Hudson Bay IRIS (Chapter 3 – Freshwater System)

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3. Freshwater System

3.1. Introduction

For millions of years, the Hudson Bay system has been slowly and continually evolving through geologic change, glaciation, and flooding. Yet in recent decades, the system has become increasingly more vulnerable to rapid change resulting from human-driven influence (i.e., regulation of freshwater systems, development and climate change). As the largest continental shelf in the world, Hudson Bay depends on annual fluxes of freshwater, with seasonal fluxes impacting the formation, breakup and melt of sea ice. Timing, duration and magnitude of freshwater flux has a major influence on the marine properties, ecological drivers, circulation patterns, and the dynamics of sea ice; with ice-free seasons elongating under climate change (Hochheim and Barber, 2014). With freshwater discharge into Hudson Bay reported to be on the decline from 1964 to 1990, increasing in recent decades (Déry et al. 2005; 2011), increasing winter discharge (Déry et al. 2011), and projected increases in precipitation across the Nelson (McCullough et al. 2012; Clair et al. 1998) and northern Québec watersheds (Sottile et al. 2010); there is much uncertainty around future freshwater discharge. With many of the key physical, biological and biogeochemical processes occurring in Hudson Bay highly dependent on the large freshwater delivery system; improved understanding of the factors influencing, historic trends, and projected futures of the freshwater regime are crucial to our understanding of the Hudson Bay system and its vulnerabilities.

This chapter begins with a description of the Hudson Bay Drainage Basin (HBDB), or landmass, including the major rivers delivering freshwater into the marine system and the human influences (regulation) affecting the timing and delivery of freshwater. Factors affecting the freshwater system such as underlying geology, permafrost, ecological units, and climatology will be discussed. Since climate warming is now occurring at unprecedented rates in the Canadian sub-
arctic (Bhiry et al. 2011), understanding the potential impacts on the freshwater system and resources for Hudson Bay are of particular concern. Projected changes (2021-2070) in river discharge will be framed in the context of historic trends (1964-2013), discussed for 21 of the 42 rivers discharging into the HBDB that have observed streamflow records. Climate-related changes to runoff and discharge resulting from changing temperature and precipitation patterns will be explored using state-of-the-art hydrologic modelling coupled to global climate model (GCM) output. We end the chapter with a brief summary of our state of knowledge for the Hudson Bay freshwater system, and possible future impacts to the system.

### 3.2. The Watershed

Draining surface water from nearly one third of the Canadian landmass into Hudson Bay, the Hudson Bay Drainage Basin (HBDB) is sandwiched between two continental divides (i.e., lines of high elevation): The Laurentian (to the south) and Arctic (to the north). Freshwater enters Hudson Bay through a network of 42 rivers with outlets into Hudson, James, and Ungava Bays (Figure 1). Water is collected from the Canadian provinces of Alberta (AB), Saskatchewan (SK), Manitoba (MB), Ontario (ON) and Québec (QC); the Northwest Territories and Nunavut (NU); and four American States (Montana, North Dakota, South Dakota, and Minnesota), eventually finding its way to Hudson Bay. The landscape spans 26° of latitude, 54° of longitude, eleven ecozones, and rises to more than 3,200 m in the western Rocky Mountain Range. With more than half the basin underlain by isolated to continuous permafrost, and a portion of the basin with non-contributing drainage area (i.e., Assiniboine and Saskatchewan River basins, tributaries of the Nelson River); the watershed is large, remote, and complex in terms of hydrology and climate. Capturing a total of 30% of water runoff in Canada, and its rivers contributing 20% of the Arctic Ocean’s freshwater supply (Canadian Geographic 2016), Hudson Bay is a large freshwater ‘bathtub’ for Canada and the Canadian Arctic.

The gross drainage area, or area that contributes water based on elevation (i.e., topography), of the HBDB is ~3.8 million km². The basin ranges in elevation from 3,200 m at the western headwaters in the Rocky Mountain Ranges (Nelson River headwaters) to 0 m (sea level) at the estuaries and river outlets of Hudson Bay.
3.2.1 Regional watersheds

Hudson Bay is fed by several large (and small) rivers forming regional watersheds that drain water from the surrounding land area (Figure 2). From west to east, the Thelon, Churchill, Nelson, Hayes and Seal to the west; Winisk and Severn in the Southwest; the Ekwan, Attawapiskat, Albany, Abitibi, Moose, and Nottaway along western and southern James Bay; the Rupert, Eastmain, and La Grande Rivière along eastern James Bay; and Grande Rivière de la Baleine, Petite Rivière de la Baleine, Nastapoca to the east; along with Foxe Basin, connected via Hudson Strait to Ungava Bay. Combined, these rivers equate to a mean freshwater discharge of ~950 km$^3$ per year, or about one fifth of the total annual river runoff to the Arctic (Déry et al. 2004; Shiklomanov et al. 2000). Table 1 lists the 42 rivers discharging into Hudson Bay (22 of 42), James Bay (13) and Ungava

Figure 1: Map of the Hudson Bay Drainage Basin (HBDB), and its regional watershed areas.
Bay (7); their size, mean annual discharge, and ranks (by size and mean annual discharge). Of these 42 rivers, some play more significant roles in the freshwater-marine coupling of the Hudson Bay system, and are described in more detail.

**Chesterfield Inlet**

Located in the northwestern arm of Hudson Bay (Figure 2), the inlet is the terminus of the Thelon River. The Thelon drains 900 km across the Northwest Territories (Whitefish Lake) into Baker Lake, NU before discharging into Hudson Bay. The inlet is formed of several islands and bays, and the community of Chesterfield Inlet, NU; residing just south of the Arctic Circle.

**Churchill River**
The Churchill River is the second largest (by area) drainage basin, discharging freshwater along Hudson Bay’s western shore (Table 1) from parts of Alberta, Saskatchewan and northern Manitoba along more than 1,600 km. The river is largely located within Canadian Shield terrain and includes a number of lakes. It is impacted by flow regulation, most notably at Southern Indian Lake where water is partially diverted south into the Burntwood River and then east into Hudson Bay through the Nelson River (Appendix A). Therefore, it is only the 10th largest contributor (by mean annual discharge) of freshwater to Hudson Bay. Regardless, owing to its large drainage area and strong seasonal cycling, the Churchill River estuary is a significant source of freshwater-marine coupling.

Nelson River

The largest by area and freshwater discharge to Hudson Bay (Table 1), the Nelson River drains more than 1.1 million km² of central and western Canada, spanning four provinces (AB, AK, MB, ON), four U.S. States (ND, SD, MN, MT), and Lake Winnipeg. Included in its drainage basin are the Saskatchewan, Assiniboine, Red, Winnipeg, Lake Winnipeg, and (lower) Nelson River basins. Lake Winnipeg (11th largest freshwater lake in the world) drains into the Nelson River, where discharge is impacted by a series of regulation points controlled for hydroelectric production by Manitoba Hydro (Appendix A). The Nelson River estuary along the western shore of Hudson Bay is arguably one of the most significant freshwater-marine couplings in Hudson Bay owing to the large volumes of freshwater discharge and strong seasonal cycles affecting sea ice formation and breakup.

