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The Mackenzie River Hydroelectric Complex – Concept Study

F. Pierre Gingras

ABSTRACT

This chapter provides an overview of a recent study of the potential of harnessing the Northwest Territories' Mackenzie River for hydroelectric development. By any standard, the proposed project is enormous; similar in scale to Quebec's enormous James Bay Hydroelectric Complex. This chapter also describes a practical implementation scenario for realizing the Mackenzie River's significant hydroelectric potential, with an overall capacity slightly greater than 13,000 MW, assuming 80% availability. Characterized by flows of up to 9,000 cubic metres per second, steep shorelines avoiding wide-area submersion, and large lakes acting as flow regulation reservoirs, the Mackenzie River project includes an upstream water control structure, six downstream powerhouses, and 10,000 km of transmission lines to bring the power to Edmonton. The complex would produce some 92 million MWh yearly, equivalent to producing 525,000 barrels of fuel per day. This clean energy could be used to assist Alberta (10,000 MW) and Saskatchewan (3,000 MW) to transition from high-carbon footprint thermal generating stations to low-carbon hydroelectric power stations as thermal generating stations approach the end of their expected life spans.

Introduction

The Mackenzie River is 1,738 kilometres long and Canada's longest river. Its watershed encompasses the Eastern slopes of the Rocky Mountains, and the northern half of the plains of Alberta and Saskatchewan, while its waters cut across the Northwest Territories as they work their way to the Beaufort Sea. At its mouth in the Beaufort Sea, its average annual flow is of 9,910 cubic metres per second (CMS). However, the Mackenzie River really bears this name only from Great Slave Lake to the sea, over a distance of 1,400 kilometres (Figure 1).

From Great Slave Lake to the village of Artic Red River (which marks the river's final approach to the Beaufort Sea), its waters run slowly at the bottom of a three to ten kilometre-wide valley, between two very high mountain ranges (Figure 2). The steep riverbanks which characterize this region offer the opportunity of building a cascade of low-head hydroelectric projects, as low as 22 to 27 metres high, with little significant flooding of lands. At first sight, the total lack of rapids in this region could mean difficult geological conditions on the riverbed, such as significant overburden depth, but this needs to be confirmed.

Downstream of Artic Red River village, the river flows into a large wetland area, approximately 200 kilometres long by 100 kilometres wide, where the river separates into a multitude of

Figure 1
Map of the Proposed Mackenzie River Hydroelectric Complex

Figure 2
Site of the Mackenzie – 2 Project ("Bassin des Murailles")
Note the steep riverbank typical of the Mackenzie River landscape.

smaller rivers, only three of which are navigable up to the Beaufort Sea, though offering the opportunity for ships from Alaska and the Bering Straits to be serviced. These wetlands are of critical importance to the environment, for example, being a major beluga "breeding ground."

The population of the Northwest Territories consists of some 40,000 people, with more than 20,000 living in the town of Yellowknife. The Governor, appointed by the Government of Canada, is assisted by a locally-elected Council. If the Mackenzie River's potential is to be harnessed as proposed in this chapter, its electricity-generating capacity far exceeds the needs of the Northwest Territories at the present time. The Mackenzie River Hydroelectric Complex is a "big project," appropriate from the perspective of Canada aspiring to become a sustainable energy powerhouse.

Project Characteristics

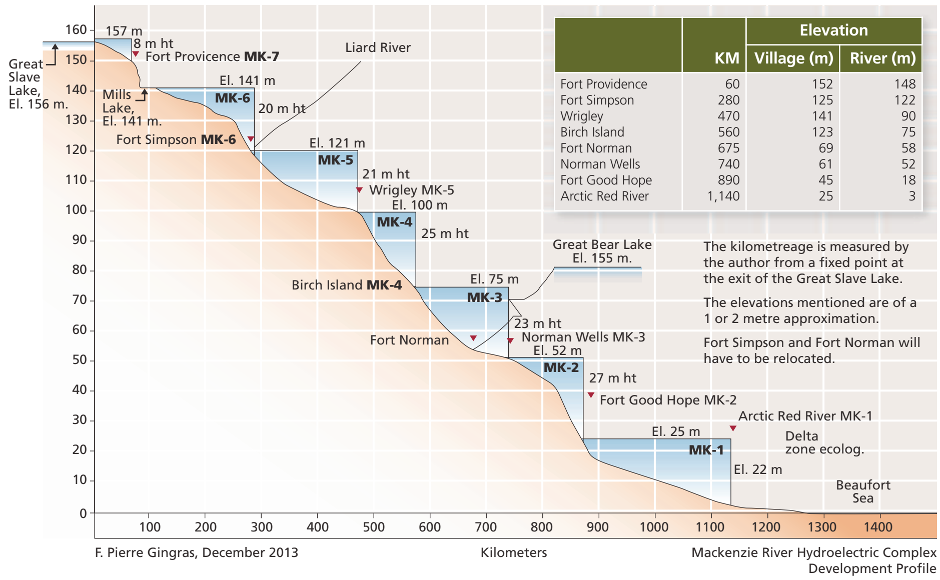
The Mackenzie River presents several unique characteristics. First and foremost is the fact that its riverbanks are generally so steep, from 15 to 40 metres, that dams of 20 to 30 metres would flood only a very limited area, despite the river's enormous power generating potential. The particular implementation proposed here consists of seven individual projects, including one water control structure and six run-of-the-river electric power generating stations, harnessing a combined head of 138 m, and representing a capacity of over 13,000 MW (Figure 3). Additional projects may also be envisaged on the Great Bear, Liard and Slave Rivers, though not considered here, the latter being particularly delicate from an environmental perspective.

