Potential Impacts of Beaver on Oil Sands Reclamation Success – an Analysis of Available Literature

B. Eaton, J.T. Fisher, T. Muhly and S-L. Chai

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REPORT SUMMARY

The North American beaver (*Castor canadensis*) is a large semi-aquatic rodent that has played a central role in shaping the Canadian boreal landscape, and colonial Canadian history. Exploitation of North American beaver populations to supply the European hat industry spurred the westward expansion of European explorers and traders into the continental interior. With intensive unregulated harvest, beavers virtually disappeared across much of their range; though populations are recovering, the species is only about 10% as abundant as it was before the fur trade took its toll. As a result, much of the recent ecological history of the Canadian boreal forest has occurred in the absence of this keystone ecosystem engineer, and the ecological state that we perceive as natural is in many regions quite different than it was a century ago.

Beavers, while playing an important role in structuring streams and wetlands by altering vegetation communities and water flow patterns, may also affect human structures. In the mineable oil sands region of northeastern Alberta, much of the landscape will be impacted by mining. Mine sites will have to be reclaimed, and those reclaimed sites will consist of engineered landforms (including water bodies and waterways); the long-term hydrological and ecological function of those sites may be vulnerable to beaver activity. In an effort to determine if approaches exist that could manage the risk of beavers colonizing and negatively impacting reclaimed sites, we performed an extensive literature search and analysis. Our objective was to examine characteristics of beaver ecology that might potentially impact reclamation plans, and to identify possible methods to mitigate those impacts. We also include information on traditional use, historical abundance, and current abundance in the mineable oil sands region to provide important historical and ecological context. Although beavers inhabit a range of aquatic habitats, the focus of our review is on watercourses that could be dammed by beavers. Of the aquatic habitats which will be constructed during reclamation, these systems are probably the most vulnerable to impacts from beaver activity. Note, however, that inlet and outflow streams from lakes may be vulnerable to beaver activity, which could impact the performance of constructed lakes in a variety of ways.

Beavers alter stream form and function, create wetlands, and change vegetation patterns. The most important predictor of beaver occurrence is stream gradient, with low gradients being associated with higher beaver activity. Stream depth and width, soil drainage, and stream substrate are also important. Although beavers may also respond to vegetation factors, such as tree or shrub species and density, hydrological factors are more important predictors of beaver occupancy of a site.

The primary forage preferred by beavers includes deciduous tree and shrub species. Aspen (*Populous tremuloides*) is the species most preferred by beaver, and is a common component of reclamation plantings and natural recolonization of reclamation sites in the oil sands region. Beavers are central-place foragers, meaning foraging is concentrated around a central home base. They typically harvest deciduous trees and shrubs up to 60 m or more from the water, but most harvest occurs less than 30 to 40 m from the water's edge. Predation (and predation risk) restricts the size of beavers' foraging areas, and may also regulate their population size. Management of wolf populations to limit predation on caribou in northeastern Alberta may have

significant indirect effects on beaver abundance and distribution by releasing them from predation pressure.

The boreal forest ecosystem of Canada evolved over millennia with the beaver as a keystone species altering hydrological systems, creating vast areas of wetlands and beaver meadows, changing vegetation communities and modifying geomorphological processes. Reclamation of functional ecosystems in the region must therefore integrate beavers and their engineered structures. The most ecologically- and cost-effective approach is to design reclaimed areas with the objective of including beaver, but directing beaver activity to areas away from vulnerable reclamation structures. Ecological function requires the presence of beaver on the post-reclamation landscape, and the species is important to First Nations peoples and other trappers in the area. Although beaver abundance can be expected to increase in the area after reclamation, their activities will result in the replacement of existing vegetation with species of lower nutritional quality to beaver (conifer trees). This is expected to result in a beaver population decline and then stabilization over time. With beavers an integral component of the functional landscape, it is important to create "beaver exclusion zones" to ensure that the impact of the species is diverted to areas where beaver activity does not damage reclamation structures.

There are very few existing studies of beaver impacts to reclaimed areas. Incorporating ecologically-based strategies for keeping beaver density low in sensitive areas at the outset of a reclamation project, and then monitoring the effectiveness of that strategy, is the best advice that can be derived from our analysis of the existing literature. Beavers could be discouraged from settling at a site by creating streams with steep gradients (>10%) that are wide and deep enough to ensure substantial water flows, are armoured with rock or cobble bottoms, and are bordered by coniferous tree species and/or grass and sedge species. Trees should be planted at high density to prevent growth of shrubs and deciduous trees in the understory, as these are preferred by beaver. Deciduous vegetation should not be planted during reclamation near sites where beavers are to be excluded, and it may be necessary to remove existing deciduous trees and shrubs and replace them with conifers, grasses and sedges in these areas. Although planting specific types of vegetation may be used to discourage beavers from settling a certain area in the short term, natural succession could eventually result in other vegetation communities attractive to beavers. Therefore, unless long-term vegetation management is envisioned, reclamation plans should not rely on using vegetation to dissuade beaver activity in sensitive areas alone, though this approach may be used in combination with other methods, especially in the few decades immediately following reclamation. Note that the goal is to plan for a maintenance-free environment in which ongoing beaver control is unnecessary, and the use of multiple strategies in tandem to guide beaver activity is more likely to achieve this goal.

More active, maintenance-intensive techniques could be used to limit the damage caused by beaver dams to sensitive areas. These techniques include lethal (e.g., kill trapping or shooting) and nonlethal (e.g., relocation) methods to reduce population density. However, these methods require constant effort, and can be expensive. Another approach is to manipulate water flow through existing beaver dams using pipe drainage systems; this allows the beaver dam to stay in place, while reducing the risk that it will trap enough water to be dangerous if the dam should fail. Again, however, these drainage systems require long-term maintenance.

One approach may be more sustainable in the long term and require less maintenance: minimize or maximize water flow through engineered channels, as beavers are less likely to use very low-flow and very high-flow watercourses. Note that beavers may still affect these channels, especially when population densities are high or other habitat is unavailable; however, the probability of beavers affecting very low-flow or high-flow channels is lower than for watercourses with more moderate flows. Creating several dispersed low-flow channels may make an area less desirable to beavers compared to a single moderate flow channel. Similarly, multiple low- to moderate-flow channels could be created, with some having characteristics that attract beavers ("decoys") and others that do not ("exclusions"), allowing water flow to continue through some channels even in the presence of beavers. "Pre-dam" fences can be installed on decoy streams to create a structure to encourage beavers to occupy a site where damage is not a concern. Discharge could be controlled by regulating water flow through exclusion streams that are not dammed, or by installing flow devices though dams on decoy streams. A similar approach might be used on culverts that allow streams to flow beneath roadways; flow devices could be used proactively at these sites, and/or oversized culverts could be installed to allow maintenance of the natural width of the stream channel and reduce the noise of running water, which attracts beaver activity.

Although many different landforms on the reclaimed landscape may be vulnerable to beaver activity, a few are considered critical areas where beaver impacts must be controlled, including the outlets of lakes, side-hill drainage systems, and constructed peatlands. Beaver activity at the outlet of constructed lakes could cause instability in containment structures, negatively affect littoral and riparian zones around the lake, and increase the probability of catastrophic outburst flooding. Damming of side-hill drainage systems could cause stream avulsion and routing of water flow into a new pathway not engineered for a stream, causing increased erosion. Flooding of constructed peatlands could convert them to open-water systems, thereby subverting their intended ecological function. These critical areas should be protected from beaver activities, while other areas should be designed to accommodate this important species.

In practice, several different approaches – tailored to specific situations and landforms – will be necessary to develop and implement plans that accommodate beavers as a part of the post-reclamation landscape. As so few data exist to inform effective reclamation in the presence of beavers, all of the methods we suggest carry an unknown degree of risk. This risk can be decreased in the future by adapting methods based on observed effectiveness. We recommend implementing a research and adaptive management program on the influence of beavers on reclamation within the context of oil sands reclamation in northeast Alberta. Lack of existing information, particularly in northeast Alberta, illustrates the need to implement research that documents the positive and negative influence of beavers on reclamation sites and tests alternative methods to prevent negative and support positive influences. Otherwise reclamation strategies will be ad-hoc and tenuous, with a mixed success rate. A research and monitoring program would ideally contribute to a standardized strategic approach to mitigating negative beaver influences on reclamation of watercourses in the oil sands region.

Beavers are, to a certain extent, unpredictable. No single approach will guarantee that a site will be unaffected by beaver activity. We suggest that multiple management approaches be simultaneously implemented at sites that are particularly vulnerable or critical for the functioning of the reclaimed landscape (e.g., outlet streams from constructed lakes). It is impossible to predict all eventualities, as the character of the reclaimed landscape will change over time due to successional processes, fire, global climate change, and resource extraction. The information we provide is the best available based on limited current knowledge, and provides the best chance for minimizing risk while accommodating this keystone species. Ultimately, the presence of beavers on reclaimed oil sands leases will increase biodiversity, enhance ecosystem goods and services, and assist in developing ecosystems that are consistent with natural systems in the boreal region.

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1 INTRODUCTION

1.1 Background

The beaver (*Castor canadensis*) is a cultural icon in Canada, featured on Alberta's coat of arms – where the imperial crown is supported on the back of a beaver – gracing our nickel, and adorning the entrance to the House of Parliament (Figure 1). The prominence of this unassuming rodent in our national culture is founded on the central role the beaver played in fueling the exploration of the lands that would become Canada. The demand for beaver pelts to satisfy the European fashion industry's desire for waterproof beaver hats spurred trade with aboriginal populations, establishment of trading posts, and drove fur traders farther and farther into the continental interior to find untapped beaver populations. As a result, starting in the early 1600s, local beaver populations were sequentially overexploited in an expanding wave that originated in eastern North America and spread west and north across the continent (Innis 1956). Beaver harvests were highest in the periods of 1700 to 1709 and 1790 to 1799, and generally declined after 1800 (Johnson and Chance 1974, Obbard et al. 1987). By 1900, the species was extirpated in many areas, and almost extinct in North America (Naiman et al. 1988).

Figure 1. A carved beaver adorns the entrance to the Canadian House of Parliament, Ottawa, Ontario.
Photo by B. Eaton.

Beaver overexploitation and local extinctions occurred in many areas of western North America before widespread European settlement, so many of the cultural memories and records that non-aboriginal peoples have of western Canada developed on a landscape unnaturally devoid of beavers (Naiman et al. 1988), a phenomenon known as "shifting baselines" (Papworth et al. 2009, Pauly 1995). As a result of this shifted baseline, current populations been incorrectly described as a "population explosion" (Novak 1987), but are in fact part of a slow return toward pre-European colonization beaver populations. Beaver recovery has created much conflict between beavers and humans, largely as a result of the predilection shared by both species to change the landscape to suit their own needs, which have often been at odds with landscape management. As a result many beavers have been labeled as nuisance animals and have been killed, relocated, or have had their dams and/or lodges destroyed (Boyle and Owens 2007, Butler 1991). However, beaver-altered habitats provide a variety of important ecological functions, such as:

1. water availability and storage (Hood and Bayley 2008a, Westbrook et al. 2006)
2. flood wave attenuation (Hillman 1998)
3. sediment storage (Butler and Malanson 2005, Green and Westbrook 2009, Pollock et al. 2003)
4. improved water quality (Maret et al. 1987, Naiman et al. 1986)
5. production of habitat for an array of other species (Aznar and Desrochers 2008, Cunningham et al. 2007, Karraker and Gibbs 2009, Nummi and Hahtola 2008, Ray et al. 2004, Rolauffs et al. 2001, Stevens et al. 2006, 2007) and
6. increased regional biodiversity (Wright et al. 2002).

Beaver have been suggested or used as restoration agents for enhancing degraded streams (McColley et al. 2011, Pollock et al. 2007). A recent analysis of the economic value of restoring beavers to a watershed in Utah suggested that, if beavers reached their regional potential, the annual value of the beavers and their activities could range from tens to hundreds of millions of dollars (Buckley et al. 2011).

In this report we review and analyze existing literature to examine beaver ecology and assess opportunities to mitigate their impact on reclamation in Alberta's mineable oil sands region. We describe the basic ecology of the beaver in North America, provide historical context in terms of past and current distribution and abundance, discuss the potential of the species to impact a variety of aquatic habitats, and offer management suggestions to accommodate the beaver in mine reclamation plans. We also offer management options for cases where beaver activity must be minimized to protect critical hydrological functions or containment structures on the reclaimed landscape.

Although beavers inhabit a range of aquatic habitats, including small streams to large rivers, and bogs to lakes, most research has been done on the effect of beavers constructing dams on watercourses, and these systems are the focus of the current review. Watercourses, in the context of this report, include streams in the vicinity of potentially vulnerable reclaimed areas, the inlet and outlet streams of constructed lakes, and sites where streams pass through culverts. Of reclaimed aquatic habitats in the mineable oil sands region, these systems are probably the most vulnerable to impacts from beaver activity. This is especially true of the inlets and outlets of constructed lakes, where beaver dams could raise the lake level (John and Klein 2004), impacting the littoral and riparian zones, potentially lead to containment failure, and increase the risk of catastrophic dam failure with subsequent negative impacts on downstream landforms (Butler and Malanson 2005). In addition, burrowing by beavers in the banks of constructed lakes, especially near the outlet, might contribute to the instability of retaining structures. Side-hill drainage systems may also be vulnerable to beaver impacts; damming in these systems could cause stream avulsion and routing of water flow into a new, unengineered pathway, and cause increased erosion (McKenna, pers. comm.).

The high risk for impact of beavers on stream systems is due to the ability of beavers to transform watercourses from lotic to lentic systems, with concomitant changes in hydrology, sedimentation patterns, stream physico-chemical characteristics, biotic communities and floodplain and riparian vegetation. Beavers may colonize larger watercourses or water bodies as well, and can establish bank dens, lodges and food caches (Butler and Malanson 1994, Collen and Gibson 2001, Naiman et al. 1988, Wheatley 1997), but do not build dams at these sites. Bank dens can cause increased erosion along the shores of ponds, lakes, and rivers, but these are typically relatively small-scale impacts (Butler 1995). However, burrows in earthen works, such as dykes, may cause structural failure in some cases (Bayoumi and Meguild 2011). Beavers may also dig canals over 100 m long to provide access to food or bank dens (Berry 1923, Butler 1995, Müller-Schwarze and Sun 2003). Canals can extend beavers' influence on vegetation around a pond, affecting erosion rates and vegetation composition. However, little is currently known about the effects and extent of beaver canals.

Flooding of constructed wetlands and watercourses by beaver activity is common elsewhere (Fitzgerald and Thompson 1988, McKinstry and Anderson 1999). For example, beavers dammed the outlet of a tailings dam near Matachewan, Ontario, resulting in a dam breach which sent tons of toxic tailings into the Montreal River (Baker et al. 1996). Beaver dams have also triggered landslides along the MacKay and Christina Rivers in the oil sands region (McKenna, pers. comm.).

