Oil Spill Trajectory Modeling Report in Burrard Inlet for the Trans Mountain Expansion Project

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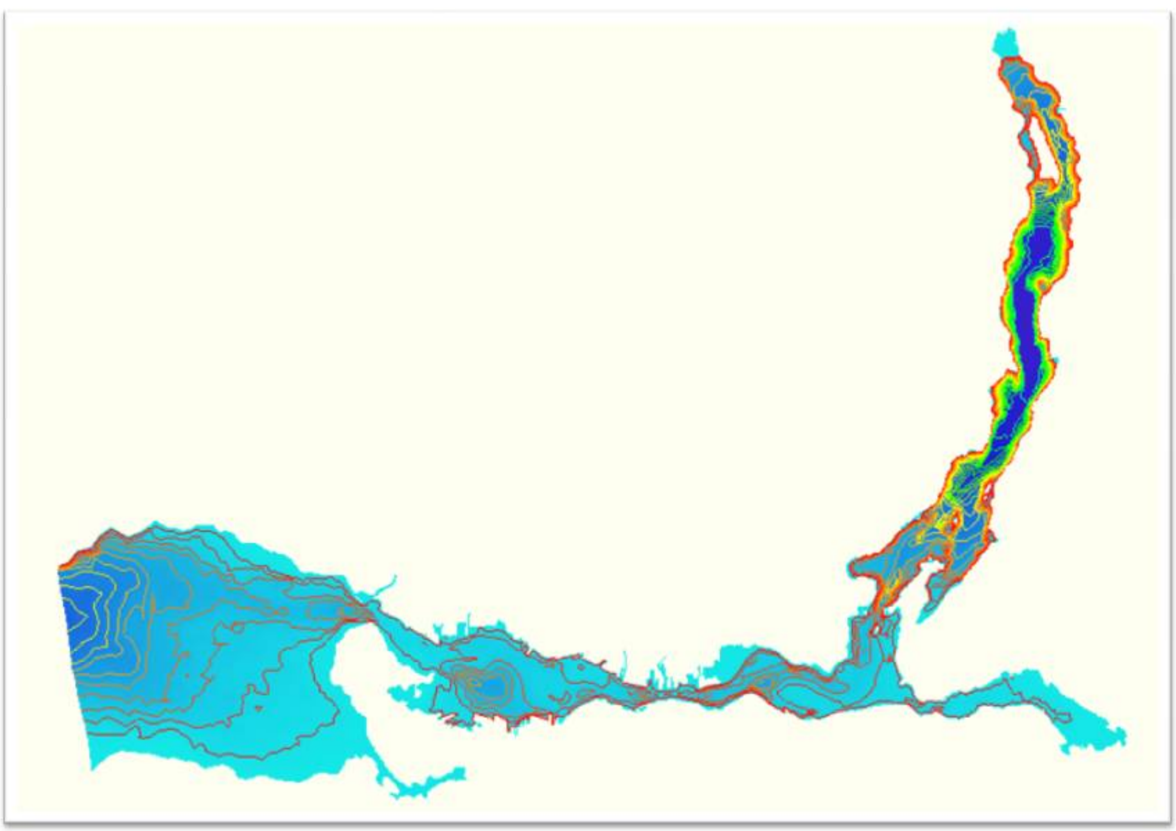

GENWEST TECHNICAL REPORT #15-03

Prepared under contract for Gowlings Lafleur Henderson LLP Reference File No. V40693

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1.0 EXECUTIVE SUMMARY

Genwest Systems Inc. ("**Genwest**") was retained by Gowling Lafleur Henderson LLP ("**Gowlings**") on behalf of the Tsleil-Waututh Nation, City of Vancouver, and the City of Burnaby (the "**Partners**") to prepare an expert report on oil spill trajectory modeling in Burrard Inlet for the Trans Mountain Expansion Project ("**Project**"). In particular, Genwest was asked to: (1) do a peer review of the marine oil spill modeling completed by Trans Mountain; (2) develop and calibrate an oil spill trajectory model for Burrard Inlet; (3) model four oil spill scenarios in Burrard Inlet; and (4) develop modeling approaches to model the trajectory of potential oil spills in Burrard Inlet.

1.1 PEER REVIEW OF THE OIL SPILL MODELING COMPLETED BY TRANS MOUNTAIN

We conducted a peer review of the oil spill modeling completed by Trans Mountain and its consultants, which Trans Mountain included, and relied upon, in its application to the National Energy Board for the Project. In general, Trans Mountain's modeling effort does a reasonable job of representing potential oil spill trajectory over most of the Salish Sea. However, we identified at least two serious shortcomings which have significant implications for oil spill trajectory modeling in Burrard Inlet: (i) the model used by Trans Mountain—SPILLCALC, which we will refer to as the "**Trans Mountain Model**"—does not allow for refloating of beached oil; and (ii) Trans Mountain's consultant made unrealistic modeling scenario assumptions to model oil spill trajectory at the Westridge Marine Terminal (the "**Terminal**").

The most serious shortcoming appears to be with the beaching algorithm in the Trans Mountain Model, which does not allow refloating. This occurs because of the parametric "holding capacity" of the shoreline: the algorithm in the Trans Mountain Model simply removes all beached oil from any additional movement and spreading. *This is strongly contradicted by experience with thousands of real spills*. Heavily oiled shoreline tends to be rewashed, particularly by tidal action in areas of rocky shorelines or man-made structures. In these areas, stranded oil is not removed, but simply retained for some number of tidal cycles. The shorelines then act as a secondary source where previously stranded oil is moved away from the shorelines by a new set of trajectory processes.

The failure to allow refloating to occur could lead to significant underestimates of both the extent and duration of concern associated with a spill. In particular, this shortcoming would be more significant in scenarios representing spills in Burrard Inlet and the Fraser Delta.

Another very serious shortcoming arises as a result of the unrealistic modeling scenario assumptions that Trans Mountain's consultant made to model oil spill trajectory at the Terminal. The scenario developed in the "Modeling the Fate and Behavior of Marine Oil Spills" for the Project report unrealistically represents the size of the spill as the excess capacity of the local booming strategy of the Terminal facility. In particular, the scenario data presented in Table 8.1.2 of the report are very misleading and reflect some significant constraints placed on the initial assumption used to define the spill. The Trans Mountain Model results show the spill trajectory problem stabilizes with a nearly constant amount of shoreline oiled with virtually no oil still moving around via transport processes. This occurs even though more than half the oil is still floating on the water. The reason for this odd behavior is the unreasonable assumption that the containment boom is always in place and always works. A significant fraction of the spill is never released to the trajectory transport process. This assumption is unrealistic given effects of wind, tidal eddies, and terminal boating activities. The effect of this assumption is that spill trajectory model is processing a "hypothesized" much smaller spill. For planning purposes a containment boom is a good idea and is bound to help. But to assume it will be 100% effective is not appropriate from an oil spill trajectory modeling perspective and is not the historical norm.

1.2 OIL SPILL TRAJECTORY MODEL FOR BURRARD INLET

We used version 1.3.9 of the General National Oceanic and Atmospheric Administration ("**NOAA**") Operational Modeling Environment ("**GNOME**") to model oil spill trajectories in Burrard Inlet. GNOME is a well-recognized and leading 2D numeric oil spill trajectory model that is used daily by NOAA and other regulatory agencies all over the world to model oil spill trajectories to inform spill response-planning, and statistical risk analyses. In particular, GNOME has been used in many high profile major oil spills, including the Exxon Valdez, Cosco Busan, and Deepwater Horizon oil spills, among others.

GNOME is an appropriate model to use to model oil spill trajectory in places like Burrard Inlet because it (i) is specifically designed as an oil spill trajectory model rather than a hydrodynamic model with a superimposed oil behaviour module, (ii) has been used successfully in response to thousands of real oil spills, (iii) is designed to be adapted to local environmental conditions, (iv) serves as the core for a number of planning and analysis tools, and (v) is in the public domain and therefore its internal processes are transparent and subject to review.

We developed and calibrated three components to model oil spill trajectories in Burrard Inlet that run in GNOME. **Burrard Inlet Model A** and **Burrard Inlet Model B** include the geographic area in Burrard Inlet up to a western boundary in the Outer Harbour. The key differences between those models are: (i) Model A has current models associated with a tidal station at First Narrows based on tidal data from January 1, 2004 through December 31, 2014, whereas Model B has current models associated with that tidal data from January 1 through December 31, 2005; (ii) Model B has current models associated with observed wind patterns in Burrard Inlet (based on data from January 1, 2005 to December 31, 2005) whereas Model A does not; and (iii) Model A has current models associated with discharges from rivers and streams into Burrard Inlet whereas Model B does not.

A third model, the **Regional Model**, includes currents (from August 18 to September 1, 2007) from a simulation using the Salish Sea Model (which covers the Salish Sea from the western end of the Strait of Juan de Fuca into the Strait of Georgia, including a part of the Outer Harbour in Burrard Inlet) that has within it the Burrard Inlet Model A.

We used commonly accepted modeling techniques to create new, or calibrate existing, current models based on the following geophysical and meteorological conditions in Burrard Inlet: (i) Kelvin wave; (ii) tidal flow; (iii) river outflows; (iv) interaction between wind and oil; (v) beaching and refloating of oil; and (vi) local wind patterns. Where possible or appropriate, we compared modeled results with predicted or observed current patterns in Burrard Inlet. Where necessary, we calibrated current models to more accurately represent observed or predicted current patterns in Burrard Inlet.

1.3 Four oil spill scenarios modeled in Burrard Inlet

We modeled oil spill trajectories from four oil spill scenarios in Burrard Inlet: (i) an oil spill of 8,000 m^3 at the Terminal; (ii) an oil spill of 16,000 m^3 at Second Narrows under the Canadian National Railway Bridge; (iii) an oil spill of 16,000 m^3 at First Narrows; and (iv) an oil spill of 16,000 m^3 in the Outer Harbour at Anchorage #8.

In another expert report prepared for Tsleil-Waututh Nation and the City of Vancouver, Nuka Research determined that the above-noted spill volumes represent reasonable worst case scenarios for oil spills at the four sites.

For each scenario: (i) we modeled an oil spill trajectory in a step-wise manner by initially starting with only one physical transport process (tidal currents), and then adding a constant wind, and then using observed winds and tides. This approach was used to describe the sensitivity of the model to various processes and numerically explore implications; (ii) we assumed that no weathering, clean up, or other mitigation occurred.[1] All of the released oil was tracked in the output (this approach is conservative in that it provides a consistent picture of the potential extent of spread of oil in Burrard Inlet); and (iii) we used 8,000 splots[2] in GNOME to represent the volume of oil released during the spill. Reasonable statistical coverage of an oil spill modeled for a few days can be achieved by using 8,000 splots in GNOME.

Based on the four scenarios evaluated in this report, we conclude that:

(a) Oil spreads quickly in the confined geophysical setting in Burrard Inlet. The combined results of all the scenarios demonstrate that oil has the potential to spread throughout Burrard Inlet, from the Indian and Port Moody Arms to the Outer Harbour and beyond.

For example, Figure 11, reproduced below, shows the results of an oil spill at Second Narrows using modeled real winds and tides at 6, 12, 24, 48, and 96 hours into the spill:

[1] I understand that the Partners' other experts have addressed these issues.
[2] A splot is a surrogate floating oil particle that is tracked and represents a statistical fraction of the spill scenario.

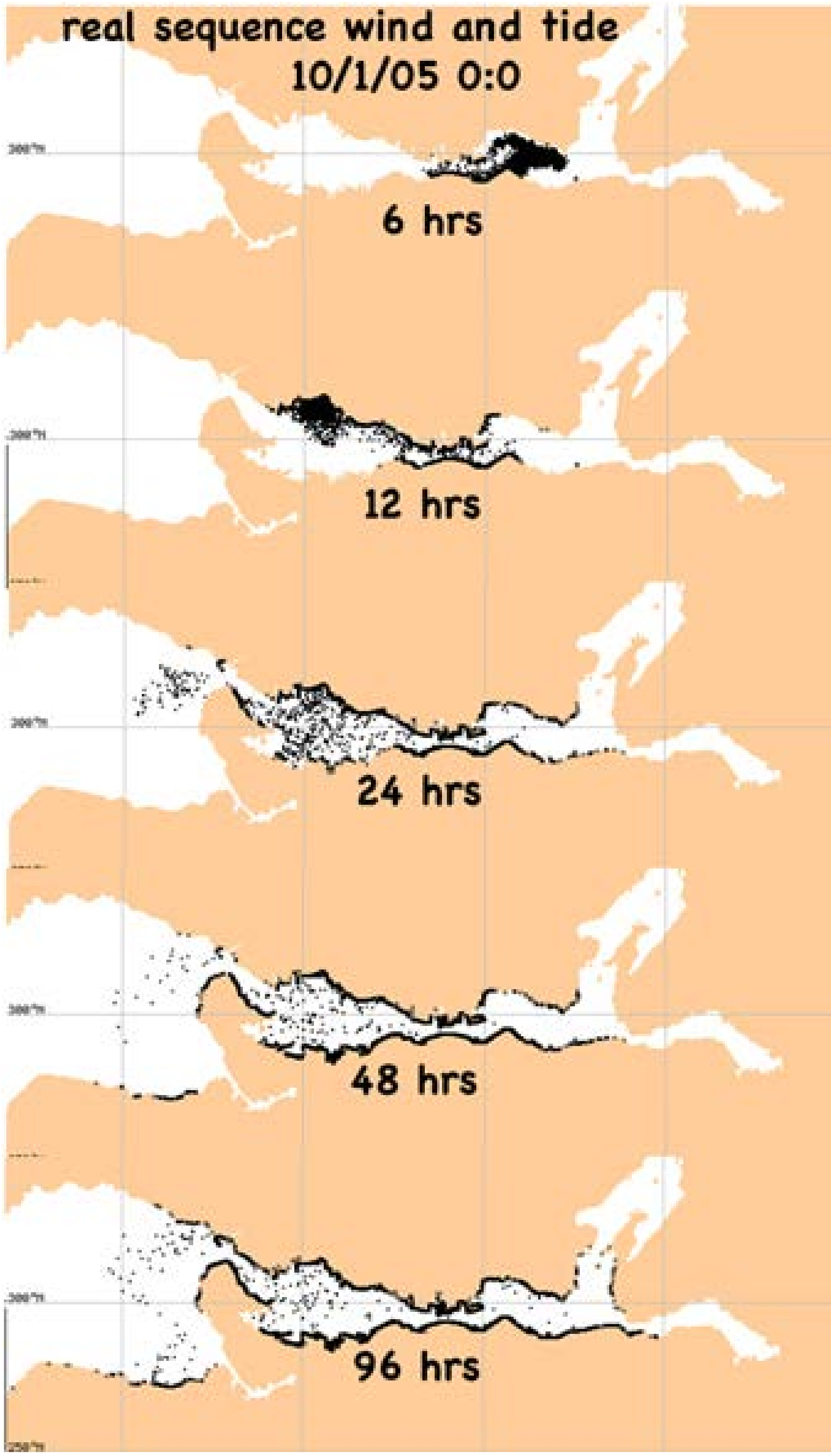

Figure 11: Results of an oil spill at Second Narrows using modeled real winds and tides

Winds varied considerably in this run. Early on during the first day of the spill, the winds moved the spill north, which led to very heavy oiling along the northern shore of the Inner Harbour. Later on, the winds refloated oil and moved it south impacting the Inner Harbour waterfront in Vancouver. Some patches of oil also moved west past First Narrows where they became stranded on the shoreline of the Outer Harbour.

Results generated using the Regional Model to model an oil spill in the Outer Harbour at Anchorage #8 show how significant amounts of oil spilled in the Outer Harbour can be transported away from Burrard Inlet, into the Strait of Georgia, and south in the Salish Sea to Turn Point, the San Juan Islands in the United States, and beyond. Figure 19, which is reproduced below, shows the oil spill trajectory of an oil spill in the Outer Harbour after 48 and 96 hours:

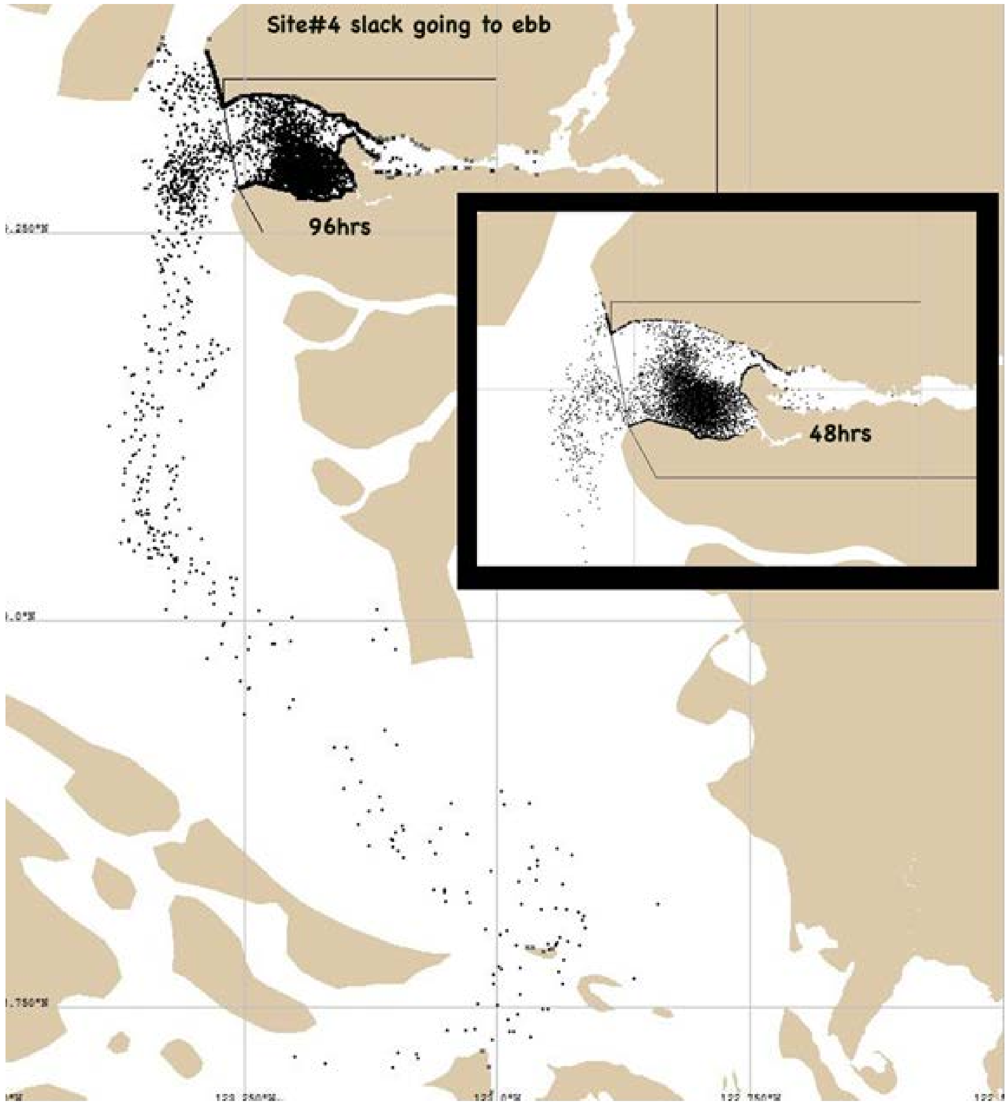

Figure 19: Oil spill trajectory time sequence in the Outer Harbour for "slack going to ebb" starting on August 19, 2007 at 01:20

(b) Continuous spills will spread more broadly throughout Burrard Inlet than instantaneous spills.

(c) Winds and tides are the major drivers of oil movement in Burrard Inlet. Variations in release time and tidal phase are important factors to consider when developing realistic oil spill scenarios. Oil spill trajectory can be more accurately modeled when tidal phase and wind events are linked.

(d) Strong winds tended to strand oil on the leeward shore, while weak winds allowed the tidal currents to more widely distribute the oil. When strong winds weakened, the oil tended to refloat and move some distance with the tidal currents. Stranding, refloating and restranding oil is a cyclical aspect of predicting oil spill behavior that is well captured in the Burrard Inlet and Regional Models.

(e) Adequate tidal data is available for Burrard Inlet. We used that data to develop the Burrard Inlet Models. However, a limited amount of empirical data on local wind behavior is publicly available. To address that issue, we used the CALMET data set to simulate the complex patterns of wind flow through the Inlet and its arms. Our simulation captured over 80% of the variability in speed and direction. We included current models associated with those wind patterns in Burrard Inlet Model B. This was an improvement which provides greater confidence for scenario results modeled in 2005.

(f) In general, the initial conditions at the spill site influenced how the spill behaved. However, after 24 hours, or two tidal cycles, the results of the scenario runs at the Terminal and Second Narrows tended to converge. This was not the case for the scenario runs at First Narrows and the Outer Harbour.

Because of the closer proximity of First Narrows and the Outer Harbour to the influence of the Strait of Georgia, the initial tidal phase led to qualitatively different four day outcomes. Oil spill trajectory at First Narrows, as a result of its strong and variable tidal currents, did not conform to a single dominant pattern.

Oil spill trajectory at the Outer Harbour was also qualitatively very different from the other sites. This was in part caused by the influence of the Fraser River outflow and predominant current patterns in the Strait of Georgia captured in the Regional Model. Oil spill trajectory was significantly influenced by the Fraser River outflow and currents in the Strait of Georgia as captured in the SSM Map.

We also developed a “stochastic” modeling approach that involves combining ten (10) random start times to capture the expected range of possible results. The environmental conditions influencing oil spill trajectory captured by this approach is the average of ten different random and independent scenarios modeled as an ensemble. We tested, and confirmed, that a randomly chosen sample size of ten start times provides a realistic representation of expected zones that would be threatened by an oil spill in each release scenario.

Our stochastic modeling also shows that: (i) a significant portion of Burrard Inlet is potentially threatened by oil spills at the Terminal, Second Narrows, and First Narrows (we did not use the stochastic modeling approach at the Outer Harbour site); (ii) a substantial amount of oil was beached; and (iii) the highest probability regions for floating oil disappear relatively quickly (because most of the oil is at least temporarily on beaches) but that oil in areas subject to lower, but still significant, percentages of the spill tends to spread covering many tens of square kilometers.

1.4 Use of the Burrard Inlet Models and the Regional Model to model oil spill trajectory in Burrard Inlet

Burrard Inlet Model B and the Regional Model provide a realistic representation of the behavior of oil spills in Burrard Inlet. They can therefore be used to realistically evaluate the possible extent of oil spread resulting from a spill at the Terminal, Second Narrows, First Narrows, and the Outer Harbour locations.

We have been informed that: (a) the Partners will be using the Models to model oil spill trajectory in Burrard Inlet arising from potential oil spills at the four sites (Terminal, Second Narrows, First Narrows, and the Outer Harbour) examined in this report; and (b) the purpose of that modeling is to generate information required to assess (i) oil spill response capacity and gap analysis, (ii) the fate and behaviour of oil spilled into Burrard Inlet, (iii) the ecological, socio-economic, and human health effects of oil spills in Burrard Inlet, and (iv) emergency response planning and public safety in relation to the Project.

We have provided instructions to the Partners that set out the appropriate modeling approaches and methods to do this modeling work.

2.0 INTRODUCTION

2.1 SCOPE OF WORK

Genwest was retained by Gowlings on behalf the Partners to prepare this report on oil spill trajectory modeling in Burrard Inlet for the Project. In particular, Genwest was asked to:

1. review and assess the oil spill trajectory modeling in Burrard Inlet completed by Trans Mountain in its application to the National Energy Board for the Project;

2. develop and calibrate an oil spill trajectory model for Burrard Inlet;

3. model four oil spill scenarios in Burrard Inlet;

4. provide the Partners with the software, location files, and all associated data, files and other information required to independently run the model; and

5. develop modeling approaches and methods to model the trajectory of potential oil spills in Burrard Inlet originating from the Project to generate information required to assess: (i) oil spill response capacity and gap analysis; (ii) fate and behaviour of oil spilled into Burrard Inlet; (iii) the ecological, socio-economic, and human health effects of oil spills in Burrard Inlet; and (iv) emergency response planning and public safety in relation to the Project.

2.2 QUALIFICATIONS

Dr. Jerry Galt, the author of this report, is a leading international authority in the field of oil spill trajectory modeling. Dr. Galt supervised the NOAA Hazardous Materials Response Division ("**HAZMAT**"). During his time at NOAA, Dr. Galt directed a multi-disciplinary scientific program that combined theoretical research and real-time computer applications at accidental oil spill scenes. Dr. Galt has directed the computer modeling component to inform and guide responses at over one thousand (1,000) oil and chemical spill responses during his distinguished career. Dr. Galt led the oil spill trajectory modeling analysis at the Amico Cadez, Exxon Valdez, Argo Merchant, and First Gulf War, and contributed to the Cosco Busan and Deepwater Horizon, oil spills, among others.

Dr. Galt has extensive expertise in all aspects of oil spill trajectory modeling, including computerized data systems, oil spill response, and oceanographic modeling. In particular, Dr. Galt:

- directed the development of NOAA's Oil Spill Simulation Model ("**OSSM**"), which is an oil spill trajectory model that simulates oil movement caused by winds, currents, tides, and spreading. NOAA's HAZMAT division used OSSM to estimate spill trajectories during oil spill responses in the United States; and

- led the development of the GNOME, which is a modernization of OSSM.

Since 2006, Dr. Galt has been a member of the Modeling Review Board of the Department of the Interior, Minerals and Management Service (which subsequently became the Bureau of Ocean Energy Management, Regulation and Enforcement and the Bureau of Safety and Environmental Enforcement). The Board is a national level centre for expertise to advise the Department of Interior on its oil and gas development issues. Dr. Galt has provided that Board with ongoing advice in relation to ocean modeling on a number of projects.

Dr. Galt holds a PhD in Physical Oceanography and Geophysical Fluid Dynamics from the University of Washington. He is the author of many leading peer-reviewed articles, reports, and book chapters in relation to oil spill trajectory modeling.

Dr. Galt is currently the Chief Oceanographer at Genwest. A copy of his CV is attached as **Appendix "A"**.

2.3 EXPERT'S DUTY

This report has been prepared in accordance with Dr. Galt's duty as an expert to assist: (i) the Partners in conducting its assessment of the Project; (ii) provincial or federal authorities with powers, duties or functions in relation to an assessment of the environmental effects of the Project; and (iii) any court seized with an action, judicial review, appeal, or any other matter in relation to the Project. A signed copy of Dr. Galt's Certificate of Expert's Duty is attached as **Appendix "B"**.

2.4 ASSUMPTIONS

Gowlings asked Genwest to model the following oil spill scenarios in Burrard Inlet:

(a) an oil spill of 8,000 m^3 at the Westridge Marine Terminal;

(b) an oil spill of 16,000 m^3 at Second Narrows under the Canadian National Railway Bridge;

(c) an oil spill of 16,000 m^3 at First Narrows; and

(d) an oil spill of 16,000 m^3 in the Outer Harbour at Anchorage #8.

I have reviewed relevant sections of the expert report prepared by Nuka Research in which Ms. DeCola concludes that the volumes of oil set out above represent credible worse case scenarios for oil spills at the respective sites.

We created or used the following data to develop the GNOME model described in this report:

- Tidal data for Burrard Inlet from January 1, 2004-December 31, 2014;[3]

[3] We derived the tidal data from a NOAA SHIO (tide) application for the current station at First Narrows.

- Meteorological (CALMET) data for Burrard Inlet from January 1, 2005 to December 31, 2005;[4]
- Shoreline data for Burrard Inlet;[5] and
- Current data for Burrard Inlet.[6]

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[4] Metro Vancouver produced detailed three-dimensional meteorological fields using the diagnostic computer model CALMET, based on surface weather data, digital land use and terrain data, and prognostic meteorological model output based on the NCAR / Penn State Fifth Generation Mesoscale Model (MM5). Metro Vancouver then provided those meteorological fields to Genwest.
[5] We hand digitized the location of the shoreline in Burrard Inlet based on aerial photographs obtained from ESRI.
[6] We derived the current data using NOAA's CATS models (application build 663 August 2014).

3.0 BACKGROUND ON OIL SPILL TRAJECTORY MODELS

Large oil spills are infrequent events and most areas, including Burrard Inlet, do not have sufficient empirical evidence that describe past incidents or accidents which can be used to predict future oil spill behavior. Under these circumstances, it is necessary to use numeric oil spill trajectory modeling to estimate how potential oil spills will behave.

Oil spill trajectory modeling is a well-developed field that is widely used to understand, plan for, respond to, and statistically estimate risk associated with both potential and actual oil spills.

Oil spill trajectory models are either two-dimensional ("**2D**"), where many of the hydrodynamic parameters are averaged over the water column, or three-dimensional ("**3D**"), where vertical variability is explicitly calculated by the model. 2D models are commonly used by lead regulatory agencies worldwide in oil spill response, planning, and statistical risk analyses. They are simpler to implement and are commonly used where the behaviour of oil spills at the water surface is the primary concern.