Hayes River

Located just south of the Nelson River, the Hayes River drains parts of northeastern Manitoba before entering Hudson Bay’s western shore immediately south of the Nelson River estuary at York Factory, MB. Originating just 90 km northeast of the northern tip of Lake Winnipeg (at Molson Lake), the river’s drainage basin is the 6th largest (by area) of the Hudson Bay system, and the 11th largest contributor of freshwater discharge to the Bay (Table 1).

Moose

Fourth largest contributor of freshwater discharge to Hudson (James) Bay, the Moose River flows north through the Hudson Plains of James Bay (Ontario) before entering James Bay at Moose
Factory, ON. It is the 7th largest drainage basin of Hudson Bay (Table 1), containing several significant tributaries such as the Abitibi, Mattagami, and Missinaibi Rivers. Affecting the Moose River are four hydroelectric developments from Ontario Power Generation, beginning in the mid-1960s, on the upstream Mattagami and Abitibi Rivers. Relative to the Nelson and La Grande Rivers, Moose River regulation has considerably less impact (i.e., more localized) on freshwater-marine coupling and cycling.

*La Grande Rivière*

Draining a significant portion of north central Québec 900 km westward into James Bay, this river is the 2nd largest in Québec, and 8th largest drainage basin or 2nd largest contributor of freshwater discharge for Hudson Bay (Table 1). Similar to the Nelson, La Grande Rivière is regulated by Hydro-Québec in a series of dikes, dams and reservoirs for hydroelectric production (Appendix A). Several tributaries of the river include the Eastmain, Opinaca, Rupert Rivers, from which water is diverted northwards into the La Grande system for hydropower production; and Caniapiscau River (tributary of the Koksoak River of Ungava Bay), which is diverted southwest into the La Grande. Resulting from its significant freshwater contributions to Hudson (James) Bay and strong seasonal cycles impacted by regulation, this river is critical to the Bay’s freshwater-marine coupling and annual cycling.

*Grande Rivière de la Baleine*

The “Great Whale River” lies to the north of La Grande Rivière, discharging directly into Hudson Bay as the 9th largest contributor of freshwater to the system (Table 1). A branch of this river now originates from the Caniapiscau Reservoir, therefore is similarly impacted by hydroelectric regulation. The lower reaches of the river experience several drops in elevation and therefore have powerful currents and a series of waterfalls and rapids.

*Foxe Basin*

Located in a shallow, north basin of Hudson Bay, Foxe Basin is situated between Baffin Island and Melville Peninsula and connected to Ungava Bay via Hudson Strait. None of the 42 Hudson Bay freshwater systems discharge directly into Foxe Basin, and only a handful of smaller freshwater discharge points exist along its rocky, steep shores. The basin remains significant to
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Hudson Bay freshwater-marine coupling, however, because of strong circulation patterns and thick, rough sea ice which dominates most of the annual cycle.

**Ungava Bay**

Connected to Hudson Bay via Hudson Strait, Ungava Bay is located at the northeast extent of the Hudson Bay drainage basin. Fairly shallow and home to numerous islands, Ungava Bay is separated from Hudson Bay via the Ungava Peninsula, and the Atlantic Ocean via Hudson Strait. Seven of the 42 freshwater rivers enter through Ungava Bay and contribute freshwater to the Labrador Sea, including (in order of drainage area) the Koksoak, Arnaud, Aux Feuilles, George, À la Baleine, Tunulic, and False Rivers, all originating from northern Québec.

*Table 1: Summary of the 42 rivers draining into Hudson Bay, James Bay and Ungava Bay, ordered regionally from west to east along the perimeter of Hudson Bay.*

<table>
<thead>
<tr>
<th>River</th>
<th>Outlet</th>
<th>Province/Territory</th>
<th>Drainage Area, DA (km²)</th>
<th>Rank (DA)</th>
<th>Mean annual discharge, Q (km³)</th>
<th>Rank (Q)</th>
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<td>3,160</td>
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<td>27</td>
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<td>21</td>
<td>6.94*</td>
<td>22</td>
<td></td>
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<tr>
<td>Thlewiaza HB</td>
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<td>27,000</td>
<td>23</td>
<td>6.9</td>
<td>23</td>
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<td>MB</td>
<td>48,100</td>
<td>12</td>
<td>11.4</td>
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<td>1</td>
<td>92.6</td>
<td>1</td>
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<td>Hayes HB</td>
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<td>6</td>
<td>19.4</td>
<td>13</td>
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<td>ON</td>
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<td>JB</td>
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<td>32.6*</td>
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<td>Broadback</td>
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<td>Rupert</td>
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<td>QC</td>
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<td>Eastmain</td>
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<td>QC</td>
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<tr>
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<td>5</td>
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<td>Innuksuac</td>
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<td>3.16*</td>
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<td>2.59*</td>
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<td>De Povungnituk</td>
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<td>3,680</td>
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<td>3,013,945</td>
<td>--</td>
<td>16.7</td>
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</table>

*Estimate based on <30 years of record (not necessarily inclusive of 1964-2013 period); some gauges/estimates seasonal; average of annual flows from Water Survey of Canada HYDAT database.
nd: insufficient points (<=3) to compute mean annual discharge, or data not available.

### 3.2.2. Geology

The HBDB sits within a large rock basin, depressed relative to surrounding Shield regions, consisting of Precambrian Shield and Hudson Platform formations (Stewart and Lockhart 2005). Shield regions are crystalline and typically rolling and deformed, while the younger carbonate-dominated Hudson Platform is more low-lying and flat. Crystalline rock formations are the oldest
and underlie the entire basin, constituting bedrock for the Québec coast (west of the Nottaway River) and eastern half of James Bay. Throughout the remainder of the HBDB, the lower bedrock layer is mixed with younger sedimentary, metamorphic, and volcanic formations from the Hudson Platform (Figure 3).

