Appendix E

Wind and waves analysis

Title of document: **Amaruq Freeboard Study**

Client: **MEADOWBANK MINE - AGNICO EAGLE MINES LIMITED**

Project: **Detailed Engineering of Water Management and Geotechnical Infrastructure at Amaruq**

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TABLE OF CONTENTS

List of figures

List of tables

List of Appendix

1.0 Introduction

Part of the Amaruq project, water management and geotechnical infrastructures need to be designed at a detailed engineering level. In this context, the objective of the present technical note is to determine the minimum freeboard and the necessary riprap required to protect the dikes against the effects of wave action and wind setup.

2.0 Data

2.1 Wind Speed

Hourly wind speed and direction, measured 10 meters above the ground, is available from Environment Canada Baker Lake A meteorological station. This station is located approximately 130 km SSE from the Amaruq mine site. Available data covers a period of 55 years between July 1963 and September 2017. The average wind speed is measured during a two minutes period, at the end of every hour, and is assumed representative for the Amaruq area.

During the period with available data and during the months with open water, July to September, there is less than 2 % of missing data for all years with the exception of 2010 which has 16 % of missing data. This was considered acceptable and available data from all years (1963-2017) was used to develop wind roses for the summer months, when no ice cover is present on water bodies. These wind roses, on which it can be seen that the dominant winds are blowing from a NNO direction during the open water period, are presented on Figure 2-1.

The same data was used to perform a frequency analyses on wind speed using the HYFRAN software. The best fit was obtained with the Gumbel probability distribution and the method of weighted moments. Obtained wind speed for different wind return periods are presented in Table 2-1.

Table 2-1 : Amaruq Wind Speed for Different Return Periods

T	Wind Speed	
[year]	[m/s]	[km/h]
5	18.4	66
10	19.8	71
20	21.1	76
30	21.9	79
50	22.8	82
100	24.1	87
200	25.3	91
500	27.0	97
1000	28.3	102

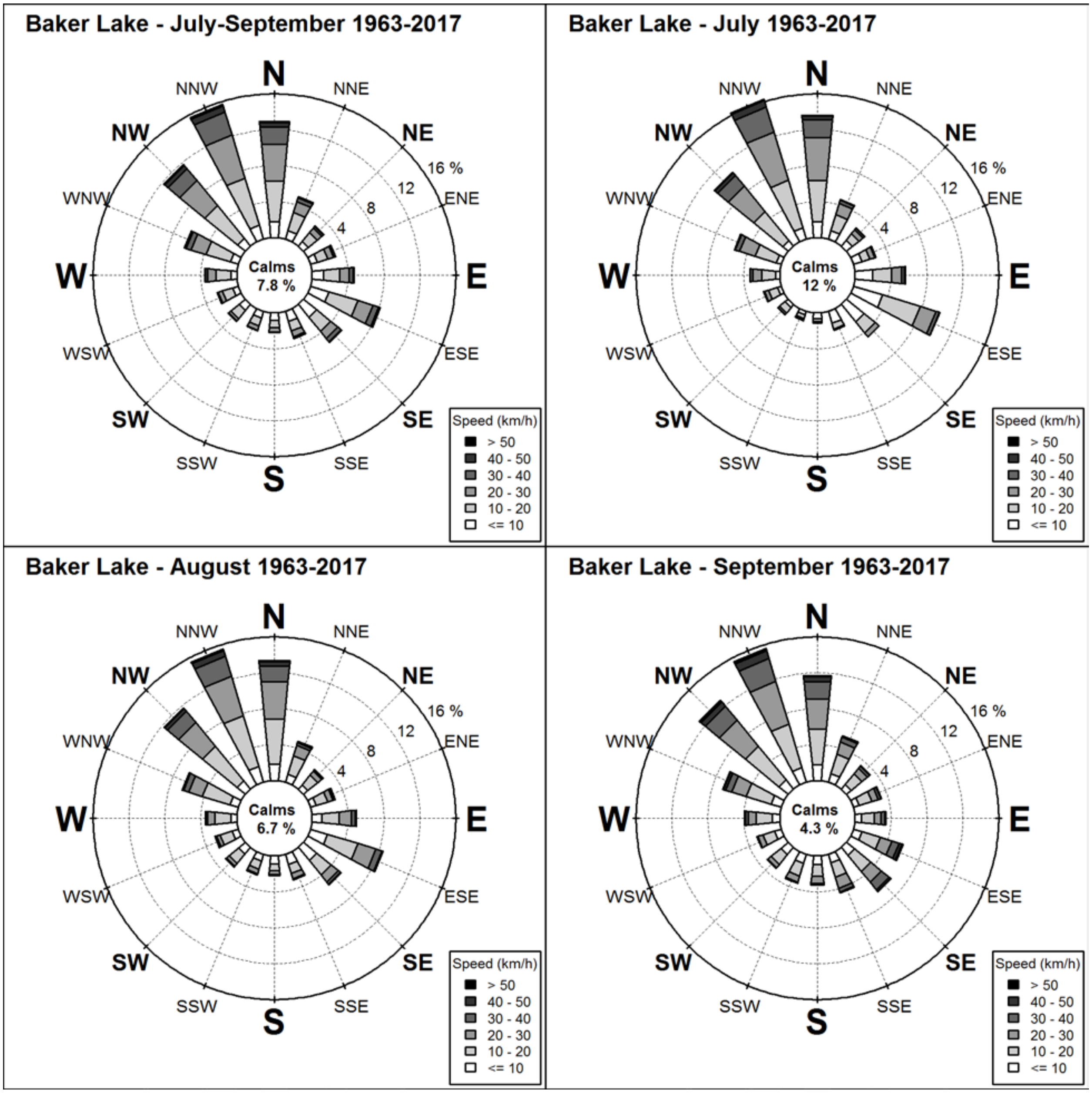

Figure 2-1 : Baker Lake A Wind Roses

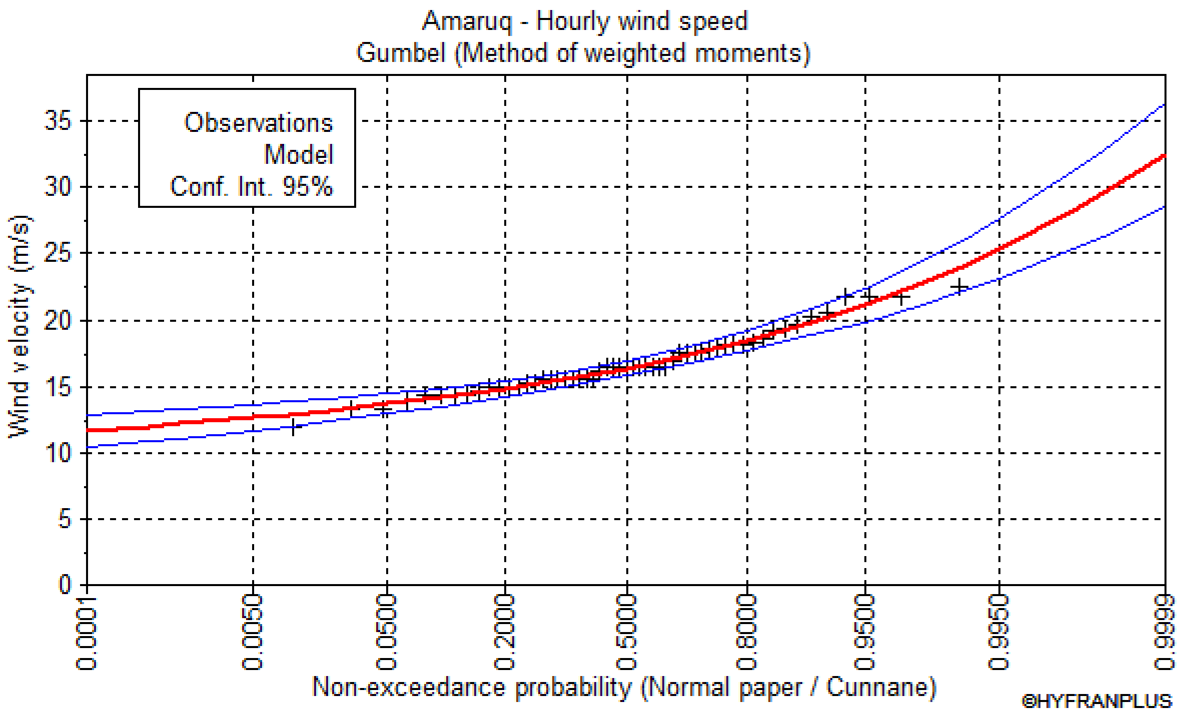

Figure 2-2 : Frequency Analyses Results

2.2 Ponds

Different pond characteristics are used as input for the wind setup and wave runup computations. They include the wind fetch length (the distance on which wind can affect a water body with the development of waves and wind setup) the bottom slope, the average depth, the depth of water at the toe of the dike, the normal operation water level, and the maximum water level during the design flood.

The fetch length, the different depths, and the bottom slope are measured with the ArcGIS software from available topographic and bathymetric data for each pond or lake. Normal operation and maximum water levels are the result of flood routing computations described in SNC-Lavalin (2018a and 2018b).

2.3 Dikes

Dike location, dike shape and lateral slope are extracted from drawings to be issued (651298-6000-4GDD-0001, 651298-6000-4GDD-0002, 651298-7000-4GDD-0001, 651298-7000-4GDD-0002, 651298-5000-4GDD-0001, 651298-5000-4GDD-0002, 651298-2500-4GDD-0007).

2.4 Riprap

The following riprap characteristics are assumed to determine the required riprap diameter and layer depth:

- Density: 2.65
- Stability coefficient: 3.5, for an acceptable level of damage (SEBJ, 1997).
- Form coefficient: 0.6, recommended for quarry stones in SEBJ (1997).

3.0 Methodology

The adopted methodology to determine the required minimum freeboard and riprap for each dike is based on the following steps (see Appendix A for detailed computations):

1. Determination of the wind fetches length.
2. Determination of the design wind speed.
3. Computation of the wind setup, which is the vertical rise in the still water level that can be observed on the leeward side of a water body due to a sustained wind in a given direction.
4. Computation of the significant wave height, which is the average height of the highest third of all waves present in a wave train, and the design wave height.
5. Computations of the wave runup, which is the vertical height difference between the maximum elevation reached by wave runup on a dike slope and the water elevation at the toe of the slope, excluding wave action.
6. Computation of the minimum freeboard required during normal operation and during the dike design flood and comparison with the available freeboard to validate the dike crest elevation.
7. Computations of the required riprap characteristics to protect the dike against wave action.

4.0 Results

4.1 Whale Tail Dike

4.1.1 Minimum Freeboard during Normal Operation

The minimum freeboard during normal operation for Whale Tail dike is computed based on a maximum normal operation water level of 156.0 m. At this water level, the maximum effective fetch is approximately 1.6 km long with a direct fetch of 1.6 km.

