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TECHNICAL REVIEW OF 3D MODELLING OF POTENTIAL EFFECTS OF MARINE STRUCTURES ON SITE HYDRODYNAMICS AND SEDIMENTATION FROM THE CONSTRUCTION OF THE PACIFIC NORTHWEST LIQUEFIED NATURAL GAS TERMINAL

Context

Pacific NorthWest Liquid Natural Gas (PNW LNG) is proposing to construct a large scale liquefied natural gas (LNG) export terminal within the Skeena River estuary (Figure 1) (hereafter referred to as the 'Project'). The Project will require dredging, blasting and pile driving to construct a suspended trestle and terminal berths.

On April 8, 2013 the Canadian Environmental Assessment Agency (the Agency) issued a Notice of Commencement that they had commenced an environmental assessment pursuant to the Canadian Environmental Assessment Act (CEAA 2012) for the PNW LNG project located on Lelu Island, BC.

The Environmental Impact Statement (EIS) and Addendum submitted by PNW LNG to the Canadian Environmental Assessment Agency (CEAA) on 28 Feb 2014 and 12 Dec 2014, respectively, provided information with regard to potential effects of marine operations and marine structures upon the sea bed and habitat at Agnew and Flora Banks (Figure 2). The Addendum also provided detailed responses to Information Requests posed by the Government of Canada in regard to sediment deposition; including a report that provides a sediment transport and deposition analysis that utilized 2D models (e.g., USCGA CMS and PTM) conducted by PNW LNG's marine engineering consultant, Hatch.

On Feb 23 2015, PNW LNG received a new Information Request from CEAA, requesting additional 3D hydrodynamic and sedimentation modelling. A Terms of Reference was developed to guide the additional assessment (Hatch, 2015 – Appendix A).

DFO Science Branch provided informal advice to DFO Fisheries Protection Program on draft pre-construction and post construction modelling undertaken by the proponent to assess the potential effects of marine operations and marine structures upon the sea bed and habitat at Agnew and Flora Banks. On May 5, 2015, the Fisheries Protection Program requested that DFO Science review the final results from the above mentioned modelling exercise to support the development of DFO's response to CEAA.

The objective of this Science Response is to review information provided with respect to the above mentioned modelling in the Proponent's May 5, 2015 submission "Pacific Northwest LNG - 3D Modelling of Potential Effects of Marine Structures on Site Hydrodynamics and Sedimentation" (Hatch, 2015), and to answer the following questions by May 19, 2015:

1. Can DFO Science comment on the level of uncertainty in the 3D model and implications for model accuracy?
2. What is DFO Science's view of the model results?

This Science Response Report results from the Science Response Process of May 19, 2015 on the Technical review of 3D modelling of potential effects of marine structures on site hydrodynamics and sedimentation from the construction of the Pacific Northwest liquefied natural gas terminal.

Background

The Proponent describes the marine environment in the region of the Project, as noted in the following excerpt of their Technical Data Report – Marine (Stantec, 2013):

- The marine environments within the region of the Project are typical of BC's North Coast, while also falling within the indelible influence of the Skeena River. While the seafloor topography and substrata are typical of the fjordic North Coast, the Skeena River estuary affects the currents, salinity, and turbidity around the Project. In turn, this influence is reflected by some of the species and habitats seen around the local assessment area (LAA).
- Many different marine habitats are found around the site of the proposed Project, most of which are common throughout the North Coast region. Rocky foreshores dominate the intertidal areas. These feature a diverse assemblage of algae and invertebrates. Soft sediments accumulate in sheltered pockets along the coast and support a community of invertebrates that live within the substrate (such as polychaetes, clams and shrimp) and eelgrass. Subtidal habitats in the area are also typical of the region. Offshore areas constitute a mix of mud, sand, and gravel, rocky outcrops, and boulders; shallower substrata, and those within channels feature are more diverse, including extensive areas of hard bottom. A particularly notable ecological feature of the region is the extensive eelgrass bed on Flora Bank and the soft-sediment areas on the adjacent Agnew Banks. The importance of this area has long been recognized. This area plays an important rearing role for ocean-bound juvenile salmon and crustaceans such as Dungeness crab and Pandalus shrimp. Flora Bank eelgrass is largely restricted to the intertidal areas owing to thick suspended sediments that limit subtidal growth. This observation was supported by field studies and remote-sensing-based mapping. The diversity of marine habitats is echoed in the species that inhabit them. Rocky areas support diverse seaweeds communities, including kelps, which contribute food and shelter to invertebrates and fish. Though largely devoid of seaweeds, soft sediments provide suitable substrate for burrowing invertebrates, crabs, shrimp and flatfish.

