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 input to Hudson Bay on the decline from 1964 to 1990, increasing in recent decades (Déry et al. 2005; 2011), documented increases in 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 so highly dependent on the large freshwater delivery system; improved understanding of the factors influencing, historic trends in, 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) effecting 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-
IRIS Chapter 3 – Freshwater System

arctic (Bhiry et al. 2011), understanding the potential impacts on the freshwater system and resources for Hudson Bay are of particular concern. Future changes will be framed in the context of historic trends, discussed for 21 rivers in the HBDB observed from streamflow records from 1964 to 2013. Climate-related changes to the freshwater system, caused by changing temperature and precipitation patterns, will be explored using state-of-the-art hydrologic modelling coupled to global climate model 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 70° 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 3,000 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 Bay (7); their size, mean annual discharge, and ranks (by size and mean annual discharge).
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.
IRIS Chapter 3 – Freshwater System

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 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 northwest 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
IRIS Chapter 3 – Freshwater System

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 eastward 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 southeast 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 Hudson Bay freshwater-marine coupling, however, because of strong circulation patterns and thick, rough sea ice which dominates most of the annual cycle.
IRIS Chapter 3 – Freshwater System

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>
</tr>
</thead>
<tbody>
<tr>
<td>Kirchoffer</td>
<td>HB</td>
<td>NU</td>
<td>3,160</td>
<td>38</td>
<td>0.81*</td>
<td>35</td>
</tr>
<tr>
<td>Brown</td>
<td>HB</td>
<td>NU</td>
<td>2,040</td>
<td>40</td>
<td>1.53*</td>
<td>33</td>
</tr>
<tr>
<td>Lorillard</td>
<td>HB</td>
<td>NU</td>
<td>11,000</td>
<td>31</td>
<td>4.49*</td>
<td>24</td>
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<td>Chesterfield Inlet</td>
<td>HB</td>
<td>NU</td>
<td>259,979</td>
<td>3</td>
<td>41.1</td>
<td>3</td>
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<tr>
<td>Diane</td>
<td>HB</td>
<td>NU</td>
<td>1,460</td>
<td>41</td>
<td>0.28*</td>
<td>37</td>
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<td>Ferguson</td>
<td>HB</td>
<td>NU</td>
<td>12,400</td>
<td>27</td>
<td>2.56*</td>
<td>31</td>
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<tr>
<td>Tha-anne</td>
<td>HB</td>
<td>NU</td>
<td>29,400</td>
<td>21</td>
<td>6.94*</td>
<td>22</td>
</tr>
<tr>
<td>Thlewiaza</td>
<td>HB</td>
<td>NU</td>
<td>27,000</td>
<td>23</td>
<td>6.9</td>
<td>23</td>
</tr>
<tr>
<td>Seal</td>
<td>HB</td>
<td>MB</td>
<td>48,100</td>
<td>12</td>
<td>11.4</td>
<td>17</td>
</tr>
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<td>Churchill</td>
<td>HB</td>
<td>MB</td>
<td>288,880</td>
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<td>19.4</td>
<td>12</td>
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<tr>
<td>Nelson</td>
<td>HB</td>
<td>MB</td>
<td>1,125,520</td>
<td>1</td>
<td>92.6</td>
<td>1</td>
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<tr>
<td>Hayes</td>
<td>HB</td>
<td>MB</td>
<td>103,000</td>
<td>6</td>
<td>19.4</td>
<td>13</td>
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<tr>
<td>Severn</td>
<td>HB</td>
<td>ON</td>
<td>94,300</td>
<td>9</td>
<td>21.6</td>
<td>10</td>
</tr>
<tr>
<td>Winisk</td>
<td>HB</td>
<td>ON</td>
<td>54,710</td>
<td>11</td>
<td>15.3</td>
<td>14</td>
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<tr>
<td>Ekwan</td>
<td>JB</td>
<td>ON</td>
<td>10,400</td>
<td>32</td>
<td>2.7</td>
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<td>Attawapiskat</td>
<td>JB</td>
<td>ON</td>
<td>36,000</td>
<td>18</td>
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<td>16</td>
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<tr>
<td>Albany</td>
<td>JB</td>
<td>ON</td>
<td>118,000</td>
<td>4</td>
<td>31.9</td>
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<tr>
<td>Moose</td>
<td>JB</td>
<td>ON</td>
<td>98,530</td>
<td>7</td>
<td>39.1</td>
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<tr>
<td>Harricana</td>
<td>JB</td>
<td>QC</td>
<td>21,200</td>
<td>24</td>
<td>10.9</td>
<td>19</td>
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<tr>
<td>Nottaway</td>
<td>JB</td>
<td>QC</td>
<td>57,500</td>
<td>10</td>
<td>32.6*</td>
<td>6</td>
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<tr>
<td>Broadback</td>
<td>JB</td>
<td>QC</td>
<td>17,100</td>
<td>25</td>
<td>10</td>
<td>20</td>
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<tr>
<td>Rupert</td>
<td>JB</td>
<td>QC</td>
<td>40,900</td>
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<td>26.7</td>
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### IRIS Chapter 3 – Freshwater System

