g., spawning, feeding, overwintering) and unable to fulfill life processes	Long-term	Severe
Water withdrawal	Winter road and ice bridge construction and maintenance, drilling, ice pad construction (for drilling platforms), hydrostatic pipeline testing, camp use	Oxygen reduction (stress to winterkill), loss of overwintering short- to long-term habitat, loss of littoral habitat, freezing of eggs and benthos, entrainment or impingement to water intakes	Short- to long-term	Minor to severe (e.g., winterkill) depending on waterbody and volume removed
Noise and pressure change	Seismic exploration	Behavioural changes, hearing loss, direct mortality of fish or fish eggs	Short-term	Minor (locally severe with explosive use)
Hydrocarbon and sump contamination	Chronic leaks and spills, to large-scale failures	Direct toxicity, mortality, developmental impairment	Short- to long-term	Minor (small leaks) to severe (major spills)
Vegetation removal	Crossing and site preparation and maintenance	Loss of shade, loss of overhead cover, reduced terrestrial invertebrates and leaf litter inputs, bank instability leading to sediment issues	Long-term	Moderate
Infilling and dredging	Winter road approaches, barge landing areas, ports, bridge abutments, channel maintenance	Direct removal of habitat, smothering of habitat, sediment issues	Long-term	Locally severe
Introduction of non-native species	Inadvertent or illegal transfer of biota	Ecosystem shifts, loss of native species, vectors to new pathogens and disease	Long-term	Minor to severe
Fishing pressure	Commercial, subsistence, or recreational fishing	Depletion of fish populations	Short- to long-term	Minor (e.g., limited harvest) to severe (e.g., stock collapse)

Note: For the purposes of this table duration estimates are: short-term, days to weeks; and long-term, months to years. Severity would vary with location, species, life stage, and the number of stressors.

Activities associated with oil and gas developments

The main activities associated with oil and gas developments include construction of access roads, stream or river crossings, seismic exploration, drilling, and construction of pipelines. Most aspects of oil and gas development in the NWT are conducted in winter, because of the relative ease of access to remote areas over frozen terrain (Anderson et al. 1996). Each of these activities is briefly discussed in the following subsections.

Access roads

Access for oil and gas development can be by air, water, or land. Of these, overland access, by winter or all-weather roads, has the highest potential for impacts to fish and fish habitat, with winter water withdrawals and water crossing construction being the activities that are most likely to impact fishes. In northern regions, winter roads can comprise a large component of the public transportation infrastructure, and are the primary form of access used by the oil and gas sector (Government of Yukon 2008). However, the importance of all-weather roads is likely to increase in the future.

Winter roads

A winter road is built overland (including across lakes, streams, and rivers) and is composed of snow, ice or a mixture thereof that remains functional only during the winter season (INAC 2010). These routes can be used for a single season or used repeatedly over several winters, and are typically constructed in December–January, once the terrain is adequately frozen, and maintained until April (Adam 1978; Hinzman and Lilly 2004). Because of their seasonal nature, and their limited use, winter roads are generally considered to have less impact on terrestrial ecosystems than permanent roads (Hinzman and Lilly 2004). For instance, if constructed properly, winter roads melt each spring without leaving a persistent footprint on the landscape, often do not require extensive land clearing to construct (especially in tundra areas), and only allow seasonal access (Adam 1978).

Winter roads can be classified into three broad categories: (*i*) winter trails, (*ii*) snow roads, and (*iii*) ice roads.

(*i*) Winter trails Winter trails are used where the load and volume of traffic are low, or are restricted to the use of high flotation vehicles only (vehicles that distribute their weight efficiently through the use of wide tracks or balloon tires) (Fig. 1). If clearing of vegetation is not required, such trails can often be made with a single pass of a vehicle. These are the least developed of the three winter road types, and require relatively little water to construct (Adam 1978).

Fig. 1. A variety of linear developments common in northern regions; (A) an all-season road, (B) a snow road, (C) a winter trail, and (D) a seismic line. These types of linear developments often cross watercourses, such as the creek (E), and could impact fish and fish habitat if not constructed and maintained properly. The Inuvik Airport is shown in the background, near the Town of Inuvik, NWT, Canada. Photo: J. Kanigan, GNWT-ENR(CIMP).

(*ii*) Snow roads Snow roads are made with compacted snow as a base to accommodate intermediate volumes of traffic and load weights (Figs. 1 and 2). Snow is compacted with graders, rollers, or drags (lumber or heavy tires dragged behind vehicles), and construction usually requires some filling of low areas with snow or grading of high spots (Adam 1978). Water is also required to consolidate snow fills. Snow roads can be built by compacting the existing snow pack or can be fabricated with artificial snow. Artificial snow is sometimes required in regions or years of low precipitation and is made with industrial snow making equipment similar to that used on ski hills. Large volumes of water are required to make artificial snow (Adam 1978). If a more durable road surface is required, then snow roads may be sprayed with water to form an ice cap (approximately 2.5 cm thick). Approximately 300 m^3 of water is required to make 1.6 km of ice-capped snow road, if a natural snow base is present (Adam 1978). Nolan (2005) reported that approximately 3500 m^3 of water is required to construct one kilometre of winter road over tundra.

(*iii*) Ice roads Ice roads are made of ice, either by thickening the existing ice cover on lakes and rivers, or by spreading water over a land-based roadway to make a smooth surface of a sufficient thickness to support the anticipated traffic (Adam 1978). On water bodies, ice roads are normally made by removing the insulating blanket of snow from the ice surface, in a swath much wider than the road, to facilitate thickening of the ice. Ice profiling is conducted to ensure that the required thickness is achieved, and if needed, subsequent spraying or flooding is carried out to increase ice thickness (Adam 1978). For example, the Tibbitt Lake to Contwoyto Winter Road Joint Venture is built annually in the NWT to service the diamond mining industry. It is 568 km long and is only open from mid-January to mid-April, when over 8000 truck loads are delivered along it. More than 85% of the road is built over frozen lakes, with the rest being over land portages (Mesher and Proskin 2008). Additionally, 40% of the NWT's highway infrastructure consists of ice roads (GNWT 2007).