The objective for oil sands reclamation involves creating self-sustaining landscapes with a mixture of boreal forest land uses (including wildlife habitat, recreation, forestry, and traditional land uses) that do not require long-term maintenance (Johnson and Miyanishi 2008). Oil sands mining companies are mandated to return the landscapes they mine to functional ecosystems with capabilities equivalent to, or better than, pre-disturbance conditions (Alberta Environment 1999). To create functional equivalency with boreal ecosystems, the reclaimed landscape must include beavers, as they fulfill critical ecological roles in these systems, enhance habitat heterogeneity, promote biodiversity, and are an important part of traditional aboriginal culture in the region. Thus, reclamation plans for the mineable oil sands region of Alberta must incorporate approaches to accommodate beavers on the landscape while protecting critical engineered structures. Closure and reclamation plans submitted by oil sands mine operators in

2011 indicate the reclaimed mine landscapes will include hundreds of kilometres of recreated stream channels, hundreds of constructed wetlands, and as many as 30 end pit lakes – all of which may be impacted by beaver activity.

There is little guidance available to operators and regulators regarding design and construction of reclaimed streams, wetlands, and lakes in the oil sands region that will accommodate beaver activity in most areas, reduce the likelihood of beaver activity impacting critical areas, and manage the residual risks of beaver activity in the absence of long-term maintenance. Many of the design decisions need to be made early in the closure planning process (in particular stream routing and geometry and dyke freeboard). Even given good design and construction, it may not be possible to reduce the residual risk of poor landscape performance due to beaver activity to an acceptable level without long-term maintenance. Even in this case, however, the speed with which beavers are able to construct and repair dams may preclude cost-effective active management.

This report provides background and design guidance related to beaver ecology, potential impacts to reclamation, and possible management actions based on the available literature and experience in the oil sands region to date. Most of this information comes from areas other than the mineable oil sands, and little research has been done on beaver ecology in the oil sands region. Therefore, the guidance provided in this review should be interpreted with this caveat in mind: information derived from the literature provides a good framework for understanding potential beaver impacts on the reclaimed landscape, and the factors that influence the location and severity of those impacts, but data from the mineable oil sands region are needed to provide local context and more precise information. To provide locally-relevant guidance, we strongly suggest that research be undertaken on the distribution and biophysical correlates of beaver structure-building that might impact performance of the reclaimed landscape. In addition, the persistence of, and area impacted by, these structures in different sites should be monitored to evaluate effectiveness, and modified to minimize ongoing risk.

1.2 Methods

We used Boolean algebra queries in a number of databases to search the scientific and grey literature for information relevant to this project. The databases queried included AGRICOLA, BIOSIS, Environmental Sciences, Enviroline, Wilson's Biological & Agricultural Index, SciSearch, NTIS: National Technical Information Service, ASFA (Aquatic Sciences and Fisheries Abstracts), Water Resources Abstracts, and TULSA (Petroleum Abstracts). A description of each database is provided in Appendix 1.

Search terms used to find relevant literature included restoration, reclamation, ecology, habitat, control, diet, population, *Castor canadensis*, North America, Canada, and Alberta. Note that papers related to Europe or South America were generally excluded from the literature search, unless they contained information relevant to restoration that was not available based on North American studies. Database queries are presented in Appendix 2. Additional papers were found by the authors through independent searches using web-based engines such as Google Scholar, by backtracking the citations in papers and forward tracking to find newer research articles that referenced particular papers, and through searches of the CEMA online library. In addition, colleagues periodically passed on papers of interest, and key individuals were interviewed to obtain relevant information for this report.

2 BEAVER ECOLOGY

2.1 Preferred Habitats

Beavers forage on land but live in water, making the wetland-terrestrial interface critical to their survival. Beavers require minimum water depths for overwintering, and will often engineer their environment to provide that habitat (Naiman et al. 1988). The most important habitat factor related to beaver occurrence is stream gradient, where low gradients (≤6%) are positively related to beaver occurrence (Allen 1983, Beck et al. 2009, Beier and Barrett 1987, Curtis and Jensen 2004, Howard and Larson 1985, McComb et al. 1990, Payne 1989, Smith 1950, Suzuki and McComb 1998). Gradients above 10% become unsuitable habitat for beaver (Suzuki and McComb 1998). Beaver also occur in streams with wider valleys (>45 m – Retzer et al. 1956, >25 m – Suzuki and McComb 1998). They are positively associated with wider and deeper streams (Beier and Barrett 1987, Howard and Larson 1985, Slough and Sadleir 1977), although only up to a point at which water flow becomes too strong for beaver dams to be maintained. It is important to consider the interaction between stream gradient, width and depth (i.e., water flow rate) when evaluating beaver habitat; low-grade wide and deep streams may not be dammed, whereas narrow and shallow high-grade streams may be dammed (McComb et al. 1990). For example, Suzuki and McComb (1998) found that beavers were positively associated with streams three to four metres wide, but were not found in streams greater than 10 m wide. Research in South Carolina found that beaver dams were positively associated with watershed sizes of 2,500 ha, but found almost no dams in watersheds < 500 ha or >5,000 ha in size (Jakes et al. 2007). Soil drainage may also be an important habitat factor for beaver, as well-drained soils were found to be negatively associated with beavers (Howard and Larson 1985). Finally, stream substrates consisting of rock and cobble may discourage construction of dams (McComb et al. 1990) and therefore use of water bodies by beavers.

Beavers in general are associated with deciduous tree (e.g., *Populous tremuloides*, *P. balsimifera*) and shrub (e.g., *Salix* spp., *Alnus* spp.) vegetation cover (Allen 1983, Beck et al. 2009, Beier and Barrett 1987, Novakowski 1967, Payne 1989, Slough and Sadleir 1977). Trembling aspen (*P. tremuloides*) in particular is important vegetation for beaver (Beck et al. 2009, Novakowski 1967, Payne 1989, Slough and Sadleir 1977). Beavers are, therefore, generally associated with early- to mid-successional vegetation stages and shade-intolerant vegetation species that benefit from disturbances such as fire and logging (Fryxell 2001, Payne 1989). Although beavers typically prefer deciduous vegetation, forage is generally less important to beaver distribution and abundance than is hydrology (Barnes and Mallik 1997, Beier and Barrett 1987). Notably, the apparently lower importance of vegetation to beavers may be a real ecological signal, or instead a result of the inherent difficulty in measuring vegetation-beaver associations – since beavers cause significant changes to vegetation communities at settled sites (Suzuki and McComb 1998).

In general, beavers are attracted to water bodies with low gradients and moderate water flows with deciduous vegetation along the banks. Beaver settlement could be minimized by creating streams with steep gradients (>10%; Suzuki and McComb 1998), that are wide and deep enough to support substantial water flows, are armoured with rock and cobble bottoms and are bordered by coniferous tree species and/or grass and sedge species. Low-flow streams or small watersheds (<500 ha) may also be less preferred by beavers (Jakes et al. 2007, Suzuki and McComb 1998); however, beavers may be adaptable to this type of habitat where preferred habitat is unavailable. For example, beavers in Minnesota were found in bogs lacking open water (Ray et al. 2004, Rebertus 1986). Creating preferred "decoy" habitat for beavers may be important in excluding beavers from reclaimed areas.

Observed habitat associations do not preclude the possibility that beavers will settle sites with less-preferred vegetation. As beaver populations increase and preferred habitats are occupied, suboptimal habitat will be colonized (DeStefano et al. 2006, Naiman et al. 1988, Nolet and Rosell 1994). This a common phenomenon in ecological systems and subtopimal habitats play an important role in population dynamics (Fretwell and Calver 1969, Kennedy and Gray 1993). Suboptimal habitats may be only temporarily occupied if they lack suitable vegetation for food and construction, if periodic high flows destroy the dam at regular intervals, or if low flows prevent the accumulation of deep enough water to allow overwintering (Howard and Larson 1985, Nolet and Rosell 1994, Slough and Sadleir 1977). However, they may remain occupied sufficiently long to damage reclamation structures.

In the mineable oil sands region, beavers are moving into some reclaimed areas once the trees are approximately 10 years old or where there is a natural source of aspen nearby (McKenna, pers. comm.). Whether reclaimed areas represent quality habitat for beavers, and are therefore being actively selected by these animals, or are actually lower quality habitat being settled by dispersing individuals who cannot access higher quality sites (Nolet and Rosell 1994) is presently unknown.

2.2 Diet

Beavers forage primarily on highly nutritious deciduous tree and shrub species. Specifically, they forage on aspen, willows (*Salix* spp.), alder (*Alnus* spp.), beaked hazel (*Corylus cornuta*), maple (*Acer* spp.), raspberry (*Rubus idaeus*), and birch (*Betula papyrifera*) (Aldous 1938, Allen 1983, Barnes and Mallik 2001, Donkor and Fryxell 1999, Doucet and Fryxell 1993, Fryxell 2001). On average, beaver subsist primarily on deciduous species (Brenner 1962, Allen 1983) rather than conifer species (Novak 1987). However, beavers may add some conifer to their diet in winter months or where it is highly abundant relative to deciduous species. Conifer species may be used in dam construction (Barnes and Mallik 2001).

Beavers select some deciduous plant and tree species over others, and this selection changes with increasing distance from the pond, suggesting that tree-species distribution with respect to the pond edge can influence beaver foraging (Gallant et al. 2004). Willow (*Salix* spp.), trembling aspen, pin cherry, beaked hazelnut, and *Rubus* species all occur extensively in northern Alberta, and are highly selected by beavers. Aspen are the preferred species for beavers, where available

(Aldous 1938, Barnes and Mallik 2001, Brenner 1962, Doucet and Fryxell 1993, Hall 1960, Hood and Bayley 2008b, Johnston and Naiman 1990c). Beavers can have a significant impact on aspen at a site, reducing aspen density and basal area by an order of magnitude (from 100s to 10s of stems/ha and 10s to 1s m^2/ha, respectively; Moen et al. 1990), nearly completely removing all aspen from many sites (Martell et al. 2006, Naiman et al. 1988).

Beavers can harvest 1.4 metric tons of woody biomass per ha in a year (Johnston and Naiman 1990c). A single beaver colony (i.e., 6 to 7 individuals consisting of an adult female, adult male, and two years of offspring) can consume up to 1 ha of deciduous forest/year, which can influence vegetation within 10s of ha around a lodge (McKenna et al. 2000). Brenner (1962) estimated that, based on daily food consumption rates of a beaver, 0.4 ha of aspen could support up to 10 beavers for one year, if herbaceous species were utilized in the spring and summer months.

Typically, beavers select smaller trees over larger ones of the same species for harvesting, exhibiting increasing preference for smaller trees with distance from shore (Aldous 1938, Jenkins 1980). However, this relationship may depend on habitat quality; in higher quality habitat beavers may be more selective in terms of species taken and will take fewer, but larger, stems at greater distances from shore (Gallant et al. 2004). At some sites aspen may respond to beaver foraging by producing toxic chemicals in sprouts, resulting in beavers selecting for older and larger aspen trees that do not have this compound, even though they have relatively lower nutritional value compared to younger aspen (Basey et al. 1988, 1990).

The bark of deciduous woody plant species is an important food source during the winter (Aleksiuk 1970, Nolet et al. 1994). Despite their preference for aspen, beavers are forage generalists and can exploit a variety of deciduous and succulent plants. Beavers also consume species of aquatic vegetation during the summer, such as cattails (*Typha* spp.; Beer 1942) and water lilies (*Nymphaeaceae* spp.; Doucet and Fryxell 1993, Northcott 1971). One unusual food type that beavers have been observed foraging on is discarded Chinook salmon (*Oncorhynchus tshawytscha*) carcasses in Alaska (Gleason et al. 2005).

The opportunistic nature of beaver foraging emphasizes the risk inherent in managing forage availability to affect beaver occurrence at reclaimed sites within a landscape. A reclaimed system seeking to minimize beaver damage could be planted with conifer-dominated stands with a high stem density that precludes shrubs and deciduous trees in the understory. Efforts should be made to remove and/or avoid planting deciduous vegetation. Coniferous vegetation and/or sedges and grasses would be less attractive to beavers, but only if highly preferred vegetation were made available elsewhere (decoy sites). However, natural succession could eventually result in other vegetation communities which attract and sustain beavers. Therefore, unless long-term vegetation management is envisioned, reclamation plans should not rely on using vegetation alone to dissuade beaver activity in sensitive areas. Rather, this approach should be used in combination with other methods, especially in the few decades immediately following reclamation.

2.3 Foraging Range

Beavers are central-place foragers; they cut fewer (but larger) branches and saplings as they move further from their lodge (Fryxell and Doucet 1991, Jenkins 1980, McGinley and Whitham 1985). Beaver home-range size varies by season, and can be up to 10 ha in summer (Wheatley 1997). Beavers can harvest deciduous trees and shrubs <200 m from the edge of the water body where they are centrally located; however, most cutting occurs <40 m from water (Allen 1983, Barnes and Mallik 2001, Donkor and Fryxell 2000, Martell et al. 2006, Voelker and Dooley 2008). Beavers inhabiting rivers tend to forage along the river in a narrow band; for example, Barnes and Dibble (1988) found that almost all stems cut by beaver were <60 m from the river bank, with most foraging <45 m from the water. In northeastern Alberta, Martell (2004) found that the maximum distance from water that beavers would forage was approximately 50 m; McKenna (pers. comm.), working in the same region, estimated a maximum distance of 65 m.

Predation may be an important mechanism limiting the extent that beavers forage from water, as beavers trade-off between energy maximization and predation risk minimization when foraging (Basey and Jenkins 1995). Beavers living in areas with predators have smaller foraging areas than areas without predators (Voelker and Dooley 2008). There is a high degree of variability in beaver space-use, suggesting that beavers are adaptable and actual distances vary with local conditions, and whether they are using lotic or lentic systems. Beavers in rivers tend to forage more along a lateral distribution along the river, rather than a perpendicular distribution from the pond. Reclamation design should manage for the upper end of this range to help ensure effectiveness.

2.4 Dams

Dam heights and sizes are highly variable depending on topography and the availability of building materials (Curry-Lindahl 1967, McComb et al. 1990). A survey of 70 dams and an aerial photo catalogue of 784 dams in northeast Alberta found that, while most dams are 1 to 2 m high, they can reach 3 m high in some situations; few watercourses were found to be too small or too large to be dammed (McKenna et al. 2000). One of the tallest dams recorded (in Wyoming) exceeded a height of 5 m (Grasse and Putnam 1955). The world's longest beaver dam ever recorded, 850 m, was found in Wood Buffalo National Park, Alberta in 2010[1]. In the mineable oil sands region, beaver dams are typically 1 to 3 m high, up to 100s of metres long, are usually on streams with low gradients (e.g., 1%), and form ponds approximately 200 m long (McKenna, pers. comm.). Risk analysis requires more data from the region to define where beaver dams are typically constructed (e.g., stream gradient, width, etc.), the longevity of individual dams, the extent of their upstream impact, changes in vegetation, and potential for aggradation of the stream bed.

[1] See http://www.geostrategis.com/p_beavers-longestdam.htm

2.5 Culverts

Beavers are known to dam or plug culverts, and may cause significant damage by flooding, washing out, or destabilizing roads (Curtis and Jensen 2004, Jensen et al. 2001). Dam-building behaviour is thought to be stimulated by the sound of running water in the culverts, which are often easily plugged because they represent a narrowing of the stream channel as it passes under the roadway (Boyles and Savitzky 2009, Jensen et al. 2001).

