HYDROVISION 2017 –DENVER, COLORADO, USA
DESIGN CONSIDERATIONS FOR THE CAPILANO ENERGY RECOVERY FACILITY AND BREAK HEAD TANK

Rob Adams, Project Manager, Knight Piésold Consultants, Vancouver, BC, Canada

1. Introduction

Metro Vancouver (MV) is a public works organization that serves 18 municipalities (over 2 million people) in the greater Vancouver region of British Columbia, Canada. Amongst numerous other functions including waste collection and disposal, one of its primary tasks is to reliably provide clean, potable drinking water (over 1.1 million m^3 per day average) to the residents of the cities served through a system of reservoirs, treatment facilities, pump stations and piping networks.

Most of Vancouver's drinking water supply comes from watersheds in the mountains on the north side of the city (North Vancouver). Three main watersheds collect fresh water in three primary reservoirs. The reservoirs are protected and the water supply has historically been clean, with little need for elaborate treatment facilities. However, issues with turbidity, though not directly affecting potability, led in the 1990's to the planning of a Filtration Plant to serve the Capilano and Seymour reservoirs (Seymour-Capilano Filtration Project, SCFP).

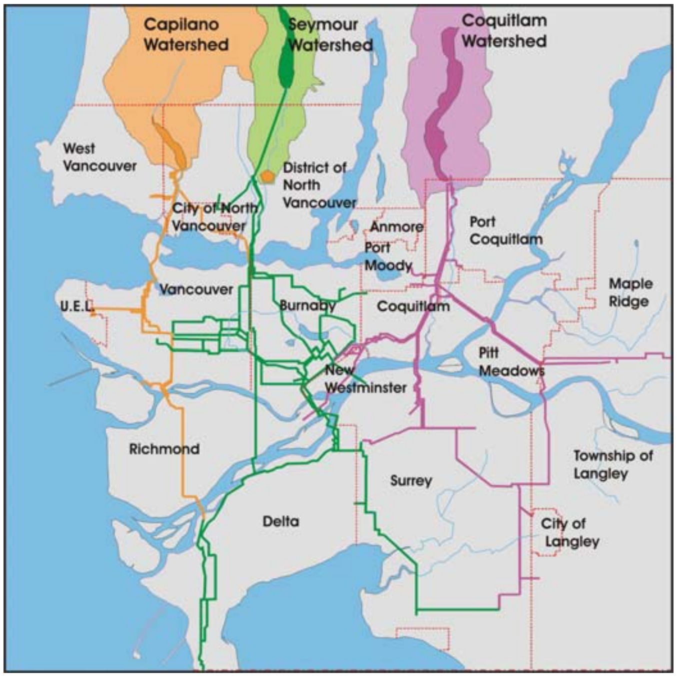


Figure 1: Metro Vancouver Water Supply System

Although filter plants could have been constructed on both reservoir outlets, difficulties in obtaining suitable land on the Capilano side led to a plan to build a common filter plant downstream of the Seymour reservoir. Raw water drawn from the Capilano reservoir is pumped by a new Capilano Pump Station through a 7 km long, 3.5m diameter Raw Water Tunnel constructed by TBM under the City of North Vancouver. The Capilano raw water is then combined with the raw water from the Seymour reservoir and is filtered and treated (chlorinated) in a new Filtration Plant. Once treated, the combined water is deposited in a large Clearwell downstream of the filter plant.

From there, the original Seymour volume is sent through the Seymour distribution main to its service area and the original Capilano volume is routed under gravity flow back to the Capilano Pump Station through a second 7 km long, 3.5m diameter Treated Water Tunnel (TWT). On the east end of the TWT, piping connects the tunnel to the Clearwell, which will act as a head pond with a 2.75m live storage height. On the west end of the tunnel, the buried piping runs from the Pump Station up a steep slope to the location of the Break Head Tank (BHT). The total static head difference to be dissipated between the water levels at the Clearwell midpoint and the Break Head Tank is 30.2 meters.