4.0 REVIEW AND ASSESSMENT OF OIL SPILL TRAJECTORY MODELING COMPLETED BY TRANS MOUNTAIN

We conducted a review of the oil spill trajectory modeling completed by Trans Mountain, which it included, and relied upon, in its application to the National Energy Board for the Project. Our peer review was based on our review of the following two reports:

- Modelling the Fate and Behavior of Marine Oil Spills for the Trans Mountain Expansion Project – November 2013, issued for use, EBA File: V13203022 [NEB Exhibit No. B21-9 to B23-28, TR-8C-12, TR S9, A56029, A56026, and A56027]; and

- Westridge Marine Terminal 2013 Interim Meteorological Report, November 2013, issued for use, EBA File: V13203055 [NEB Exhibit No. B20-21, TR-8C-8, TR S5, A3S474].

Our review was somewhat augmented by my discussions with Dr. Jim Stronach, who I understand played a role in developing the oil spill trajectory model used by Trans Mountain, about the background modeling efforts that contributed to that model.

Our detailed review is set out in **Appendix "C"**.

In general, the Trans Mountain modeling effort is a 3D complex coupled hydrodynamic—spill trajectory set that does a reasonable job of representing potential oil spill behavior over most of the Salish Sea, subject to the general limitation that it has problems resolving all of the non-linear complexity associated with the Gulf and San Juan Islands, and Puget Sound. Representation of extended forecast scenarios by the Trans Mountain Model therefore lacks detailed accuracy.

There are, however, some serious limits to the: (i) trajectory algorithms in SPILLCALC, which I will refer to as the "**Trans Mountain Model**", and (ii) modeling scenario assumptions made by Trans Mountain's consultant. These limits will likely lead to significant misrepresentations in the final trajectory analysis results.

4.1 LIMITS TO TRAJECTORY ALGORITHMS

The most serious shortcoming appears to be with the beaching algorithm in the Trans Mountain Model, which could lead to significant underestimates of both the extent and duration of concern associated with a spill. In particular, this shortcoming would be more significant in scenarios representing spills in Burrard Inlet and the Fraser River.

Briefly, the Trans Mountain Model's approach to beaching processes significantly weakens the accuracy of the results of the trajectory analysis. It does not allow for refloating. This occurs because of the parametric "holding capacity" of the shoreline. The algorithm in the Trans Mountain Model simply removes all beached oil from any additional movement and spreading. *This is strongly contradicted by experience with thousands of real spills*. Heavily oiled shoreline tends to be rewashed, particularly by tidal action in areas of rocky shorelines or man-made structures. In these areas, stranded oil is not removed, but simply retained for some number of tidal cycles. The shorelines then act as a secondary source where previously stranded oil is moved away from the shorelines by a new set of trajectory processes. In the early history of oil spill trajectory analysis (when trajectories were done by people, not models), it was commonly assumed that oil was sort of like a tennis ball, you got about 3½ bounces against shorelines (with each "bounce" leaving residual oil on the shoreline). This is particularly true in a river environment where proximate shoreline is the rule. Moreover, rivers that flow through built up urban areas are particularly prone to rewashing, trapping oil under piers and repeatedly providing secondary sources to extend the trajectory analysis problem in both time and space. Numerous spills in San Francisco Bay have demonstrated this sort of behavior.

A second potential shortcoming of the Trans Mountain Model is the use of a smaller than normal wind drift factor. The actual hydrodynamic resolution of the very thin surface shear layer is not reported. There is no explicit mention of Stoke drift or Langmuir circulation components and it seems likely that the scenarios presented (using a 1% drift factor) may underestimate the coupling between oil movement and local winds. For example, NOAA modeling for emergency response defaults to random values of wind drift between (1-4½%). This could lead to fairly large differences in estimated trajectories, particularly when compounded against beaching and refloating algorithms. Overall this could lead to a quite different set of threatened areas and resources.

4.2 Limiting assumptions of modeling scenario

The Terminal scenario developed in the Modeling the Fate and Behavior of Marine Oil Spills for the Trans Mountain Expansion Project report unrealistically represents the size of the spill as the excess capacity of the local booming strategy of the facility. In particular, the scenario data presented in Table 8.1.2 of the report are very misleading and reflect some significant constraints placed on the initial assumption used to define the spill. The results show the spill trajectory problem stabilizes with a nearly constant amount of shoreline oiled with virtually no oil still moving around via transport processes. This occurs even though more than half the oil is still floating on the water. The reason for this odd behavior is the unreasonable assumption that the containment boom is always in place and always works. A significant fraction of the spill is never released to the trajectory transport process. This assumption is unrealistic given effects of wind, tidal eddies, and terminal boating activities. The effect of this assumption is that spill trajectory model is processing a "hypothesized" much smaller spill. For planning purposes a containment boom is a good idea and is bound to help. But to assume it will be 100% effective is not appropriate from an oil spill trajectory modeling perspective and is not the historical norm.

5.0 OIL SPILL TRAJECTORY MODELING IN BURRARD INLET

5.1 GEOPHYSICAL SETTING

Burrard Inlet is a geophysically complex, fjord-like embayment. It is comprised of (i) a western entrance called the Outer Harbour, (ii) an Inner Harbour adjacent to the City of Vancouver, (iii) a Central Harbour adjacent to the City of Burnaby, (iv) Port Moody Arm, and (v) Indian Arm. The Outer Harbour is connected through a set of narrows at Stanley Park (**First Narrows** under the Lions Gate Bridge) to the Inner Harbour. The Inner Harbour is connected to the Central Harbour by **Second Narrows** under the Ironworkers Memorial Bridge and the Burrard Inlet Canadian National Railway Bridge. Further eastward, the Inlet bifurcates into two extensions. The Port Moody Arm extends eastward ending as a relatively shallow estuary. Indian Arm extends northward as a fjord with a classic sill at the entrance and a deeper interior basin. In the Outer Harbour, English Bay is located at the southeast corner of the Inlet and provides an entrance into the very small inlet of False Creek.

Movement of water in one sub-basin in Burrard Inlet necessarily interacts with water in the other sub-basins as they are all interconnected.

For the purposes of this report, Burrard Inlet includes all marine waters east of the north-south line from Point Atkinson in West Vancouver to Point Grey on the University of British Columbia campus just west of Vancouver with the boundaries shown on the following map:

Figure 1: Map of Burrard Inlet

The total east-west length of Burrard Inlet is about 30 km, with Indian Arm extending approximately 20 km to the north.

Important geophysical attributes that influence oil spill trajectory in Burrard Inlet include:

- *Topographic relief*: the northern shoreline of Burrard Inlet, in particular in Indian Arm, is backed by relatively high mountains (approximately 1000-1500 meters in altitude). This topographic relief influences local wind direction.
- *Thermal heat island*: Vancouver and Burnaby are “thermal heat islands” (i.e. they are developed areas that hold heat) that influence local wind patterns extending over the waters of Burrard Inlet;
- *Freshwater discharge in Burrard Inlet*: the influence of streams and rivers that discharge directly into Burrard Inlet on oil spill trajectory is very local as that freshwater discharge represents a minor fraction of the water balance in Burrard Inlet and the influence of the outflow on water movement in Burrard Inlet is minor;
- *Connection to the Strait of Georgia*: Burrard Inlet is connected to the Strait of Georgia along its western boundary. These systems are strongly coupled and their currents are synchronized across a common interface. The Strait of Georgia is itself a component of the much larger and complex Salish Sea, which includes multiple connected passes through several well defined island groups, as well as two well separate outlets to the Pacific Ocean; and
- *Discharge from the Fraser River*: The Fraser River discharges into the Strait of Georgia. It is by far the largest source of fresh water and sediment entering the Salish Sea. The Fraser discharge moves locally and some of the fresh water and sediment enter Burrard Inlet, particularly during peak flows.

5.2 The GNOME oil spill trajectory model

We used version 1.3.9 of the GNOME to model oil spill trajectories in Burrard Inlet.

GNOME is a well-recognized and leading 2D numeric oil spill trajectory model that is used daily by NOAA and other regulatory agencies all over the world to model oil spill trajectories to inform spill response, planning, and statistical risk analyses. In particular, GNOME has been used in many “high profile” major oil spills, including the Exxon Valdez, Cosco Busan, and Deepwater Horizon oil spills, among others.

GNOME, along with its predecessor, the Oil Spill Simulation Model (“**OSSM**”), has been undergoing rigorous, testing and ongoing development for over 40 years. It is in the public domain, maintained by NOAA’s Office of Response and Restoration, and freely distributed from their website.

5.3 The GNOME for Burrard Inlet

GNOME can be run in two modes. The “standard” mode uses “default” options for many of the model parameters. GNOME files that can be used in the “standard” mode are called "location files." The "diagnostic" mode provides users with greater control over model parameters, and the ability to import other hydrodynamic models. GNOME files that can be used in the "diagnostic" mode are called "SAV files." Location files and SAV files contain map(s) and associated current models (based on geophysical and meteorological conditions) that govern water and oil transportation processes.

We generated three SAV files to be run in GNOME's diagnostic mode to model oil spill trajectories in Burrard Inlet: two for modeling oil spill scenarios that remain within Burrard Inlet ("**Burrard Inlet Models**"), and one for modeling oil spill scenarios where oil is anticipated to move outside of Burrard Inlet and into the Strait of Georgia and beyond ("**Regional Model**"). The SAV files are described in **Appendix "D"**.

5.3.1 Burrard Inlet Models

We created the Burrard Inlet Models by: (1) generating a regional map of Burrard Inlet using aerial photographs to detail shoreline location and features; (2) overlaying an unstructured triangular grid with a nominal spacing of approximately 100 meters with more than 30,000 triangles on that map; (3) adding bathymetric contours to the map based on more than 16,000 bathymetric points;[7] and (4) adding current models to generate current patterns associated with transport processes caused by geophysical and meteorological conditions in Burrard Inlet.

The current models that were developed or calibrated for the Burrard Inlet Models are described below in section 6.3.3.

Two SAV files for Burrard Inlet were created and are described in Appendix D: BurrardInlet.sav and Burrard_statistics.sav. We will refer to the BurrardInlet.sav file as "**Burrard Inlet Model A**" and Burrard_statistics.sav as "**Burrard Inlet Model B**". Burrard Inlet Model A has five current models whereas Burrard Inlet B has eight. There are three key differences between the models shown in the table below:

[7] A map showing the bathymetric contour lines of Burrard Inlet is attached as **Appendix "E"**.

	Current model associated with tidal station at First Narrows	Current models associated with observed wind patterns in Burrard Inlet	Current models associated with discharges from rivers and streams into Burrard Inlet
Burrard Inlet Model A	Based on January 1, 2004–December 31, 2014 tidal data	No	Yes
Burrard Inlet Model B	Based on January 1, 2005–December 31, 2005 tidal data	Yes	No

Burrard Inlet Model A can be run anytime starting from 00:00 hours on January 1, 2004 through 24:00 hours on December 31, 2014. Burrard Inlet Model B can be run anytime starting from 00:00 hours on January 1, 2005 through 24:00 hours on December 31, 2005.

5.3.2 Regional Model

In describing how the Region Model was built, we will refer to the map of Burrard Inlet and the current models that are included in the Burrard Inlet Model A as the "**Burrard Inlet Map**".

The Burrard Inlet Map ends at the western boundary of the Outer Harbour. An additional map with associated current was therefore required to model how a spill scenario starting in the Outer Harbour might affect the Salish Sea.

The U.S. Department of Energy's Pacific Northwest National Laboratory previously developed the Salish Sea Model ("**SSM**") to provide a general trajectory analysis platform in the Salish Sea.[8] SSM's state variables for tides, winds, and water characteristics are coupled with those of the Pacific Ocean across the open boundaries at the western end of the Strait of Juan de Fuca and the northern extent of the model domain in the Strait of Georgia.

The developers of SSM ran a simulation that produced two calendar weeks of simulated 3D currents (including wind effects) from August 18, 2007 to September 1, 2007. They subsequently developed a GNOME location file that allows GNOME users to model oil spills in the SSM domain space.[9] That location file contains a map of the Salish Sea and the currents generated by the model based on actual environmental conditions for that two week

[8] For more information on the SSM, please refer to the Pacific Northwest National Laboratory's website: http://pugetsound.pnnl.gov/PSGB/PSGB_Collaboration/Oil_Spill_Modeling_GNOME_Format.stm. A map showing the SSM Salish Sea Main Computational Domain and Surface Grid Representation is attached as **Appendix "F"**.
[9] The SSM location file is available on NOAA's website here: response.restoration.noaa.gov/gnome.

period ("**SSM Map**"). The SSM domain, as depicted in the SSM Map, stops at the center of the Outer Harbour and the interior of Burrard Inlet is not represented or modeled.

GNOME has a feature which allows for more than one map (and its associated current models) to be included in a SAV file. To model the movement of oil between Burrard Inlet and the Strait of Georgia and beyond in the Salish Sea, we created a **Regional Model** by adding the SSM and Burrard Inlet Maps to the SAV file for the Regional Model.

The grids of the SSM and Burrard Inlet Maps, and the area where the Maps overlap in English Bay, are shown in the following map:

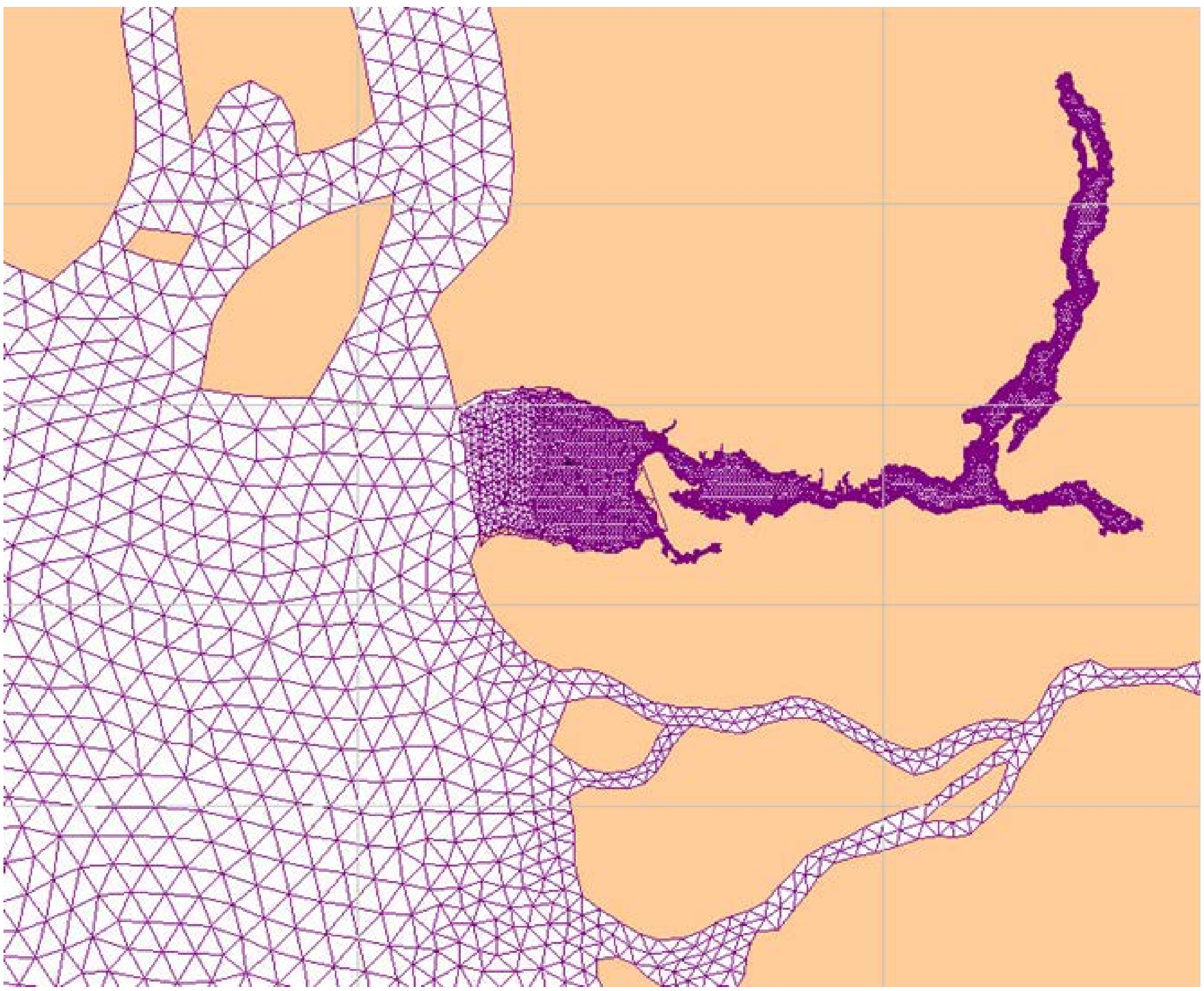

Figure 2: Map showing the relative location of the SSM and Burrard Inlet Maps

Where the grids in the SSM and Burrard Inlet Maps overlap, pollutant elements (Lagrangian particles—referred to as splots) in GNOME will use the transport processes and shoreline characteristics of the first map listed in GNOME.

We embedded the SSM Map in the Burrard Inlet Map by placing the Burrard Inlet Map in the GNOME map list before the SSM Map. The behaviour of particles within the bounds of the Burrard Inlet Map will therefore be governed by the transport processes in that Map. The behaviour of particles that move through the Outer Harbour off of the Burrard Inlet Map will subsequently be governed by the transport processes in the SSM Map. Particles transported across the boundary in the opposite direction will be governed by transport processes in the Burrard Inlet Map.

We used the SSM location file in the Regional Model instead of a second GNOME location file[10] that was independently developed by NOAA based on other modeling because it does a better job of representing the Fraser River discharge, and the domain in the "other" NOAA GNOME file does not cover the northern part of the Outer Harbour. Importantly, although restricted in its temporal domain, the two weeks of time in the SSM location file captures an example of the range of the spring/neap cycle in the Salish Sea necessary to model oil spill trajectory.

5.3.3 Current models used in the Burrard Inlet Models

We used commonly accepted modeling techniques to create new, or calibrate existing, current models based on the following geophysical and meteorological conditions in Burrard Inlet: (a) Kelvin Wave; (b) tidal flow; (c) river outflows; (d) interaction between wind and oil; (e) beaching and refloating of oil; and (f) local wind patterns.

Where possible or appropriate, we compared modeled results with predicted or observed current patterns in Burrard Inlet. Where necessary, we calibrated the current models to more accurately represent observed or predicted current patterns in Burrard Inlet.

(a) Kelvin Wave

The major exchange of water and pollutants between Burrard Inlet and the Strait of Georgia occurs through the common boundary of the Burrard Inlet and SSM Maps at the western edge of the Outer Harbour. The progressive tidal wave that moves along the eastern shore of the Strait of Georgia is the primary dynamic process responsible for the exchange. Locally, the tidal wave moves from the vicinity of the Fraser River delta toward the entrance of Howe Sound.

As the currents stream north, the earth's rotation tends to bank them to the east (Coriolis effect), which floods high water into the Outer Harbour. This generally progressive edge wave is common in large tidal basins and is referred to as a "Kelvin Wave." Most of the volume of water crossing the outer boundary of the Outer Harbour moves along bathymetric

[10] See the Strait of Juan de Fuca location file User's Guide: http://response.restoration.noaa.gov/sites/default/files/Gnome_StraitJuanDeFuca_UG.pdf.

contours and exits the northern section of the Outer Harbour entrance back into the Strait of Georgia and toward Howe Sound.

The SSM Map contains a representation of this “Kelvin Wave”. **Appendix “G”** shows the currents generated by the Burrard Inlet Models matching this observed pattern.

(b) Tidal flow into Burrard Inlet

As the tidal wave in the Strait of Georgia floods water into the Outer Harbour, it raises the sea surface (“**high water**”) which creates a hydraulic head at First Narrows. This causes some of the water flooding into the Outer Harbour to turn east and move toward the Narrows. As the water rises, it forces flow through the Narrows and generates the tidal currents inside Burrard Inlet.

We ran a numeric simulation of tidal currents in Burrard Inlet driven by high water in the Outer Harbour to generate a current model based on tidal currents.[11] A stable pattern of currents was obtained after a few hundred iterations. We further calibrated the current model by adjusting the flood currents observed at the tidal station at First Narrows from January 1, 2005 through December 31, 2005 with the strength of the Kelvin Wave currents predicted by the SSM Map in the outer regions of the Outer Harbour. This calibration creates a smooth transition between the two Maps and adjusts the fractional volume of the Outer Harbour flood that is directed through the First Narrows to match observed values.

The current model generated by this process was added to the Burrard Inlet Models. That model successfully reproduces observed tidal flow and tidal excursions in Burrard Inlet.

(c) River Outflows

We modeled the discharge of water from the Capilano, Seymour, and Indian Rivers, as well as Lynn Creek, into, and subsequent movement in, Burrard Inlet. We included a current model associated with that discharge in the Burrard Inlet Model A.

Discharges of water from rivers and creeks in Burrard Inlet have a localized influence on oil spill trajectory because the volume of water discharged by the small number of rivers and creeks that drain into Burrard Inlet is small relative to the volume of water in Burrard Inlet. From an oil spill trajectory point of view, discharges from rivers and creeks in Burrard Inlet typically influence only the areas directly around their outflows. They limit the extent to which tidal or wind driven transport can push oil upstream.

[11] During the numeric simulation: (1) geometry and conservation of water volume were enforced; and (2) non-linear bottom friction (hydraulic impedance) – where it is easier for water to flow through a deep channel than a shallow one – and the volume of the tidal prism in the various basins and arms of Burrard Inlet were taken into account. The modeling protocol used to generate these currents has strong continuity and dynamic constraints that force the distribution of water within the model to conform to observed tidal volumes.

The current model associated with river outflow does not, therefore, need to be activated during oil spill trajectory modeling unless a spill scenario focuses specifically on a location near a river or creek as it will have a minimal impact on oil spill trajectories.

However, the current patterns in the SSM Map capture currents associated with the late stages of the Fraser River freshet, which occurred from August 18, 2007 to September 1, 2007. This is important because the Fraser River does have an impact on oil spill trajectories.

(d) Interaction between wind and oil

Wind over the water surface influences the movement of oil in two somewhat distinct ways: (i) through wind driven surface currents; and (ii) wind interactions with the oil slick.

(i) Wind Driven Surface Currents

Winds produce shallow currents that drive a relatively weak flow and pile water up against shorelines. This creates pressure gradients that result in additional currents. These kinds of currents are typically a few percent of the wind speed, and they depend on bathymetric constraints, the direction of the wind relative to the shoreline, and orography.

Wind driven surface currents can lead to quite complex patterns. Although small compared to tidal currents, they often result in nearshore bands of flow and cross channel eddies that contribute to pollutant mixing, particularly during slack periods of tide.

We modeled wind driven surface currents in Burrard Inlet. The current model we developed generated results similar to predicted patterns of wind driven currents. For example, wind driven surface currents generated by an easterly drainage wind component over Port Moody Arm in the model run shown in **Appendix "H"** are characterized by downwind drift along shallow shorelines with a much weaker return (up wind) flow into the deeper sections, and weak cross channel eddies.

We included a current model associated with wind driven surface currents in the Burrard Inlet Models A and B. However, they are typically not activated unless wind pattern data is used in the simulation.

(ii) Wind Interaction with Oil Slicks

Wind over the water surface interacts with oil transport processes by transferring momentum from small gravity waves to the thin surface film of floating oil. Gravity waves are absorbed by the slick making it look smooth compared to the area around it. This process drives the slick across the water it is floating on.

Observations indicate that this process should be a few percent of the wind speed. A nominal value used in many models is 3%. A more careful observation suggests that there is a good deal of scatter around this value. This is particularly true if Langumir circulation is present (windrows), which typically occurs when winds exceed 5 knots. In the central convergence rows of the cells, some of the floating slick may move at twice the nominal speed.

GNOME already models this process by using a random distribution of drift factors over a range of values (default 1-4.5%). Historical observations indicate that this is a reasonable approach to model oil spill trajectories in Burrard Inlet.

(e) Beaching and Refloating Oil

Oil particles can become stranded when oil transport processes carry them to the vicinity of a shoreline. Currents typically will not strand oil by themselves. The beaching process is caused by sub-grid scale diffusive movement which is a short range displacement or an onshore component of oil slick wind transport.

Heaviest shoreline stranding tends to occur with onshore winds. Once the oil is on the beach, a variety of processes can take place that result in oil becoming stranded for a period of time. Those processes are largely dependent on the geomorphology of the shore, the energetics of the wave field, and the normal component of the local wind field.

GNOME already simulates beaching and refloating of oil by a simple first order “rewashing” model which is characterized by a refloating half-life. Half-life values observed in the natural environment vary from a few hours for rocky or armored areas to years for protected, low energy salt marshes.

GNOME results for Burrard Inlet are sensitive to refloating half-lives of 9 hours or less, but converge after 12 hours or more. It would be appropriate to use a refloat half-life value of less than 12 hours based on the geomorphology of Burrard Inlet (about a third to half of the shoreline in Burrard Inlet is rocky or armored). However, oiled surfaces will spend some fraction of their time above the water level because of the tidal range experienced in the Inlet. This extends the effective rewash time so that an 18 hour half-life is appropriate. We therefore used an estimate half-life time of 18 hours to model oil spill trajectories in Burrard Inlet.

(f) Local Winds

Winds are an important forcing factor in oil spill trajectory modeling. In fjord-like environments like Burrard Inlet with significant topographic relief, wind pattern information is pivotal.

In its standard mode, GNOME allows for wind to be entered as a constant or as a time-dependent, spatially uniform progression. In some situations, these modeling constraints provide limited utility for multi-day scenarios when a progression of weather systems move through the area.

This feature must be used in the Burrard Inlet Model A and in the Regional Model.

However, current models associated with the four major wind patterns in Burrard Inlet were added to the Burrard Inlet Model B. Those four current models were developed using the method described in **Appendix “I”**.

5.3.4 Estimates of Uncertainty in GNOME

GNOME shares a common characteristic with all other oil spill trajectory models: it approximates a number of different processes with algorithms that are themselves approximations. Model results are therefore representative of the range of possible oil spill trajectories with some level of associated uncertainty.

Uncertainty ranges are built into the algorithms for each of the major processes in GNOME. The accuracy of trajectory predictions in GNOME is estimated by a second set of oil particles (in addition to the oil particles showing the predicted oil spill trajectory) which is randomly perturbed beyond the actual model parameters but within the range of the expected errors of each algorithm.

Over a statistical collection, these oil particles experience the entire scatter associated with estimated uncertainty in the model. On each trajectory run, the “uncertainty” can be turned on and the outlying oil particles are mapped in red, which represent the range of possible trajectory outcomes based on the estimated uncertain in the model algorithms.

Figure 3, below, shows the trajectory forecast of an oil spill, as well as the uncertainty of that prediction, based on a typical run:

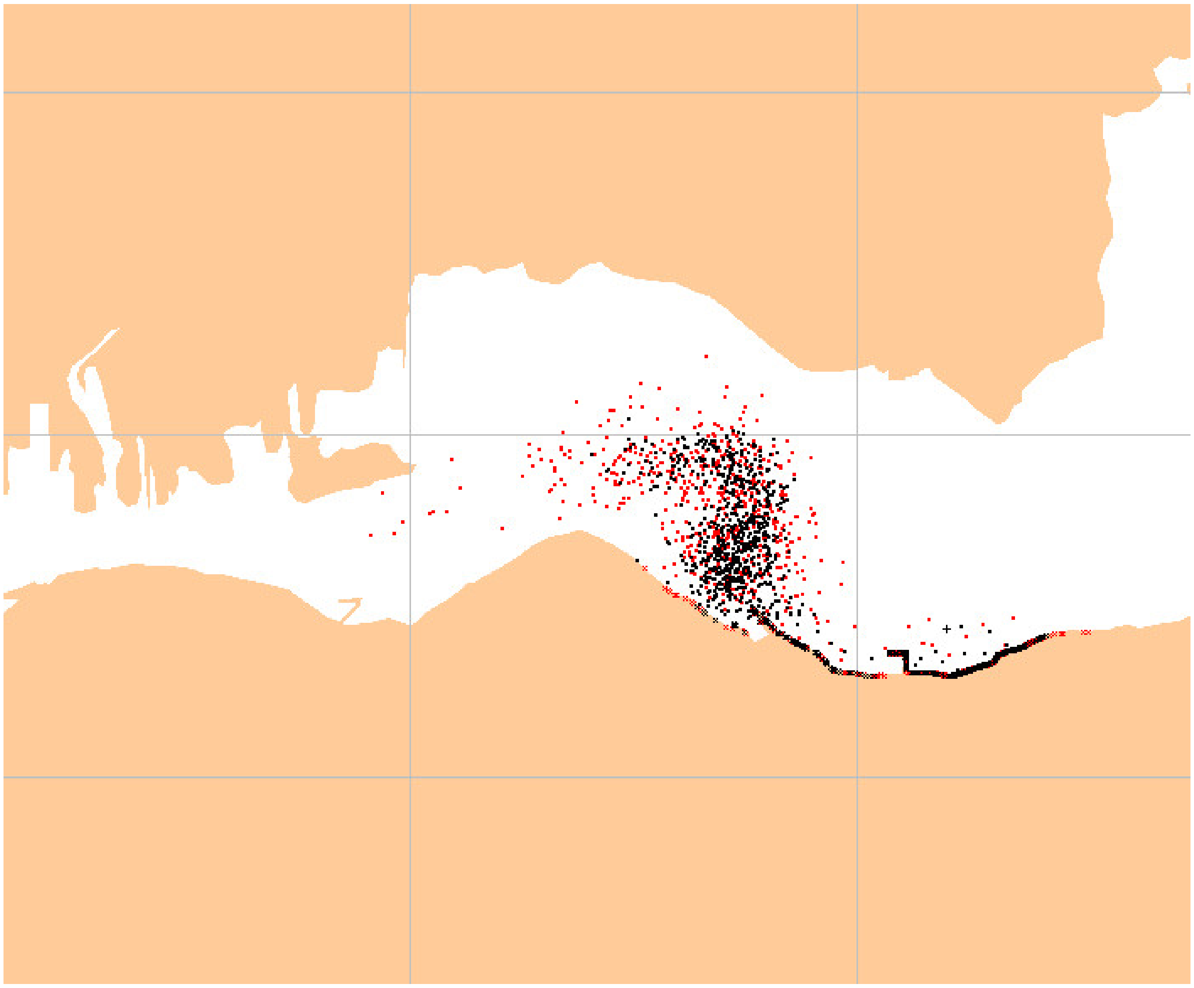

Figure 3: Zoomed in map of Burrard Inlet in the Central Harbour showing GNOME output for predicted oil spill trajectory (in black) and the level of uncertainty associated with the predicted oil spill trajectory (in red)

The red particles show the areas of Burrard Inlet that could be impacted by oil in this model run based on the uncertainty associated with the parameters in the model. They typically show up as a halo surrounding the forecasted spill.