Several factors influence the probability that beavers will obstruct a culvert. In New York State, Jensen et al. (2001) found that the size of the culvert inlet opening and stream gradient had a significant effect on the probability a culvert would be plugged. Few culverts on streams with >3% gradient and with oversized culverts were plugged, compared to streams with little gradient that passed through narrow culverts (Jensen et al. 2001). Curtis and Jensen (2004) found that beavers were unlikely to occupy roadside sites near culverts or bridges where the stream gradient was >3% or where >50% of the area within 100 m of the stream was devoid of woody vegetation. This information provides a starting point for mitigating beaver threats to roads, but more data applicable to the oil sands region are needed.

2.6 Canals

Beavers dig canals to extend their foraging area away from the main body of their ponds, (Berry 1923, Müller-Schwarze and Sun 2003), to access bank dens (Butler and Malanson 1994), and to divert water into the ponds they have created (Cowell 1984, Rebertus 1986). Canals may extend from ponds in a dendritic pattern, sometimes linking multiple wetlands together (Hood, pers. comm.). Canals range from less than 1 m to more than 100 m in length, from 0.35 to > 1 m in width, and up to 1 m deep (Berry 1923, Butler 1995, Cowell 1984, Müller-Schwarze and Sun 2003). In some cases, beavers may use excavated sediment to bank both sides of a canal to form a levee (Berry 1923). Similar to the case with bank dens, it is likely that canals are more readily built in relatively soft sediment, and are not constructed in rocky substrates (Olson and Hubert 1994).

Because canals allow beavers to extend their foraging range from a central location, they influence the area over which beaver foraging can impact vegetation composition and structure. However, the form and impact of canals has rarely been examined explicitly, and almost nothing is known of their importance in the mineable oil sands region of Alberta.

2.7 Lodges and Bank Dens

After the dam, the structure mostly commonly associated with beavers is the lodge. A dome-shaped pile of logs, sticks and mud, the lodge provides refuge from enemies and the elements, and a safe place to birth and rear the young. A lodge has several underwater entrances that lead to a hollow space above the water level where beavers can feed, groom and shelter. An air vent is maintained in the top of the structure to provide oxygen. Lodges can range in size up to 6 m in diameter at the water’s surface, and stand over 2 m high and may be constructed in as little as 2 nights (Müller-Schwarze and Sun 2003).

Beavers build the typical lodge – a mound surrounded on all sides by water – in dammed wetlands or in lakes. However, beavers will also dig burrows in the banks of rivers, lakes or ponds, the entrances of which may be covered with a pile of sticks to form a bank den (Müller-Schwarze and Sun 2003). These are often constructed in the banks of rivers too wide to effectively dam (Barnes and Dibble 1988, Gill 1972), but may also be built at pond sites (Ffolliott et al. 1976). Burrows can extend several metres into the bank sediment, disrupting tree root systems and causing tree tipping and bank slumping (Butler and Malanson 1994). In prairie rivers, bank burrows are associated with the presence of riparian trees, moderately dense willow/shrub stands, deeper rivers, channels < 70 m wide, concave to straight bank profiles, and sand/mud bank substrate (Butler and Malanson 1994); burrows are not found where the bank is composed of gravelly or rocky alluvium.

2.8 Density

Density varies with the number of beaver families in an area, and the number of individuals per family. Beaver density is most heavily influenced by historical overexploitation that drove population to near-extinction, and population processes that have allowed beaver to being to recover. For these reasons, it is difficult to disentangle the relative influence of past population processes from local landscape characteristics on beaver density. In a population at equilibrium – which beavers have not likely obtained yet – density is influenced food resources, water depth, mortality rates, and territoriality.

Typically, beaver abundance is reported by proxies, such as the number of beaver dams, bank dens, lodges, or food caches identified during ground, boat, or aerial surveys. These counts are used to estimate the number of beavers in an area using relevant conversion factors, such as the average number of dams used by a family, or the average number of individuals in a family. Estimates of abundance are generally standardized to area or length of river or lakeshore that was surveyed. These assumptions and conversions result in highly variable estimates of beaver density, with unknown but doubtful accuracy; little is well known about beaver densities across their range.

In the northern part of the beavers' range, counts of winter food caches are thought to be the best indicator of relative abundance; a colony is thought to construct only one food cache, but may use multiple dens (Hay 1958, Novak 1987, Salter and Duncan 1986), though colony members generally stay in the same lodge during the winter as a single family unit (Hood, pers. comm.). Caches may be the only visible indicator of colonies that construct bank dens instead of lodges (Westworth 2002), and cache size may provide indirect evidence of the size of individual beaver colonies (Easter-Pilcher 1990). From food-cache surveys conducted in multiple areas between 1975 and 2004, cache density ranges from 0.09 to 0.84/km^2 (data summarized in Westworth 2002 and Hood et al. 2009), where each cache is assumed to represent one colony (Searing 1979 cited in Westworth 2002). This suggests that beaver density in the region ranges from 0.57 to 5.3 beavers/km^2, but with limited precision and unknown accuracy.

The density of beaver dams and lodges can vary one to two orders of magnitude across and even within regions, depending on factors such as stream and forage quality, water levels, and disease

(Table 1) (Collen and Gibson 2001, Fuller and Markl 1987, Novak 1987). Beavers live in highly social colonies but these colonies are territorial; territoriality may limit beaver density (in addition to food carrying capacity and predation; Collen and Gibson 2001) but data to support this contention remain very sparse.

Mean family size for northern populations (Alaska and northern Ontario) is 3.2 to 4.2 (Boyce 1974, Hakala 1952 cited in Novak 1987, Hendry 1966 cited in Novak 1987), though it is considered to average 6.3 individuals per colony for the mineable oil sands region (Searing 1979 cited in Westworth 2002).

Table 1. Beaver densities in North America.

Dam / Lodge Density	**Colony / Family Density**	**Location**	**Source**
0.1 dams/km		Oregon	McComb et al. 1990
2.0 to 3.9 dams/km		Minnesota	Naiman et al. 1988
3.1 dams/km		Camrose Creek, Alberta	Loates and Hvenegaard 2008
8.6 to 16.0 dams/km		Quebec	Naiman et al. 1986
0.57 lodges/km		Camrose Creek, Alberta	Loates and Hvenegaard 2008
	0.01 to 1.5 colonies/km^2	Canada	Larson and Gunson 1983
	0.15 to 4.6 colonies/km^2	North America	Novak 1987
	3.5 colonies/km^2	central Alberta	Larson and Gunson 1983
	3.9 families/km^2	Alberta (aspen parkland)	Novak 1987
	0.4 to 0.9 families/km^2	Northern Alberta	Fuller and Keith 1980
	0.4 to 0.8 colonies /km^2	US (in favourable habitats)	Allen 1983
	0.58 to 0.86 colonies /km^2	central Minnesota	Allen 1983
	0.5 to 0.6 colonies /km	Green River (Colorado and Utah)	Allen 1983
	0.35 colonies /km	Yampa River (Colorado)	Allen 1983

2.9 Natural Predators

Beaver predators (Collen and Gibson 2001) include:

- wolf (*Canis lupus*; Forbes and Theberge 1996; see also Latham et al. 2011)
- coyote (*Canis latrans*; Packard 1960)
- black bear (*Ursus americanus*; Hakala 1952)
- lynx (*Felix lynx*; Saunders 1963)
- wolverine (*Gulo luscus*; Rausch and Pearson 1972)
- otter (*Lutra canadensis*; Reid et al. 1994, Seton 1929)
- red fox (*Vulpes vulpes*; Rosell et al. 1996)
- mink (*Mustela vison*); Rosell et al. 1996)
- cougar (*Felis concolor*; Rosell et al. 1996), and
- fisher (*Martes pennanti*) (Rosell et al. 1996).

Wolves may be the most significant beaver predator (Collen and Gibson 2001, Potvin et al. 1992), and beavers are known to be an important food item of wolves in northeast Alberta (Latham et al. 2011). Wolves may play a role in regulating beaver populations in some areas (Potvin et al. 1992, Shelton and Peterson 1983), as risk of wolf predation may limit the distance that beavers will forage from ponds (Basey and Jenkins 1995, Shelton and Peterson 1983). Three years of wolf control in Quebec resulted in a 20% increase in beaver density in areas where beavers were not trapped (Potvin et al. 1992). Two years post-wolf control, beaver densities declined again to pre-wolf control densities (Potvin et al. 1992). Wolf control to limit predation on caribou in northeast Alberta may, therefore, have significant indirect effects on beaver abundance and distribution, as well as foraging range.

2.10 Traditional Use

Beavers have been historically important for aboriginal peoples (Novak 1987), and remain so today in many aboriginal communities in northern Canada (Kuhnlein et al. 1994, Wein and Freeman 1995, Wein et al. 1991). The beaver has great cultural significance for many aboriginal peoples. The Cree, Dene, and Métis peoples of northeastern Alberta hold the beaver in high regard. Garibaldi (2009) describes it as a cultural keystone species, one important in shaping the cultural identity of a people, and fulfilling major roles in diet, material technology, and/or spiritual practices (Garibaldi and Turner 2004). In some areas, traditional ecological knowledge is being used by aboriginal peoples to actively manage beaver populations to allow sustained harvest (Berkes et al. 2000).

Beaver trapping provides an important source of income for many First Nations and other Canadians. The number of commercially trapped beaver pelts has fluctuated nationally over the past 40 years, and has shown a decline in Alberta over the last 15 years (Figure 2). The number of beaver pelts harvested closely correlated with price per pelt until the early 1990s, after which these two values were only loosely associated (Figure 2). However, trapping beavers for fur remains an important economic activity in Alberta, with approximately 2,400 trappers active in the province in the 2011/12 season (Alberta Environment and Sustainable Resource Development 2012). Although only a small proportion of registered trappers within the province are First Nations (Poole and Mowat 2001), trapping remains an important part of the economy for northern aboriginal communities (Heritage Community Foundation 2000). The average number of beaver pelts collected annually in Alberta from 2007 to 2012 was 12,075; the harvest of beaver pelts for 2011 to 2012 was valued at almost $500,000 (Alberta Environment and Sustainable Resource Development 2012).

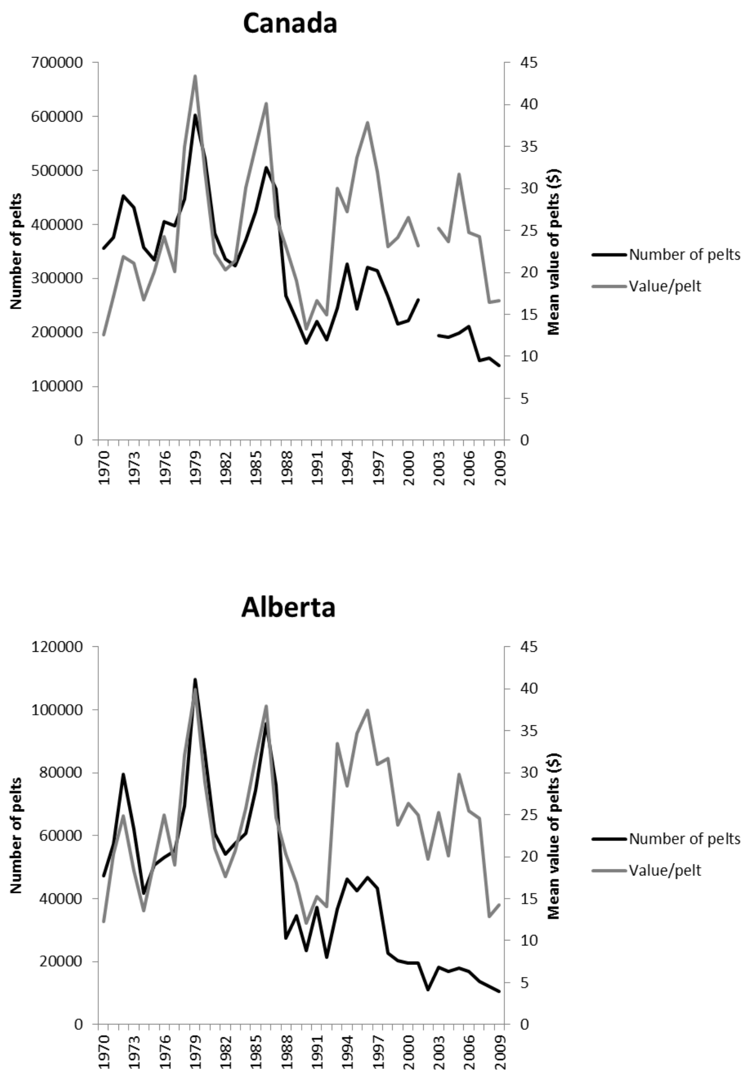


Figure 2. The number of beaver pelts trapped commercially in Canada and Alberta, and the mean value per pelt, 1970 to 2009 (Statistics Canada 2010, 2011a,b). Note that there were no data reported nationally in 2002.

2.11 Distribution and Recovery

The beaver is widespread in North America, occurring throughout the continent from the northern limits of the treeline in the Arctic to the deserts of northern Mexico, and from the Atlantic to the Pacific coasts. Within that range, the species is usually absent from arid regions of the southwestern and midwestern USA where surface water supplies are inadequate, and the Florida panhandle (Novak 1987). It has been estimated that 60 to 400 million beavers inhabited the continent before the arrival of Europeans (Seton 1929). Exploitation of the species on a large scale began in the 17th century in eastern North America, where annual kills of 80,000 animals were recorded in the Hudson River and western New York State from 1630 to 1640; annual exports of approximately 15,000 pelts from the region were still occurring at the end of the 17th century (Duncan 1984). With declining populations in the east, however, trappers and fur traders moved west[2], where massive harvests followed the invention of the steel jaw trap in 1825, resulting in extirpation of the species in much of the Rockies and the Southwest USA (Duncan 1984).

Beaver populations are still recovering from overexploitation and widespread extirpation. Some (unverifiable) estimates claim that 6 to 12 million individual beavers currently inhabit North America (Naiman et al. 1988). It is clear that current beaver abundance in many regions of North America is far lower than before European contact. However, once beavers recolonize an area, they are able to increase in abundance relatively rapidly under the right conditions. For example, the species was exterminated in Ohio, USA, by 1830; it was not until almost 100 years later (1936) that the species was again observed in the state (Chapman 1949). However, by 1961, 317 active colonies were reported from the state; this had increased to 467 colonies (estimated to include 2,260 individual beavers) by 1965 (Bednarik 1966, as reported in Henry and Bookhout 1969).

Evidence derived from chronosequences of aerial photographs indicate that beaver abundance has increased in the mineable oil sands region starting in the mid-1970s, suggesting local recovery of the population from previous severe decline (Martell et al. 2006). This increase mirrors patterns in beaver abundance observed elsewhere. For example, analysis of aerial photographs that spanned 46 years in the boreal forest of northern Minnesota documented rapid expansion of beavers into desirable sites in the first two decades, followed by a period with much slower colonization of additional new habitat (Johnston and Naiman 1990a,b). In total, the number of colonized sites in an area of 294 km^2 increased from 71 to 835 over this period (Johnston and Naiman 1990b).

Beaver recovery is occurring on a continental scale, suggesting that reclamation plans for the mineable oil sands industry will necessarily manage for the presence and activities of beavers. Plans should not be developed only based on current beaver populations, but acknowledge that

[2] For a recent article on historic beaver trapping, and the recovery of the species in North America, see: Backhouse, F., 2012. *Rethinking the beaver*. Canadian Geography, December 2012 issue; http://www.canadiangeographic.ca/magazine/dec12/beaver.asp.

population densities will fluctuate naturally, and will likely increase over the next few decades as the species recovers from past over-exploitation.