The radials used to obtain the fetch lengths are presented on Figure 4-1. Table 4-1 presents the different wind speeds computed for different wind return periods.

Table 4-2 presents the significant and design wave heights, wind setup, and wave runup values for different wind return periods. These values were obtained based on:

- An average depth of 5.2 m (entire water body).
- A depth of water of 2.0 m at the foot of the dike.
- A bottom slope of 1.0 % at the foot of the dike.
- A dike slope of 1.5H:1V.

Based on these results, the obtained minimum freeboard, corresponding to a 1000 years return period wind when the lake is at a normal water level of 156.0 m, is approximately 2.0 m and the corresponding minimum required dike crest elevation is 158.0 m.

The necessary riprap diameter and layer thickness to protect the dike slope against wave action are given in Table 4-3 for different wind return periods. A riprap D_{50} of 420 mm is obtained for a wind with a 100 years return period.

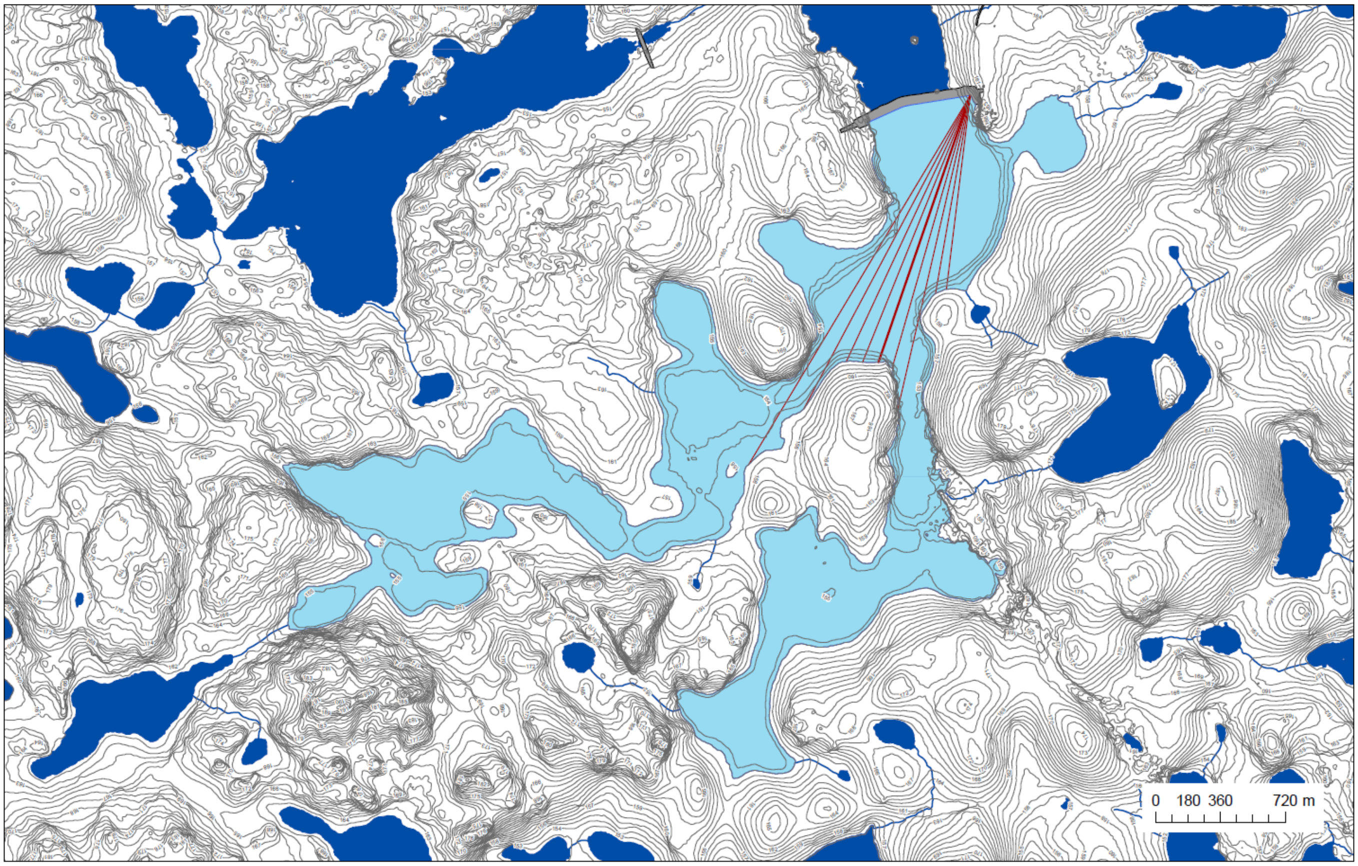

Figure 4-1 : Whale Tail Dike Radials – Normal Operation Water Level (156.0 m)

Table 4-1 : Whale Tail Dike – Wind Speed for Different Return Periods (Normal Water Level)

T [year]	U_{G10} [m/s]	U_{S10} [m/s]	U_G [m/s]	U_W [m/s]	U_A [m/s]
5	18.4	15.3	15.6	18.7	26.0
10	19.8	16.4	16.7	20.0	28.3
20	21.1	17.3	17.7	21.2	30.4
30	21.9	17.9	18.3	21.9	31.7
50	22.8	18.6	19.0	22.8	33.1
100	24.1	19.6	20.0	23.9	35.3
200	25.3	20.4	20.9	25.0	37.3
500	27.0	21.7	22.1	26.6	40.1
1000	28.3	22.6	23.1	27.7	42.3

Table 4-2 : Whale Tail Dike – Wave Heights, Wind Setup, and Wave Runup (Normal Water Level)

T [year]	Hs [m]	H design 5% [m]	Wind setup [m]	Wave runup 5% [m]	Wave runup 5% & wind setup [m]
5	0.54	0.73	0.02	1.20	1.22
10	0.58	0.80	0.02	1.30	1.33
20	0.63	0.86	0.03	1.40	1.42
30	0.65	0.89	0.03	1.46	1.49
50	0.68	0.93	0.03	1.52	1.56
100	0.73	1.00	0.04	1.62	1.66
200	0.77	1.05	0.04	1.72	1.75
500	0.83	1.13	0.04	1.85	1.89
1000	0.87	1.19	0.05	1.95	1.99

Table 4-3 : Whale Tail Dike – Riprap (Normal Water Level)

T [year]	Hs [m]	H design 5% [m]	Stone weight Minimum [kg]	Stone weight Mean [kg]	Stone weight Maximum [kg]	Stone diameter D_{min} [mm]	Stone diameter D_{50} [mm]	Stone diameter D_{max} [mm]	Minimum layer thickness
5	0.54	0.73	17	44	52	230	310	320	580
10	0.58	0.80	22	57	66	250	330	350	630
20	0.63	0.86	27	71	82	260	360	380	650
30	0.65	0.89	31	80	93	270	370	390	680
50	0.68	0.93	36	92	107	290	390	410	730
100	0.73	1.00	43	111	129	310	420	440	780
200	0.77	1.05	51	131	152	320	440	460	800
500	0.83	1.13	63	163	190	350	470	500	880
1000	0.87	1.19	74	191	223	370	500	520	930

4.1.2 Minimum Freeboard during the Dike Design Flood

Whale Tail dike design flood is 1/3 between a 1000-yr return period flood and the probable maximum flood. The minimum freeboard during the design flood is based on a maximum normal operation water level of 157.0 m. At this water level, the maximum effective fetch is approximately 1.9 km long with a direct fetch of 1.6 km.

The radials used to obtain the fetch lengths are presented on Figure 4-2. Table 4-4 presents the different wind speeds computed for different wind return periods.

Table 4-5 presents the significant and design wave heights, wind setup, and wave runup values for different wind return periods. These values were obtained based on:

- An average depth of 6.2 m (entire water body).
- A depth of water of 3.0 m at the foot of the dike.
- A bottom slope of 1.0 % at the foot of the dike.
- A dike slope of 1.5H:1V.

Based on these results, the obtained minimum freeboard, corresponding to a wind with a 100 years return period when the lake is at a maximum water level during the design flood, is approximately 1.8 m and the corresponding minimum required dike crest elevation is 158.8 m.

The necessary riprap diameter and layer thickness to protect the dike slope against wave action are given in Table 4-6 for different wind return periods. A riprap D_{50} of 450 mm is obtained for the 100 years return period wind.

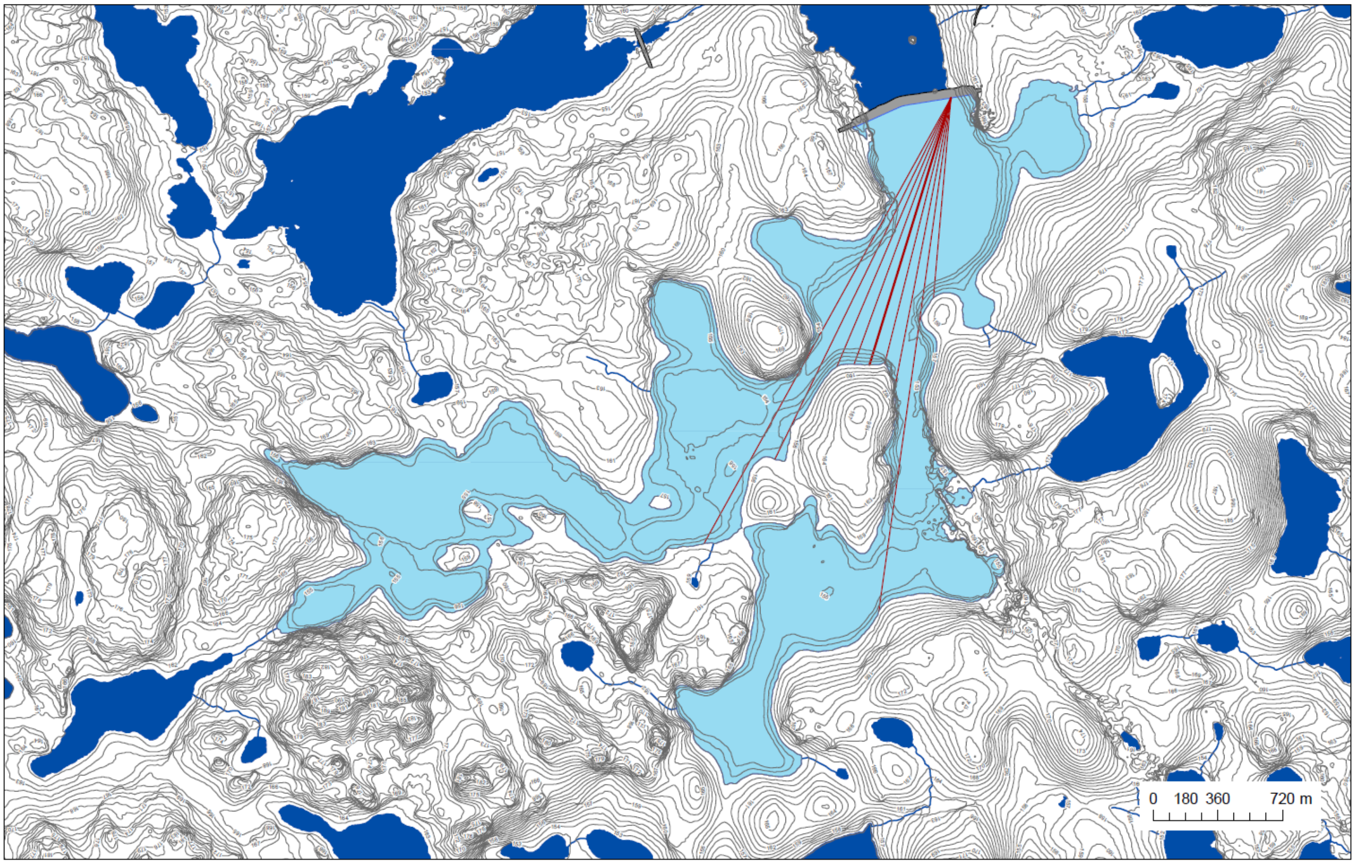

Figure 4-2 : Whale Tail Dike Radials – Maximum Water Level (157.0 m)