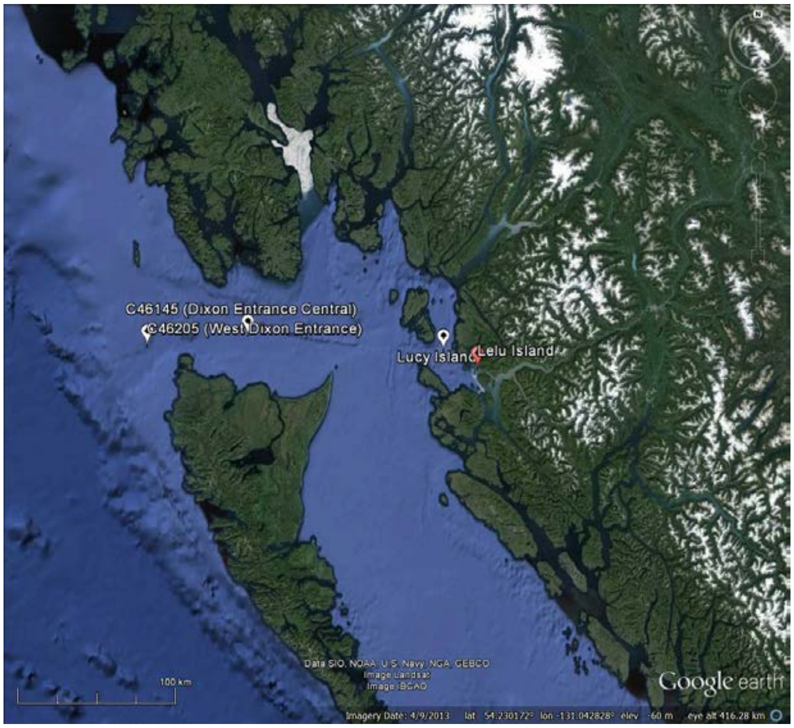

Figure 1. Map of the area of interest, in the context of the BC coast.

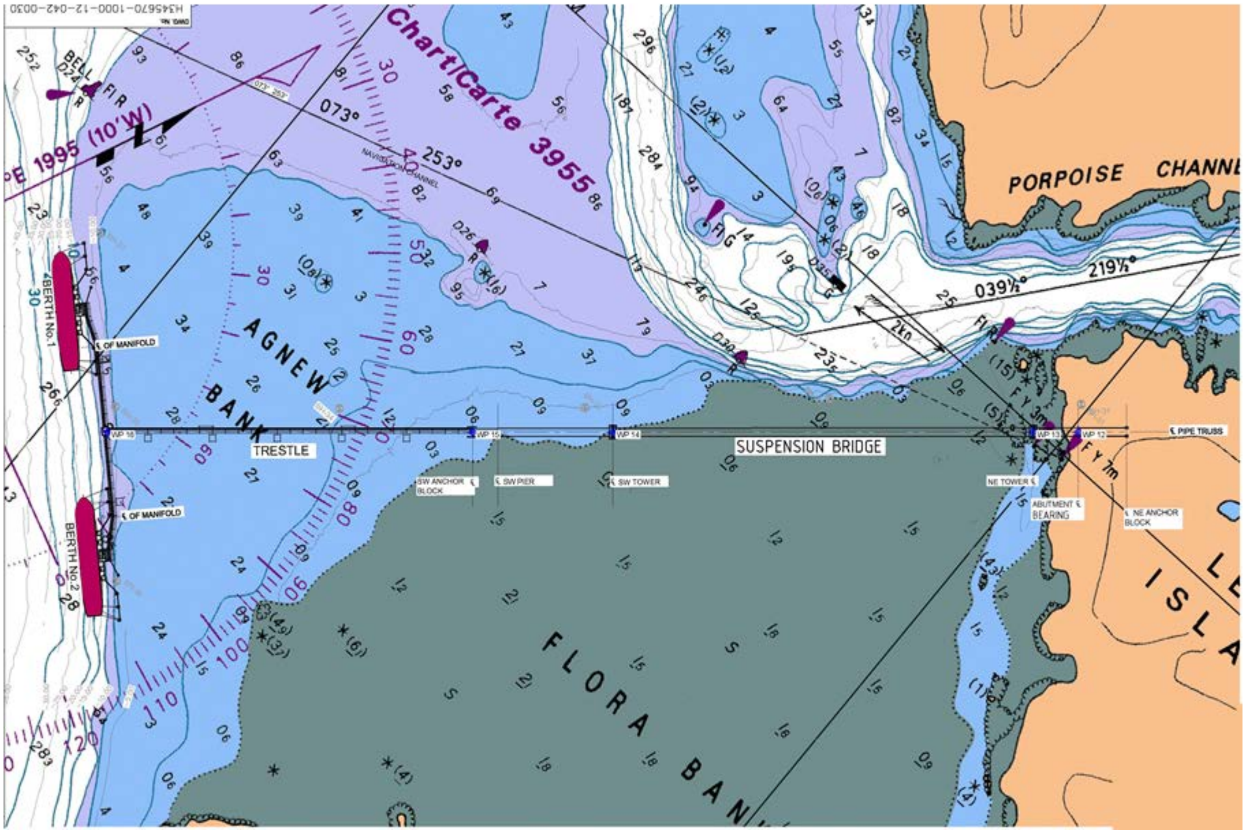

Figure 2. Skeena Estuary and Flora and Agnew Banks. (from Hatch, 2015. Pacific Northwest LNG - 3D Modelling of Potential Effects of Marine Structures on Site Hydrodynamics and Sedimentation – May 5, 2015, Figure 1-1: Location of the Proposed LNG Terminal).