6.0 OIL SPILL TRAJECTORY RESULTS FROM FOUR OIL SPILL SCENARIOS IN BURRARD INLET

We modeled oil spill trajectory from four oil spill scenarios in Burrard Inlet:

(a) an oil spill of 8,000 m^3 at the Westridge Marine Terminal;[12]

(b) an oil spill of 16,000 m^3 at Second Narrows under the Canadian National Railway Bridge;[13]

(c) an oil spill of 16,000 m^3 at First Narrows;[14] and

(d) an oil spill of 16,000 m^3 in the Outer Harbour at Anchorage #8.[15]

For each scenario:

- we modeled oil spill trajectory in a step-wise manner by initially starting with only one physical transport process (tidal currents), and then adding a constant wind, and then using observed winds and tides. This approach was used to describe the sensitivity of the model to various processes and numerically explore implications;
- we assumed that no weathering, clean up, or other mitigation occurred. All of the released oil was tracked in the output. This approach provides a consistent picture of the potential extent of spread of oil in Burrard Inlet;
- we ran the model using a set of parameters that remained constant and varied the parameters described below; and
- we used 8,000 splots in GNOME to represent the volume of oil released during the spill. Reasonable statistical coverage of an oil spill modeled for a few days can be achieved by using 8,000 splots in GNOME.

(a) Scenario 1: an oil spill of 8,000 m^3 at the Westridge Marine Terminal

We used the Burrard Inlet Models to model an instantaneous release of 8,000 m^3 of oil at the Westridge Marine Terminal (**"Terminal**").

Each splot represents a scaled fraction of the spill. In this scenario, each splot is a particle in the model that represents 1 m^3 of oil.

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[12] Latitude 49.291089 North, Longitude 122.950338 West.
[13] Latitude 49.295371 North, Longitude 123.024432 West.
[14] Latitude 49.315409 North, Longitude 123.138569 West.
[15] Latitude 49.289444 North, Longitude 123.199722 West.

(i) Tidal Currents

Tides play a major role in oil transport in Burrard Inlet. We therefore ran Burrard Inlet Model A initially using only the current models associated with tidal currents. We modeled two types of spills: ones that occurred at “slack going to flood” and others that occurred at “slack going to ebb”.

Figure 4, below, shows a screen capture of the trajectory of an oil spill that we modeled during an example of a “slack going to flood” condition that occurred on January 2, 2004 at 21:35 at 6, 12, 24, 48 and 96 hours into the spill run:

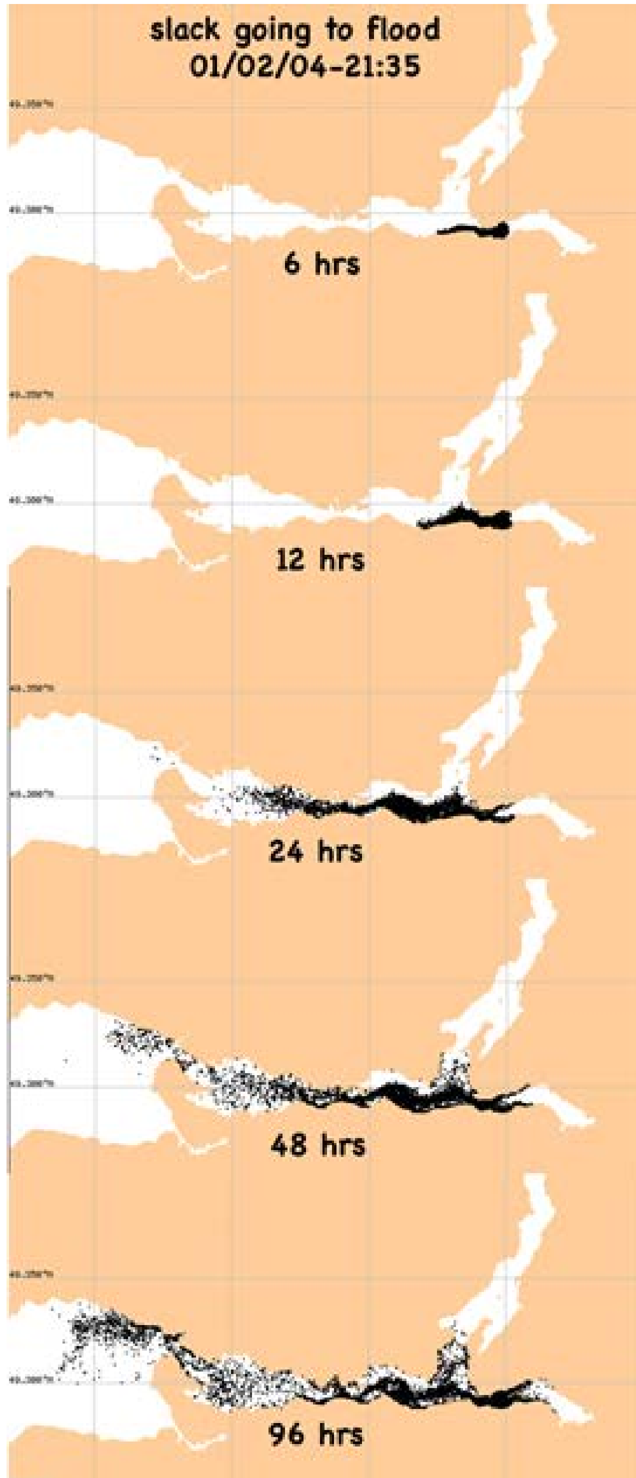

Figure 4: Oil spill trajectory time sequence at the Terminal for "slack going to flood" starting on January 2, 2004 at 21:35

The movement of oil after 6 hours was “up estuary” toward Port Moody. The first tidal current reversal shifted the center of the spill back towards the spill location at the Terminal (as shown in the screen shot at 12 hours). After a full additional tidal cycle, the heavy center of mass of the spill was located in the Central Harbour with a significant amount of oil having passed through Second Narrows into the Inner Harbour (shown in the screen shot at 24 hours).

Subsequent tidal oscillations continued to diffuse oil throughout Burrard Inlet. By 48 hours, some oil had migrated through First Narrows into the Outer Harbour and north into Indian Arm as far as Belcarra Regional Park and Strathcona District Park. That trend continued to develop at 96 hours.

Oil spill trajectory was primarily influenced by tidal sloshing and diffusion during this run, which did not model the effects of wind (which would have pined oil against the shorelines). Beaching and refloating therefore had a very minor influence on the movement of oil during this run.

Figure 5, below, shows a screen capture of the trajectory of an oil spill that we modeled during an example of a “slack tide going to ebb” that occurred on January 1, 2004 at 02:25 at 6, 12, 24, 48 and 96 hours into the spill run:

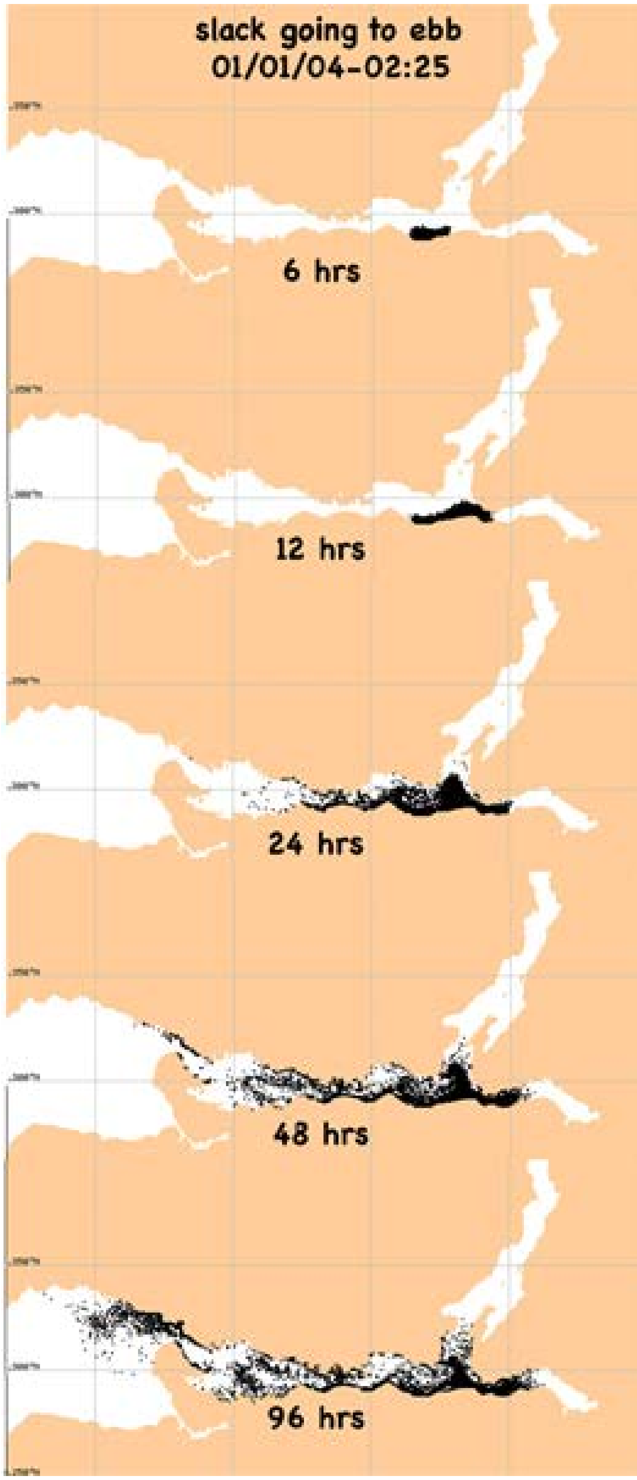

Figure 5: Oil spill trajectory time sequence at the Terminal for "slack going to ebb" starting on January 1, 2004 at 02:25

The oil spill trajectory modeled during this run resembles the previous run, with the exception that the initial displacement was toward Second Narrows. By 24 hours, or two tidal cycles, the distribution was similar to the previous run. Heavy concentrations moved “down estuary” into the region just west of Second Narrows.

Second Narrows has the strongest currents in Burrard Inlet, which enhance cross channel mixing toward the northern shore. The next flood cycle carried a cluster of oil particles eastward to the entrance to Indian Arm (shown in the screen shot at 48 hours). Continued tidal oscillations distributed more oil through First Narrows and into the Outer Harbour, as well as into southern Indian Arm.

(ii) Steady Nominal Wind

We assumed a constant, steady wind and used Burrard Inlet Model A to explore how wind currents would impact the trajectory of an oil spill originating at the Terminal. We used a wind current of 3 knots from the SSW. Our assumption was based on the CALMET wind model results which, as we describe in Appendix “I” show a 3 knot SSW wind as being the dominant wind pattern in Burrard Inlet.

Figure 6, below, shows a screen captures at 24 hours of the trajectory of: (1) an instantaneous release of oil during a “slack going to flood” condition that occurred on January 2, 2004 at 21:35; (2) an instantaneous release of oil during a “slack going to ebb” that occurred on January 1, 2004 at 02:25; and (3) a continuous release of oil on January 2, 2004 at 21:35:

Figure 6: Three oil spill scenarios at the Terminal with a steady 3 knot SSW Wind after 24 hours

Initial tidal conditions were important in determining the areas that were impacted by oil after 24 hours. Oil primarily moved into the north shore of the Port Moody Arm in the first scenario (flood), whereas it mainly moved into Indian Arm in the second scenario (ebb).

The difference between these two runs suggests that tidal phase and wind direction interact in a complex way.

Oil threatened more shoreline under the continuous release scenario than under both instantaneous release scenarios.

(iii) Observed Winds and Tides

We used the Burrard Inlet Model B to model the effects of forcing with observed winds and tide sequences to obtain a more accurate representation of oil spill trajectory in Burrard Inlet.

Figure 7, below, shows screen captures of the trajectory of an oil spill that we modeled using Burrard Inlet Model B starting on September 1, 2005 at 00:00 at 6, 12, 24, 48 and 96 hours into the spill run:

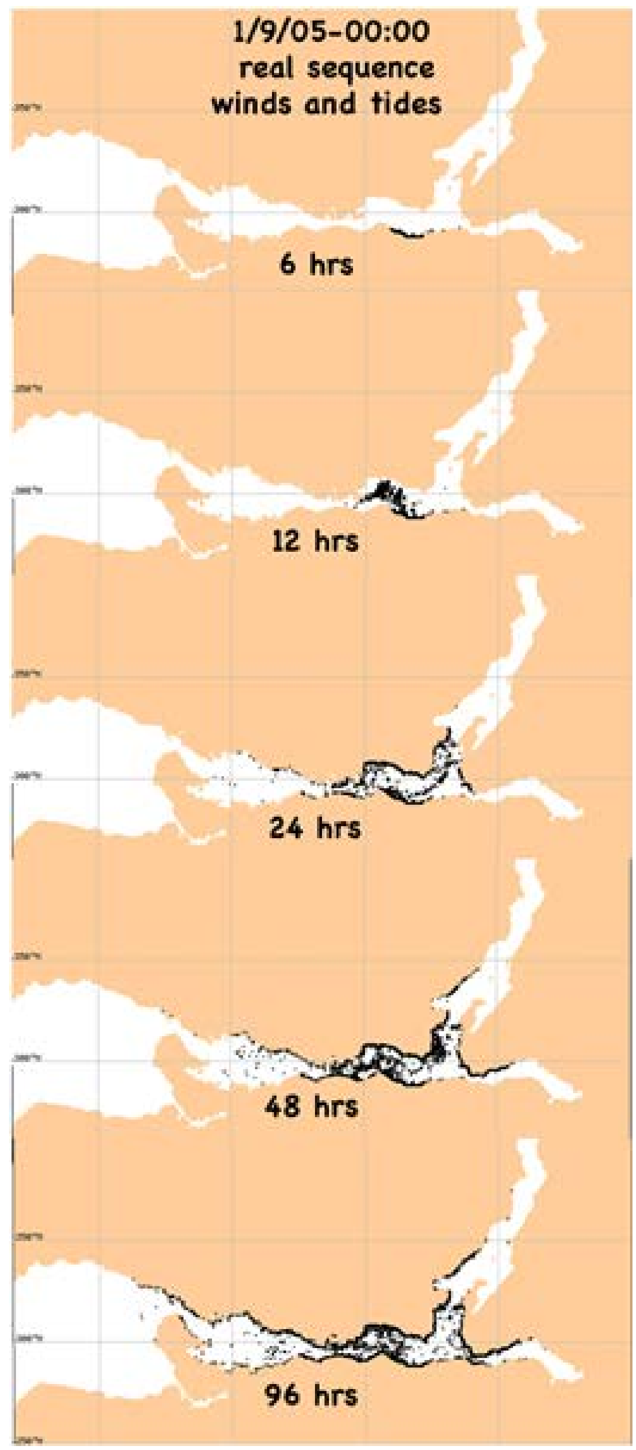

Figure 7: Results of an oil spill at the Terminal using modeled real winds and tides

At 12 hours at the end of the first tidal cycle, oil was either beached on the south shore or floating in the Central Harbour. The oil subsequently spread in all possible directions. By 96 hours, oil was found in the Inner Harbour and First Narrows, Port Moody Arm and halfway up Indian Arm.

Although this last run was based on real sequence information, it is one of nearly an infinite number of scenarios. This sort of scenario investigation presents a generally realistic indication of the physical processes moving oil around Burrard Inlet and the potential extent of spread.

(b) Scenario 2: an oil spill of 16,000 m^3 at Second Narrows under the Canadian National Railway Bridge

We used the Burrard Inlet Models to model an instantaneous release of 16,000 m^3 of oil at Second Narrows under the Canadian National Railway Bridge ("**Second Narrows**"). As in Scenario 1, for each model run we assumed that no weathering, clean up, or other mitigation occurred. All of the released oil was tracked in the output. Each splot represents 2 m^3 of oil.

(i) Tidal Currents

We used the same parameters to model oil spill trajectory based on tidal currents at Second Narrows that we used to model oil spill trajectory at the Terminal.

Figure 8, below, shows screen captures of the trajectory of an oil spill at Second Narrows that we modeled during an example of a "slack going to flood" condition that occurred on January 2, 2004 at 21:35 at 6, 12, 24, 48 and 96 hours into the spill:

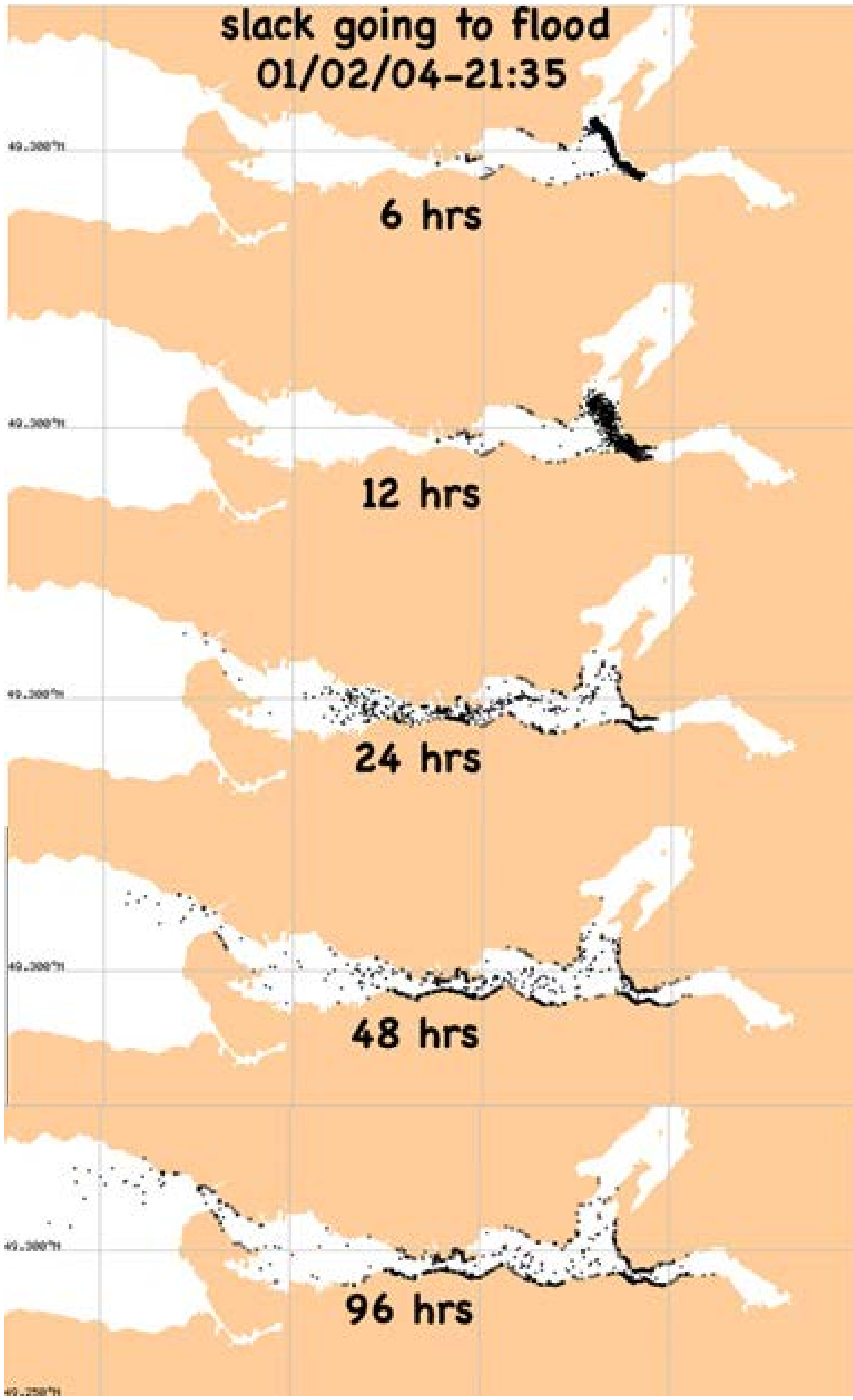

Figure 8: Oil spill trajectory time sequence at Second Narrows for "slack going to flood" starting on January 2, 2004 at 21:35

The stronger currents in Second Narrows yielded a greater tidal excursion taking the major cluster of oil particles as far as the entrance to Port Moody Arm and southern Indian Arm. The relatively weak following ebb tide spread the oil back into the junction of Port Moody and Indian Arms, but did not return it to Second Narrows. The next complete tidal cycle moved oil back through Second Narrows into the Inner Harbour. By 24 hours, oil was scattered from First Narrows to the channels leading to Port Moody and Indian Arms.

A great deal of oil beached even though this run did not include any wind. The stranding was caused entirely by the random diffusive process in the nearshore zone. Oil stranding was particularly prominent where the channel was narrow. In these narrow channels, the random diffusive processes act over a significant part of the channel width.

From a physical processes point of view, eddy currents are frequently observed around the Second Narrows during peaks in tidal flow.

Figure 9, below, shows screen captures of the trajectory of an oil spill at Second Narrows that we modeled during a “slack going to ebb” condition that occurred on January 1, 2004 at 02:25 at 6, 12, 24, 48 and 96 hours into the spill:

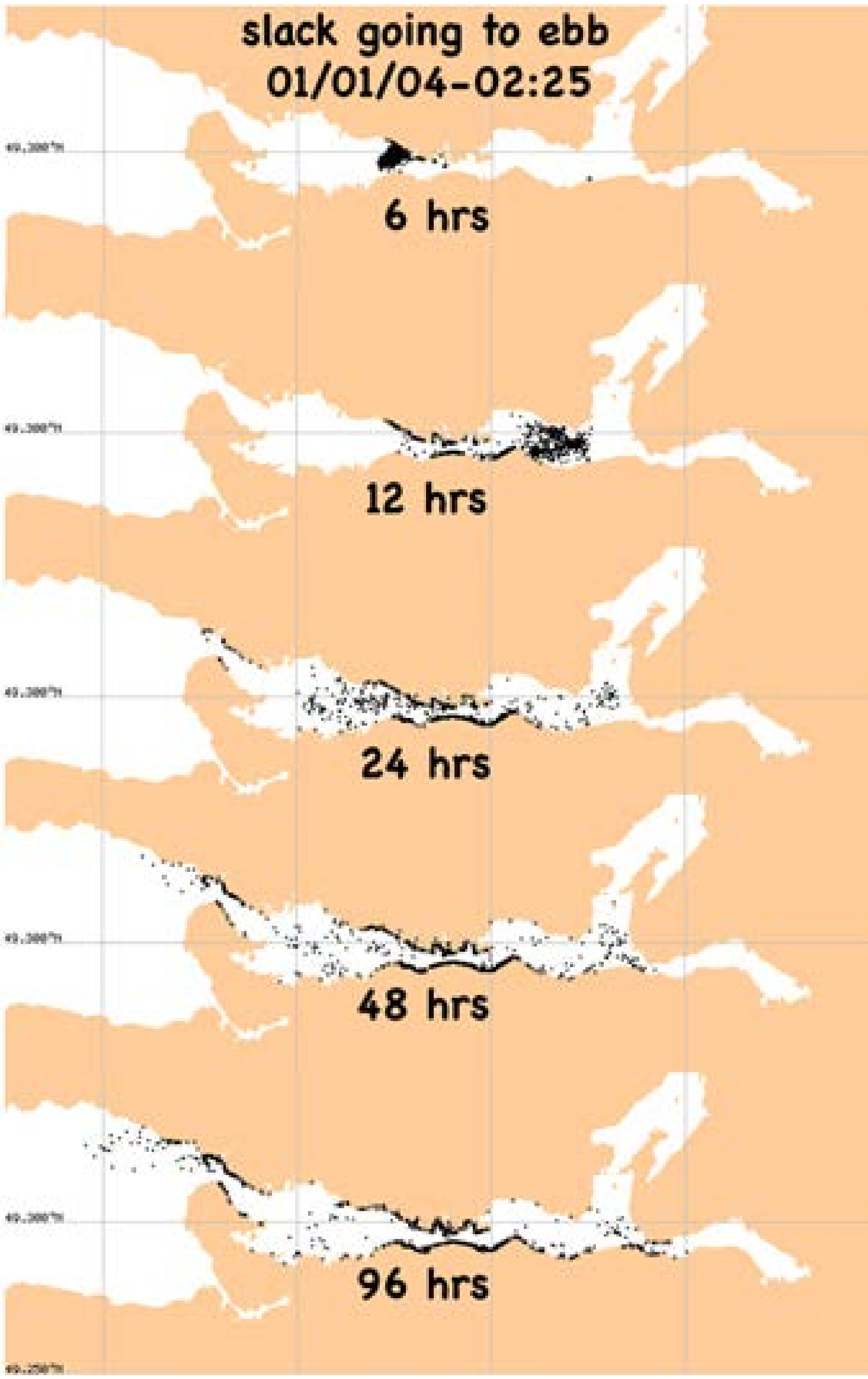

Figure 9: Oil spill trajectory time sequence at Second Narrows for "slack going to ebb" starting on January 1, 2004 at 02:25

Initially, oil dispersed west away from Second Narrows into the Inner Harbour. By 12 hours, oil had moved back past the Second Narrows spill site as far east as Indian Arm. The significant asymmetry in oil dispersion based on tidal cycles illustrates an important feature of Pacific Northwest tides. They are “mixed”, which means that they typically show a strong diurnal inequality.

For this case, the original -0.9 knot ebb was followed by a 2.0 knot flood, which was then followed by a -3.7 knot ebb and a 2.5 knot flood. This illustrates why tidal flow should not be modeled as just shifting oil back and forth symmetrically. It is more complicated and it is essential to have a tidal model that properly represents the sequential patterns of the tides. The Burrard Inlet Models were calibrated against tidal currents forecasted in First Narrows. As a result, they represent the asymmetric aspects of the tidal cycle in Burrard Inlet.

Similar to oil spill trajectory at the Terminal, the distribution of oil at Second Narrows after 24 hours converged, showing few differences in oil spread produced by tidal conditions at spill initiation under no wind conditions.

(ii) Steady Nominal Wind

We modeled oil spill trajectory based on currents and steady nominal winds at Second Narrows using the same parameters, except for spill size and location, that we used to model oil spill trajectory at the Terminal.

