HUNTING FOR HYDRO

A PAPER PREPARED FOR PRESENTATION TO

UNIVERSITY OF TORONTO HYDRO ENGINEERING STUDENTS

By

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***Abstract* – The discovery, design and contracting methods used on hydro plants has changed over the years. This paper describes these changes, and how the changes have affected engineering work.**

***Index Terms* - Design, Hydro, Construction, Contracts, Costs.**

1. Newfoundland. 2. Amazon jungle. 3. Bolivia Andes at 4,900m. 4. Turkey. 5. Sri Lanka. 6. Panama.

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I. INTRODUCTION

Water has been used as a source of power since about 24BC, when Strabo described a water-wheel driven corn mill at Cabeira in the Pontus (8). Many plants have now celebrated 100 years of continuous service. So hydro is now considered to be a mature industry and few young engineers think of hydro as a suitable career, believing it is a "buggy whip" industry, soon to disappear. However, this is not the case. Hydro is currently enjoying a renaissance both here in Canada, and around the world. In Newfoundland, Newfoundland Hydro is working on the development of the Gull Island site on the Churchill River in Labrador. In Quebec, the Peribonka powerplant has recently been commissioned, Rupert River (Eastmain 2) is under construction, and the government has recently instructed Hydro Quebec to speed up the rate of development of new plants, to supply an insatiable demand for power from both the USA and Ontario.

Figure 1. Generator floor, Peribonka powerhouse. 3 Francis units, of 128MW at 67.6m rated head.

In Manitoba, the Wuskwatim site is currently under construction, Conawapa is being prepared for development, and the Pointe du Bois site will be completely re-built. Out west, in British Columbia, a large number of small, high-head run-of-river plants are under construction.

Figure 2. Pointe du Bois in Manitoba.

Overseas, hydro plants are being built in all developing countries, and China has just completed the construction of the largest hydro plant in the world at Three Gorges, with a capacity of over 22,000MW. Worldwide, over 106,000MW of capacity has recently been commissioned, and over 155,000MW of capacity is in the planning stage, counting only powerplants with capacities in excess of 2,000MW (13).

Figure 3. 4.5MW Marion creek, BC. 1.1m^3/s Coanda intake, head = 495m. (Source - Pentti Sjoman, P.Eng.)

The first and oldest continuously-operated hydroelectric facility was built in Canada, and is located in St. Stephen, New Brunswick, where a rope-driven generator originally powered the electric lights for a mill when it opened in 1882, and in 1888 started providing power to homes in the town. New Brunswick Power now owns and operates this as part of the Milltown Dam hydroelectric station (13).

All this work cannot be undertaken without the participation of many civil, geotechnical, mechanical and electrical engineers. Moreover, operation and maintenance of the plants requires many more engineers. In Canada, all hydro consultants are now overloaded with work, and are continually seeking more staff, a difficult task, since, as mentioned, few graduating engineers select hydro as a career. Utilities are also looking for staff; since at several, about 50% of their hydro engineers are due to retire within the next 5 years.

II. FINDING HYDRO SITES.

How does a company go about finding and developing a hydro site? Prior to mapping, and satellite imagery, the only method was to look for rapids and waterfalls, usually known to the local inhabitants. The site had to satisfy several criteria, such as -

- Easy access. Remote sites are expensive to develop.
- Nearby transmission lines.
- Competent rock foundations.
- A market for the power.

Once a site is discovered, the development proceeded slowly through several stages requiring many years of work, and often interrupted due to unexpected technical difficulties. Perhaps the best way of illustrating the process would be to describe development of the 5,428MW Churchill Falls (initially called Grand Falls) hydro plant in Labrador.

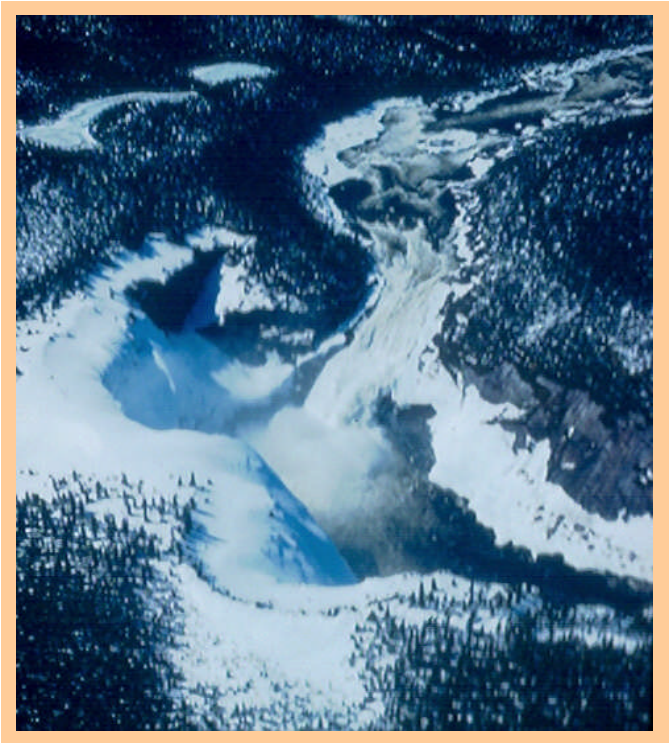

Figure 4. Churchill Falls – before diversion, June 1954.

III. CHURCHILL FALLS – INITIAL DISCOVERY.

John McLean, on instructions from his employer, the Hudson's Bay Company explored Labrador, and after a discussion with the local Naskaupi Indians saw the Grand Falls on the Hamilton River in August 1839. News of the huge falls eventually reached the Geographical Club of Philadelphia, and in 1891, H. Bryant along with Professor C. Kenaston of Washington, set out and arrived at the falls on 2nd September 1892. They measured the height at 316ft by lowering a weighted rope down the near-vertical gorge cliffs. News of the falls reached Ottawa, and Albert Lowe, an 1882 geological graduate from McGill College employed by the Geological Survey of Canada, arrived at the falls on 2nd May, 1894, and estimated the flow at 50,000cfs. The first assessment of the falls potential was made by Wilfred Thibaudeau, an 1883 engineering graduate from Laval, employed by the Commission for the Management of Running Waters in Quebec, in a 1915 report wherein he developed the "Channel scheme" concept with a head of over 1,000ft, eventually used in the project.

Due to the remoteness of the site, and the vast amount of power, ($9.81 \times 1{,}500 m^3/s \times 300 m \times 0.85 = 3{,}750{,}000 kW$) nothing more was done until 1952 (9).