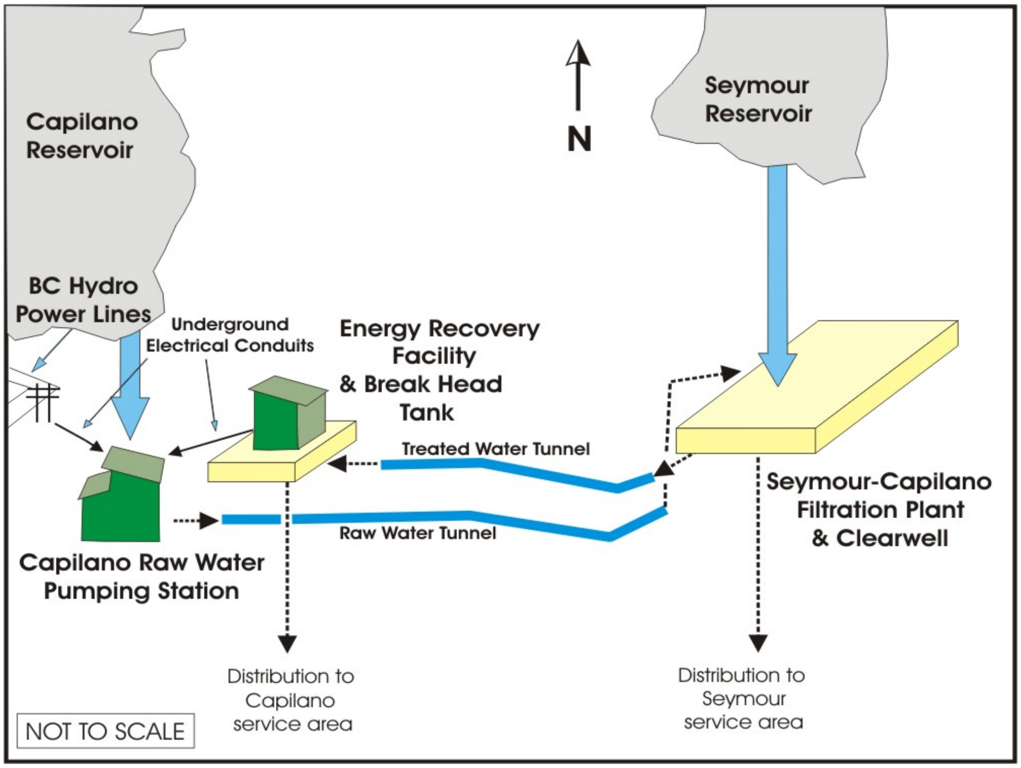


Figure 2: Seymour-Capilano Filtration Project

Figure 3: Seymour-Capilano Filtration Plant

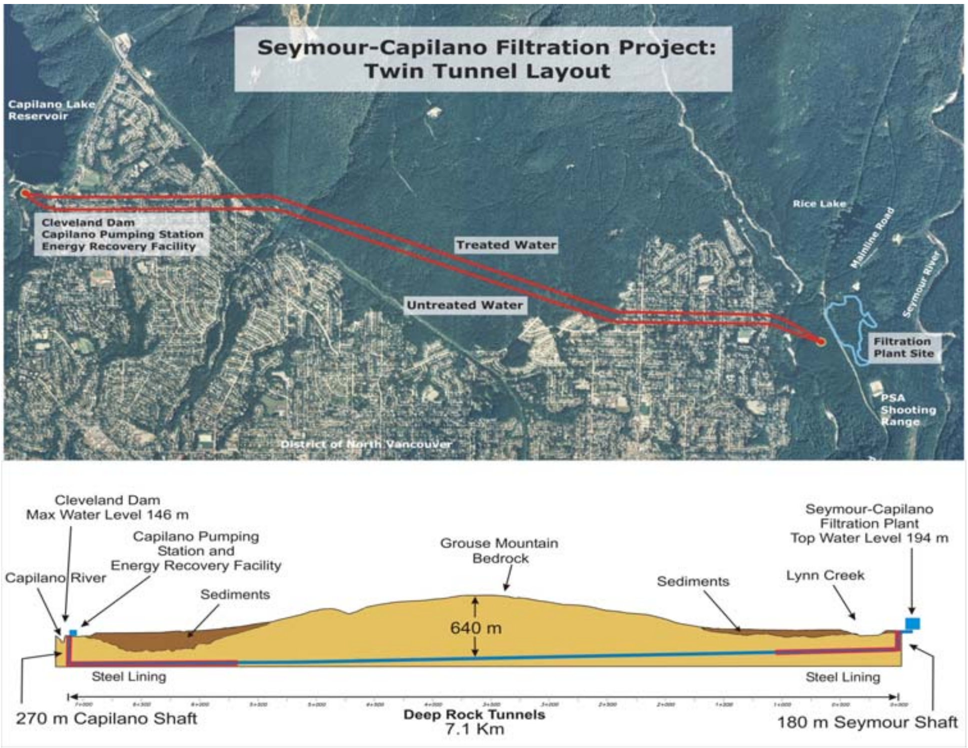


Figure 4: Twin Tunnels Route

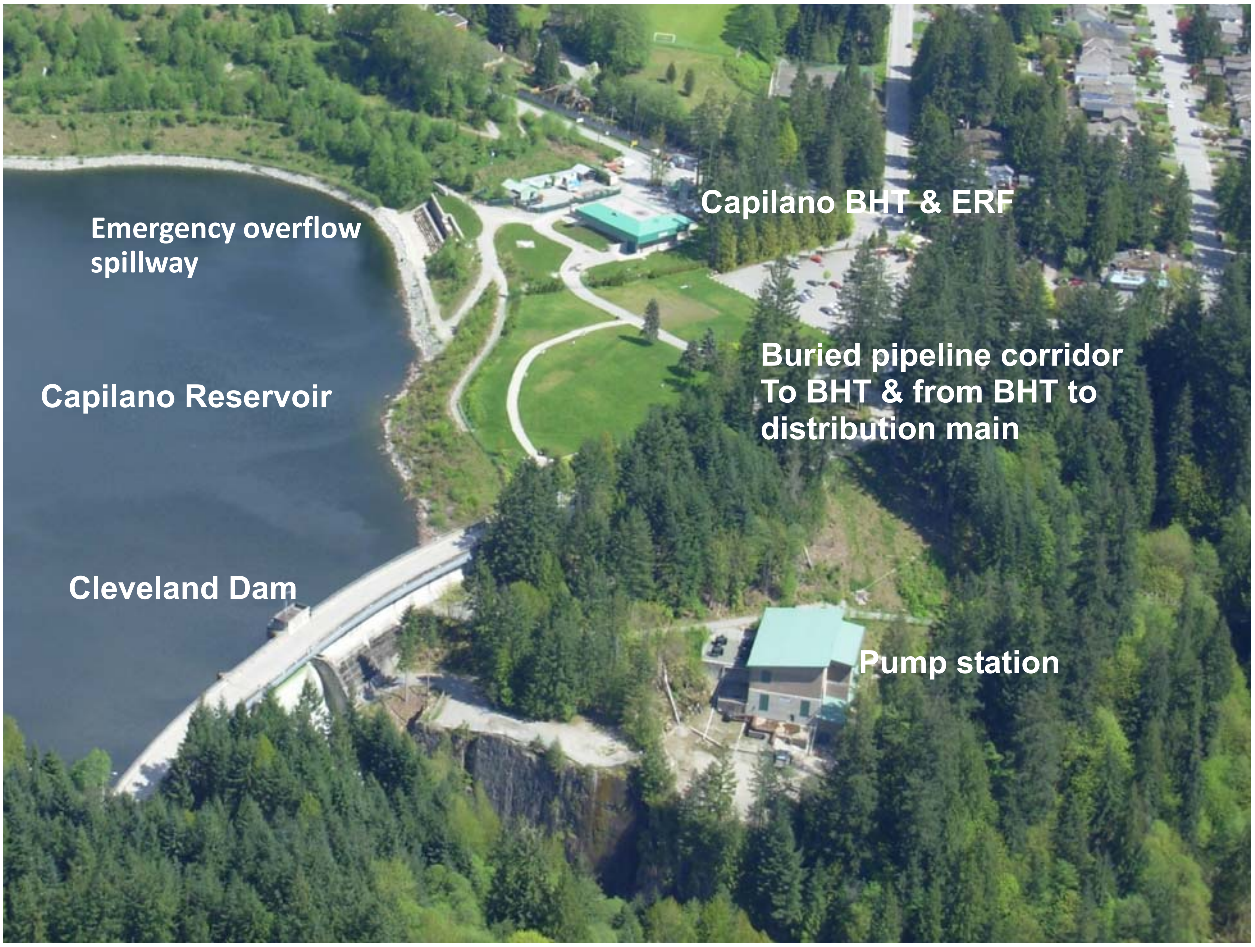


Figure 5: Capilano Facilities

2. Capilano Break Head Tank (BHT) and Energy Recovery Facility (ERF)

The BHT is located on east side of the Cleveland Dam at the terminus of the 8 km Treated Water Tunnel and piping system. The primary purposes of the tank are to break the head resulting from gravity flow from the Clearwell, as the additional head would overpressure the existing Capilano distribution main, and to act as a stable head pond for the gravity-fed distribution main. The secondary purpose is to recover energy from the head difference and generate electricity to partially displace the load at the newly constructed Capilano Pump Station.