Glaciation has had a profound effect on the formation of the Hudson Bay coastline, with continental ice sheets covering the basin at least twice in history and possibly as many as seven times (Shilts 1982, 1984). Many of the modern characteristics of the HBDB were formed from the retreat of ancient ice sheets, particularly the retreat of the most recent Laurentide Ice Sheet at the end of the Little Ice Age. Shaping the modern landscape were the abrupt drainages of lakes Agassiz and Barlow-Ojibway, which resulted in the penetration of the Hudson Strait marine system further down into Hudson and James Bays (Josenhans and Zevenhuizen 1990). Glacial retreat has altered the elevation of the drainage basin because of “unloading the land”, resulting in isostatic rebound, or lifting the landmass between 0.7 and 1.3 m per century (varying rates depending on where in the watershed you are) (Barr 1979). In the lowlands, surficial sediments around James Bay and along the western shore of Hudson Bay are heavily influenced by tidal activity and dominated by coastal marshes. At the watershed level, the glaciolacustrine regions of southwestern James Bay will influence the subsurface movement of water. Permafrost and poorly drained sedimentary deposits yield numerous wetlands and highly organic, shallow soil complexes (Tornocai 1982).
Continuous and discontinuous permafrost, common at latitudes above 51°N (Woo 1986), tends to limit the interaction of wetlands with groundwater (Woo and Winter 1993). In the HBDB, permafrost is continuous north of the Cape Henrietta Maria area (boundary between Hudson and James Bays), but transitions to sporadic and isolated moving further south toward the Hudson Bay lowlands (Figure 4). In addition to affecting the hydrology of the region, permafrost acts to stabilize otherwise weak soil and wetland complexes common to the region. Infrastructure in the north has long depended on this added rigidity for construction of roads, railways, buildings and hydroelectric transmission lines. But in response to accelerated warming in Arctic regions, permafrost soil temperatures have increased by approximately 2°C since the 1970s (Burn and Zhang 2009); resulting in slope instability, slumping, and damage to infrastructure that puts
communities and infrastructure at risk (Figure 5). Thermokarst, or the thawing of ice-rich soils that result in subsidence, naturally shapes and erodes the landscape of the HBDB, but is anticipated to do so at a faster pace and in more drastic ways under the influence of accelerated warming due to climate change (Kokelji et al. 2013).

Figure 4: Permafrost regions within the Hudson Bay drainage basin.
3.2.3. Physiography

The landscape of the HBDB spans 11 ecozones (Figure 6): extending from the glacierized, Rocky Mountains at the western edge, moving across the dry Prairie region and continental interior, to the mid-latitude cool-wet Boreal forest region, and northern Arctic tundra at higher latitudes (Déry et al. 2011). A small portion of the basin contains glaciers, which are housed in the Canadian Rockies (Saskatchewan River basin) and drain east through the Saskatchewan River, emptying into Lake Winnipeg, and continuing downstream to Hudson Bay along the Nelson River. Land cover for the HBDB (Figure 7) illustrates that a large portion of the basin, particularly along the Precambrian Shield and Boreal Forest region, is covered by open surface water in the form of lakes and wetlands.

Wetlands include bogs, fens, marshes, sloughs and swamps; all of which impact hydrologic systems by storing water. The exposed surface water retained in wetlands is susceptible to high evaporation rates during summer. West of Hudson Bay in the subarctic Shield region, wetlands are scattered across a landscape of bedrock with shallow organic soils and discontinuous permafrost. Field studies in this region have shown these wetlands moderate flow, except during winter and spring when shallow soils remain frozen (Roulet and Woo 1986). The James Bay lowlands, outside of the Canadian Shield, are home to peatland wetlands across the thermokarst land surface, formed by the collection of meltwater from discontinuous permafrost in shallow depressions (Pienitz et al. 2008). Projected increases in temperature within this region can increase evapotranspiration, affecting vegetation composition and causing loss of peat, which will impact
freshwater discharge timing and magnitude (Moore 2002). Minerotrophic boreal fens, occurring as alternating patterned pools and vegetated strings, produce scattered runoff (Zeeb and Hemond 1998) and are abundant east of James Bay, covering 20% of La Grande Rivière basin (Tarnoca et al. 2000). In recent decades increased aqualysis, or increasing surface water coverage as hollows fill with water, of fens in the HBDB has been observed (Tardif et al. 2009).

The Prairies, which drain to Hudson Bay via the Nelson River, are home to another type of wetland: pothole depressions (Figure 8). They are glacial relics that can be permanent features, or disappear from one year to the next (Euliss et al. 2004). The low relief of the prairie regions results in internal drainage, or regions that do not contribute water to streams but instead drain to pothole wetlands, local lakes or sloughs (Pomeroy et al. 2005). The net result is a reduced basin drainage area (i.e., effective drainage area), lower than that determined by elevation change alone (i.e., gross drainage area). Approximately 23% of the Nelson River Basin contains prairie terrain that does not contribute directly to streamflow (PFRA 1983).
Figure 7: Landcover map of the Hudson Bay drainage basin.

Figure 8: Prairie potholes located within the Saskatchewan River region of the Hudson Bay Drainage Basin (photo courtesy of Centre for Hydrology, University of Saskatchewan).
3.2.4. Hydroclimate

The HBDB spans several climatic zones. Mean annual air temperature ranges from 4°C (Canadian Prairies and upper mid-west US States) to -12°C in Nunavut. In northern and southern regions of the basin, climate tends to be drier (~200 mm annually) with wetter conditions for the Boreal Forest region (~800 mm annually). Generally, the HBDB is characterized by long, cold winters having significant snowpack accumulation ranging from 100 mm mean annual snow water equivalent (SWE) in the Prairies, to 400 mm SWE in northern Québec (Déry et al. 2005). Snow cover typically begins by early October (mid-November in the south) and stays until mid-June (mid-April in the south) (McKay and Gray 1981). The primary driver of streamflow, or freshwater discharge, in the basin is snowmelt, with peak annual flow typically resulting from the spring melt: the basin therefore is classified as a nival (i.e., snowmelt-driven) regime.

Given most of the HBDB lies in mid- to high-latitude regions of Canada, observed climatological and hydrometric data are scarce and intermittent at times. Coulibaly et al. (2013) note that more than half of the HBDB is either ungauged or does not meet current World Meteorological Organization (WMO) standards for hydrometric gauging. Where hydrometric gauges do exist, significant gaps in records are common with data availability varying over time. Prior to 1964, there are an insufficient number of gauges with consistent data to accurately evaluate streamflow, limiting any historic trend analyses to 1964 and later (Déry et al. 2011). Care needs to be taken in the interpretation of streamflow data in this region due to the presence of possible error resulting from ice-affected discharge, frequent changes in the river regime (e.g., erosion and sedimentation), vegetation growth/decay, animal intrusion (i.e., beaver dams), and infrequent gauge maintenance due to the remote location of the gauges. Gauged streamflow data are collected by a number of partners, including the Water Survey of Canada, Ministère de l'Environnement du Québec, and hydroelectric regulators (Manitoba and Québec Hydro).

3.2.5. Regulation

Over the past century, many rivers and lakes in the HBDB have been developed and regulated to utilize the wealth of water resources available. These resources come in the form of hydroelectric generation, domestic drinking water, and agricultural irrigation supply. In many cases the regulation of reservoirs has provided additional local benefits including flood mitigation, enhanced
transportation routes, and recreational facilities. While these developments have benefited from the resources within the watershed, they have also altered the magnitude and timing of freshwater entering Hudson Bay; changes which should be considered when modelling freshwater discharge to the Bay.

There are well over 250 dams within the watershed listed in the Canadian Dam Association’s register (Figure 9); however, only a handful of these structures possess reservoirs with active storage large enough to significantly influence the timing and magnitude of freshwater reaching Hudson Bay on a monthly to annual basis. In the Nelson basin, these reservoirs include Reindeer Lake, Lake Diefenbaker, Lac Seul, Lake of the Woods, Cedar Lake, Lake Winnipeg, and Southern Indian Lake; and in La Grande basin, they include Caniapiscau, La Grande-3, Robert-Bourassa, and Eastmain (Figure 10). Major regulation points within the HBDB and their inception dates are summarized in Table 2. It should be noted, however, that there was a stepped introduction of regulation in specifically the La Grande and Nelson systems, which impacts the historic discharge across several different decades.