IV. CHURCHILL FALLS – INITIAL ASSESSMENT.

In 1952, Joey Smallwood, Premier of Newfoundland, with the assistance of the Rothschild banking company in Britain, formed the British-Newfound Corporation (Brinco) to develop the hydro and mineral potential in Labrador. Next year, they engaged the services of Denis Stairs, the president of Newfoundland Light and Power, and a vice-president of Montreal Engineering Company to undertake an initial assessment of the hydro potential at the falls. Stairs, in a 10-page report estimated that the potential was at least 4,000,000HP, but extensive surveys would be required to more accurately estimate the potential and cost.

After much discussion within Brinco, the initial estimate of $100,000 for the survey work was expanded to $3,000,000. Montreal Engineering was contracted to survey the drainage area above the falls, Shawinigan Engineering to survey the area around the channel diversion and the falls, and both companies were to cooperate on the production of a pre-feasibility report. It was, by far, the largest hydro survey ever undertaken in Canada.

At this time, there were no maps of the area, with the Canadian maps showing Labrador as a blank area described as "Unexplored territory". So, the first task was to determine the approximate drainage area, accomplished in the winter month of March 1954 by a 10-man team based at the Menihek powerplant construction camp, and at a tent camp by Lake Mitchikamau. With the help of precision barometers and two Beaver aircraft, daily expeditions out over the tundra indicated that the drainage area could be about doubled by diverting the vast Michikamau Lake inflow with a canal into Lobstick Lake and a dam on the Naskaupi River (1). A storage dam at the Lobstick Lake outlet would control the flow, discharging water into Flour Lake, and then Jacopie Lake where a diversion dam would direct flow into a 50km-long series of lakes and canals to the north of the river, to a forebay dam south of Sona Lake about 20km downstream of the falls. There an intake and tunnel would convey the water down to an underground powerplant, and out to the river through a tunnel.

The interim report on the winter work confirmed the viability of the "channel scheme" and stated that "the cost per horsepower of the ultimate development will be very low", and that the topography was "exceptionally favorable".

Since the potential was still unknown, the terms of reference for the report were to determine the cost and project arrangement for 4 capacities of 1 million to 4 million horsepower with interim reports each spring, and a final report in April of 1957.

With no maps, high level aerial photos were obtained from Ottawa, assembled into a mosaic, and the probable drainage area was outlined on a drawing overlaid on the photos. The potential dam sites were added, and plans made to undertake the survey work. All transport was by Beaver or Norseman aircraft and locally with Bell helicopters. Canso flying boats were used to transport survey crews into and out of the base camps at Sandgirt and Sona Lakes (1).

Figure 5. Start of survey work, crew arriving, July 1954.

400 tons of supplies was flown into the area with ski-equipped DC3 aircraft, and dumped on the ice near 11 camps to be established later. 180 men were recruited for the surveys from

Newfoundland, and offers were made to all 3rd year civil engineering students at UNB and Nova Scotia Tech. About half accepted the offer, and many continued on to careers in the hydro industry. Two summers were spent on survey work for aerial photo control and precise leveling.

Figure 6. Survey tent camp – August 1955.

Tent camps provided accommodation, and one crew traveled over 900km by canoe from Muskrat Falls, near Goose Bay all the way up the Hamilton River to near the falls, and from there traveled from Whitefish Lake, through a series of lakes to Jacopie Lake, Flour Lake, Lobstick Lake on to Michikamau Lake, and across to Orma Lake. During this journey, control levels were established for all the survey camps. Altogether, 500km^2 were mapped, 6,900 river soundings, 120 test pits, 238km of seismic ground profiles and 1,800m of diamond drilling were obtained (2). During the winter, four cableways for river stream-flow gauging were established. The supply route was long, with food orders being sent by radio to the base camp at Sandgirt, from there again by radio to an office in Seven Islands, and phoned from there to a supplier in Montreal. Orders were assembled and sent by chartered DC3 to Seven Islands, loaded onto the Iron Ore work train, to be off-loaded at Mile 286, an abandoned railway construction camp, where a rail siding, warehouse, airstrip and a dock for float planes was established. There the supplies were loaded onto Beaver aircraft and flown to the base camps, to be re-distributed on to the tent camps.

Figure 7. Access road survey crew – lunch, August 1955.

In 1955, the 160km access road rout was surveyed and flagged, from Mile 286 on the Quebec North Shore and Labrador Railway to the falls, and in 1956, the first half of the road reached the Atikonak River crossing. It was completed to the Falls in 1957, including the construction of dykes across the outlet of Gabbro Lake (Figure 10).

Figure 8. Access road construction, August 1956.

Figure 9. Typical timber crib bridge on access road.

In April of 1956, the final report indicated that by correlating the Hamilton River flows with those for the Outardes River in Quebec, and estimating the construction and transmission costs to the Labrador border, it was calculated that a 4,000,000HP development would cost about $350,000,000, and energy could be produced for $0.003/kWh (8). Cost per kilowatt was $117. Today, most hydro developments cost upward of $3,500/kW.

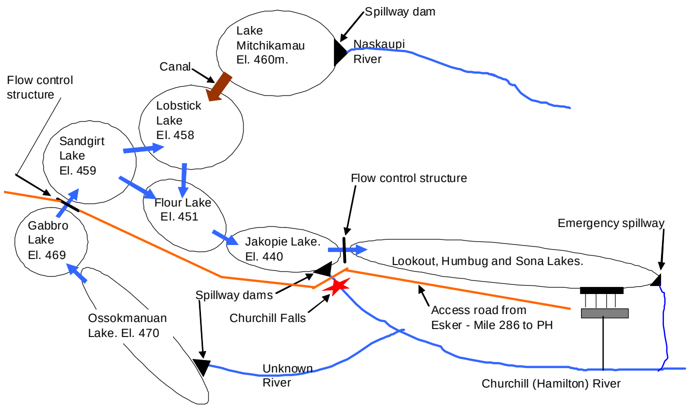

Figure 10. Schematic showing project arrangement as developed during 1955-57 surveys.

The report included preliminary drawings for the structures, and a section through the powerhouse is shown in Figure 11. It is interesting to compare this section with that finally built, as shown in Figure 23.