In some areas, ground-fast ice is harvested from lakes using special ice-chipping equipment. These ice chips are applied to the road surface as an aggregate. Water is then sprayed over the aggregate, filling in the interstitial spaces and forming a thicker road surface more quickly than watering snow or frozen soil (Adam 1978). Ice roads can accommodate large loads and high traffic volumes; hence, these types of roads are favoured as perennial supply routes. Ice roads have the greatest water requirements of the three winter road types, ranging from 1300 to 3500 $m^3 \cdot km^{-1}$ (Adam 1978; Nolan 2005). On perennial roads, it is common to withdraw water from the same waterbodies year after year to facilitate road construction (Adam 1978).

Remote locations and high transport costs dictate that water needs to be taken from the closest possible source (Nolan 2005). Because of the high volume of water required and the high transportation costs associated with moving water, winter road construction begins to become financially unfeasible if the distance between water sources is greater than 8 km (Adam 1978).

Some winter roads may be a combination of the types mentioned here. For example, a snow road may cross a river, thus requiring an ice bridge, or it may have low traffic spur roads where only winter trails are needed (Cott 2007). Regardless of the type of winter road, it is important that they remain clean, as discolouration from dirt absorbs solar energy and induces premature melting.

All-weather roads

In the NWT, all-weather roads are not used as extensively for oil and gas exploration as winter roads due to the remoteness, high cost, and difficulty of construction in the north. However, all-weather roads are used where oil and gas infrastructure has been established (such as at Norman Wells) or near communities (Fig. 1). For example, Husky Energy has an all-weather road about 40 km southeast of Norman Wells to access shale oil reserves (Wohlberg 2014). With increased development associated with long-term projects, the construction of all-weather roads to secure these facilities is inevitable. Unlike winter roads, all-weather roads require not only clearing of vegetation but also removal of topsoil and construction of a permanent roadbed. In the NWT, roadbeds are normally made from compacted gravel. For high volume roadways, the tops are often capped with chip-seal (a mix of crushed

Fig. 2. Linear developments associated with northern oil and gas development shown in the summer; (A) a snow road, (B) seismic lines (the horizontal line is several decades older than the vertical line as evident by the forest regeneration), and (C) secondary access roads including bridges over a small watercourse. This is a pump-jack and gathering system in the Cameron Hills, southern NWT, Canada. Photo: M. Palmer, GNWT-ENR(CIMP).

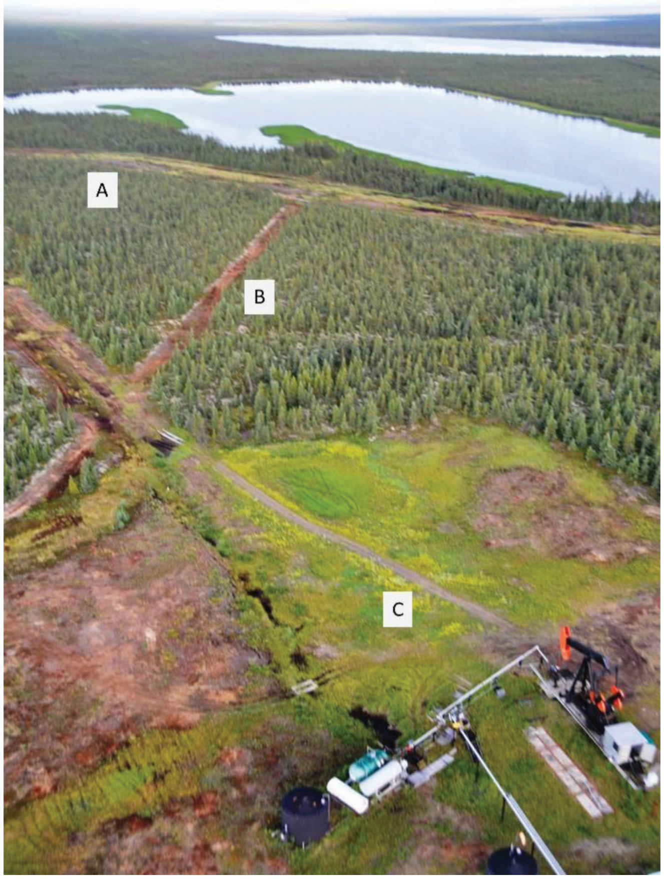

Fig. 3. (A) A perched culvert like this would prevent upstream movement of most species of fish. Photo: K. Maier, GRRB. (B) A decommissioned sump adjacent to a lake in the Mackenzie Delta, NWT. Note the ponding and slumping on top of and around the sump, the different vegetative cover compared to the adjacent landscape, and the drainage towards the lake. Photo: J. Kanigan, GNWT-ENR(CIMP).

rock and tar). This type of roadbed is much more resilient to heaving from permafrost than asphalt roads (Walsh et al. 2009).

Watercourse crossings

The Northwest Territories landscape is defined by a multitude of lakes and rivers, with approximately 163 000 km^2 of its surface area covered by water. This represents nearly 1/5 of the surface freshwater of Canada (Senes Consultants Ltd 2005). Watercourse crossings routinely required for accessing potential oil and gas deposits in the NWT are remote. These can be classified into several categories, including ice bridges, ford crossings, roadbeds with culverts, and bridges.

Ice bridges

Ice bridges are crossings made of ice and snow. In most cases, the ice on the waterbody is thickened by flooding, typically using water from the same waterbody (Knowland et al. 2010). If the grades leading to the ice bridge are steep, snowfill may be added and frozen to build up the roadbed at some crossing locations. The NWT Fishery Regulations dictate that temporary crossings over any ice-covered stream shall only be constructed with clean ice or snow unless otherwise authorized (Government of Canada 2014).

Ford crossings

Ford crossings are stream or river locations where vehicles drive directly across a stream during open-water conditions. They are normally used at locations with shallow water, hard substrate, and low gradient banks, so site modification or construction is usually not required. Armouring of the stream bed and banks may be necessary for heavily used fords.

Roadbeds with culverts

Culverts are required for most all-weather road crossings and some winter road crossings. They come in a variety of shapes and sizes, with the most common being a corrugated steel tube (Fig. 3). Other varieties include box and open arch culverts. Culverts can be installed strictly for drainage purposes or to maintain flow and fish passage at a stream crossing site with the roadbed built above. Proper installation of a round culvert includes embedding 10%–20% of the culvert diameter into the substrate, to allow for some backfilling of streambed material. An advantage of open box or arch culverts is that the natural streambed, and fish habitat, is maintained (UW-E and WDNR 2004; Hotchkiss and Frei 2007).