![Figure 9: Location of dams in the Hudson Bay Drainage Basin based on CDA criteria (2003) (Natural Resources Canada, 2008).](image-url)
Table 2: HBDB Rivers affected by regulation and their commissioning dates [adapted from Déry et al. 2005].

<table>
<thead>
<tr>
<th>River</th>
<th>Structure</th>
<th>First Year Commissioned*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albany</td>
<td>Diversion</td>
<td>1937</td>
</tr>
<tr>
<td>Caniapiscau</td>
<td>Diversion</td>
<td>1985</td>
</tr>
<tr>
<td>Churchill</td>
<td>Dam, Reservoir, Diversion</td>
<td>1937</td>
</tr>
<tr>
<td>Eastmain</td>
<td>Diversion</td>
<td>1980</td>
</tr>
<tr>
<td>Koksoak</td>
<td>Diversion</td>
<td>1982</td>
</tr>
<tr>
<td>La Grande Rivière</td>
<td>Dam, Reservoir</td>
<td>1980</td>
</tr>
<tr>
<td>Moose</td>
<td>Dam</td>
<td>1963</td>
</tr>
<tr>
<td>Nelson</td>
<td>Dam, Reservoir, Diversion</td>
<td>1957</td>
</tr>
<tr>
<td>Opinaca</td>
<td>Diversion</td>
<td>1980</td>
</tr>
<tr>
<td>Rupert</td>
<td>Diversion</td>
<td>2009</td>
</tr>
</tbody>
</table>

*note that in some cases rivers may have been affected pre-construction, during the period of construction. Date reflects the first structure, however in some cases additional structures were added altering the river over a period of time.

Appendix A provides a more detailed description of the significant regulation points in the HBDB, and their influence on freshwater discharge into Hudson Bay.
3.3. **Historic Freshwater Regime**

3.3.1. **State of Hydrologic Knowledge**

The HBDB, like the pan-arctic as a whole, is a primarily snowmelt-driven, nival streamflow regime with strong seasonality. The greatest discharge occurs during spring as snowmelt runoff can contribute up to three times as much volume as normal or low flow (i.e., baseflow) volumes during the rest of the year. Despite this, the HBDB has the lowest variation in inter-seasonal freshwater discharge of all the major pan-arctic watersheds: 46% of HBDB discharge occurs during spring, whereas the range is 46-66% across all pan-arctic drainage basins (Lammers et al. 2001). Given parts of the HBDB reach fairly far south (relative to other pan-arctic basins), higher amounts of rainfall-runoff in warm seasons would be possible. Mean annual freshwater discharge into Hudson Bay exceeds 525 km$^3$ yr$^{-1}$, accounting for approximately 12% of all freshwater exports to the pan-arctic ocean system (Déry et al. 2011).

Woo et al. (2008) provide an excellent description of the subarctic nival regime, which characterizes streamflow over the majority of the HBDB landscape. Long and cold winters allow snowpacks to accumulate and rivers remain ice-covered (Prowse and Ferrick 2002), with a few (if any) significant mid-winter melt events. As air temperatures rise and snowmelt begins, seasonally frozen soils and permafrost reduce infiltration into the subsurface, causing meltwater to reach streams primarily as overland flow, or direct runoff (Hayashi 2013). As upper soil layers thaw, they can contribute large quantities of soil water runoff to nearby stream networks. Warming temperatures drive spring snowmelt and river ice break-up, resulting in the spring freshet (i.e., rise in flow) that typically begins during March in the southern regions and May or June further north. For example, Woo et al. (2008) show that the Rupert River in Québec has a later freshet than the Missinaibi River in Ontario, where peak discharge occurs in May. Warmer years with earlier spring snowmelt experience higher April flow volumes but tend to have a lower overall magnitude of freshet (i.e., peak streamflow) due to snowmelt occurring over a longer period of time (Burn and Hag Elnur 2002). Discharge declines during summer as evapotranspiration often exceeds rainfall. Autumn brings frontal rainstorms to the basin that produce peak streamflows, second in magnitude only to those that occur during spring. Come December and the return of colder air temperatures, discharge drops as snowpacks begin to accumulate and runoff becomes negligible.
The abundance of lakes and wetlands, and presence of glaciers in parts of the HBDB provide variations to typical nival regimes (Woo 2000).

Glaciers exist in the HBDB in the headwaters of the Saskatchewan River Basin in the Canadian Rocky Mountains, which ultimately drain to Hudson Bay via the Nelson River. Existing at high altitudes and having cold surfaces, glaciers allow prolonged snow fall storage compared to lower altitude regions with warmer temperatures. Glaciers reduce streamflow seasonality by providing later (i.e., based on temperature alone) snowmelt runoff and by contributing glacial meltwater runoff during the summer (Meier and Tangborn 1961, Chen and Ohmura 1990). In the upper North and South Saskatchewan River basins, glacial melt is estimated to contribute (on average from 1975-1998) 44% of July-September streamflow (Comeau et al. 2009). The extent and volume of glaciers in the Canadian Rockies has been in general decline since the neo-glacial maximum around 1850. August to October streamflow in glacierized basins of the Rockies has declined since the 1990s despite increases in late summer precipitation since 1950 (Demuth and Pietroniro 2003). Further glacier decline in the Canadian Rockies is anticipated and will result in a transition towards a more typical nival regime for those headwater basins (Comeau et al. 2009).

Lakes are abundant throughout the Precambrian Canadian Shield. Regardless of size, lakes modify streamflow by storing and releasing large volumes of water, and through evaporative loss. Lakes can be considered hydrologic “gatekeepers” as, depending on their location within a stream network, they can lead to intermittent downstream flow (Spence 2006, Phillips et al. 2011). Perhaps most significantly, lakes can buffer extreme floods, such as those typically occurring in late spring.

The nival regime of the HBDB is also modified by the presence of wetlands (Section 3.2.3). Wetlands variably store, transmit and contribute water at different times over a year, and are not necessarily directly linked to stream networks, therefore often preventing or delaying runoff by storing water. In general, wetland-heavy regions produce relatively lower runoff volumes than non-wetland terrain, and less peaked streamflow with longer recession periods (Roulet and Woo 1988). Summer flows from a network of fens can be near-zero during dry summer years (Tardif et al. 2009), affecting total runoff and freshwater discharge in wetland-dominated regions. Over time, water-filled fen hollows can merge to form shallow lakes that produce more frequent runoff events (relative to fen-dominated landscapes); however, peak runoff volumes become lower (Tardif et al.
The semi-arid climate and low relief of the Prairies result in low runoff generation, where numerous potholes across the landscape are often the terminus of this limited amount of runoff. Since streamflow from prairie landscapes largely depends on the interconnectivity of potholes, amounts can vary widely from year-to-year (Stichling and Blackwell 1957).