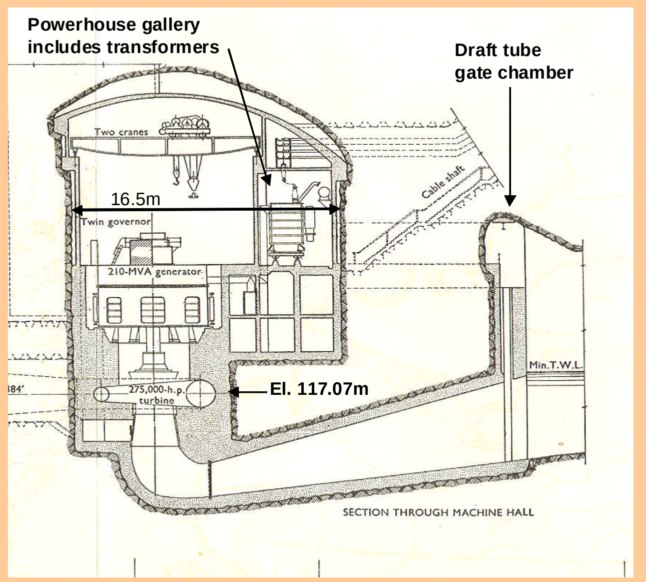

Figure 11. Pre-feasibility report - powerhouse section.

V. CHURCHILL FALLS – INTERIM WORKS

With completion of the access road to the Falls in 1957, Brinco started looking for a buyer for the enormous amount of power. The search continued for many years. Meanwhile, an iron ore mine was discovered at Wabush, at the western extremity of Labrador, and the Iron Ore Company (IOC) asked Brinco if they could supply 120,000HP in two units. This was too small a capacity to justify construction of the Churchill development, so a search was made for something smaller. It was found near Churchill Falls, where the Scott Falls and Thomas Falls on the Unknown River, collectively known as the “Twin Falls” are located close to a dry canyon which meets the Churchill River canyon below the falls. A $47,000 contract was awarded to Shawinigan Engineering to assess the site, and in November 1957, their report indicated that 133,000HP could be developed at a cost of $41,000,000, or $413/kW.

Figure 12. Twin Falls intake.

The project required damming the Unknown River at the outlet of Lake Ossokmanuan with a weir and two sluice gates (Figure 14). Another dam further downstream on the Unknown River at Twin Falls (shown in Figure 13) would divert the flow into a short canal to an intake at the crest of the gorge, where penstocks would carry the water down to the powerhouse. The developed head would be about 91m, and would divert flow away from the Churchill Falls, hence it was always regarded as a temporary plant.

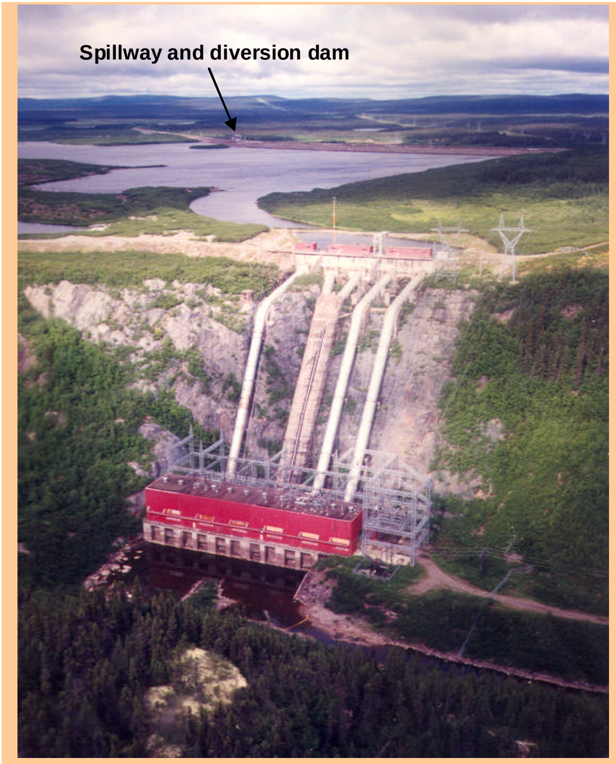

Figure 13. Twin Falls, 1999 – 5 units, now abandoned.

A contract was signed in September 1959, and work started immediately to upgrade the access road, extend the road 20km to the site, and build an airstrip. Montreal Engineering was retained by the IOC mining company to monitor the work. The first two units started delivering power in June 1962, two more units powered up in September 1964, and a final fifth unit was added in 1967, for a total of 300,000HP. The fifth unit was used to power the Churchill Falls construction camp.

Figure 14. Ossokmanuan control structure.

The Ossokmanuan structure was designed to that the weir level could be increased for the future Churchill development, as shown in Figure 14. Twin Falls ceased operation shortly after Churchill Falls started operation, was maintained as an emergency power source for a few years; was mothballed, and eventually all easily recovered equipment was removed, (note no hoist on intake gantry, Figure 12) and the project is now abandoned. There was a local small village with about 102 persons for the operators, larger than would be required now, since the plant was built before automation became common in hydro plants. It included a nurse and a small Hudson's Bay general store. The village was later demolished. Management of the project provided a much-needed learning experience for Brinco on power project development, and the project was used as a training facility for future Churchill Falls operators.

VI. CHURCHILL FALLS – FEASIBILITY REPORT.

By 1963, the initial cost estimates for the project were almost 10 years old, and becoming obsolete due to the rapid advances being made in hydro and construction equipment. Hence, in February of 1963, a contract was awarded to Acres for further work, the terms of reference being to estimate the cost of a full development, to be constructed in one step.

A draft was ready by May, with the final report at year end proposing the installation of 10 units at 600,000HP at an estimated cost of $627,000,000, or $104.5/HP. The Acres work included extensive site soil investigations, more topography, and hydrology studies with the longer water records now available for the Labrador Rivers.

Brinco then asked Acres to form a joint venture with Bechtel, a large contractor based in San Francisco. Their first assignment was to check the Acres work, particularly the cost estimate, which they endorsed. This encouraged Brinco to award contracts for a bridge over the Hamilton River, just above the falls, and continuation of the access road to the powerhouse site.

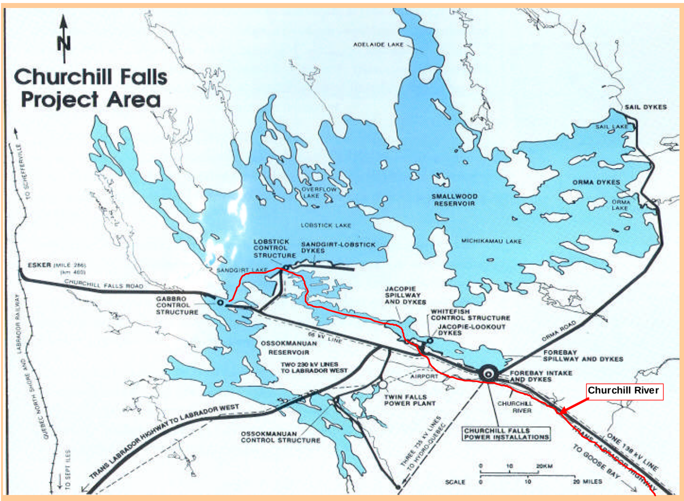

Figure 15. Churchill development – as built.