<table>
<thead>
<tr>
<th>Location</th>
<th>Province</th>
<th>Code</th>
<th>Annual Flow (m³/s)</th>
<th>Mean Annual Discharge (m³/s)</th>
<th>Mean Annual Flow (m³)</th>
<th>Mean Annual Flow (L/s)</th>
</tr>
</thead>
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<td>Pontax JB QC 6,090</td>
<td>JB</td>
<td>QC</td>
<td>6,090</td>
<td>34</td>
<td>3.1</td>
<td>28</td>
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<td>Eastmain JB QC 44,300</td>
<td>JB</td>
<td>QC</td>
<td>44,300</td>
<td>14</td>
<td>13</td>
<td>15</td>
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<tr>
<td>Opinaca JB QC 3,700</td>
<td>JB</td>
<td>QC</td>
<td>3,700</td>
<td>36</td>
<td>32.8</td>
<td>5</td>
</tr>
<tr>
<td>La Grande Rivière JB QC 96,600</td>
<td>JB</td>
<td>QC</td>
<td>96,600</td>
<td>8</td>
<td>80.5</td>
<td>2</td>
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<tr>
<td>Roggan JB QC 9,560</td>
<td>JB</td>
<td>QC</td>
<td>9,560</td>
<td>33</td>
<td>4.04*</td>
<td>25</td>
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<tr>
<td>Grande Rivière de la Baleine HB QC</td>
<td>HB</td>
<td>QC</td>
<td>43,200</td>
<td>15</td>
<td>19.8</td>
<td>11</td>
</tr>
<tr>
<td>Boutin HB QC 1,390</td>
<td>HB</td>
<td>QC</td>
<td>1,390</td>
<td>42</td>
<td>0.5</td>
<td>36</td>
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<tr>
<td>Petite Rivière de la Baleine HB QC</td>
<td>HB</td>
<td>QC</td>
<td>11,700</td>
<td>28</td>
<td>3.7</td>
<td>26</td>
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<tr>
<td>Goulet HB QC 5,970</td>
<td>HB</td>
<td>QC</td>
<td>5,970</td>
<td>35</td>
<td>nd</td>
<td>--</td>
</tr>
<tr>
<td>Nastpoca HB QC 12,500</td>
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<td>QC</td>
<td>12,500</td>
<td>26</td>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td>Innuksuac HB QC 11,200</td>
<td>HB</td>
<td>QC</td>
<td>11,200</td>
<td>30</td>
<td>3.16*</td>
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<td>11,300</td>
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<td>2.59*</td>
<td>30</td>
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<td>De Povungnituk HB QC 28,000</td>
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<td>QC</td>
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<td>QC</td>
<td>45,200</td>
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<td>Aux Feuilles UB QC 41,700</td>
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<td>QC</td>
<td>41,700</td>
<td>16</td>
<td>nd</td>
<td>--</td>
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<tr>
<td>Koksoak UB QC 110,136</td>
<td>UB</td>
<td>QC</td>
<td>110,136</td>
<td>5</td>
<td>nd</td>
<td>--</td>
</tr>
<tr>
<td>False UB QC 2,140</td>
<td>UB</td>
<td>QC</td>
<td>2,140</td>
<td>39</td>
<td>0.97*</td>
<td>34</td>
</tr>
<tr>
<td>À la Baleine UB QC 29,800</td>
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<td>QC</td>
<td>29,800</td>
<td>20</td>
<td>nd</td>
<td>--</td>
</tr>
<tr>
<td>Tunulic UB QC 3,680</td>
<td>UB</td>
<td>QC</td>
<td>3,680</td>
<td>37</td>
<td>2.21*</td>
<td>32</td>
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<td>George UB QC 35,200</td>
<td>UB</td>
<td>QC</td>
<td>35,200</td>
<td>19</td>
<td>23.3*</td>
<td>9</td>
</tr>
<tr>
<td>Total, Average</td>
<td>--</td>
<td>--</td>
<td>3,013,945</td>
<td>--</td>
<td>16.7</td>
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</tr>
</tbody>
</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 drainage 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. Permafrost and poorly drained sedimentary deposits yield numerous wetlands and highly organic, shallow soil complexes (Tornocai 1982).