Predicting the changes to the currents and resulting sedimentation patterns, which may result from the construction and installation of the terminal facility, in these diverse and complex habitats, is necessary to assess the potential effects on the fish that inhabit the area (Figures 1 and 2). Conducting hydrodynamic modelling for the area potentially impacted, in both the pre-construction and post-construction state is necessary to understand the potential changes. Recognizing this deficiency in the draft Project EIS, CEAA requested additional analysis to be undertaken, as outlined in the Terms of Reference for 3D Modelling agreed to by CEAA and the proponent (see excerpt below).

The objective of the PNW LNG Delft3D modeling exercise is to respond to the CEAA Information request of Feb. 23, 2015 and to confirm and refine PNW LNG's determination of the Environmental Impact Statement and Addendum as to whether the proposed PNW LNG marine terminal infra-structure on Agnew Bank is likely to have significant adverse effects on fish and fish habitat by:

1. Using the Delft3D model to characterize the baseline natural hydrodynamic and sediment transport regime using the inputs and model verification runs described below;
2. Predicting the effects of PNW LNG's proposed marine terminal infrastructure on the hydrodynamic and sediment transport regime and long-term implications for morphology of Agnew and Flora Banks;
3. Assessing the potential for adverse effects on fish and fish habitat due to any changes to the hydrodynamic regime or sedimentation processes; and
4. Applying and incorporating the model results to answer questions and address concerns expressed by the Government of Canada regarding the 2D model work completed in 2014, specifically those of Natural Resources Canada (NRCan) dated January 9, 2015 (Appendix 1) and February 26, 2015 (Appendix 2), and the Department of Fisheries and Oceans (DFO) dated February 27, 2015 (Appendix 3).

To prepare this response, the following document from the Proponent was reviewed:

Hatch, 2015. Pacific Northwest LNG - 3D Modelling of Potential Effects of Marine Structures on Site Hydrodynamics and Sedimentation. 214 p. + Appendices A – D (35 p).

This CSAS Science Response reviews the modelling conducted by the Proponent to address the above items 1, 2, and 4 as presented in "Pacific Northwest LNG - 3D Modelling of Potential Effects of Marine Structures on Site Hydrodynamics and Sedimentation" (Hatch , 2015), hereafter called the "Report". Assessing the potential for adverse effects on fish and fish habitat due to any changes to the hydrodynamic regime or sedimentation process is not within the scope of this review.

Analysis and Response

Predicting the currents, and resulting sedimentation patterns, in diverse and complex habitats is done by conducting hydrodynamic modelling. Further, to understand the potential changes in the hydrodynamic regime, additional modelling must be done for the pre and post construction stages, taking into account the changes in flow resulting from installation of the marine structures. The following are the key components that such a modelling exercise would entail for the area of interest (Agnew and Flora Banks, Figure 2):

1. **Model Selection:** A model, subject to forcing from tides, remotely and locally generated waves, wind-driven and buoyancy-driven currents, and allowing for sediment transport is required. The Delft3D model is a reliable model that has modern model components for

these processes, aptly coupled together, and that allows for the representation of marine structures.

2. **Model Set-up Calibration and Validation:** Delft3D should be implemented, with spatially fine-resolution integration grids, in the vertical and horizontal directions, and driven by appropriate boundary forcings. Models have parameters, like bottom roughness coefficients, that are selected for a wide range of conditions; for example, studies of marine storms and their impacts on the ocean from a number of other locations, such as the Gulf of St. Lawrence, the Gulf of Maine, the North Sea, etc. for optimal simulations. These parameters need to be tuned, or calibrated, for a selected set of severe storms, whereby model outputs of critical variables like wave heights would be compared to measured observations from buoys. Evaluation of the model can then involve a second independent set of severe storms, comparing model estimates with observations from buoys. This should include the following:

   Outer boundary conditions: These refer to the driving fields for the outer boundary grid-points, including wave data for the wave model, SWAN, which is the wave model within Delft3D; temperature, salinity and currents data for the ocean model component of Delft3D; and atmospheric fields, in the case where a mesoscale atmospheric model is implemented to specify the atmospheric driving fields within the area of interest.

   Waves: Waves generally need to have a large domain grid, because often swell waves propagate from large ocean basin-scale distances, sometimes even crossing the Pacific, to impact coastal ocean areas. Alternately, if the wave model is implemented on a small domain grid, then reliable wave data (e.g. from NOAA’s global wave model simulations) can be used to specify wave conditions at all the boundary grid points of the integration domain.

   Tides: Tides over the region can be characterized as mixed and dominantly semi-diurnal. Tidal heights and currents typically show a pronounced fortnightly modulation, with the tidal range varying between seven meters during spring tides, to about four meters during neaps. Since the modelled region is relatively small, tidal forcing is included as a forcing at the boundaries, and the astronomical forcing is neglected.

   River discharge: Flora and Agnew Banks are located within the immediate proximity of the Skeena River, which drains a large watershed with an areal extent of 56,000 square kilometers. The rate of freshwater discharge from the Skeena typically varies from a minimum of about 410 cubic meters per second in March, to over 4300 cubic meters per second in June, during the spring freshet (Morrison et al., 2012). Inclusion of the Skeena River discharge in the model is important for establishing the cross-shore density stratification and the buoyancy-driven circulation. In addition to being the dominant source of fresh water, the Skeena River also is a major source of suspended solids for the region. Sediment concentrations in Skeena River water have a marked seasonal variation, peaking during the spring freshet (e.g., Figure 2.6 of the report).