However, with more detailed information on the topography, and the effect of inflation, the estimated project cost increased to $800,000,000 by December 1966. It was then realized that much more survey work was required in the field to determine the exact quantities, costs and material sources for the numerous dams, dykes, spillways, control structures and powerplant comprising the development. This was instituted in the summer of 1967, after a letter of intent was signed with Hydro Quebec, and resulted in a 16-volume comprehensive report with a total thickness of 1.5m describing in detail all aspects of the project, in effect this became the final definitive "feasibility report". This work produced several changes to the concept. The reservoir level was increased, eliminating the canal from Lake Mitchikamau. The forebay was split in two, with an upper western forebay 4.3m higher than the forebay at the intake, to eliminate the possibility of frazil ice forming in the shallower reaches of a single forebay, and the number of units was increased to 11 to have a "spare" unit for use during a repair.

VII. CHURCHILL FALLS – CONTRACT NEGOTIATIONS.

During the following 3 years after 1963, there were difficult contract negotiations with Hydro Quebec. By July 1966, Brinco had spent over $13,000,000 on the project, had a serious cash flow problem, and had to cancel the road work east of the bridge over the falls. Finally, on October 13, 1966, a letter of intent was signed with Hydro Quebec for the delivery of 32.2 billion kWh of energy per year at $0.0025/kWh, equivalent to revenue of $80,500,000 per annum, decreasing to $0.0021/kWh after 40 years.

Two weeks after signing the letter, a contract for completion of the access road and camp construction was placed. Joey Smallwood changed the name of the river and falls to Churchill, in honor of Winston Churchill, who had introduced Smallwood to Rothschild at the beginning.

VIII. CHURCHILL FALLS – CONSTRUCTION.

The detailed design and construction management was undertaken by Acres Canadian Bechtel of Churchill Falls, with Acres on design, and Bechtel on construction management.

Their staff peaked at 531 persons, but 22 outside consulting firms were also contracted for advice and services. During construction, over 50,000 men worked on the project, with site staff peaking at 6,245. By end August 1968, over $77million had been spent on the project, still without a firm contract with Hydro Quebec. Over the next months, financing for the project was arranged at interest rates of 7.75% to 7.875%, and on 15 May, 1969, a contract was signed with Hydro Quebec, for energy at $0.0029645/kWh declining to $0.0025426/kWh for the last 15 years of the contract. With the cost of transmission to Montreal, the cost of delivered power increased by $0.002/kWh to 0.5cents/kWh. Construction was completed at a cost just below one billion dollars, or $190/kW.

Much has been made of this "ridiculously low price" for the energy. Now, hydro costs 6 to 8 cents/kWh, and Hydro Quebec is purchasing wind energy at even higher prices. But when the contract was signed, most hydro energy was being produced at rates of between 2 and 4 mills. (10 mills = 1 cent) Also, nuclear energy was on the horizon, with projected costs of less than 2 mills, with the perception that "it will not be worth while installing switches to turn off the lights". Moreover, the Canadian Electricity Association annually published charts of the average cost of electricity in Canada, and these showed a steadily declining cost to well below 4 mills in 1967. So for 1968, it was a fair contract. What was forgotten; was an escalation clause for the operating costs, which by 1990 had become so high, that revenues no longer covered costs.

Figure 16. Gabbro flow control structure.

All control structures and spillways are similar, with hoists on towers, stair access at one end, and the hoist house cantilevered out at the other end, so that parts can be hoisted up when repairs needed (Figures 16, 18). Also, there is an emergency diesel housed in one of the downstream end piers.

The project was officially started with the usual gold-plated first-shovel ceremony by Joey Smallwood on 17 July, 1967, reservoir filling commenced on 1 July 1971, and the first unit started delivering power on 6 December, 1971. Inauguration ceremonies took place on 16 June, 1972.

Figure 17. Underground powerhouse generator floor. 11 units, total capacity 5,428MW. Length = 296m. Height = 47m. Width = 25m.

Figure 18. Lobstick flow control structure. Stoplogs in place for repairs to middle sluice.

Figure 19. Tailrace surge chamber.

Figure 20. Typical dyke. Total crest length = 64.4km.

Work was undertaken on a unit price basis for the civil work, with designs by consultants. Equipment was contracted on a lump sum basis, plus hourly rates for installation.

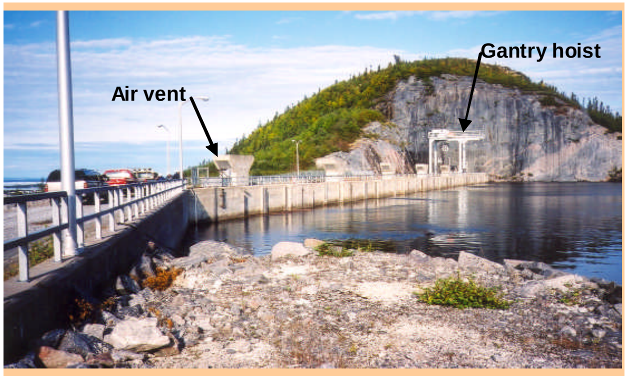

Figure 21. Churchill Falls intake structure.

Figure 22. Powerhouse roof arch, suspended ceiling.

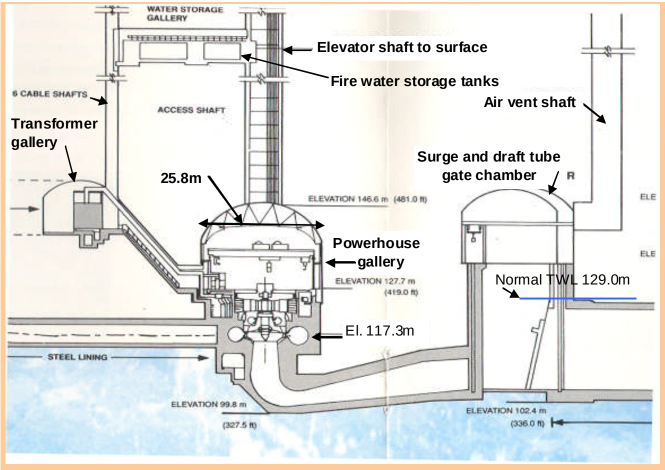

Figure 23. Section through powerplant, as built.

IX. Modern site discovery methods.

Now, with Google Earth, it is possible to find hydro sites from your office, and this is where the search should begin. All that is needed is to follow rivers until a waterfall or set of rapids appears. As an example in Ontario, follow the Missinabi River north until the Thunderhouse Falls and Hells Gate Canyon appear (50-03-10N 83-11-07W). Often, there are several photos of the site, one of which is shown below. There is a head of at least 65m over a distance of 6km.