Bridges

Bridges are permanent or semi-permanent structures that are constructed to facilitate passage over a watercourse (Fig. 2). In the NWT, permanent bridges are often used in conjunction with annual winter roads as there is often insufficient snow or suitable water sources to accommodate snow fill at the onset of winter road construction (December). By installing permanent bridges, snow is only required to build up the road approaches, increasing the length of the winter road season (DOT 2012).

Seismic exploration

Seismic surveys employ acoustic methods to obtain a "picture" of the subsurface geology in an area. More specifically, a sound is generated and directed into the ground (AANDC 2011). The sound energy reflects off geological formations and is received by recorders called geophones (on land) or hydrophones (in water). The deeper the search, the more energy is required to conduct the survey (AANDC 2011). Geophysicists interpret these sound recordings to predict where hydrocarbon deposits may be located (Bott 1999). In forested areas, seismic exploration requires the cutting of "seismic lines" (Figs. 1 and 2). There are three primary sound energy sources used in northern Canada: airguns, vibroseis, and explosives (Cott et al. 2003).

Airguns

Airguns are only used in aquatic seismic surveys. Airguns were developed and are primarily used for large-scale marine seismic surveys, but the equipment has been scaled down and modified for lake and river applications. An airgun is essentially a cylinder that compresses air and releases it through a small port into the water column. The air bubble collapses under the pressure of the water column and produces a low frequency sound. Although a single airgun may be used for very small seismic programs, a series of airguns, known as an array, are typically towed behind a vessel along with hydrophones to receive the returning signal (OERA 2012). The airguns are fired at regular alternating intervals of 6 to 10 s depending on the speed of the vessel.

Vibroseis

Vibroseis is a seismic technique where a large vibrating pad is lowered beneath a tracked vehicle, making contact with the earth. The vibrations from this pad act as the energy source (MRCSP 2010). Like airguns, the energy is low frequency and the waveform is relatively slow. Because direct contact with solid substrate is required to transmit the energy signal, vibroseis is primarily used on land or on those portions of lakes that are frozen to the bottom. Data from vibroseis conducted on lakes covered with floating ice are of lower quality as the energy is lost travelling through the ice and water column prior to entering the substrate (Hall et al. 2001).

Explosives

Explosives have historically been the energy source of choice for land-based seismic surveys in the north. In this type of survey, a hole is drilled into the earth using a portable drill rig and a charge is loaded down the hole. The shock wave from the detonated charge acts as the energy source and returning signals are received by geophones (Bott 1999). Charge sizes and burial depths vary. In many areas within the NWT, it is necessary to deploy charges beneath the bed of lakes or rivers to obtain the required data due to the number of lakes in close proximity to each other. In other areas, it is usually possible to avoid using explosives in waterbodies without sacrificing data quality. In the NWT, explosives are no longer authorized in lakes that are not frozen to the bottom because of potentially adverse effects on fish (Cott et al. 2003).

Drilling

Once a potential oil or gas deposit is located, an exploratory well is drilled to confirm the presence of hydrocarbons and to assess the size and quality of the reserve. If deemed economically viable, one or more production wells are then drilled to facilitate extraction. These drilling activities are usually preceded by site preparation.

Site preparation

First, a site is located that will be the most direct and technically feasible route from the surface to the potential subsurface reserve. Then, a winter or all-weather road is constructed. Next, the site is cleared and graded to make a pad to support the drilling infrastructure. Because of the short duration of an exploratory drilling operation, winter road access and ice platforms are used whenever possible to minimize impacts. For production wells, gravel is required for pad creation. Gravel can come either from quarries or from natural glacial deposits, such as eskers. Additional clearing is required to make a camp for rig operations (Pembina Institute 2004*b*).

Drilling

Exploratory wells are typically small-diameter borings (e.g., 15 cm) that are constructed using portable diamond drilling rigs. By comparison, production wells are usually larger-diameter holes (up to 120 cm) that are bored using larger drill rigs. Drilling of both types of wells requires the use of "drilling mud" as a lubricant for the drill stem. The mud also carries drill cuttings to the surface. Once at the surface, the cuttings get separated from the mud and are disposed. The drilling mud is recirculated as much as possible (Bott 1999). The amount of cuttings depends on the diameter of the hole and the depth of the drilling target, which can be several hundreds of metres below the surface. This mud is usually a combination of bentonite clay, water or hydrocarbon, and a variety of chemicals (Alberta Environment 2007). Sometimes hydrocarbon-based fluids are used instead of water, and when drilling through permafrost, salt is added to the water to avoid freezing (Pembina Institute 2004*b*). Production wells are similar to exploration wells but operate for a longer duration and are typically supported with more permanent infrastructure.

A large pit, termed a sump, is normally dug into the ground near the drill rig to accommodate waste drilling mud and cuttings (Fig. 3). Camp grey and (or) black water is also often deposited into a sump. In the NWT, sumps are often built in permafrost with the aim of freezing the disposed material, keeping it stable. However, recently companies have trucked drilling wastes out of the NWT to disposal facilities because of public concern about the impacts of sumps in the NWT (Kanigan and Kokelj 2010).

Pipelines

Pipelines are constructed to transport oil or gas from production sites to processing or distribution centres. The diameter of a pipeline depends on the volume of oil or gas to be moved. There are two main types of pipeline: gathering systems and transmission systems. The *gathering system*, a series of small diameter pipelines, collects the oil or gas from individual wells and sends it to a central battery for some level of separation and processing (Fig. 2). The *transmission system*, a large-diameter pipeline, transports the hydrocarbons from the central battery to the processing or distribution centre. To maintain the pressure required to move the oil or gas through the pipeline, compressor stations (for gas pipelines) or pumping stations (for oil pipelines) have to be built at intervals along the pipeline route (Pembina Institute 2004*c*).

There are typically four main steps involved in pipeline construction: (*i*) construction of access roads, (*ii*) clearing of land, (*iii*) construction of the pipeline, and (*iv*) construction of pipeline-associated facilities.

Pipeline construction

Like roads, pipelines require right-of-way (ROW) preparation, preparation of lake and stream crossing approaches, and in-water works associated with stream crossings (Goodchild and Metikosh 2005). Construction of stream crossings is the associated activity that is most likely to affect aquatic ecosystems. There are several different types of stream crossings, with the method selected depending on the characteristics of the stream and the underlying geology of the crossing area. The most common types of stream crossing include: open trench, trenchless, and aerial (CAPP et al. 2005).