Hydrology

At its mouth, the average flow of the Mackenzie River is 9,910 cubic metres per second (CMS) while at the Great Slave Lake discharge, it is 4,835 CMS. Between these two points, several large rivers flow into the Mackenzie River, in particular, the Liard River at Fort Simpson, which contributes a non-regulated flow of 2,434 CMS.

Great Slave Lake covers an area of some 28,568 square kilometres, and contains an active reserve of water of some 57 cubic kilometres in the marling between elevations 155 and 157 m. This represents approximately 37% of the Mackenzie River's annual flow at the lake's discharge, or 25% of the flow at Fort Simpson (i.e., downstream of the confluence of the Liard and Mackenzie Rivers). As a result, water levels need only be managed within one metre variations about its average elevation at 156 m, that is to say, within its natural marling to have sufficient flow regulation capacity for the entire downstream complex.

Figure 3
Mackenzie River Profile – 156 m Head over 1,200 km (Project Head: 138 m)



Hydrology

	Basin Km²	Average Flow CMS
Fort Providence, Mack-7	970,000	4,825
Liard River	277,100	1,926
Providence at Simpson	42,500	295
Fort Simpson Mack-6	1,290,000	7,046
Fort Simpson at Wrigley	56,400	392
Wrigley, Mack-5	1,346,400	7,438
Wrigley at Keele	21,600	150
Redstone River	18,000	125
Birch Island, Mack-4	1,386,000	7,703
Keele River	21,800	151
Keele at Fort Norman	5,800	41
Great Bear River	156,800	1,089
Fort Norman, Mack-3	1,570,400	8,994
Mountain River	14,800	103
Fort Norman at Fort Good Hope	16,700	116
Fort Good Hope, Mack-2	1,601,900	9,213
F. Good Hope at Arctic Red River	47,700	331
Arctic Red River, Mack-1	1,649,600	9,544
Peele River	28,400	197
Delta Mackenzie	10,200	71
Estimated Total	1,688,200	9,812
Mackenzie River, Downstream of Fort Providence, Total	835,200 (164 km)	5,085

Geology

Knowledge of the overburden depth on the Mackenzie River riverbed remains the only key unknown needing further clarification, and recognition drilling must be considered a top priority at each proposed site. Indeed, this 1,200 kilometre long, flat-bottomed valley of 3 to 10 kilometres width, whose river is 1 to 2 kilometres wide on average, suggests significant overburden, mainly due to the lack of rapids from Great Slave Lake to the Beaufort Sea, despite an overall drop of 156 metres (Figure 3). Based on known drillings and past bridge construction at various sites, it seems realistic to consider a 5 to 6 m water depth, and a 6 to 8 m overburden depth as normal everywhere. Permafrost is present everywhere.

Environment

Although it is possible to propose a design for this complex consisting of only three or four dams for harnessing the Mackenzie River's potential, surely less expensive to build, the implementation scenario proposed here deliberately aims to minimize the flooding of lands by means of seven smaller, run-of-the-river generating station projects. The reservoir or forebay of each project is contained within steep shore banks in almost every case. The highest dam proposed here has a height of 27 metres. This scenario also avoids any development downstream of "Artic Red River" due to the environmental importance of the wetlands found there.

Each proposed generating station incorporates hydraulic structures facilitating the flow of fish, such as fish elevators, fish scales, etc. Several fish spawning grounds will also result from the construction of dams.

At each construction site, a new worker village will be added to an existing village, and industrial installations will need to be built. These installations are designed to remain in place at the end of construction.