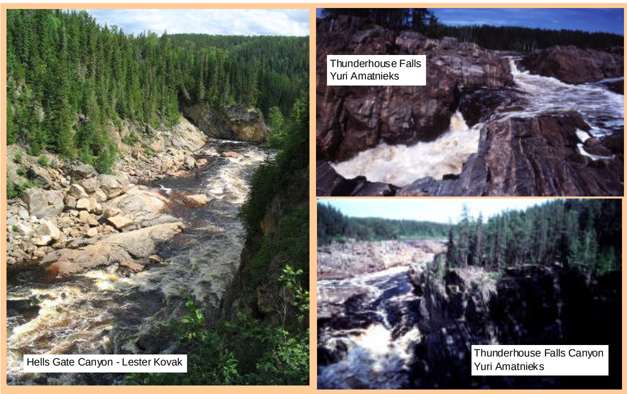

Figure 24. Missinabi River Falls – source – Google Earth.

In British Columbia, there are over 80,000 mountain-side creeks where high head run-of-river small hydro plants could be built. Shortly after Google Earth became available, a BC consultant was contracted to look for possible creek plants, the criteria being (a) high head, (b) within 10 km of a road and a 25kV transmission line, and (c) a minimum drainage area of a few square kilometers. Many sites were found, and then RETScreen (10) was used to rank the sites in order of economic viability. The hydro module for RETScreen was developed by the author and Mr. K. Bennett in 1995, and has been updated twice since then. It can be downloaded free over the internet.

A typical high-head small hydro site in British Columbia is on the eastern shore of Lake Powell (El 56m), where there is a creek flowing out of a perched lake at El. 1,124m, only 3.0km from Lake Powell. The lake is at 50-10N, 124-18.5W. The conduit/head ratio is only about 3.1, indicating a very attractive site, but expensive due to the long transmission distance.

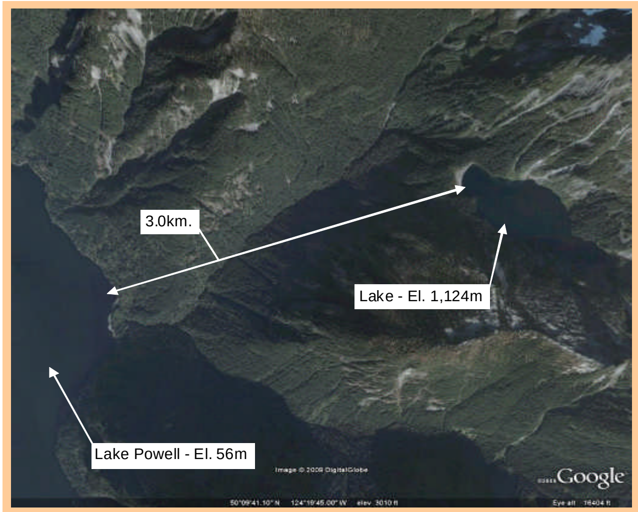

Figure 25. Lake Powell small hydro site.

Others have found sites on Google Earth, checked the topography using web-based mapping (14) and hiked into the creek, installed automatic water level recording gauges, and filed a claim on the site. Over the next few of years, the site is visited every few months to download the data. Water level recorders are now available with internal batteries lasting 10 years, and with memories capable of storing 40,000 readings. After this, the flows are analyzed to see if they are adequate to support an installation of at least 5MW, and if so, a search for a developer is instituted, to whom the site claim is sold. Now there are many small hydro developers active in BC such as Plutonic, Cloudworks and Canadian Hydro Developers.

X. Modern pre-feasibility assessment.

Again, Google Earth has greatly facilitated this task. Google data, combined with a site inspection, and use of computer programs, reduces the work to a few hours. Several programs are available. One is Hydrobot (3), a program developed for small and micro hydro sites in Scotland with capacities of less than 5MW. According to the website (11), the program works as follows -

"Hydrobot is a geographical model using data from many different sources to survey an area for hydropower potential. It does this by mapping the river paths and calculating the flows throughout the year, then testing many different layouts in all potential sites. Hydrobot selects the best solution in each place, according to the user's preferences. Hydrobot has been used to survey the whole of Scotland in a report for the Scottish Government.

Because Hydrobot is automated, it can generate results more easily and quickly than a person visiting the site. The output is a pre-feasibility study: the first investigation of any hydro project. A pre-feasibility study assists the client and developer to decide whether a full feasibility study is warranted at that site, since a feasibility study requires considerable time and investment. The pre-feasibility study is not an exact quote for a project, but aims to be a reasonable estimate of the most suitably sized scheme at each site. Two types of hydro scheme are currently modelled by Hydrobot:

- those with a new weir and penstock (pipe); and

• existing weirs, without a penstock or storage pond, but with some existing structures.

Hydrobot takes into account the reduction in costs where a weir already exists. Every scheme is different and these factors can only become clear during the full feasibility study. Currently the modeled schemes are “run-of-river” rather than storage schemes, which means the flow will vary throughout the year, heavily influenced by rainfall.”

Currently the program is only available in the UK, but plans are to license the program for use in areas where there is digital mapping available to a large scale. Using Hydrobot, an analysis of a potential stream can be undertaken for about $60.

Another program is HydroHelp (12), a series of programs developed to by the author allows engineers to obtain an initial assessment of a hydro site, with a minimum of site data. All programs use Microsoft Office, Excel 2003 on Windows XP. The user starts by using HydroHelp 1 (4) for turbine selection. The program guides the user through the turbine selection process from a total of 28 types of turbines, ranging from very low head “pit” units to high head multi-jet impulse units.

If the turbine selected by the program is not suitable, the user can de-select the turbine by entering a 0 in the column adjacent to the type of unit selected by the program. The program will then revert to the next best unit based on cost. In the example provided in Figure 27, there are 7 suitable turbines, hence selection of the optimum unit is often difficult.