2.12 Previous Research on Beaver Impacts to Reclamation

Beavers have significant potential to affect mine sites and reclaimed wetlands. McKenna et al. (2000) cite the damage caused when beavers blocked the spillway of the Matachewan Consolidated Gold tailings dam in Ontario, resulting in overtopping of the reservoir and the release of toxic chemicals into the Montreal River, a tributary of the Ottawa River system. They also describe the potential for beavers to affect reclaimed sites in Alberta's oil sands, but no research on the actual effects yet exists. In fact, very little research has been done on the impacts of beavers on reclaimed sites. The small amount of research that exists suggests that beavers can cause damage by burrowing, which causes soil erosion; by impounding water behind dams, which floods areas and can cause catastrophic erosion in the event of a sudden dam breach; and by removing vegetation through dam-building and foraging activities.

With no information on the effects of beavers on reclaimed sites in North America, it is useful to look at their effects elsewhere as a guide. In Lithuania, European beavers (*Castor fiber*) were one of the most significant sources of damage to land reclamation canals, the most abundant water body in that landscape (Ulevičius et al. 2009). On average, a single beaver colony (of 1 or 2 beavers) impounded 0.4 ha of water. Burrowing activity at a site released a mean of 1.3 m^3 of eroded soil per burrow; at an average of 36 burrows per km of reclamation canal, this resulted in release of 46.8 m^3 of soil per km of canal. The degree of impoundment and burrowing varied with topography; there was more channeling and burrowing activity and wider beaver impoundments in hilly uplands than on flat plains (Jasiulionis and Ulevičius 2011). Though beaver activity damaged the canals, it also provided noted ecological benefits, though these have not been studied long-term (Ulevičius et al. 2009).

The long-term effects of herbivory at reclaimed mine sites remains ambiguous. In a reclaimed mine landscape in Ohio, Voelker and Dooley (2008) found little evidence that beaver foraging (which was restricted to 20 to 40 m from water's edge) altered the successional trajectories of plant communities, a finding that echoed Donkor and Fryxell's (1999) research in boreal forests. However, Voelker and Dooley (2008) recognize the limits of existing short-term evidence to answer these long-term ecological questions, and recommend that much more research is needed to inform our understanding of the effects of beavers on vegetation at reclaimed sites.

Burchsted et al. (2010) show that beaver damming creates patchy discontinuities in stream and river systems, compared to free-flowing water that is characteristic of human-dominated systems. Using hierarchical patch analysis, they illustrate that these discontinuities are important to ecological and hydrogeomorphic functioning of fluvial systems. They contend that river restoration projects must incorporate beaver dams to emulate natural function – such as creating sources and sinks for sediment transport (Butler and Malanson 2005) – but much more research is needed to understand the cumulative impacts of beaver-induced discontinuities (Burchsted et al. 2010).

The Tres Rios Constructed Wetlands project[3] in Arizona also faced beaver problems, as beavers immigrated into the wetland from adjacent areas (Taylor et al. 2008). Though beavers aided ecological processes, they also foraged heavily on woody vegetation and left some areas relatively bereft of vegetation, and undermined constructed dikes and islands. Population densities were high, and moreover, beavers from surrounding areas were likely coming into the constructed wetland to forage (Taylor et al. 2008), possibly in a source-sink population dynamic (*sensu* Fryxell 2001). Thus, a conflict arose between maintaining beavers and their key ecological role in reclaimed ecological systems, and preventing damage to reclaimed systems from over-browsing. The planning assumptions for the project included the following (Taylor et al. 2008), and these assumptions likely apply to reclamation projects in Alberta:

1. ponds provided optimum beaver habitat and beavers would continue to occupy these sites;
2. presence of some beavers should be considered a desirable component of these wetland habitats;
3. current high beaver populations would continue to be a destructive force;
4. under foraging pressure from high beaver populations, the current aquatic vegetation would continue to decline, and over time mature deciduous trees would likely disappear;
5. without management, existing vegetation would be replaced by less palatable and highly competitive species; and
6. beaver populations could be expected to decline with declining habitat quality.

Taylor et al. (2008) researched and tested multiple non-lethal methods to prevent beaver damage, and found them all to be generally ineffective. They recommend more research on the effects of beavers on reclaimed wetlands, and advocate planning for beaver control at the design stages of reclamation projects, instead of reactive actions after beavers become a problem.

2.13 Potential Beaver Impacts on Mineable Oil Sands Reclamation

Since a functional ecosystem is the target for reclamation designs, it is important that these designs incorporate beavers on the landscape, while still protecting sensitive areas. Beavers are, to a certain extent, unpredictable; no single approach will guarantee that a site will be unaffected by beaver activity, but will only alter the relative risk. We suggest that multiple management approaches be simultaneously implemented at sites that are particularly vulnerable or critical for the functioning of the reclaimed landscape. It is impossible to predict future risk, as the reclaimed landscape will change over time due to successional processes, fire, global climate change, and resource extraction. Ultimately, the presence of beavers on reclaimed oil sands

[3] See https://riosalado.crowdmap.com/reports/view/42

leases will increase biodiversity, enhance ecosystem goods and services, and develop ecosystems that are consistent with natural systems in the boreal region.

3 WATER BODY DESIGN IN RECLAMATION PLANS

Surface mining of bitumen-bearing sand in northeast Alberta has, and will continue to, dramatically alter the landscape. Alberta's *Environmental Protection and Enhancement Act* (EPEA) mandates the reclamation of mined areas and plant sites, and associated areas that have been affected by mining and processing activities and infrastructure (e.g., overburden dumps, tailings ponds and disposal areas), to self-sustaining, locally-common boreal forest ecosystems . However, reclaimed ecosystems will differ from the natural systems that formerly occurred in the area in terms of hydrology, soil properties, distribution and diversity of ecosite types, connectivity, habitat complexity, and a host of other factors (Alberta Environment 2008, Brown 2005, Hobbs et al. 2009, Purdy et al. 2005, Richardson et al. 2010). For example, a shift from peatland-dominated systems to areas with increased abundance of marshes, lakes, and upland landforms is expected (Johnson and Miyanishi 2008, Trites et al. 2012).

Here we briefly describe the aquatic systems that will exist on the reclaimed landscape. These are the aquatic systems available to beavers, and beavers will undoubtedly colonize reclaimed areas in the future.

3.1 Lakes

Mined-out pits or excavated areas will be transformed into pit lakes or end-pit lakes on many oil sands leases (Hrynyshyn 2012). These are usually constructed at the lowest topographic position on an individual mine site, and more than one lake may be constructed per lease. Some pit lakes and end-pit lakes will also contain tailings materials and/or process-affected water that will be capped with freshwater. These lakes function as a receiving area for overland drainage from the lease, attenuating peak flows, and retaining and diluting process-affected water. Retention of process-affected water in the lake provides time for microbial activity to assist in the breakdown of toxic naphthenic acids and other organic constituents in the water flowing off the lease, and inputs of freshwater from precipitation assists in diluting the process-affected water, further reducing its toxicity. Constructed lakes also serve as a settling basin for sediment carried by overland water flow. Although they are initially the end-point for water running from the mine lease, pit lakes and end-pit lakes will eventually be connected to the regional water drainage system.

Most constructed lakes will have an inlet stream and outlet stream (Hrynyshyn 2012). These areas represent the locations where beaver activity may have the greatest effect on reclamation and remediation outcomes by changing the intended flow rates into and out of the lake. Water body design teams must determine how to accommodate beaver activity, which may change water balance in constructed lakes or affect the area contributing water to these lakes. Beaver activity on outlet channels may block or reduce flows, raise water levels, and create the potential for catastrophic flooding downstream in the event of dam failure (Hrynyshyn 2012).

3.2 Wetlands

Wetlands were common in the mineable oil sands region before mining began in the area. Bogs and fens covered 43% of the area, marshes 2%, shallow water wetlands 1% and swamps <1%. The current plan for reclamation of the area is to construct wetlands on many of the soft tailings deposits that will be created on the post-mining landscape (Alberta Environment 2008). Creation of marshes is well understood and has been done on the reclaimed oil sands landscape and other areas (Daly 2011). Creation of fens, however, is more difficult, and is an active research area in the mineable oil sands region of Alberta. One of the challenges is that wetlands created during reclamation will have elevated levels of salinity (Trites and Bayley 2009); as a result, vegetation species for some sites may be restricted to salt-tolerant species for some time following reclamation.

Wetlands on reclaimed landscapes may or may not be connected to local groundwater systems. Wetlands which are disconnected from groundwater sources, called “perched wetlands”, rely on overland flow and precipitation for water. Other wetlands will receive water from a wider variety of sources, including groundwater, surface water, precipitation, and seepage from tailing ponds and pit lakes. The base of containment dykes may be an appropriate area to construct saline fens, which would capture and help bioremediate potentially contaminated seepage water (BGC Engineering Inc. 2010). Wetlands may also be associated with the edges of lakes, rivers, and may occur periodically along stream courses, where they are important in controlling flow, promoting sediment retention, and for improving water quality and reducing toxicity.

Beavers may play a dramatic role in the performance of these wetlands, and in many cases may cause significant increases in water depth and changes to hydroperiods. In the case of constructed fens, there are plans to restrict beavers during initial establishment, but recognition that portions of the fens may be converted by beavers into beaver ponds or marshes in the longer term (McKenna, pers. comm.) – a plan that protects engineered structures while allowing natural succession arising from ecological function.

3.3 Rivers/Streams

Although rivers and streams are particularly vulnerable to beaver activity, they are an important component of reclaimed landscapes as they help ensure that adequate flushing occurs to remove saline pore water from mining materials, and avoid excess salinity buildup in vegetation during reclamation. Engineered watershed design minimizes uncontrolled water flow, which could impact the landscape surface, as well as vegetation growth and survival (Carrera-Hernández et al. 2012). Watercourses will be constructed using a dendritic pattern of drainage channels that feed a main outlet channel, which leads to an end pit lake. Constructed creeks collect seepage at the base of dykes and other landforms, and constructed wetlands will attenuate flows and provide bioremediation sites for potentially contaminated water. Watercourses will be designed to exit the lease from one or more points into the naturally-occurring regional drainage system (e.g., the Athabasca River) and may feed into, or cross, neighbouring mine leases.

Rivers and streams on the reclaimed landscape will vary in size, flow rate, depth, substrate, and slope. Watercourses should be constructed to mimic natural systems where possible, including complex substrate, habitat, and bank characteristics, and sinuosity to reduce velocity and provide depositional and erosional zones. Among a list of eight design considerations for drainage channels, Ade et al. (2011) include four with caveats about beaver activity (emphasis added):

1. Adequately sized channels to convey bankfull discharge (considering basin size and land types) and accommodate the high roughness and associated flow depths and widths resulting from *blockages by* debris and *beaver dams*
2. Adequately sized floodplains to convey floods *as a result of numerous beaver dams* and debris accumulation along the length of the channel
3. Deep channel/valley depths (at least 4 m) *in locations where beaver dams are not desired*
4. Passive erosion control features (bed and bank material, bank vegetation, *natural channel obstructions like* debris, *beaver activity* and geometric irregularity)

Adopting these approaches will increase the likelihood of achieving the overall reclamation goal of producing a self-sustaining landscape that approaches natural landscapes in form and function. However, beavers can cause aggradation of stream beds over time, raising valley floors by successive cycles of dam-building with sediment retention in the channel or on the associated floodplain and terraces during overbank floods (Butler and Malanson 2005, Kramer et al. 2012, Ruedemann and Schoonmaker 1938, Westbrook et al. 2011). Sediment accumulation rates vary between rates of 2 to 28 cm/yr (Butler and Malanson 1995), 3 to 6.5 cm/yr (Butler and Malanson 2005), and 4 to 39 cm/yr (Meentemeyer and Butler 1999). Working in a semi-arid region of Oregon, Pollock et al. (2007) estimated that aggradation rates behind 13 beaver dams had occurred at rates as high as 0.47 m/yr shortly following initial dam construction, but had leveled off to 0.075 m/yr by the sixth year after the stream was dammed. The authors estimated that, for one of their sites, it would take approximately 70 years for the current stream bed to rise 3.5 m (Pollock et al. 2007). Note that the rate at which aggradation occurs is influenced by the length of time that a stream is actively dammed, and therefore the number of years a site is occupied by beavers should be used to estimate the rate at which sediment will accumulate. Therefore, beaver activity can change the depth of channels/valleys over time, and may impact the performance of constructed watercourses.

4 RISKS TO RECLAMATION PERFORMANCE

The following section describes the potential impacts of beaver activity on performance of reclaimed streams, lakes/ponds, vegetation, soils and ecosites. Impacts to stream and lake/pond performance may compromise the effectiveness of pit lakes designed to store and remediate oil sands tailings and process-affected water. The potential magnitude of beaver activity such as catastrophic dam failure is high, so mitigating the effects of beaver on reclaimed landscape is of particular importance to manage future risk. This must be balanced with the need to retain beavers for ecosystem function; some reclamation designs actually stipulate the creation of artificial ponds which mimic beaver ponds so that fish can survive in reclaimed watercourses until beavers are able to establish in these systems and form ponds (Shell Canada Limited 2008).

4.1 Potential Impacts to Stream Performance

Beavers primarily impact stream performance by creating dams to impound water. Impounding water can significantly impact stream morphology and hydrography, sediment and organic matter deposition and ultimately the structure of ecological communities (Naiman et al. 1986, 1988), essentially converting lotic ecosystems to a mixed lentic and lotic ecosystem. Impacts of beaver dams on stream performance are complex, depending on watercourse size, successional status, substrate, and hydrological characteristics (Gurnell 1998, Martell et al. 2006, Naiman et al. 1988). Beaver impacts at local scales ultimately scale-up to influence as much as 50% of a landscape (Collen and Gibson 2001) and can persist for decades (Naiman et al. 1988), by influencing stream flow, channel characteristics, siltation and erosion.

4.1.1 *Stream Flow*

Beavers primarily impact stream flow by building dams to contain water, which decreases stream velocity (Naiman et al. 1988) by dissipating stream energy (Gurnell 1998). In general, older beaver dams may be more efficient at reducing stream velocity than newer dams (Meentemeyer and Butler 1999). Beaver dams also stabilize stream flow throughout the year (Collen and Gibson 2001, Gurnell 1998). For example, Duncan (1984) reported that up to 30% of the water in an Oregon catchment was held in beaver ponds during dry periods. Increased water storage due to beaver dams may result in higher water flows in watercourses during typical low-flow periods and locations (e.g., late summer and in intermittent streams; Collen and Gibson 2001). Damming also decreases the magnitude of flooding during peak discharge periods (Gurnell 1998) and increases the recurrence interval of flooding events (Nyssen et al. 2011). The magnitude of beavers' effects on stream flow increases as the number of beaver dams in a watercourse increases (Grasse 1951, Gurnell 1998). Ultimately, the degree to which stream flow is modified varies widely depending on watercourse and ecosystem characteristics (Collen and Gibson 2001, Gurnell 1998, Rosell et al. 2005).