Open-trench crossings

Open-trench crossings are constructed by digging a trench into the bed of the watercourse and laying the pipeline into the trench. The trench is then backfilled with the previously excavated material (CPEC 2009). The open-trench method is often used for ephemeral streams that are dry or have low flow at the time of excavation, or for water-courses that are too large for other crossing method technology (CPEC 2009). For very wide crossings, such as across the Mackenzie River, drag line dredges or barge-mounted dredges are needed to construct open-trench crossings (CAPP et al. 2005). Isolation of the work site by diverting water around the crossing location is used when trenchless crossings are not possible or practical, for streams that have sensitive habitats or fish species, or when the timing of construction corresponds with fish spawning (CAPP et al. 2005; CPEC 2009). The means of water diversion is dependent on the water volume and flows present. In some cases it may be possible to permanently re-channelize the watercourse away from the pipeline ROW, but more often it is directed through a flume or culvert (CAPP et al. 2005). This type of crossing is limited by the size of stream to be crossed and the flow present.

Trenchless crossings

Trenchless crossings are the least invasive crossing type to aquatic systems, as no in-water work is normally required. A large diameter directional drill or punch is used to bore a hole under the watercourse (CPEC 2009). Then, the pipeline is fed through the bore hole. The entry and exit position of the drill and bore is dependent on the grade of the stream and the flexibility of the pipe. For low gradient streams, the pipe can be initially inserted fairly close to the stream. For streams in valleys, the directional drilling may have to be conducted several hundred metres from the stream to be able to curve under the streambed appropriately. This method cannot be used where large rocks or bedrock are present because there is a greater risk of collapsed bore holes, damaged pipes, and lost equipment (CAPP et al. 2005). With high-pressure directional drilling there is a risk of a frac-out: when the pressure of the drill pushes mud and (or) fluids up to and through the surface (Nugent 2011), potentially contaminating the water.

Aerial crossings

An aerial crossing is a pipeline that is suspended above the watercourse. This is most often accomplished by attaching the pipeline underneath a bridge or a structure built specifically to support the pipeline. In either case, the amount of in-water work is minimal and the pipeline normally spans the entire watercourse (CAPP et al. 2005; CPEC 2009).

Pipeline maintenance

Pipelines, like all infrastructure, need to be maintained. Inspections of pipelines and pipeline crossings are conducted routinely, paying particular attention to stream crossings for evidence of erosion and permafrost slumping. If problems are encountered, remedial action, such as stabilizing stream banks, is taken. Riparian vegetation should be kept around pipeline ROWs that are near a stream or river as much as possible to keep the bank stable and protect fish habitat (CPEC 2009). However, pipeline ROWs need to be kept free of trees, shrubs, and buildings so that there is always free access to the pipeline for emergency and maintenance purposes (PPLIEC 2012).

Ancillary activities

With the development of oil and gas resources comes a variety of closely associated ancillary activities that may impact aquatic environments. The larger the development, the greater the amount of ancillary activities there will be. The development of large pipeline projects would make smaller reserves throughout the Mackenzie Valley economically viable, and then lead to a spider web of ancillary developments such as: access to new sites, camps, barge landings, quarries, sumps, aircraft landing strips, and staging areas. The populations of communities will grow, and there will be an influx of transient workers — all augmenting the demand on aquatic resources.

Camps are required for all aspects of oil and gas development. During initial access construction, camps are mobile, often a series of sleigh-mounted trailers towed by a bulldozer known as a "cat train". The camps utilized during seismic exploration and exploratory drilling tend to be less mobile, set up in a central location, and removed each season. At the main production areas, permanent camps are erected and maintained for the life of the reserve. Mobile camps are used for pipeline construction, moving along with the construction. Camps can be small, supporting less than a dozen workers, or large, supporting hundreds of individuals. Camps will have further demands on fresh water for potable and domestic use proportional to the size of the workforce (MGP 2004*b*).

Closure and reclamation

Once oil and gas reserves in a given area are exhausted, the infrastructure used to extract and transport is no longer needed and is normally removed. Historically, very little clean up occurred, leading to a legacy of contaminated sites scattered throughout the north. Today, comprehensive closure and reclamation plans are required for northern development proposals (INAC 2007*b*). Closure of a pipeline and associated facilities entails the decommissioning and removal of above-surface infrastructure, such as buildings, wells, fuel storage, and compressor stations. Soils are tested for hydrocarbon contamination and remediated as required. Access roads are decommissioned, and culverts and bridges removed. Road and pipeline ROWs are scarified and revegetated. Natural drainage patterns are re-established if possible (INAC 2007*b*). Materials, such as aggregates, used for drill pads are reused if possible; otherwise drill pads are capped with stockpiled soil overburden and seeded. Sumps are capped, seeded, and monitored over time for leaching and slumping (Fig. 3). Because pipeline removal can be very environmentally disruptive, pipelines are usually drained, sealed with grout, and left buried in place (Swanson et al. 2010).

Potential effects of linear developments on fish

Each of the wide range of activities associated with development of oil and gas deposits in northern Canada has stressors with the potential to alter the physical or chemical characteristics of receiving water systems. In turn, such alterations in the quality of aquatic habitats can adversely affect fish and other organisms that utilize these ecosystems. In addition, other activities associated with oil and gas development can have direct impacts on fishes (Table 1). The key mechanisms through which fish and other aquatic organisms may be impacted are discussed in the following sections.

Sediment mobilization and deposition

Sediment release into waterbodies is one of the main concerns associated with linear development activities, and can occur at almost every stage of development. The pathways that result in sediment mobilization include: surface runoff, bank erosion, and slumping, infilling, or re-suspension due to digging or dredging in waterbodies. Introduction of sediment can impact the health and behaviour of fish directly, or indirectly through changes to their habitat (DFO 2000). There have been numerous reviews on the effects of suspended and deposited sediments on aquatic ecosystems (Newcombe and Macdonald 1991; Kerr 1995; Berry et al. 2003; Robertson et al. 2006). Although few studies of sediment effects have been conducted on northern fish species, it is likely that they are similar to those that have been elsewhere in North America.