This proposed complex is entirely located in the Northwest Territories, with a population of 40,000, located mainly in the town of Yellowknife. As a result, only a small number of people will be affected directly, and where they are, they can be compensated for any inconvenience. The completion of the proposed complex would open an important corridor toward the Beaufort Sea. In addition to the main road presently under construction, an airport, village and campsite will be built in each community hosting a hydroelectric power generating station, including an electric power grid, and community and industrial services. Moreover, it is in the interest of contractors to hire workers within these local communities, reducing the cost of transportation to and from worksite, and contributing to building the pool of highly qualified workers within the Northwest Territories.

Design Criteria

Load Factor

A load factor of 80% was retained for two main reasons. First, a lower load factor of 60%, such as that employed in Quebec's James Bay complex, would have required a larger reservoir capacity for each individual power station, resulting in the flooding of a wider geographic area. The second rests on the assumption that it is best to maximize energy output while minimizing power output in order to lower overall project costs. In other words, if the same amount of energy is to be delivered, at a lower load factor (i.e., 60%), this means that the same amount of energy is delivered in a shorter period of time, resulting in higher power generating and transmission capacity across the board. Clearly, this assumption will need to be reviewed over the next years. However, it is generally considered more profitable for peak power demands to be addressed locally, rather than by oversizing generating and transmission capacity over thousands of kilometres.

Powerhouse Design

The six proposed powerhouses are almost identical. For the purposes of this study and preliminary cost estimation, the James Bay Hydroelectric Complex' La Grande-1 powerhouse design was employed as the basic template for each one , with only the number of units (18 to 24) and the height of the water intake being adapted to every site's unique characteristics (Table 1). The turbines are assumed to be of the Kaplan Type, functioning at low speed to protect fish, with a nominal flow of 500 CMS each. All 138 Kaplan turbines are assumed to be identical for ease of procurement, maintenance and costs.

Table 1
Powerhouse Characteristics
Kaplan turbines, 500 MCS, 23 m head, 103.5 MW
(Ref. La Grande – 1)

	Basin Km^2	Av. Flow (CMS)	Design flow 80% (CMS)	Head (m.)	MW	No. of Turbines
Fort Providence, Mack – 7	970,000	4,825	6,031	9	—	
Fort Simpson Mack – 6	1,290,000	7,046	8,807	20	1,622	18
Wrigley, Mack – 5	1,346,400	7,438	9,297	21	1,798	19
Birch Island, Mack – 4	1,386,000	7,703	9,628	25	2,140	19
Norman Wells, Mack – 3	1,570,400	8,994	11,242	23	2,383	23
Fort Good Hope, Mack – 2	1,601,900	9,213	11,516	27	2,798	23
Artic Red River, Mack – 1	1,649,600	9,544	11,930	22	2,379	24
Total				138	13,120	138

Spillway Design

The powerhouse spillways are designed to be equipped with 2,000 CMS capacity gates, 12 metres wide x 20 metres high, similar to the La Grande – 1 spillway gates. The number of gates needed in each case is 15 to 29, depending on the estimated flow at each site (Table 2). Each gate is equipped with its own winch, and each spillway pass is equipped with slots for a set of stop logs, upstream and downstream of the pass. For several powerhouses, the tailrace of the passes will be concreted at the end, to lower the cofferdam elevation.

Table 2
Spillway Characteristics
Gates : 12 m wide x 20 m high,
2,000 CMS/pass
(ref. La Grande – 1)

	Average Flow (CMS)	Spring Flood (CMS)	No. of Gates
Fort Providence, Mack – 7	4,825	28,950	15
Fort Simpson, Mack – 6	7,046	42,276	22
Wrigley, Mack – 5	7,438	44,628	23
Birch Island , Mack – 4	7,864	47,184	24
Norman Weels, Mack – 3	8,994	53,964	27
Fort Good Hope, Mack – 2	9,213	55,278	28
Artic Red River, Mack – 1	9,544	57,264	29

Dams and Cofferdams

Assuming approximately 5 metres of water and 6 to 10 metres of overburden over the bedrock, the cofferdams are integrated to the dam itself. The dams are of the gravel-fill type. Asphalt cores could be used to hasten the construction schedule.

The cofferdams will be built employing a massive fill of boulders, covered by a gravel filter on the outside made watertight with till or clay. Usually built in a second construction phase while the river is diverted by the spillway, the upstream cofferdam is usually some five to seven metres higher than the downstream one.

The dams being of rather low height, the outside slopes will be 3 to 1 (vertical), meaning that it will be acceptable to leave the overburden in place under the structure, except under the core itself. The final choice on site for each individual generating station project will likely depend on whether the powerhouse and spillway can be constructed simultaneously in the first phase, saving one to two years on construction time.