Blowing snow is an important winter process on the Prairies, Hudson Bay lowlands, Arctic tundra and in the mountain alpine. Blowing snow sublimation losses are estimated between 15-41% of annual snowfall on the Canadian Prairies (Pomeroy and Gray 1995), 28% in Western-Canadian Arctic tundra (outside of the HBDB but representative of the Hudson Bay lowlands; Pomeroy et al. 1997), and 17-19% in the alpine region of the Canadian Rockies (MacDonald et al. 2010). Boreal forest stands intercept large quantities of snowfall, which then become prone to wind-driven sublimation, with losses estimated between 13-40% of total snowfall depending on canopy type and density (Pomeroy et al. 1998).

Historical trend analyses of streamflow discharge for the HBDB region have shown earlier peak discharge with decreased mean annual and monthly flow, except during the spring snowmelt period (Déry et al. 2005; McClelland et al. 2006). Increasing spring and winter discharge in subarctic regions has been attributed to warmer springs, and upper layer permafrost thaw, which can also increase summer flow (Yang et al. 2002, Smith et al. 2007). Trend analyses for western HBDB, particularly the Nelson-Churchill River basin, show strong decreasing trends in flow occurring in southeastern Manitoba and southern Alberta from the 1960s to 1990s (Westmacott and Burn 1997). From the 1910s to 2002, nine of 11 Albertan rivers show declining annual flow volume, partly due to irrigation (Rood et al. 2005). Conversely, increasing flow trends are occurring in mid- to northern Alberta, mid- to northwestern Manitoba, and the Winnipeg River basin, with concern for potential future flooding in these areas (Westmacott and Burn 1997). Mean annual flows in the Winnipeg River basin are increasing (58% from 1924-2004) due to increases in winter discharge (60-110%) affected by regulation (St. George 2007). Years exhibiting extreme low annual flows in the Winnipeg River basin are the result of lower spring runoff following relatively dry autumns and summers.

Barriers to historic trend analyses include the lack of consistent (without gaps) streamflow records distributed across high latitude regions and accounting for anthropogenic influence due to regulation in the records. In Section 3.3.2, we conduct our own comprehensive trend analysis using
gap-filled historic discharge surrounding Hudson Bay, updating the previous works of Déry et al. (2005, 2011).

**3.3.2. Trends in Historic Streamflow Record**

River discharge forms the largest input of freshwater into Hudson (including James) Bay and influences sea ice formation, sediment and pollutant fluxes, marine conditions, and ecological processes. Here 21 major rivers of the Hudson Bay drainage system (Appendix B), covering 2.55 million km², are used to assess historic variations and trends in freshwater discharge into Hudson Bay. This includes rivers affected by streamflow regulation (i.e., through dams, water retention in reservoirs, and diverted flows for enhanced hydropower production). Regulation typically enhances winter flows and reduces summer flows (Déry et al. 2011). Streamflow data are sourced from the Water Survey of Canada, Manitoba Hydro, Hydro-Québec and the Centre d’Expertise Hydrique du Québec and gaps are in-filled using the strategy of Déry et al. (2005) to provide continuous records for 1964-2013, a period of 50 years. They are then assessed for variations and trends over time (see Appendix B for methodology).

Based on the 21 rivers with sufficient gauged streamflow data, discharge into Hudson Bay averages 528.6 km³ yr⁻¹ with annual variations of ±53.7 km³ yr⁻¹ (Table 3). An overall positive trend in Hudson Bay river discharge is observed from 1964 to 2013 (Figure 11). There is a
noticeable decreasing trend in the first half of the study period, followed by a marked increasing trend in the second half (Figure 11). Déry et al. (submitted) similarly report rising annual discharge to Hudson and James Bay since 1990.

Of note, significant increases are observed in the Nelson and La Grande Rivière systems as flows are augmented by diverted waters from neighboring rivers (Table 2; Appendix A). Portions of the Churchill River flow are retained by Southern Indian Lake and diverted into the Nelson River through the Burntwood River to enhance Manitoba Hydro’s capacity to generate hydro-electricity on the lower Nelson River. Similarly, La Grande Rivière forms Hydro-Québec’s largest hydroelectric facility, where flows from adjacent basins augment its power production by diverting portions of the Eastmain (since 1976), Caniapiscau (since 1980) and Rupert (since 2009) rivers, particularly during winter when hydroelectricity demand is highest (Hernández-Henríquez et al. 2010). These diversions increase freshwater releases into the estuaries of the Nelson and La Grande Rivière basins, greatly affecting local seawater salinity, sea ice production and melt, and ecological processes. Overall discharge to the Hudson Bay system, however, remains unaffected as all freshwater generated by the HBDB still makes its way into the Bay.
Table 3: Statistics of the mean, standard deviation (SD), coefficient of variation (CV) and change over time of seasonal/annual river discharge into Hudson Bay, 1964-2013.

<table>
<thead>
<tr>
<th>Season</th>
<th>Mean (km³ yr⁻¹)</th>
<th>SD (km³ yr⁻¹)</th>
<th>CV</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>80.7</td>
<td>15.7</td>
<td>0.19</td>
<td>80.4*</td>
</tr>
<tr>
<td>Spring</td>
<td>163.6</td>
<td>18.2</td>
<td>0.11</td>
<td>-4.8</td>
</tr>
<tr>
<td>Summer</td>
<td>153.2</td>
<td>22.8</td>
<td>0.15</td>
<td>-2.1</td>
</tr>
<tr>
<td>Fall</td>
<td>131.2</td>
<td>18.0</td>
<td>0.14</td>
<td>11.2</td>
</tr>
<tr>
<td>Annual</td>
<td>528.6</td>
<td>53.7</td>
<td>0.10</td>
<td>11.0</td>
</tr>
</tbody>
</table>

*Statistically-significant changes (p < 0.05).

In turn, discharge for rivers with active diversion has declined markedly. Rivers affected by diverted flows are the Churchill, Eastmain, Caniapiscau, and Rupert. While these diversions do not generally affect total streamflow input into Hudson Bay, discharge from the Caniapiscau River diverts water from Ungava Bay, entering into James Bay instead. While other rivers show some timing advances of spring flow, they do not offset the influences of flow regulation.

On a seasonal basis, streamflow from 1964 to 2013 discharging into Hudson Bay has increased during winter due to the regulation of flows and hydroelectric power demand during colder seasons (Figure 12). This is compensated by declining flows during summer when water is retained in large reservoirs, most notably in La Grande Rivière and Nelson River. There is minimal change in streamflow during spring or fall over the study period. In unregulated rivers of the study domain, advances in the timing of the spring freshet reflect earlier onsets of snowmelt, which is the main source of freshwater discharge for Hudson Bay.