Figure 10, below, shows a screen captures at 24 hours of the trajectory of: (1) an instantaneous release of oil during a “slack going to flood” condition that occurred on January 2, 2004 at 21:35; (2) an instantaneous release of oil during a “slack tide going to ebb” that occurred on January 1, 2004 at 02:25; and (3) a continuous release of oil on January 2, 2004 at 21:35:

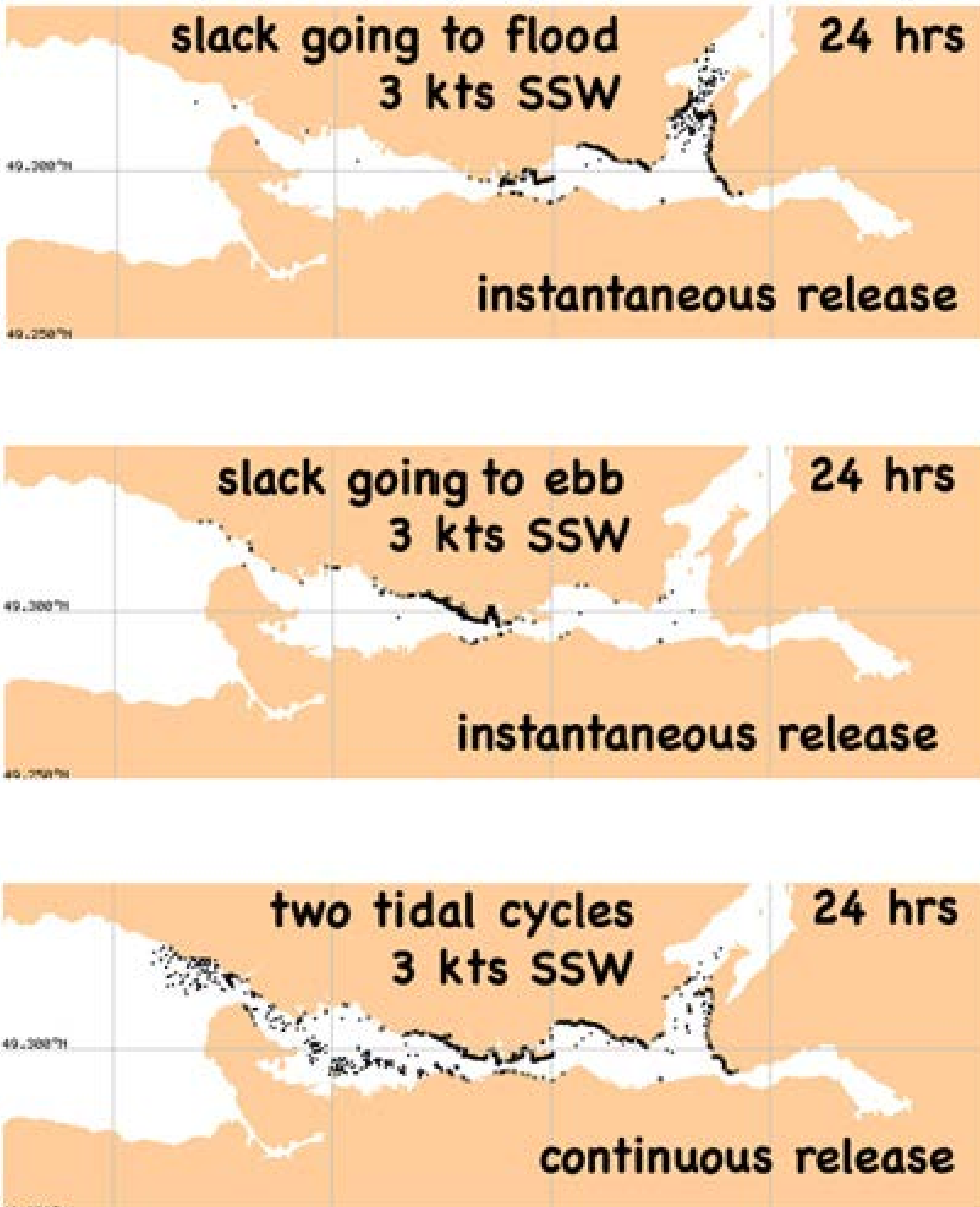

Figure 10: Three oil spill scenarios at Second Narrows with a steady 3 knot SSW Wind after 24 hours

The first panel shows the results for a run where the spill was released instantaneously at slack going to flood. A substantial amount of oil was stranded “up estuary” and significant amounts of oil moved up Indian Arm. The second panel shows the results for the slack going to ebb run. Most of the oil was stranded along the northern shore of the Inner Harbour. The third panel shows results similar to the Terminal scenario where continuous release of oil threatens more shoreline than instantaneous release.

As in the scenario modeled for the Terminal, the wind and phase of the tide in the Second Narrows scenario interact to produce an asymmetry in the initial movement of the spill.

(iii) Observed Winds and Tides

We used the Burrard Inlet Model B to model the effects of forcing with observed winds and tide sequences to obtain a more accurate representation of oil spill trajectory in Burrard Inlet.

Figure 11, below, shows screen captures of the trajectory of an oil spill that we modeled using Burrard Inlet Model B with tides and the CALMET wind data starting on October 1, 2005 at 00:00 at 6, 12, 24, 48 and 96 hours into the spill run:

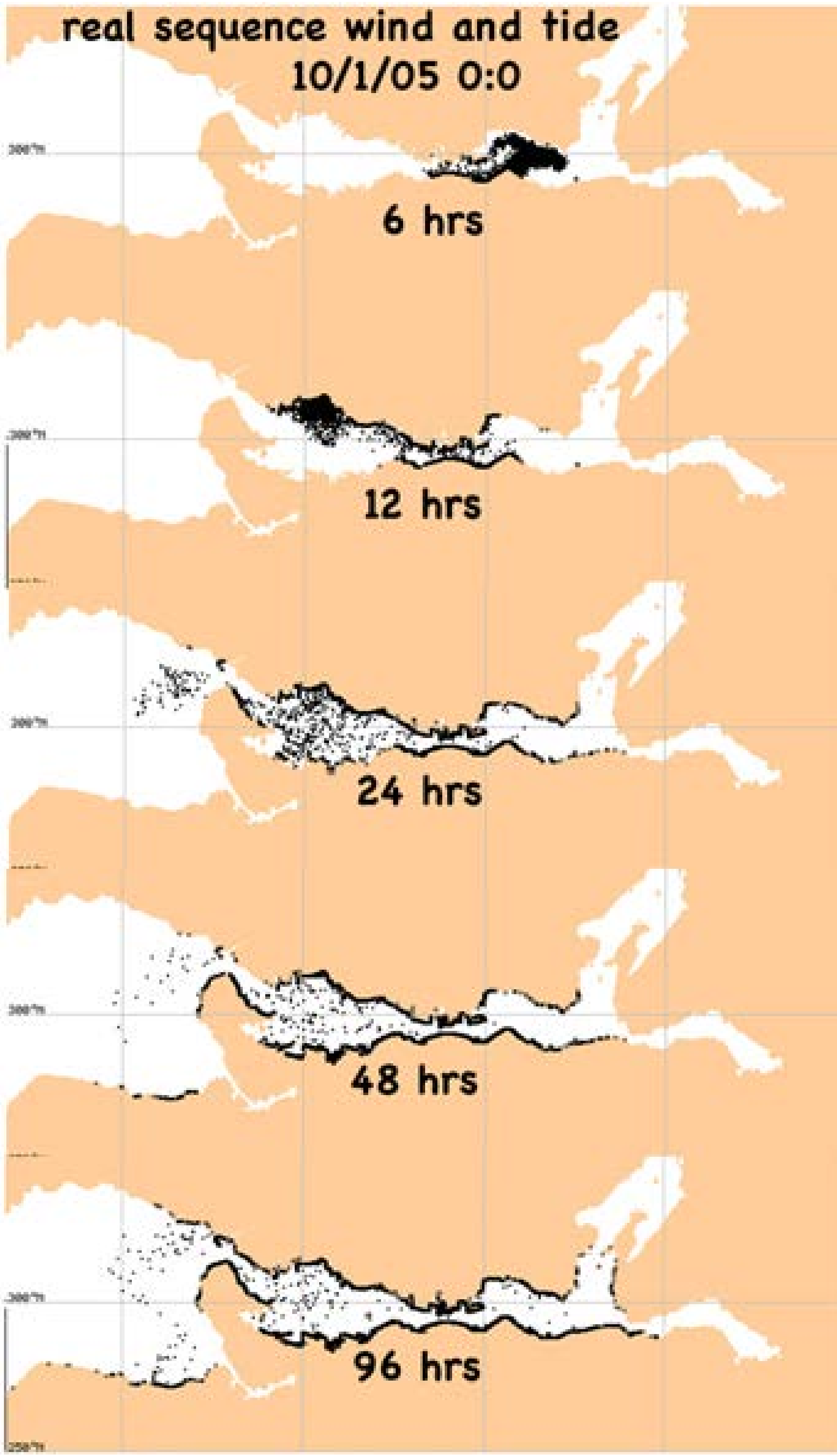

Figure 11: Results of an oil spill at Second Narrows using modeled real winds and tides

Winds varied considerably in this run. Early on during the first day of the spill, the winds moved the spill north and led to very heavy oiling along the northern shore of the Inner Harbour. Later on, the winds refloated oil and moved it south impacting the Inner Harbour waterfront in Vancouver. Some patches of oil also moved west past First Narrows where they became stranded on the shoreline of the Outer Harbour.

(c) Scenario 3: an oil spill of 16,000 m^3 at First Narrows

We used the Regional Model to model an instantaneous release of 16,000 m^3 of oil at First Narrows as water and oil is exchanged freely between the Outer Harbour and the Strait of Georgia, outside of the bounds of the Burrard Inlet Models.

As in Scenarios 1 and 2, for each model run we assumed that no weathering, clean up, or other mitigation occurred. All of the released oil was tracked in the output. We also used 8,000 splots. Each splot therefore represents 2 m^3 of oil.

(i) Tidal Currents

Oil spill trajectory modeling using the Regional Model is restricted to the time span covered by the SSM current data archive and incorporated into a GNOME location file. This period covers the two weeks between August 18 and August 31, 2007. We therefore chose a tidal cycle of “slack going to flood” that started on August 24, 2007 at 13:48.

Figure 12, below, shows screen captures of the trajectory of an oil spill at First Narrows that we modeled during an example of a “slack going to flood” condition that occurred on August 24, 2007 at 13:48 at 6, 12, 24, 48 and 96 hours into the spill:

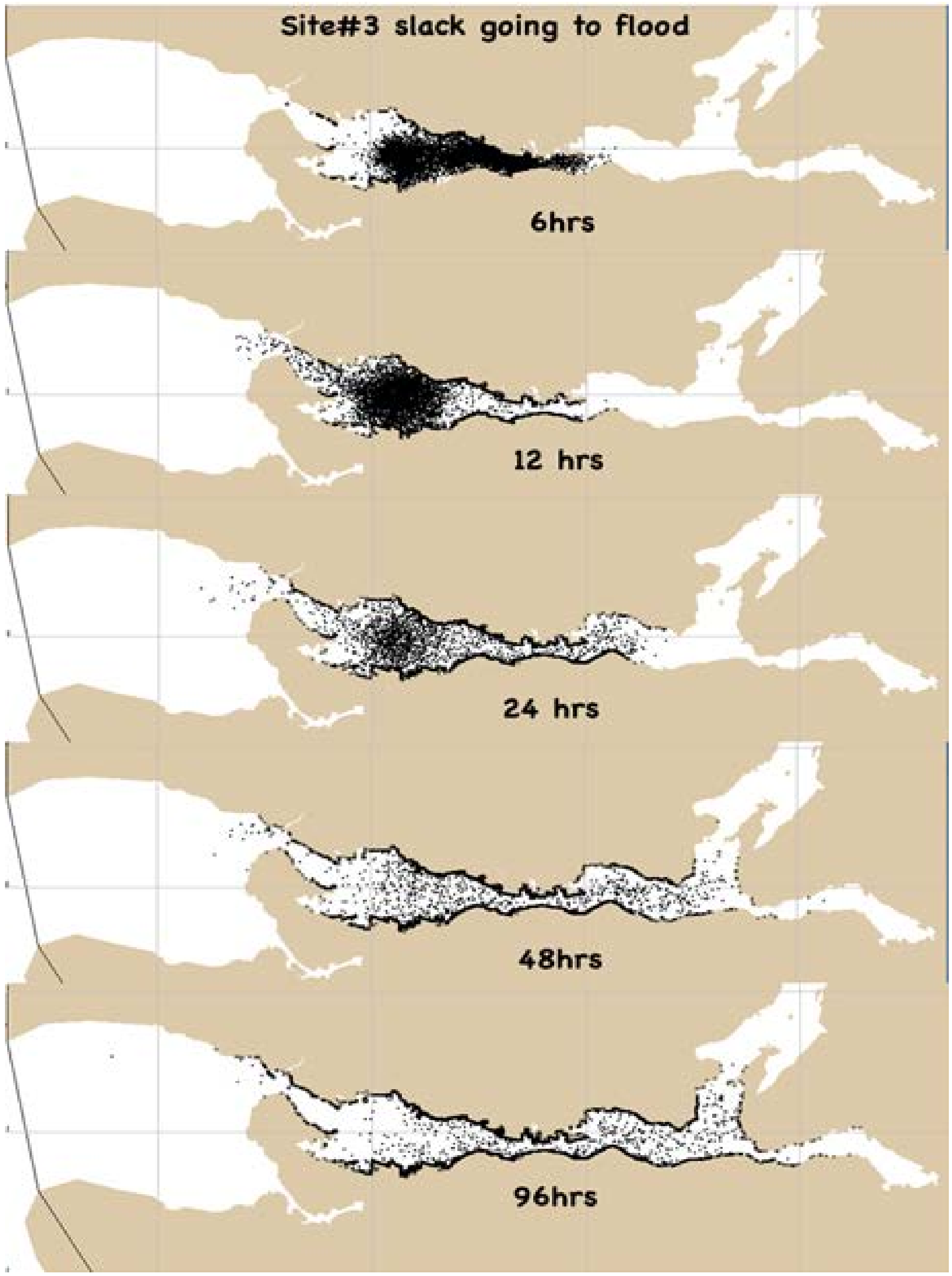

Figure 12: Oil spill trajectory time sequence at First Narrows for "slack going to flood" starting on August 24, 2007 at 13:48

During the first 6 hours of this run, the entire spill was carried into and nearly through the Inner Harbour. The eastern front moved as far as the Second Narrows. During the following ebb (out to hour 12), the center of mass of the spill moved back towards the center of the Inner Harbour. Heavy shoreline stranding of oil occurred from the center of the Inner Harbour to Second Narrows.

Subsequent tidal cycles continued to refloat and disperse the spill. After 96 hours, the spill extended from the eastern portion of the Outer Harbour to Indian Arm and the entrance to Port Moody. The heaviest concentrations of oil were centered on Second Narrows.

Figure 13, below, shows screen captures of the trajectory of an oil spill at First Narrows that we modeled during a “slack going to ebb” condition that occurred on August 19, 2007 at 01:20 at 6, 12, 24, 48 and 96 hours into the spill:

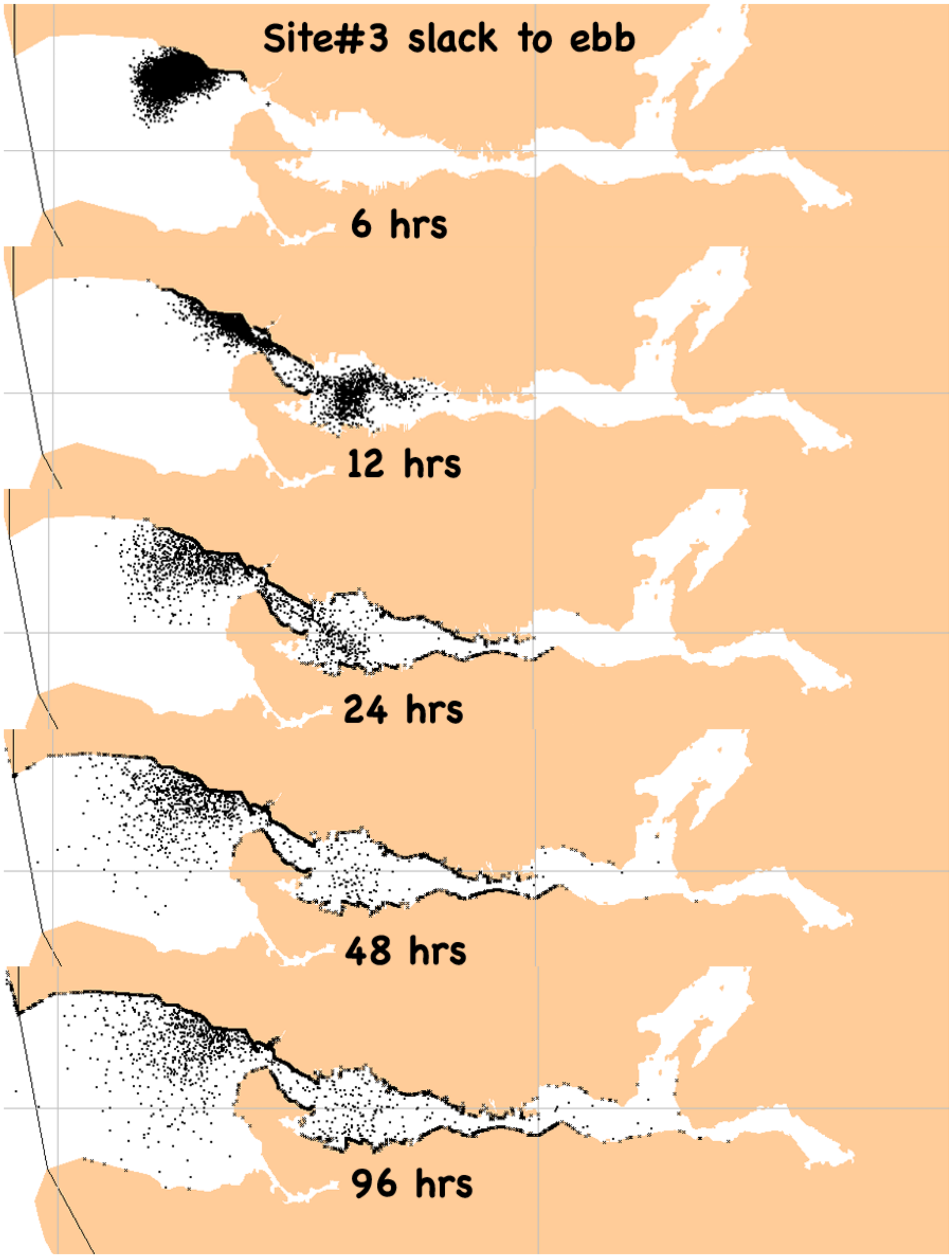

Figure 13: Oil spill trajectory time sequence at First Narrows for "slack going to ebb" starting on August 19, 2007 at 01:20

This run showed an initial displacement of the spill into the eastern portion of the Outer Harbour. The following flood swept it back through First Narrows throughout the Inner Harbour. Subsequent tidal cycles centered the mass of the spill on First Narrows. The spill extended through the Outer Harbour and into the Strait of Georgia on the west and through Second Narrows to the east.

Initial tidal phase, in the absence of wind, led to qualitatively different outcomes after 96 hours. Oil spill trajectory in Second Narrows did not behave in this manner (the outcomes were qualitatively similar). We conclude based on these results that the asymmetric current regime on the two sides of First Narrows made a difference in how the oil spread over time.

(ii) Steady Nominal Wind

For the steady nominal wind run, we used a 3 knot wind from the SSW. However, because of the asymmetric effects of the currents and the open exchange of water and oil between the Outer Harbour and the Strait of Georgia, the First Narrows scenario was expanded to include a numerical investigation of a second wind pattern. Two runs were added with a 3 knot wind from the east (representing the Fraser Valley drainage wind pattern).

Figure 14, below, shows screen captures at 24 hours of the trajectory of: (1) an instantaneous release of oil during a “slack going to flood” condition that occurred on August 24, 2007 at 13:48 with a 3 knot SSW wind; (2) an instantaneous release of oil during a “slack going to ebb” condition that occurred on August 19, 2007 at 01:20 with a 3 knot SSW wind; (3) an instantaneous release of oil during a “slack going to flood” condition that occurred on August 24, 2007 at 13:48 with a 3 knot wind from the east; and (4) an instantaneous release of oil during a “slack going to ebb” condition that occurred on August 19, 2007 at 01:20 with a 3 knot wind from the east:

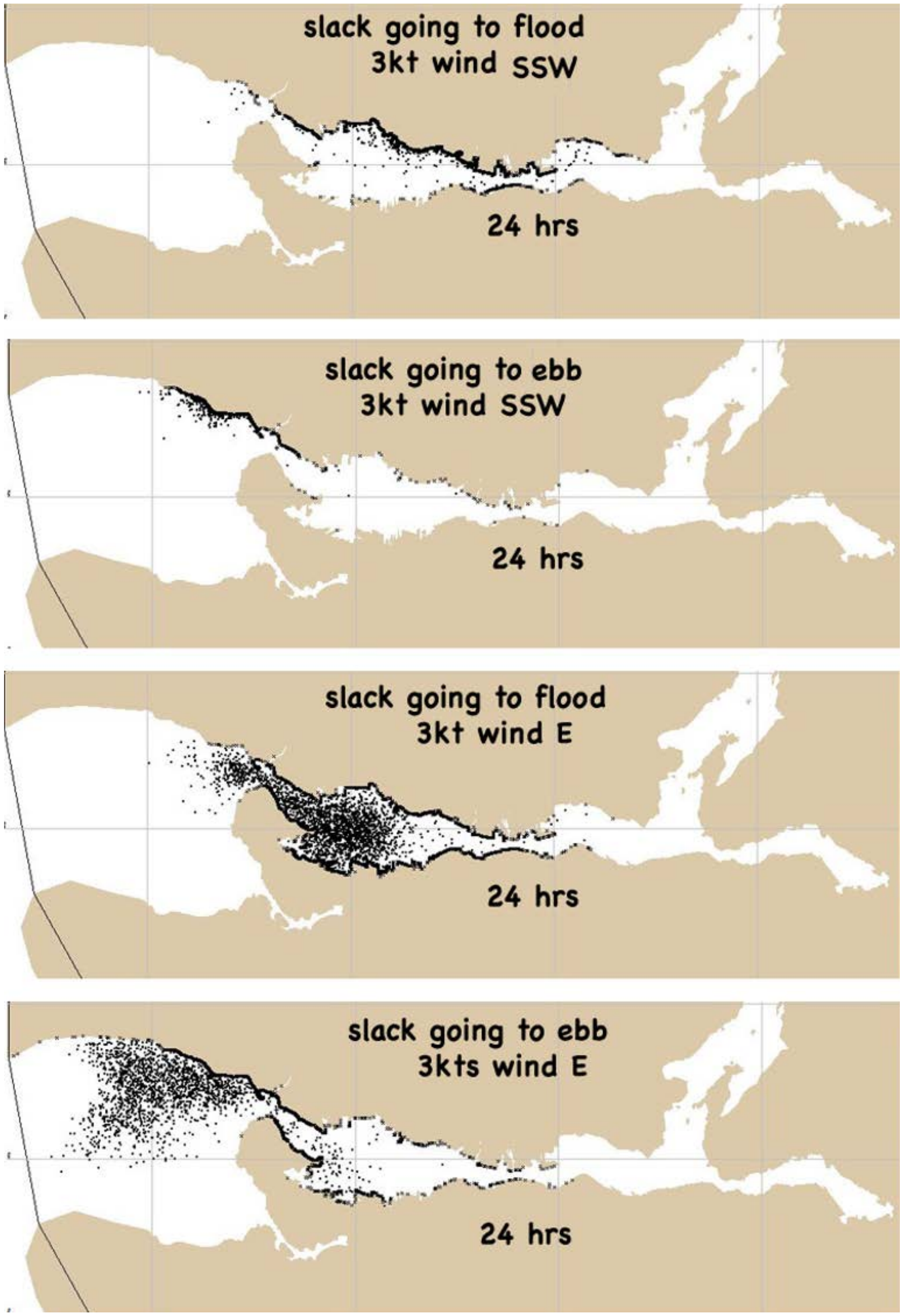

Figure 14: Two oil spill scenarios at First Narrows with a 3 knot SSW wind and two scenarios with a 3 knot wind from the east after 24 hours

The two upper panels show runs for flood and ebb conditions with a 3 knot SSW wind. The two lower panels use the same tidal patterns, but with a 3 knot wind from the east.

SSW winds stranded and held oil along the northern shorelines of the Outer and Inner Harbour. Far less oil was stranded by the east winds. There were also strong asymmetric results based on initial tidal phase.

For the ebb case shown in the fourth panel, the western limit of the spill at 24 hours was just starting to exit the Outer Harbour into the Strait of Georgia.

(iii) Real Winds and Tides

It is not possible to use the Regional Model to model oil spill trajectory based on real wind and tide sequence because the time periods for the SSM Map and CALMET wind data do not overlap.

We therefore used Burrard Inlet Model B to do so, with the caveat that any oil that exits the western boundary of the Outer Harbour into the Strait of Georgia (i.e. moves off of the Burrard Inlet Map) will simply be “off the map” and no longer traced.

We modeled oil spill trajectory at First Narrows based on observed wind and tide sequences using the same parameters, except for the date on which the spill occurred, that we used to model oil spill trajectory at Second Narrows.

Figure 15, below, shows screen captures of the trajectory of an oil spill that we modeled using the Burrard Inlet Model B with tides and the CALMET wind data starting on January 2, 2005 at 00:00 at 6, 12, 24, 48 and 96 hours into the spill run:

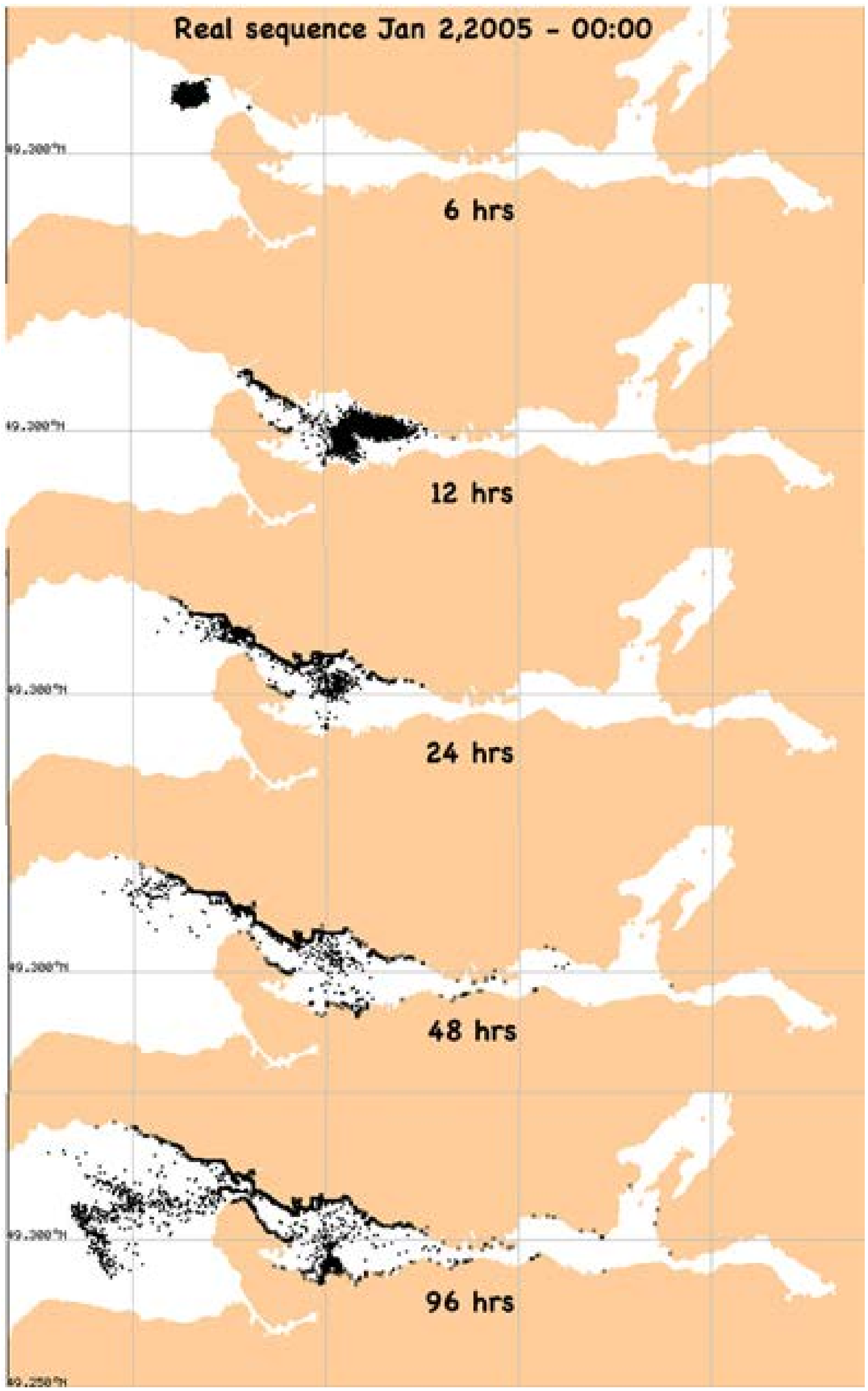

Figure 15: Results of an oil spill at First Narrows using modeled real winds and tides

Initially, a strong ebb tide carried the oil into a relatively quiet section of the Outer Harbour under relatively calm wind conditions. The next flood, at 12 hours, moved the spill virtually intact into the Inner Harbour. After this, a southern wind pushed it to the northern shore. Late in the run a northerly wind refloated stranded oil and moved it toward or even onto the southern shorelines.