   Density stratification: Vertical and lateral gradients in seawater density over the region are due mainly to variations in salinity arising from coastal freshwater runoff. The model could be initialized with a climatological salinity field, or the variations in salinity may be allowed to develop in response to freshwater runoff at the coast.

3. **Model Application - Present Climate storm conditions:** Simulations using present climate conditions (i.e. historical data from past 20+ years) should be done with the composite Delft3D model system. This should involve a representative sample of present severe storms, and also long-time simulations driven by oceanic forcing fields. Thus, it

would be possible to estimate the results of episodic storms on ocean fields, including waves, currents, and sediments, as well as the results of long-term processes.

4. **Model Application - Extreme conditions:** Big storms are the drivers of episodic change in coastal areas. It is important to reliably simulate the extreme conditions that might occur for the desired period of the infrastructure that is being considered. For this study, the 50-year return period is a minimum requirement. Statistics of extreme events do not generally involve occurrences at regular intervals, therefore, it would be preferable to consider a longer time, such as the 100-year return period.
5. **Model Application - Marine structure effects:** Simulations listed above should compare conditions with the marine structures in place, compared to the baseline results with no marine structures.

Evaluation

This Science Response focuses on key deficiencies in the modelling conducted that have the potential to bring into question the validity of the conclusions in the Proponent's application or supporting documents, for both the base case and the post-construction scenarios modelled.

Model Selection

The use of the Delft3D is appropriate for the intended application. Delft3D is a well-known 3D modeling system which can be used to investigate hydrodynamics, waves, sediment transport and morphology, and water quality for estuarine and coastal areas. Details are available on the website. This code is open source, and has component modules for ocean currents, Delft3D flow (FLOW), morphology (MOR) and waves (WAVE). Delft3D has been used successfully for many applications around the world, for example in Netherlands, USA, Hong Kong, Singapore, Australia, Venice, etc. The software is continuously improved, with new modelling techniques, in response to new research developments, and is maintained and updated by Delft Hydraulics Institute.

Delft3D was coupled with the SWAN numerical model to account for the effects of wave growth and propagation on hydrodynamic conditions. SWAN is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions.

At the centre of Delft3D, is the FLOW module, which is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation code that calculates non-steady flow and transport phenomena, resulting from tidal and meteorological forcing on a curvilinear, boundary fitted grid, or spherical coordinates. In 3D simulations, the vertical grid can use sigma coordinates, or alternately, geopotential coordinates. Sediment transport is computed by the MOR module (for suspended and total bed load) and morphological changes for an arbitrary number of cohesive and non-cohesive fractions. Currents and waves are drivers for sediment transport. For suspended loads, this module includes advection-diffusion, so that density effects can be taken into account. An important feature of MOR is dynamic feedback between FLOW and WAVE modules, so that currents and waves can adjust to local bathymetry, allowing simulations on time scales from days (for storm impacts) to centuries (climate change impacts). Delft3D can keep track of the bed composition to build up a stratigraphic record. MOR can include features needed to simulate dredging and dumping scenarios.

Model Setup Calibration and Validation

(Section 2, pages 13-44; Section 3, pages 45-64)

Tides: Tidal motions are forced at the open boundaries of the model domain. Comparisons with observed water levels and tidal currents suggest that the model is performing well for tides.

Buoy wind data: The wind forcing used to drive the model consists of a uniform wind field derived from measurements at a local buoy. There is error in using buoy wind data measured at one single point, for example from Environment Canada (EC) buoys or the PNW buoy, rather than using detailed gridded atmospheric winds as driver fields, as DFO has advocated in the previous several, informal reviews. Gridded winds from a mesoscale atmospheric model, such as WRF (Weather Research and Forecasting) model can be constructed. The model is open source, can be downloaded from the internet, and has a user base of several thousand, worldwide. Regarding the former approach, namely the application of buoy winds, it is noted in Table 2-1, page 20, and in Section 10, page 203 that, "It was assumed that spatially uniform winds based upon local measurements at Holland Rock were more accurate than far field winds generated by climate models". No evidence was presented to support this statement. On the other hand, the assumption that there are "uniform winds" is bound to be invalid, given the complicated coastal topography and coastlines, with mountain ranges etc.

Buoy wave data: Wave direction data from NOAA WW3 is used at the outer boundary, plus wave heights from one buoy, (buoy 46205). Measurements at one single point cannot represent the variability of the wave field along the entire outer boundary of the wave model regional grid domain shown on page 17. The latter approach of using a single buoy for waves at the boundary is not the present standard for the waves research community. This approach, adopted by the Proponent, will result in errors; quantifying the magnitude of such errors would require further analysis and is beyond the scope of the present review. Nevertheless, evidence that the approach taken by the Proponent introduces errors is clear in the comparisons between model waves and buoy wave observations at buoy 46145 at Central Dixon Entrance, located about 50 km from buoy 46205 (pages 63-65). Notable errors in the model estimates for significant wave heights occur, sometimes by as much as 50%. Model estimates for peak wave periods also show notable errors. Suggesting that this is not important because the location is far from Flora Bank, and the PNW buoy is more representative of the location of the proposed LNG terminal ignores the fact that, in this study, the model is driven by buoy data at outer boundary points, and therefore should do well in comparisons with Buoy 46145. These errors lead to errors in the swell waves that impact Flora Bank and the area around the proposed marine structures.