Figure 3: Hudson Bay Drainage Basin underlying geology.
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 effecting 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.

Figure 5: Damage to rail lines connecting Thompson MB to Churchill MB as a result of thermokarst creating subsurface instability [photo taken by Dr. Marolo Alfaro, University of Manitoba, Civil Engineering, 2012]

3.2.3. **Physiography**

The landscape of the HBDB spans eleven 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 swap; 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 relicts 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 6: Ecozones of Hudson Bay Drainage Basin
IRIS Chapter 3 – Freshwater System

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.

![Figure 9: Location of dams in the Hudson Bay Drainage Basin (Natural Resources Canada, 2008).](image-url)
IRIS Chapter 3 – Freshwater System

Figure 10: Location of major reservoirs within the Hudson Bay Drainage Basin.

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.
Historic Freshwater Regime

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 magnitudes 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 with 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. 2009). 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.

In Section 3.3.2, we conduct our own comprehensive trend analysis of 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 km$^2$, 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 525.4 km$^3$ yr$^{-1}$ with annual variations of $\pm 50.4$ km$^3$ yr$^{-1}$ (Table 3). An overall positive trend in Hudson Bay river discharge is observed from 1964 to 2013 (Table 3).
Of note, significant increases are observed in the Nelson and La Grande Rivière systems as flows are augmented by diverted waters from neighbouring rivers (Table 2; Appendix A). Portions of the Churchill River flow are retained by South 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 (km$^3$ yr$^{-1}$)</th>
<th>SD (km$^3$ yr$^{-1}$)</th>
<th>CV</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>80.4</td>
<td>15.2</td>
<td>0.19</td>
<td>81.4*</td>
</tr>
<tr>
<td>Spring</td>
<td>162.7</td>
<td>18.8</td>
<td>0.11</td>
<td>-5.7</td>
</tr>
<tr>
<td>Summer</td>
<td>152.1</td>
<td>23.2</td>
<td>0.15</td>
<td>-6.8</td>
</tr>
<tr>
<td>Fall</td>
<td>130.2</td>
<td>17.8</td>
<td>0.13</td>
<td>7.4</td>
</tr>
<tr>
<td>Annual</td>
<td>525.4</td>
<td>50.4</td>
<td>0.096</td>
<td>7.0</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).
IRIS Chapter 3 – Freshwater System

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
IRIS Chapter 3 – Freshwater System

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.

3.1. Projected Freshwater Regime

To come by end of summer/early fall 2016, along with Appendix C

3.1.1. Projected future climate

Outline top-down approach, and summarize first the projected changes to climate for the entire basin (MH already has analyses for western side and there is the potential to do this for the eastern, HQ, side as well).

3.1.2. Projected future flow

Discuss the methodology used to derive the projected record, including watershed models and resolution, climate data, and downscaling techniques. We will also summarize any projections in the literature in the context of our own methods; justifying our choice of methodology.

3.4.2.1 Review of existing projections

3.4.2.2 HYPE model projections

3.1.3. Trends in Projected Streamflow Record

Trend analysis of H.B. streamflow from historic to future regimes.

3.1.4. Projected Regulated Regime

3.2. Summary

To come end of summer/early fall 2016
3.3. Acknowledgements

Hydrometric data were provided by the Water Survey of Canada, Manitoba Hydro, Hydro-Québec, and Centre d'Expertise Hydrique du Québec, and we acknowledge these groups for their contributions to this research and access to the data. Funding for this research was from the Natural Sciences and Engineering Research Council of Canada, Manitoba Hydro, and partners of the BaySys project. We thank David Hah for assistance with data extraction and Bunu Sharma and Mark Gervais for figure preparation. Photos in this chapter were provided by Marolo Alfaro (permafrost) and the Centre for Hydrology, University of Saskatchewan (Prairie Potholes).

3.4. References


IRIS Chapter 3 – Freshwater System


IRIS Chapter 3 – Freshwater System


IRIS Chapter 3 – Freshwater System


IRIS Chapter 3 – Freshwater System


Prairie Farm Rehabilitation Administration. 1983. The determination of gross and effective drainage areas in the Prairie Provinces. PFRA Engineering Branch, Agriculture Canada, 78 pp.


IRIS Chapter 3 – Freshwater System


Saskatchewan Watershed Authority. 2012. Lake Diefenbaker Reservoir Operations: Context and Objectives. 47 pgs. Available online:


Sottile, M.-F., Bourdages, L. and Côté, H. 2010. Projected changes in precipitation in Quebec. Available online:


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IRIS Chapter 3 – Freshwater System