Oil spill trajectories at First Narrows are complex. We further explored oil spill trajectories at First Narrows by conducting additional model runs at one month intervals for five months.

Figure 16, below, shows screen captures of the trajectory of an oil spill at 24 hours that we modeled using Burrard Inlet Model B with tides and the CALMET wind data starting on February 2, March 2, April 2, May 2, and June 2, 2005:

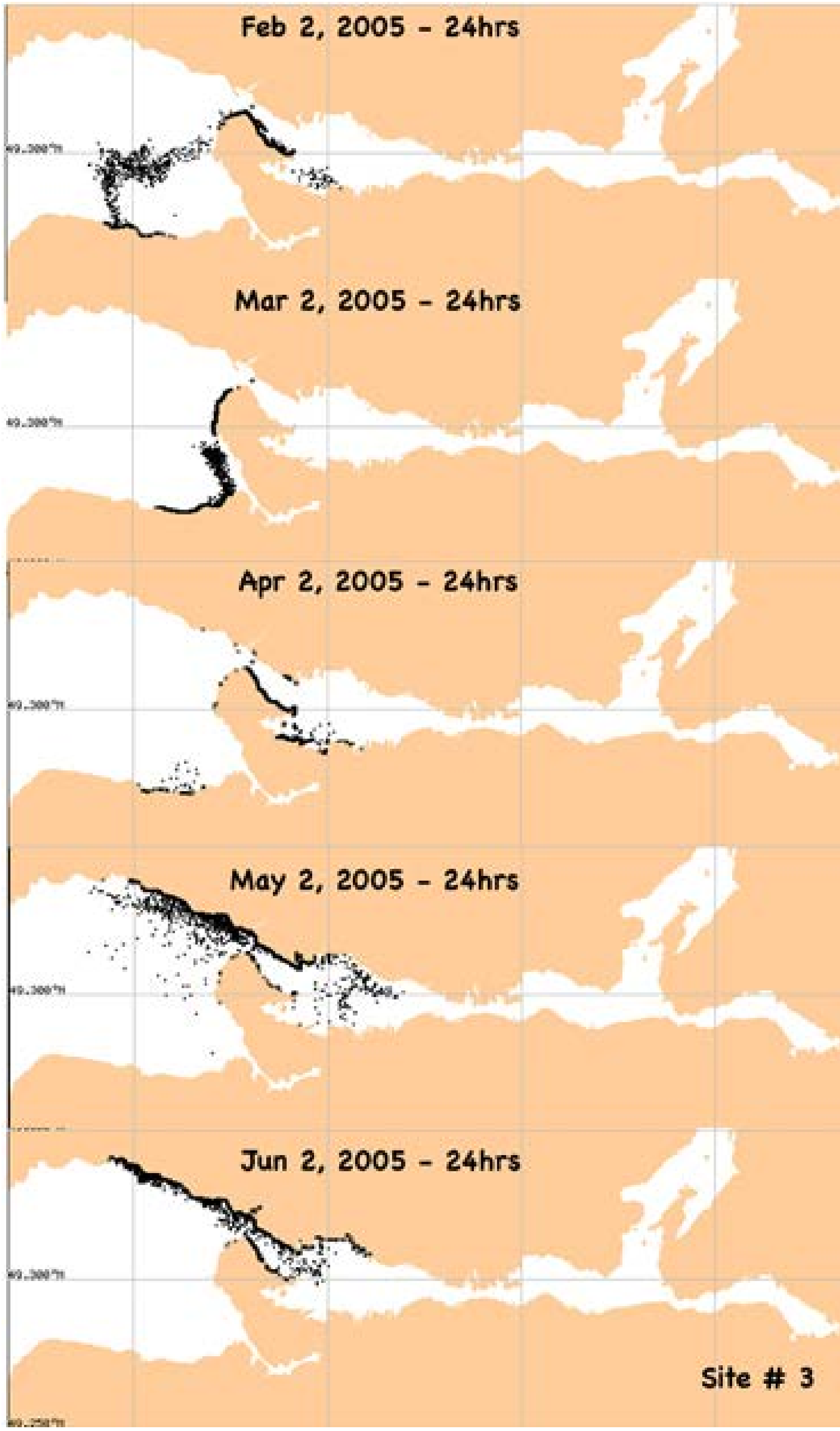

Figure 16: Results of an oil spill at First Narrows after 24 hours at one month intervals in 2005 using modeled real winds and tides

Initial tidal conditions and wind patterns on the dates shown in Figure 16 lead to very different trajectory outcomes. This analysis confirms that oil spill trajectory at First Narrows modeled at different times does not conform to a single dominant pattern.

(d) Scenario 4: an oil spill of 16,000 m^3 in the Outer Harbour at Anchorage #8

We used the Regional Model to model an instantaneous release of 16,000 m^3 of oil in the Outer Harbour at Anchorage #8 ("**Outer Harbour**"), which is in a relatively weak current zone in the south central portion of the Outer Harbour.

As set out above, use of the Regional Model is limited to the span of time represented in the SSM Map. The wind can be set for the Burrard Inlet Model A component of the Regional Model. The wind effects in the SSM Map region cannot be set, but they are implicitly included in the archived currents. We modeled oil spill trajectory from a spill in the Outer Harbour based on these limitations.

For each model run we assumed that no weathering, clean up, or other mitigation occurred. All of the released oil was tracked in the output. We also used 8,000 splots. Each splot represents 2 m^3 of oil.

(i) Tidal Currents

As set out above, oil spill trajectory modeling using the Regional Model is restricted to the time span covered by the SSM current data archive and incorporated into a GNOME location file. This period covers the two weeks between August 18 and August 31, 2007. We therefore chose a tidal cycle of "slack going to flood" that started on August 24, 2007 at 13:48.

Figure 17, below, shows screen captures of the trajectory of an oil spill in the Outer Harbour that we modeled during a "slack going to flood" condition that occurred on August 24, 2007 at 13:48 at 6, 12, 24, 48 and 96 hours into the spill:

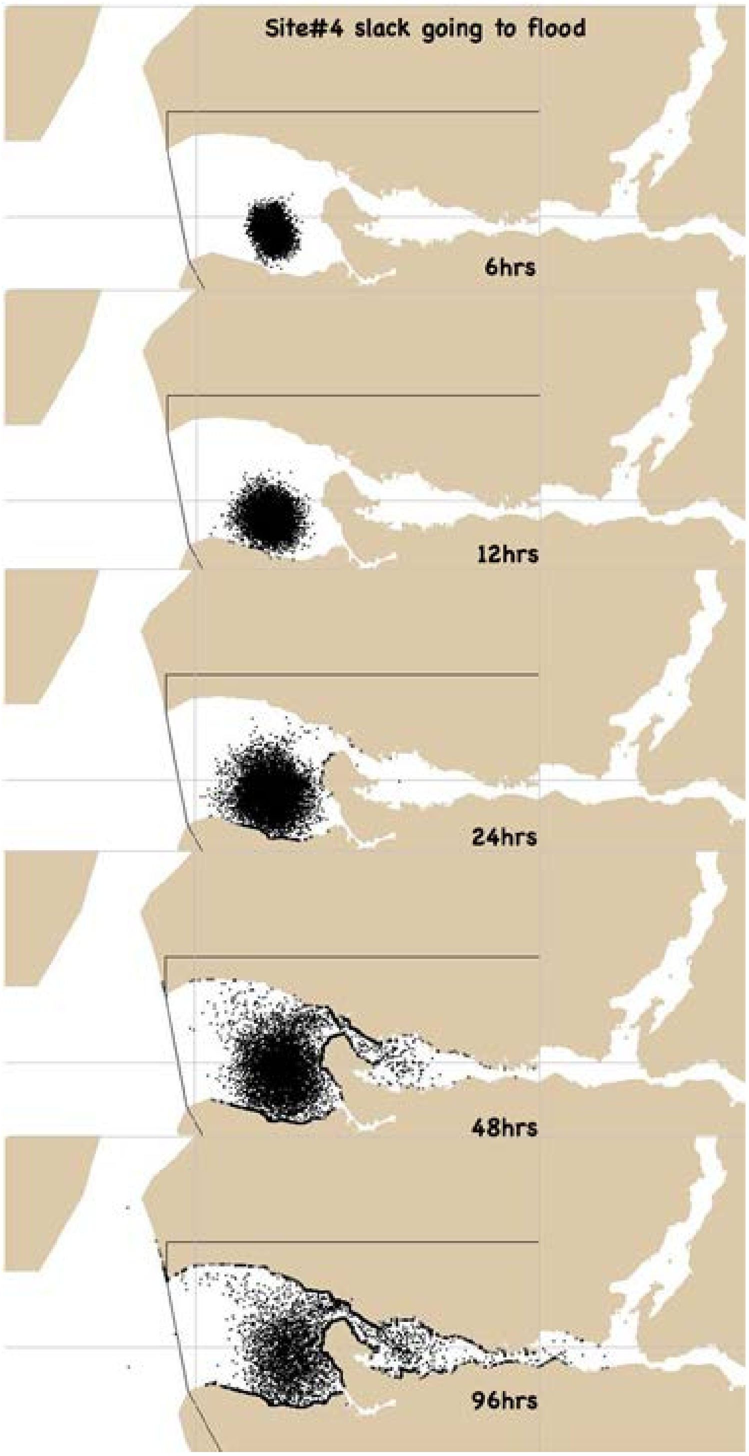

Figure 17: Oil spill trajectory time sequence in the Outer Harbour for "slack going to flood" starting on August 24, 2007 at 13:48

The low energy environment in the Outer Harbour, modeled without any wind effects, resulted in very little initial dispersal of oil from the spill. After two tidal cycles, oil spread enough to fill the south-central part of the Outer Harbour and portions of the oil approached the location in the Outer Harbour where oil and water are transported into First Narrows by the flood tide (the "**inhale region**"). After this, subsequent tidal cycles pumped oil into the Inner Harbour. At 96 hours, the center of gravity of the spill was still in the vicinity of the initial location and few splots moved into the Strait of Georgia.

The trajectory of an oil spill in the Outer Harbour during a "slack going to ebb" condition was qualitatively very different from the previous run or other scenarios. The results are presented in the following two figures.

Figure 18, below, shows screen captures of the trajectory of an oil spill in the Outer Harbour that we modeled during a "slack going to ebb" condition that occurred on August 19, 2007 at 01:20 at 6, 12, 24 hours into the spill:

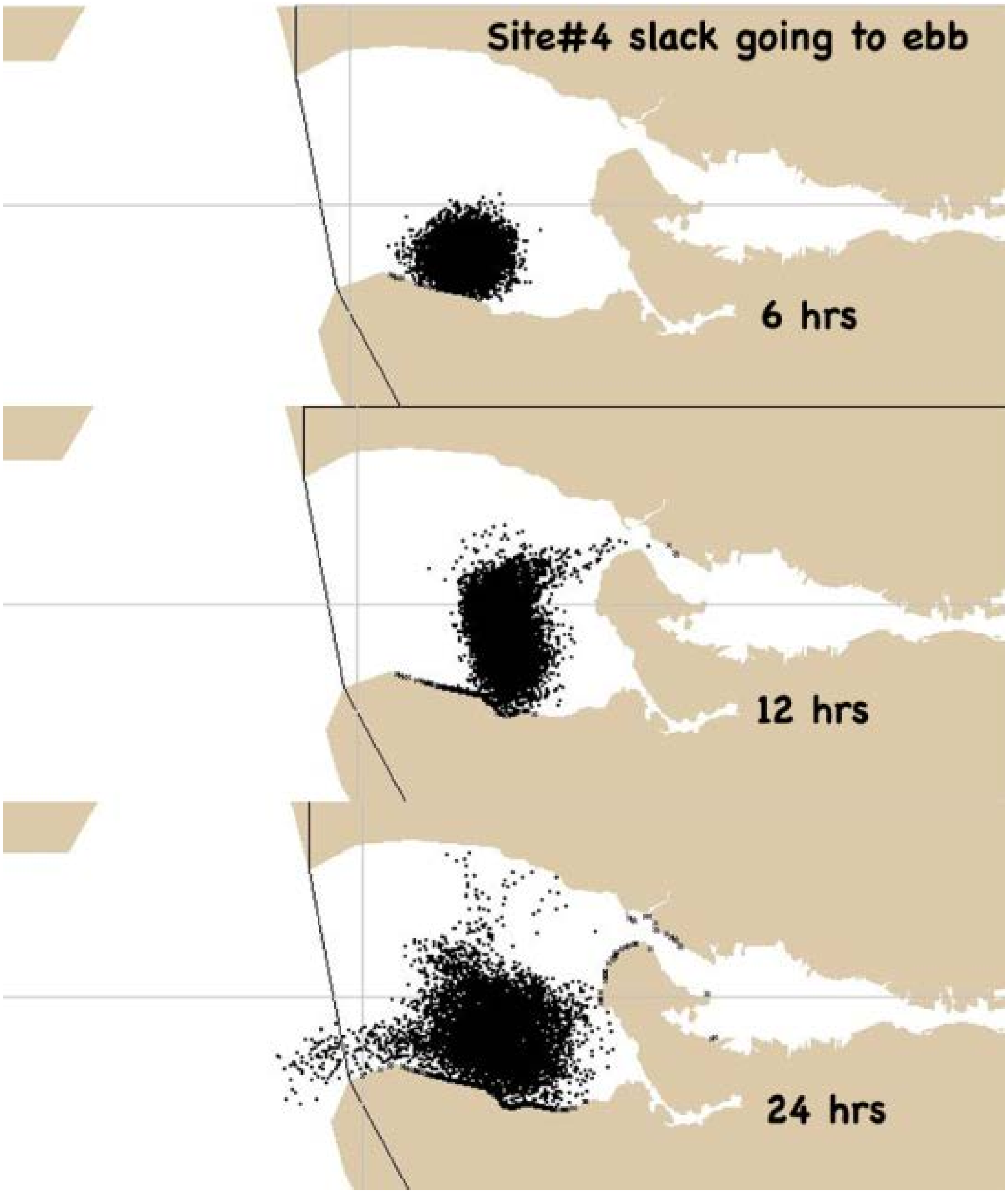

Figure 18: Oil spill trajectory time sequence in the Outer Harbour for "slack going to ebb" starting on August 19, 2007 at 01:20

At the beginning of the run (shown in Figure 18), the spill distribution shifted slightly west. This put it in a position to interact with the Strait of Georgia Kelvin tidal wave. The initial flood carried oil back toward First Narrows. The next full tidal cycle (at 24 hours) started a major oil exchange between Burrard Inlet and the Strait of Georgia.

Figure 19, below, shows screen captures of the trajectory of an oil spill in the Outer Harbour that we modeled during a "slack going to ebb" condition that occurred on August 19, 2007 at 01:20 at 48 and 96 hours into the spill:

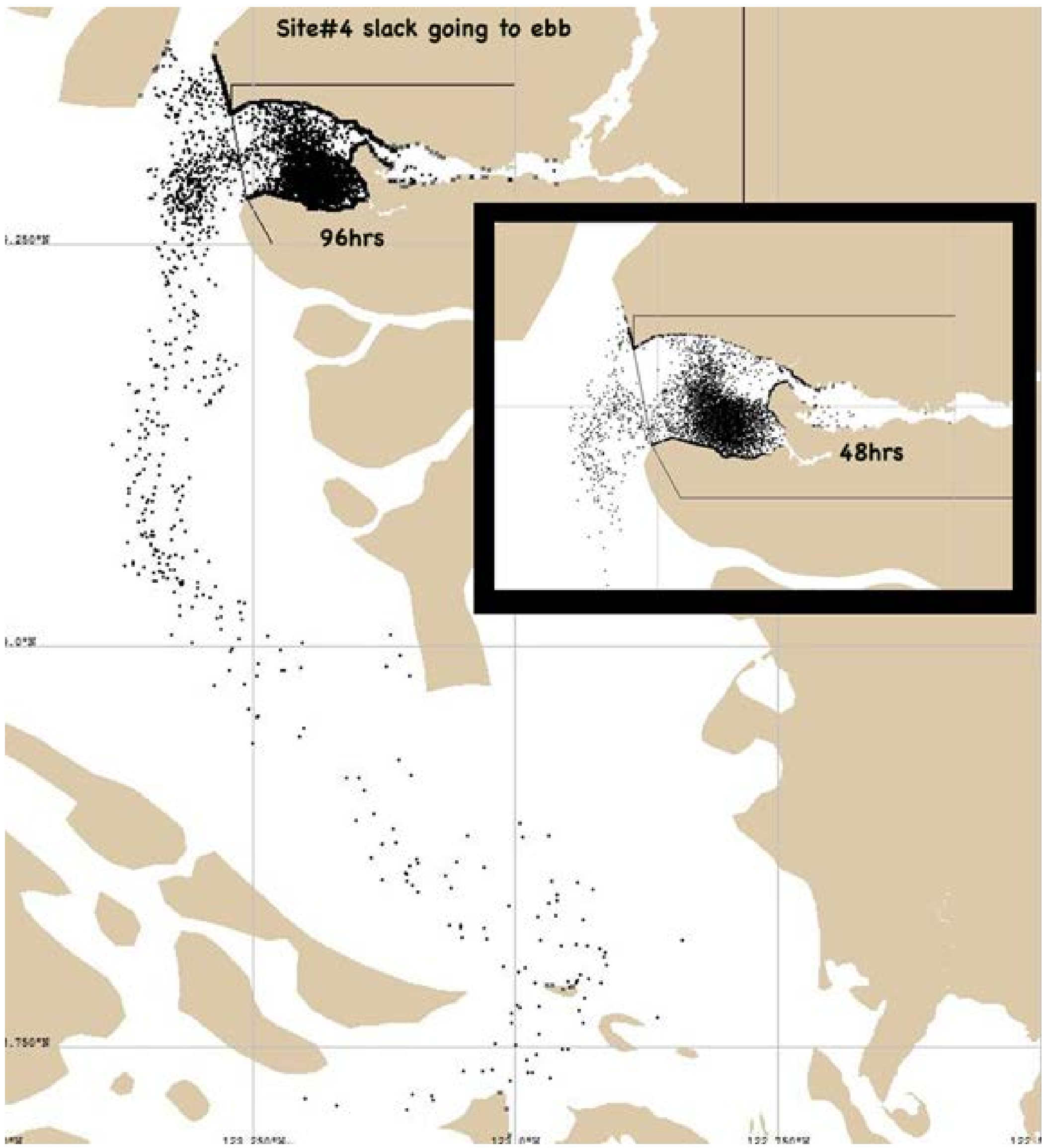

Figure 19: Oil spill trajectory time sequence in the Outer Harbour for "slack going to ebb" starting on August 19, 2007 at 01:20

By 48 hours, a significant amount of oil had moved out of the Outer Harbour although the oil spill's center of gravity was still in the vicinity of the initial spill location. The oil which moved into the Strait of Georgia entered into an entirely different hydrodynamic regime. Two distinct, physical transport processes were present.

First, the situation space in the SSM Map in August 2007 included a significant Fraser River outflow through its northern channel. As this fresh water moved north along the coast, it displaced the floating oil offshore. Very little stranding occurred once oil moved into the Strait, outside and south of Burrard Inlet.

The tidal flow of this Fraser River water also entered the "Kelvin" tidal wave pattern in western Outer Harbour. It pushed oil into the northern portion where it then exited in the vicinity of Bowen Island and Howe Sound.

Second, the physical processes in the SSM Map portion of the Regional Model were a general "down estuary" or southeastern drift toward the center of the Strait of Georgia. This movement averaged more than half a knot per hour. Within two days, the leading edge of the splot distribution made it to the vicinity of Turn Point and the northern San Juan Islands in the United States.

(ii) Steady Nominal Wind

For the steady nominal wind run, we used a 3 knot wind from both the SSW and east as in the First Narrows scenario.

Figure 20, below, shows screen captures at 24 hours of the trajectory of: (1) an instantaneous release of oil during a "slack going to flood" condition that occurred on August 24, 2007 at 13:48 with a 3 knot SSW wind; (2) an instantaneous release of oil during a "slack going to ebb" that occurred on August 19, 2007 at 01:20 with a 3 knot SSW wind; (3) an instantaneous release of oil during a "slack going to flood" condition that occurred on August 24, 2007 at 13:48 with a 3 knot wind from the east; and (4) an instantaneous release of oil during a "slack going to ebb" that occurred on August 19, 2007 at 01:20 with a 3 knot wind from the east:

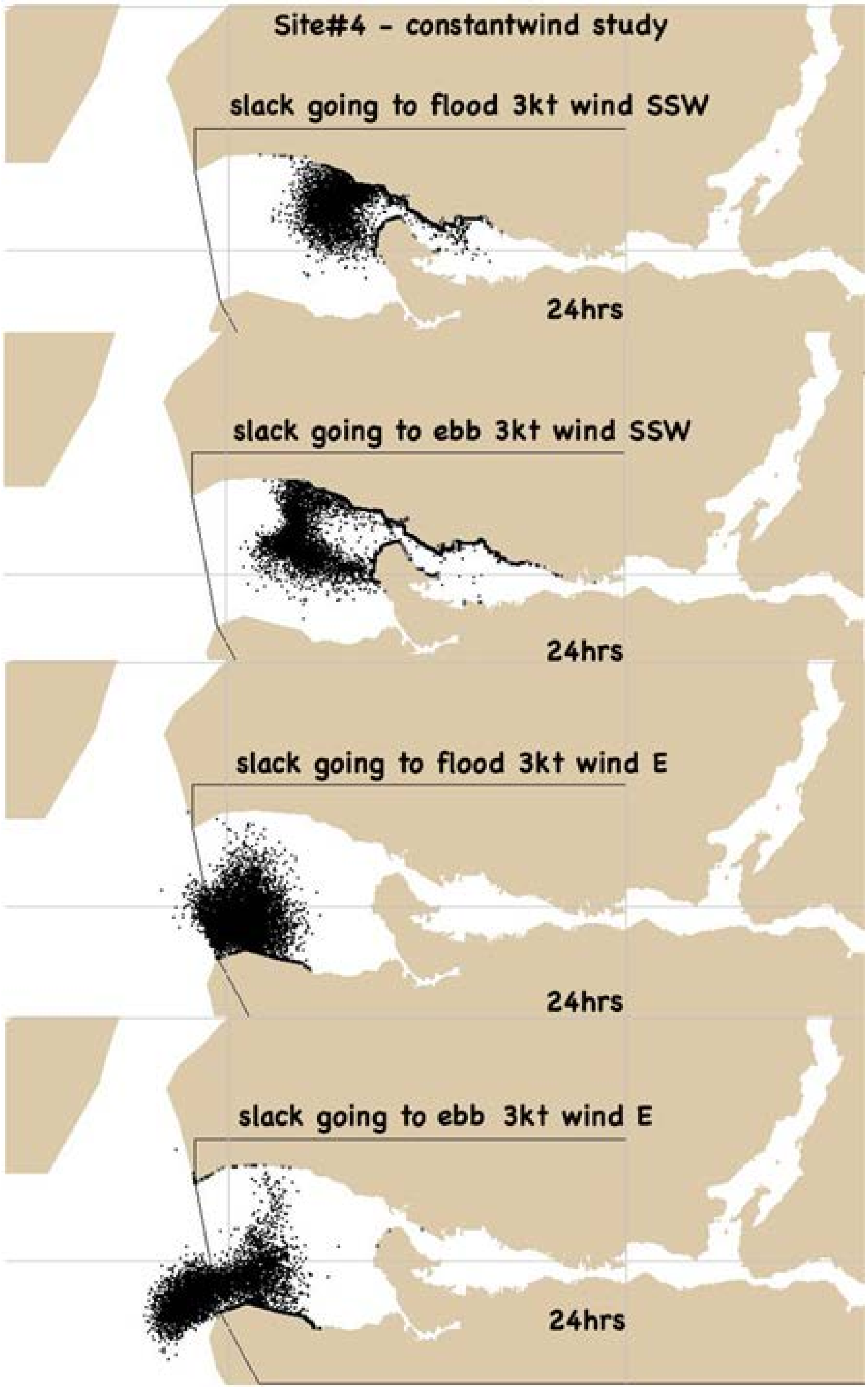

Figure 20: Two oil spill scenarios at First Narrows with a steady 3 knot SSW wind and two scenarios with a 3 knot wind from the east after 24 hours

In the first two panels representing SSW winds, oil from the spills drifted downwind toward the location First Narrows “inhale region” and into the interior part of Burrard Inlet.

In the last two panels, the winds from the east protected the interior sections of Burrard Inlet by pushing the oil westward into the Strait of Georgia, where it interacted with the hydrodynamic regime there.

(iii) Real Winds and Tides

It is not possible to use the Regional Model to model oil spill trajectory based on real wind and tide sequences because the time periods for the SSM Map and CALMET wind data do not overlap.

(e) Conclusions

Based on the four scenarios evaluated in this report, we conclude that:

1. Oil spreads quickly in the confined geophysical setting in Burrard Inlet. The combined results of all the scenarios demonstrate that oil has the potential to spread throughout Burrard Inlet, from the Indian and Port Moody Arms to the Outer Harbour and beyond. Continuous spills will spread more broadly throughout Burrard Inlet than instantaneous spills.

2. Winds and tides are the major drivers of oil movement in Burrard Inlet. Variations in release time and tidal phase are important factors to consider when developing realistic oil spill scenarios. Oil spill trajectory can be more accurately modeled when tidal phase and wind events are linked.

3. Strong winds tended to strand oil on the leeward shore, while weak winds allowed the tidal currents to more widely distribute the oil. When strong winds weakened, the oil tended to refloat and move some distance with the tidal currents. Stranding, refloating and restranding oil is a cyclical aspect of predicting oil spill behavior that is well captured in the Burrard Inlet and Regional Models.

4. Adequate tidal data is available for Burrard Inlet. We used that data to develop the Burrard Inlet Models. However, a limited amount of empirical data on local wind behavior is publicly available. To address that issue, we used the CALMET data set to simulate the complex patterns of wind flow through the Inlet and its arms. Our simulation captured over 80% of the variability in speed and direction. We included current models associated with those wind patterns in Burrard Inlet Model B. This was an improvement which provides greater confidence for scenario results modeled in 2005.

5. In general, the initial conditions at the spill site influenced how the spill behaved. However, after 24 hours, or two tidal cycles, the results of the scenario runs at the

Terminal and Second Narrows tended to converge. This was not the case for the scenario runs at First Narrows and the Outer Harbour.

Because of the closer proximity of First Narrows and the Outer Harbour to the influence of the Strait of Georgia, the initial tidal phase led to qualitatively different four day outcomes. Oil spill trajectory at First Narrows, as a result of its strong and variable tidal currents, did not conform to a single dominant pattern.

Oil spill trajectory at the Outer Harbour was also qualitatively very different from the other sites. This was in part caused by the influence of the Fraser River outflow and predominant current patterns in the Strait of Georgia captured in the Regional Model. Oil spill trajectories were significantly influenced by the Fraser River outflow and currents in the Strait of Georgia as captured in the SSM Map.

7.0 STOCHASTIC SCENARIO MODELING

Any individual scenario run based on a single start time can provide a realistic but not necessarily representative result of oil spill trajectory in Burrard Inlet. A "stochastic approach", which involves combining the results of a number of random start times, can, however, capture the expected range of possible results.

We used Burrard Inlet Model B to perform our stochastic scenario modeling. For each stochastic run, we:

- selected ten (10) random start times from 2005;
- ran Burrard Inlet Model B and compiled the results by elapsed time; and
- statistically analyzed the results.

We carried out this stochastic modeling approach for oil spills at the Terminal (Site #1), Second Narrows (Site #2), and First Narrows (Site #3) locations. We describe the stochastic approach that we used to model oil spill trajectory in Burrard Inlet in greater detail in **Appendix "J"**.

The 18 figures in **Appendix "K"** provide a graphic representation of the distribution of probability of oil being present in a 1 km^2 area ("**probability density**") for a series of times (3, 6, 12, 24, 48, and 96 hours) from a spill at Sites #1, #2, and #3. The environmental conditions influencing oil spill trajectory in those figures is the average of ten different random and independent scenarios modeled as an ensemble.

These figures are rich in information about how the geometry, tidal currents, and weather patterns are expected to influence the potential patches of moving oil. For example, in the screen shot of Site #1 after 24 hours shown on Figure 31 in Appendix "K", contoured values are represented in percentage of the total spill within a 1 km^2 area of the reference point. The highest probability density is found in the Central Harbour and the southern end of Indian Arm, which is greater than percentage 8% per km^2. There is therefore an 8% probability of finding oil in each 1 km^2 area found in those locations.

Generally speaking the pink and blue areas shown in these figures are potential high and medium probability areas of having oil present.

The sum total of the stochastic modeling results shown in these figures demonstrate that a significant fraction of Burrard Inlet is potentially threatened by the modeled spills.