Regarding the discussion of "Weekly Cases vs. Time Series Approach" in section 4.1, from the Pierson-Moskowitz relations; it is well known that the equilibrium wave state for 5m/s winds is a significant wave height (Hs) of about 0.6m. This is much less than the 4 m wave height suggested on page 28 of the analysis. This is a serious inconsistency in this test, as mean weekly winds of 5 m/s cannot generate mean weekly wind-generated waves of 4 m. Therefore, much of this wave energy must be swell; however, as noted above in the discussion on "buoy wave data", it is evident that the modelling approach does not reliably simulate swell waves.

River discharge: Skeena River discharge is introduced at a model open boundary as a discharge of low salinity water (10 ppt). Flow rates are scaled from values measured upstream from the mouth at Usk. Use of the scaled Usk flow rates is a reasonable approach to setting the Skeena River discharge into the model.

Stratification: The model is initially unstratified and salinity is set to a uniform value of 32 ppt. This implies the necessity of allowing the model to develop vertical stratification and lateral density gradients in response to discharge from the coast. In particular, a sufficient time for adjustment to the coastal runoff must then be allowed. Typically, such a time scale would be of the order of one year. Other forcings that stratify the water column were not included in the analysis, but given that freshwater discharge has the greatest influence on the nearshore density field, this omission is likely less significant.

Sediments: It is important to estimate how errors in winds and waves could influence, or generate errors in estimates for sediment transport. Page 38 describes erosion or deposition rates which vary linearly with τ, the bottom shear stress, which varies linearly with wind speed, or Hs2:

$$Erosion = M_l\left({}^{\tau}/_{\tau_{ce}} - 1\right)$$

A similar relation applies for deposition. Therefore, errors in wave height lead to at least double the errors in erosion or deposition rate. The estimated rate is $\sim H_S^2$, implying that a 10% error in waves yields a 20% error in erosion or deposition rates. Put another way, because the similarity scaling relates winds to waves^2, a 10% error in winds implies approximately a 40% error in sediment transport. More detailed discussion is presented by Natural Resources Canada, the lead for this topic.

Model Application- Present-Climate Storm Conditions

Long-term Simulations (Section 2.5.1 pages 23- 31)

To simulate the ocean response over a year, 52 integrations, each lasting for a 12.4 hour tidal cycle were run without interruption. The forcing in these runs consists of a ‘representative’ semi-diurnal tidal cycle, along with weekly averages of wave, wind and river forcings, with the averaging done sequentially over 52 consecutive weeks. This procedure was repeated five times. While the hydrodynamics in this procedure is integrated for a total of 134 days, fluxes of sediment to and from the sea bed are scaled by a factor, MORFAC, to accelerate the morphological evolution of the model. Based on this scaling factor, the simulations are said to represent a 5 year integration of the morphology.

The consequences of this approach are examined for each of the four main forcings that drive currents and suspended sediment in the model. This is followed by a comment on the use of MORFAC in the model.

Representative tidal cycle: By forcing with an ‘average’ or ‘representative’ tidal cycle (see Appendix D.1), the fortnightly modulation of sea level and tidal currents is eliminated. Thus the largest tidal currents, which occur during spring tides, are absent from the simulation. Since sediment transport is dominated by large or extreme events, elimination of the strongest tidal currents will bias the simulation, effectively underestimating the magnitude and frequency of the flows that are most likely to suspend and transport sediment. Similarly, the smaller neap tidal currents, which are most likely to allow sediment deposition, are also absent from the simulations.

Weekly averages of wind and waves: Weekly averaged fields are used for winds and waves. As with the approach taken for the tides, the largest currents associated with peak wind and wave events due to storms are eliminated by the averaging procedure. This results in the under-prediction of storm conditions such that currently most are likely to fall below the threshold that would suspend sediment. Wind speeds of 5m/s cannot generate severe sea-state conditions. Therefore, any study based on this approach essentially filters out storms and extreme events, underestimating or eliminating the states most likely to drive sediment transport.

River Discharge: Since the river discharge varies only gradually on a year-long time scale, the use of weekly-averaged flow rates is, in itself, unlikely to have much effect on the results. Nevertheless, as detailed in the next section, the river forcing, along with its associated sediment load is completely misrepresented in the so-called ‘long-term’ simulations.