While the seasonality of Hudson Bay inflows can be explained in large part by flow regulation, long term changes are likely also attributable to climatic change. This is due to increasing precipitation (despite decreases in snowfall) in the Hudson Bay drainage basin and possible permafrost degradation (St. Jacques et al. 2009). As air temperatures warm in the Hudson Bay region, the atmosphere’s ability to carry more moisture increases, leading to possible enhancements of precipitation, such as was observed in 2005. This results in an intensification of the water cycle marked by more precipitation, such as rain-on-snow events and more frequent mid-winter melts, and increasing river discharge into Hudson Bay (Déry et al. 2009).
Figure 11: Overall trends in Hudson Bay freshwater discharge (1964-2013).

Figure 12: Seasonal trend analysis (1964-2013) for 21 Hudson Bay freshwater rivers.
3.3.3. Impact of Regulation on Trends in Streamflow

With a substantial portion of the Hudson Bay freshwater system being regulated or controlled by man-made structures, dams, diversions and reservoirs (Section 3.2.5), damping of the natural season cycle occurs and tends to “flatten” annual streamflow variation, as noted by Anctil and Couture (1994). This can impact the Hudson Bay freshwater system by increasing the salinity in rivers discharging into Hudson Bay (Whittaker 2006; Messier et al. 1986), affecting sea ice formation and melt (LeBlond et al. 1994), and timing of freshwater discharge into the Bay by increasing (decreasing) winter (summer) streamflow (Déry et al. 2011). When performing historic streamflow trend analyses, trends are developed from observed streamflow records – which include the effects of river regulation. Therefore, to fully assess trends in streamflow as a result of changing historical climatic conditions (separate from those driven by regulation), streamflow records would need to be “naturalized” and all effects from regulation removed. Given the amount and complexity of regulation within the HBDB (Appendix A), this would difficult at best and in many cases, a guess of what the naturalized flow regime would have looked like.

Instead, we have interpreted the records “as-is”, including the effects of regulation. Déry et al. (2011) studied the effects of regulation on freshwater discharge into Hudson Bay by looking at observed records pre- and post-regulation. They found, as a result of the James Bay Hydroelectric Complex, mean annual streamflow input to Hudson Bay decreased by 7.1 km$^3$ in a more recent period (1995-2008), and that notable increases in discharge in some regulated rivers may be partly explained by inter-basin diversion from the Caniapiscau River into the La Grande Rivière system. Interannual variability in streamflow discharge to Hudson Bay increased post-regulation for both the regulated and natural rivers, but had little seasonal variability with the exception of spring discharge caused by earlier snowmelt (Déry et al. 2011). Long term storage introduced by flow regulation impacts the intensity of the hydrograph by diminishing spring snowmelt peak flows and “flattening” the hydrograph (Woo et al. 2008).

It is therefore expected that regulation within the HBDB, particularly the Nelson and La Grande Rivers, will alter the timing and variability of streamflow both historically and into the future. Several studies have shown, however, that the presence and filling of reservoirs seems to have relatively little influence on the long term trends in total annual streamflow entering Hudson Bay (Déry et al. 2011; McClelland et al. 2006). Since there is no method to predict future operations
for the hydroelectric utilities regulating streamflow discharge (i.e., it depends on a number of factors related to economics, supply and demand for the systems), changes in regulation will not be considered in our analyses of future streamflow regimes.

### 3.4 Projected Freshwater Regime

Projecting change to a system as expansive and complex as the HBDB is no small task. Given the lack of existing studies that specifically look to quantify possible changes in the freshwater regime over the entire HBDB, we developed our own models and projections to analyse the impacts of a changing climate river discharge. For the reasons outlined above, future regulation could not be projected, therefore this section does not include changes in the freshwater regime associated with future hydroelectric development. In this section, we focus on the climate-induced change and the anticipated state of HBDB freshwater exports in the future (2021-2070) relative to a historic reference period (1981-2010). This involves establishing a system of models such that hydrologic models are driven by scenarios of future climate established by climate models. Our methods and results are discussed in the subsequent sections.

#### 3.4.1 Projected future climate

Global Climate Models (GCMs) reproduce the physical processes and weather of planet Earth as it revolves around the sun. The virtual Earth ‘climate model’ will generate movement of the atmosphere and ocean akin to what we know from radar and satellite images of the real world. In climate model experiments, scientists let these virtual Earths evolve over periods of 250 years and more.

The atmospheric processes of a climate model include the transfer of solar radiation (i.e., energy from the sun), which depends on the constituent gases of the atmosphere. By burning fossil fuels, humans are changing these constituent gases. Using scenarios that estimate the future gas composition of the atmosphere, climate models serve as virtual laboratories to assess the impact of measured and projected future changes of greenhouse gases on the energy budget of Earth. While representing the same system, model simulations differ to some extent from the real world and amongst each other, providing a range of possible futures. When studying future climate change, this range needs to be considered.
Climate model simulations from the fifth generation of the Coupled Model Intercomparison Project (CMIP5; Taylor, et al. 2012) were used to drive a hydrological model over the HBDB domain to produce projected streamflow. Like in many other climate change impact studies, using the full set of around 150 CMIP5 simulations would have exceeded computational capacity, therefore 19 scenarios spanning the uncertainty range of the ensemble were used (refer to Appendix C).

The HBDB is anticipated to experience substantial warming during the 21st century. Retreating Arctic sea ice and reductions in Pan-Arctic snow cover extent and duration amplify regional warming through cryosphere/albedo positive feedbacks (Serreze et al., 2007; Déry and Brown, 2007). GCMs project greater temperature increases from 2021-2050 at high (northern) latitudes, with diminishing values moving southward (Figure 13). Climate data indicate average annual temperatures over the HBDB are expected to increase 2 to 3°C by 2050, up to nearly 5°C above 65° latitude by 2070 (Figure 13). GCMs project precipitation increases associated with this regional warming (Figure 14), with increases along a strong latitudinal gradient (lower to the south, highest in the north) ranging from 0-15% by 2050, up to 30% in the northern HBDB by 2070. There is little longitudinal variation in the precipitation increases, illustrating the importance of Arctic amplification on hydrological changes in the Hudson Bay drainage basin.
3.4.2 Projected future flow

Computer-based modelling is needed to generate future streamflow projections. In some cases, statistical estimation can be used to extrapolate recent historical (based on observed data) trends, however due to the nature of climate change (a change from, or deviation from historical patterns) and long-term outlook in this study, hydrological models are the preferred method. Hydrological models take inputs of precipitation and temperature and calculate a suite of hydrologic processes: evapotranspiration, snowmelt, runoff and streamflow. Each simulated process is combined to compute overall streamflow for a given hour or day. Comparisons with the historical reference period (1981-2010) are then made by averaging the output into monthly, seasonal, or annual trends for analysis.

3.4.2.1 Review of existing projections

Regionally the effects of climate change on the HBDB are expected to alter the volume of runoff and river discharge, seasonal contributions and timing of discharge, and spatial and temporal discharge patterns. In this section, we discuss existing global projections of runoff for the HBDB
from the latest global climate modelling efforts (The Coupled Modeling Intercomparison Project Phase 5; CMIP5) driven by the latest atmospheric forcing scenarios (Representative Concentration Pathways; RCPs).