Table 4-4 : Whale Tail Dike – Wind Speed for Different Return Periods (Maximum Water Level)

T [year]	U_{G10} [m/s]	U_{S10} [m/s]	U_G [m/s]	U_W [m/s]	U_A [m/s]
5	18.4	15.3	15.5	18.6	25.9
10	19.8	16.4	16.6	19.9	28.2
20	21.1	17.3	17.6	21.1	30.3
30	21.9	17.9	18.2	21.9	31.6
50	22.8	18.6	18.9	22.7	33.0
100	24.1	19.6	19.9	23.9	35.2
200	25.3	20.4	20.8	25.0	37.2
500	27.0	21.7	22.1	26.5	40.0
1000	28.3	22.6	23.1	27.7	42.2

Table 4-5 : Whale Tail Dike – Wave Heights, Wind Setup, and Wave Runup (Maximum Water Level)

T [year]	Hs [m]	H design 5% [m]	Wind setup [m]	Wave runup 5% [m]	Wave runup 5% & wind setup [m]
5	0.58	0.79	0.02	1.29	1.31
10	0.63	0.86	0.02	1.40	1.42
20	0.67	0.92	0.02	1.50	1.53
30	0.70	0.96	0.02	1.57	1.59
50	0.73	1.01	0.03	1.64	1.67
100	0.78	1.07	0.03	1.75	1.78
200	0.83	1.13	0.03	1.85	1.88
500	0.89	1.22	0.04	1.99	2.02
1000	0.94	1.28	0.04	2.10	2.14

Table 4-6 : Whale Tail Dike – Riprap (Maximum Water Level)

T	Hs	H design	Stone weight			Stone diameter			Minimum
		5%	Minimum	Mean	Maximum	D_{min}	D_{50}	D_{max}	layer
[year]	[m]	[m]	[kg]	[kg]	[kg]	[mm]	[mm]	[mm]	thickness
5	0.58	0.79	22	55	65	240	330	350	600
10	0.63	0.86	28	71	83	260	360	380	650
20	0.67	0.92	34	88	103	280	390	410	700
30	0.70	0.96	39	100	117	300	400	420	750
50	0.73	1.01	45	115	134	310	420	440	780
100	0.78	1.07	54	138	161	330	450	470	830
200	0.83	1.13	63	163	190	350	470	500	880
500	0.89	1.22	79	203	237	370	510	540	930
1000	0.94	1.28	93	238	278	390	540	560	980

4.1.3 Summary

In summary, for Whale Tail dike:

- The minimum freeboard required during normal operation, corresponding to a 1000 years return period wind with a normal operation water level of 156.0 m, is approximately 2.0 m and the corresponding required minimum dike crest elevation is 158.0 m.
- The minimum freeboard required during the dike design flood, corresponding to a 100 years return period wind when the water level reaches a maximum of 157.0 m, is approximately 1.80 m and the corresponding required minimum dike crest elevation is 158.8 m.

Therefore, with a design dike crest elevation of 159.0 m, Whale Tail Dike is adequately designed and protected from wind and wave action.

The recommended riprap, to protect the dike slope against a 100 years return period wind when the water is at its maximum level during the design flood, has a D_{50} of 450 mm and a minimum layer thickness of 830 mm (Table 4-6).

These results are conservative as they are based on a SSE fetch direction, while the dominant wind direction is oriented NNW. Therefore, the probability of a strong wind being directed towards the dike in the most critical direction of the longest fetch and during an important flood is low.

4.2 Mammoth Dike

Mammoth dike is located on the eastern side of Mammoth Lake, and its role is to separate and protect the mine site from possible Mammoth Lake water increases during floods. Mammoth dike will be built with non-erodible material (bituminous geomembrane). Therefore, even if the dike was overtopped by waves no or very limited damages would be expected. The dike minimum freeboard was determined following the same methodology used for erodible dikes.

4.2.1 Minimum Freeboard during Normal Conditions

Mammoth dike water level during normal conditions (outside flood periods) is between approximately 152.0 and 152.4 m, based on available measurements. The dike thermal cap upper elevation is 152.7 m (drawings 0017 and 0018). Therefore, wind and wave action is not an issue during normal conditions as there would be no water at the foot of the dike.

4.2.2 Minimum Freeboard during the Dike Design Flood

Mammoth Lake design flood is 1/3 between a 1000-yr return period flood and the probable maximum flood. The minimum freeboard during the design flood for Mammoth dike is based on a maximum water level of 153.5 m. This water level was estimated based on hydraulic computations made with the HEC-RAS software, for the river reach between Mammoth Lake and Lake A12, and taking into account the diversion channel from Whale Tail South. Because not sufficient concomitant discharge and water level measurements were available to properly calibrate the hydraulic model, a sensitivity analyses was performed. The maximum Mammoth Lake water level during the dike design flood was conservatively obtained by applying a safety factor of 1.5 to the peak discharge and by considering a Manning n value of 0.07 for the whole river reach. Note that no safety factor was applied to take into account possible ice jam conditions. However, because the topography is relatively flat with relatively large flow sections, the formation of an important ice blockage is considered unlikely. At a water level of 153.5 m, the maximum effective fetch length is approximately 1.9 km with a direct fetch of 2.3 km.

The radials used to obtain the fetch lengths are presented on Figure 4-3. Table 4-7 presents the different wind speeds computed for different wind return periods.

Table 4-8 presents the significant and design wave heights, wind setup, and wave runup values for different wind return periods. These values were obtained based on:

- An average depth of 5.0 m (entire water body).
- A depth of water of 0.8 m at the foot of the dike.
- A bottom slope of 1.0 % at the foot of the dike.
- A dike slope of 2H:1V.

Based on these results, the obtained minimum freeboard, corresponding to a wind with a 100 years return period when Mammoth Lake reaches a maximum water level of 153.5 m during the design flood, is approximately 1.3 m and the corresponding minimum required dike crest elevation is 154.8 m.

The necessary riprap diameter and layer thickness to protect the dike slope against wave action are given in Table 4-9 for different wind return periods. A riprap D_{50} of 400 mm is obtained for the 100 years return period wind.

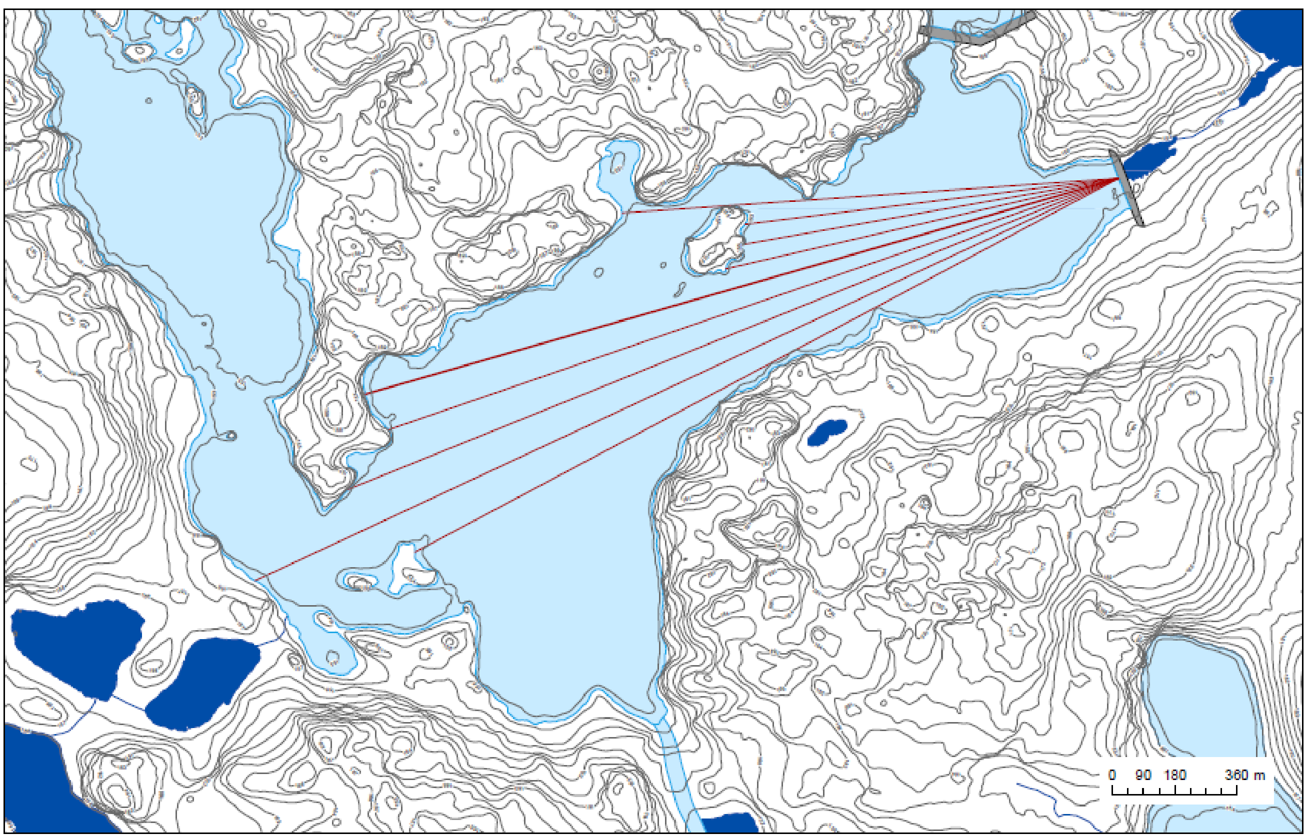

Figure 4-3 : Mammoth Dike Radials – Maximum Water Level (153.5 m)

