March 9, 2015 Reference No. 1314470516-023-L-Rev0

Toby Seward, Community Development and Protective Services
City of Nanaimo
455 Wallace Street
Nanaimo, BC
V9R 5J6

COLLIERY DAMS, NANAIMO BC
SUMMARY OF LOWER DAM HYDRAULIC MODELLING METHODS

Dear Mr. Seward,

1.0 INTRODUCTION

As requested Golder Associates Ltd. (Golder) has undertaken additional effort for the City of Nanaimo (CON) in relation to the ongoing dam safety assessment for the Colliery Dams in Nanaimo, BC. As directed by the CON, this letter provides additional technical detail relating to findings provided in Golder's letter "Auxiliary Spillway - Conceptual Design", dated January 16, 2015 (Golder 2015). In particular, this letter provides a more detailed technical description of the hydraulic modelling, the findings of which were presented in the January 16 letter including:

- Lower Dam Spillway Capacity Modelling,
  - Overview of the HEC-RAS software package
  - Suitability of HEC-RAS for Modelling the Lower Dam's existing spillway
  - The development of the Lower Dam's existing spillway rating curve
- Lower Dam Overtopping Modelling,
  - Overview of the HEC-HMS software package
  - Lower Colliery Lake storage routing
  - Lower Colliery Dam overtopping and right abutment flow analysis

This letter is focused solely on the hydraulic portion of the existing Lower Colliery Dam spillway capacity analysis and does not address the hydrologic portion.

2.0 HEC-RAS OVERVIEW

The U.S. Army Corps of Engineers HEC-RAS computer program version 4.1.0 User's Manual includes the following abstract.

> "The Hydrologic Engineering Center's (HEC) River Analysis System (HEC-RAS) software allows you to perform one-dimensional steady and unsteady flow river hydraulics calculations. HEC-RAS is an integrated system of software, designed for interactive use in a multi-tasking, multi-user network environment. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities.
>
> The HEC-RAS system will ultimately contain three one-dimensional hydraulic analysis components for: (1) steady flow water surface profile computations; (2) unsteady flow simulation; and (3) movable boundary sediment transport computations. A key element is that all three components will use a common geometric data representation and common geometric and hydraulic computations routines. In addition to the three hydraulic analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed.
>
> The current version of HEC-RAS supports Steady and Unsteady flow water surface profile calculations, sediment transport computations, and water quality analysis. New features and additional capabilities will be added in future releases."

3.0 SUITABILITY OF HEC-RAS FOR MODELLING THE LOWER DAM'S EXISTING SPILLWAY

HEC-RAS is a viable tool for developing the rating curve of the Lower Dam's existing spillway for the following reasons:

- The spillway flows exhibit predominate one-dimensional characteristics (from upstream to downstream);
- The program's ability to model transitions such as the converging chute;
- The program's ability to model both sub-critical (approach flow from the lake, hydraulic jumps due to chute convergence) and super critical (flow down the steep concrete chute downstream of the bridge) flow regimes;
- The program's ability to model obstructions such as the center pier;
- The program's ability to model bridges including piers, abutments, and decks;
- The program's ability to account for various types and independent boundary conditions at both the upstream (level pool, normal depth flow) and downstream (super critical flow down waterfall) limits of the modeled reach;
- The program's ability to model various surface roughness, in this case concrete, influences on flow; and
- The programs ability to combine all these individual parameters into one comprehensive model allowing for evaluation of the spillway performance as a whole as well as at specific locations.

4.0 LOWER DAM'S EXISTING SPILLWAY RATING CURVE DEVELOPMENT

The development of the Lower Dam's existing spillway rating curve, the flow capacities at various reservoir pool elevations, utilized HEC-RAS for the reasons listed in the previous section. HEC-RAS requires the physical geometry of the system to be defined by individual cross sections, cut perpendicular to the flow, associated with the reach centerline alignment, and oriented by stationing along the reach centerline. Existing topographic survey data was utilized to create this geometry. Additional field measurements were also taken during a site visit to both verify the provided survey information as well as collect further measurements at the bridge.