One of the prime drivers of the BHT design was the limited real estate available and restrictions on the available land. Metro Vancouver’s property is confined between a public park and housing developments parking area to the east and south, and watershed land and lake to the north and west. To further limit the area available, there were stands of old-growth trees and an existing filter blanket area that could not be disturbed. Furthermore, there are fish stocks in the lake and a salmon hatchery less than a kilometer downstream, so no release of any chlorinated water from the tank into the Capilano Reservoir, from underground leakage or surface overflow, was permitted.

Figure 6: Excavation during construction. Note overflow channel and spillway

3. Design Philosophy

a) Ensure maximum reliability of the treated water supply to the Capilano system through the BHT facility, by provision of simple, robust and reliable equipment, 100% redundancy of the PRV lines providing the primary water supply, and ease of maintenance while the facility is in operation under all normal and fault conditions.

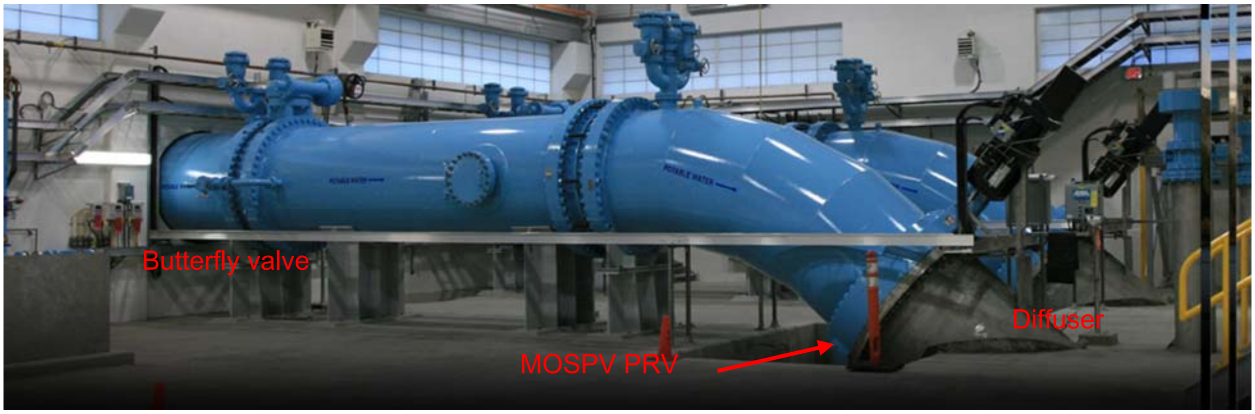
b) Provide ease of access to equipment for maintenance and repair without requiring personnel or equipment entry into the tank, and minimise the need for tank opening or entry, to prevent contamination. To permit maintenance while the facility is in operation, the principle of “no moving parts in the tank” was adopted. This imposed limitations on equipment selection (e.g. turbine type), ratings and settings, but ensured that entry into the tank is only required for periodic inspection and cleaning.

c) Although the energy recovery turbine is an integral part of the process, electricity generation is a desirable secondary benefit and turbine operation is secondary to that of the PRVs. This means that whenever turbine operation is outside of its defined limits, or may potentially jeopardize PRV operation, or continuity or cleanliness of the water supply, optimization of the turbine design and operation may not be fully realized.

4. BHT Design Flow and PRV Selection

The facility can be divided into two parts with respect to the design flows. The Break Head Tank, complete with two PRV (pressure reducing valve) lines, each capable of 100% redundancy, is the basic facility, with a design flow that was based on forecasts for water demand by the City of Vancouver from the Capilano system. The 20 year forecast Peak Daily/Hourly demands were used to set the rated design flow for the PRVs and BHT of 12.5 m^3/s.

The PRVs are each rated for the full BHT design flow and are required to have a turndown very close to zero. They must be fully controllable with predictable stroke-flow characteristics and good energy dissipation over the entire flow range. They must be capable of parallel operation with the ERF turbine and must be capable of satisfactory end-of-line operation in order to be installed in the Machine Hall above the tank. They are required to have low noise and vibration, be reasonably compact, and have demonstrated acceptable operation. Types considered included fixed cone valves, submerged radial discharge valves, and multi-orifice, sliding plate valves (MOSPV). The MOSPV type was selected due to demonstrated acceptable operation elsewhere in the Metro Vancouver system. The PRVs are 66” diameter with a design flow of 12.5 m^3/s, and minimum turndown to 2%. They were specified to operate as end-of-line valves complete with diffusers to submerge the discharge, and were supplied complete with hydraulic actuators and 66” butterfly valves for isolation.