Table 4-7 : Mammoth Dike – Wind Speed for Different Return Periods (Maximum Water Level)

T [year]	U_{G10} [m/s]	U_{S10} [m/s]	U_G [m/s]	U_W [m/s]	U_A [m/s]
5	18.4	15.3	15.5	18.6	25.9
10	19.8	16.4	16.6	19.9	28.2
20	21.1	17.3	17.6	21.1	30.3
30	21.9	17.9	18.2	21.9	31.6
50	22.8	18.6	18.9	22.7	33.0
100	24.1	19.6	19.9	23.9	35.2
200	25.3	20.4	20.8	25.0	37.2
500	27.0	21.7	22.1	26.5	40.0
1000	28.3	22.6	23.1	27.7	42.2

Table 4-8 : Mammoth Dike – Wave Heights, Wind Setup, and Wave Runup (Maximum Water Level)

T [year]	Hs [m]	H design 5% [m]	Wind setup [m]	Wave runup 5% [m]	Wave runup 5% & wind setup [m]
5	0.57	0.78	0.03	1.13	1.16
10	0.62	0.85	0.04	1.19	1.23
20	0.67	0.91	0.04	1.20	1.24
30	0.70	0.95	0.04	1.21	1.25
50	0.73	1.00	0.05	1.21	1.26
100	0.78	1.06	0.05	1.22	1.27
200	0.76	1.04	0.06	1.22	1.28
500	0.82	1.12	0.07	1.24	1.30
1000	0.86	1.17	0.07	1.24	1.32

Table 4-9 : Mammoth Dike – Riprap (Maximum Water Level)

T [year]	Hs [m]	H design 5% [m]	Stone weight Minimum [kg]	Stone weight Mean [kg]	Stone weight Maximum [kg]	Stone diameter D_{min} [mm]	Stone diameter D_{50} [mm]	Stone diameter D_{max} [mm]	Minimum layer thickness
5	0.57	0.78	16	40	47	220	300	310	550
10	0.62	0.85	20	52	61	240	320	340	600
20	0.67	0.91	25	64	75	260	350	370	650
30	0.70	0.95	28	73	85	270	360	380	680
50	0.73	1.00	33	84	98	280	380	400	700
100	0.78	1.06	39	101	118	300	400	430	750
200	0.76	1.04	37	96	112	290	400	420	730
500	0.82	1.12	46	118	137	310	420	450	780
1000	0.86	1.17	53	136	159	330	450	470	830

4.2.3 Summary

In summary, for Mammoth dike:

- Not enough water is expected to exist at the foot of the dike, during normal conditions outside flood periods, to allow for the formation of waves.
- The minimum freeboard during the dike design flood, corresponding to a 100 years return period wind when the water level reaches a maximum of 153.5 m, is approximately 1.3 m and the corresponding required minimum dike crest elevation is 154.8 m.

Therefore, to be adequately protected from wind and wave action the minimum required Mammoth dike crest elevation is 154.8 m.

The recommended riprap, to protect the dike slope against a 100 years return period wind when the water is at its maximum level during the design flood, has a D_{50} of 400 mm and a minimum layer thickness of 730 mm (Table 4-9).

These results are conservative as they are based on a SW fetch direction, while the dominant winds direction is oriented NNW. Therefore, the probability of a strong wind being directed towards the dike in the most critical direction of the longest fetch and during an important flood is low. Also, the maximum lake water level was estimated conservatively in terms of design flood peak discharge and Manning n value, but no ice jam conditions were considered.

4.3 Waste Rock Storage Facility Dike

The Waste Rock Storage Facility (WRSF) dike is used to contain the Waste Rock Storage Facility snowmelt and runoff water before it can be pumped towards the Attenuation Pond for treatment. No spill towards the Environment is allowed during floods smaller or equal to its design flood. The WRSF dike will be built in non erodible material (bituminous geomembrane). Therefore, even if the dike was overtopped by waves no or very limited damages would be expected. The dike minimum freeboard was determined following the same methodology used for erodible dikes.

4.3.1 Minimum Freeboard during Normal Operation

The WRSF pond will be operated to remain empty outside of important flood periods. Therefore, there will be no water and wave during normal operation.

4.3.2 Minimum Freeboard during the Dike Design Flood

The WRSF design flood is a spring flood resulting of the combination of a 100-yr return period snow cover melting in 25 days with a 72 h duration 2-yr return period rainfall happening during the last three days of the snow melt. The minimum freeboard for the WRSF dike is based on a maximum water level during the design flood of 157.0 m, (SNC-Lavalin, 2018b) corresponding to the dike core elevation. At this water level, the maximum effective and direct fetch lengths are approximately 0.3 km.

The radials used to obtain the fetch lengths are presented on Figure 4-5. Table 4-10 presents the different wind speeds computed for different wind return periods.

Table 4-11 presents the significant and design wave heights, wind setup, and wave runup values for different wind return periods. These values were obtained based on:

- An average depth of 2.0 m (entire water body).
- A depth of water of 2.0 m at the foot of the dike.
- A bottom slope of 1.0 % at the foot of the dike.
- A dike slope of 3H:1V.

Based on these results, the obtained minimum freeboard, corresponding to a wind with a 100 years return period when the pond has its maximum water level of 157.0 m during the design flood, is approximately 0.6 m, and the corresponding minimum required dike crest elevation is 157.6 m.

The necessary riprap diameter and layer thickness to protect the dike slope against wave action are given in Table 4-12 for different wind return periods. A riprap D_{50} of 150 mm is obtained for the 100 years return period wind.

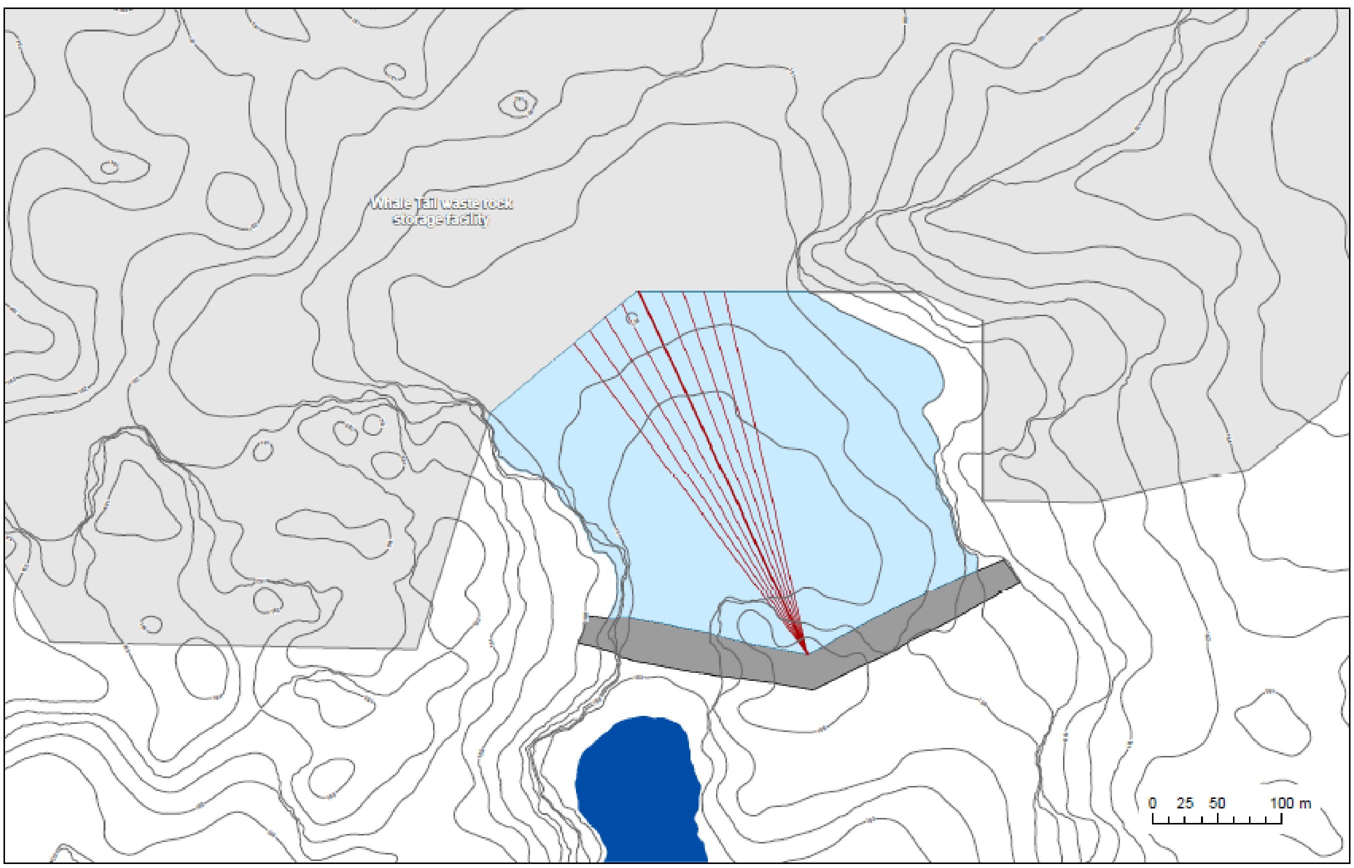

Figure 4-4 : WRSF Dike Radials – Maximum Water Level (157.0 m)

Table 4-10 : WRSF Dike – Wind Speed for Different Return Periods (Maximum Water Level)

T [year]	U_{G10} [m/s]	U_{S10} [m/s]	U_G [m/s]	U_W [m/s]	U_A [m/s]
5	18.4	15.3	16.3	19.5	27.4
10	19.8	16.4	17.4	20.9	29.8
20	21.1	17.3	18.5	22.2	32.1
30	21.9	17.9	19.1	22.9	33.5
50	22.8	18.6	19.8	23.8	35.0
100	24.1	19.6	20.9	25.1	37.3
200	25.3	20.4	21.9	26.2	39.5
500	27.0	21.7	23.2	27.9	42.5
1000	28.3	22.6	24.2	29.1	44.9

Table 4-11 : WRSF Dike – Wave Heights, Wind Setup, and Wave Runup (Maximum Water Level)

