**Connectivity in Canadian watersheds: controls on flows and properties of water, sediment and chemicals, and implications for water resources and aquatic ecosystems**

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**Introduction**

One of the greatest impacts of humans on the planet is the fragmentation of landscapes and watersheds. Natural land cover has been modified for agriculture, forestry, urbanization and other land uses, as well as associated infrastructure such as road networks, pipelines and electrical power lines. River channels have been modified by channelization, the construction of dams, reservoirs and hydro-power facilities, and the abstraction of water, amongst others. The individual and cumulative impacts of these modifications have profoundly affected the flows of water and associated constituents – like sediment and chemicals – through watersheds and ultimately their delivery to coastal zones (e.g. deltas) and the global ocean. Thus, Grill et al. (2019), in an assessment of the connectivity of major rivers, determined that only 37% of rivers longer than 1000 km are free-flowing over their entire length and 23% flow uninterrupted to the global ocean. There is a wide variation in the degree to which watershed and river connectivity has been modified, with the greatest disconnectivity (i.e. a reduction in connectivity) typically occurring in areas with the highest population densities. But even in parts of the planet with low population densities, like Canada, Grill et al. (2019) identified that many large rivers, such as the Columbia, Nelson and Mackenzie, are heavily modified.

While most of the disconnectivity in watersheds (i.e., the contributing land and associated channel network) is a function of human activity (Vörösmarty et al., 2010; Grill et al. 2019), there are also “natural” processes and events that modify connectivity. Many of these are associated with climate change, such as changes in precipitation patterns, the increase in the frequency and magnitude of wildfires, and changes in the cryosphere including melting. Thus while Canada may appear to be less impacted compared to many other countries with higher population densities, recent and anticipated global environmental changes are likely to greatly affect connectivity in watersheds. Here, we identify some of the key activities and processes that affect the connectivity of Canadian watersheds. While many of these are likely to affect most watersheds in the world, some of these activities and processes are likely to be especially important in Canada. While emphasis is placed on the flows of water, sediment and chemicals (e.g., nutrients and contaminants), we also consider related properties such as water temperature that are highly impacted by changes in connectivity and thus affect aquatic ecosystems.

**Types of connectivity**

The concept of connectivity in understanding the routing of water, sediment and chemicals in watersheds has received much attention over the last 15 years (e.g. Brierley et al. 2006; Bracken and Croke 2007; Fryirs et al. 2007; Borselli et al. 2008; Bracken et al. 2013, 2015; Fryirs 2013; Poeppl et al. 2020); for useful reviews on water and sediment connectivity see X and Najafi et al. (2020). Conceptually, it is useful to consider connectivity as a combination of structural and functional components (Wainwright et al. 2011), where the former relates to the configuration of landscape elements and the latter addresses process dynamics. Keesstra et al. (2018) have identified that a problem with this approach is that structural connectivity tends to view landscape topography as essentially static over time, whereas over medium to long time scales this may not be true, especially as humans modify the landscape. Instead, Keesstra et al. (2018) advocate that water and sediment connectivity should be considered in terms of time-independent and time-variant properties. The latter is particularly important in the context of global environmental changes, such as land use/land cover and climate changes, where thresholds and boundaries are breached. Thus increases in precipitation could increase surface runoff, thereby increasing connectivity, while decreases in precipitation could decrease surface runoff and connectivity.

**How changes in land use affect connectivity (*emphasis on Canadian situation and examples*)**

* Land clearance increases runoff (e.g. reduced evapotranspiration etc) and soil erosion. This increases connectivity. Deforestation and forest harvesting practices thus important in this context. However, if riparian areas are logged, this may cause an increase in large woody debris in channels which can cause a short- to medium-term decrease in connectivity. Especially relevant for British Columbia. Forest logging results in an increased frequency of landslides. A study carried out by Guthrie (2002) in three watersheds of Vancouver Island indicated up to 12 times more landslides reaching streams following logging activities.
* Large scale agricultural development increases connectivity (runoff, sediment, chemicals) by the removal of physical barriers and by the planned removal of excess water via drainage ditches and subsurface drainage etc. Jackson and Pringle (2010) have demonstrated ecological benefits of reduced hydrologic connectivity in some intensively developed landscapes. There have been recent developments in BMPs to help reverse this (see later section). Prairies (esp. Alberta, Saskatchewan, Manitoba and Ontario).
* Draining of wetlands for agriculture, urban and resource development. This increases connectivity (McCauley et al., 2015). Most of country has seen removal of wetlands?

**How changes in river channels affect connectivity *(emphasis on Canadian situation and examples)***

* Dams and reservoirs, including smaller run-of-river projects. Reduce connectivity via trapping of sediment and associated chemicals, and modifying flow regimes. Modifies (i.e. increases) river water temperatures. Most provinces.
* Channelization in urban areas. Southern part of provinces (esp BC, Ontario, Quebec) but also Edmonton, Saskatoon, Winnipeg, Halifax etc
* Culverts. Highest in large urban centres but also any land use (agriculture, resource development, pipelines etc). Mainly the provinces.