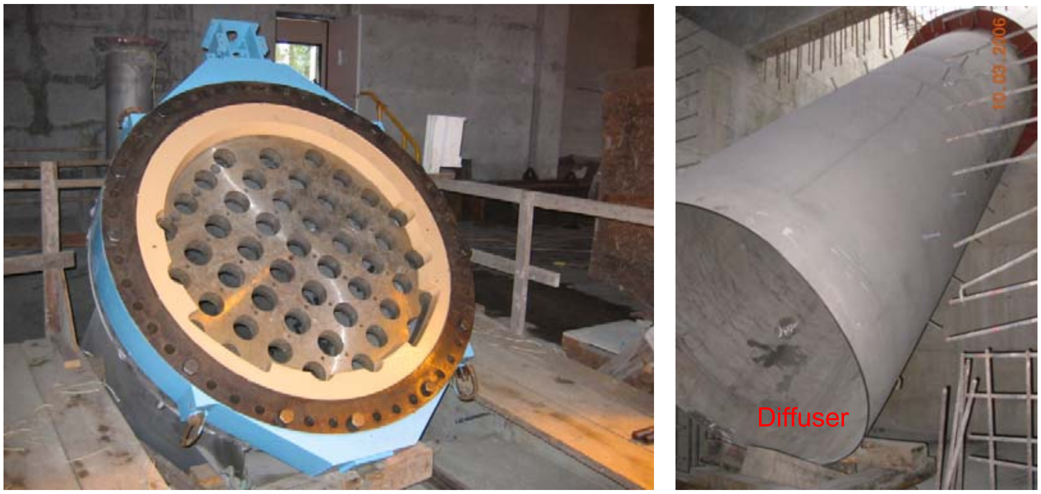


Figure 6: Multi-orifice, sliding plate, energy dissipating PRVs

5. ERF Design Flow and Turbine Selection

Five years of digitized historical water demand data from the Capilano water distribution main were available. On the assumption that the flow demand range would not change substantially in the first 5-10 years of operation, this record was used to build a Flow Duration Curve (FDC) to determine the design flow for the ERF turbine, as shown in Figure 7. Since a Francis turbine has a typical turndown of about 40%, and has relatively low part-load efficiencies, we did not want the machine to operate at part-load for many years, which would be the case if the design flow was based on the same 20 year forecast as was used for the PRV design (12.5 m^3/s). The design flow selected was 7.5 m^3/s, with an assumed turndown to 3.0 m^3/s for a Francis machine, which bracketed almost 95% of the daily and hourly average flow duration curves.

Note that the turbine was also required to operate over a relatively large net head range, relative to the average static head of 30 meters, due to high losses (varying with the square of the flow) over a long (8 km) tunnel and pipe conveyance. While the static heads will vary between 28.9m to 31.5m depending on Clearwell level, the net head will vary from 26m at the 7.5 m^3/s design flow to 29.5m at a turndown of 3 m^3/s. However, the net had can fall to as little as 20m at 7.5 m^3/s when operating in parallel with a PRV at 5 m^3/s for a total of 12.5 m^3/s through the upstream conveyance.

Two types of turbines were considered for this head: horizontal axis Francis and horizontal axis Kaplan. A Francis turbine is a single regulated turbine with a fixed blade runner and adjustable guide vanes/wicket gates. It has a turndown to roughly 40% of its design flow and, at these heads, a positive submergence (suction head). This means that, although it has relatively poor part load efficiencies compared to a Kaplan machine, and has a narrower net head range, the runner centerline could be located well above the tailwater level. This allowed the Francis machine to be installed in the

Machine Hall on top of the tank, with the draft tube discharging into the break head tank below it. This means that all parts are accessible for maintenance with the BHT on-line and operating, per the Design Philosophy (no moving parts in the tank). Although the head and flow ranges, and efficiencies, are not as good as those of the Kaplan, a Francis machine is simple, robust, easy to operate and maintain, and is less expensive.

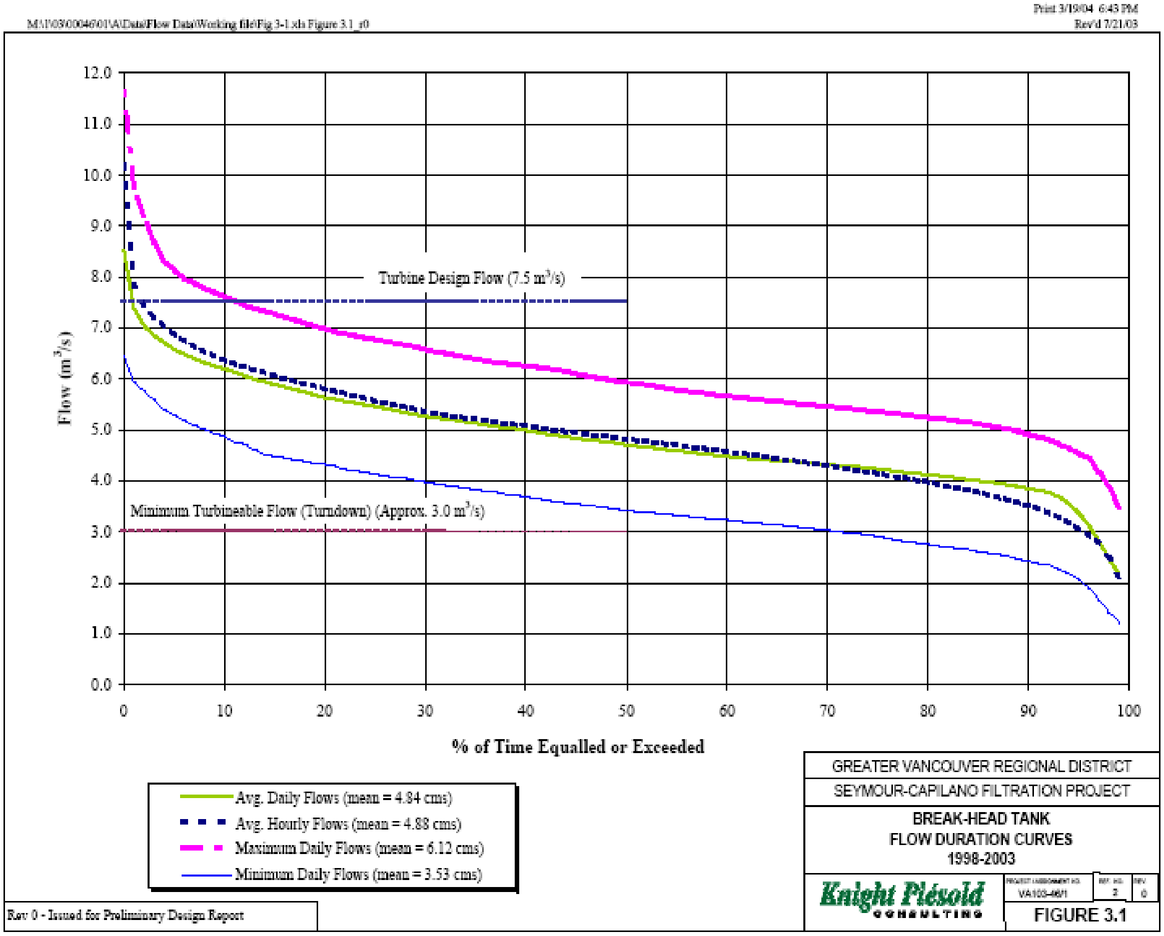


Figure 7: ERF Flow Duration Curve

A Kaplan turbine is a double-regulated machine with adjustable guide vanes/wicket gates and propeller type blades that have a variable pitch capability. It has a relatively large flow range, with good turndowns to roughly 15% of design flow and good part-load efficiencies. It also has a relatively large net head operating range, which is desirable in this case. However, it is more expensive and, at this head and flow, would require a negative submergence (suction head) with the runner below tailwater level. This would require it to be installed in a dry Machine Hall below ground adjacent to the tank, discharging into the tank below the water level. This would have greatly increased the BHT footprint, required an isolating gate in the tank and possibly an oil-filled gearbox.