Adverse effects include: altered blood chemistry (Servizi and Martens 1987), clogging and abrasion of gills (Goldes et al. 1988; Reynolds et al. 1989), altered territorial and foraging behaviour (Berg and Northcote 1985), reduced resistance to disease (Singleton 1985), impaired feeding and growth (McLeay et al. 1984; Sigler et al. 1984; Reynolds et al. 1989), and decreased survival and (or) reproduction (CCME 2002). Reid et al. (2003) reported that Rainbow Trout (*Oncorhynchus mykiss*) held in areas with elevated suspended sediment levels associated with construction of open-trench pipeline watercourse crossings had increased respiration rates and quicker loss of equilibrium compared to reference fish held at an upstream location.

Exposure to inorganic sediments also has the potential to result in a variety of indirect effects on fish. For example, releases of fine sediments can reduce light penetration thereby inhibiting photosynthesis and plant productivity, scour periphyton off substrates, and smother aquatic plants in depositional areas (Singleton 1985; Robertson et al. 2006). Similarly, the distribution, abundance, and diversity of benthic invertebrate communities can be altered by exposure to suspended sediments and associated turbidity. Adverse effects on benthic invertebrates result from abrasion of respiratory organs, interference of food uptake by filter-feeding invertebrates, reduction in the availability of periphyton to grazers, scouring and increased drift of invertebrates, and clogging of interstitial spaces in stream-bed substrates (Singleton 1985). As a result of these sediment-related effects on aquatic plants and benthic invertebrates, the feeding and growth of fishes can be negatively impacted. Reproduction can be compromised if reduced water clarity makes it difficult for fish to locate and court each other (Robertson et al. 2006). Spawning areas that are smothered by sediments can be unsuitable for egg deposition. Incubating eggs and emerging fry can be suffocated if sediment has clogged interstitial spaces in spawning substrates post-egg deposition (Robertson et al. 2006).

Winter is a sensitive time for fishes in northern regions, particularly in streams where overwintering habitat is often critically limited (Cunjak 1996). Sediment deposition in stream pools can minimize the suitability of these areas as overwintering habitats (Birtwell et al. 2005). Increased sediment can increase the stress, and in some cases mortality, of overwintering fishes in streams, and may limit the overall productive capacity of these systems (Birtwell et al. 2005; Robertson et al. 2006). Sediment released from linear development activities can displace fish from winter habitats. Fish exposed to high suspended sediments associated with the winter construction of a river crossing in the NWT were observed to drift downstream, avoiding high turbidity and presumably searching for better foraging locations (Porter et al. 1974).

There is the potential for lake-bed sediments to be re-suspended after explosives detonation, and for these sediments to disturb fishes; however, these effects are usually limited both temporally and spatially. Water quality monitoring of detonated buried seismic charges showed little to no change (i.e., <3 m diameter from the shot hole, returning to background levels within 10 min; Cott and Hanna 2005). Similar findings were reported from water quality monitoring of seismic operations at Parsons Lake (Golder Associates 2002) and during underwater construction blasting in Lake Erie (Teleki and Chamberlain 1978).

Fish passage restrictions

In addition to their effects on habitat quality, roads and ice bridges have the potential to temporarily or permanently affect the quantity of aquatic habitat available to fishes. Specific habitats are required at different times of year to fulfill specific life processes, such as feeding areas, spawning grounds, and overwintering habitat. Access to these habitats, when they are required, is essential to the survival of fish species. Many fish species, such as Arctic Grayling (*Thymallus arcticus*), require access to smaller tributaries for spawning in the spring (Scott and Crossman 1973). Ice bridges that freeze to the river bottom and are not properly decommissioned prior to freshet can act as barriers that prevent or restrict access to preferred spawning habitats. In the north, spawning seasons are short and if fish are unable to access preferred spawning habitat or their spawning areas are disturbed they can be forced to spawn in undesirable locations (Cott et al. 2010), may abandon their spawn (re-absorbing eggs; Auer 1996), or be subject to increased predation while holding (Brown et al. 2003).

Culverts are often cited as "minor" instream works; however, an improperly installed culvert can impact entire fish populations by restricting access to many kilometres of upstream (or downstream) habitats. Such habitats may be required by fishes during critical life history stages, such as spawning or early rearing. Improper culvert installation can occur in a variety of ways. A "perched" or "hanging" culvert is one where the outlet is higher than the stream below (Fig. 3). This difference in elevation can be too great for fish to move upstream, by swimming or jumping, making only downstream fish movements possible (Park et al. 2008; MacPherson et al. 2012). Undersized culverts can also create a barrier to fish passage by increasing the flow velocity to rates that are too great for fish to pass, particularly if the distance through the culvert is long (MacPherson et al. 2012). High water velocities can also result in downstream erosion and scour at the outlet, creating a perched culvert over time (Park et al. 2008; MacPherson et al. 2012). Culverts can settle, get dammed by beavers (*Castor candensis*), or fill with bed material, all of which can obstruct fish passage. Culverts must serve as a conduit that connects upstream and downstream habitats. If this corridor is not maintained, the result is habitat fragmentation and overall habitat loss (Park et al. 2008; MacPherson et al. 2012).

Water withdrawal impacts

Winter water withdrawal from lakes may adversely affect aquatic biota in several ways, such as oxygen depletion, loss of overwintering habitat, loss of littoral habitats, desiccating or freezing of incubating eggs, and fish impingement in water intakes (Gaboury and Patalas 1984; Jansen 2000; Turner et al. 2005; Cott et al. 2008*a*; Cott et al. 2008*b*). Water for winter road construction can be withdrawn with pumps from a fixed station or from several sources using water trucks. In winter, useable habitat may be limited by availability of oxygen; lakes frequently have the highest oxygen concentrations in the water layer closest to the ice (Casselman 1978). Unfortunately, water withdrawal for winter road construction tends to be from this upper layer and thus removes the most oxygenated water in the lake, decreasing the total winter oxygen mass of the lake (Cott et al. 2008*a*). Small lakes typically have limited water volumes prior to water extraction and water volumes are further reduced as ice thickens (Cott et al. 2008*a*). With the onset of ice-cover, oxygen inputs into lakes are greatly reduced. Often the only available water sources are small lakes (<50 ha), with limited or no recharge capabilities (Cott et al. 2005). Atmospheric inputs from wind and wave action are eliminated and ice and snow cover limit light penetration and curtail photosynthesis by primary producers (Welch et al. 1976; Wetzel 2001). Biological oxygen demands, mainly from decomposing organic material, further decrease the winter oxygen levels in lakes (Greenbank 1945; Davis 1975; Wetzel 2001). Compared to the open water season, the habitat available for overwintering fish is limited by all these factors (Casselman 1978; Stefan et al. 2001). Fish can be severely stressed by low winter oxygen conditions, leading to mass fish mortality referred to as "winterkill" (Greenbank 1945). The effects of low winter oxygen concentrations may vary depending on climate, land use, lake characteristics, connectivity, species present, and natural disturbance regimes (Rogers and Bergersen 1995; Danylchuk and Tonn 2003; Turner et al. 2005).