Use of MORFAC: ‘MORFAC’ refers to a scaling parameter that can be used to accelerate morphological changes when using Delft3D. The manual for Delft3D explains the use of

MORFAC under two circumstances. The first is for the coastal ocean where tides are normally present. In this case, the hydrodynamic model is integrated using the time-dependent forcing seen by the ocean, and changes to the morphology are accelerated by the scale factor MORFAC. In this analysis, this is how a MORFAC factor greater than unity should have been used. The manual for Delft3D also mentions using MORFAC in a river application, where there is no periodic tidal forcing. In that case, the time evolution of the hydrodynamics is compressed. The manual mentions an example in which the variation in a river hydrograph that actually takes place over 20 days may be compressed into one that takes place over 2 days with MORFAC=10. The manual states that "for river applications, changing the morphological factor must be associated with changing all external time-varying forcings." It is also stated that "*For coastal applications only the overall simulation time should be adjusted*." [Emphasis added.] In situations where a river flow and tides are both present, the manual warns that the results may be difficult to interpret when using a morphological factor greater than unity.

The modelling approach adopted by the Proponent inappropriately utilizes the second type of application of MORFAC, in which the hydrodynamics are accelerated. In particular, contrary to the instructions given in the manual for coastal applications, the time varying forcing for the wind, waves and river discharge have been compressed in time such that 1 week of time is compressed into 12.4 hours. One consequence, for example, is that the annual variation in the discharge of Skeena River has been compressed into one that takes place over 26.9 days. Figure 2.9 of the report shows this compressed variation of the river flow. This representation of the river discharge is completely different from the actual time-varying discharge to which the ocean responds. There are several consequences resulting from this misrepresentation, including:

- Since the volume of freshwater discharged into the coastal ocean is the integral of the flow rate over time, the amount of freshwater entering the coastal waters will be drastically reduced from the actual discharge. In particular, it can be shown that for any given time period, it will be reduced to 7.4% of the actual freshwater discharge. Over the course of a year, the Skeena River discharges a total of 49.3 cubic kilometers of freshwater (Morrison et al, 2012). In contrast, the model predicts that about 3.6 cubic kilometres of freshwater is discharged over a period that is purported to represent a year.
- The amount of total suspended solids (TSS) deposited by the river into the coastal ocean over a given period is likewise drastically reduced to just 7.4% of its actual value.
- There is, in fact, no freshet river flow driving the model in the long-term simulations. A freshet is a period of sustained large river flow associated with snow melt. Empirical values for the Skeena River indicate this period lasts for about three months (May – July), and accounts for over half of the annual discharge (Morrison et al 2012). In the simulation, the model is forced with a rapidly varying river discharge for a total of 134 days. This is radically different than the time variation of the actual river discharge that drives the coastal ocean.
- Since the actual total simulation time is 134 days, the model ocean has insufficient time to adjust to the annual cycle of river discharge, or to seasonal changes in the overall coastal circulation. As a result of the insufficient adjustment time, the stratification and associated baroclinic flows are not properly established.
- The severe underrepresentation of the freshwater discharge is likely to have an impact on the currents over the study area. This is evident from the short test case conducted with the actual river discharge. This case shows that relatively modest changes to the river discharge can lead to appreciable changes in the currents over the study area (Figure 4-20). These results emphasize that it is important to model the river discharge properly.

- The severe underrepresentation of the release of total suspended solids from the river may have a significant impact on the deposition of sediment over the study area in the 'long-term' simulation. This calls into question all the results presented in Section 8.2 of Appendix B, as well as any conclusions regarding water clarity.

Spin-Up Time: For the hydrodynamic component of the Delft3D model, the spin-up time necessary to develop stratification is in the order of one year. A spin-up time of less than one year will underestimate local ocean stratification. In the case of modelling waves, the Delft3D spin-up procedure, which is 24.8 hours, is also not adequate for the SWAN model, for large intense storms. Based on several decades of DFO ocean wave research, a minimum of 48 hours, preferably 72 hours, should be allowed. When the spin-up time is too short, such as the one used in this study, the wave model estimates will be biased low, compared to observations collected at buoys.

Model Application- Extreme Storm Events

(Section 2.5.1 pages 23- 31 and Section 9 pages 182-202)

The rationale for considering weather extremes is that changes in extreme events can result in significant impacts to society and the environment. The Intergovernmental Panel on Climate Change (IPCC), (2007) suggests that in a changing climate, "… confidence has increased that some extremes will become more frequent, more widespread and/or more intense during the 21st century". Therefore, evaluation of the implications of weather extremes should be carefully considered because of the likelihood of occurring.

In this assessment, the proposed infrastructure is designed with the assumption that climate is stationary, with an unchanging mean state; even though it is widely accepted that climate change is occurring, and that climate means, variability and extremes may be changing. It is now common practice to design new infrastructures based on historical information on weather and climate extremes. To account for changing climate, the maximum value of a particular variable in the historical record, like winds or waves, is assumed to be the appropriate value for design. The World Meteorological Organization (WMO) recommends that "adaptation strategies to climate change should now begin to account for the decadal scale changes (or low-frequency variability) in extremes observed in the past decades, as well as projections of future changes in extremes, such as are obtained from climate models. Some types of infrastructure currently have little margin to buffer the impacts of climate change." (WMO, 2009).