Figure 8: ERF turbine and generator. Note cooling water jacket on turbine inlet pipe.

Therefore, despite poorer part load efficiencies and turndown levels, the Francis turbine was selected in order to meet the Design Philosophy, particularly no moving parts in the tank. It was specified with coatings/ lubricants to meet NSF standards and has an overshot arrangement to allow a deeper setting. To reduce the possibility of any oil leakage into the potable water tank below, the generator and bearings are located in a concrete containment recess and the bearing cooling water system is closed loop, with the bearing cooling water cooled by a water jacket/ coil fitted on the turbine inlet pipe so that the turbine flow cools the coolant.

Figure 9: Machine Hall with ERF turbine line (background) and PRV/BHT lines

6. Hydraulic Transients (Waterhammer)

Whether it is a PRV or the ERF turbine operating, both are fed by a very long (8 km) and relatively small diameter upstream tunnel and pipe conveyance. This means that opening and closing times of the gates or valves must be carefully controlled to prevent excessive hydraulic surge transient (waterhammer) pressures in the upstream piping due to rapid closure. For the case of too rapid openings, the possibilities of flow separation have to be examined as well. Since there was no space to install an effective surge tank, surge pressures are accommodated by additional steel pipe thicknesses and device ratings, and controlled within allowable limits by slow movements of the valves or turbine gates as determined by digital hydraulic transient modelling. In addition, when a Francis turbine trips, as the runner accelerates into overspeed, the flow can reach a “choke” point where it rapidly decelerates, also causing a surge pressure that must be modeled and accommodated.

Various combinations of opening and closing of the PRVs, PRV isolation valves, turbine gates and turbine inlet valve were modeled as well. Note that both the Francis turbine and synchronous generator were specified to be robustly designed and constructed (bearings, poles, windings, rotating exciter, etc.) to permit up to 10 minutes at full runaway speed with an inoperable bearing oil cooling water supply. This was determined to be sufficient time for the guide vanes (wicket gates) to close in a time slow enough to keep surge pressures within acceptable limits, without requiring a surge tank or synchronous bypass valve. The final design full stroke closing times were determined to be 125 seconds for wicket gates and 175 seconds for the PRVs.

7. Break Head Tank Arrangement and Operation

The Break Head Tank design was driven by the competing requirements for a relatively large buffer volume of live storage water versus the requirement for a relatively small footprint. Whether it is a PRV operating between 0 – 3 m^3/s (the turbine turndown limit, the ERF turbine operating between 3 – 7.5 m^3/s, or both operating together in parallel between 7.5 – 12.5 m^3/s, water flow is controlled by level control in the tank. Water demand from the city flows through a ramp and bellmouth at the bottom of the tank into the Capilano distribution main pipe, but a minimum dead storage volume must be created in order to provide sufficient submergence over the outlet to prevent vortices that could entrain air in the distribution main. In this case the required submergence was tested in a physical model and found to be 3 meters over the top of the outlet pipe.

Above this minimum submergence level, a live storage volume was required to act as a buffer against unlikely, but possible dramatic changes in demand that cannot be met by slow moving flow control devices (PRV or wicket gates). The extreme conditions are an instantaneous cessation of demand (to zero), while operating at full design flow with a PRV and/or wicket gates wide open, or an instantaneous increase in demand (from zero) with the PRV and/or gate devices closed. In either case, buffer volumes (water heights) are required above and below the live storage midpoint (set point) to allow for water flow into the tank while the device is slowly closing or water flow out while the device is opening, until it reaches its final state, respectively, and supply meets demand in equilibrium at the set point. The final total live storage volume provided was 2000 m^3, with a live storage height of 3.4 meters (half above the midpoint of the live storage range for positive buffer and half below the midpoint for negative buffer).

The underground tank is comprised of three sections. The flow from the devices initially discharges into the PRV discharge chamber and/or turbine tailrace, which have downstream walls that rise above the set point water level in the tank and act as weirs to provide the required submergence (net positive suction head) on the PRV and turbine discharges. This submergence is required to provide a back-pressure to prevent sub-atmospheric conditions at the turbine runner discharge that could cause cavitation and damage to the runner metal. The weir is designed to provide the required +2.6 meters from the tailwater level up to the runner centerline at the turbine design flow. After passing over the discharge weir, the water flows around two channels until it reaches the main storage chamber, after passing through flow training baffles designed to minimize circulation that might cause vortices. At the end of the storage chamber is a bellmouth entry into the water distribution main that feeds the city.

Automatic opening or closing of the turbine gates or operating PRV, and balancing of supply and demand is determined by level control in the tank through the unit and plant PLCs. The level set point is at the middle of the live storage height. If the city demand increases, the level will drop and the operating device (PRV, turbine or both) will open to add water until the set point is again reached. If city demand drops, the level will rise and the control system will throttle the device(s) until the level drops to the set point. PLCs (Programmable Logic Controllers) are provided for each PRV line and the ERF turbine, so that each device is controlled independently under its own level control when dispatched by the Master PLC according to the device's permissible head and flow range. The Master PLC also controls all other facility functions and monitors all data and instrumentation inputs and outputs and reports to both a local Human-Machine Interface (HMI) computer and to a remote HMI at the System control center.

The final feature of the BHT is an overflow system that acts as a tank relief valve. Along the north edge of the channel that leads to the Storage Chamber, an overflow weir is provided with its crest just above the top of the allowable live storage height. If demand drops suddenly and the flow control devices (turbine, PRVs) fail open, uncontrolled rising water levels could surcharge the tank roof (also the Machine Hall floor). The overflow weir permits water to spill from the tank to an underground waterway that leads to a baffled and stepped overflow spillway that discharges into the Capilano Reservoir.