Even if fishes in low oxygen environments survive the winter, they may endure physiological stress and sub-lethal effects that can affect growth, reproduction, and the long-term population viability (Evans et al. 2002; Evans 2007). Decreasing water levels can also cause substrates in the shallow littoral zone to freeze, destroying fish eggs, reducing benthic invertebrate populations, and damaging plant communities (Jansen 2000; Mills et al. 2002; McGowan et al. 2005; Turner et al. 2005). In addition, small fishes, such as Ninespine Stickleback (*Pungitius pungitius*) and the young-of-the-year of other species, can be at risk of entrainment into the intake or impingement on intake screens when water is being withdrawn from lakes and streams (Cott et al. 2005; Nordlund 2008).

Cott et al. (2008*a*) evaluated the impacts of winter water withdrawal by removing 10% of the under-ice water from one small lake and 20% from another. Dissolved oxygen concentrations, temperature, overwintering habitat, and fish population parameters were measured and compared to reference lakes. By April, the depth of the water column at which ≥4 mg·L^{-1} of dissolved oxygen (a tolerance threshold for most freshwater fish) was observed had declined by 0.2 m in the lake subjected to 10% water withdrawal but no effects were observed on total volume-weighted oxygen or volume of overwintering habitat (Cott et al. 2008*a*). In contrast, 20% water withdrawal caused a 0.7 m reduction in the oxygen concentration profile at 4 mg·L^{-1}, a 26% decline in the volume-weighted oxygen concentration, and a 23% reduction in the volume of overwintering habitat compared to pre-withdrawal reference conditions. The abundance of littoral benthic invertebrates and Northern Pike (*Esox lucius*) was not impacted by water withdrawals in either of the lakes investigated (Cott et al. 2008*a*). Further studies are needed to evaluate linkages between the physical, chemical, and biological effects of water withdrawals in small lakes in the north.

Water withdrawals from small streams also have the potential to adversely affect fisheries' populations. As the lowest stream flows are typically observed during the winter months, stream-dwelling fishes are particularly sensitive during this time (Cunjak 1996). Winter water withdrawals can reduce flows to such an extent that freezing of pools or migration corridors becomes possible. Such effects can affect habitats located many kilometres downstream of the withdrawal point.

Impacts from noise and pressure changes

A variety of activities associated with oil and gas development can expose northern fishes to noise or instantaneous pressure changes (IPCs) beyond those that occur in aquatic ecosystems under natural conditions. For example, seismic exploration, exploratory drilling, ice-road traffic, and other activities can increase ambient noise levels in lakes and streams. Seismic surveys can also cause IPCs in waterbodies. In turn, such alterations in ambient sound or pressure levels can affect sensitive fish species or life stages (Popper et al. 2005; Mann et al. 2009).

In terms of natural background noise, subarctic lakes fluctuate between very quiet (~64 dB re 1 μPa at 200–300 Hz) and relatively loud, because of short-duration ice cracks (>125 dB re 1 μPa at the same frequency range; Mann et al. 2009). In a study by Mann et al. (2009), the under-ice noise produced by a variety of anthropogenic sources (e.g., drilling rigs and ice-road traffic) was measured at a winter-based diamond exploration project to infer the potential impact of noise on fishes in the lake. While the magnitude of all anthropogenic noises measured fell within the normal range of ambient sound levels, anthropogenic noises tended to have much longer duration (Mann et al. 2009). The sounds from ice cracks last less than one second (Milne 1966; Stein 1988). In contrast, compressors and drills can run uninterrupted for hours (Mann et al. 2009). Similarly, seismic surveys and ice-road traffic can result in elevated noise levels for extended periods.

The effects of noise on the hearing and behaviour of fishes are not well understood. Nevertheless, there is evidence that human-produced noise can have effects on fishes (McCauley et al. 2003; Popper et al. 2005). For example, exposure to low frequency sounds can lead to temporary or possibly permanent hearing loss in fish (McCauley et al. 2003; Smith et al. 2004*a*, 2004*b*; Popper et al. 2005). Exposure to sound originating from airguns has been shown to scare or otherwise disturb fishes from their regular activities. It has been suggested that the continual firing of airguns as a seismic vessel is moving up a river system can disturb normal migration by "herding" fish upstream prematurely. However, in a study using hydroaccoustics to observe fish movement (predominantly coregonids) in response to airgun firing in the Mackenzie River, Jorgenson and Gyselman (2009) did not find evidence of herding.

Changes in ambient sound levels affect different species in different ways. For example, Morris and Winters (2005) determined that caged Arctic Char (*Salvelinus alpinus*) experienced no physical damage when exposed to vibroseis-generated sounds in an Alaskan river. However, wild Broad Whitefish (*Coregonus nasus*) observed by underwater video exhibited an immediate and rapid flight response when exposed to the same noise (Morris and Winters 2005). In contrast, Racca et al. (2004) observed no response in Northern Pike, Lake Whitefish (*Coregonus clupeaformis*), Lake Trout (*Salvelinus namaycush*), or Inconnu (*Stenodus leucichthys*) exposed to sound stimuli in Arctic lakes under ice cover. As overwintering fishes need to conserve energy to survive, particularly in northern areas when the ice-covered season is protracted, it is possible that unnecessary disturbances could hamper their overwintering success. In addition, Burbot (*Lota lota*), a winter-spawning predatory fish that live in lakes and rivers throughout the NWT, are known to vocalize at spawning time, presumably to attract or select mates. Persistent anthropogenic noise could mask the acoustic communication of this species and impact reproduction (Cott et al. 2014).