HydroHelp 1- Turbine selection - BAKER issue, January 2009.		
BAKER FALLS	Enter data in blue cells only.	Comment.
Project input data. Date of estimate --- >		5-Jan-09
Headpond full supply level, m.	877.00	
Headpond low supply level, m.	875.00	
Head loss to turbine, % of gross head, at full load.	4.50	Comment
Normal tailwater level, m.	440.00	Comment
Flood tailwater level, m.	445.00	Comment
Design powerplant flow, cubic meters per second.	10.00	
Desired number of units.	2	
Summer water temperature, degrees Celsius.	15	
System frequency, Hz.	60	
Generator power factor.	0.90	
Maximum allowable gearbox power, MW.	2	Comment
Design standard & generator quality, industrial = 0, utility = 1.	0	Comment
Inflation ratio since 2008	1.01	
Program output - turbine heads and flow.	Reaction unit.	Impulse unit.
Maximum gross head FSL to normal and flood TWL, m.	437.00	432.00
Rated net head 1/3 drawdown to normal and flood TWL, m.	416.70	409.42
Rated flow per unit, cubic meters per second.	5.00	5.00
Recommended type of reaction turbine.		
No suitable reaction turbine, select impulse unit.		If no suitable turbines, change number of units.
Recommended type of impulse turbine.		
Vertical axis, 4 jet, 1 runner impulse turbine.		

Figure 26. Example - HydroHelp 1 turbine selection, input.

IMPULSE TURBINES		
Horizontal axis low head impulse turbines.	Comment	Comment
Horizontal axis BANKI (Ossberger) turbine.	-----------------	1
Horizontal axis, 1 jet, 1 turgo runer turbine.	-----------------	1
Horizontal axis, 2 jet, 1 turgo runner turbine.	-----------------	1
Horizontal axis impulse turbines.	Comment	
Horizontal axis, 1 jet, 1 runner impulse turbine.	-----------------	1
Horizontal axis, 2 jet, 1runner impulse turbine.	---- YES ----	1
Horizontal axis, 1 jet per runner, 2 runner impulse turbine.	---- YES ----	1
Horiz. axis, 2 jets per runner, 2 runner impulse turbine.	---- YES ----	1
Vertical axis impulse turbines.		
Vertical axis, 1 jet, 1 runner impulse turbine.	-----------------	1
Vertical axis, 2 jet, 1 runner impulse turbine.	-----------------	1
Vertical axis, 3 jet, 1 runner impulse turbine.	---- YES ----	1
Vertical axis, 4 jet, 1 runner impulse turbine.	---- YES ----	1
Vertical axis, 5 jet, 1 runner impulse turbine.	---- YES ----	1
Vertical axis, 6 jet, 1 runner impulse turbine.	---- YES ----	1

Figure 27. HydroHelp 1 output (partial).

Once the type of turbine has been selected, the user proceeds to the other programs, HydroHelp 2 for Francis turbines in surface powerplants, HydroHelp 6 for Francis turbines in underground powerplants, HydroHelp 3 for impulse turbines or 4 for Kaplan turbines, both in surface powerplants. All HydroHelp programs have an input sheet where all input data is grouped. Although there is a large amount of data input, 186 to 235 items in each program, all can be derived from maps and a casual site inspection with a GPS position locator, without having to resort to surveys and geotechnical investigations. With about 200 data entries, the perception may be that there is just too much information required. This is not the case. The large data entry is due to the numerous options available within the programs, for pipelines, surface or buried in rock or earth; tunnels, lined or unlined or partially lined; surge tanks in rock or above ground steel tanks; relief valves or inlet valves or neither; and so on. For a typical site, the number of data entries is probably less than 50. A full site investigation is necessary if the pre-feasibility assessment indicates an economic project.

The programs calculate all basic structure dimensions, from reservoir wave heights and the corresponding average rip-rap size on the dam, to the capacity of the powerhouse crane. All hydraulic computations are undertaken, such as governor open-close times, surge tank design, relief valve size, conduit friction losses, and provide a chart on suitability for isolated operation. Schematics are provided for surge and waterhammer levels. Sufficient dimensions are shown on typical generic sections of the required structures, to allow a draftsman to produce general drawings for the project. Charts are provided for turbine efficiency and for overall project efficiency, including conduit losses. Water to wire costs for the generating equipment are developed, along with cost of all ancillary electromechanical equipment, from intake gates to spillway gates and powerplant elevators. The end result is a comprehensive pre-feasibility cost assessment with a 3-page detailed cost estimate listing quantities, unit prices and costs. A cost summary is also developed as shown in Figure 27, and there is an “Executive summary” page suitable for transferring onto a report.

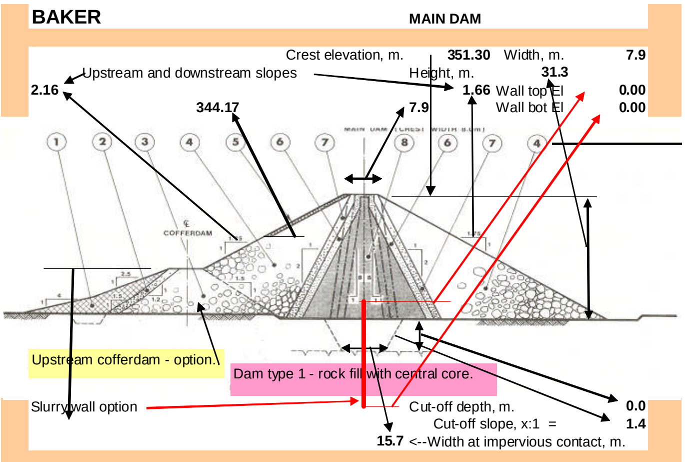

Figure 28. Dimensioned drawing showing data for a dam in HydroHelp 2. The program can accept a large number of dams, limited only by the computer memory capacity.

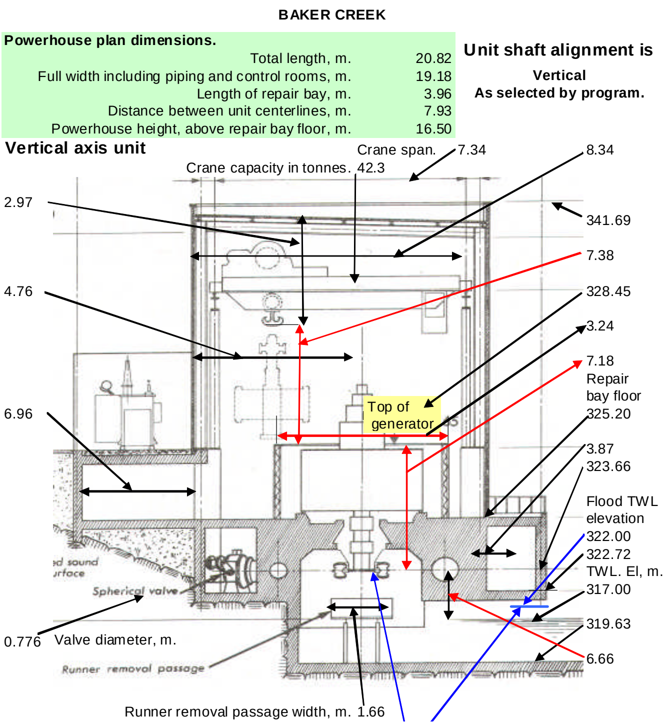

Figure 29. HydroHelp 3 generic impulse powerhouse section.