Navigation Locks

A navigation lock is assumed at each site, 15 metres wide and 6 metres deep by 150 metres long. Usually, the lock is located between the spillway and the rock fill dam to be used as the resting wall for the fill. These locks will enable access by ships and barges along the entire length of the Mackenzie River, from Great Slave Lake to the Beaufort Sea.

The Mackenzie Hydroelectric Complex

Technical Description

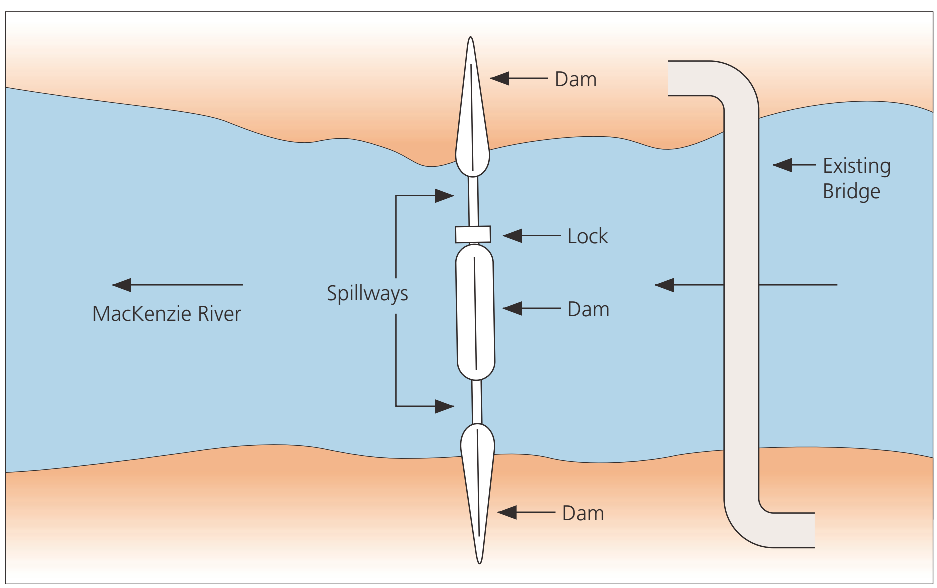
The complex is composed of seven individual projects, the most upstream being a hydraulic control structure for Great Slave Lake. The following provides a summary description of each project, from upstream to downstream (i.e., Figures 1 and 3).

Mackenzie – 7, Fort Providence

From Great Slave Lake (el. 156 m) to Mills Lake (el. 141 m), the 16 metre head is almost evenly spread over an 80 km distance, mostly composed of swamp lands. The only practical objective of this project is to build a control structure which manages Great Slave Lake's marling, plus or minus one metre, to regulate the flow of the Mackenzie River. The height of the dam presently appears insufficient for building an economically attractive electric power generating station.

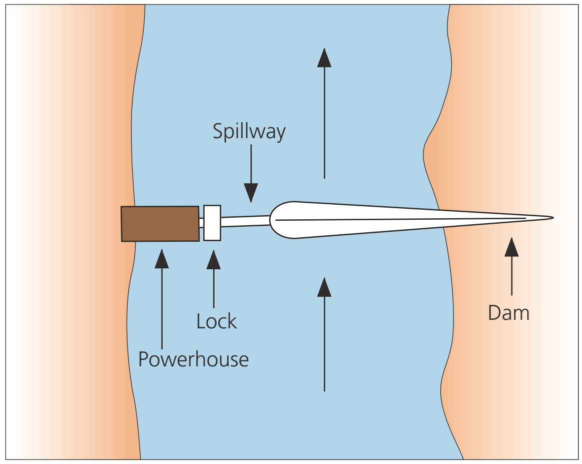
Approximately one kilometre downstream of a recently built bridge, the shorelines are steep enough to build a seven metre high dam. This height is sufficient to have effective control of the spillway, and the project is articulated around two spillways of seven and eight passes respectively, located on each side of the river, having a combined spillway capacity of 29,000 CMS (Figure 4). Individual gates will have a width of 14 metres and a height of 12 metres to ensure that ice can be sent downstream. A navigation lock is located on the left side of the right spillway (i.e., the right spillway being to the right of an observer looking downstream), in the river center. The site is closed by three rock fill dams, one on each shoreline, and in the centre of the river.