Detonation of explosives and associated IPCs also have the potential to adversely affect fish in northern ecosystems. The results of gross examinations indicate that fish subjected to IPCs can be injured or killed (Govoni et al. 2003). In addition, secondary infections have been observed in fish that survive the original exposure. Some sub-lethal effects of IPCs are more subtle and are only detectable by histopathological tissue examinations (Govoni et al. 2003). The specific effects that have been observed include vascular injuries, injuries to the swim bladder, and secondary damage to tissues near the swim bladder, such as the liver, kidney, and pancreas, as a result of rapid expansion of the swim bladder during the negative pressure phase of the IPC (Govoni et al. 2003). Godard et al. (2008) noted injury to juvenile Rainbow Trout eyes, kidneys, and swim bladders at pressures of ≥69 kPa. Pile driving activities have a similar sound signature to explosives and can have similar impacts on fish. Popper et al. (2013) investigated the physiological effects to five different fish species from exposure to various sound levels generated by pile driving. Barotrauma, tissue damage resulting from rapidly increased pressure, occurred at different sound exposure levels depending on the fish species.

In addition to the direct effects on juvenile and adult fish, explosives in and around waterbodies can adversely affect fish by creating pressure waves that disturb the gravel in which the eggs are incubating. The intensity of such pressure waves is determined by measuring peak particle velocity (Wright 1982; Wright and Hopky 1998). The results of field experiments using Lake Trout eggs and laboratory experiments using Rainbow Trout eggs demonstrated that peak particle velocites less than 13 mm/s were unlikely to affect incubation success (Faulkner et al. 2006; Faulkner et al. 2008). Similarly, no injury was observed in Rainbow Trout eggs exposed to IPCs from explosives of up to 270 kPa in the outer Mackenzie River Delta (Peters et al. 2006).

Hydrocarbon contamination

Oil and gas exploration and development can result in accidental releases of petroleum hydrocarbons and other contaminants to aquatic ecosystems. Such releases of contaminants can range from small (e.g., from equipment) to catastrophic (e.g., from oil extraction and transportation infrastructure). The effects of contaminant spills on northern fish communities are dependent on the nature of the material, the size of the spill, the location of the release, and the duration of exposure to the associated contaminants. Not only can oil from a ruptured or leaking pipeline cover the ground or water and smother plants and animals in the vicinity, but hydrocarbons from oil, especially polycyclic aromatic hydrocarbons, are toxic to fish (Hose et al. 1996; Carls et al. 1999; Colavecchia et al. 2004). Exposure of the early life stages of fish to oil, and the polycyclic aromatic hydrocarbons within it, has been shown to result in mortality and blue sac disease, manifested as hemorrhaging, pericardial and yolk sac edema, craniofacial and spinal deformities, and induction of P450 (CYP1A) enzymes (Hose et al. 1996; Carls et al. 1999; Colavecchia et al. 2004; Schein et al. 2009). A spill that affected fish spawning grounds could impair the recruitment of the next generation of fish, especially if the oil was mixed into the water by a chemical dispersant (to clean up the spill) or the natural turbulence of a fast-flowing river (Schein et al. 2009).

Sump failure

Sumps are holes dug in the ground for the disposal of liquid waste, such as drilling mud or camp grey water. Sumps are often used in remote areas due to the high transportation costs associated with removal of heavy liquid waste products. When a sump is full they are usually capped with soil and allowed to refreeze naturally; however, there have been issues with sumps thawing and slumping and with ponding of water on the surface and edges of capped sumps (Fig. 3). In addition, as air temperatures at the end of winter (April) are trending warmer than in the past (Environment Canada 2010), drilling wastes normally deposited at this time may not freeze completely before the sump is capped. This can result in the drilling wastes seeping upwards and being released into the environment (Kanigan and Kokelj 2010). If the climate continues to warm, sumps built in cold permafrost (–6.0 °C mean annual ground temperature) will stay frozen longer than those in warm permafrost (–3.0 °C mean annual ground temperature; Kanigan and Kokelj 2010). Therefore, the locations of future sumps must be chosen carefully to minimize sump failure, or alternate waste disposal methodologies may be required. Sump failure can be harmful to fish if wastes get into fish bearing waters.

Removal of raparian vegetation

By necessity, riparian vegetation at crossing locations needs to be removed when constructing a watercourse crossing (Fig. 2). Riparian vegetation is critical in stabilizing stream banks, controlling erosion, and filtering contaminants. Insects and other small animals use riparian vegetation as habitat and when they fall into the water they become an important food source for fishes (Allan et al. 2003). Leaves and branches falling into the water from the riparian zone also provide nutrients and structure to the stream ecosystem (Smokorowski and Pratt 2006). Some researchers suggest that overhanging vegetation is important as it moderates water temperature through shading (Johansen et al. 2005; see Smokorowski and Pratt 2007 for more references), while others believe that shading can be detrimental, limiting light penetration and in situ productivity (Growns et al. 2003; see Smokorowski and Pratt 2007 for more references). Reduced in-stream structural complexity can be detrimental to fish diversity and can change species composition (Smokorowski and Pratt 2006). Crossings associated with linear developments are normally constructed perpendicular to the flow of a stream. The amount of riparian clearing at each crossing site varies, but is usually less than 100 m wide, and an individual stream rarely gets crossed more than a few times by a single pipeline development. To mitigate potential impacts, riparian vegetation can be removed in such a way that root masses are maintained to provide bank stability. The extent of riparian vegetation removal can be localized and minimized, and the resultant impacts from a single pipeline development are likely negligible to the overall functioning of a stream if best management practices are followed; however, if there is an erosion issue on a clear-water stream, the impacts could be significant and continuous if not properly addressed in the early stages. The use of heavy machinery along stream banks can compact soil, which in turn decreases infiltration and increases runoff. Compacted soils are difficult for plant roots to penetrate and stabilize (Cott and Moore 2003).

Infilling and dredging of habitat

Infilling is the term used to describe activities that result in aquatic habitats being physically covered with material. Such materials are often obtained from terrestrial sources, but may also be acquired by dredging of nearby aquatic habitats. In addition to habitat destruction within the footprint of the infilled area, infilling can also introduce sediments and other materials into waterbodies. Infilling is commonly required when constructing barge landings, water intake structures, and even artificial islands (e.g., Imperial Oil, Norman Wells) for well pads in large lakes or rivers. As with infilling, dredging results in destruction of benthic habitats by removing substrates, re-suspending sediments, and smothering substrates in areas where suspended sediments settle. Both of these activities can have adverse effects on fish through direct effects on the fish themselves (i.e., due to exposure to suspended sediment) or by reducing the quality or quantity of habitat that is available to them (Semple et al. 1995; Schueler 1997).