T [year]	Hs [m]	H design 5% [m]	Wind setup [m]	Wave runup 5% [m]	Wave runup 5% & wind setup [m]
5	0.24	0.33	0.01	0.39	0.40
10	0.26	0.36	0.01	0.42	0.44
20	0.28	0.39	0.02	0.45	0.47
30	0.30	0.41	0.02	0.47	0.49
50	0.31	0.42	0.02	0.50	0.51
100	0.33	0.45	0.02	0.53	0.55
200	0.35	0.48	0.02	0.56	0.58
500	0.38	0.52	0.02	0.60	0.63
1000	0.40	0.54	0.03	0.63	0.66

Table 4-12 : WRSF Dike – Riprap (Maximum Water Level)

T [year]	Hs [m]	H design 5% [m]	Stone weight Minimum [kg]	Stone weight Mean [kg]	Stone weight Maximum [kg]	Stone diameter D_{min} [mm]	Stone diameter D_{50} [mm]	Stone diameter D_{max} [mm]	Minimum layer thickness
5	0.24	0.33	1	2	2	80	110	120	200
10	0.26	0.36	1	3	3	90	120	130	230
20	0.28	0.39	1	3	4	100	130	140	250
30	0.30	0.41	1	4	4	100	140	150	250
50	0.31	0.42	2	4	5	110	140	150	280
100	0.33	0.45	2	5	6	110	150	160	280
200	0.35	0.48	2	6	7	120	160	170	300
500	0.38	0.52	3	8	9	130	170	180	330
1000	0.40	0.54	4	9	11	140	180	190	350

4.3.3 Summary

In summary, for the WRSF dike:

- The WRSF pond will be empty during normal operation.
- The minimum freeboard during the dike design flood, corresponding to a 100 years return period wind when the water level is at a maximum of 157.0 m, is approximately 0.6 m and the corresponding required minimum dike crest elevation is 157.6 m.

Therefore, with a design dike crest elevation of 158.0 m, the WRSF dike is adequately designed and protected from wind and wave action.

The recommended minimum riprap, to protect the dike slope against a 100 years return period wind when the water is at its maximum level during the design flood, has a D_{50} of 150 mm and a minimum layer thickness of 280 mm (Table 4-12).

These results are based on a NW fetch direction, which is close to the NNW dominant winds direction.

4.4 North East Dike

The North East (NE) pond will be used to store runoff water before it can be pumped towards Mammoth Lake. A design flood with a 10-yr return period is used to design the pumping station to avoid any spill towards Nemo Lake, and a design flood of 100-yr is used to determine the minimum freeboard and dike height.

4.4.1 Minimum Freeboard during Normal Operation

The NE pond will be operated to remain empty outside of important flood periods. Therefore, there will be no water and no wave during normal operation.

4.4.2 Minimum Freeboard during the Dike Design Flood

The NE dike minimum freeboard design flood is a spring flood resulting of the combination of a 100-yr return period snow cover melting in 25 days with a 72 h duration 2-yr return period rainfall happening during the last three days of the snow melt. The minimum freeboard is based on a maximum water level during the design flood of 156.8 m.(SNC-Lavalin, 2018b) At this water level, the maximum effective fetch is approximately 0.4 km with a direct fetch of 0.7 km.

The radials used to obtain the fetch lengths are presented on Figure 4-5. Table 4-13 presents the different wind speeds computed for different wind return periods.

Table 4-14 presents the significant and design wave heights, wind setup, and wave runup values for different wind return periods. These values were obtained based on:

- An average depth of 1.5 m (entire water body).
- A depth of water of 1.5 m at the foot of the dike.
- A bottom slope of 1.0 % at the foot of the dike.
- A dike slope of 3H:1V.

Based on these results, the obtained minimum freeboard, corresponding to a wind with a 100 years return period when the pond reaches a maximum water level of 156.8 m, is approximately 0.7 m and the corresponding minimum required dike crest elevation is 157.5 m.

The necessary riprap diameter and layer thickness to protect the dike slope against wave action are given in Table 4-15 for different wind return periods. A riprap D_{50} of 160 mm is obtained for the 100 years return period wind.

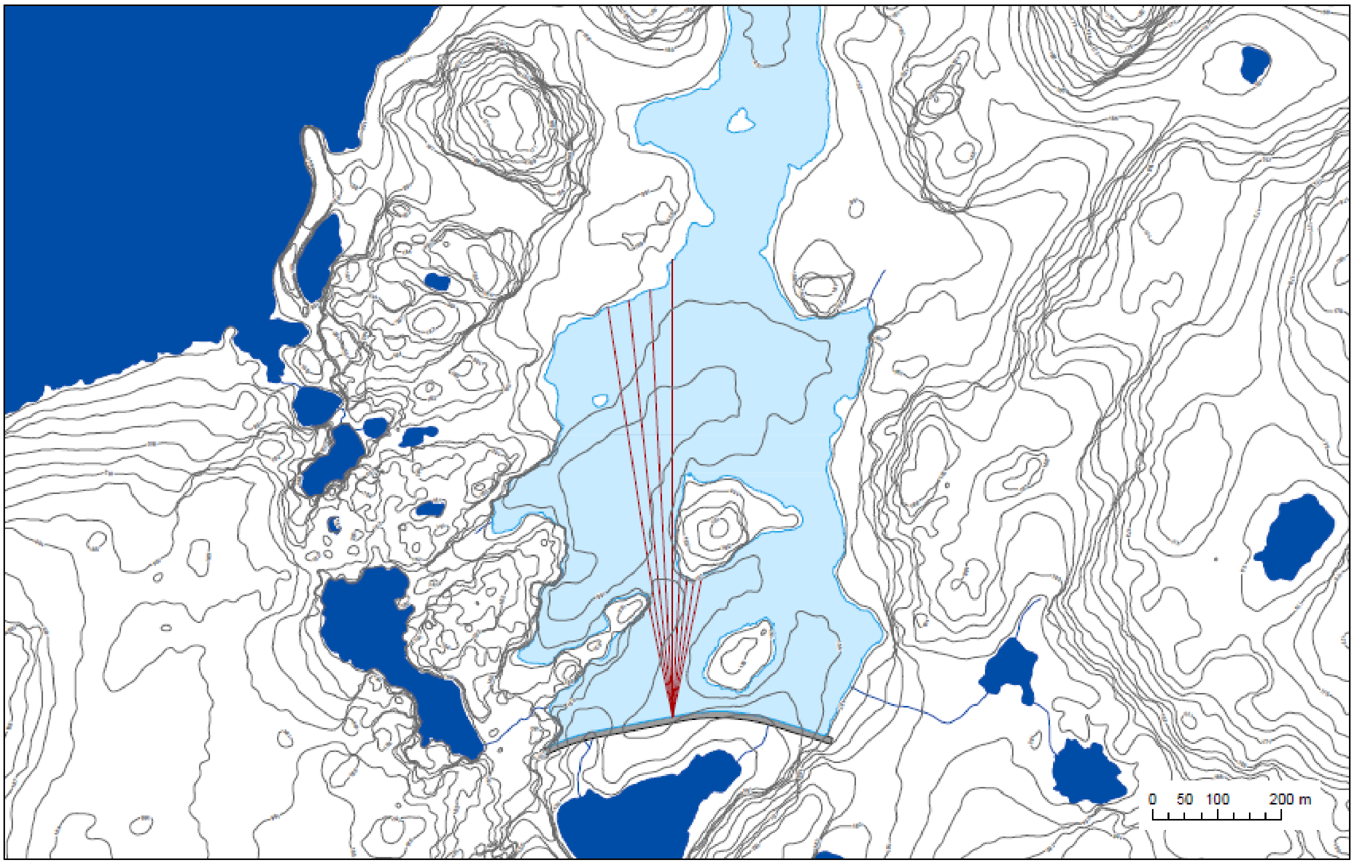

Figure 4-5 : NE Dike Radials – Maximum Water Level (156.8 m)

Table 4-13 : NE Dike – Wind Speed for Different Return Periods (Maximum Water Level)

T [year]	U_{G10} [m/s]	U_{S10} [m/s]	U_G [m/s]	U_W [m/s]	U_A [m/s]
5	18.4	15.3	16.1	19.3	27.1
10	19.8	16.4	17.2	20.7	29.4
20	21.1	17.3	18.3	21.9	31.6
30	21.9	17.9	18.9	22.7	33.0
50	22.8	18.6	19.6	23.5	34.6
100	24.1	19.6	20.7	24.8	36.8
200	25.3	20.4	21.6	25.9	38.9
500	27.0	21.7	22.9	27.5	41.9
1000	28.3	22.6	24.0	28.8	44.2

Table 4-14 : NE Dike – Wave Heights, Wind Setup, and Wave Runup (Maximum Water Level)

T [year]	Hs [m]	H design 5% [m]	Wind setup [m]	Wave runup 5% [m]	Wave runup 5% & wind setup [m]
5	0.26	0.36	0.04	0.42	0.45
10	0.28	0.39	0.04	0.45	0.49
20	0.30	0.41	0.05	0.48	0.53
30	0.31	0.43	0.05	0.50	0.55
50	0.33	0.45	0.05	0.52	0.58
100	0.35	0.48	0.06	0.56	0.62
200	0.37	0.50	0.07	0.58	0.65
500	0.39	0.54	0.07	0.63	0.70
1000	0.41	0.56	0.08	0.66	0.74

Table 4-15 : NE Dike – Riprap (Maximum Water Level)

T	Hs	H design	Stone weight			Stone diameter			Minimum
		5%	Minimum	Mean	Maximum	D_{min}	D_{50}	D_{max}	layer
[year]	[m]	[m]	[kg]	[kg]	[kg]	[mm]	[mm]	[mm]	thickness
5	0.26	0.36	1	3	3	90	120	130	230
10	0.28	0.39	1	3	4	100	130	140	250
20	0.30	0.41	2	4	5	100	140	150	250
30	0.31	0.43	2	5	5	110	150	150	280
50	0.33	0.45	2	5	6	110	150	160	280
100	0.35	0.48	2	6	7	120	160	170	300
200	0.37	0.50	3	7	8	130	170	180	330
500	0.39	0.54	3	9	10	130	180	190	330
1000	0.41	0.56	4	10	12	140	190	200	350

4.4.3 Summary

In summary, for the NE dike:

- The NE pond will be empty during normal operation.
- The minimum freeboard during the dike minimum freeboard design flood, corresponding to a 100 years return period wind when the water level reaches a maximum of 156.8 m, is approximately 0.7 m and the corresponding required minimum dike crest elevation is 157.5 m.

Therefore, a minimum dike crest elevation of 157.5 m is required to properly protect the NE dike from wind and wave action.

The recommended riprap, to protect the dike slope against a 100 years return period wind when the water is at its maximum level during the design flood, has a D_{50} of 160 mm and a minimum layer thickness of 300 mm (Table 4-12).

These results are based on a NNW fetch direction, which is also the dominant winds direction.