The following cross sections, listed from upstream to downstream, were included to model critical elements and transitions of the spillway system:

Table 1: Cross Sections Upstream to Downstream

Cross Section*	Description	Notes
1, 2, and 3	Upstream of spillway, used to model flow transition from the reservoir pool to the spillway entrance.	Utilize ineffective flow areas to identify the zone of flow convergence.
4	Most upstream limit of the concrete spillway.	
5	Most upstream limit of the low-center-pier.	
6	Upstream bounding section for bridge.	Note, bridge deck and pier modeled in HEC-RAS using the bridge/culvert editor.
7	Downstream bounding section for bridge.	
8	Upstream limit of chute spillway left side taper.	Also includes beginning of low-center pier taper.
9	Continuation of chute spillway left side taper and low-center pier taper.	
10 and 11	Downstream limit of the low-center pier, continuation of chute spillway left side taper.	
12	Chute floor slope change.	
13	Downstream limit of chute spillway left side taper.	
14	Downstream limit of concrete chute spillway.	
15 and 16	Downstream of spillway, used to model super critical flow down the rock waterfall.	

*Note that additional cross sections were interpolated between these defined cross sections at every 3.5 meters and every 1 meter for critical areas. The automated interpolation feature included in HEC-RAS was used to accomplish this.

Ineffective flow areas were established at each cross section along the spillway at locations corresponding with the top, inside face of each side wall in order to ensure that only flow capacity through the spillway is included. Adjacent flow capacity associate with dam and abutment overtopping flows were accounted for using a different method and is described in a forthcoming section of this letter.

Manning's roughness values were associated with each cross section and distributed according to the different material types present in the system. A value of 0.013 was used to describe all portions of the concrete chute spillway. A value of 0.03 was used to describe the upstream reservoir bottom. A value of 0.06 was used to describe the downstream rock waterfall surface.

Boundary conditions were established for the modeled reach. The upstream boundary condition was set to normal depth and the downstream condition to critical depth. These conditions were chosen due to the expectation of sub-critical flow within the reservoir upstream and super-critical flow down the waterfall downstream.

Flow data was established using the steady flow data editor. A range of flows from 5 to 105 cubic meters per second (cms) were identified in 5 cms increments. Additionally, the critical range of flows between 35 and 40 cms were identified in 1 cms increments to better define the hydraulic jump that occurs near the upstream limit of the spillway chute taper.

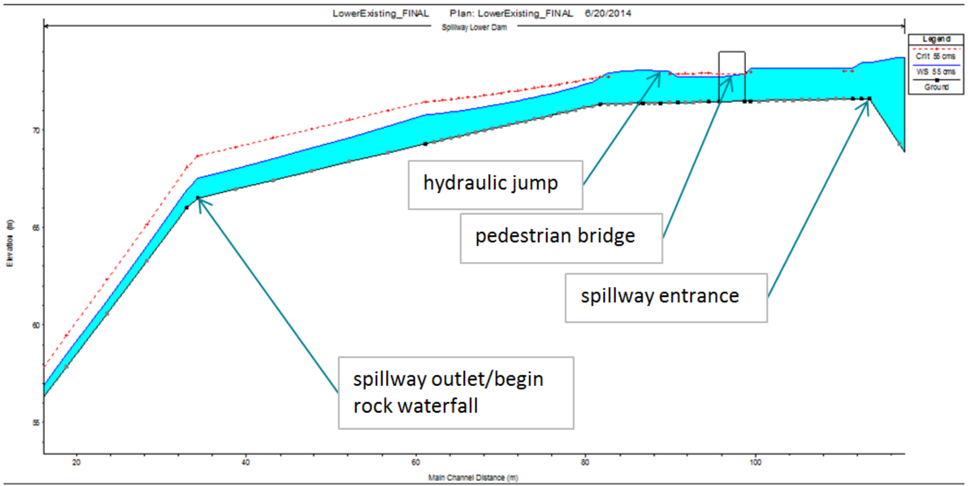
The model simulation was run performing a steady state analysis and modelling a mixed flow regime. Mixed flow means that both sub-critical and super-critical flows are analyzed and the controlling flow regime for a given cross section and flow combination will govern.