In this analysis, extreme events are modelled by taking the 20-year time series for winds at the Holland Rock buoy, and applying standard Gumbel distribution methodology to estimate the extreme winds for desired return periods; for example 50-years, 100-years etc. These estimates for 50-year extreme winds are then used to 'scale-up' a present climate storm to an estimated intensity that appears to match the intensity of the 50-year winds at Holland Rock. However, this particular 'scaled-up' procedure does not in fact represent the 50-year extreme storm family very well for the Project area. The following outlines deficiencies or errors in the modelling presented:

- **Base Cases** (Page 182): Storm cases listed in Table 9-1 are quite weak. A longer time series of data is required, as is available at Holland Rock, in order to select more intense candidate storms. As indicted on page 183 of the report, the winds for extreme storms at Holland Rock are 33 m/s and 31.4m/s/ for 100 and 50-year returns, respectively. The modelling conducted uses winds much less than either of these known values.
- **100-year waves at Holland Rock**: As was calculated for winds (Figure 9-1), the 50-year wave, and the 100-year wave at Holland Rock should be modelled. This can be

calculated from the known buoy data as the record is long enough (20 years listed in Table 2-1).

- **The 50-year extreme storm** (Page 186): The artificial 'extreme' storm used by the proponent is very poorly constructed. The peak winds last only for 1 hour, and the direction is such that the marine structures have no sheltering effect on Flora Bank, i.e. they are downstream from Flora Bank, thus very little effect is seen on Flora Bank. Different storm configurations should be considered for the 'extreme' 50-year storm so that the most severe storm scenario can be tested, not the most gentle scenario. During the famous 'Perfect Storm' in the North Atlantic in 1991, peak waves were generated and developed over a 24 hour period, reaching 17m, and maintained at that maximum strength for about 6 hours. Peak winds also reached about 33 m/s for 6 hours during the storm, which are rather similar to what is conceivable to occur in the area being modelled, based on Figure 9-1.
- **Extreme event** (Page 188): The 'extreme' storm case that is presented is not complete. The orientation of the artificial case should have several scenarios, including the cases where the waves pass Flora Bank first, then the marine structures second; and vice versa, with waves hitting the marine structures first, then Flora Bank, second, etc. The latter cases would show the impact of the marine structures on the Flora Bank area. The extreme storm cases should also consider storms where uniform winds are blowing at various angles with respect to the marine structures, Flora Bank and Agnew Bank, and holding steady for at least half a day, or more, and include simulations with, and without, the marine structures to see the full effects of the marine structures on the surrounding region. Model runs should show the full possible effects. Winds should be at the 50-year return levels, at least, and ideally also include 100-year return levels.
- **Morphology** (Pages 198-202): The effect of extreme storms on morphology is modelled so that the minimal possible effect of the marine structures is tested, rather than cases where the marine structures can effect Flora Bank (see details above)

Representation of Marine Structures and their effects

(Section 2.6, Pages 33 – 37)

The marine structures that are proposed to be installed on the seabed adjacent to Flora Bank consist of an anchor block and a tower that will support a suspension bridge, and a series of trestle bents arranged along the length of a trestle. There is also the berth for ships to dock, which will be supported by a set of piles. The anchor block is easily the largest of the structures, with dimensions of 45 metres x 44 metres, while the dimensions of the tower are 20 metres x 36 metres. Both will extend through the water column. The trestle bents consist of piles of 1.2 metre diameter. The number of piles in each trestle bent is not mentioned.

Due to the relatively coarse resolution of the model (from 1000 to 60 metres), all of the structures are smaller than the grid spacing. Accordingly, they have been parameterized in the model as 'porous plates', which is one of the options available in DELFT3D to represent sub-gridscale structures. Drag coefficients must be specified for each of the porous plates. In this regard, a fractional reduction in the flow rate through a grid cell containing a porous plate (the 'permeability') is assumed based on the dimensions of the structure relative to the grid scale. A drag coefficient for the porous plate is then specified to achieve this assumed permeability.

The following are some observations regarding the modelling of the marine structures:

- The use of porous plates seems warranted in cases of the trestle and the berth which are both extended linear structures. For these structures the supports are small and widely spaced and the assumed permeability of 90% seems reasonable.

- A set of auxiliary experiments in an idealized setting (a model of a canal) were conducted to calibrate the drag coefficient of the porous plates to obtain the required permeability. While such experiments are useful as a guide to setting the drag coefficient, no information is given as to whether the desired permeability is actually achieved in the regional model.
- There should be drag specified in both of the horizontal coordinate directions, at least for the anchor block and tower. No specific information is given, but the fact that only a single drag coefficient is specified for each suggests that this is not the case.
- In the case of the anchor block and the tower, flows impinging on such large structures will be blocked on the upstream side and accelerated along the sides of the obstacle. At the trailing edge there will be boundary layer separation and a turbulent wake in the lee of the structures. Given the proximity of the proposed structures to Flora Bank, the jet-like flows and vortices that will be shed in the lee of the structure can be expected to impinge on the sides of the Bank during flood tide. There is potential for these energetic flows to scour the Bank.
- The relatively coarse resolution of the model (which necessitates the porous plate parameterization) is problematic for modelling the effect of the two large structures (the anchor block and the tower), and it is far from clear whether the effects of these structures is adequately represented. In particular, it is likely that the model is unable to adequately resolve the strong flows and shear generated in the lee of the structures. The turbulent flows and vortices that will be shed in the lee of the anchor block and tower are probably absent in the simulations, and the jet-like separated flows are bound to be more diffuse than in reality. All of this is likely to bias the results to underestimating the effects of these large structures. The obvious remedy for these problems would have been to conduct simulations that are of locally much higher resolution (perhaps in a nested model) in which the marine structures and turbulent flows are explicitly resolved.
- It is evident from several of the figures in the Report (e.g., Figure 5-10, 5-14) that some of the largest perturbations to the currents in the model are due to the anchor block and the tower. This emphasizes the need to represent the influence of these two structures accurately since they seem to have most importance.