4.5 Attenuation Pond

The Attenuation Pond will be built entirely in excavation. Therefore, if waves are overtopping the pond, there is no risk of dike failure. However, the pond minimum freeboard was determined following the same methodology previously used for dikes.

4.5.1 Minimum Freeboard during Normal Operation

The minimum freeboard during normal operation for the Attenuation Pond is computed based on a maximum normal operation water level of 142.0 m. At this water level, the maximum effective fetch is approximately 0.3 km long with a direct fetch of 0.3 km.

The radials used to obtain the fetch lengths are presented on Figure 4-6. Table 4-16 presents the different wind speeds computed for different wind return periods.

Table 4-17 presents the significant and design wave heights, wind setup, and wave runup values for different wind return periods. These values were obtained based on:

- An average depth of 4.0 m.
- A depth of water of 5.0 m at the foot of the pond.
- A bottom slope of 8.0 % at the foot of the pond.
- A dike slope of 5H:1V.

Based on these results, the obtained minimum freeboard, corresponding to the 1000 years return period wind when the pond is at a normal water level of 142.0 m, is approximately 0.40 m.

The necessary riprap diameter and layer thickness to protect the pond slope against wave action are given in Table 4-18 for different wind return periods. A riprap D_{50} of 120 mm is obtained for a wind with a 100 years return period.

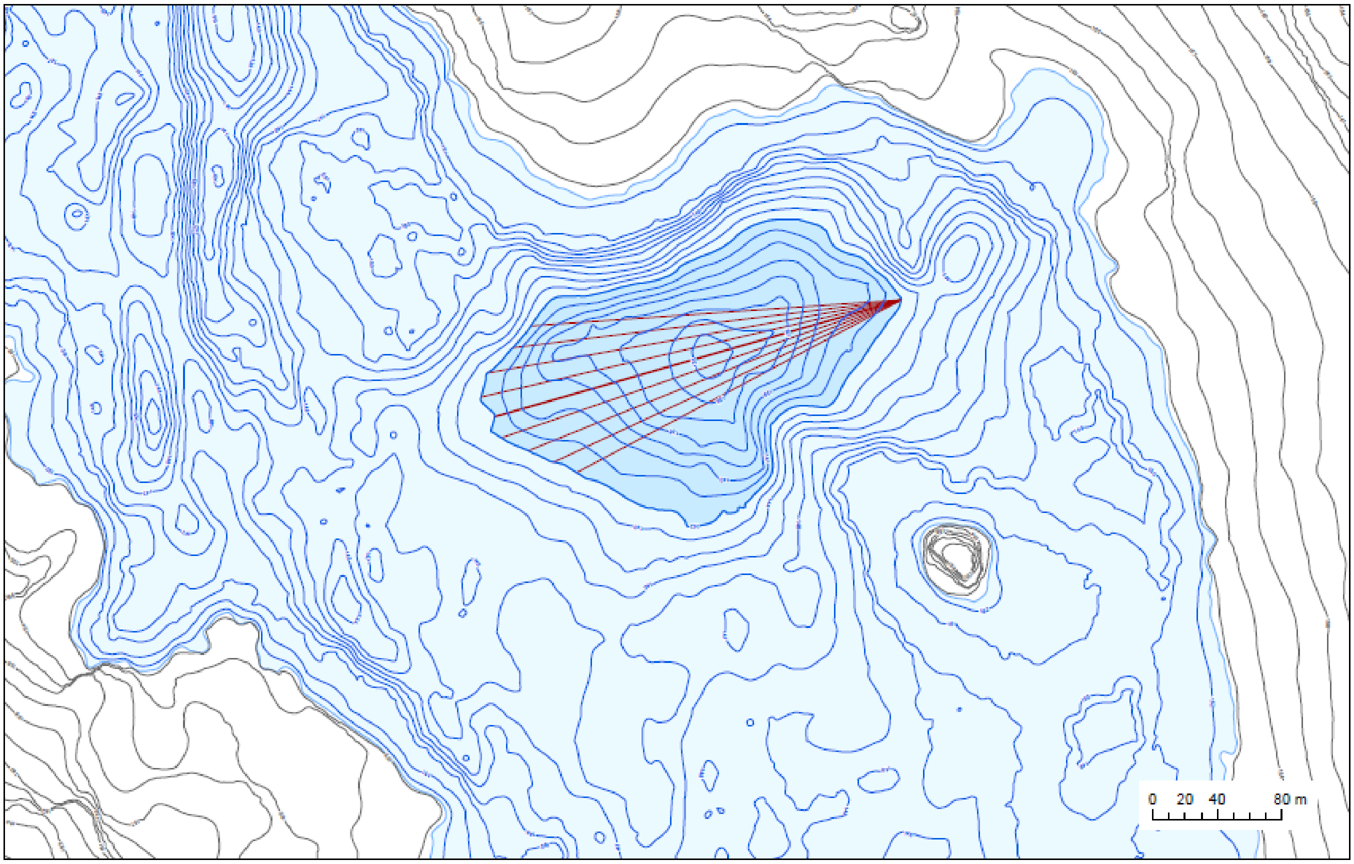

Figure 4-6 : Attenuation Pond Dike Radials – Normal Operation Water Level (142.0 m)

Table 4-16 : Attenuation Pond Dike – Wind Speed for Different Return Periods (Normal Water Level)

T [year]	U_{G10} [m/s]	U_{S10} [m/s]	U_G [m/s]	U_W [m/s]	U_A [m/s]
5	18.4	15.3	16.4	19.6	27.7
10	19.8	16.4	17.5	21.0	30.1
20	21.1	17.3	18.6	22.3	32.3
30	21.9	17.9	19.2	23.1	33.8
50	22.8	18.6	20.0	24.0	35.3
100	24.1	19.6	21.0	25.2	37.7
200	25.3	20.4	22.0	26.4	39.8
500	27.0	21.7	23.4	28.1	42.9
1000	28.3	22.6	24.4	29.3	45.3

Table 4-17 : Attenuation Pond Dike – Wave Heights, Wind Setup, and Wave Runup (Normal Water Level)

T [year]	Hs [m]	H design 5% [m]	Wind setup [m]	Wave runup 5% [m]	Wave runup 5% & wind setup [m]
5	0.22	0.31	0.01	0.21	0.22
10	0.24	0.33	0.01	0.23	0.24
20	0.26	0.36	0.01	0.25	0.26
30	0.27	0.37	0.01	0.26	0.27
50	0.28	0.39	0.01	0.27	0.28
100	0.30	0.42	0.01	0.29	0.30
200	0.32	0.44	0.01	0.31	0.32
500	0.35	0.47	0.01	0.33	0.34
1000	0.36	0.50	0.01	0.35	0.36

Table 4-18 : Attenuation Pond Dike – Riprap (Normal Water Level)

T	Hs	H design	Stone weight			Stone diameter			Minimum
		5%	Minimum	Mean	Maximum	D_{min}	D_{50}	D_{max}	layer
[year]	[m]	[m]	[kg]	[kg]	[kg]	[mm]	[mm]	[mm]	thickness
5	0.22	0.31	0	1	1	70	90	90	180
10	0.24	0.33	0	1	1	70	100	100	180
20	0.26	0.36	1	2	2	80	100	110	200
30	0.27	0.37	1	2	2	80	110	110	200
50	0.28	0.39	1	2	2	80	110	120	200
100	0.30	0.42	1	2	3	90	120	130	230
200	0.32	0.44	1	3	3	90	130	130	230
500	0.35	0.47	1	4	4	100	140	140	250
1000	0.36	0.50	2	4	5	110	140	150	280

4.5.2 Minimum Freeboard during the Pond Design Flood

The Attenuation Pond design flood is a spring flood resulting of the combination of a 100-yr return period snow cover melting in 25 days with a 72 h duration 2-yr return period rainfall happening during the last three days of the snow melt. The minimum freeboard during the design flood for the Attenuation Pond is based on a maximum water level during the design flood of 145.5.0 m (SNC-Lavalin, 2018b). At this water level, the maximum effective and direct fetch lengths are approximately 0.4 km.

The radials used to obtain the fetch lengths are presented on Figure 4-7. Table 4-19 presents the different wind speeds computed for different wind return periods.

Table 4-20 presents the significant and design wave heights, wind setup, and wave runup values for different wind return periods. These values were obtained based on:

- An average depth of 7.5 m.
- A depth of water of 7.0 m at the foot of the pond.
- A bottom slope of 8.0 % at the foot of the pond.
- A dike slope of 5H:1V.

Based on these results, the obtained minimum freeboard, corresponding to a wind with a 100 years return period when the pond reaches a maximum water level of 145.5 m during the design flood, is approximately 0.4 m and the corresponding minimum pond shore elevation is 145.9 m.

The necessary riprap diameter and layer thickness to protect the pond slope against wave action are given in Table 4-21 for different wind return periods. A riprap D_{50} of 140 mm is obtained for the 100 years return period wind.