Figure 4
General Arrangement:
Mackenzie – 7 at Fort Providence



Mackenzie – 6, Fort Simpson

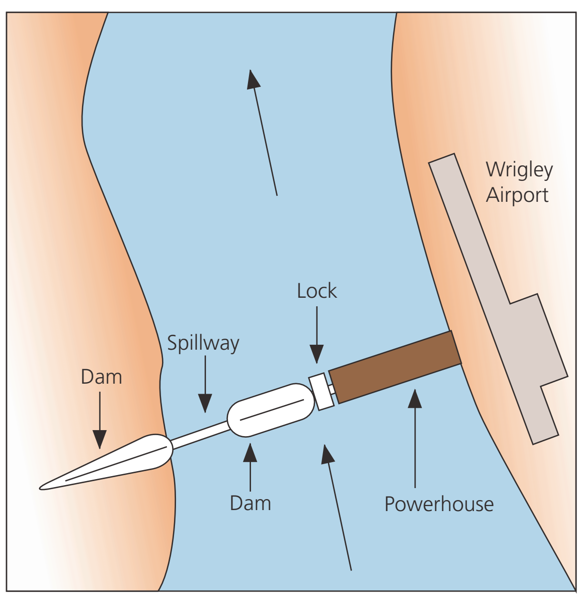
Figure 5
General Arrangement:
Mackenzie – 6 at Fort Simpson



Two kilometres downstream of Fort Simpson, below the confluence of the Mackenzie and the Liard rivers, is proposed a 20 metre high dam (Figure 5). Needed to modulate the flow of the combined Mackenzie and Liard rivers, this dam unfortunately submerges the village of Fort Simpson, slated for displacement on higher ground on the west (left) bank. The maximum upstream water control level is defined by Mills Lake, at elevation 141 m, in order to protect the large wetlands at its periphery. The downstream level is defined by the river's elevation at the village of Wrigley, elevation 121 m, resulting in a 20 m head. At this location, the river is large enough to build both the powerhouse and spillway in a single construction phase. The 1,622 MW powerhouse is equipped with 18 turbine-generator units while the 44,000 CMS spillway has 22 gates of width 12 metres by height 20 metres. A dam of 2 kilometres is needed on the east end of the structures to complete the closure of the river.

Mackenzie – 5, Wrigley

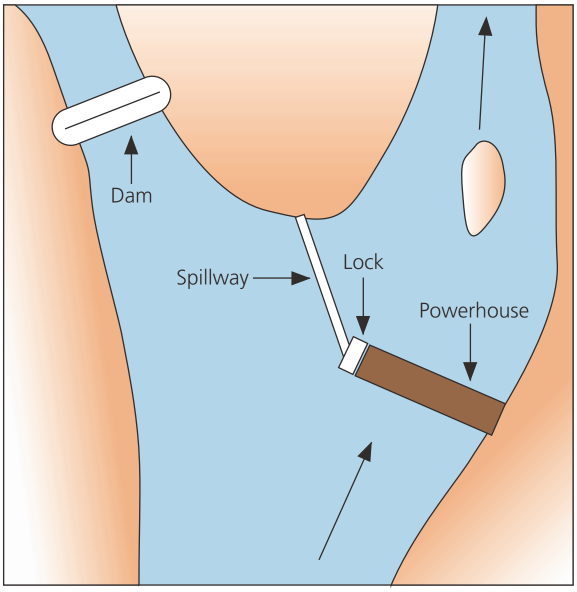
Figure 6
General Arrangement:
Mackenzie – 5 at Wrigley



Immediately facing Wrigley airport, even though river width is insufficient to build both powerhouse and spillway in a single construction phase, this site is recommended to avoid local flooding (Figure 6). The spillway, capacity 46,000 CMS, is located on the west side of the river and is built in the initial construction phase. The next phase consists of the construction of the powerhouse on the east (i.e., right) side of the river, consisting of 19 generators and 1,798 MW harnessing a head of 21 m, located near the future transmission system and village. A short rock fill dam is found at the center, to be closed at the end of the project, in order to maintain the lowest possible upstream water levels throughout construction.

Mackenzie – 4, Birch Island

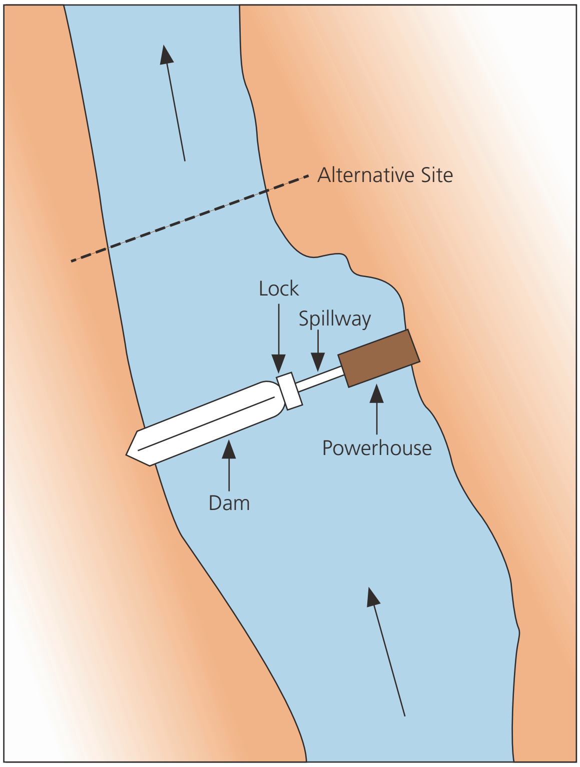
Figure 7
General Arrangement:
Mackenzie – 4 at Birch Island