Conclusions

DFO Science has previously conducted four reviews and provided feedback on draft analyses conducted by the Proponent on the baseline hydrodynamic regime, and the potential changes that may occur as a result of the installation of marine structures near Flora Bank. Many of the deficiencies and problematic aspects of the analyses noted in these previous reviews remain unaddressed in the final Appendix B: Pacific Northwest LNG – 3D Modelling of Potential Effects of Marine Structures on Site Hydrodynamics and Sedimentation. This review has again identified numerous and significant deficiencies and errors in the modelling procedures, input data, and assumptions, as well as in the assessment of uncertainties. Therefore, the results and conclusions presented in the Proponent’s analysis are not substantiated. Given the nature of these deficiencies, it is likely that the magnitude and extent of the impact of the marine structures is underestimated.

The following are the main observations and conclusions of this review:

- In the ‘long-term’ simulations, the model is driven by a ‘representative’ tide, along with weekly-averaged winds, waves and a river discharge in which the annual cycle is compressed into a 26.9 day period. This modelling procedure is of doubtful validity, and at variance with instructions given in the manual for the model. In the case of the river discharge, it is demonstrably incorrect.

- The weekly averaging of the winds and waves eliminates the peaks in these forcing fields associated with the passage of storms, while use of a representative tide eliminates the largest tidal currents associated with spring tides. As a result, the likelihood of exceeding the critical threshold for sediment suspension and transport is underestimated in the model. As well, elimination of neap tides reduces the likelihood of meeting the threshold for sediment deposition.
- The volume of freshwater and amount of suspended sediment discharged from the Skeena River into the coastal ocean is severely underrepresented in the model. This will lead to an underestimation of the buoyancy-driven circulation, as well as of the total suspended solids (TSS) in the water column. This observation casts considerable doubt on the assessment made regarding the impact of changes in the distribution of total suspended solids and in water clarity.
- The ‘spin-up’ time allowed for the circulation driven by waves, winds and (especially) the buoyancy forcing to become established is too short. As a result, these motions are likely underrepresented. Similarly, the spin-up time allowed for the wave-module in Delft3D, per se, is too short, and would likely result in wave simulation estimates that are biased low.
- The anchor block and tower are, by far, the largest of the marine structures the Proponent proposes to install. Despite their large size (44m by 45m in one case), the grid resolution of the model is insufficient to explicitly represent these structures, and they are instead parameterized as porous plates. As a result, the model does not properly represent the acceleration of the flow that will occur on the sides of these blocks. The resolution of the model is also insufficient to represent properly the downstream turbulent wake and separated flows on either side of the anchor blocks, and the vortices generated by these anchor blocks that will be shed downstream and interact with Flora Bank. There is potential for these energetic flows to scour the sides of Flora Bank, but it is not possible to assess the extent to which this will occur based on the reported simulations.
- The analysis does not adequately consider an extreme storm for the 50-year return period, or an appropriate set of 50-year extreme storms, thereby underestimating the potential impact of the installation of marine structures on the surrounding environment. Although the Proponent does estimate the 50-year and 100-year winds at the Holland Rock buoy, based on 20 years of observed data, and application of standard extremal analysis, applying the well-known Gumbel distribution relation for the wind data, several of the other conditions needed to estimate extreme 50-year extreme storm impacts are scaled back or not explored. In particular, the analysis only considers a storm propagation direction that orients the marine structures downstream from Flora Bank, thus making it essentially impossible for the marine structures to impact Flora Bank. In addition, to fully explore the maximum severity of possible 50-year extreme storms, the duration of the maximum storm-generated winds should be modelled for multiple hours not one hour, for example half a day, and the winds considered at the known maxima, not scaled back by 15%, as in the current analysis.

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Sources of information

Hatch, 2015. Pacific Northwest LNG – 3D Modelling of Potential Effects of Marine Structures on Site Hydrodynamics and Sedimentation. H345670-0000-12-124-0012, Rev.0

Intergovernmental Panel on Climate Change, 2007. IPCC Fourth Assessment Report: Climate Change 2007. (Accessed 19 May 2015)

Morrison, J., M. G. G. Foreman & D. Masson. 2012. A Method for Estimating Monthly Freshwater Discharge Affecting British Columbia Coastal Waters. Atmosphere-Ocean, 50:1, p.1-8.

Stantec Consulting Ltd., 2013. Pacific Northwest LNG Technical Data Report – Marine. Project No. 1231-10537.

World Meteorolgical Organization. 2009. Guidelines on Analysis of extremes in a changing climate in support of informed decisions for adaptation. Climate Data and Monitoring WCDMP-No. 72. (Accessed 19 May 2015)

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