The programs do not include any hydrologic or financial analysis. However, hydrologic data can be entered into the programs by defining the operating hours on the turbines. The program will then calculate the energy taking into account conduit losses and all equipment efficiencies. Also, there is no financial analysis, since developers have their own methods of assessing financial viability once the cost is known.

BAKER CREEK Estimated cost, in millions of dollars. CAN $	Estimate date	5-Jan-09
Clearing for all structures.	0.36	
Access roads and bridge.	7.82	
Embankment dam.	0.41	
Side stream approx. total cost, including intake and equip.	0.00	
Intake, de-sander and weir spillway.	3.64	
Tunnels and vertical bore.	0.00	
Surge tank cost, if required.	0.00	
Steel pipelines and penstocks.	9.41	
Tailrace.	0.05	
Powerhouse.	2.22	
Sub-total civil work including access.		23.92
Ancilliary mechanical equipment, summary.	2.09	
Substation cost, disconnects and transformer.	0.42	
Transmission lines.	1.31	
Generating equipment, inlet valve, switchgear and controls.	21.13	
Sub-total electromechanical and transmission work.		24.95
Feasibility studies and site investigations.	0.98	
Environmental work.	1.00	
Detailed designs and contract documents.	1.02	
Site supervision work.	2.08	
Civil contingencies and unforseen cost allowance.	6.07	
Electromechanical contingencies.	1.89	
Interest during construction.	3.34	
Sub-total overheads and interest.		16.37
Total project cost in millions of $ ------------------------------ >	65.2	CAN $

Figure 30. Typical HydroHelp 3 cost estimate summary.

XI. Modern Feasibility Assessment.

Feasibility assessment has not changed. Site geotechnical investigations are still necessary, but ground survey work is no longer necessary, since contours can be obtained by the LIDAR (Light Detection And Ranging) process. The LIDAR instruments are mounted in an aircraft and only collect elevation data. To make these data spatially relevant, the positions of the data points must be known. A high-precision global positioning system (GPS) antenna is mounted on the upper aircraft fuselage. As the LIDAR sensor collects data points, the location of the data are simultaneously recorded by the GPS sensor. After the flight, the data are downloaded and processed using specially designed computer software. The end product is accurate, geographically registered longitude, latitude, and elevation (x,y,z) positions for every data point. These "x,y,z" data points allow the generation of a digital elevation model (DEM) of the ground surface.

Figure 31. Small hydro in BC.

However, what has changed; is the introduction of the design-build (DB) method of constructing hydro sites. In this concept, a contractor, manufacturer and consultant will form a consortium to both design and build the project for a lump sum. Of course, the risk to the consortium is high, so cost can be higher than with the construction approach used at Churchill. For hydro sites with capacities of less than about 200MW, the DB approach is commonly used, with the bidders having to undertake a brief feasibility assessment and design in order to cost the work. On the larger projects, the project owner will select about 3 DB contractors and offer a fee to submit a bid, thus offsetting, to some extent, the contractor's bidding cost.

XII. Modern Construction Contracting Methods.

Most large utilities such as Hydro Quebec, build projects using the unit price approach for the civil work, with the design undertaken by consultants, and construction supervised by their own engineers for rigid quality control. Equipment is awarded on lump sum contracts, with installation again supervised by their engineers. On the other hand, all creek small hydro work in BC is undertaken with DB contracts, and so is work on larger projects for Columbia Hydro. Often the DB development concept differs substantially from that conceived in the pre-feasibility report, due to the contractor's ability to optimize structure designs and costs more effectively than a consultant. Developers favor the DB approach since the project cost is known before work starts, enabling the developer to arrange financing.

With DB the risk of cost overruns is transferred from the owner to the contractor. Often this results in litigation to recover unforeseen expenses after completion of the project. Also, the risks in the project may be so high, that the DB cost becomes excessive, and the owner has to revert to the more traditional contracting methods. The DB approach is best suited to sites where there is no underground work, and where the foundation conditions are well known.

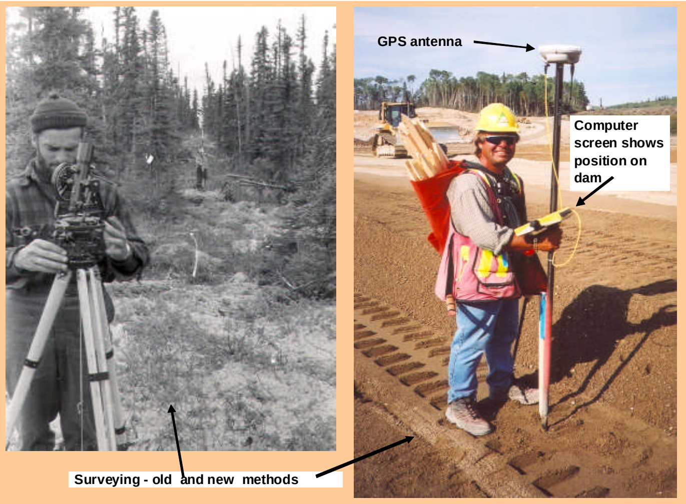

Figure 32. Survey methods, old and new.

Another difference with past construction work is the disappearance of the site survey crew. Many surveyors, rodmen and draftsmen were employed with site work. No more. Now, the survey crew consists of one person using a GPS coupled to a computer wherein the screen shows the location and position with respect to the structure being built. Limits of dam placement materials can be seen on the computer screen, so all the surveyor has to do is hammer a stake into the ground at the required location (Figure 32).

XIII. Conclusions.

The availability of Google Earth has greatly simplified the search for hydro sites. All of the large hydro sites are already known. However, small hydro sites remain to be discovered and developed, hence this dissertation has concentrated on the methodology for finding new small hydro sites.

Hydro hunters have been very active in BC, where 118 licenses for small hydro plants have been issued, and currently there are 577 applications for more licenses (15). A map showing all mountain creeks where there are licenses is shown in Figure 33. But developers need help in assessing costs.

What can be learned from the Churchill experience, is that a great deal of up-front money has to be committed before a hydro site can be deemed to be financially viable. Most of the money is spent on site surveys, geotechnical investigations, cost analysis, environmental studies and permit applications. Many years ago, environmental and permit work was minimal compared to the other costs. Now, these can and often exceed the cost of engineering work.