At the present time, there is no village or road access at this site. Even so, the site is recommended in order to minimize flooding. Steep shorelines and the presence of an island make this an ideal site (Figure 7). Diverting the river initially on its west branch enables the project site (i.e., for both powerhouse and spillway) to be enclosed by cofferdams, and built in a single phase upstream of the island. Following this, the spillway is used to divert the river while a 500 metre dam is built on this west branch. The spillway, capacity 48,000 CMS, is equipped with 24 standard 12 by 20 metre high gates. Harnessing a head of 25 metres, the 2,140 MW powerhouse is equipped with 19 turbine-generator units.

Mackenzie – 3, Norman Wells

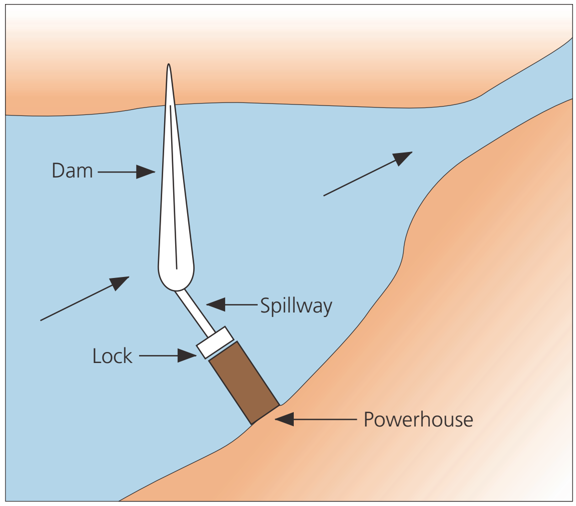
Figure 8
General Arrangement:
Mackenzie – 3 near Norman Wells



This site is located 30 kilometres upstream of Norman Wells, near the mouth of Prohibition Creek (Figure 8). Unfortunately, the village of Fort Norman needs to be relocated or abandoned. A 23 m head is harnessed to build a powerhouse consisting of 23 turbine-generator units, for a total of 2,383 MW. The spillway, capacity 54,000 CMS, equipped with 27 gates, is built with the powerhouse in a single phase. The dam is 2.5 kilometres long. A narrower site, three kilometres downstream, may also be worthy of consideration.

Mackenzie – 2, Fort Good Hope

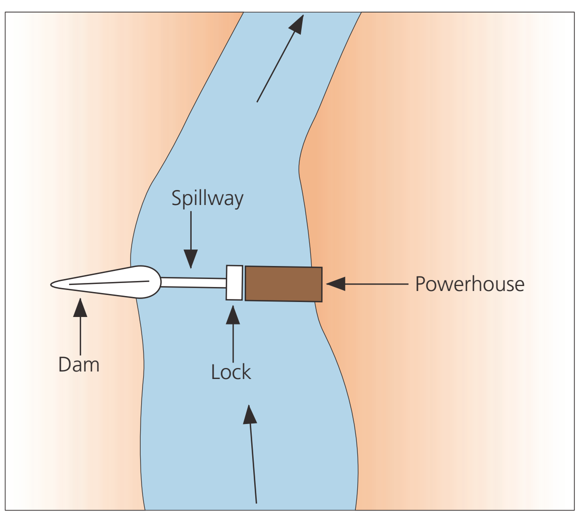
Figure 9
General Arrangement:
Mackenzie – 3 near Fort Hope



The highest dam of the Mackenzie River Hydroelectric Complex is located at the downstream end of what is called the "Bassin des Murailles" because of the very high cliffs which surround this river basin (Figure 9). The site is approximately 15 kilometres upstream of Fort Good Hope. Between these two locations, the river is either too swift or too narrow to embed the structures, or is encumbered with shallow water needing expansive dredging. On the left side of the river, rocky features and islands indicate a high probability of establishing favourable foundations. The site allows the construction of both powerhouse and spillway in a single phase. The powerhouse, with 23 turbine-generator units and a capacity of 2,798 MW, would be one of the largest in Canada. Spillway capacity is 58,000 CMS, with 28 gates. The dam, located on the northern side of the river, is 1,700 metres long.