This modelling results in water surface profiles along the entire reach and for each flow quantity evaluated. In this case 25 water surface profiles were calculated. Combining each flow rate with the resulting water surface elevation in the upstream reservoir pool creates a 25 point rating curve that describes the full range of the existing spillway's capacity performance. This rating curve was utilized as part of the HEC-HMS modelling described in subsequent sections of this letter. Information on the rating curve is provided below (Golder 2014).

Table 2: Lower Dam Spillway Rating Curve

Lower Dam Spillway Rating Curve			
W.S. Elev. Meters (msl)	Q (m^3/sec)	Head (meters above crest)	Notes
71.60	0.0	0	Crest Elevation
71.99	5.0	0.4	
72.21	10.0	0.6	
72.40	15.0	0.8	
72.57	20.0	1.0	
72.73	25.0	1.1	
72.87	30.0	1.3	
73.02	35.0	1.4	
73.04	36.0	1.4	
73.06	37.0	1.5	
73.10	38.0	1.5	
73.12	39.0	1.5	
73.14	40.0	1.5	
73.24	45.0	1.6	
73.33	50.0	1.7	
73.43	55.0	1.8	Top of dam elevation: 73.4 m-msl

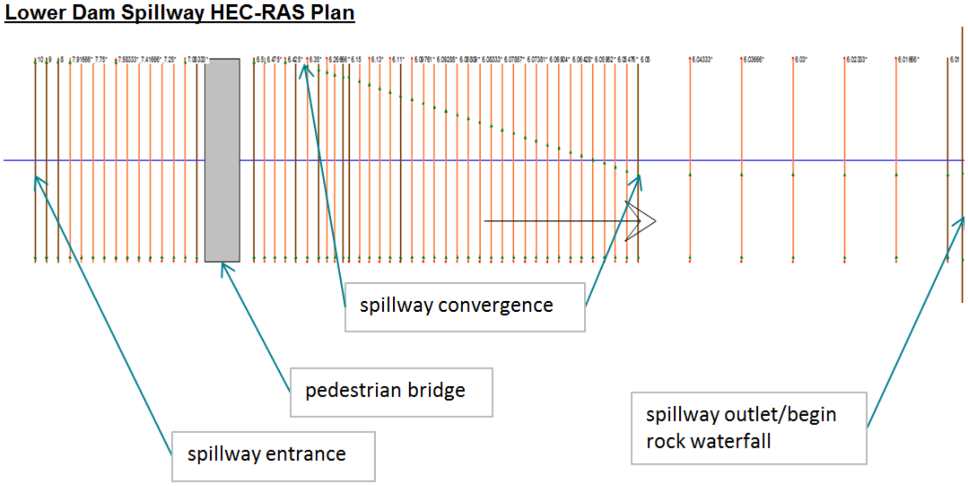
Lower Dam Spillway HEC-RAS Profile



Note: Black nodes on 'ground' line indicate user defined cross sections. Grey nodes indicate cross sections interpolated by HEC-RAS.

Figure 1: Lower Dam Spillway HEC-RAS Profile

Lower Dam Spillway HEC-RAS Plan



Note: Dark red lines indicate user defined cross sections. Orange lines indicate cross sections interpolated by HEC-RAS.

Figure 2: Lower Dam Spillway HEC-RAS Plan

5.0 HEC-HMS OVERVIEW

The U.S. Army Corps of Engineers HEC-HMS computer program version 3.5 User's Manual includes the following abstract.