4.1.2 *Channel Modification*

Damming by beavers primarily modifies watercourse channels by increasing their width. For example, the riparian width in streams with beaver dams was found to be triple the size of similar streams without beavers in a Wyoming, USA study (McKinstry et al. 2001). This effect has also been documented in Alberta where beaver activity increased the width of riparian zones along first- and second-order streams (Martell et al. 2006). Hill and Duval (2009) found that a beaver dam constructed in an agricultural area of Ontario caused a 20 m increase in width of the flooded zone adjacent to the stream, with a 1.0 m increase in the depth of the water table in the riparian zone. This resulted in increased soil saturation in this zone, with potential impacts on nitrogen cycling and uptake of nitrates by plants.

Damming also typically gives the channel gradient a stair-step profile (Gurnell 1998, Naiman et al. 1988). Furthermore, damming can increase the complexity of a local channel network as dams encourage the establishment of braided channel systems (Gurnell 1998, Polvi and Wohl 2012). Finally, damming can also decrease channel depth upstream of dams over the long-term through increased trapping of sediment (see next section). Ultimately, beavers increase diversity in channel width and depth along watercourses (Gurnell 1998, Polvi and Wohl 2012).

In addition to creating dams, beavers actively dig canals in areas of relatively low topographic relief. These features may range from <1 m to more than 100 m in length, from 0.35 to >1 m in width, and are typically >0.5 m in depth (Berry 1923, Gurnell 1998). Their main purpose is to transport logs to the lodge or dam, though they may also divert additional water to the beaver pond (Butler and Malanson 1994, Hood and Bayley 2008a), provide access to additional food resources, and serve as travel routes (Gurnell 1998). Canal building increases the zone of influence of beavers on the landscape surrounding their focal pond, and can increase inputs of sediment and nutrients into the pond (Gurnell 1998).

4.1.3 *Blocking of Culverts*

Human activities inevitably come with infrastructure, such as roads, and the construction of culverts to allow water flow under the roadway. Culverts, because they usually cause a narrowing of the stream channel, are often targeted by beavers for damming. Plugging of culverts and flooding of roads are typically amongst the top complaints about beaver damage in different jurisdictions across North America (D'Eon et al. 1995, McKinstry and Anderson 1999, Payne and Peterson 1986, Wigley and Garner 1987).

Roads, and associated culverts, will be common on the reclaimed landscape in the mineable oil sands region; they will be needed to provide access to sites for ongoing reclamation work, monitoring and other activities, and will therefore be potentially vulnerable to beaver activity. Blocking of culverts can cause saturation of the roadbed, resulting in settling, formation of potholes, and loss of road stability; in some cases the road can be completely flooded or washed out (Curtis and Jensen 2004, Jensen et al. 2001, Nolte et al. 2005). This can result in significant road repair costs (Jensen et al. 2001) or ongoing beaver management costs (Boyles and Savitzky 2008).

4.1.4 *Siltation and Sedimentation*

Beaver dams are sediment traps. Dams decrease the velocity of watercourses, which allows sediment to drop from suspension, resulting in increased siltation of watercourse beds (Collen and Gibson 2001). For example, McCullough et al. (2005) found that stream bed aggradation (sediment deposition) averaged 65 cm in a reach where beavers had been established for 12 years. Meentemeyer and Butler (1999) found that the depth of sediment averaged 24.6 cm in beaver ponds <6 years old and 45 cm in ponds >10 years old. Siltation also deposits into the adjacent floodplain due to raised water levels from damming (Pollock et al. 2007). Indeed, siltation due to flooding enlarges the littoral zone and aids establishment of emergent vegetation (Pollock et al. 2007). There is little quantitative information on the volumes of sediment and their rates of accumulation (Gurnell 1998). However, Naiman et al. (1988) found that relatively small dams could retain as much as 6,500 m^3 of sediment. Ultimately, increased sediment storage in the watercourse bed results in decreased sediment yield downstream (Gurnell 1998).

Beaver dams can contribute to the restoration of incised river channels. For example, in the Columbia River basin in eastern Oregon, beaver dams caused increased sediment accumulation and channel aggradation (Pollock et al. 2007). Pond area is a strong predictor of sedimentation volume (Butler and Malanson 1995); other influencing factors are stream discharge, slope, upstream surface material and the extent of erosion-prone areas in the watershed (Meentemeyer and Butler 1999). In Montana, sedimentation volume ranged from 24.6 cm in a young pond (38 m^2) to 267 m^3 in an older pond (588 m^2; Meentemeyer and Butler 1999). In the Colorado River, sediment thickness as a result of beavers was on average 6 cm and ranged to 120 cm. Approximately 750 m^3 of sediment deposition occurred on the floodplain during the dam's 6.5 year life. In a central Ontario beaver pond, 7 to 12 cm of sediment had been deposited during the 20 to 27 years after establishment, a sedimentation rate of 0.35 to 0.6 cm/yr over 20 years or 0.26 to 0.44 cm/yr over 27 years (Butler and Malanson 1995). Palaeoecological evidence suggests that entire valley floors have been raised by beaver activity over millions of years (Ives 1942). Siltation due to beaver dams can also significantly alter stream chemistry, including mitigating stream acidity (Smith et al. 1991).

4.1.5 *Erosion*

Beaver dams decrease discharge amount and rate during peak flow events, thereby reducing the possibility of flooding (Collen and Gibson 2001) and ultimately stream-bank erosion (Apple et al. 1984, Parker 1986). Beaver dams could contribute to greater erosion during the course of routine burrowing, but much more so in the event of dam failure.

Beaver dams typically affect stream channel erosion by increasing channel aggradation as sediment loaded water enters a beaver pond, slowing in velocity and dropping sediment (Parker et al. 1985, Rosell et al. 2005). The introduction of woody debris into streams can help stabilize low-order streams (Gurnell 1998). Downstream of dams, bank sloughing in areas with erosive soils can occur when water underloaded with sediment increase erosion potential as the stream regains lost sediment (Meentemeyer and Butler 1999). Construction of bank burrows in larger rivers can cause tree tipping by disrupting root systems, and bank slumping (Butler and Malanson 1994).

4.1.6 *Potential Impacts of Dam Failure*

Beaver dams can fail due to abandonment, high-intensity precipitation, rapid snowmelt, beavers, muskrats or river otters (Reid et al. 1988) burrowing through the dam, human destruction and increased water pressure following the collapse of upstream dams (Cenderelli 2000). Occasionally, beaver dams can experience catastrophic failures (outburst flooding) resulting in flood-wave action, displacement of sediment downstream, and rapid entrenchment (Butler and Malanson 2005). Failure of one beaver dam in Alberta produced a flood wave which was 3.5 times greater than the maximum discharge recorded in 23 years (Hillman 1998). Failure of one beaver dam can cascade to failures in downstream dams through water-sediment surges (Marston 1994). Cascading dam failures can cause severe erosion. However, risk of erosion due to dam blowout events is typically mitigated in watercourses with multiple beaver dams, as a series of dams acts as a "failsafe" against the impact of a single dam failure (Collen and Gibson 2001).

4.2 Potential Impacts to Lake and Pond Performance

The effect of beaver dams on outflow varies between lentic and lotic systems. While beavers alter lotic systems by causing marked alterations in water movement, lower reductions in kinetic energy occur when beavers dam ponds and lakes. In lakes and ponds, even a low dam at or near the outlet can flood a relatively large area (Johnston and Naiman 1987). The outlets of end pit lakes may be vulnerable to damming by beavers, with the potential for increases in lake depth, destruction of the narrow lake littoral zones, and flooding of riparian areas. For example, Reddoch and Reddoch (2005) documented lake-level rise of 1 m as a consequence of a dam across the outlet of a lake, changing shoreline vegetation. Beavers had a similar effect on a bog, increasing water depth by 0.6 m, impacting the vegetation community (Mitchell and Niering 1993). However, the potential impact of beaver dams on performance of pit lakes in the mineable oil sands region is thought to be extremely small, as the outflow channels will be built with a minimum depth of 4 m to ensure that beaver dams are washed out in the event of a major flood (Shell Canada Limited 2007). Maximum height of beaver dams in the mineable oil sands region is thought to be 2.5 m (Shell Canada Limited 2007), though more data are needed from the region to verify this estimate.

4.3 Potential Impacts to Revegetation Performance

Beavers are ecosystem engineers (Jones et al. 1994, 1997). Through water impoundment, beavers alter the physical, geomorphological, hydrological, and biological components of forest ecosystems at spatial and temporal scales beyond their foraging activities (Naiman and Melillo 1984, Naiman et al. 1986). Beavers remove large amounts of woody vegetation for forage and for dam-building, and the resulting loss of tree density may have significant effects on woody plant biomass and community composition (Barnes and Dibble 1988, Donkor and Fryxell 2000). In the mineable oil sands region, beavers will start to harvest aspen when individual stems reach approximately 4.5 m in height (10 to 15 years after planting) (McKenna, pers. comm.).

Beaver browsing and felling of woody plants impacts boreal systems more than any similar activity in any other biome, as the light and nutrient stresses occurring in boreal systems prevent rapid vegetation regrowth (Johnston and Naiman 1990a).

4.3.1 *Loss of Biomass*

Beavers likely have a greater impact on woody vegetation in riparian zones than any other herbivore, due to the volume and clustered distribution of their harvesting activity (Johnston and Naiman 1990a). An individual beaver cuts approximately a metric ton of wood per year (Johnston and Naiman 1987) during the course of foraging and dam-building. Beavers take both very small saplings and large trees over 40 cm in diameter (Johnston and Naiman 1990a). In California, beaver activity led to the local extinction of *P. tremuloides* and *P. trichocarpa* in 4% to 5% of stream reaches with beaver activity (Beier and Barrett 1987). In Alberta, beavers removed most or all *Populus* trees within 30 to 40 m of occupied ponds (Martell et al. 2006). Johnston and Naiman (1990a) found that a single colony of about six beavers decreased above-ground biomass at a pond by over 40% after only 6 years; a single beaver removed an average of 1.4 Mg/ha/yr of tree biomass. The majority of woody material went unused for foraging or dam-building, and the coarse woody debris left on the forest floor changes a stand's structural complexity.

Beavers may reduce stand biomass loss beyond immediate tree removal; they can also affect tree growth. McGinley and Whitham (1985) found that beaver foraging caused differences in growth form of cottonwoods (*Populus fremontii*), and the degree of this difference varied with distance to water. Close to water, cottonwoods were dense and shrubby with predominately vegetative reproduction; conversely, cottonwood growth was tall and straight, with mainly sexual reproduction, farther from water (McGinley and Whitham 1985). Vegetative (clonal) reproduction after beaver browsing was likewise observed in *P. angustifolia* and *P. tremuloides*. Different growth forms result from a pruning effect from beaver browsing as well as chemical defenses induced by herbivory, which in turn reduced herbivory by beavers (Rosell et al. 2005).

The loss of biomass is intensive, but not extensive, as tree removal is highly clustered in space. As central-place foragers, beavers stay close to water and move out only small distances from that water body; the spatial extent of wood removal is generally limited to less than 60 to 100 m of a water body (Donkor and Fryxell 1999); in Alberta boreal systems 85% or more of foraging occurs within 40 m of a water body (Hood and Bayley 2008b, Martell et al. 2006). Biomass loss from beaver harvesting is thus concentrated close to water, and has much less impact on forest stands beyond this distance. The impact of beaver activity on vegetation community composition may be more widespread.

4.3.2 *Vegetation Composition*

Beavers feed on a variety of terrestrial woody and herbaceous plants, but they do preferentially select some species for foraging (Rosell et al. 2005; see section 2.2 Diet). Beavers also select aspen for dam-building, although conifers are occasionally used as well (Barnes and Mallik 2001). There is also evidence that beavers may preferentially select trees based on stem size instead of species (Barnes and Mallik 1996). The selective removal of woody plants by species and size has the potential to change forest composition and successional trajectory.

Beavers prefer to browse on deciduous species as they are more easily digestible. These early-successional plants require more light and nutrients than do later-successional species such as conifers. Rosell et al. (2005) suggest that boreal forests are therefore highly susceptible to the effects of beaver foraging, since these soils are nutrient-poor and nutrient competition is intense; slight perturbations can alter the outcome of competition and change vegetation composition (see also Flanagan and van Cleve 1983). Removing a large amount of biomass may increase light penetration and decrease competition for soil and nutrients, but the effect of removal on succession is variable. Close to water, more light and nutrients reverses succession and promotes growth of deciduous species; farther from water, conifers may be released from light competition, thus expediting succession (Johnston and Naiman 1990a, Naiman et al. 1988, see also Rosell et al. 2005). More light and nutrients may favour both forage and non-forage species, but data suggest that the trend is to increase net primary productivity of non-forage woody species (Barnes and Dibble 1988, Johnston and Naiman 1990a).

Over long time periods, beaver activity may replace deciduous stands with unpalatable non-forage species in some areas (Rosell et al. 2005). Community composition after replacement is difficult to predict, however, as it depends on local environmental conditions. In Ontario, recruitment by preferred species (*Populus tremuloides*, *Acer* spp., *Corylus cornuta*, *Alnus* spp., and *Salix* spp.) was related to beaver foraging intensity, but also to edaphic (soil) moisture, such that the relative effects of beaver foraging *vs.* soil conditions on vegetation structure could not be reliably disentangled (Donkor and Fryxell 2000).

Although the observed impacts of woodcutting on riparian and terrestrial forest composition have been variable among studies and study areas, trends do emerge. In general, forest stands become more open, and understory vegetation (shrubs, etc.) become more dominant (Johnston and Naiman 1987). Beaver activity increases the dominance of conifers relative to deciduous species close to ponds (Barnes and Mallik 2001, Donkor and Fryxell 2000, Johnston and Naiman 1990a). In Ontario boreal forests, plant species richness and diversity peaked ca. 25 m from ponds (Donkor and Fryxell 2000). Of course, the impacts to vegetation wrought by beavers are not limited to herbivory. Beaver damming impounds water, raising the water table, and changing water availability in adjacent riparian forests (Martell et al. 2006). Changes in water level may flood out and kill some riparian vegetation while favouring others such as willow and alder (Rosell et al. 2005). In flatter areas, inundation will be more widespread and so will the effects on vegetation, but the exact nature of these changes are extremely difficult to predict for any given site.

4.4 Potential Impacts to Soil Performance

Beaver activity was initially thought to increase soil erosion potential by the felling and flooding of trees and other vegetation; however, studies have shown that over the long-term, beaver activity has positively impacted soil performance by reducing erosion potential (Parker 1986), reducing the possibility of flooding (Bergstrom 1985) and increasing nutrient availability in low flow years (Flanagan and van Cleve 1983). These effects are not systematic and vary by site according to geographic location, relief and habitat type (Fuller and Peckarsky 2011, Rosell et al. 2005).

Beaver dams retain precipitation runoff during high flows and slowly release it during periods of drought, an activity which lessens erosion potential during both flooding and drought (Parker 1986). Beaver dams have the potential to protect areas from soil erosion, especially in periods of drought, where aridity is directly linked to soil erosion (Sauchyn et al. 2002). Beavers create and maintain wetlands that lessen aridity, an important ecosystem service given anthropogenic wetland loss and predicted increases in the incidence of drought (Hood and Bayley 2008a).