Mackenzie – 1, Artic Red River

Figure 10
General Arrangement:
Mackenzie – 1 near Arctic Red River



Here again, due to swift currents, a narrow riverbed and high shorelines, the complex' final downstream dam is located approximately 15 kilometres upstream of the village of Artic Red River (Figure 10). Site construction requires two phases, the first focusing on spillway construction, so that the river can subsequently be diverted to build the powerhouse. The 22 metre head is harnessed by means of 24 turbine-generator units for a total capacity of 2,379 MW. The spillway is equipped with 29 gates to accommodate a flow of 58,000 CMS.

Transmission System

To connect the Mackenzie Hydroelectric Complex to the Alberta power grid near Edmonton, some 10,000 kilometres of transmission lines will be needed, based on a 735 kV transmission technology scenario, a technology pioneered in Canada and used successfully in both Quebec and the United States for nearly 50 years (i.e., the 765 kV class transmission technology). At a present cost of 1.5 million dollars per kilometre, a single line has a transmission capacity of approximately 2,000 MVA; 10,000 kilometres of 735 kV lines would therefore cost approximately 15 billion dollars. Incorporating appropriate static var compensation, line capacity can be increased to approximately 2,800 MVA / line. For cost estimation purposes, compensation and associated switching stations are assumed to equal the cost of the transmission lines, resulting in a total transmission system cost of approximately 30 billion dollars. Accounting for inflation and financing until construction end in 2034, this amount rises to approximately 60 billion dollars. This project could be built from 2025 to 2034 at the rate of approximately 1,000 kilometres/year.

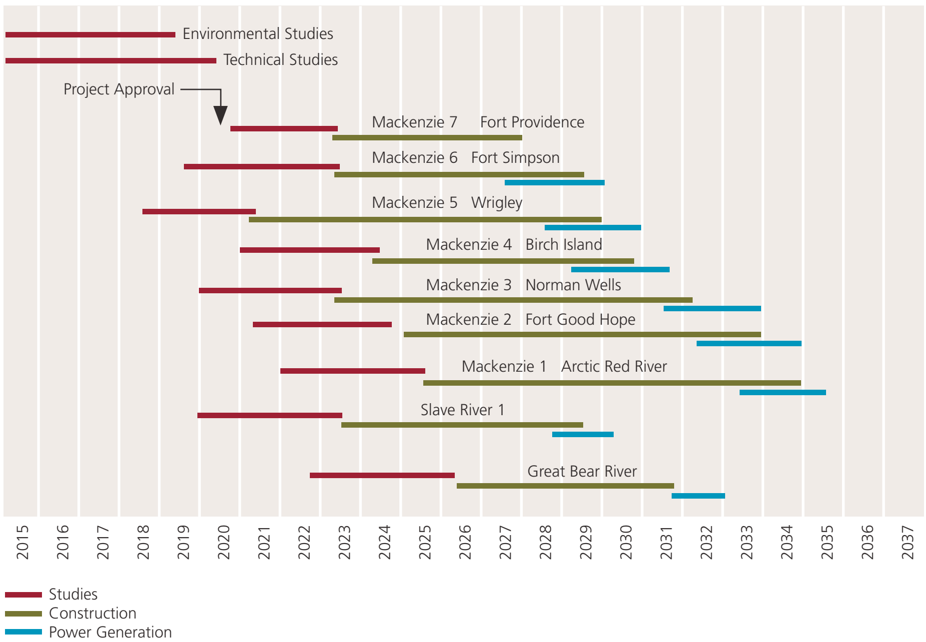
Construction Planning

To manage ice covers and potential winter ice jams, the complex should be built upstream to downstream, as proposed in Figure 11. Top priority goes to Mackenzie 6 and 5, respectively at Fort Simpson and Wrigley, Mackenzie 7 being built faster in the absence of a powerhouse.

The schedule presented here assumes that nothing at all will be done over the next two years, besides publishing the main facts about the project, weighing its advantages and assessing its feasibility and acceptability. From 2015 to 2021, six years are needed to study environmental impacts and identify appropriate corrective measures as needed. In the meantime, geological and hydrological technical surveys should move forward in order to confirm existing knowledge and collect new data establishing the project's feasibility, costs estimates and, more importantly, its profitability.

Even so, the Mackenzie Hydroelectric Complex implementation scenario proposed here incorporates such a pragmatic approach from both an environmental and a design perspective (i.e., in the way each site is similar to the other), that two to three years of design work may well be saved.