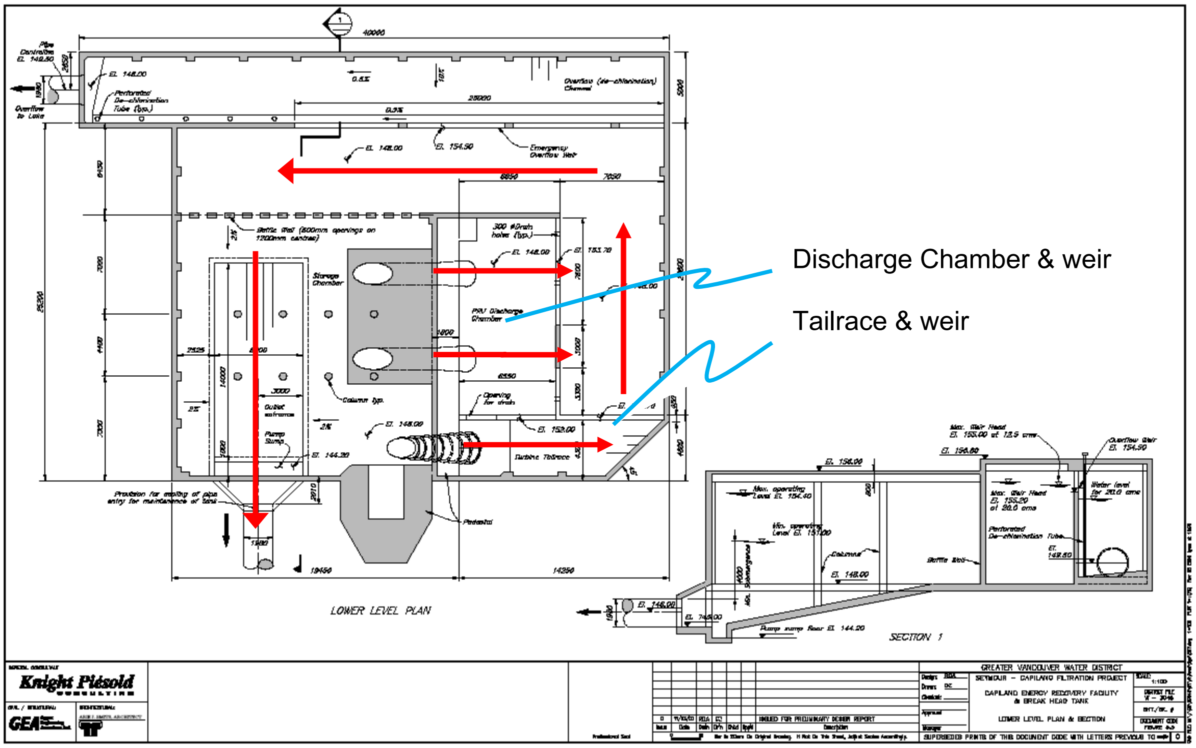


Figure 10: Break Head Tank – Underground Water Chambers

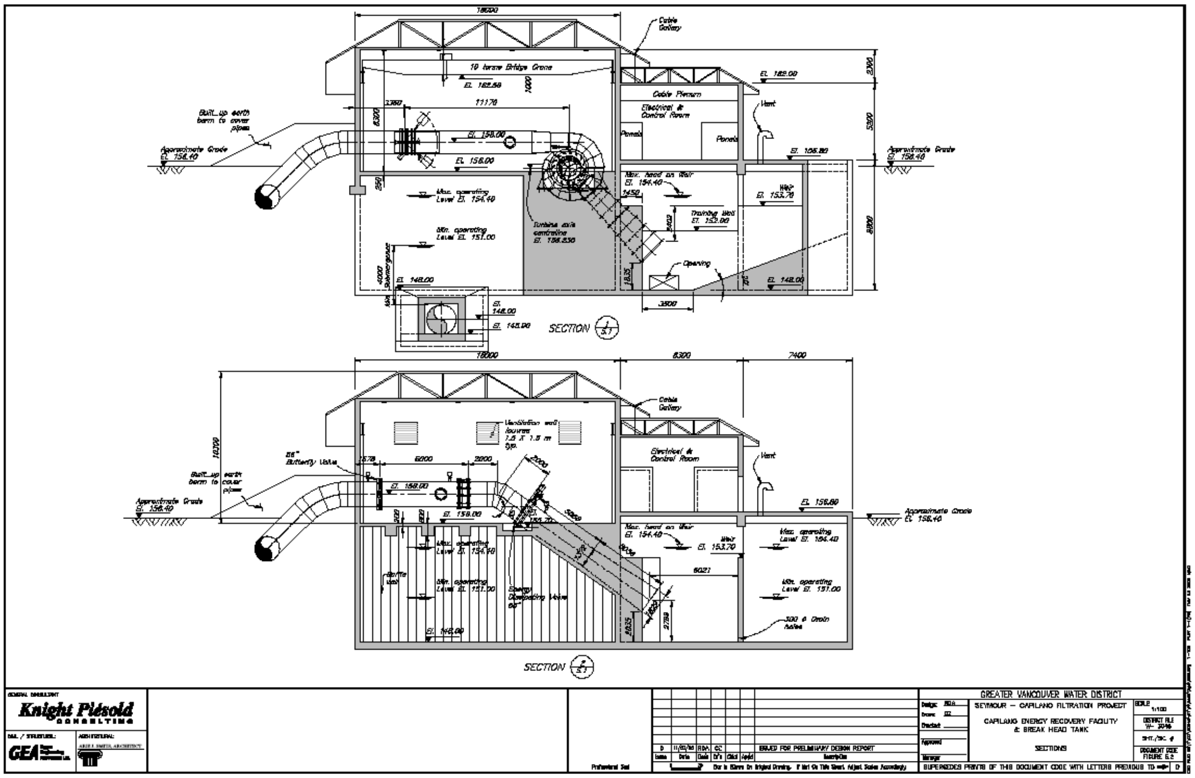


Figure 11: Break Head Tank – Sections through flow control devices (turbine and PRV)