> "The Hydrologic Modelling System (HEC-HMS) is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It supersedes HEC-1 and provides a similar variety of options but represents a significant advancement in terms of both computer science and hydrologic

engineering. In addition to unit hydrograph and hydrologic routing options, capabilities include a linear quasi-distributed runoff transform (ModClark) for use with gridded precipitation, continuous simulation with either a one-layer or more complex five-layer soil moisture method, and a versatile parameter estimation option.

The program features a completely integrated work environment including a database, data entry utilities, computation engine, and results reporting tools. A graphical user interface allows the user seamless movement between the different parts of the program. Simulation results are stored in the Data Storage System HEC-DSS and can be used in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation.

Program functionality and appearance are the same across all supported platforms. It is available for Microsoft Windows®, Sun Microsystems Solaris™, and Linux® operating systems."

6.0 STORAGE ROUTING ANALYSIS OF THE EXISTING LOWER COLLIERY LAKE

The HEC-HMS model uses the hydrologic parameters defined, which are not part of this letter, to calculate an inflow hydrograph, or a distribution of flow over time. The inflow hydrograph is essentially continually variable and defines the flow into the reservoir for various modeled storm events. In the case of the Lower Colliery Lake and Dam, once flow enters the reservoir it has to either be stored within the reservoir or discharged through one or more of the following outlets; through the spillway, over the top of the dam, or over a portion of the right abutment.

The HEC-HMS software operates using time steps, slicing the hydrographs into quantifiable segments. During each time step the software calculates the total volume of flow into the reservoir, subtracts the total flow out of the reservoir, and accounts for the difference by either adding or subtracting to or from the total storage within the reservoir. The addition and subtraction of volume to and from the reservoir storage results in changes to the reservoir pool elevation. During periods of heavy rainfall, the reservoir elevation rises until the point where the rate of flow into the reservoir matches the rate of flow out of the reservoir. After the most intense portion of the inflow passes and begins to decrease, the outflow capacity of the system begins to exceed the rate of inflow and thus the reservoir elevation begins to recede, ultimately returning to normal pool.

To account for the affect that reservoir storage has on the Lower Colliery Lake and Dam system, a stage-storage relationship has been defined. Utilizing available topographic information for the area surrounding the lake, reservoir areas at particular elevations have been input into HEC-HMS to account for available storage from the normal pool elevation to an elevation above the existing top of dam.

7.0 DAM OVERTOPPING AND RIGHT ABUTMENT FLOW ANALYSIS OF EXISTING LOWER COLLIERY DAM

HEC-HMS provides several options for modelling reservoir outflows; some relatively automated, and others completely user defined. For the Lower Colliery Dam existing spillway, a user defined option was selected and the results of the HEC-RAS analysis, discussed above in Section 4.0, were utilized.

For flows that exceed the Lower Colliery Dam existing spillway's capacity, the "Dam Tops" function of HEC-HMS was utilized. The "Dam Tops" function uses the weir equation to account for flow over non-level profiles of dam crests, saddle dikes, and abutments. The weir equation calculates flow based on three variables; the length of the weir, the head over the weir, and a coefficient that establishes the efficiency of the weir configuration. The non-level weir lengths were developed from the available topographic survey information and were input into HEC-HMS in a manner which allowed the flows overtopping the dam versus the flows overtopping the right abutment to be discerned. The head over the weir is calculated by HEC-HMS through reservoir storage routing as described in Section 6.0 above. The weir coefficient was selected by analyzing the depth of flow versus the width of the crest as described in, *King and Brater Handbook of Hydraulics*, for broad crested weirs.

The resulting distribution of water flow released from the reservoir through the three outlets from the reservoir (over the dam, over the spillway, or over the right abutment) is shown diagrammatically on the attached Figure 3. The figure also includes a table which indicates outlet flows for various return period events, ranging from a 2 year return period event, through to the 1000 year, plus 2/3 PMF (PMP).