We conducted a further analysis to investigate the stability of the (i) statistical ensemble based on the CALMET and tidal model data, and (ii) 10 element ensemble. At Site #1, we repeated the stochastic approach set out above twice using different random start times.

The figure in **Appendix "L"** shows the probability density distributions for the three statistically independent estimates of the 12 hour distribution at Site #1. As expected, these are not identical. At the detailed level, there are differences. However, the general span of the distribution and the patch sizes of the high concentration areas as well as their general locations are consistent. This provides confidence that the general distributions shown in these figures are a realistic representation of expected threatened zones anticipated in an actual release scenario. This also indicates that 10 runs used in an ensemble is a reasonable approach.

However, it should be noted that the data only covers the span of one year. Extreme events, such as a 10 or 50 year storm, are not, therefore, captured by the model. A substantial amount of oil was beached during the stochastic runs (between 50% and 90% over all cases and for all times), and acted as a secondary source during each of the four day scenario runs. Some of the beached oil was rewashed, which added new floating oil, while some of the floating oil was beached or re-beached.

We conducted an additional analysis which focuses exclusively on the areal coverage of floating oil. The purpose of this analysis is to provide a statistical view of the oil that would be drifting around Burrard Inlet which could be seen in overflights and would be the target of traditional oil spill recovery operations. The 3 figures in **Appendix "M"** show the area enclosed by each of the ⅛%, ¼%, ½%, 1%, 2%, 4%, 8%, and 16% percent of the spill on the x-axis and the area of the spill (in km^2) on the y-axis. Generally speaking, the results shown in those figures indicate that the highest probability regions for floating oil disappear relatively quickly (because most of the oil is at least temporarily on the beaches) but that oil in areas subject to lower, but still significant, percentages of the spill tends to spread covering many tens of square kilometers. This is particularly true for Site #3 (First Narrows), where in four days an area of nearly 90 km^2 might expect to have some floating oil present.

8.0 USE OF THE BURRARD INLET MODELS AND THE REGIONAL MODEL TO MODEL OIL SPILL TRAJECTORY IN BURRARD INLET

Burrard Inlet Model B and Regional Model provide a realistic representation of the behavior of oil spills in Burrard Inlet. They can therefore be used to realistically evaluate the possible extent of oil spread resulting from a spill at the Terminal, Second Narrows, First Narrows, and the Outer Harbour locations.

I have been informed that: (a) the Partners will be using the Models to model oil spill trajectory in Burrard Inlet arising from potential oil spills at the four sites (Terminal, Second Narrows, First Narrows, and the Outer Harbour) examined in this report; and (b) the purpose of that modeling is to generate information required to assess: (i) oil spill response capacity and gap analysis; (ii) the fate and behaviour of oil spilled into Burrard Inlet; (iii) the ecological, socio-economic, and human health effects of oil spills in Burrard Inlet; and (iv) emergency response planning and public safety in relation to the Project.

I provided instructions to the Partners, which, are based on the appropriate modeling approaches and methods to do this modeling work. My instructions to the Partners are set out in **Appendix "N"**.

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Appendix “A”: CV of Dr. Jerry Galt

DR. JERRY A. GALT

Chief Oceanographer

TECHNICAL EXPERTISE

Dr. Galt has extensive experience in computerized data systems, oil spill response and oceanographic modeling. He supervised the Hazardous Materials Response Division of the National Oceanic and Atmospheric Administration (NOAA). He directed a multi-disciplinary scientific program combining theoretical research and real-time computer applications at accidental spill scenes. He directed the computer modeling component at over one thousand oil and chemical spill responses during his career.

EDUCATION

Ph.D. Physical Oceanography/Geophysical Fluid Dynamics, University of Washington, 1969

M.S. Oceanography, University of Washington, 1967

B.S. Applied Mathematics, University of Washington, 1967

B.S. Physics, University of Washington, 1963

EMPLOYMENT

2000–Present:	Genwest Systems, Information Use Strategist/Chief Oceanographer
2006-Present:	Member of the MMS modeling review board attending meetings at Reston VA Offices and MMS sponsored conference in New Orleans
1973-2000:	National Oceanic and Atmospheric Administration, Hazardous Materials Response Division, Division Chief
1970-1973:	Naval Postgraduate School, Monterey, California, Assistant Professor of Oceanography

RELATED PROJECT EXPERIENCE

Oil Spill Simulation Model (OSSM™)

Directed the development of OSSM™ by the Hazardous Materials Response Division (HAZMAT) of the National Oceanic & Atmospheric Administration Office of Response & Restoration. OSSM™ is an oil spill trajectory model that simulates oil movement due to winds, currents, tides, and spreading. HAZMAT used this model during spill responses to calculate the best guess of the spill's trajectory.

OSSM™ lets one predict how winds, currents, and other processes might move and spread oil spilled on the water.

OSSM™ demonstrates how predicted oil trajectories are affected by inexactness ("uncertainty") in current and wind observations and forecasts.

OSSM™ shows how spilled oil is predicted to change chemically and physically ("weather") during the time that it remains on the water surface.

General NOAA Oil Modeling Environment (GNOME™)

Led the development of GNOME™, a publicly available version of OSSM™, which is useful for planning and educational purposes.

GNOME™ utilizes Location Files or prepackaged geographically specific oceanographic and meteorological datasets to assist users.

Current Analysis for Trajectory Simulations (CATS™)

Led the development of CATS™, an application that quickly generates two-dimensional current patterns from digitized finite element vertices and assumptions regarding the local physical oceanographic dynamics and boundary conditions. The current patterns created can be output in a public domain digital format and can be used directly in all of the NOAA HAZMAT trajectory models such as OSSM™ and GNOME™.

Using the finite element method, CATS™ quickly and efficiently solves barotropic steady-state current patterns in topographically complicated domains.

Dispersant Mission Planner – ExxonMobil (with NOAA , API, USCG, and other agency and oil industry consultants)

Participated in the refinement of earlier models (developed by Genwest Systems & Allen, Spiltec) to facilitate the assessment of system performance and Effective Daily Application Capacities (EDACs) involving the use of chemical dispersants. Continued development and refinement of system performance simulations leading to the Response Options Calculator (ROC), currently used by industry and agencies in the United States and abroad to assess mechanical, burning and dispersant daily recovery, burning and application potentials.

Modeling Review Board—The Dept. of the Interior, Minerals and Management Service {subsequently Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) and Bureau of Safety and Environmental Enforcement (BSEE)}

Provided ocean modeling expertise in an advisory capacity by reviewing the progress and quality of modeling in the Bering Sea and Atlantic Ocean, assisting in the implementation of a new ocean circulation modeling initiative in the Gulf of Mexico, and reviewing ongoing circulation modeling studies in the outer continental shelf regions and the integration of study results in the Oil Spill Risk Analysis (OSRA) model.

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Appendix “B”: Certificate of Expert’s Duty

I, Dr. Jerry Galt of Arlington, Washington, U.S.A. have been engaged on behalf of the Tsleil-Waututh Nation to provide evidence in relation to Trans Mountain Pipeline ULC's Trans Mountain Expansion Project application currently before the National Energy Board.

In providing evidence in relation to the above-noted proceeding, I acknowledge that it is my duty to provide evidence as follows:

1. to provide evidence that is fair, objective, and non-partisan;

2. to provide evidence that is related only to matters within my area of expertise; and

3. to provide such additional assistance as the tribunal may reasonably require to determine a matter in issue.

I acknowledge that my duty is to assist the tribunal, not act as an advocate for any particular party. This duty to the tribunal prevails over any obligation I may owe any other party, including the party on whose behalf I am engaged.

Date: March 26, 2015 Signature: ____________

Appendix “C”: Peer Review of the Oil Spill Trajectory Modeling Completed by Trans Mountain

INTRODUCTION:

Building a hydrodynamic model of a large complex geophysically realistic region is a multi-decade person-year effort. As such they all come with a genealogy of sorts and this model application presented by Tetra Tech is no exception. This work can be traced back several decades through a series of models developed for the Salish Sea region by researchers at UBC and associated with marine researchers in the Canadian oceanographic, meteorological, and fisheries service. Additional references indicate the authors are acquainted with possible specialized model refinements that would be significant in transport issues related to hydrocarbons and their by products. This certainly represents a credible model of the dominant physical process that governs the general currents in the area.

That being said there are several extensions and innovations presented in this study which need to be considered in terms of their validation histories. The first of these is the inclusion of 3-dimensional flow fields. While many modern modeling efforts have gone to this step, we should remember that the vast majority of calibration and verification efforts have been focused on the comparison of model results to well-established tidal height data. In general, skill is associated with how accurately the phase and amplitude of major tidal components are predicted. This report mentioned just this sort of comparison. What is not so widely considered is that the major tidal components are largely dependent on the depth averaged transports or vertically integrated currents. Thus the extensive comparisons to tidal height data says very little about shear within the water column and models which include 3-dimensional flow have not been verified for these shear flows, or differential layer motion with anything like the same accuracy that is expected for the vertically integrated or depth averaged flow.

The second extension seen in this report is the increased resolution required to cover areas of special interest. This has required finer grid insets and extension to the historical domain. In this case of an inset used to represent the Straits of Georgia region influenced by the Fraser River, the procedure is one of interpolating state field data back and forth between the base model and zoom model and is a reasonably well-established procedure. On the other hand the grids representing Burrard Inlet and the Fraser River are extensions of the model domain and represent new models. This does not make them wrong, but it does mean that the level of verification and historical acceptance is less than that of the general modeling framework in which they are embedded.

This modeling program is large and complex and has many particular facets. As one might expect the "devil is in the details" and there are many.

DETAILED CONSIDERATIONS:

1) Inundation is represented in the model by turning on a series of additional "thin" layers as tidal rise floods a region. The author does not specify how this algorithm works, but from the models' antecedents I assume that the mechanism is similar to model developed by (USGS) Ralph Chen for San Francisco Bay. At various times (NOAA) HAZMAT worked with Dr. Chen using this model to estimate oil transport in San Francisco Bay. The (on–off) shallow water

flow fields were difficult to interface with oil transport algorithms and particularly beaching. This is never actually explained in the documentation although the authors do say that for the cases modeled this did not seem to be a factor (i.e. the oil did not go there).

2) The report states that 3-D trajectory fields are limited to a single model grid. This does not seem to present a domain problem for studying cases where the pollutant is introduced into the domain sufficiently removed from the single grid boundary. The use of 3-D currents to trace the dissolved fraction of the pollutants is much more complex and does suggest some reservations. From a mass balance point of view the removal of the dissolved component from the floating (essentially 2-D) Lagrangian particle modeling framework is straightforward, but to then reconstitute them as a scalar field in a 3-D Eularian framework is riddled with technical problems. Patchiness, grid size and numerical dispersion to name some specifics. With this in mind, the surface oil trajectories are not likely to be compromised, but 3-D dispersed fields should probably be considered as interesting, but not strongly represented.

3) The validation of the inset and extension sub-models is generally vague and qualitative. Using a single ADCP record for Burrard Inlet and concentrating on the upper layer is basically looking at the barotropic component of the flow and as stated above suggests that the depth averaged behavior is correct but does not say much about the 3-D aspects of the model. An additional reference is shown in the Appendices that documents a 3-D internal seiche as seen by the model when applied to a stratified lake. It should be noted that the internal fields (baroclinic components) are very much in phase indicating that a surface motion (barotropic) is simply rocking the layers back and forth, and thus not a particularly strong verification of the models 3-D behavior. All this being said, the model does show good behavior for the barotropic (depth averaged) flow and from an “oil trajectory modeling” point of view this may be sufficient to provide useful results. Oil is primarily a floating (surface) pollutant and depth averaged models tend to get tidal excursions right. As long as the other oil movement mechanisms are correctly applied depth averaged models have done well at representing oil trajectories.

4) Using the model to hindcast the movement of a search and rescue target is an interesting anecdotal addition to the model verification. The area from Active Pass to Turn Point is notorious for its filamentous rips and strong convergence lines. It is not likely that this or any model does particularly well at predicting these sorts of details. For the model to successfully represent a single trajectory may be fortuitous.

5) The report of the modeling work does not present any spatial details of the wind reanalysis for Burrard Inlet. Since the wind is very important for oil trajectory algorithms and there is significant orography around the Inlet (particularly Indian Arm); this is a shortcoming. It would certainly be hard to evaluate the output from CALMET without some wind pattern data. It seems likely that drainage winds in Indian Arm and the Fraser River valley are significant contributors to the movement and spreading of oil slicks and how these details are resolved is of interest.

6) On a larger scale the hydrodynamic model has problems resolving all of the non-linear complexity associated with the Gulf and San Juan Islands. The coupling of hydraulic impedances through the many complex channels is a truly formidable task. In particular, areas such as Active Pass and Cattle Point are not truly resolved. Net anti-cyclonic circulation around the San Juan Islands and seiche behavior in Bellingham Bay are only approximated. To the south Puget Sound is not particularly well resolved. All this means that the representation of extended forecast scenarios will lack detailed accuracy. This is not a specific problem with Trans Mountain’s modeling efforts, but rather a warning on the general complexity of the regional modeling problems.

7) The use of CALMET for the air dispersion component for the trajectory modeling is a commonly used approach, but the atmospheric stability characterization uses the older PG stability classes that assume Gaussian plume dynamics and fairly long averaging times. This is similar to what is used in NOAA's ALOHA modeling component of CAMEO. A stronger approach such as is used by NIST's HYSPLIT model picks up the Monin-Obukhov length stability parameterization from a regional meteorological model and is generally thought to do a better job at representing small-scale pollutant distributions over variable terrain. Whether this added level of effort is necessary for this admittedly smaller component of the study is an open question. As a point of reference, this same issue came up in proposed hazmat planning studies of emergency response during the widening of the Panama Canal.

In addition to the above issues that generally relate to the hydrodynamic and meteorological modeling components of this study, there are some details of the oil trajectory subcomponent SPILLCALC and the set up of trajectory scenarios that suggest some additional comments.

8) The initial spreading of the spilled Lagrangian element (traced oil volume) is a somewhat contrived algorithm. While it may be a simple heuristic patch it should be recognized as introducing a scatter (and uncertainty) in the location of the spill site.

9) The use of a wind drift factor is standard in most oil trajectory models. The details in SPILLCALC however are definitely not. The physical background of this algorithm is based on two different processes. First, a floating oil film interacts with the small wind waves (ripples) such that the waves are dampened. This is why an oil slick appears smooth compared to surrounding waters and is distinguished in SAR and SLAR images as a region of reduced Bragg scattering. Over a number of years NOAA—HAZMAT response personnel have measured this differential oil/water drift for individual oil patches and the result is that the oil seems to crawl across the water it is floating on at a speed correlated reasonably with 0.75-1.5% the wind speed. The second process is that wind and waves over water develop a thin shear layer in the surface current structure. This near surface drift is described as Stokes Drift and Langmuir Circulation and introduces significant shear in the first part of a meter directly beneath the surface. This very thin layer is typically not resolved in the supporting hydrodynamic transport model; particularly if the upper layer cell size is larger than a part of a meter and does not include Langmuir Cells. Because of this, most oil trajectory models simply parameterize this effect as an additional 2% of the wind speed with

occasionally a rotational angle. Adding these effects together, the standard (or nominal) wind drift factor is taken as about 3% of the wind speed.

The Trans Mountain reports do not present enough details to determine if the Stokes Drift and Langmuir Circulation are represented in the model advective fields and if they are not then the 1% drift factor use will significantly underestimate the effects of local winds on oil movement as represented by this model study.

10) The description of small scale spreading in the model introduces a minimum thickness as a surrogate for patchiness. This is common in oil weathering models because the spreading of the composite slick envelop is dominated by the large scale hydrodynamic dispersion processes and the actual spreading on the oil is dominated by oil properties (dispersion droplet size, density, viscosity, etc.) and small scale hydrodynamic such as Langmuir cells or windrows. The difference in the typical length scales of these two processes results in patchiness. The choice of "a minimum" simplifies the computations but introduces a significant uncertainty that then propagates throughout all of the complex coupling of the weathering routines. This weakness is not unique to SPILLCALC but it should be recognized as a heuristic patch that weakens the algorithms and trajectory estimates of the scenario outcomes. To get around the "minimum thickness" assumption, stronger patchiness algorithms based on more detailed droplet statistics have been proposed and implemented in test models, but as of yet have not been quantitatively calibrated against actual data.

11) Within the spill scenario development, the value that is used for D in the random walk component is never specified and it appears to be left as a "tuning" parameter. For long time scales, larger scale hydrodynamic will tend to dominate, but during the initial few hours of the spill the choice of this value could be significant, particularly if it interacted with other aspects of the scenario parameterization (see beaching considerations below).

12) The SPILLCALC approach to beaching processes is a serious shortcoming that weakens the results of the trajectory analysis. Up to the parametric "holding capacity" of the shoreline this algorithm simply removes the oil from any additional movement and spreading. This is strongly contradicted by experience with thousands of real spills. Heavily oiled shoreline tends to be rewashed, particularly by tidal action and in cases of rocky shorelines or man-made structures. In these cases, the stranded oil is not removed, but simply delayed and then acts as a secondary source, being moved along by a new set of trajectory processes. In the early history of oil spill trajectory analysis (when trajectories were done by people, not models), it was commonly suggested that oil was sort of like a tennis ball, you got about 3½ bounces against shorelines (leaving residual oil on all of them). This is particularly true in a river environment where proximate shoreline is the rule. Rivers through built up urban areas are particularly prone to rewashing, trapping oil under piers and repeatedly providing secondary sources to extend the trajectory analysis problem in both time and space. Numerous spills in San Francisco Bay have demonstrated this sort of behavior. An additional trapping effect has been seen in rivers during freezing conditions. As ice grows, oil droplets will be encapsulated within the ice, which is then frozen along the

shorelines or drifts downstream. Whenever and wherever this ice melts it releases the oil as a secondary source for an extended trajectory problem. During the Ashland Oil spill on the Monongahela River it was estimated that up to 30% of the spill may have be incorporated into the ice matrix and contributed to the new sources after the melt and well down into the Ohio River beyond Pittsburgh.

13) The scenario data presented in table 8.1.2 of the report is very misleading and reflects some significant constraints placed on the initial assumption used to define the spill. Basically, the results show the spill trajectory problem stabilizes with a nearly constant amount of shoreline oiled, virtually no oil still moving around via transport processes, yet over half the oil is still floating on the water. The reason for this odd behavior is that the ground rules for the scenario postulate that the containment boom is always in place and always works. A significant fraction of the spill is never released to the trajectory transport process. With wind effect, tidal eddies, and terminal boating activities being what they are, that seems a bit optimistic. In actuality, the spill trajectory model is processing a “hypothesized” much smaller spill. For planning purposes a containment boom is a good idea and is bound to help. But to guarantee its effectiveness suggests more faith than historical certainty.

CONCLUSIONS:

The Trans Mountain modeling effort is a complex coupled hydrodynamic—spill trajectory set that does a reasonable job of representing potential oil spill behavior over most of the covered Salish Sea region subject to the general limitations described in item 6) above. There are however some troubling components in the trajectory algorithms and specification of scenarios that may lead to significant misrepresentations in the final trajectory analysis results.

The most serious shortcoming appears to be with the beaching algorithm in SPILLCALC. As described in item 12) above, this could lead to significant underestimates of both the extent and duration of concern associated with a spill. This would be more significant in scenarios representing spills in Burrard Inlet and the Fraser River and somewhat less critical in modeled spills of the Straits of Georgia and the Straits of Juan De Fuca.

A second potential shortcoming of the SPILLCAL formulation is the use of a smaller than normal wind drift factor as described in item 9) above. The actual hydrodynamic resolution of the very thin surface shear layer is not reported, however there is no explicit mention of Stoke drift or Langmuir circulation components and it seems likely that the scenarios presented (using a 1% drift factor) may seriously underestimate the coupling between oil movement and local winds. For example, NOAA modeling for emergency response defaults to random values of wind drift between 1 to 4½ %. This could lead to fairly large differences in estimated trajectories, and particularly when compounded against beaching and refloating algorithms. Overall this could lead to a quite different set of threatened areas and resources.

Appendix “D”: SAV Files for Modeling Oil Spill Trajectories in Burrard Inlet

Genwest generated three SAV files to be run in the Diagnostic mode of GNOME version 1.3.9 (and later) for intuition building and objective quantitative and qualitative analysis of oil spill scenarios. These scenarios are entitled BurrardInlet.sav, Burrard_statistics.sav, and SSM_Burrard.sav.

Two of the SAV files (BurrardInlet.sav, Burrard_statistics.sav) are for use solely for oil spill scenarios that will remain within Burrard Inlet, whereas SSM_Burrard.sav is for use on oil spill scenarios where oil is anticipated to move outside of Burrard Inlet and into the Strait of Georgia and beyond.

BurrardInlet.sav contains a map of Burrard Inlet that ends at the western boundary of English Bay. The built-in GNOME diffusion function is used to reflect uncertainty associated with the model. No wind mover has been activated. The user should create a constant or variable wind mover based on the scenario created for planning purposes. Five current models are included. One current model is associated with tidal currents associated with the tidal station at First Narrows. Tidal data from January 1, 2004 through December 31, 2014 are associated with this current model. There are also current models associated with Capilano River, Indian River, Lynn Creek and Seymour River. The currents associated with these models cause very localized effects so are not active. Should a spill occur near one of these areas and outflow data is known, the current can be made active and set to reflect the outflow.

The SAV file can be run for anytime from starting at 0000 hours January 1, 2004 through 2400 hours December 31, 2014. However, any scenario should be started early enough to be completed prior to the end of December 31, 2014.

Burrard_statistics.sav contains a map of Burrard Inlet that ends at the western boundary of English Bay. The built-in GNOME diffusion function is used to reflect uncertainty associated with the model. No wind mover has been activated as this file has built-in wind patterns from the 2005 CALMET data. Eight current models are included. One current model is associated with tidal currents associated with the tidal station at First Narrows. Tidal data from January 1, 2005 through December 31, 2005 are associated with this current model. There are also current models associated with the four wind patterns that account for eighty percent of the variance in the 2005 CALMET data. There are models to reflect a north wind that would drain out of Indian Arm and an east wind that would drain out of English Bay. The SAV file can be run for anytime from starting at 0000 hours January 1, 2005 through 2400 hours December 31, 2005. However, any scenario should be started early enough to be completed prior to the end of December 31, 2005.

SSM_Burrard.sav contains a map of Burrard Inlet that ends at the western boundary of English Bay and a map for the Salish Sea. The built-in GNOME diffusion function is used to reflect uncertainty associated with the model. No wind mover has been activated. The user should create a constant or variable wind mover based on the scenario created for planning purposes. Two current models are included. One current model was created by the Pacific Northwest National Lab with tidal currents generated by PNNL for a time period from August

18, 2007 to August 31, 2007. The other model covers Burrard Inlet with an overlap from the western end of English Bay to Lions Gate. The inside model is influenced by the current patterns of the PNNL model. The SAV file can be run for anytime from starting at 0000 hours August 18, 2007 through 2400 hours August 31, 2007. However, any scenario should be started early enough to be completed prior to the end of August 31, 2007. This file will help build intuition of how a spill scenario starting in English Bay might affect the Salish Sea.

Appendix “E”: Map Showing Bathymetric Contour Lines in Burrard Inlet Used For the Burrard Inlet Models A & B

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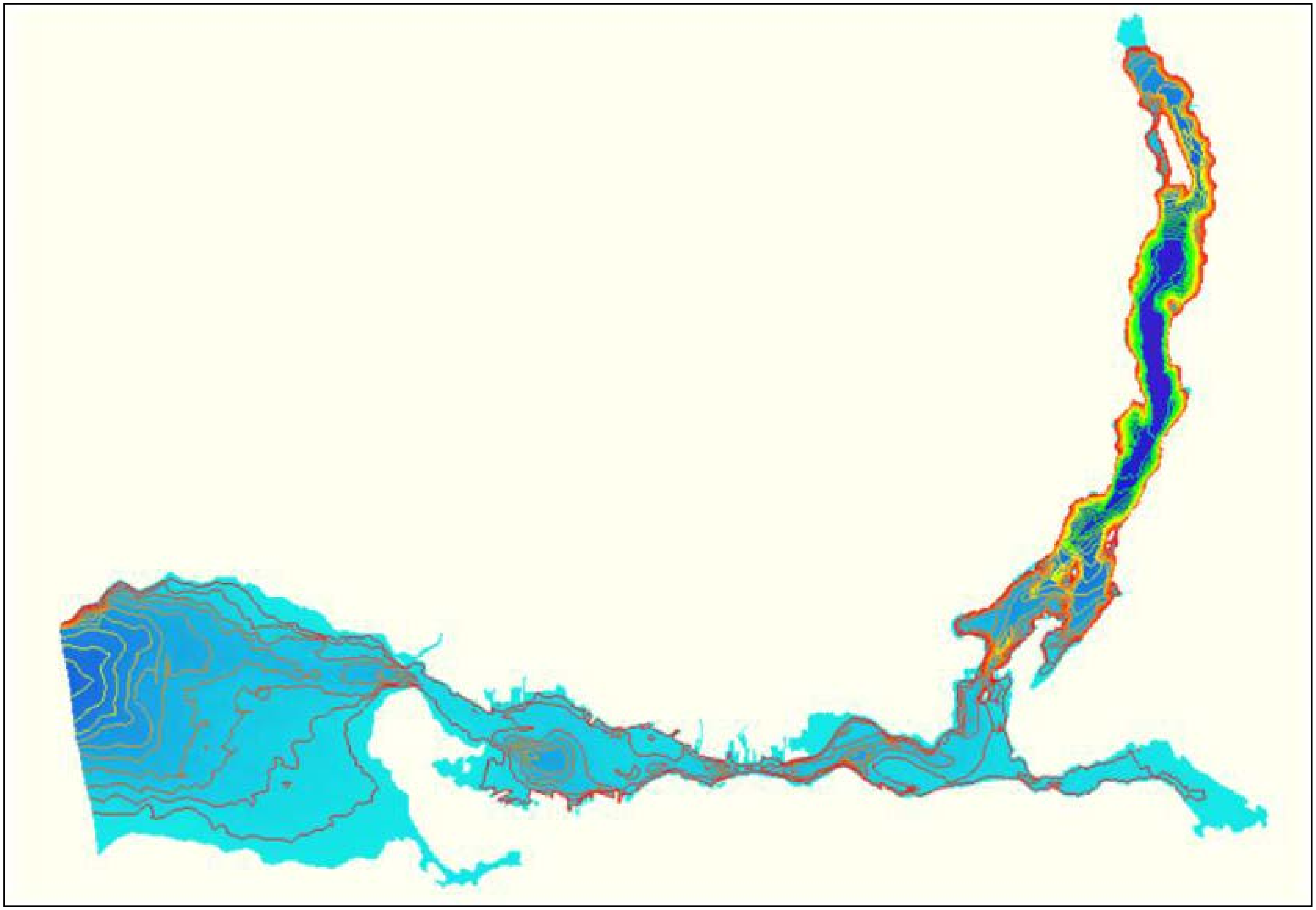

Appendix “F”: Map Showing the SSM Salish Sea Main Computational Domain and Surface Grid Representation