Fishing pressure

The areas of the NWT in which linear developments from oil and gas exploration and other developments are occurring are very remote and the fisheries resources found in these areas have been previously protected by virtue of their inaccessibility. However, these large-scale developments are dependent on delivering a workforce to these previously inaccessible areas. The combination of increased access to potential fisheries and increased populations can have serious implications for fish populations (Post et al. 2002). Many fish in the NWT are slow-growing, late-maturing, and spawn inconsistently after reaching maturity to conserve resources (see Richardson et al. 2001; Evans et al. 2002). This low productivity makes northern fishes particularly sensitive to overexploitation (Healey 1978; Sullivan 2003). In low-productivity systems prey is limited, making northern fishes (particularly piscivores) that have received little or no fishing pressure vulnerable to angling (Schindler 2001). The low productivity of northern systems also makes fish populations, especially slow-growing species, vulnerable to subsistence and commercial fishing (Schindler 2001). When access is gained to a previously unexploited fish populaton, the consequences can be dramatic (Gunn and Sein 2000; Sullivan 2003). For example, Gunn and Sein (2000) examined the effects of a 12 km forestry road built into a small lake that was previously inaccessible by road. The road was not marked, maintained (plowed during the winter), or advertised. Fishing for Lake Trout by the public began the winter following construction and continued for five months until catches dropped off, making the location unattractive to anglers. The short fishery resulted in a population reduction of 70% compared to pre-access abundance estimates, indicating that angling pressure can have a tremendous impact on fisheries resources in boreal lakes. A project of the magnitude of the previously proposed MGP would require a workforce of about 9000, which is equivalent to approximately 20% of the 2011 population of the entire NWT (GNWT 2011; Statistics

Canada 2012). This large influx of people has the potential to drastically increase the fishing pressure. Despite an abundance of lakes and rivers in the NWT, the limited transportation infrastructure concentrates fishing pressure on waterbodies that are readily accessible. Unless fishing is controlled using sound fisheries management strategies with public participation, fish populations near these access routes could easily become overexploited.

Introduction of non-native species

Introduced species are a substantial and growing threat to the integrity of aquatic ecosystems worldwide (Deacutis and Ribb 2002). The results of studies conducted in the United States and elsewhere show that exchange of ballast water from transoceanic vessels represents the single largest transport vector of non-native aquatic species (Carlton 1996; Ruiz et al. 1997). As oil and gas resources are commonly transported to foreign markets by transoceanic vessels, introductions of exotic, possibly invasive, species into the NWT have the potential to occur when barges coming from Asia exchange ballast water in the Mackenzie River. It is not known what impact such alterations in flora and fauna associated with ballast-water-associated introductions could have on northern ecosystems. The extreme climate of the NWT has probably precluded the establishment of invasive species thus far; however, with a warming climate this could change (Schindler 2001). There are many instances of range expansions of North American species historically residing in more southerly climates into the NWT, such as Pacific salmon (Dunmall et al. 2013). If these species can gain a foothold, then it is possible that non-native invasive species can as well, and could out-compete native species, resulting in large-scale and unpredictable shifts in ecosystems. Interbasin transfers of aquatic organisms can also occur in association with oil and gas development activities. More specifically, movement of water from lakes and rivers to facilitate various aspects of pipeline development could result in native aquatic organisms from one area being transferred to another inadvertently (Rahel 2007; Kerfoot et al. 2011). Such transfers could introduce species into areas where they previously did not occur. Furthermore, different populations of the same species that have been genetically isolated for a long period of time could be inadvertently intermingled through such inter-basin transfers (Brunner et al. 1998). Such mixing of fish populations could have implications for genetic diversity and the fitness of populations. Finally, while the use of live bait for angling is prohibited in the NWT (Drake and Mandrak 2014*a*), there is the potential for bait-bucket transfer of potentially invasive species from upstream jurisdictions or through illegal use of bait in NWT waters. The use of live bait has been shown to be a significant vector of invasive aquatic species (including pathogens), particularly in large waterbodies that sustain high fishing pressure (Drake and Mandrak 2014*b*).

Summary

Linear developments associated with oil and gas exploration and development, like those of transportation and other industry sectors, have the potential to negatively impact northern fishes. By virtue of their ecology, northern fishes are particularly vulnerable to impacts (Reist et al. 2006; Christiansen et al. 2013). When development activities increase in an area the impacts associated with these activities become cumulative in space and time. The cumulative effects of anthropogenic impacts, natural disturbances, and more complex stressors, such as climate change, can exacerbate the negative effects to fish and fish habitats and can be difficult to predict (Bradford and Irvine 2000). Heightened environmental awareness has led to advances in technology and best management practices that work to minimize impacts to fish. Also, directed and applied research and monitoring efforts on key development activities have allowed for the development of more effective mitigation and threshold determination. This, when coupled with continued research on the ecology of northern fishes, allows for more sound management decisions to be made. However, many large data gaps exist in both our understanding of how linear developments impact fish as well as our knowledge of northern fish ecology. These knowledge gaps are particularly pronounced when using new unproven technologies or when operating in areas where the fish and aquatic systems have not been well studied. Proper monitoring is needed at existing developments, and such monitoring needs to be adaptive to be able to respond to change and additional stressors. Also, when new "hot spots" are identified where future development is likely, monitoring programs should be designed and implemented that are capable of monitoring change over time. Collectively, pre-development data and the use of representative un-impacted reference sites should be collected to establish ecological baseline conditions. Regardless of the monitoring conducted on existing or anticipated linear developments, plans should be developed that will allow for adaptive management that can mitigate impacts effectively when detected early. Fish are an integral component of northern aquatic ecosystems and add to the biodiversity of the NWT. In the NWT, fish are actively used for commercial, recreational, and subsistence purposes, and are of significant economic and cultural importance to northern people. Healthy fish populations and habitats also epitomise the northern wilderness that Canadians value as part of our national identity. Linear developments are required to facilitate the natural resource projects that drive Canada's economy, but should be conducted in a manner that maintains the integrity of our aquatic ecosystems.

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