The Intergovernmental Panel on Climate Change’s Fifth Assessment Report (IPCC AR5) presents a summary of global projections for several climate variables (e.g., temperature and precipitation) and annual mean runoff changes for 2081-2100 relative to a 1986-2005 (Collins et al., 2013). An overall increase in mean annual runoff is projected across all scenarios for the HBDB, with greater increases in the northern and eastern regions. More uncertainty surrounding changes in runoff exist in the southern parts of the HBDB, including the Nelson River drainage basin (Figure 3-4 in Jiménez Cisneros et al., 2014). The coastal region, northern (Nunavut), and eastern (northern Quebec) regions indicate better agreement among projections (i.e., greater certainty) and typically coincide with increasing runoff.

Other studies have evaluated projected changes in earth’s freshwater regime at finer spatial and temporal scales relative to the IPCC’s global projections. These studies show increasing trends in annual runoff in North America that is more pronounced than the global trend (Alakam et al. 2013), with increasing winter water supply but decreasing summer water supply (Kumar et al. 2014). Koirala et al. (2014) projected mean streamflow increases for the majority of the HBDB, most intensely in the northern and eastern regions. Higher magnitude flow events are largely projected to decrease, but low flow events are projected to increase.

The hydropower utilities have also undertaken their own projection studies for the Nelson-Churchill (Manitoba Hydro, 2015c) and La Grande Rivière (Centre d’expertise hydrique du Quebec, 2015) basins. Hydro Québec, using data from CMIP3, found both temperature and precipitation to be increasing over the eastern HBDB domain, with temperatures projected to rise between 2.5°C to 4.5°C, and precipitation from 10% to 15% along a south to north gradient (Guay et al., 2015). This is projected to translate into a 2% increase in average annual streamflow in the south, up to a 14% increase in the northern sections of the eastern HBDB region. Manitoba Hydro reports statistically significant increasing temperature trends (up to +1°C/decade), projected up to 2°C to 3.4°C by 2050 (Manitoba Hydro, 2015c). Historical records indicate increasing precipitation trends from 10 to 40 mm/year/decade, with projected increases from 6% to 11% by 2050 (with the exception of summer, which may decrease by nearly 1% up to a 2.5% increase). For the Nelson
and Churchill Rivers, this translates into projected increases in runoff (7% to 23%) for all major tributaries by 2050.

### 3.4.2.2 HYPE model projections

Flow projections derived in this study for the HBDB from 2021-2070 are achieved using hydrological modelling forced by time series projected daily precipitation and temperature (Section 3.4.1). The pan-arctic implementation of the HYPE hydrological model (Arctic-HYPE; Andersson et al., 2015), developed by the Swedish Meteorological and Hydrological Institute, is used in this study. Appendix C describes the Arctic-HYPE model setup for the HBDB and the historical calibration performed that is necessary to have confidence in projected flow regimes.

It is important to openly acknowledge that projected discharge is highly dependent on the input data used to setup and calibrate the hydrologic model, and the future climate scenarios used to drive the model. Observed hydrologic records are relatively short relative to the projected time period analysed here, and data are not comprehensive of all Hudson and James Bay inflows (i.e., only 21 of 42 rivers were gauged). The model is calibrated to the rivers having observed data, and the model assumed to reasonably represent the hydrology of other regions, which may or may not be the case. Similarly, the climate scenarios used to drive the model simulations contain considerable variability in their interpretations of future climate. Though the range of all scenarios was reasonably represented, no one scenario is more correct than another – and similarly, for the projected discharge. Results need to be used with caution in the context that these are reasonable representations of what the future discharge regime may look like. Similarly, scenarios of future flow do not encompass possible changes to the regulated regime, further discussed in Section 3.4.4. It should be noted that all projections presented herein are preliminary and subject to change based on on-going research from the BaySys project.

### 3.4.3 Trends in Projected Streamflow Record

Despite the different approaches to modelling, projected changes are in agreement with those reported in other studies (Section 3.4.2.1). Driving the Arctic-HYPE model with projected air temperature and precipitation over the HBDB reveals the latitudinal dependence of 21st century climate change. Streamflow is anticipated to increase more substantially in response to the stronger precipitation trends (i.e. above 65°N), with more modest changes in other parts of the drainage...
basin (Figure 15). Based on the mean of all the climate models, Figure 15 shows projected change in distributed discharge over the HBDB for 2021-2050 and 2041-2070 relative to the 1981-2010 reference period. Flows in the north-eastern HBDB (i.e., La Grande system) are generally increasing, with more modest increases in the western HBDB (i.e., Nelson River system), and generally decreasing mean annual discharge across the Canadian Prairies. Modest increases within the Nelson River are the result of contrasting sub-basin results, where the model projects increasing river discharge from the Rocky Mountain headwaters (i.e., Saskatchewan River) but decreasing river discharge across the remainder of the Canadian Prairies (generally not statistically significant with p>0.05).

Changes in mean annual runoff are similarly projected to increase (Figure 16) relative to the 1981-2010 reference period over much of the HBDB. Significant increases in runoff are projected for the headwater region of the Saskatchewan River and the northern and north-eastern regions, with the notable decreases in runoff across the Canadian Prairies where increasing evapotranspiration offsets increases in precipitation. Figure 16b shows mean annual runoff (2021-2070) for the HBDB region as depth averaged over sub-basin area (in mm).

Figure 15: Projected change in mean annual discharge over HDBD relative to 1981-2010 reference period for (a) 2021-2050 and (b) 2041-2070. The mean projection from all CMIP5 models is shown.
Interesting to note is the longitudinal gradient in river discharge and runoff (not seen in temperature and precipitation) projected across the HBDB, with the largest runoff yields occurring to the east (and extreme west), and the largest (most significant) changes occurring in the northern (>30% increases) and western (>30% decreases) portions of the basin.

Relative to the historic period (Section 3.3.2), Figure 17 shows that the recent decadal increasing trends in river discharge continue, however at an intensified rate with projected annual average discharge to Hudson Bay (for the same 21 rivers) increasing by 1.29 km$^3$ yr$^{-1}$ from 2021-2070. This aligns with global trends in pan-arctic discharge reported in the literature, such as those from Eurasia that report increased moisture transport to high northern latitudes (Zhang et al., 2013).
Seasonally, the largest projected increases in river discharge occur for fall and winter streamflow, with the smallest increases occurring during summer (Figure 18). Statistics of projected discharge trends by season from Arctic-HYPE are reported in Table 4. In future time horizons, all seasons experience statistically significant increases in discharge greater than those observed during the historic period. Not unexpectedly, the statistics indicate a large range (variability) in future streamflow, which is largely due to uncertainty (variability) in the future climate used to drive the hydrologic model (Section 3.4.1). Greater projected increases to fall and winter low streamflow coupled with more moderate increases to spring and summer flows will result in a gradual flattening of the annual seasonal hydrograph.