**How changes in climate affect connectivity *(emphasis on Canadian situation and examples)***

*Changes in precipitation (and temperature?)*

* Permafrost degradation across northern Canada, particularly along the southern permafrost boundary. Loss of permafrost may lead to greater soil water infiltration rates and less surface runoff. Degrading and disappearing permafrost may lead to greater subsurface lateral connectivity. Hence a shift from surface to subsurface water flows.
* Greater proportion of precipitation falling as rain rather than snow. Loss of major spring freshets dominated by snowmelt. More rain may result in greater soil water infiltration rates, thus shifting runoff generating mechanisms from the surface to subsurface. This may, however, be offset by greater fractions of convective precipitation with high intensity events where infiltration rates are attenuated and storm flow is instead generated.
* If the Canadian Prairies undergo drying in response to global climate change, reduced connectivity in the Prairie pothole regions. Prairie potholes depend on the “fill and spill” mechanism for surface lateral transfer. Drying of the Canadian Prairies may increase the non-contributing area of the region, affecting mainly the Nelson River Basin.
* Increasing frequency of droughts owing to climate change is also having an effect on hydrological connectivity in lake-dominated watersheds in Canada (Spence et al., 2019). This is happening mainly due to a decline in lake levels below outlet elevations.

Steph and others to cover water connectivity (also water quality (dissolved solids) and water temperature)

*Wildfire*

Recent years have seen a pronounced increase in the magnitude and intensity of wildfires in Canada, especially British Columbia, such that areas burnt are at historic levels. In 2018, for example, about 1% of the land surface of British Columbia experienced wildfires. In Canada, the effects on downstream aquatic systems can be profound, with dramatic changes in the amount and timing of runoff and sediment and chemical fluxes (e.g. Silins et al. 2009; Owens et al. 2013). These changes are often documented for several years following severe wildfires and can extend over large areas (Silins et al. 2014; Emmerton et al. 2020).

Decreases in evapotranspiration and infiltration, and increase in soil hydrophobicity can increase the amount and timing of surface runoff and erosion and discharges of material fluxes in rivers (Owens et al. 2013). These changes occur in the first few years (e.g. 1-3 years) following wildfire after which conditions start to return to pre-fire conditions as vegetation and soils recover. Over the medium term (e.g. 3-10 years), standing burnt trees along the riparian corridor may collapse due to a loss of root strength which may cause log-jams thereby decreasing connectivity. Conversely, the loss of root strength in riparian vegetation and steeper hillslopes may cause bank erosion and shallow mass movements over longer time sales (5-20 years) thereby increasing connectivity for sediment and chemicals.

*The cryosphere*

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**Canadian regional variations in these activities and processes *(summarizing issues addressed above)***

Map and or table

* Urban development – south portion of country from Vancouver to Halifax etc
* Forest harvesting – especially BC
* Agricultural development – especially Prairie provinces but also elsewhere as we see a northward shift in the agricultural sector in coming decades
* Resource development – all provinces and some territories
* Beavers (ephemeral changes in connectivity)
* Changes in precipitation patterns (amounts and timing) – across Canada, greatest changes in the far north, possible drying in southern Canada.
* Wildfire – most forested parts of country
* Cryosphere – glaciers in BC, Alberta and Yukon; permafrost in northern part of provinces and in territories

**Impacts on water resources (?), human water security, aquatic ecosystems**

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**What is required to address issues of connectivity?**

* Limit fragmentation of landscapes and watersheds. Reduce linear structures like roads and pipelines that impede runoff or cross rivers. This will require expanding inventories of road crossing and other instream structures like dams (Januchowski-Hartley et al., 2013).
* In the river channel network, limit the number of dams and structures like culverts that impede flow of water and constituents. Strong movement to decommission dams in the USA for this reason. (Magilligan et al., 2016). Or, have structures that are better designed to meet the needs of the project while meeting environmental objectives; e.g. better designed culverts. Also operation of dams and impediment structures can meet both needs, e.g. summer temperature management plan to supply suitable flows and water temperature in the Nechako River.
* Mitigation measures to control runoff and sediment delivery. This includes such things as changes in tillage practices, retention/detention ponds and in-field and riparian buffers. Typically been utilized most in agricultural landscapes and to an increasing degree in forested and resource development (e.g. mining) land uses. But there is a need to assess their effectiveness especially in the context of multiple stressors (e.g. runoff, sediment, nutrients and contaminants) and what it is that we are trying to protect (e.g. soil degradation vs off-site impacts) (Rickson et al. 2014; Boardman and Foster 2021).
* But we need to consider measures that are relevant to the specific landscape/region in question. Thus in river corridors we may wish to increase connectivity by removing obstructions like dams and culverts. On modified landscapes we may wish to decrease connectivity by installing/recreating wetlands, retention/detention ponds and riparian buffers. In wildfire-impacted landscapes we may wish to decrease connectivity by increasing vegetation cover and protecting riparian zones. Areas of permafrost degradation require special consideration.

**Perspective/closing comments**

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