In the boreal forest where nutrient availability is low, beaver ponds can accumulate nitrate, silica and phosphorous by trapping sediment and organic matter (Correll et al. 2000). These nutrients can influence nutrient cycles across the entire watershed (Naiman et al. 1988), especially in low-flow years. Phosphorous and nitrate concentrations were found to increase downstream of beaver ponds in the Colorado Rocky Mountains in low-flow years; nutrient concentrations decreased in high-flow years due to beaver activity (Fuller and Peckarsky 2011). If beavers abandon their ponds, and their dams resist structural failures in the long-term, nutrients are released from mineralised organic matter and "beaver meadows" are the resulting organically rich, alluvial plains that result from sedimentation (Gurnell 1998).

Beaver impoundments have been linked to increased methyl mercury (MeHg) levels, produced from enhanced microbial activity and oxygen depletion in some areas. MeHg is a potent neurotoxin that can undergo biomagnification in aquatic food webs causing risk in humans who consume affected fish (Roy et al. 2009).

4.5 Spatial Scale of Beaver Impacts

We have necessarily focused here on the local-scale effects of beavers on revegetation performance, but it is important to consider the landscape-scale effects of beavers on vegetation dynamics. Beavers alter the age-distribution of water bodies across a landscape (Martell et al. 2006), thereby affecting species richness at large spatial scales (Wright et al. 2003). As beaver density decreases, the distances between beaver-impacted water bodies may increase, potentially affecting dispersal of plants, recolonization success, and successional trajectories (Wright et al. 2003; see also Johnson and Naiman 1990b). Increased beaver dam density may impede the movement of resident and migratory fish species, especially in periods of low discharge (Kemp et al. 2012, Schlosser 1995, Shell Canada Ltd. 2007). By altering hydrology and vegetation at local scales, beavers increase habitat heterogeneity, thereby increasing species richness of plants at spatial scales encompassing patches with and without beavers (Wright et al. 2002). With marked changes in vegetation come concomitant changes in habitat quality for other wildlife species (e.g., birds, moose) that are adapted to beaver-dominated systems (Jones et al. 1994), although specific effects have rarely been studied.

The spatial extent of beavers' impact on a landscape varies markedly with beaver density and topography (see review in Rosell et al. 2005), but the result is that efforts to manage beavers may affect site-scale succession by impeding landscape-scale plant dispersal and colonization dynamics. However, currently there is not enough research or data upon which to weigh these trade-offs.

4.6 Maintaining Target Ecosites Post-reclamation

It is not straightforward to project the effects of beaver herbivory on the maintenance of post-reclamation target ecosite phases. Barnes and Dibble (1988) projected a major reduction in density of preferred deciduous woody species in beaver-impacted forests in Wisconsin, based on Horn's (1975) model of forest succession. Barnes and Mallik (2001) noted that browsed aspen had not re-established 12 years after abandonment of sites by beavers, and predicted that riparian stands would become dominated by conifers in the absence of a fire event. The existing literature suggests some repeated patterns of beaver impacts:

1. Deciduous trees within 30 to 40 m of the shore may be completely removed;

2. Deciduous species close to water (50 to 200 m, varying among studies) will be heavily browsed and adopt small, bushy growth forms;
3. Conifer species close to water will be much less intensely browsed, but will be occasionally harvested for dams;
4. Stands will be heterogeneous with many light gaps, creating a patchwork of early-successional deciduous and late-successional conifers;
5. Stand understories will contain high densities of coarse woody debris.

The sum effect of beaver activity is high heterogeneity in under- and over-storeys, with conifers having high relative dominance. If target ecosites are planned as heterogeneous stands (rather than homogeneous monocultures for intensive timber production) then achieving target ecosite phases in the presence of beavers is more likely. Notably, forest-stand heterogeneity supports a higher diversity of mammals (Fisher and Wilkinson 2005), birds, vascular plants, and other biotic components (Song 2001), all which contribute to ecosystem function. Since boreal forest species evolved in conjunction with beavers, the range of natural variability currently observed in boreal systems is in part a result of the stand heterogeneity resulting from millennia of beaver activity.

4.7 Examples of Potential Failure Modes on the Reclaimed Landscape

Here we provide a short list of potential ways in which features of the reclaimed landscape may be impacted by beaver activities. This list is not meant to be exhaustive, merely to indicate the potential impacts of beavers on reclamation in the mineable oil sands region.

Examples of potential impacts:

- Blockage of a channel leading to permanent avulsion and erosion of adjacent downslope areas;
- Blockage of a plateau area or lake outlet, leading to a dam breach and a loss of water and/or tailings;
- Outburst floods from catastrophic beaver dam failure, causing erosion of reclamation materials; in some cases outburst flooding may cause a series of beaver dam failures along the same channel;
- Flooding of wetlands, reducing their capacity to provide bioremediation (treatment) or other intended functions; fens may be especially vulnerable to this type of impact;
- Changes to the downstream water balance and duration of flows; and
- Burrowing into banks of channels and dykes causing increased sedimentation and structural failure.

5 RISK MITIGATION OPTIONS

The following section provides tactics for mitigating the risk of beaver activity to reclaimed sites, particularly streams. From a strategic perspective, we reiterate that beavers are native species in the boreal Alberta landscape and key components of a functional boreal ecosystem. Risk mitigation tactics can be applied at the site-level scale to discourage beaver use and/or minimize effects of beavers on a site. However, mitigation tactics should promote beaver use of non-reclaimed areas at landscape and watershed scales. At this large scale, tactics such as decoy streams to encourage beaver use of low risk areas should be applied to mitigate risk at the reclamation site while contributing to landscape functionality.

5.1 Stream Design

Elements can be incorporated into stream designs that will minimize the probability of beavers settling and damming a reclaimed watercourse. Creating stream channels with a steeper stream gradient (>10%; Suzuki and McComb 1998) may be a particularly effective means to deter beavers. However, it may not be feasible to design such channels across much of the flat boreal landscape of northeast Alberta.

Minimizing or maximizing water flow through channels may be another effective means to deter beavers, as beavers are less likely to use very low-flow and very high-flow channels (Jakes et al. 2007, McComb et al. 1990, Suzuki and McComb 1998). This approach only lessens the risk however; beavers may still affect these channels, especially when population density is high or other habitats are unavailable. For example, low-flow channels in the Cooking Lake Moraine east of Edmonton, Alberta – where few streams exist – are heavily targeted by beavers, resulting in flooding issues (Hood, pers. comm.). However, the probability of beavers affecting very low-flow or high-flow channels is lower than for watercourses with more moderate flows.

Creating several dispersed low-flow channels may make an area less desirable to beavers compared to a single moderate flow channel. Such a strategy may be appropriate for very flat and wet landscapes. Similarly, multiple low- to moderate-flow channels could be created with some having characteristics that attract beavers (i.e., stream “decoys”), diverting them from engineered structures that are designed to be less suitable for beavers. This decoy approach can help ensure that flow continues through some channels even with beavers in the landscape.

“Pre-dam” fences (also called beaver fences, deep-water fences and diversion dams) that attract beavers can be installed on decoy streams (Brown et al. 2001). The intent is to create a structure (usually consisting of heavy-wire mesh fence set across a watercourse) to encourage beavers to dam a “decoy” site where damage is not a concern. DeVries et al. (2012) showed that the installation of log flow-choke structures to emulate some of the natural hydraulic functions of beaver dams resulted in greater persistence of natural dams in the inundation zone created by these structures. Flow-chokes were constructed by either (1) installing log walls jutting from the side of the stream that constricted and directed the flow over a sill log on the bed of the stream, or (2) using the same basic design but extending the walls across the entire stream, but leaving an opening in the lower part of the wall to allow over- and through-flow (DeVries et al. 2012). They also used a more passive approach to promote beaver activity in a stream; this consisted of placing large logs (called “beaver assist structures”) in the stream channel to provide a foundation for a future dam. These logs were placed across the stream channel bottom at the crest of a riffle and anchored by driving small logs vertically into the substrate (DeVries et al. 2012).

Water flow downstream could be controlled by regulating water flow through alternate streams that are not dammed, or by installing flow devices through dams on decoy streams (see below). Alternatively, creating channels with high flow rates (i.e., wide and deep) may deter beavers, as dams may be incapable of containing high-flow events. However, again the success of such a design may depend on local topography and watershed size upstream of the reclaimed watercourse.

Armouring stream banks and bed with cobble may also be an effective means to deter beaver damming, as stream substrates consisting of rock and cobble decrease the likelihood that beavers will construct a dam (McComb et al. 1990). Designs that maximize soil drainage around the site may also be effective, as beavers are less likely to dam areas with well drained soils (Howard and Larson 1985), likely because it is more difficult to contain water that easily drains below the soil surface. The effectiveness of these tactics is limited by the practicality of applying them in the wet and flat boreal landscape. Furthermore, a beaver colony can impact an area 10s of hectares in size (McKenna et al. 2000, Wheatley 1997). Beavers may travel by water several hundred metres upstream or downstream to forage and obtain building materials (e.g., up to 800 m upstream and 300 m downstream; Boyce 1980). It may be impractical to apply armouring or soil deposition across such a large area upstream and downstream of the reclaimed site.

Stream-design tactics to deter beavers from settling or damming an area have not been systematically tested to measure their success and practicality across the flat and wet boreal landscape of northeast Alberta. Ideally the various tactics described above should be applied and monitored in various locations to measure their success at deterring beavers. A monitoring program would inform optimal stream design to deter beavers under different environmental conditions.

5.2 Revegetation

Deciduous tree and shrub vegetation species preferred by beavers are described in section 2.2. Alberta Environment (2010) provides guidance on species to be planted in various targeted ecosite phases (see Table G.1 in Alberta Environment 2010). A comparison of these two lists shows that high-quality plants for beavers may be planted in certain ecosite phases when following the reclamation guidelines for forest vegetation (Alberta Environment 2010). However, if mitigation of beaver impacts on the reclaimed landscape is desired, revegetation strategies on these ecosites must be carefully planned to avoid including beaver forage in areas where impacts of beaver activity on stream flow are of concern (e.g., inflow and outflow streams to tailings ponds).

The use of deciduous trees and shrubs should be minimized at reclamation sites where beaver damming and settlement is a concern. Reclaimed tree composition should be conifer-dominated as much as possible (i.e., minimal aspen). In fact, it may be beneficial to remove aspen and willow from areas near the reclaimed site (i.e., approximately 800 m upstream and 300 m downstream), if possible (Curtis and Jensen 2004, Miller 1975; Hood, pers. comm.). However, vegetation removal may be required regularly (e.g., annually) as deciduous species respond favorably to harvest. Planting of conifer species immediately following removal of aspen may be required. Harvest of coniferous forest near reclaimed sites should be avoided as it produces optimal conditions for aspen regeneration, thus attracting beaver activity (Landriault et al. 2009).

Avoiding the use of deciduous species in site reclamation may be challenging, as they are early- to mid-successional species that are typically shade-intolerant and benefit from disturbance (Fryxell 2001, Payne 1989). In addition to mechanical removal of deciduous vegetation at sites, planting sedges and grasses and/or coniferous species should be preferred tactics at sites where beaver damming is a concern. Although beavers prefer aspen, they use many different deciduous species as food. There does not appear to be a particular unpalatable deciduous species that could be planted at sites to deter beavers. The use of vegetation to manage beavers at a particular site should be viewed as a short-term strategy, as it is difficult to predict the long-term trajectory of the vegetation community in the face of natural disturbance (e.g., fire, pest outbreaks), succession, and climate change in a region. Vegetation could be included as one part of a multi-faceted approach to beaver management in an area when combined with engineered approaches to managing substrate and flow.

5.3 Beaver Management

Beaver management programs can consist of (1) lethal and/or non-lethal trapping and removal of beavers; (2) use of beaver deterrents; and (3) the installation and maintenance of devices in beaver dams and watercourses to prevent or minimize damage caused by beavers (Partington 2002). Each of these activities requires at least annual active maintenance and has varying success under different ecological and management conditions. Ultimately, management practices should be tried and evaluated within the Alberta boreal context to assess what combinations of practices are cost-effective for the region.

5.3.1 *Hydrologic Protection*

There are several tools that can be used to prevent damming and/or regulate water flow upstream of beaver dams and thus minimize damage to sites. Fences with unnatural shapes and large perimeters (e.g., triangles, rectangles) can be installed in watercourses to prevent initial damming of the watercourse (Figure 3; Brown et al. 2001, Simon 2006). Typically they are installed to prevent damming of culvert openings (Collen and Gibson 2001), but they could potentially be installed upstream of any narrow section of a watercourse where damming is a concern.

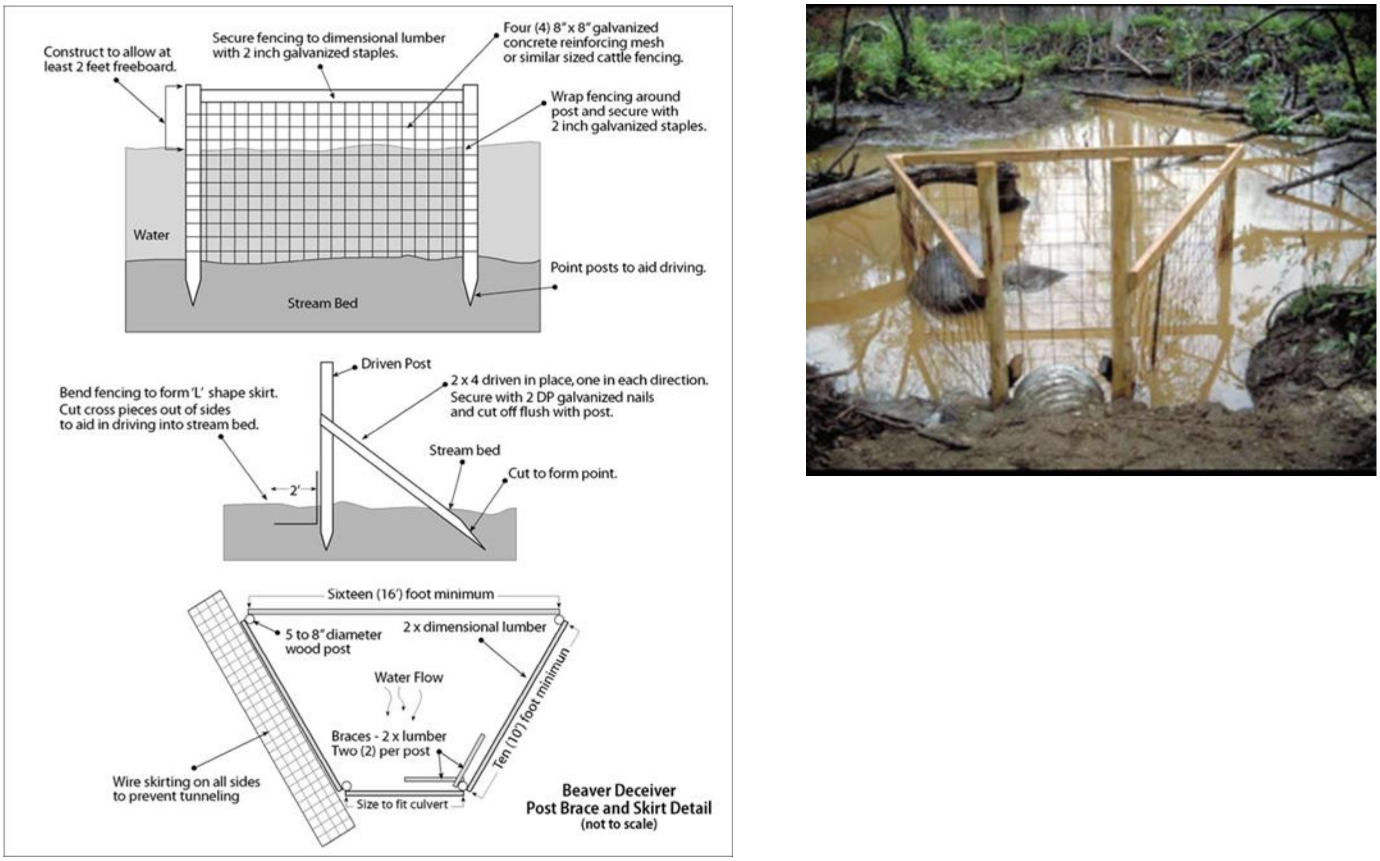


Figure 3. Illustration (left) and picture (right) of fencing installed at culvert opening to prevent damming by beavers.
Fences consist of posts and wire mesh installed tight to stream beds with unnatural shapes and large perimeters. Typically they are installed at culvert openings, but they could potentially be installed upstream of any narrow section along a watercourse.
Illustration: http://wdfw.wa.gov/living/species/graphics/beaver8.jpg;
Photo: http://www.humanesociety.org/assets/images/270x224/animals/beavers/beaver_deceiver_closeup_270x224.jpg

To prevent plugging or damming of culverts associated with roads, culverts should be oversized, with inlet opening areas of at least 2.1 m^2 when streams have a gradient of 0%, and 0.8 m^2 when stream gradient is up to 3% (Jensen et al. 2001). Culverts should always be enlarged to at least the size of the natural stream width to prevent constriction and sounds of running water, which attract beaver activity (Jensen et al. 2001). The probability of beavers damming a culvert drops when stream gradient exceeds 3% or where >50% of the area within 100 m of the culvert is devoid of woody vegetation (Curtis and Jensen 2004). This information can be used to guide landscape design for areas associated with roads on the reclaimed landscape. Landform design can be combined with fencing and other devices (e.g., pond levelers, see below) to reduce the probability of beavers obstructing culverts and damaging roads.