8.0 CLOSURE

We trust that the factual information provided herein meets your present requirements. Should you have any questions regarding the above, please do not hesitate to contact us.

GOLDER ASSOCIATES LTD.

ORIGINAL SIGNED

Bruce R. Downing, P.Eng.
Principal

ORIGINAL SIGNED

Joshua K. Myers, P.E.
Senior Water Resources Engineer

BRD/kn
Attachment: Figure 3: Lower Colliery Dam Overtopping

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9.0 REFERENCES

Golder Associates Ltd. 2014. Report on “Colliery Dams – Hydraulics, Hydrology and Dam Breach Analysis”, July 2014.

Golder Associates Ltd. 2015. Letter on “Colliery Dams, Auxiliary Spillway - Conceptual Design”, dated January 16, 2015.

IMPORTANT INFORMATION AND LIMITATIONS OF THIS REPORT

Standard of Care: Golder Associates Ltd. (Golder) has prepared this report in a manner consistent with that level of care and skill ordinarily exercised by members of the engineering and science professions currently practising under similar conditions in the jurisdiction in which the services are provided, subject to the time limits and physical constraints applicable to this report. No other warranty, expressed or implied is made.

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The report is of a summary nature and is not intended to stand alone without reference to the instructions given to Golder by the Client, communications between Golder and the Client, and to any other reports prepared by Golder for the Client relative to the specific site described in the report. In order to properly understand the suggestions, recommendations and opinions expressed in this report, reference must be made to the whole of the report. Golder can not be responsible for use of portions of the report without reference to the entire report.

Unless otherwise stated, the suggestions, recommendations and opinions given in this report are intended only for the guidance of the Client in the design of the specific project. The extent and detail of investigations, including the number of test holes, necessary to determine all of the relevant conditions which may affect construction costs would normally be greater than has been carried out for design purposes. Contractors bidding on, or undertaking the work, should rely on their own investigations, as well as their own interpretations of the factual data presented in the report, as to how subsurface conditions may affect their work, including but not limited to proposed construction techniques, schedule, safety and equipment capabilities.

Soil, Rock and Groundwater Conditions: Classification and identification of soils, rocks, and geologic units have been based on commonly accepted methods employed in the practice of geotechnical engineering and related disciplines. Classification and identification of the type and condition of these materials or units involves judgment, and boundaries between different soil, rock or geologic types or units may be transitional rather than abrupt. Accordingly, Golder does not warrant or guarantee the exactness of the descriptions.

Special risks occur whenever engineering or related disciplines are applied to identify subsurface conditions and even a comprehensive investigation, sampling and testing program may fail to detect all or certain subsurface conditions. The environmental, geologic, geotechnical, geochemical and hydrogeologic conditions that Golder interprets to exist between and beyond sampling points may differ from those that actually exist. In addition to soil variability, fill of variable physical and chemical composition can be present over portions of the site or on adjacent properties. **The professional services retained for this project include only the geotechnical aspects of the subsurface conditions at the site, unless otherwise specifically stated and identified in the report.** The presence or implication(s) of possible surface and/or subsurface contamination resulting from previous activities or uses of the site and/or resulting from the introduction onto the site of materials from off-site sources are outside the terms of reference for this project and have not been investigated or addressed.

Soil and groundwater conditions shown in the factual data and described in the report are the observed conditions at the time of their determination or measurement. Unless otherwise noted, those conditions form the basis of the recommendations in the report. Groundwater conditions may vary between and beyond reported locations and can be affected by annual, seasonal and meteorological conditions. The condition of the soil, rock and groundwater may be significantly altered by construction activities (traffic, excavation, groundwater level lowering, pile driving, blasting, etc.) on the site or on adjacent sites. Excavation may expose the soils to changes due to wetting, drying or frost. Unless otherwise indicated the soil must be protected from these changes during construction.