The magnitude of initial expenditures is where developers have a great deal of difficulty, in that they do not have the financial resources available to large utilities, and hence have to limit initial expenditures. This poses a considerable problem, since, as mentioned previously, financing cannot be obtained until the cost is almost fixed, and this will not occur until all contracts have been placed.

The probable accuracy of the project cost estimate, as the project evolves is shown in Figure 34. Note that estimates are usually optimistic; often erring on the low side.

The cost estimates made during the development of the project are as follows. They start with –

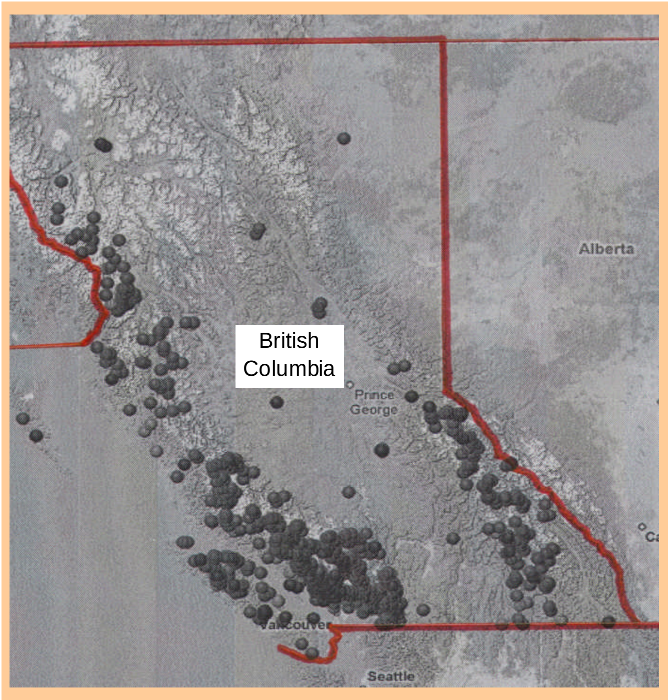

Figure 33. Registered small hydro sites in BC.

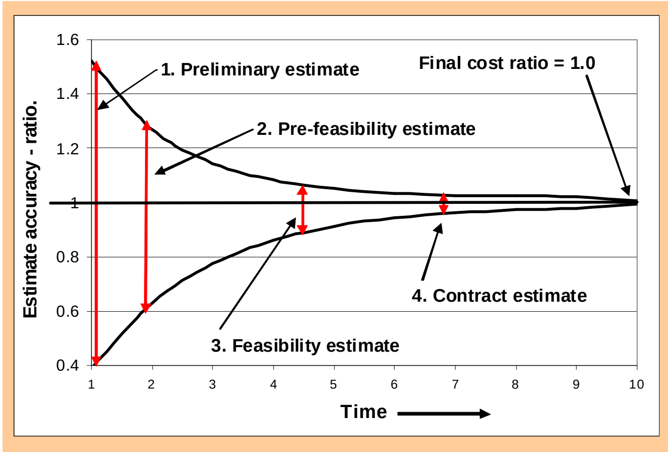

Figure 34. Accuracy of cost estimate during evolution of a hydro project.

(1) A preliminary estimate obtained from an initial survey or from a program such as RETScreen. The accuracy is probably in the region of +50% to -40%. This latter number indicates that the final cost could be some 2.5 times the preliminary cost estimate.

(2) A pre-feasibility estimate, developed from a site inspection and using a program such as HydroHelp 2, 3 or 4. Accuracy probably 30% too high, to 40% too low.

(3) A detailed feasibility estimate developed after some geotechnical work and site surveys. Accuracy likely in the region of 5% too high to 12% too low.

(4) A contract estimate developed after all contracts awarded. Accuracy in region of 2% high low to 4% too low.

An idea of the money required to investigate a site can be determined from some simple rules devised by the author many years ago (4, 5).

The ballpark cost of a small run-of-river hydro site, of less than about 50MW capacity, can be derived from the following equation –

Cost ($) = k $(kW/h^{0.3})^{0.82}$. -------------------------------- (1)

The value for the coefficient k varies according to the project size, and the type of project. An analysis of 20 run-of-river high head creek small hydro projects in BC has indicated an average value for k = 60,000, with a range between 50,000 and 85,000. This factor only applies to the BC creek sites, and should not be used elsewhere. “k” factors for other areas and types of powerplants can be determined by applying the formula to existing developments where the head, power and cost is known.

Based on data compiled by the World Bank (7), a feasibility report should be undertaken for about 10% of the design cost, and a pre-feasibility report for about 2% of the design cost. Since design cost is in the region of 6% of the project cost, a pre-feasibility report should cost somewhere in the region of 0.0012 of the project cost. On this basis, a pre-feasibility report should cost about –

Pre-feasibility report cost $ = 72 $(kW/h^{0.3})^{0.82}$. ------- (2)

For example, a 15,000kW development with a head of 500m, would require an expenditure of around – $72(15000/500^{0.3})^{0.82}$ = $41,000 for the pre-feasibility report. This work would include an assessment of the hydrology by co-relation with nearby gauges, a site inspection to determine dam location, conduit route, powerhouse location, access and transmission routes, along with some basic dimensions, sufficient to enter data into a HydroHelp or similar program. Once the approximate cost is determined, a financial analysis would complete the work.

After this stage, costs escalate rapidly, with feasibility work costing 5 to 10 times the pre-feasibility work, a sum of money quite outside the financial capability of a small developer. At this point, a large developer usually takes over, who continues the work in association with a contractor and consultant, eventually producing a contract estimate if the project is perceived to be economic.

In conclusion, I hope that this dissertation has helped you understand how hydro developments are discovered and built, and I also hope that it will encourage some of you to pursue a career in the hydropower industry.

XIV. References.

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[15] http://www.ippwatch.info/w/

XV. Biography

Jim Gordon graduated from Aberdeen University in 1952 with a first class honors degree in Civil Engineering and commenced work with Montreal Engineering. During this time he was the Chief Design Engineer for 6 hydro projects which received awards “for excellence in design” by the Association of Consulting Engineers of Canada. He has worked in 15 countries, and for 9 years he was the Vice-President Hydro, retiring in 1990. Since then, he has practiced as a private consultant, providing advice to consultants and hydro utilities on design, cost, mechanical equipment selection, and has served on many review boards. He was awarded the Rickey Medal by the American Society of Civil Engineers, and the Distinguished Service Award by the Canadian Electrical Association. He has authored or co-authored 84 papers covering a wide range of subjects, from vortices at intakes, to turbine cavitation and generator inertia. He has been an invited speaker at 26 seminars, and is the author of 43 “Lessons learned” articles published in HRW (Hydro Review Worldwide).

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