Table 4: Statistics of the mean, standard deviation (SD), coefficient of variation (CV) and change over time of modelled seasonal/annual river discharge into Hudson Bay, 2021-2070.

<table>
<thead>
<tr>
<th>Season</th>
<th>Mean (km$^3$ yr$^{-1}$) [range of projections]</th>
<th>SD (km$^3$ yr$^{-1}$)</th>
<th>CV</th>
<th>Change (%) [range of projections]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>68.9 [62.0 – 77.3]</td>
<td>14.1</td>
<td>0.20</td>
<td>35.4* [-3.9 – 88.9%]</td>
</tr>
<tr>
<td>Spring</td>
<td>174.9</td>
<td>22.9</td>
<td>0.13</td>
<td>9.0*</td>
</tr>
</tbody>
</table>

Figure 17: Projected annual average trends in discharge for 21 Hudson Bay freshwater rivers (2021-2070).
### 3.4.4 Projected Regulated Regime

In all scenarios of future streamflow, regulation within major river systems (Section 3.2.5) was assumed to be held constant (i.e., no modification of reservoirs, storage volume or existing rule curves was made). Though this assumption is not entirely realistic, there is no mechanism to forecast future regulation within the HBDB. What we do know, however, is that air temperatures are expected to continue to rise across the HBDB over the 21st century (Section 3.4.1). Irrespective of the GHG emissions scenarios used in developing projections of Earth’s future climate, the higher (northern) latitudes are expected to experience warming of at least two to three times the global average.

<table>
<thead>
<tr>
<th>Season</th>
<th>Median Discharge (km$^3$ yr$^{-1}$)</th>
<th>Discharge Variability</th>
<th>Change (p &lt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>85.1 [69.5 – 102.7]</td>
<td>17.7</td>
<td>0.21</td>
</tr>
<tr>
<td>Fall</td>
<td>113.5 [93.1 – 134.5]</td>
<td>23.6</td>
<td>0.21</td>
</tr>
<tr>
<td>Annual</td>
<td>442.5 [402.6 – 510.9]</td>
<td>56.5</td>
<td>0.13</td>
</tr>
</tbody>
</table>

*Statistically-significant changes (p < 0.05).

![Preliminary Results Chart]

**Figure 18:** Projected seasonal trends (2021-2070) for 21 Hudson Bay freshwater rivers.
In an effort to mitigate potential future increases in air temperature, there is a current thrust towards a low carbon economy fueled largely by international climate agreements to reduce the world’s greenhouse gas emissions and reliance on non-renewable energy sources. The development of additional capacity to generate hydropower remains a priority for Canada’s energy sector in partnership with Canada’s First Nations peoples. Hydroelectricity forms a low-carbon and renewable source of energy such that development of infrastructure related to its generation will progress into the 21st century. Construction of new and/or expansion of existing hydroelectric facilities on HBDB rivers is either ongoing or in the planning stages by hydroelectric companies in Manitoba, Ontario and Québec; most notably for the Nelson, Moose and La Grande Rivière systems, respectively. Expansion of hydroelectric facilities in the Canadian Prairies is also anticipated, while the possible introduction of hydropower generating stations in Nunavut is foreseen if economic activity (especially in the mining sector) expands rapidly in the coming decades. Thus the 21st century will observe continued development of hydroelectric facilities on rivers in the HBDB as demands for low-carbon energy sources rise.

Given these circumstances, it is likely that flow regulation in HBDB will intensify in the 21st century, particularly in systems with large water storage capacity. Peak demand for hydropower in Canada occurs in winter in relation to domestic, commercial and industrial heating. Hence the seasonal shifts in HBDB river discharge observed in the latter half of the 20th century and early 21st century will amplify in the coming decades. This will sustain trends towards greater river discharge during winter, while decreasing river discharge in summer in regulated rivers. Warmer air temperatures in summer may increase energy demands for domestic, commercial and industrial climate control, especially during intense heat waves; however, this is likely to have a secondary impact at most on flow regulation annually. Increasing air temperatures and reductions in the duration of seasonal ice cover will also enhance evaporation from reservoirs, thereby reducing water availability in regulated systems. It is expected, therefore, that the HBDB will experience less seasonality during the 21st century, with increases in winter river discharge and decreases in summer river discharge. The ‘shoulder’ seasons (spring and autumn) are less likely to observe trends associated with flow regulation. River discharge to Hudson and James Bay in summer may also be affected by the competing effects of rising energy demands for climate control and of diminishing water availability through evaporation from reservoirs. Thus the hydrological regime...
of the HBDB will likely progress towards greater control of flows during the 21st century, with the primary impact being a reduction on the seasonality of its river discharge.

3.5 Summary

In recent decades, the HBDB has been undergoing significant change to both climate (temperature and precipitation) and development of hydroelectric complexes, consequentially affecting the freshwater regime. In decades to come, temperatures are expected to continue to increase, possibly seeing a +5°C temperature change in the northern (>65° latitude) HBDB by 2070. As air temperatures warm, the atmosphere can hold more moisture, resulting in increases in precipitation of up to 30% by 2070 – again impacting higher latitude regions most significantly. Previous studies and our own findings are in agreement that river discharge to the HBDB is expected to continue to increase but at a faster rate than during the recent historic period (1.13 km³/yr⁻¹/yr⁻¹ from 1964-2013), with our projections indicating 1.29 km³/yr⁻¹/yr⁻¹ more discharge on average (2021-2070) from 21 of the 42 rivers entering Hudson and James Bays. Increasing trends in river discharge exist across all seasons and are most prominent in fall and winter, but more moderate during summer where higher temperatures and evapotranspiration may offset increasing precipitation. Runoff across the HBDB is also generally increasing along a longitudinal (east to west) gradient with the largest increases along the northern and eastern portions of the Bay, and the smallest increases across the western Canadian Prairie basins. Though we project (and have observed in recent decades) these changes to be occurring within the HBDB, the exact causes and relative contributions of each change factor (e.g., climate, hydroelectric regulation, land use change, etc.) are yet unknown. Based on the projected changes to temperature and precipitation, historical development of regulation in the HBDB, and increasing political will toward greener energy sources, development of hydroelectric facilities within the HBDB is anticipated to continue in the decades to come – and will continue to also influence the seasonality of river discharge in regulated rivers.

The interface between the freshwater and marine system will undoubtedly be impacted by such projected increases to river discharge and the degradation of spring run-off peaks relative to seasonal low flows. This undoubtedly will alter freshwater-marine system circulation, exchange, and sea ice formation/breakup process. The impact of large shifts in both the timing and magnitude of freshwater export into Hudson and James Bays, and associated effects on the stability of the
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water column; sea ice formation, decay and breakup; and freshwater-marine ecosystem interfaces are not well understood. Results from our work are contributing toward a large interdisciplinary project focused on exploring these interface effects (i.e., BaySys), and the relative contributions of hydroelectric regulation in altering the delivery of freshwater exports to Hudson and James Bays.

3.6 Acknowledgements

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