The outlets of end pit lakes may be vulnerable to damming by beavers. Outlet streams may be protected by armouring the stream channel and banks with cobble and by incorporating a French drain that extends 100 m into the lake from the outlet, and a similar distance downstream. This approach would allow water flow to continue, even if beavers do dam the lake outlet. However, there is a risk of sediment build-up over time in French drains, reducing performance (McKenna, pers. comm.). For this reason, it is advisable to combine multiple approaches to protect critical areas such as end pit lake outlets. These might include making the lake outlet 50 to 80 m wide to make it difficult to dam, and providing enough freeboard (e.g., 6 m) to absorb some rise in lake level without failure of the containment structures in the event beavers do dam the lake outlet (McKenna, pers. comm.).

Beavers may construct bank burrows in the side of earthen works, such as dykes and the banks of end pit lakes, sometimes causing structural failure or slumping (Bayoumi and Meguild 2011, Butler and Malanson 1994). Banks can be protected with gravelly or rocky substrates to protect them from burrowing beavers (Olson and Hubert 1994).

Side-hill drainage systems may also be vulnerable to beaver impacts, where damming could cause stream avulsion and routing of water flow into a new, unintended pathway (McKenna, pers. comm.). Approaches to dissuade beavers from colonizing streams should be used at these sites.

Beavers are known to flood peatlands such as fens and bogs even in the absence of channelized water, resulting in conversion to open-water wetlands in some cases (Mitchell and Niering 1993, Rebertus 1986, Reddoch and Reddoch 2005). To protect fens and bogs being constructed during the reclamation process, it may be necessary to monitor potentially sensitive sites and use active means to manage the beaver populations. These could include drainage pipe systems (see below) through any dam constructed at a site and physical removal of the dam and beavers.

5.3.2 *Dam Removal or Alteration*

Physical removal of dams from a site is generally ineffective as beavers quickly rebuild damaged or removed dams rather than move to new areas (Collen and Gibson 2001, Miller 1975). Alternatively, pipe drainage systems can be installed within existing dams to maintain and manipulate water flow along watercourses while maintaining dams in place (Brown et al. 2001, Miller and Yarrow 1994, Partington 2002, Roblee 1984). Drain pipe systems (e.g., “Clemson” pond levelers, Castor Masters, etc.) are designed to move water through a dam in a manner that goes undetected by beavers (Nolte et al. 2000, Simon 2006).

Drain pipe systems consist of a pipe (e.g., wood, metal, PVC, plastic) that runs through the beaver dam, and a caged intake with an end cap that prevents blockage and moves water quietly from underneath (Figure 4). The inlet is usually placed at least 6 m from the dam to minimize the chance that beavers detect the leak (Simon 2006). The height of the outlet is set based on the amount of flow needed through the pipe to maintain minimal desired flooding upstream

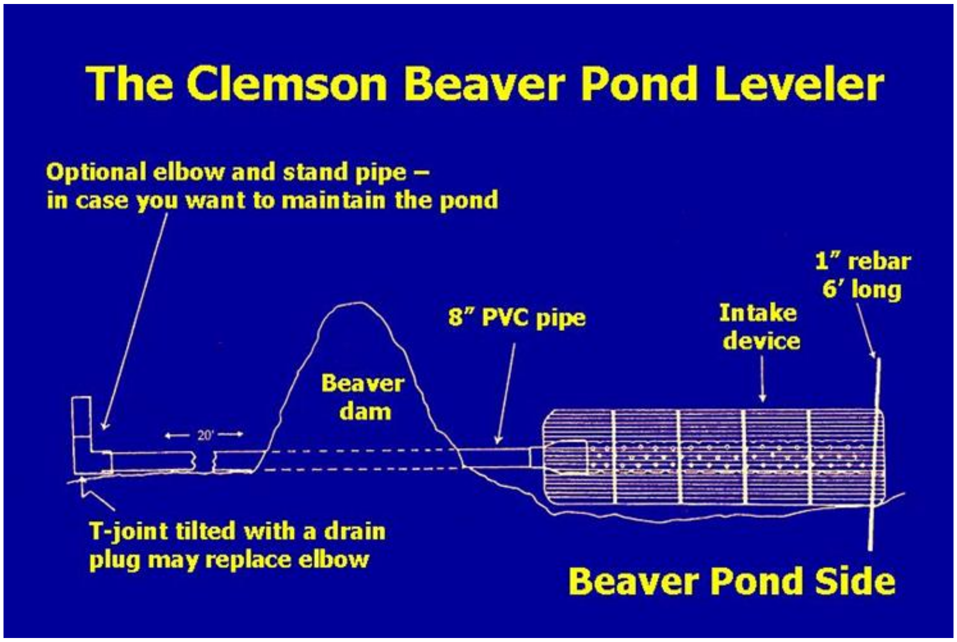
(Laramie 1963). Choosing pipe size can be challenging, as pipes that are too large will allow too much water flow, potentially resulting in beavers damming downstream, and pipe sizes that are too small may be ineffective at maintaining water flow during flood events (Partington 2002). In the Beaver Hills moraine of Alberta, pipe with a diameter of 61 cm (24 inches) works well; the ends of the pipe can be fenced off to prevent tampering by beavers (Hood, pers. comm.). These systems could be emplaced very early – during road construction and culvert installation – as a proactive management tool. Installation may take a day for two people (Roblee 1984). Drain pipes require monthly to yearly checks to clear debris and ensure they are functioning properly (Laramie 1963, Roblee 1984), but routine maintenance typically takes 30 minutes or less (Simon 2006). Devices typically remain in good condition after two years (Nolte et al. 2000). Success rates at controlling water levels vary among sites but have ranged from 98% (Boyles and Savitzky 2009), 87% (Simon 2006), 82% (Roblee 1984) to 50% (Nolte et al. 2000). Success rates are higher when pipes are maintained post-installation (Nolte et al. 2000).

5.3.3 *Barrier Protection*

Physical barriers, such as fencing, may be useful for smaller sites. Beavers do not climb, and therefore fences do not need to be installed particularly high (e.g., 0.5 m above water; Nolte et al. 2003). Note, however, that beavers will pile up mud and debris to the point where they can get over a fence in some cases (Hood, pers. comm.). Beavers also dig, so fencing would have to be sunk into the ground a half metre or more, or a floor should be added to the bottom of the fence to prevent digging (Hood, pers. comm.). Fencing is costly and, therefore, can only be used to cover a limited extent of a watercourse and it impedes movements of other animal species (Nolte et al. 2003), some of which may be important to reclamation, such as seed dispersers.

5.3.4 *Beaver Control*

Lethal control of beavers may be necessary to prevent damage to some sites. However, lethal control is a fairly intensive and requires long-term management commitment; control must occur annually (Fitzgerald and Thompson 1988, Partington 2002, Payne 1989) as beavers will disperse from adjacent areas to fill emptied habitats, particularly if it is high-quality habitat (Nolte et al. 2003). Beavers are capable of dispersing 10s to 100s of kilometres from adjacent sites (Chubbs and Phillips 1994, Hibbard 1958). Nevertheless, once initial lethal control to remove beavers from an area has been completed, annual removal becomes more cost-effective, as heavily exploited beaver populations tend to have lower densities (Nordstrom 1972), higher proportions of younger age classes that die earlier (Boyce 1974, 1981) and fewer young (Peterson and Payne 1986). Trapping using Conibear No. 330 traps is the most simple and effective way of controlling beavers (Collen and Gibson 2001). Other methods of control include: poisoning (Hill 1976); sterilization (Brooks et al. 1980); and shooting (Hammerson 1994, Miller and Yarrow 1994). Trapping may be most appropriate where topography or logistical issues make dam prevention or installation of flow devices difficult, or where there is a high risk of damage to sites due to changes to water flow or flooding (Simon 2006).



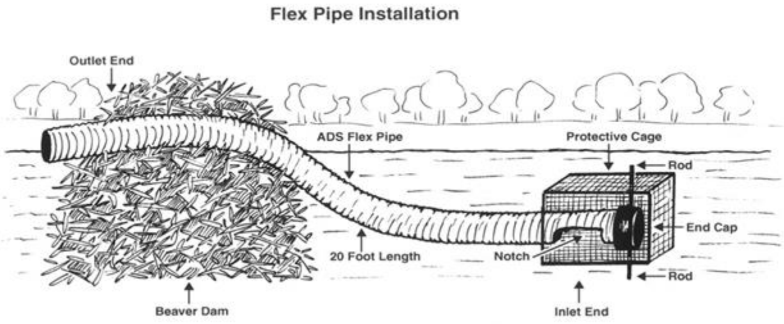


Figure 4. Drain pipe systems installed within beaver dams to regulate water flow. The system typically consists of a pipe (e.g., wood, metal, PVC, plastic) that runs through the beaver dam, and a caged intake with an end cap that prevents blockage and moves water quietly from underneath in a manner that goes undetected by beavers.
Source: top: http://1.bp.blogspot.com/-UmpdmZ9gG3k/TamdsuAfn5I/AAAAAAAAAA4/bdGRzGRN23k/s1600/Clemson_Levelor.jpg; Bottom: Simon 2006.

Direct culling at reclaimed sites may be an effective measure, but an important consideration in lethal control or sterilization programs for any wildlife species is public perception and acceptance of these measures. The general public typically favours non-lethal over lethal control measures in wildlife management (Simon 2006). Furthermore, members of the public that do not experience wildlife damage tend to have more favorable views of the species causing the damage than do others, and beavers appear to be no exception (Jonker et al. 2006, Purdy et al. 1985).

Finally, aboriginal people living in the oil sands region may have unfavourable views of lethal control. Beavers are considered a cultural keystone species by aboriginal people in Fort MacKay, Alberta (Garibaldi and Straker 2009). Therefore, some sectors of the public living inside and outside of the oil sands region may not support lethal control and/or sterilization of beavers to prevent damage to oil sands sites.

Translocation of beavers from areas of concern may be an alternative to lethal control; however, it is generally more expensive and intensive than lethal control. Furthermore, success rates may be low for individual animals at release sites. McKinstry and Anderson (2002) found that within six months of release, 30% of 114 translocated beavers died and 51% dispersed from the release sites.

5.3.5 *Tree and Vegetation Protection*

Vegetation can be protected at sites using textural or chemical repellents at the base of trees (Collen and Gibson 2001, Nolte et al. 2003, Taylor et al. 2008). Textural repellents can include paint, heavy wire mesh, hardware cloth, galvanized metal and tar paper (Collen and Gibson 2001). Nolte et al. (2003) tested the effectiveness of textural repellents at protecting established trees from beavers at wetland sites in Arizona. Trees painted with textural repellent tended to be damaged less often than unprotected trees indicating this tactic was somewhat successful, although trees were not completely protected from damage. Chemical repellents such as commercial deer repellents have been shown to be effective in some cases (de Almeida 1987, Hammerson 1994).

Natural beaver odours capitalize on beavers' territorial nature and may repel beavers from a site. Welsh and Muller-Schwarze (1989) tested the effectiveness of beaver castoreum and anal gland secretion at deterring beavers from colonizing sites and found that scented sites were colonized less often than unscented sites. Muller-Schwarze and Heckman (1980) tested the effectiveness of using preputial gland secretions on "scent mounds" they built near unoccupied beaver lodges at deterring beavers from re-establishing abandoned sites. Scent mounds may act as territorial markers for beavers and deter dispersers from establishing occupied territories (Aleksiuk 1968). Of the seven scented unoccupied lodges none were occupied after four months, compared to four of nine control (i.e., unscented) sites that became occupied.

Faecal extracts from predators may also be an effective means to deter beavers from some sites, but care should be taken when producing these extracts to minimize the risk of transferring disease to animals in the area. Engelhart and Muller-Schwarze (1995) tested the effectiveness of solvent extracts of predator faeces (i.e., wolf, coyote, dog [*Canis familiaris*], black bear, river otter, lynx and African lion [*Panthera leo*]) at deterring beavers from feeding on aspen. They found that 27% of stems were consumed at unscented control sites compared to 17% of stems at scented sites in the summer, and 60% compared to 48% respectively, in autumn. There were no significant differences in effects between types of predator faeces used.

Alternatively, chemicals may be used to attract beavers to decoy sites (i.e., away from areas of concern). Application of fructose and polyethylene glycol can be used to attract beavers to certain sites. For example, they have been used to increase the palatability of invasive species to beavers (Taylor et al. 2008). Chemical deterrents (or attractants) will be most effective when formulated so that they last long in any weather, they are cost-effective and easy to manufacture, when beaver densities are relatively low, and when used in combination with other management tactics (Welsh and Muller-Schwarze 1989).