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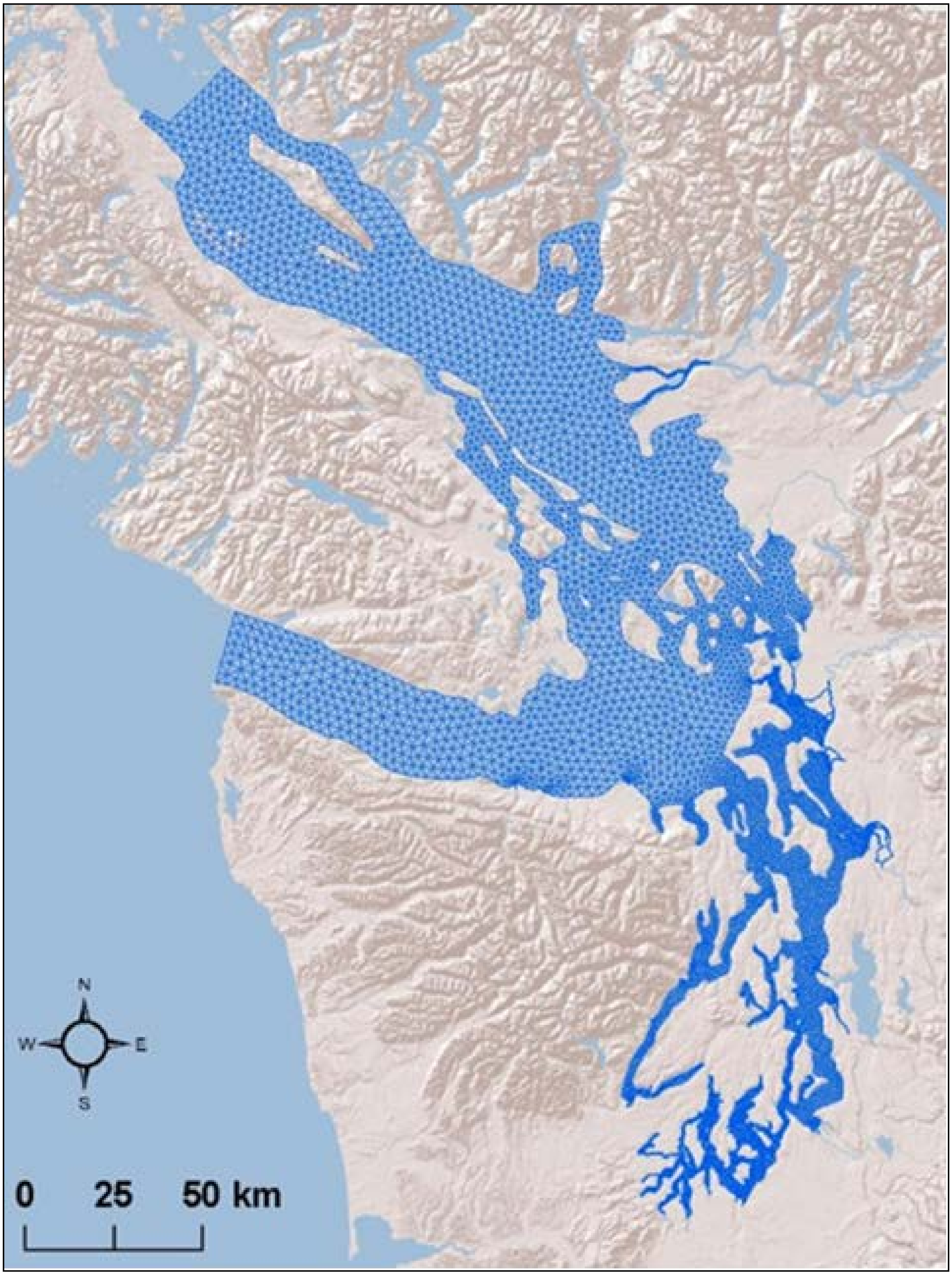

Appendix “G”: Modeling Results (During High Water Flood) For the Western Section of the Outer Harbour

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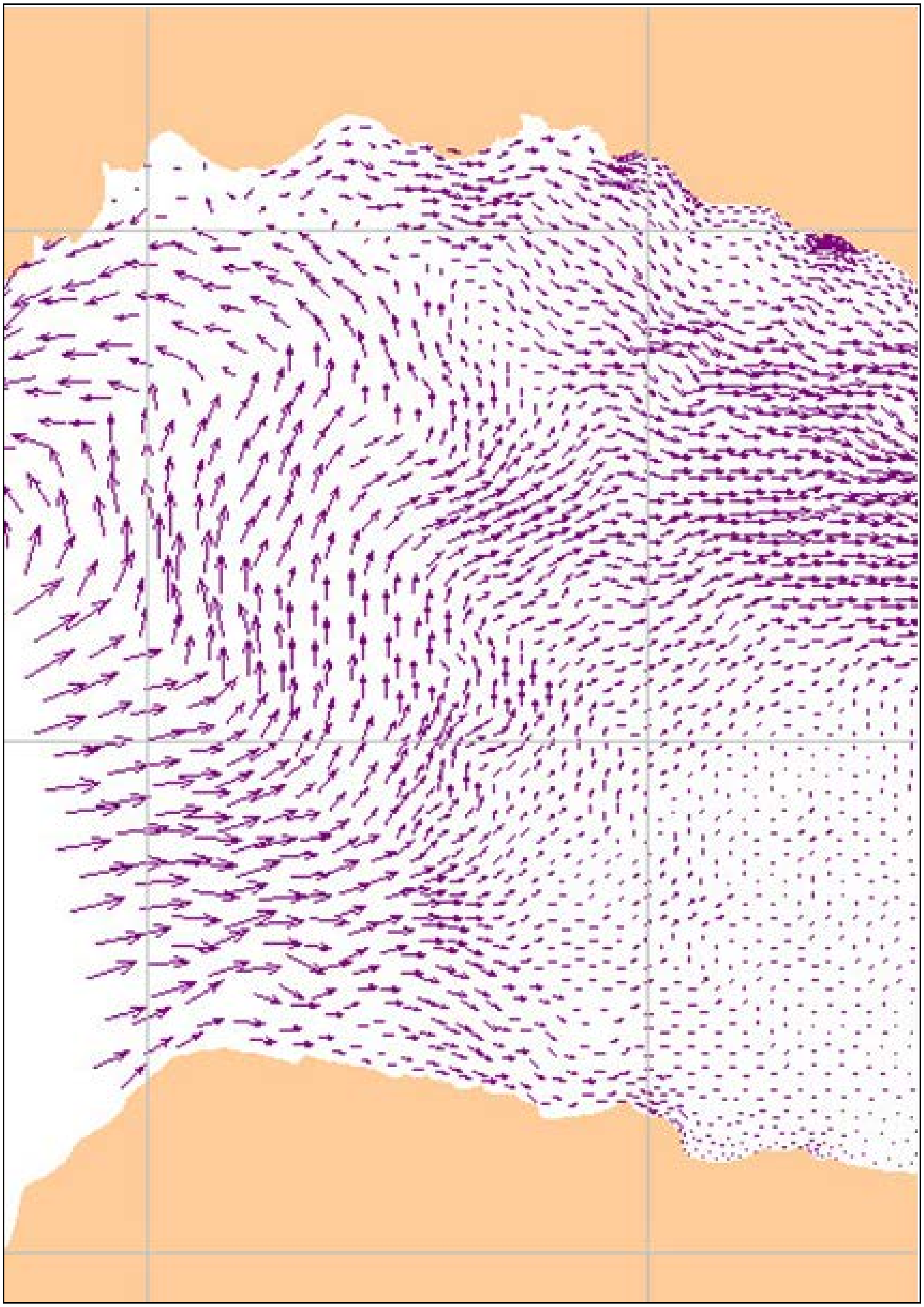

Appendix “H”: Example of Wind Driven Flows Generated By An Easterly Drainage Wind Component Over Port Moody Arm

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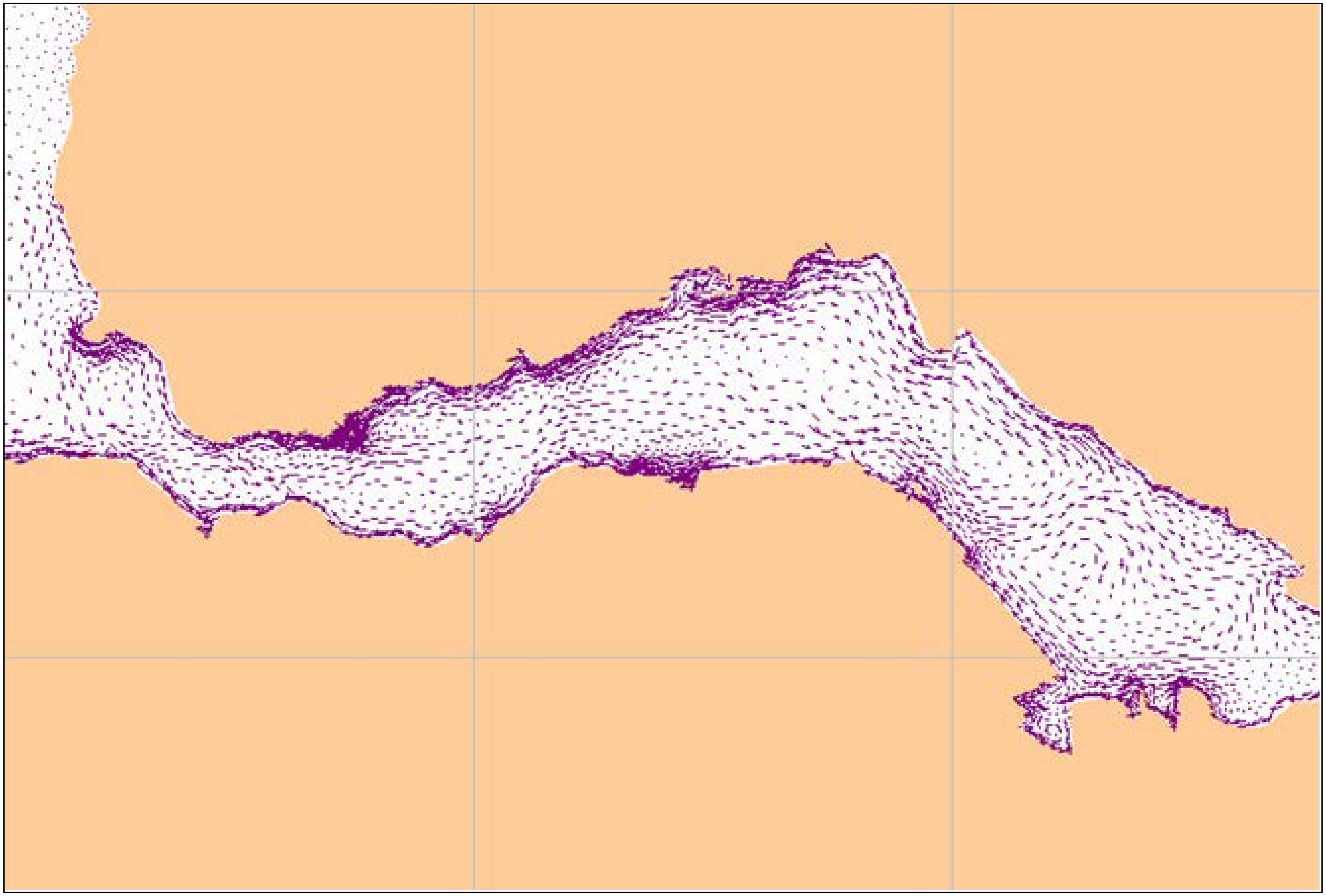

Appendix “I”: Description Of the Method Used To Develop the Four Current Models

Metro Vancouver produced detailed three-dimensional meteorological fields using the diagnostic computer model CALMET, based on surface weather data, digital land use and terrain data, and prognostic meteorological model output based on the NCAR / Penn State Fifth Generation Mesoscale Model (MM5). Metro Vancouver then provided those meteorological fields to Genwest.

We developed the four current models using information derived from the CALMET meteorological model. CALMET is a diagnostic meteorological model that contains high resolution meteorological data for 2005 and detailed resolution of the spatial topography of Burrard Inlet.

Eleven hypothetical meteorological stations were identified in Burrard Inlet. A twelfth hypothetical meteorological station was located at the Vancouver International Airport. A year-long hourly wind record was generated for each of these hypothetical stations.

We modeled wind patterns based on the 2005 hourly wind data from each of the twelve stations. The model created a synthetic observation grid spanning the situation space for wind patterns based on the 2005 meteorological data.

We calculated the following correlation matrix spanning each of the 24 components of the wind patterns (12 stations, each with an east and north component):

1.000	0.087	0.757	0.374	0.357	-0.078	0.512	0.144	0.467	0.098	0.219	-0.008	0.331	0.033	0.330	0.027	0.338	0.022	0.271	0.026	0.349	-0.014	0.230	-0.033
0.087	1.000	-0.253	0.495	-0.026	-0.468	-0.320	-0.398	-0.307	-0.468	-0.283	-0.433	-0.194	-0.477	-0.139	-0.478	-0.182	-0.476	-0.115	-0.479	0.016	-0.496	-0.035	-0.399
0.757	-0.253	1.000	0.191	0.485	0.194	0.785	0.404	0.661	0.401	0.383	0.269	0.416	0.305	0.384	0.294	0.440	0.282	0.323	0.286	0.326	0.267	0.145	0.200
0.374	0.495	0.191	1.000	0.240	-0.312	-0.023	-0.139	-0.052	-0.250	-0.162	-0.295	-0.087	-0.318	-0.032	-0.328	-0.042	-0.332	-0.030	-0.352	0.114	-0.383	0.071	-0.295
0.357	-0.026	0.485	0.240	1.000	-0.150	0.567	-0.014	0.570	-0.016	0.386	-0.087	0.494	-0.089	0.450	-0.090	0.383	-0.091	0.338	-0.100	0.393	-0.078	0.247	-0.101
-0.078	-0.468	0.194	-0.312	-0.150	1.000	0.242	0.848	0.206	0.852	0.322	0.767	0.134	0.825	0.077	0.806	0.199	0.791	0.133	0.741	-0.028	0.722	-0.164	0.648
0.512	-0.320	0.785	-0.023	0.567	0.242	1.000	0.364	0.891	0.413	0.530	0.313	0.598	0.358	0.545	0.347	0.570	0.320	0.461	0.363	0.361	0.373	0.141	0.261
0.144	-0.398	0.404	-0.139	-0.014	0.848	0.364	1.000	0.291	0.952	0.327	0.808	0.171	0.846	0.129	0.821	0.275	0.810	0.163	0.760	0.028	0.713	-0.145	0.647
0.467	-0.307	0.661	-0.052	0.570	0.206	0.891	0.291	1.000	0.350	0.746	0.254	0.697	0.322	0.607	0.314	0.565	0.289	0.490	0.323	0.418	0.330	0.337	0.207
0.098	-0.468	0.401	-0.250	-0.016	0.852	0.413	0.952	0.350	1.000	0.388	0.915	0.202	0.911	0.146	0.886	0.304	0.865	0.177	0.827	0.003	0.794	-0.193	0.750
0.219	-0.283	0.383	-0.162	0.386	0.322	0.530	0.327	0.746	0.388	1.000	0.320	0.648	0.383	0.525	0.377	0.466	0.370	0.394	0.355	0.332	0.342	0.341	0.275
-0.008	-0.433	0.269	-0.295	-0.087	0.767	0.313	0.808	0.254	0.915	0.320	1.000	0.150	0.886	0.102	0.854	0.268	0.827	0.157	0.793	-0.033	0.771	-0.286	0.796
0.331	-0.194	0.416	-0.087	0.494	0.134	0.598	0.171	0.697	0.202	0.648	0.150	1.000	0.206	0.950	0.207	0.786	0.206	0.718	0.230	0.579	0.235	0.300	0.129
0.033	-0.477	0.305	-0.318	-0.089	0.825	0.358	0.846	0.322	0.911	0.383	0.886	0.206	1.000	0.135	0.987	0.281	0.959	0.162	0.912	-0.020	0.869	-0.178	0.764
0.330	-0.139	0.384	-0.032	0.450	0.077	0.545	0.129	0.607	0.146	0.525	0.102	0.950	0.135	1.000	0.131	0.871	0.136	0.807	0.167	0.634	0.172	0.276	0.075
0.027	-0.478	0.294	-0.328	-0.090	0.806	0.347	0.821	0.314	0.886	0.377	0.854	0.207	0.987	0.131	1.000	0.265	0.980	0.147	0.938	-0.036	0.891	-0.178	0.763
0.338	-0.182	0.440	-0.042	0.383	0.199	0.570	0.275	0.565	0.304	0.466	0.268	0.786	0.281	0.871	0.265	1.000	0.267	0.858	0.296	0.621	0.289	0.186	0.209
0.022	-0.476	0.282	-0.332	-0.091	0.791	0.320	0.810	0.289	0.865	0.370	0.827	0.206	0.959	0.136	0.980	0.267	1.000	0.131	0.946	-0.046	0.884	-0.151	0.739
0.271	-0.115	0.323	-0.030	0.338	0.133	0.461	0.163	0.490	0.177	0.394	0.157	0.718	0.162	0.807	0.147	0.858	0.131	1.000	0.147	0.829	0.166	0.244	0.078
0.026	-0.479	0.286	-0.352	-0.100	0.741	0.363	0.760	0.323	0.827	0.355	0.793	0.230	0.912	0.167	0.938	0.296	0.946	0.147	1.000	-0.087	0.964	-0.194	0.764
0.349	0.016	0.326	0.114	0.393	-0.028	0.361	0.028	0.418	0.003	0.332	-0.033	0.579	-0.020	0.634	-0.036	0.621	-0.046	0.829	-0.087	1.000	-0.090	0.364	-0.133
-0.014	-0.496	0.267	-0.383	-0.078	0.722	0.373	0.713	0.330	0.794	0.342	0.771	0.235	0.869	0.172	0.891	0.289	0.884	0.166	0.964	-0.090	1.000	-0.221	0.766
0.230	-0.035	0.145	0.071	0.247	-0.164	0.141	-0.145	0.337	-0.193	0.341	-0.286	0.300	-0.178	0.276	-0.178	0.186	-0.151	0.244	-0.194	0.364	-0.221	1.000	-0.384
-0.033	-0.399	0.200	-0.295	-0.101	0.648	0.261	0.647	0.207	0.750	0.275	0.796	0.129	0.764	0.075	0.763	0.209	0.739	0.078	0.764	-0.133	0.766	-0.384	1.000

Figure 21: Correlation matrix spanning each of the 24 components of the wind patterns

The directional stability of the wind is high (typical of areas constrained by local topography) when two components for the same station are highly correlated. Stable patterns in the wind field are represented by high correlations between adjacent stations.

Figure 22, below, shows the rows in the correlation matrix for the north and east components of the wind patterns at the station in Vancouver International Airport:

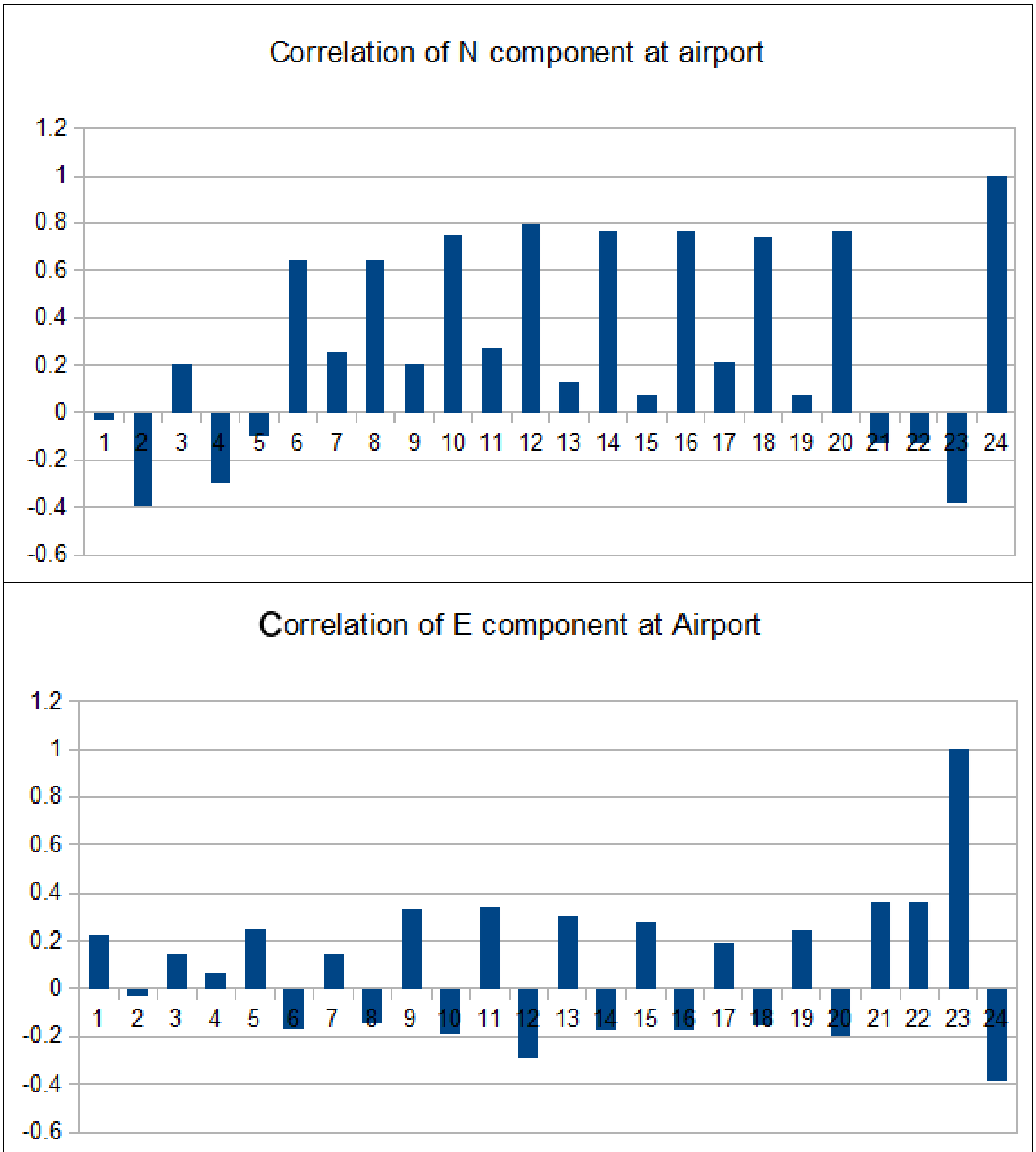

Figure 22: Correlation of the north and east components of the wind patterns at the Vancouver International Airport station

The north component of the winds at the Airport station (#24) is strongly correlated with the north components (even numbers in first bar graph) of a number of the stations, but not correlated with the east components (odd numbers in first bar graph) of those stations.

The east component of the winds at the Airport station (#23) is not particularly correlated with the east component (odd numbers shown in second bar graph) or the north component (even numbers shown in second bar graph) of any of the other eleven stations.

The results shown in Figure 22 suggest that wind patterns may be important but the Airport is not a particularly good indicator of the overall system.

We decomposed the correlation matrix using Singular Value Decomposition techniques.[16] This analysis: (i) provides a set of empirical orthogonal functions (“**EOFs**” or patterns) that are an alternate 24 dimension space which represents the original 24 component Cartesian spaces of the correlation matrix; and (ii) ranks the vectors with respect to the fraction of the total variance each accounts for in the original wind data set. The result is a ranking of the patterns with respect to their significance to the whole data set.

Figure 23 shows the relative significance of each pattern:

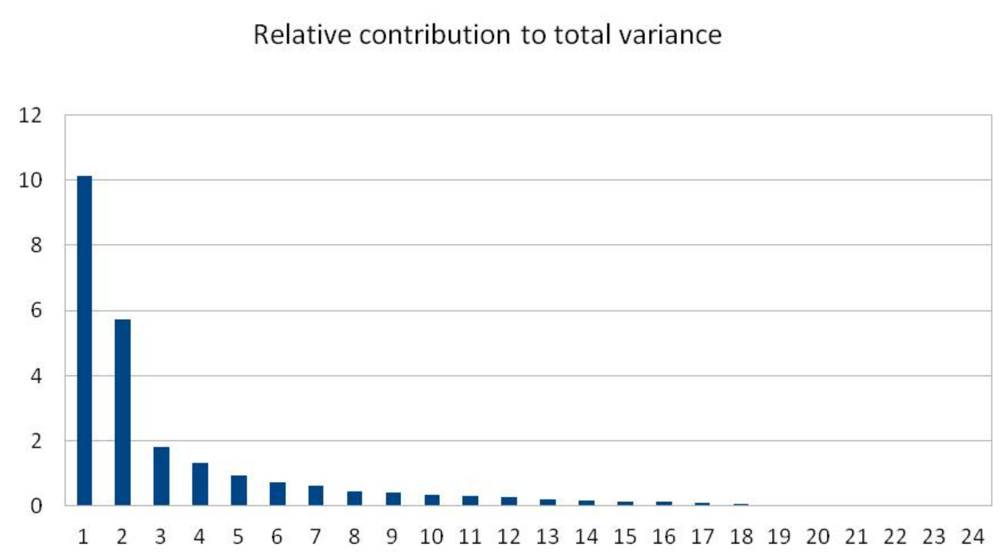

Figure 23: Contribution of each wind pattern to the variance of the original wind pattern data set

The first four EOFs account for over 80% of the all the variability in the original wind pattern data set. This means that instead of viewing the 12 wind locations as made up of 24 independent components of information, most (>80%) of the variance can be represented with 4 standard patterns, which are shown below in **Figure 24**:

[16] (Strang 1988).

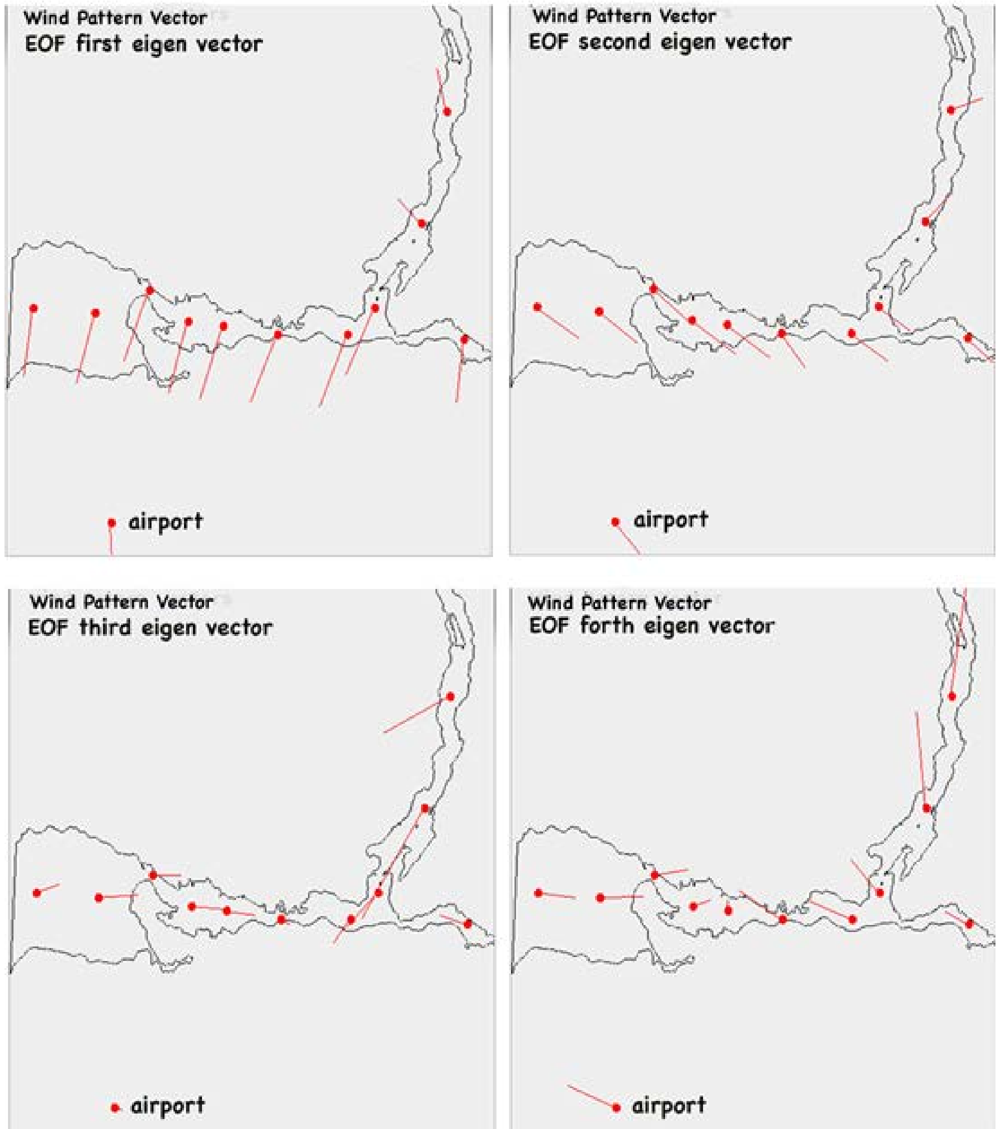

Figure 24: The top 4 patterns which account for >80% of the variance of the original wind pattern data set

Pattern #1, shown on the map in the upper left-hand corner, is a flow from the SSW. It is the most common contributor to variations in wind with annual mean value of approximately 3 knots. Pattern #1 likely represents the typical wind associated with a low pressure region moving in over Vancouver Island during winter storms

Pattern #2, shown on the map in the upper right-hand corner, has an annual mean value of approximately 1 knot. It likely represents a drainage wind down the Fraser River Valley associated with an inland high pressure weather pattern.

Patterns #3 and #4, shown on the maps in the lower left-hand and right-hand corners of Figure 24, respectively, are less energetic and more complex. They suggest convergence patterns over sections of Burrard Inlet that may be associated with a “thermal island” effect related to the very urbanized south shore. The subspace represented by the Pattern #3 – Pattern #4 plane is an independent wind drainage pattern down Indian Arm.

The results of the wind pattern analysis indicate that a simplified modeling approach can be used to approximate regional winds in Burrard Inlet.

To do so, we integrated the four wind patterns we identified above into an independent model. For every hour of the 2005 wind record extracted from CALMET, we projected the amplitudes of the 24 component wind data into 4 dimensional pattern vectors.