Sample Disposal: Golder will dispose of all uncontaminated soil and/or rock samples 90 days following issue of this report or, upon written request of the Client, will store uncontaminated samples and materials at the Client’s expense. In the event that actual contaminated soils, fills or groundwater are encountered or are inferred to be present, all contaminated samples shall remain the property and responsibility of the Client for proper disposal.

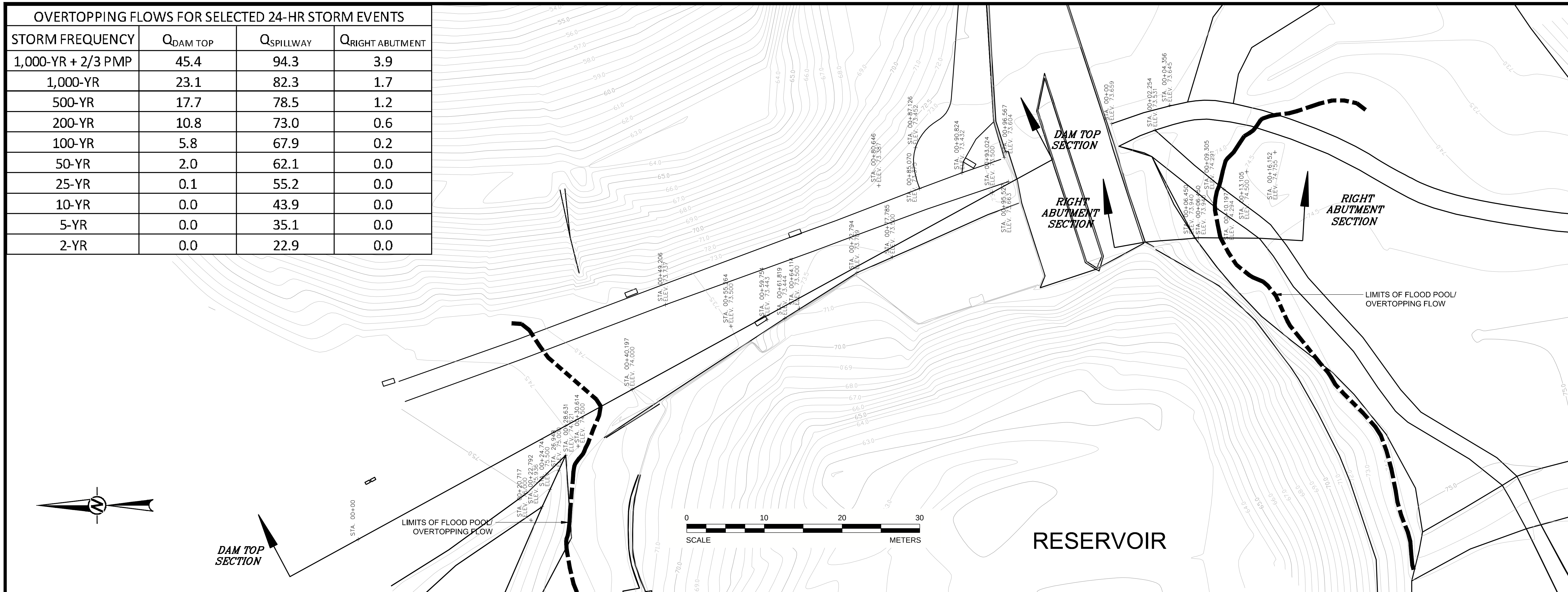
Follow-Up and Construction Services: All details of the design were not known at the time of submission of Golder’s report. Golder should be retained to review the final design, project plans and documents prior to construction, to confirm that they are consistent with the intent of Golder’s report.