Figure 11
Mackenzie River Hydroelectric Complex Construction Schedule



Mackenzie River Hydroelectric Complex Estimates

The cost of the Mackenzie hydroelectric complex is estimated at 114 billion of dollars at the end of construction in 2034, including 60 billion for the transmission system to Edmonton (Table 3). In fact, the investment would likely not need to finance this amount as the project could begin to generate revenue with the first flow of power in 2027; construction could even be suspended for some years after the first power stations are commissioned and producing power in order to finance subsequent power stations.

To this cost of 114 billion dollars, 540 million must be added for the environmental assessment, preliminary design, technical surveys and authorization procedures.

Table 3
Mackenzie River Hydroelectric Complex Estimates
(Millions of Dollars)

Project	Total Cost	Financing	Inflation	Cost ($, 2014)
Mack – 7	1,713	250	433	1,030
Mack – 6	8,349	1,407	1,414	3,630
Mack – 5	6,767	1,579	1,574	3,614
Mack – 4	8,116	1,812	2,077	4,227
MacK – 3	9,697	2,966	2,101	4,629
Mack – 2	10,197	1,929	3,023	5,244
Mack – 1	9,793	2,078	2,911	4,803
	54,632	12,021	13,533	27,177
	100%	22%	24.8%	49.7%
Power Lines	60,000			

Profitability Study

With an installed power output of 13,120 MW, assuming 80% availability over 8,766 hours per year, the yearly energy produced will amount to 92,007,936 MWh.

Table 4
Commissioning Schedule
Yearly added power (MW)

	2027	2028	2029	2030	2031	2032	2033	2034	2035
Power, total (MW)	13,120	270	1,010	1,725	2,075	2,189	2,427	2,380	1,042

Yearly Energy Production Value

The yearly production value is estimated here using three different situations, namely:

Electricity cost in Quebec:
- 8 ¢/KWh or $80/MWh in 2013, with an inflation at a yearly rate of 5% to the year 2034;
- About $202/MWh in 2034:
- Production of 92,000,000 MWh/year;
- Income of 18.58 billion dollars in 2034;
- For a 114 billion dollar project,
- Return of 16.3%/year on the investments

Electricity cost in Ontario:
- $140/MWh in 2013, or $353/MWh in 2034
- Income of 32.46 billion dollars in 2034
- Return of 28.5%/year on the investments

Equivalent energy for oil production

- $100/barrel in the year 2013:
- 5% inflation yearly rate to the year 2034, or 252 $/barrel;
- Energy production equivalent of 191.5 million barrels yearly; or 525,000 barrels/day,
- Income of 55.93 billion dollars in the year 2034;
- Return on this investment of 49%/year.

Conclusion

The Mackenzie River Hydroelectric Complex described in this chapter truly is a "big project," on a scale comparable to the largest hydroelectric complexes ever built. Characterized by flows of up to 9,000 cubic metres per second, steep shorelines avoiding wide-area submersion, and large lakes acting as flow regulation reservoirs, the project harnesses more than 13,000 MW, available 80% of the time, and delivers its high added-value energy through a 10,000 kilometre transmission system to Edmonton. The complex would produce some 92 million MWh yearly, equivalent to producing 525,000 barrels of fuel oil per day. At current Ontario electricity rates, assuming a 5% yearly inflation rate to 2034, this energy output would produce a gross annual revenue of about 32.4 billion dollars, for a total project cost of 114 billion dollars. This clean energy could be used to assist Alberta (10,000 MW) and Saskatchewan (3,000 MW) transition from high-carbon footprint thermal generating stations at the end of their useful life, to low-carbon hydroelectric power, and powerfully contribute to "Canada becoming a sustainable energy powerhouse!"

Biography

F. Pierre Gingras has been deeply involved for over 47 years in the execution of major hydroelectric projects, especially as Chief Planning and Cost Engineer for Hydro-Québec's Major Dam Projects like the Manicouagan and James Bay complexes, rebuilding of existing works, and some 200 other hydroelectric projects studies. Retired, he is continuing to study various projects with the Montreal Economic Institute, the Canadian Society of Senior Engineers, the Canadian Academy of Engineering, and some large engineering firms. Among major outcomes of this work is the "Eau du Nord" (Northern Waters) project, intended to direct additional flows into the St. Lawrence River Basin, a technical and economic study for a pan-Canadian high-tension distribution network, and a comprehensive integrated management plan for the entire St. Lawrence River Basin with emphasis on managing the disastrous environmental effects of climate change. In 2013, he completed the first preliminary study about the huge Mackenzie River hydroelectric project.