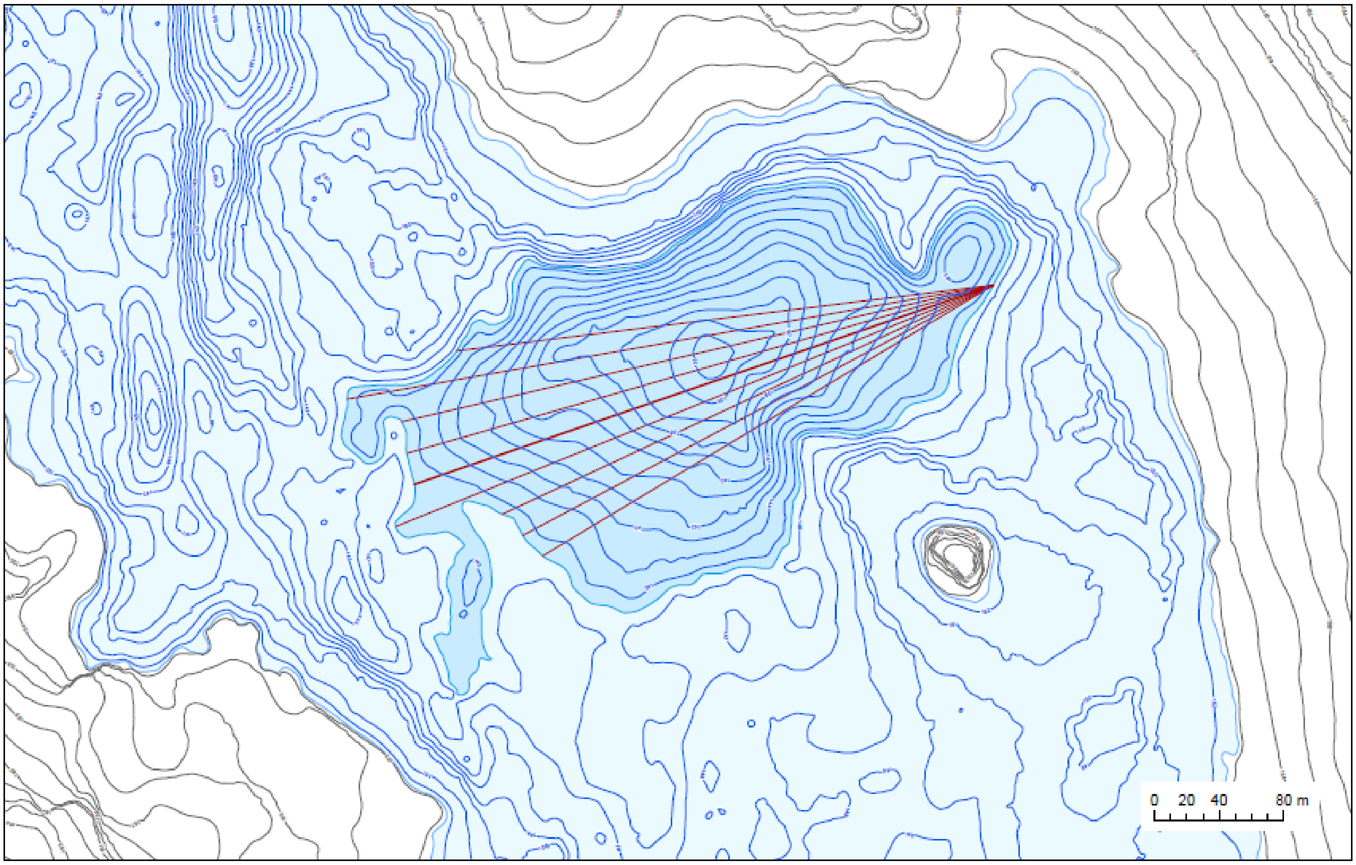

Figure 4-7 : Attenuation Pond Radials – Maximum Water Level (145.5 m)

Table 4-19 : Attenuation Pond – Wind Speed for Different Return Periods (Maximum Water Level)

T [year]	U_{G10} [m/s]	U_{S10} [m/s]	U_G [m/s]	U_W [m/s]	U_A [m/s]
5	18.4	15.3	16.2	19.4	27.2
10	19.8	16.4	17.3	20.7	29.6
20	21.1	17.3	18.3	22.0	31.8
30	21.9	17.9	19.0	22.8	33.2
50	22.8	18.6	19.7	23.6	34.8
100	24.1	19.6	20.7	24.9	37.0
200	25.3	20.4	21.7	26.0	39.1
500	27.0	21.7	23.1	27.7	42.1
1000	28.3	22.6	24.1	28.9	44.5

Table 4-20 : Attenuation Pond – Wave Heights, Wind Setup, and Wave Runup (Maximum Water Level)

T [year]	Hs [m]	H design 5% [m]	Wind setup [m]	Wave runup 5% [m]	Wave runup 5% & wind setup [m]
5	0.26	0.36	0.00	0.25	0.26
10	0.29	0.39	0.00	0.28	0.28
20	0.31	0.42	0.01	0.30	0.30
30	0.32	0.44	0.01	0.31	0.31
50	0.34	0.46	0.01	0.32	0.33
100	0.36	0.49	0.01	0.35	0.35
200	0.38	0.52	0.01	0.36	0.37
500	0.41	0.56	0.01	0.39	0.40
1000	0.43	0.59	0.01	0.41	0.42

Table 4-21 : Attenuation Pond – Riprap (Maximum Water Level)

T [year]	Hs [m]	H design 5% [m]	Stone weight Minimum [kg]	Stone weight Mean [kg]	Stone weight Maximum [kg]	Stone diameter D_{min} [mm]	Stone diameter D_{50} [mm]	Stone diameter D_{max} [mm]	Minimum layer thickness
5	0.26	0.36	1	2	2	80	110	110	200
10	0.29	0.39	1	2	2	80	110	120	200
20	0.31	0.42	1	3	3	90	120	130	230
30	0.32	0.44	1	3	3	90	130	130	230
50	0.34	0.46	1	3	4	100	130	140	250
100	0.36	0.49	2	4	5	100	140	150	250
200	0.38	0.52	2	5	6	110	150	160	280
500	0.41	0.56	2	6	7	120	160	170	300
1000	0.43	0.59	3	7	8	120	170	180	300

4.5.3 Summary

In summary, for the Attenuation Pond:

- The minimum freeboard during normal operation, corresponding to a 1000 years return period wind with a normal operation water level of 142.0 m, is approximately 0.4 m.
- The minimum freeboard during the dike design flood, corresponding to a 100 years return period wind when the water level reaches a maximum of 145.5 m, is approximately 0.4 m.

Therefore, the minimum pond top elevation being 246.0 m, a minimum freeboard of 0.5 m would be adequate for the Attenuation Pond.

The recommended riprap, to protect the pond slope against a 100 years return period wind when the water is at its maximum level during the design flood, has a D_{50} of 140 mm and a minimum layer thickness of 250 mm (Table 4-21).

5.0 Conclusion

Minimum freeboard values were computed for the main dikes and water management infrastructures located on and around the Amaruq mine site. Even if all infrastructures do not contain a dike, and if some of the dikes are non erodible, the same methodology was applied to all of them. The following tables present a summary of the obtained results.

Table 5-1 : Amaruq Freeboard Study Results Summary

Infrastructure name	Freeboard design flood	Normal operation		Design flood conditions		Minimum dike or pond top elevation [m]	Design dike or pond top elevation [m]	Design dike core elevation	Actual minimum freeboard [m]
		Water level [m]	Minimum freeboard [m]	Maximum water level [m]	Minimum freeboard [m]				
Whale Tail dike	1/3 1000-PMF	156.0	2.0	157.0	1.8	158.8	159.0	157.0	2.0
Mammoth dike	1/3 1000-PMF	No water	No water	153.5	1.3	154.8	155.0	153.5	1.5
WRSF dike	100-yr	No water	No water	157.0	0.6	157.6	158.0	157.0	1.0
NE dike	100-yr	No water	No water	156.8	0.7	157.5	157.5	156.8	0.7
Attenuation Pond	100-yr	142.0	0.4	145.5	0.4	145.9	146.0	No dike	0.5

Table 5-2 : Minimum Riprap

Infrastructure name	Minimum riprap	
	D_{50} [mm]	Layer depth [mm]
Whale Tail dike	450	830
Mammoth dike	400	730
WRSF dike	150	280
NE dike	160	300
Attenuation Pond	140	250

6.0 References

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CDA (2013): Canadian Dam Association, Dam Safety Guidelines, Technical Bulletin, Hydrotechnical Considerations for Dam Safety, 2007 revised 2013.

SEBJ (1997): Société de l'Énergie de la Baie James, Guide pratique, Dimensionnement du riprap, Juin 1997.

SNC-Lavalin (2018a): Design Report of Whale Tail Dike, 651298-2700-4GER-0001, 2018 *(To be issued)*.

SNC-Lavalin (2018b): Water Management Infrastructures, 651298-8000-4HER-0001, 2018 *(To be issued).*

USACE (1984): US Army Corps of Engineers, Shore Protection Manual, Volume 1, Coastal Engineering Research Center, 1984.

USACE (2006): US Army Corps of Engineers, Coastal Engineering Manual, Coastal Engineering Research Center, 2006.

APPENDIX A
Detailed Freeboard and Riprap Computations

Fetch

Two types of fetches can be differentiated:

- Direct fetch: the distance between the point of interest, a point located on a dike for example, and a direct line towards the opposite shore of a water body. Direct fetch needs to be representative of the distance affected by wind contributing to the development of wind setup.
- Effective fetch: used to compute the significant wave height, the effective fetch is obtained by averaging the length of a series of radials between the point of interest and the opposite shore of a water body. The effective fetch takes into account the fetch reduction that could result from a narrow water body or a water body with an irregular shape.

Different methods can be used to compute the effective fetch. The adopted method is described in CDA (2013) and consists in averaging the length of nine radials at three degrees intervals.

To be conservative, the longest effective fetch, obtained for any point on a dike axis in relation to the water body shore shape, was adopted in the present study for the significant wave computations. Unless otherwise indicated, the direct fetch is selected as being the radial located in the middle of the nine radials used to compute the effective fetch.

Wind Speed

Available wind speed data was measured over land, at an elevation of 10 meters, and is representative of the average wind speed, in m/s, for two minutes duration gusts. However, for wave height computations, this data needs to be transformed into an adjusted wind speed over water, or wind stress factor, used to transfer the wind momentum and energy from the atmosphere to the water surface. The following methodology was adopted (USACE, 2006):

1. Wind gust speeds measured 10 m over land (U_{G10}) are transformed into sustained wind speeds over land at a height of 10 m (U_{S10}) using the following equation (valid if t_{1mile} < 3600s):

$$U_{S10} = \frac{U_{G10}}{\left(1.277 + 0.296 * TANH\left(0.9 * \log_{10}\left(\frac{45}{t_{1mile}}\right)\right)\right)}$$

   With t_{1mile} being the time needed, in seconds, for the wind gust to travel a one mile distance.

2. Hourly sustained wind speeds (U_{S10}) are transformed into wind speeds at the ground level (U_G) using the following equation (valid if t_{minFC} < 3600s):

$$U_G = \frac{U_{S10}}{\left(1.277 + 0.296 * TANH\left(0.9 * \log_{10}\left(\frac{45}{t_{minFC}}\right)\right)\right)}$$

   With t_{minFC} being the minimum time needed, in seconds, to be fetch limited.

3. Wind speeds at the ground level (U_G) are transformed into wind speeds at the water level (U_W):

$$U_W = R_L * U_G$$

   With R_L being the ratio of wind speed over water to wind speed over land, having a recommended value of 1.2 for fetches less than 16 km long.

4. Wind speeds at the water level (U_W) are transformed into the adjusted wind speeds, or wind stress factors, U_A:

$$U_A = 0.71 * {U_W}^{1.23}$$

Wind Setup

Wind setup is computed using the following equation (CDA, 2013):

$$S = \frac{{U_W}^2 F}{KD}$$

With:

S: wind setup above still water level [m].

U_W: wind speed over water [m/s].

F: direct fetch [km].

K: constant value, K = 4850.