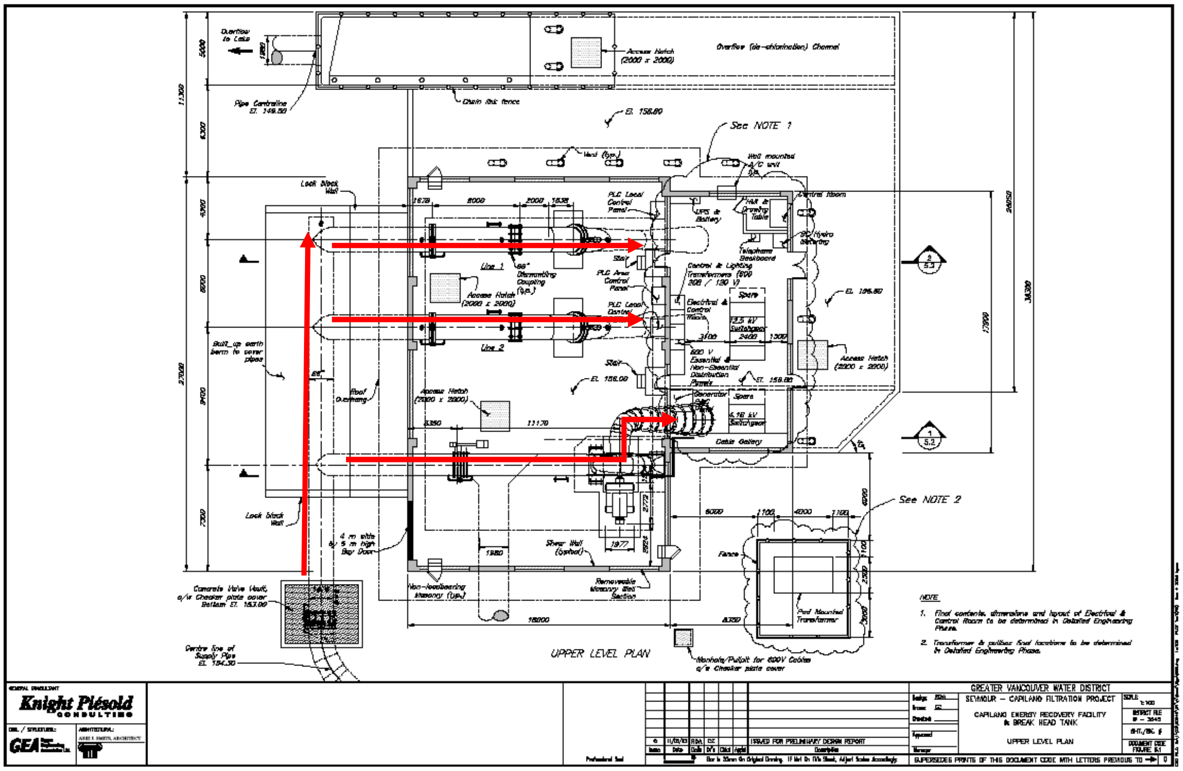


Figure 12: Plan of Machine Hall and Electrical Room with Turbine and PRV lines

8. Physical Hydraulic Model

Metro Vancouver and KP agreed during the design phase that the hydraulics of the facility were important enough to commission a physical model to test them. Northwest Hydraulics (NHC) of Vancouver BC was engaged to perform a large (1:10) scale physical hydraulic model of the tank layout and operation. KP has in the past collaborated with NHC on many run-of-river hydro plant intake models and we have always found that they pay their way and can also be used to calibrate CFD computer models. Lessons learned from modelling of the tank operation included:

a) Even at maximum design flow, a vortex did not appear over the tank outlet until the water level was one meter below the calculated design level and 3 meters above the top of the outlet pipe. This provided an additional meter of live buffer storage.

b) The hydraulics worked satisfactorily with smooth flow of the discharge over the weirs and through the waterways. Minor geometry adjustments were made to reduce corner eddies and areas of turbulence. Flow guiding baffles were introduced to reduce large scale swirl around the Storage Chamber, which also assisted in supporting the roof of the tank.

c) Surging within the PRV discharge chamber and the turbine tailrace was minimal.

d) Sufficient air space was provided above the maximum water level to supply atmospheric conditions above the water and prevent water contact with the ceiling.

e) The floor of overflow channel could be raised by 1.5m, reducing excavation costs.

f) The overflow channel required an air vent over its outlet to prevent surging.

Figure 13: Model test - Flow through the Discharge Chamber and Tailrace and over weirs (left). Vortex appearing as submergence above the outlet decreases (right).

Figure 14: Model test - Flow through the Discharge Chamber and Tailrace and over weirs (left). Flow (spill) over overflow weir into overflow channel to spillway.

9. De-chlorination Facility

The Capilano reservoir supports fish populations and other aquatic species. Uncontrolled discharge of treated water from the overflow system is therefore not acceptable due to its chlorine content, which in sufficient concentrations could kill the fish. The overflow channel is therefore provided with a de-chlorination system to treat the spilled water with calcium thiosulphate to neutralize the chlorine before discharge into the lake. The system starts with a calibrated V-notch weir located in the overflow channel. Level transmitters located above the weir measure the flow and report to the PLC which signals a sprinkler system to dose the water in proportion to the flow, and according to stage-discharge curves calibrated in the physical model test and during commissioning. The dosing equipment is located in a skid in a small hut above the channel. It consists of a small tank of calcium thiosulphate solution and three metering pumps, one for each order of magnitude of discharge up to the facility design flow.

Figure 15: Spill from Tank into overflow channel (left) and view of overflow weir from inside the tank (right)

Figure 16: Dechlorination Skid with Tank and Metering Pumps (left). V-notch flow measuring weir in overflow channel (right)

Figure 17: View of interior of Storage Chamber from the bottom of the outlet ramp

Figure 18: Flow over tailrace weir and PRV discharge weir (left). Interior of discharge chamber showing ends of PRV diffusers (right)

Figure 19: View of MOSPV PRV from downstream end in diffuser (left) and from upstream in piping in Machine Hall (right)

10. Overflow Spillway

The overflow spillway is the terminus of the overflow channel and is designed to spread the flow out over a 40 meter span to reduce its depth and concentration. Discharge from the channel occurs through 20 Tideflex valves. These valves are made of reinforced rubber and are designed with a watertight curled lip. When the head of water behind them reaches approximately 500 mm, they uncurl, allowing water to escape. The main point of these valves is that they require no electrical power to operate, and when not discharging, curl up to close and prevent vermin from entering and contaminating the sealed tank. The concrete spillway is provided with baffle blocks, steps and riprap to dissipate the energy from the de-chlorinated water before it discharges into the lake.