6 CONCLUSION

Previous studies of beaver impacts to reclaimed or restored areas are extremely limited. Of the research analyzed within our extensive literature search, the conclusions are general in nature: beavers are important to ecosystem function, but allowing high densities of beavers in reclaimed areas results in over-grazing of vegetation, and excessive impoundment of water thus thwarting reclamation objectives. Creating a plan at the outset of a reclamation project for keeping beaver densities low at key watercourse structures is the best advice that may currently be derived from existing research. Tables 2a and 2b provide a summary of potential mitigation strategies in response to different probabilities (called "threat level" in the Tables) that beavers will impact a reclaimed site. These strategies, and the different parameters on which the threat levels are based, have been gleaned from numerous sources, based on studies in a variety of jurisdictions, geomorphic and ecological settings and, therefore, they should be taken as guidelines subject to verification in the oil sands context. A beaver mitigation plan can be derived from existing knowledge, but an active adaptive management plan is needed to research its efficacy in northern Alberta.

Beaver management options summarized above come from beaver research and management programs conducted in different parts of North America. We caution that the management options described above may have greater or lesser success in northeast Alberta compared to other areas. For example, Snodgrass (1997) compared beaver management programs in South Carolina to programs in Minnesota and found substantial differences in success, indicating that outcomes of beaver management programs should be tested regionally.

We recommend implementing a research and adaptive management program on the influence of beavers on reclamation in conjunction with oil sands reclamation in northeast Alberta. Lack of existing information, particularly in northeast Alberta, obviously illustrates the need to implement research that documents the influence of beavers and tests the efficacy of different methods to reduce beaver damage to reclaimed sites. Without such a plan, reclamation strategies will be ad-hoc, high-risk, with a mixed success rate, and with no ability to be reliably imported to other reclamation sites. A research and monitoring program would ideally contribute to a standardized strategic approach to mitigating negative beaver influences on reclamation of watercourses in the oil sands region.

Table 2a. Beaver threat matrix. The factors that influence beaver occurrence at a site are provided, along with how these factors are related to potential impact (threat) from beaver activity on a reclamation landscape.

For each factor, several potential mitigation strategies are provided; while use of some or all of these options is not a guarantee that there will be no beaver activity at a site, they should reduce the likelihood of beaver impact if properly implemented. Note that values provided in the Parameters column are approximations from, in some cases, multiple literature sources; these should be verified by research and monitoring in the oil sands region if possible, and should be taken as guidance, not absolute, values. An example of how to use Table 2a is given in Table 2b.

Characteristic	Parameters	Threat *	Mitigation Strategies †										
			Site level								Landscape level		
Primary factors			1	2	3	4	5	6	7	8	9	10	11
Stream gradient	<6%	High	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
	6% to 10%	Moderate	✓	✓					✓	✓		✓	✓
	>10%	Low											
Valley floor width	Narrow (<25 m)	Low											
	Wide (>25 m)	High	✓		✓	✓		✓	✓	✓	✓	✓	✓
Channel width	Narrow (3 to 4 m)	High	✓	✓			✓	✓	✓	✓	✓	✓	✓
	Moderate (5 to 10 m)	Moderate	✓			✓	✓	✓	✓	✓		✓	✓
	Wide (>10 m)	Low											
Stream depth	Shallow	High	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Moderate	High	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
	Deep	Low											
Area of watershed	Small (<500 ha)	Low											
	Moderate (500 to 5,000 ha)	High	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Large (>5,000 ha)	Low											
Stream flow rate	Low	Low											
	Moderate	High	✓	✓	✓				✓	✓	✓	✓	✓
	High	Low											
Stream velocity	Low	Low											
	High	High	✓	✓				✓	✓	✓	✓	✓	✓
Secondary factors			1	2	3	4	5	6	7	8	9	10	11
Riparian vegetation	Deciduous (especially aspen), shrubs	High	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
	Mixedwood	Moderate	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
	Conifer, grass, sedges	Low											
Soil	Poorly drained	High	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
	Well drained	Low											
Stream substrate	Sediment	High		✓	✓	✓		✓	✓	✓	✓	✓	✓
	Cobble, rock	Low											
Abundance of predators	Low	High	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
	High	Low											

Table 2a. Continued.

* **Threat Level (**note: where multiple Threats exist, design and build to the highest Threat Level)
High – Design and build only in areas where damage is not of concern, or in decoy streams.
Medium – Design and build in areas where variable beaver activity/damage is acceptable.
Low – Design and build in areas where damage is to be avoided or mitigated as much as possible.

† **Beaver mitigation strategies - Implement where the Threat Design and Build Conditions cannot be met**

Site-scale		
Deterrents	1	Armour bottom and banks of stream with cobble or rock. These may be covered in sediment over time, depending on stream velocity and sediment input rates, but should provide protection for a number of years.
	2	Create narrow valleys.
	3	Create wide channels.
	4	Design areas with maximum soil drainage to discourage beaver activity in that area.
	5	Create streams with steep gradients, being aware that erosion may be a concern.
	6	Build multiple separate or braided low-flow channels to discourage beaver activity.
Attractors	7	Install “pre-dam” fences (also called beaver fences, deep-water fences, beaver assist structures and diversion dams) that attract beavers on decoy streams or on non-sensitive reaches of constructed or nearby natural streams to direct beaver activities to non-critical areas; can install pond-levellers (see #8) on these dams to maintain water levels and reduce the risk of catastrophic dam failure.
	8	Use pond levelers or French drains to allow beavers to remain in certain areas on the stream, while reducing the risk of catastrophic dam failure. Pond levelers can be installed in conjunction with pre-dam fences (see #7) or on natural beaver dams in non-sensitive stream reaches.
Landscape-scale		
Deterrents	9	Embed reclaimed habitat within landscapes that facilitate (by design, or naturally) high predator populations to keep beaver populations in check.
	10	Plant buffers around sensitive areas using non-preferred species such as conifer, grasses and sedges. Buffers should be 200 to 300 m wide to prevent beavers from having access to food species.
Attractors	11	Build decoy streams: multiple low- to moderate-flow channels, some with characteristics attractive to beavers, to guide beaver activities to desired areas and away from target sites.

Notes:
Using multiple mitigation strategies increases the level of protection.
It is important to protect the inlets and outlets of engineered lakes and other water bodies to ensure beavers do not change lake levels or develop the potential for failure of engineered landforms (e.g., dykes).

Table 2b. An example of how to use the Beaver Threat Matrix outlined in Table 2a.

A reclaimed stream will have multiple features depending on landform and engineering constraints, and the reclamation objectives for flow and biodiversity. A reclaimed stream can be best protected from beaver activity by not incorporating certain characteristics which would attract beavers when designing and constructing the stream. When this is not possible, reclaimed streams can be protected from beaver activity to some degree by altering other characteristics, as outlined in the Beaver Treat Matrix. For example, a stream may be designed with a low gradient and a narrow channel, in a landscape where wolf abundance is low. All 3 of these factors lead to high risk of beaver activity, which can be mitigated using a combination of strategies; these could include:
Site-scale Strategies
• armouring the bottom with rock or cobble (mitigation option #1 in Table 2a) • creating a narrow valley around the stream (#2) • using soil with maximum drainage ability (#4) • building multiple low-flow channels across the area (#6) • adding pre-dam fences in decoy streams to entice beavers to use these watercourses, rather than the one you are trying to protect (#7) • using pond-levellers on existing beaver dams in the area, or in association with pre-dam fences, to maintain beaver ponds in non-sensitive streams or non-sensitive reaches of the reclaimed stream (#8)
Landscape-scale Strategies
• planting a buffer of conifer adjacent to the stream (#10) • building decoy streams in this landscape that local beavers will use instead of this reclaimed stream (#11)

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8 GLOSSARY

8.1 Terms

Aggradation

Increase in land elevation through deposition of sediment.

Avulsion

The rapid abandonment of a water course by a stream or river and formation of a new channel.

Bankfull Width

The width of a stream from the top of one bank to the top of the other bank at the point where water just begins to overflow onto a floodplain.

Castoreum

A bitter strong-smelling creamy orange-brown substance produced by the castor glands of both male and female beavers. Beavers use this secretion, combined with urine, to mark their territories. The substance is used in the manufacture of perfumes.

Extirpate

Local extermination of a species, although the species still persists in other areas (e.g., a species may be extirpated in Alberta, but still survive in Saskatchewan).

First Order Stream

A first order stream is the smallest of streams; these flow into and "feed" larger streams but do not normally have any water flowing into them. In addition, first and second order streams generally form on steep slopes and flow quickly until they slow down and meet the next order waterway. First through third order streams are also called headwater streams and constitute any waterways in the upper reaches of the watershed.

Lentic

Referring to standing water, as in ponds and lakes.

Lotic

Referring to moving water, as in streams and rivers.

Preputial Gland

Glands located at the front of the genitals of some mammals. The glands produce and secrete pheromones.

Reach

A comparatively short length of river, stream channel or shore. The length of the reach is defined by the purpose of individual studies.

Riparian

Refers to terrain, vegetation or simply a position adjacent to or associated with a stream, flood plain, or standing water body.

Second Order Stream

A joining of two first order streams forms a second order stream.

8.2 Acronyms

CKS	Cultural Keystone Species
EPEA	*Environmental Protection and Enhancement Act*
OSRIN	Oil Sands Research and Information Network
PVC	Polyvinyl Chloride
SEE	School of Energy and the Environment

APPENDIX 1: Databases for Literature Search

AGRICOLA 1970 - present

As one of the most comprehensive sources of U.S. agricultural and life sciences information, the AGRICOLA (AGRICultural OnLine Access) database serves as the catalog and index to the collections of the National Agricultural Library (NAL) and the research of the U.S. Department of Agriculture (USDA). AGRICOLA has been available online since 1970 and contains more than 4.1 million citations to journal articles, book chapters, monographs, theses, patents, software, audiovisual materials, and technical reports related to agriculture. The database contains thousands of records with links to online full-text documents.

AGRICOLA encompasses all aspects of agriculture and allied disciplines, including animal and veterinary sciences, entomology, plant sciences, forestry, aquaculture and fisheries, farming and farming systems, agricultural economics, extension and education, food and human nutrition, agricultural engineering and technology, and earth and environmental sciences. The NAL Agricultural Thesaurus (NALT) and Library of Congress Subject Headings (LCSH) serve as the controlled vocabularies for indexing and cataloging records.

This extensive database has been maintained since 1970 to provide selective worldwide coverage of primary information sources in agriculture and related fields.

BIOSIS 1926 to present

BIOSIS Previews® contains citations from Biological Abstracts® (BA), and Biological Abstracts/Reports, Reviews, and Meetings® (BA/RRM) (formerly BioResearch Index®), the major publications of BIOSIS®. Together, these publications constitute the major English-language service providing comprehensive worldwide coverage of research in the biological and biomedical sciences. Biological Abstracts includes approximately 350,000 accounts of original research yearly from nearly 5,000 primary journal and monograph titles. Biological Abstracts/RRM includes an additional 200,000+ citations a year from meeting abstracts, reviews, books, book chapters, notes, letters, and selected reports.

Environmental Sciences 1967- present

Environmental Sciences contains abstracts and bibliographic citations providing comprehensive coverage of the environmental sciences. The research areas range from agricultural biotechnology and air quality to waste management and water resource issues. Abstracts and citations are drawn from over 6,000 serials including scientific journals, conference proceedings, reports, monographs, books and government publications.

Enviroline 1975 – 2008 coverage ends 2008

Enviroline covers the world's environmental related information. It provides indexing and abstracting coverage of more than 1,000 international primary and secondary publications reporting on all aspects of the environment. These publications highlight such fields as management, technology, planning, law, political science, economics, geology, biology, and chemistry as they relate to environmental issues. Enviroline corresponds to the print Environment Abstracts.

Wilson's Biological & Agricultural Index 1983 - present

Biological & Agricultural Index provides thorough, reliable indexing of 258 periodicals common to most libraries. Periodical coverage includes a wide range of scientific journals, from popular to professional, that pertain to biology and agriculture. About 45% of the focus is on agriculture. Types of materials indexed include feature articles, biographical sketches, reports of symposia and conferences, review articles, abstracts and summaries of papers, selected letters to the editor, special issues or monographic supplements, and book reviews.

SciSearch

SciSearch®: A Cited Reference Science Database is an international, multidisciplinary index to the literature of science, technology, biomedicine, and related disciplines produced by Thomson Scientific. SciSearch contains all of the records published in the Science Citation Index® (SCI®), plus additional records in engineering technology, physical sciences, agriculture, biology, environmental sciences, clinical medicine, and the life sciences. SciSearch indexes all significant items (articles, review papers, meeting abstracts, letters, editorials, book reviews, correction notices, etc.) from more than 6,100 international scientific and technical journals.

NTIS

The NTIS: National Technical Information Service database comprises summaries of U.S. government-sponsored research, development, and engineering, plus analyses prepared by federal agencies, their contractors, or grantees. It is the means through which unclassified, publicly available, unlimited distribution reports are made available for sale from agencies such as NASA, DOD, DOE, HUD, DOT, Department of Commerce, and some 240 other agencies. Additionally, some state and local government agencies contribute summaries of their reports to the database. NTIS also provides access to the results of government-sponsored research and development from countries outside the U.S. Organizations that currently contribute to the NTIS database include: the Japan Ministry of International Trade and Industry (MITI); laboratories administered by the United Kingdom Department of Industry; the German Federal Ministry of Research and Technology (BMFT); the French National Center for Scientific Research (CNRS); and many more.

ASFA (Aquatic Sciences and Fisheries Abstracts) 1971 - present

Overwhelmingly cited by a majority of aquatic science librarians as their primary database, the ASFA (Aquatic Sciences and Fisheries Abstracts) series is the premier reference in the field of aquatic resources. Input to ASFA is provided by a growing international network of information centers monitoring more than 5,000 serial publications, books, reports, conference proceedings, translations, and limited distribution literature. ASFA is a component of the Aquatic Sciences and Fisheries Information System (ASFIS), formed by four United Nations agency sponsors of ASFA and a network of international and national partners.

Water Resources Abstracts 1967 - present

Water Resources Abstracts offers a comprehensive range of water-related topics summarizing the world's technical and scientific literature on water-related topics covering the characteristics, conservation, control, pollution, treatment, use and management of water resources in the life and physical sciences, as well as the engineering and legal aspects of the conservation, control, use, and management of water.

TULSA (Petroleum Abstracts) 1965 - Present

TULSA (Petroleum Abstracts), produced by Petroleum Abstracts, contains bibliographic references with abstracts to scientific articles, patents, meeting papers, and government reports of interest to geologists, geophysicists, petroleum engineers, and other technical professionals and managers in the oil and gas exploration and production industry.

APPENDIX 2: Boolean Terms Used During the Literature Search

Search 1:

Castor canadensis AND North America AND (restoration OR reclamation)

OR

Castor canadensis AND North America AND (ecology or habitat or control or diet or population) NOT (Europe or South America) AND Alberta

Search 2:

Castor canadensis AND North America AND (ecology or habitat or control or diet or population) NOT (Europe or South America) AND Canada

Search 3:

Castor canadensis AND North America AND (ecology, habitat, control, diet, population) NOT (Europe or South America)

Search 4:

Castor canadensis AND North America AND (restoration OR reclamation)

OR

Castor canadensis AND North America AND (ecology or habitat or control or diet or population) NOT (Europe or South America)

LIST OF OSRIN REPORTS

OSRIN reports are available on the University of Alberta's Education & Research Archive at https://era.library.ualberta.ca/public/view/community/uuid:81b7dcc7-78f7-4adf-a703-6688b82090f5. The Technical Report (TR) series documents results of OSRIN funded projects. The Staff Reports (SR) series represent work done by OSRIN staff.

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