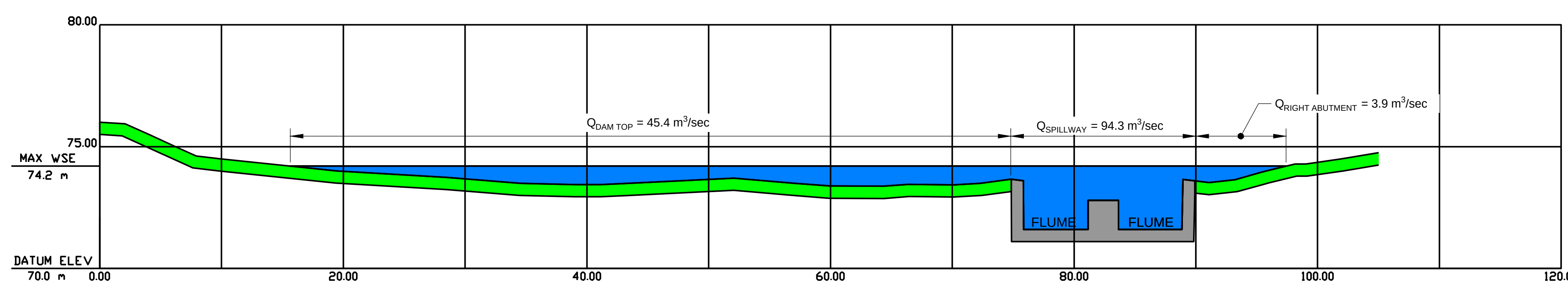
During construction, Golder should be retained to perform sufficient and timely observations of encountered conditions to confirm and document that the subsurface conditions do not materially differ from those interpreted conditions considered in the preparation of Golder’s report and to confirm and document that construction activities do not adversely affect the suggestions, recommendations and opinions contained in Golder’s report. Adequate field review, observation and testing during construction are necessary for Golder to be able to provide letters of assurance, in accordance with the requirements of many regulatory authorities. In cases where this recommendation is not followed, Golder’s responsibility is limited to interpreting accurately the information encountered at the borehole locations, at the time of their initial determination or measurement during the preparation of the Report.

Changed Conditions and Drainage: Where conditions encountered at the site differ significantly from those anticipated in this report, either due to natural variability of subsurface conditions or construction activities, it is a condition of this report that Golder be notified of any changes and be provided with an opportunity to review or revise the recommendations within this report. Recognition of changed soil and rock conditions requires experience and it is recommended that Golder be employed to visit the site with sufficient frequency to detect if conditions have changed significantly.

Drainage of subsurface water is commonly required either for temporary or permanent installations for the project. Improper design or construction of drainage or dewatering can have serious consequences. Golder takes no responsibility for the effects of drainage unless specifically involved in the detailed design and construction monitoring of the system.

OVERTOPPING FLOWS FOR SELECTED 24-HR STORM EVENTS			
STORM FREQUENCY	$Q_{DAM\ TOP}$	$Q_{SPILLWAY}$	$Q_{RIGHT\ ABUTMENT}$
1,000-YR + 2/3 PMP	45.4	94.3	3.9
1,000-YR	23.1	82.3	1.7
500-YR	17.7	78.5	1.2
200-YR	10.8	73.0	0.6
100-YR	5.8	67.9	0.2
50-YR	2.0	62.1	0.0
25-YR	0.1	55.2	0.0
10-YR	0.0	43.9	0.0
5-YR	0.0	35.1	0.0
2-YR	0.0	22.9	0.0





0 10 20 30
HORIZONTAL SCALE METERS

0 20 40 60
VERTICAL SCALE METERS

REV	DATE	REVISION DESCRIPTION	DES	CADD	CHK	RVW

PROJECT
CITY OF NANAIMO
COLLIERY DAMS
NANAIMO, BC, CANADA

TITLE
LOWER COLLIERY DAM OVERTOPPING
$Q_{1000\text{-YR} + 2/3\ PMP}$

Golder Associates

PROJECT No.		1314470516	FILE No.
DESIGN	-	-	SCALE AS SHOWN
CADD	JCD	01/26/15	FIGURE
CHECK	JKM	01/26/15	
REVIEW	BD	01/28/15	

FIGURE 3