Figure 20: Overflow Spillway with Tideflex valves (left), baffles and steps (right)

11. Energy Recovery Facility - Load Displacement Turbine

The Energy Recovery Facility (ERF - i.e. hydro-generating unit) is intended as a load displacement facility to generate electric power and energy to offset consumption by the adjacent pumping station. It is connected, however, to both the pump station and to the local BC Hydro grid via a nearby 12.5/69 kV substation and can deliver energy into the grid if the pump station is not operating. The rated capacity of the turbine-generator is 1800 kW, or 2 MVA at 0.9 power factor. The self/air cooled generator generates at 4.16 kV and is stepped up to 12.5 kV through an oil-filled transformer located just outside the building. Excitation is provided by a brushless rotating exciter with rotating diodes. The generator is fitted with a full suite of protective relays for interconnection to the BC Hydro substation. The turbine is provided with a 66” butterfly-type turbine inlet valve for emergency shut-off or isolation for maintenance. As previously noted, both the Francis turbine and synchronous generator were specified to be robustly designed and constructed (bearings, poles, windings, rotating exciter, etc.) to permit up to 10 minutes at full runaway speed with an inoperable bearing oil cooling water supply.

Based on the existing flow duration data and limited operation to-date, the average annual generation will be 9.5 GWh. Figure 17 shows the typical annual ERF generation profile versus typical pump station load profile. While the ERF will not come anywhere close to the peak load, there are parts of the average year where it will provide a significant portion of the load. In BC, where 90% of the generation is hydroelectric, a small facility like this may not have a significant impact on the grid, but in jurisdictions where fossil fuels are the prime energy source, renewable hydraulic energy recovery projects such as this could make a difference.

Figure 6: Hourly Load Profile versus Generation for Years 6 to 10

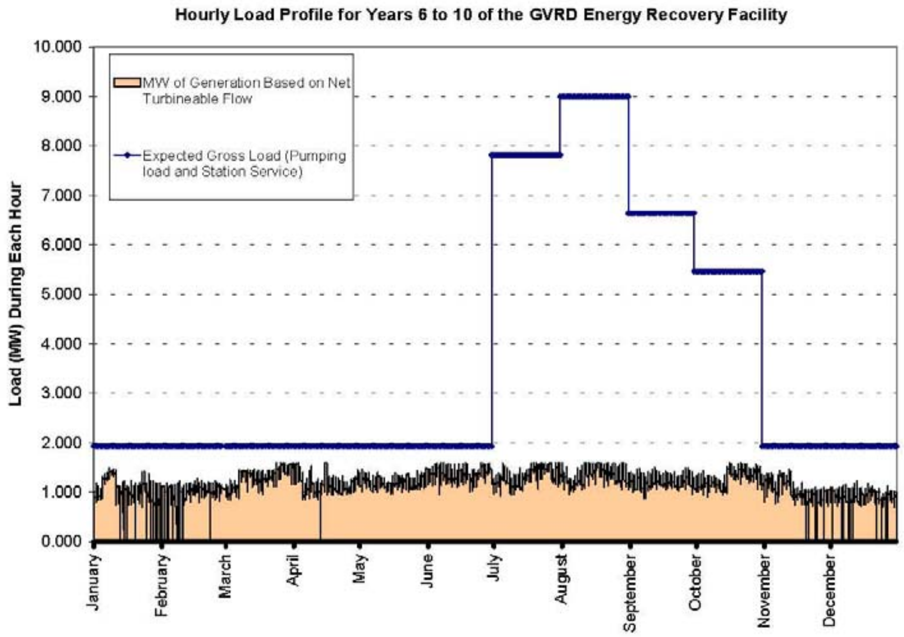


Figure 21: Typical Annual ERF Generation and Pump Station Load Profiles

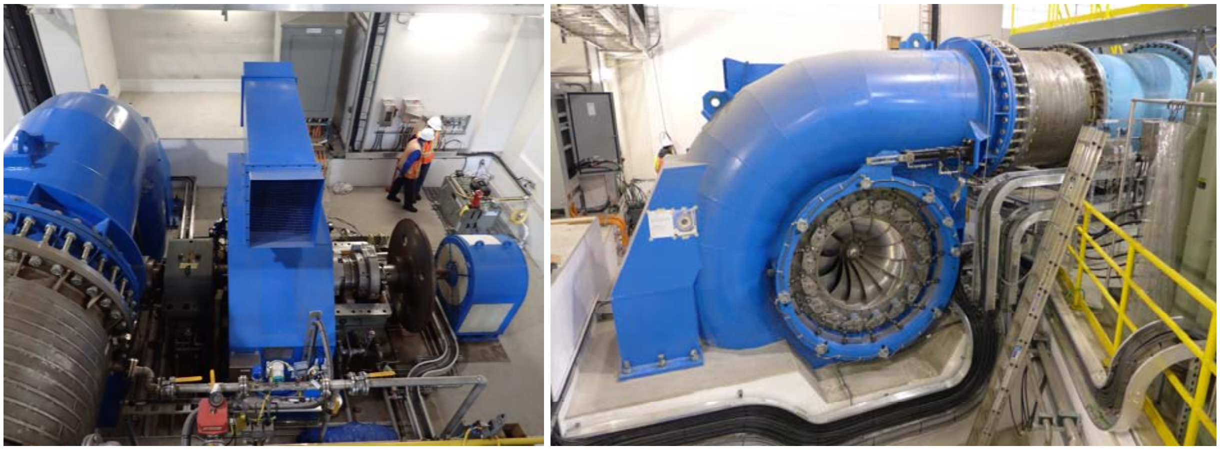


Figure 22: Energy Recovery turbine and generator

Rob Adams (P.Eng.) is a Specialist Engineer with Knight Piésold Consultants of Vancouver, Canada. He has 20 years experience in the power generation and hydroelectric industries and has contributed to numerous public and private sector hydroelectric projects in North America and Africa. He wishes to thank his design team for their support and expertise on this project, particularly Adrian Gygax (GEA Engineering - structural), Cor Potgieter (CPA Engineering – Instrumentation & Control), David Levi (Knight Piésold - Electrical), Mike Pullinger (Knight Piésold - Installation and Commissioning), Jeremy Haile (Knight Piésold – Principal), Dan Friedman (Knight Piésold - Project Management/ Site Supervision) and Steve Hart (Architectural).

Abstract: The Capilano Break Head Tank is located at the Capilano reservoir in North Vancouver and provides a controlled terminus for the Treated Water return tunnel from a new filter plant at Seymour reservoir to its origin at Capilano. The facility is designed to dissipate the pressure from the gravity fed tunnel prior to discharge into the Capilano supply main, and act as a stable head pond for the potable water distribution system for the City of Vancouver. An energy recovery hydro-turbine was installed to generate electrical energy to displace load at the adjacent pump station. Design considerations for the facility and the energy recovery turbine are discussed in this paper.

Figure 23: View of Capilano Reservoir and Watershed