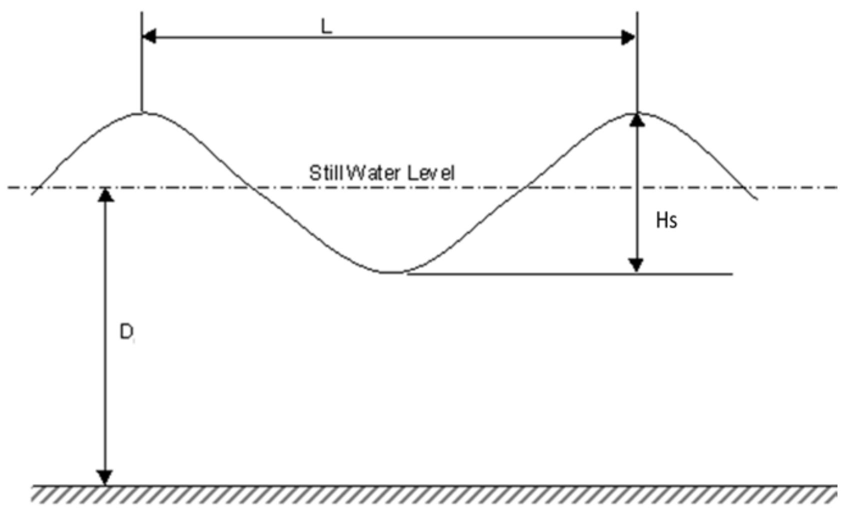
D: average water depth [m].

Significant Wave and Design Wave

The significant wave height is the average height of the highest third of all waves present in a wave train. The lakes and ponds around Amaruq mine site are relatively small. Therefore, their significant wave height will be limited by the fetch length during periods of sustained winds. Based on the linear wave theory, the following assumptions can be made (USACE, 2006):

- The deep water wave length, L, expressed in meters, is equal to 1.56 times the square of the deep water wave period, T, expressed in seconds.
- If the ratio of the average pond depth to the deep water wave length (D/L) is smaller than 0.5, the significant wave is a deep water wave.
- If the ratio of the average pond depth to the deep water wave length (D/L) is larger or equal to 0.5, the significant wave is a transitional or shallow water wave.

Significant Wave Height (Hs)



The following equations are used to estimate significant wave height for deep water (USACE, 1984):

$$H_s = 0.01616 * U_A * F^{1/2}$$

$$T = 0.6238 * (U_A * F)^{1/3}$$

$$t_{min} = 0.893 * \left(\frac{F^2}{U_A}\right)^{1/3}$$

With:

Hs: significant wave height [m].

U_A: adjusted wind speed or wind stress factor [m/s].

F: effective fetch length [km].

T: wave period [s].

t_{min}: minimum wind duration to reach wave growth equilibrium [h]

The following equations are used to estimate significant wave height for shallow water (USACE, 1984):

$$H_S = 0.283 \frac{U_A^2}{g} tanh\left(0.53\left(\frac{gD}{U_A^2}\right)^{3/4}\right) tanh\left(\frac{0.00565\left(\frac{gF}{U_A^2}\right)^{1/2}}{tanh\left(0.53\left(\frac{gD}{U_A^2}\right)^{3/4}\right)}\right)$$

$$T = 7.54 \frac{U_A}{g} tanh\left(0.833\left(\frac{gD}{U_A^2}\right)^{3/8}\right) tanh\left(\frac{0.0379\left(\frac{gF}{U_A^2}\right)^{1/3}}{tanh\left(0.833\left(\frac{gD}{U_A^2}\right)^{3/8}\right)}\right)$$

$$t_{min} = 0.15 * \left(\frac{U_A}{g}\right)\left(\frac{gT}{U_A}\right)^{7/3}$$

With:

Hs: significant wave height [m].

U_A: adjusted wind speed or wind stress factor [m/s].

g: gravity ($9.81 m/s^2$).

D: average water depth [m].

F: effective fetch length [km].

T: wave period [s].

t_{min}: minimum wind duration to reach wave growth equilibrium [h]

For dike design purposes a design wave height larger than the significant wave is generally selected, depending on the required tolerance for overtopping. Commonly adopted design waves are (CDA, 2013):

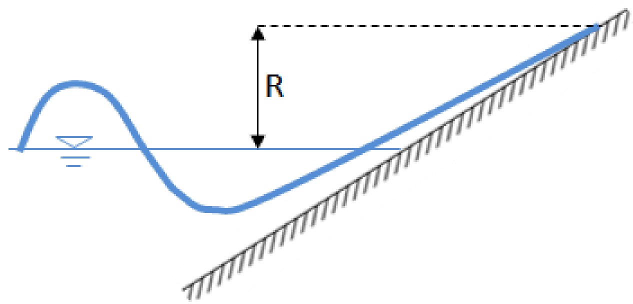
- The average of the highest 10% of all waves, $H_{10} = 1.27\ H_s$.
- The average of the highest 5% of all waves, $H_{10} = 1.37\ H_s$.
- The average of the highest 1% of all waves, $H_{10} = 1.67\ H_s$.

For the dikes constructed part of the Amaruq project, the selected design wave is the average of the highest 5 % of all waves in a wave train.

Wave Runup

The wave runup height is the vertical height difference between the maximum elevation reached by non breaking wave runup on a slope and the still water elevation at the toe of the slope.

Wave Runup (R)



The depth at which waves start breaking can be estimated with the following equation (USACE, 1984):

$$D_{break} = \frac{H_{break}}{0.75 + 25m - 112m^2 + 3870m^3}$$

With:

D_{break}: water depth at which the waves start breaking [m].

H_{break}: wave height of the breaking waves [m].

m: bottom slope [%].

The water depth at the dike foot plus the wind setup can be compared with the design wave height to determine the maximum non breaking wave height used to compute wave runup. Wave runup with a 5 % exceedence can be computed with the following equations (SEBJ, 1997):

$R = 3.5 * \cot(\alpha)^{-1} * H$, $\cot(\alpha) > 2.7$

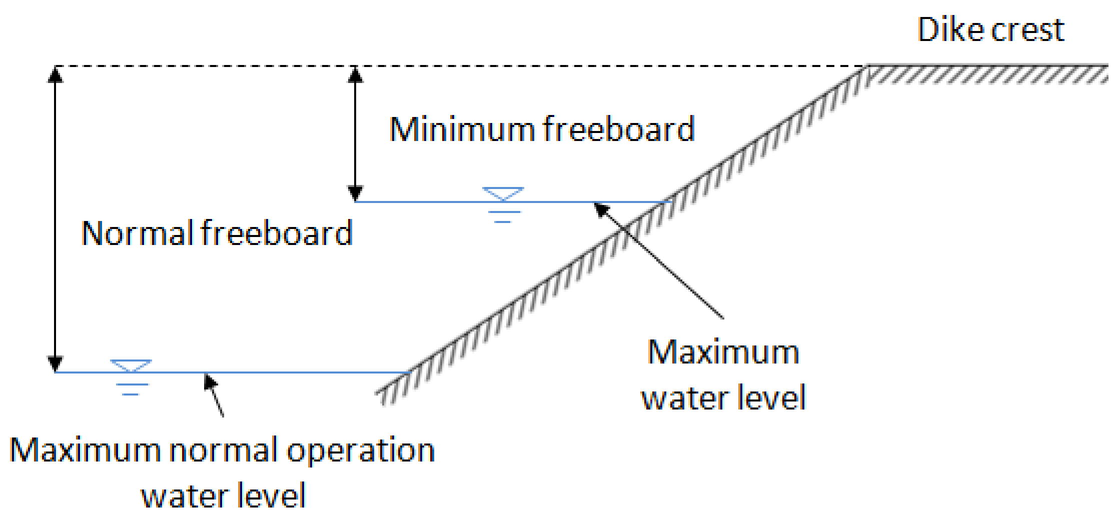
$R = 1.95 * \cot(\alpha)^{-0.44} * H$, $\cot(\alpha) \leq 2.7$

Freeboard

The freeboard of a structure is the minimal vertical distance between the still water level and the crest of the containing structure. Two different freeboards can be differentiated:

- Normal freeboard: the vertical elevation difference between the maximum normal operation water level and the dike crest elevation.
- Minimum freeboard: the vertical elevation difference between the maximum water level, reached during the dike design flood, and the dike crest elevation.

Normal and minimum Freeboard



For an embankment structure, the crest level should be set so that the structure is protected against the most critical of the following cases (CDA, 2013):

- No overtopping by 95% of the waves caused by the most critical wind with a frequency of 1/1000 years when the reservoir is at its maximum normal elevation.
- No overtopping by 95% of the waves caused by the most critical wind when the reservoir is at its maximum extreme level during the passage of the inflow design flood (IDF). The most critical wind for that case depends on the size of the reservoir and of the watershed.

According to CDA (2013), the most critical wind when the reservoir is at its maximum extreme level during the passage of the inflow design flood is function of the dam rating in terms of consequences in case of a dam failure, and the following wind return periods are suggested:

Wind Return Period for Minimum Freeboard Determination (CDA, 2013)

Consequence dam	Wind AEP [year]
Low	100
Significant	10
High, very high, or extreme	2

However, for dikes associated with a high consequence dam having a relatively small watershed, the maximum water level will likely be reached when the storm is still over the dam watershed. In these conditions, using a 2-year return period wind to determine the minimum freeboard would not be very conservative. For this reason, the wind return periods suggested by CDA (2013) for the computation of the minimum freeboard are not used in the present study. In spite, the following table (CDA, 2006) is used:

Wind Return Period for Minimum Freeboard Determination (CDA, 2006)

Duration between the end of the storm and the time of the maximum reservoir level	Wind AEP [year]
Less than 6 hours	100
6 to 12 hours	20
12 to 48 hours	5
More than 48 hours	2

To be adequately designed and protected against wind and wave action, a dike crest elevation needs to be set so that both the normal and the minimum freeboard are respected.

Riprap

Different methods exist to design the necessary riprap to protect a dike slope against wave action. A conservative approach is the one presented in SEBJ (1997) that is adopted for the present study. The following equations can be used to determine the minimum, median (D_{50}), and maximum stone weights of the riprap later:

$$M_{min} = \frac{\rho_r H_S^3}{K(S_r - 1)^3 cot(\propto)}$$

$$M_{median} = \frac{\rho_r H_D^3}{K(S_r - 1)^3 cot(\propto)}$$

$$M_{max} = 3 * M_{min}$$

With:

M_{min}: riprap minimum stone weight [kg].

M_{median}: riprap median (50 %) stone weight [kg].

M_{max}: riprap maximum stone weight [kg].

ρ_r: rock volumic mass [kg/m^3].

Hs: significant wave height [m].

K: stability coefficient [-].

S_r: rock density [-].

cot(α): embankment slope [H:1V].

H_D: design wave height [m].

The stone diameter can be estimated with the following equation:

$$D = 1000 * \left(\frac{M}{C\rho_r}\right)^{1/3}$$

With:

D: stone diameter [mm].

M: stone weight [kg].

C: coefficient of form [-].

ρ_r: rock volumic mass [kg/m^3].

According to SEBJ (1997), the minimum riprap layer thickness is 2.5 times the minimum stone diameter.