Figure 25, below, shows the CALMET data in red and the 4 component projections in blue for four randomly chosen hours in the 2005 CALMET data:

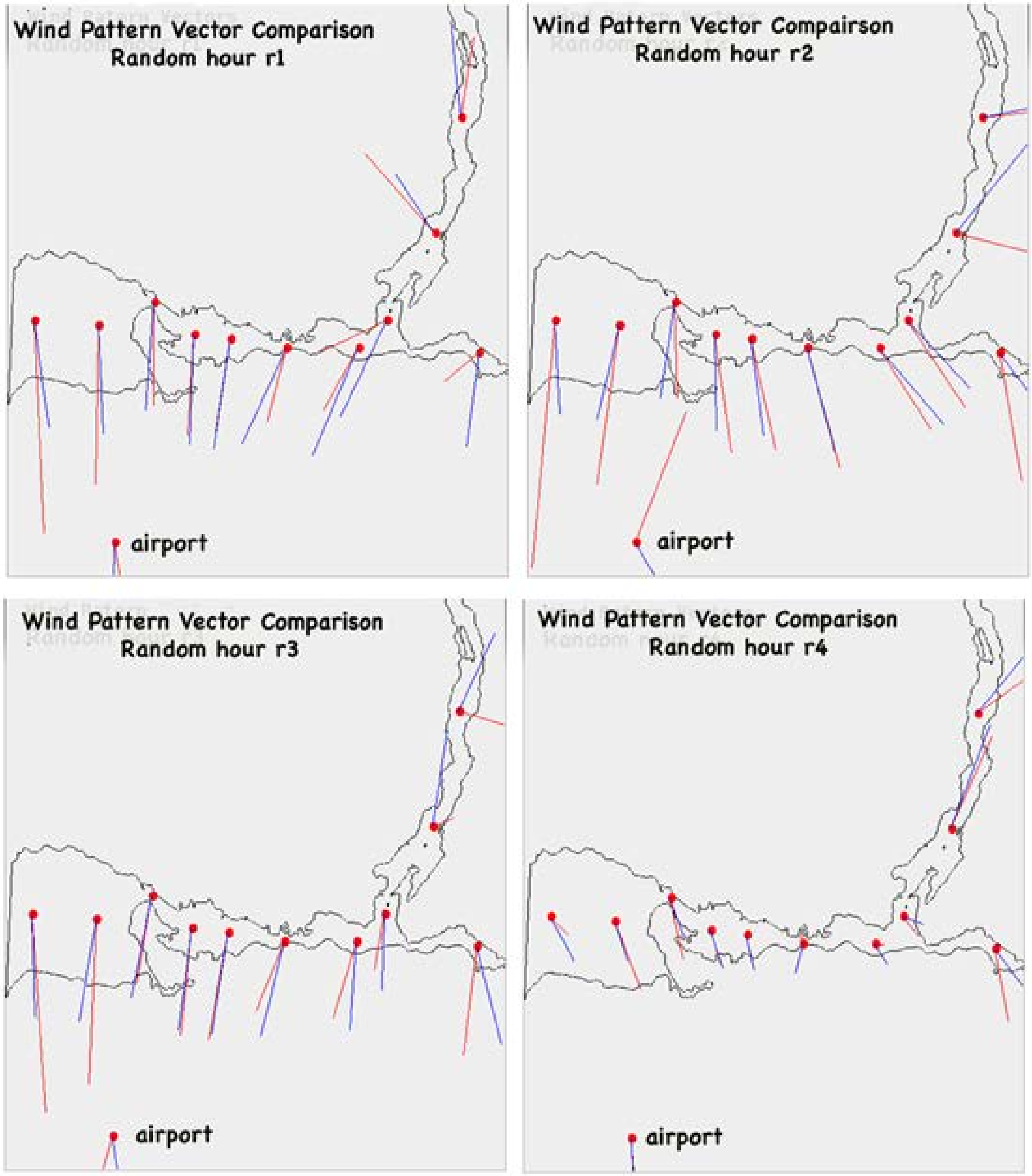

Figure 25: Comparison of the CALMET data and the 4 top patterns for four randomly chosen hours in the 2005 CALMET data

The four component projections do a good job of representing the major variance in the 24 component CALMET data.

This analysis created a simpler model of hourly regional wind patterns that were incorporated into GNOME. The wind from this simpler model captured >80% of the CALMET data variance and, more importantly, preserved transitions as various weather events moved through the area.

The adjunct study results for 2005 were applied to GNOME to develop statistical studies of wind events superimposed on real time tidal phases. It spanned the natural geophysical variations and correlations represented over the study period. The pattern data was extended over the water of Burrard Inlet by using a least squared neighbor smoothing routine and a 100 × 100 grid.

Appendix “J”: Stochastic Scenario Modeling

1. Stochastic Scenario Development

When investigating potential spill events, none of the details of the actual spill scenario (i.e., the time, nature of the spill, and the environmental conditions that exist when the spill happens) are known. All that is known is that spill conditions will be "a situation" drawn from the existing environmental "situation space" for the region.

The first question that comes to mind is, "What is known about the situation space for the region?" This might be more directly posed as (i) "how many different kinds of weather are possible?", and (ii) "how many different kinds of tides are there?" since these are the primary drivers of spill movement in Burrard Inlet. Then comes the question of whether these variables are statistically independent of each other or correlated.

These questions are normally studied by looking at a series of empirical observations. A year's worth of data might show a large number of wind variations and correlated events. It is not, however, particularly likely to capture rare events like 50 or 100 year storms.

The same is true for a year's worth of tidal current data. Generally speaking, ten or more years of coupled current and wind data are thought to provide a strong basis for analysis. For example, the ten year record in the studies used in the Deep Water Horizon response included five hurricanes which represented extreme events.

In Burrard Inlet, available empirical data sets of wind and tidal currents are much more limited. There are, however, dynamic modeling components of correlated wind and current patterns available for 2005 using the CALMET wind fields and the GNOME tidal current fields. This "synthetic climatology" can be used as a sample space to create an ensemble of spill runs that will span the data represented by that year. A single year's record will probably not provide a representation of rare or extreme events, but it will contain a lot of independent events and give a fair picture of average conditions.

The framework for creating an ensemble of spill runs to illustrate scenario variability starts with considering how many initial set-ups can be represented by the 2005 data archive. There are 8,760 individual hours in a year and 8,592 potential hourly starts (cutting out the week at the end to avoid running out of data). Picking any one of these hours at random will give an independent run for a scenario. Picking 10 random starts will provide an ensemble for a scenario.

Figure 26, below, shows an ensemble of spills starting on the 20th day of the first five months of 2005 starting at 00:00 at the Terminal:

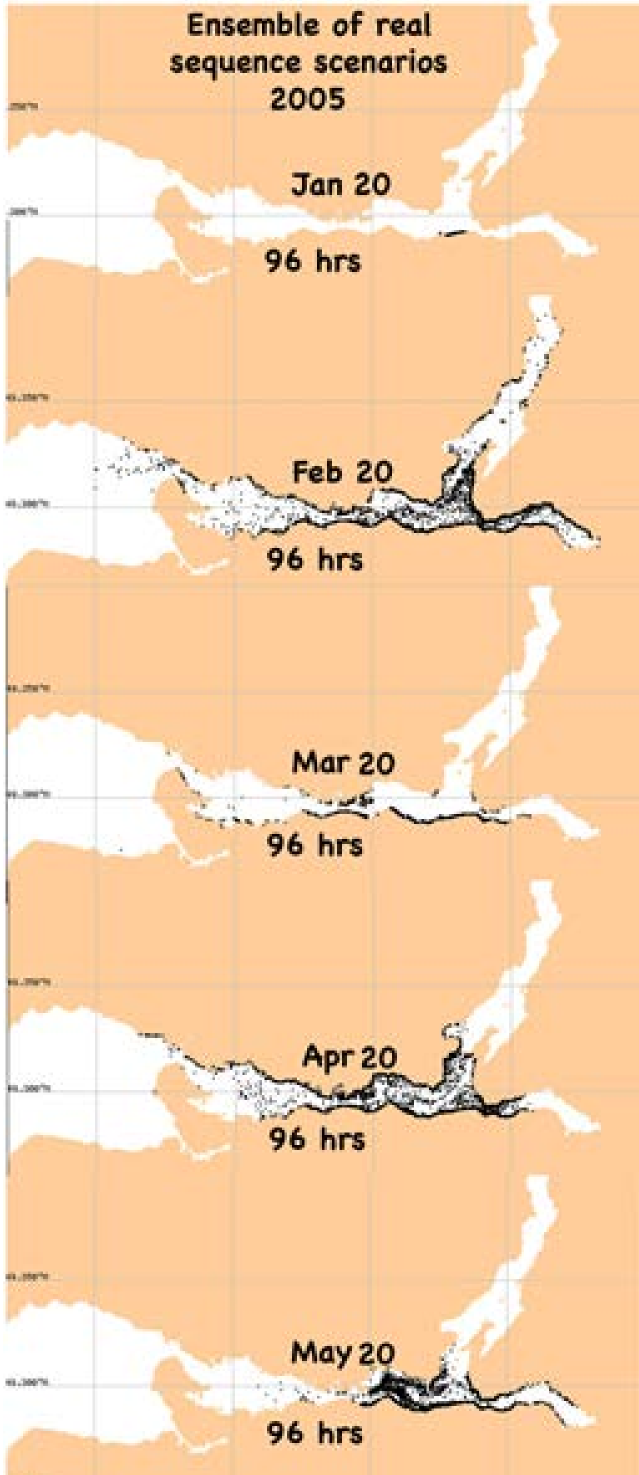

Figure 26: Ensemble of spills starting on the 20th day of the first five months of 2005 at 00:00 at the Terminal, after 96 hours

Oil spill trajectory shown in Figure 26 varies considerably among the five panels. In the January 20 scenario, oil remained very close to the Terminal whereas in the February 20, April 20, and May 20 scenarios, oil spread throughout Burrard Inlet from the Outer Harbour to Indian and Port Moody Arms.

We modeled the first 12 hours of a potential oil spill by taking the following steps: (i) for each of the five cases shown in the Figure 26, we reran the spill scenario using 2,000 splots; (ii) we saved individual splot files; and (iii) we combined all five splot files. This produced a map with 10,000 splots representing the sum of all the spill runs for the ensemble.

Figure 27, below, shows the ensemble of spill runs containing the 10,000 splots:

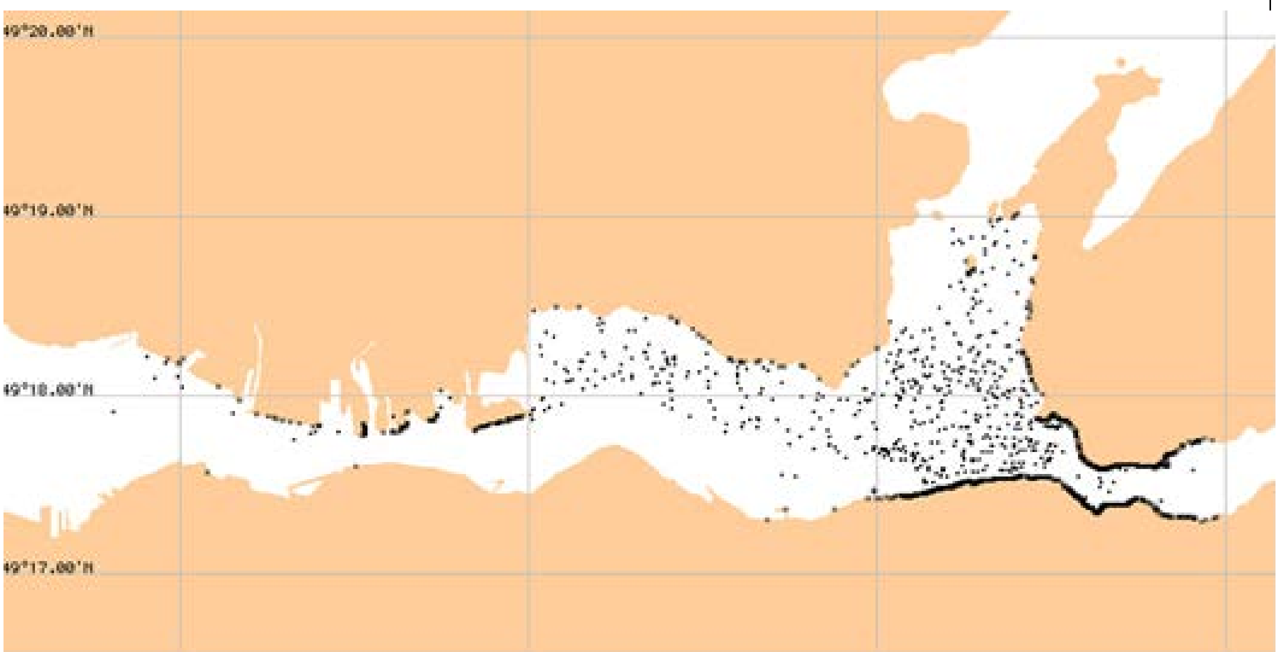

Figure 27: Ensemble threat estimate of where any oil spill could reach in the first 12 hours of an oil spill at the Terminal

The results shown in Figure 27 can be used to calculate the stochastic probability of oil threatening any specific area in Burrard Inlet. For example, if a polygon encompassing a section of shoreline contains 250 splots, there would be a 2.5% probability (250 out of a possible 10,000) of oil being present there after 12 hours.

2. Stochastic probability distribution for selected sites

We performed a further stochastic analysis for a spill at the Terminal, Second Narrows, and First Narrows using an ensemble run with 10 randomly selected start times. For each start time, we ran the Burrard Inlet Model B with an instantaneous release of 1,000 splots for 96 hours. The result was an ensemble of 10 randomly chosen distributions for each period of elapsed time at each site.

We added the splots for each of the 10 runs, which produced a statistical ensemble of 10,000 splots. The 10,000 splots represent the Lagrangian point probability distribution of "the presence of oil" given a random spill for which the start time is unknown.

The Lagrangian distribution probability represents "chunks or pieces" of pollutants. We calculated the Eulerian density, which represents "percent probability" per "unit area," by calculating the % of splots per km^2 and mapped the results in the 18 figures set out in **Appendix "K"**. The 18 figures show the contours of the probability densities at 3, 6, 12, 24, 48, and 96 hours at each site. The contours of the probability densities represent the entire stochastic distribution of hypothetical trajectories. They conserve mass and integrate to 100% of the hypothetical spills.

The probability of finding oil at any area of interest shown on the map can be calculated. For example, if a shell fish resource covers 2 km^2 and it falls between the 4% and 8% contours, there is an 8–16% probability of oil impacting the resource for a spill at the time shown in the figure.

The figures in Appendix "K" show pollutants spreading quickly throughout Burrard Inlet. The complex geometry and strong advection associated with various narrows induces many eddies which make the distribution patchy. Shoreline concentrations accumulate along the narrows and floating, concentrated patches appear in the sub-basins. The highest value represented in these figures is 8% per km^2. The greatest density of oils is located in those contours.

We further explored the stability of the statistical ensembles, and whether 10 randomly chosen start times are sufficient to reach stability by performing a simulation experiment at the Terminal using different randomly selected start times. The figure in **Appendix "L"** shows the probability density distributions for three statistically independent estimates of the 12 hour distribution. As expected, the estimates are not identical. However, the general span of the distribution and the patch sizes of the high concentration areas as well as their general locations are consistent. These results suggest that the results shown in the figures in Appendix "K" for 10 randomly chosen start times are a realistic representation of expected threatened zones anticipated in an actual release scenario.

3. Stochastic summary graphs

The figures in Appendix "K" are a graphic representation of the distribution of probability for a series of times (3, 6, 12, 24, 48, and 96 hours) into a hypothetical spill whose location is known but for which the initial time and thus the tidal phase and weather conditions are unknown. The environmental conditions influencing oil spill trajectory in those figures is the average of ten different random and independent scenarios modelled as an ensemble.

The figures in Appendix "K" are rich in information about how the geometry, tidal currents, and weather patterns in Burrard Inlet are expected to influence the trajectory of an oil spill.

Since each of the figures includes all of the released oil, the smallest probability contour has an upper limit which will be less than the total area represented on the map. On the other end of the scale, the highest probability contour will approach zero area (because all of the oil is initially in the contained state). Since no contour line can cross another, the area of each successive contour will be greater than or equal to the preceding one. This means that if the 2% contour encloses 10.3 km^2, there are 10.3 km^2 in the model domain that have a greater than 2% probability of having oil present within 1 km^2 of the observation point.

The stochastic runs at Sites #1, #2, and #3 show the probability distribution for the released oil from an ensemble of ten different scenarios for each site. A substantial amount of that oil was beached (between 50% and 90% over all cases and for all times), and acted as a secondary source during each of the four day scenario runs. Some of the beached oil was rewashed, which added new floating oil, while some of the floating oil was beached or re-beached.

We conducted an additional analysis which focuses exclusively on the areal coverage of floating oil. The purpose of this analysis is to provide a statistical view of the oil that would be drifting around Burrard Inlet which could be seen in overflights and would be the target of traditional oil spill recovery operations.

The 3 figures in **Appendix "M"** show the area enclosed by each of the ⅛%, ¼%, ½%, 1%, 2%, 4%, 8%, and 16% percent of the spill on the x-axis and the area of the spill (in km^2) on the y-axis. Each figure in Appendix "L" shows how the probability densities are distributed as the spill scenario progresses through time, and provides the aerial extent of each of the probability densities threat zones.

Generally speaking, the results shown in those figures indicate that the highest probability regions for floating oil disappear relatively quickly (because most of the oil is at least temporarily beached) but that oil in areas subject to lower, but still significant, percentages of the spill tends to spread covering many tens of square kilometers. This is particularly true for Site #3 (First Narrows), where in four days an area of nearly 90 km^2 might expect to have some floating oil present.

Appendix “K”: Stochastic Probability Densities

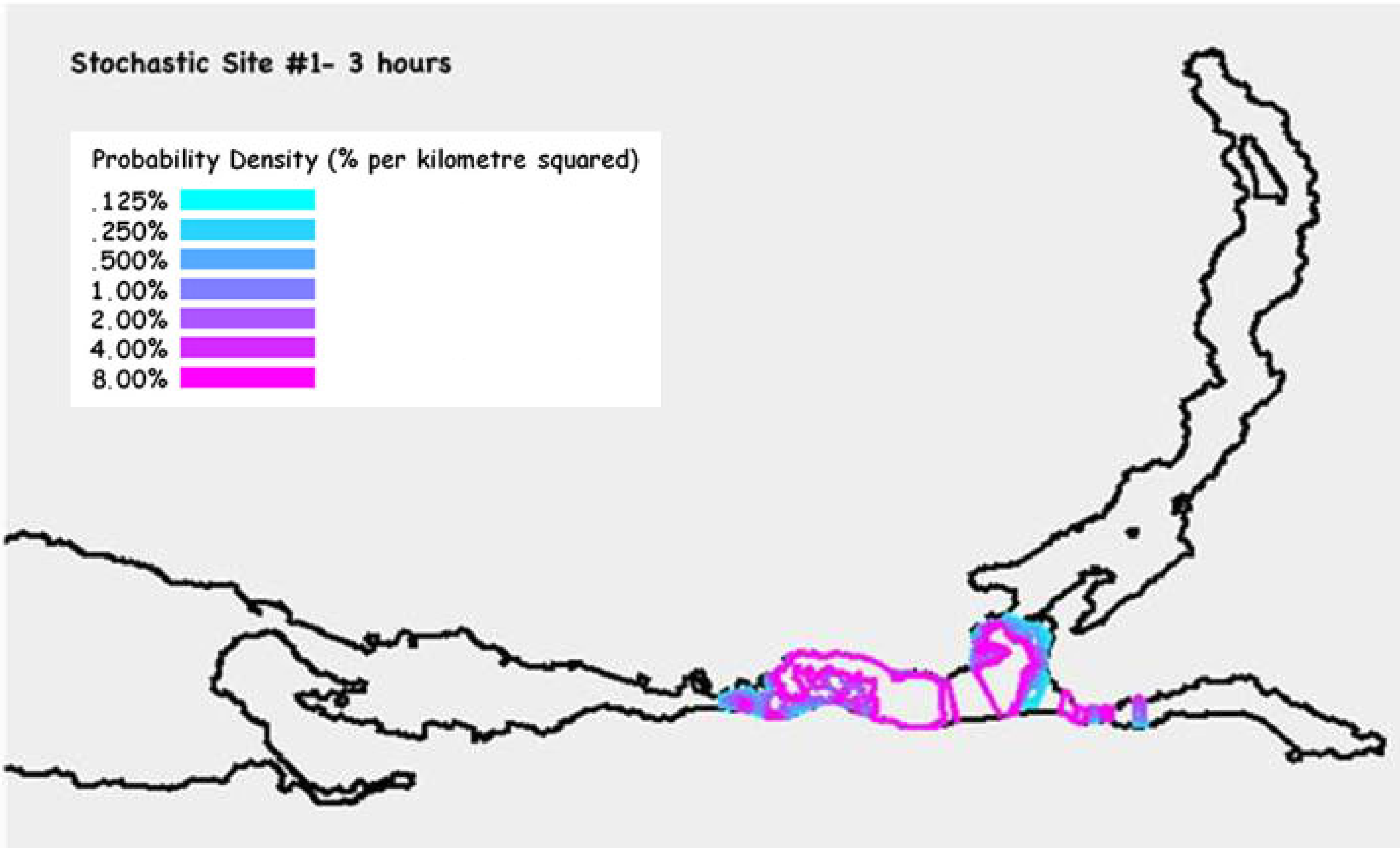

Figure 28: Stochastic Site #1—3 hour

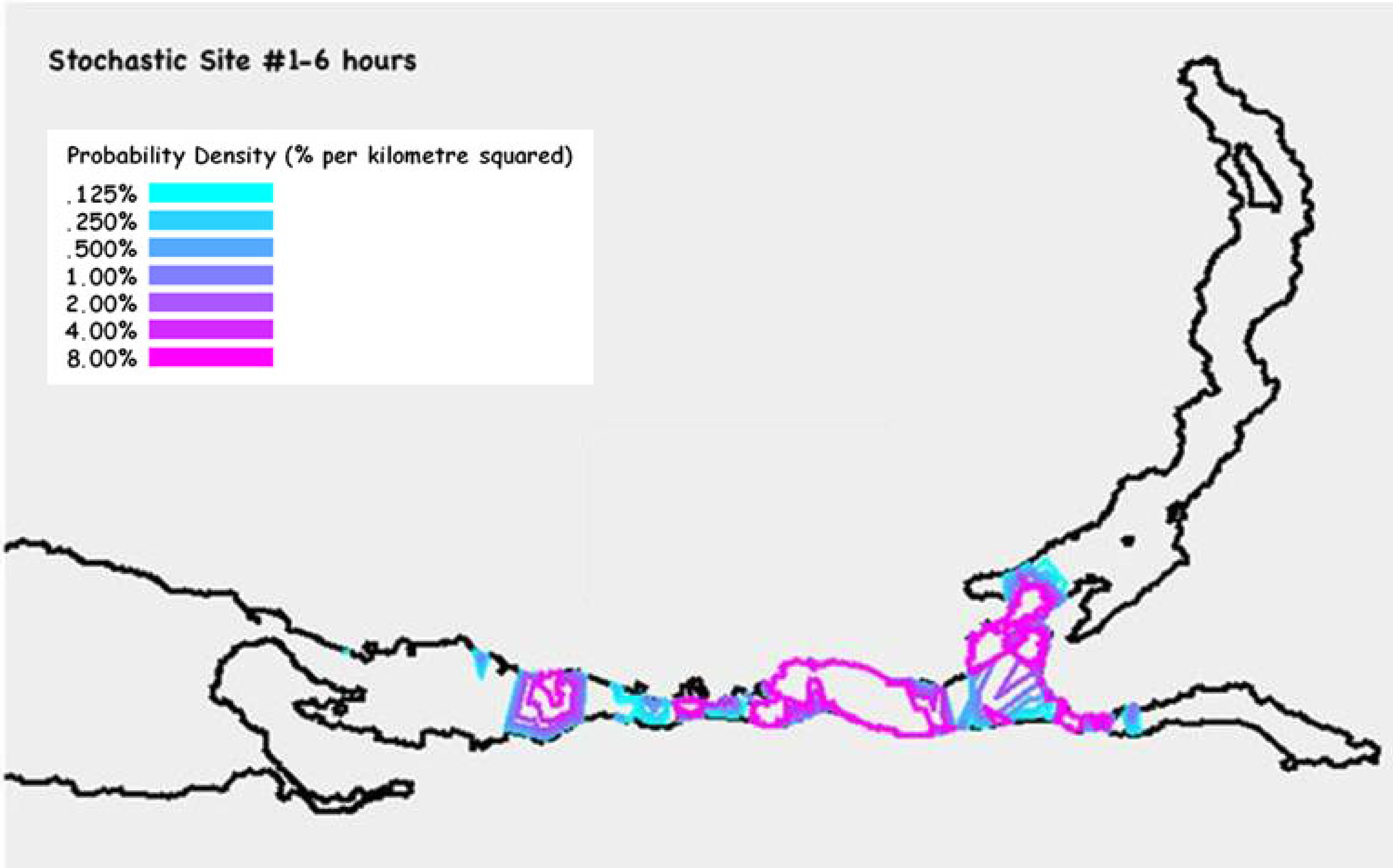

Figure 29: Stochastic Site #1—6 hours

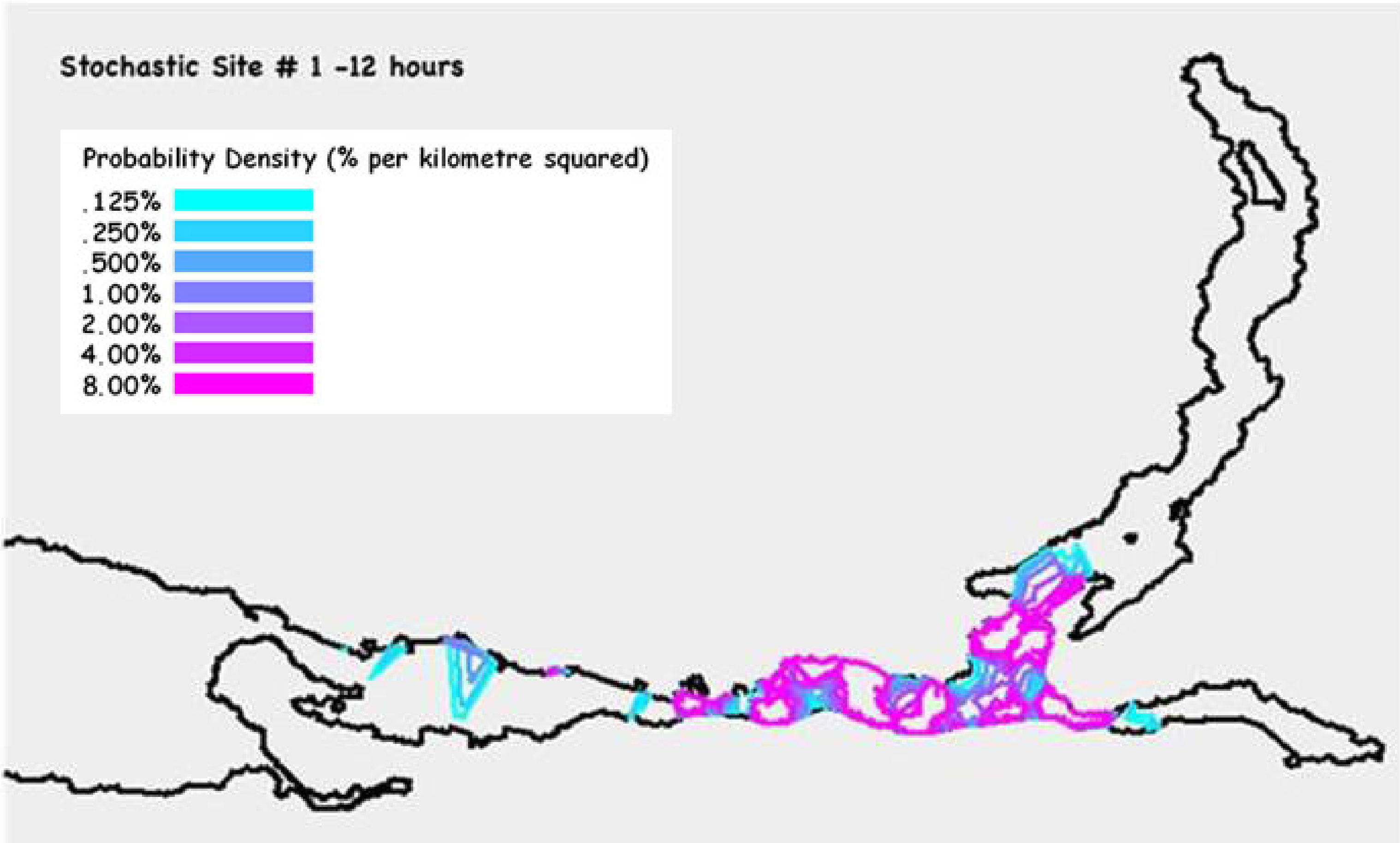

Figure 30: Stochastic Site #1—12 hours

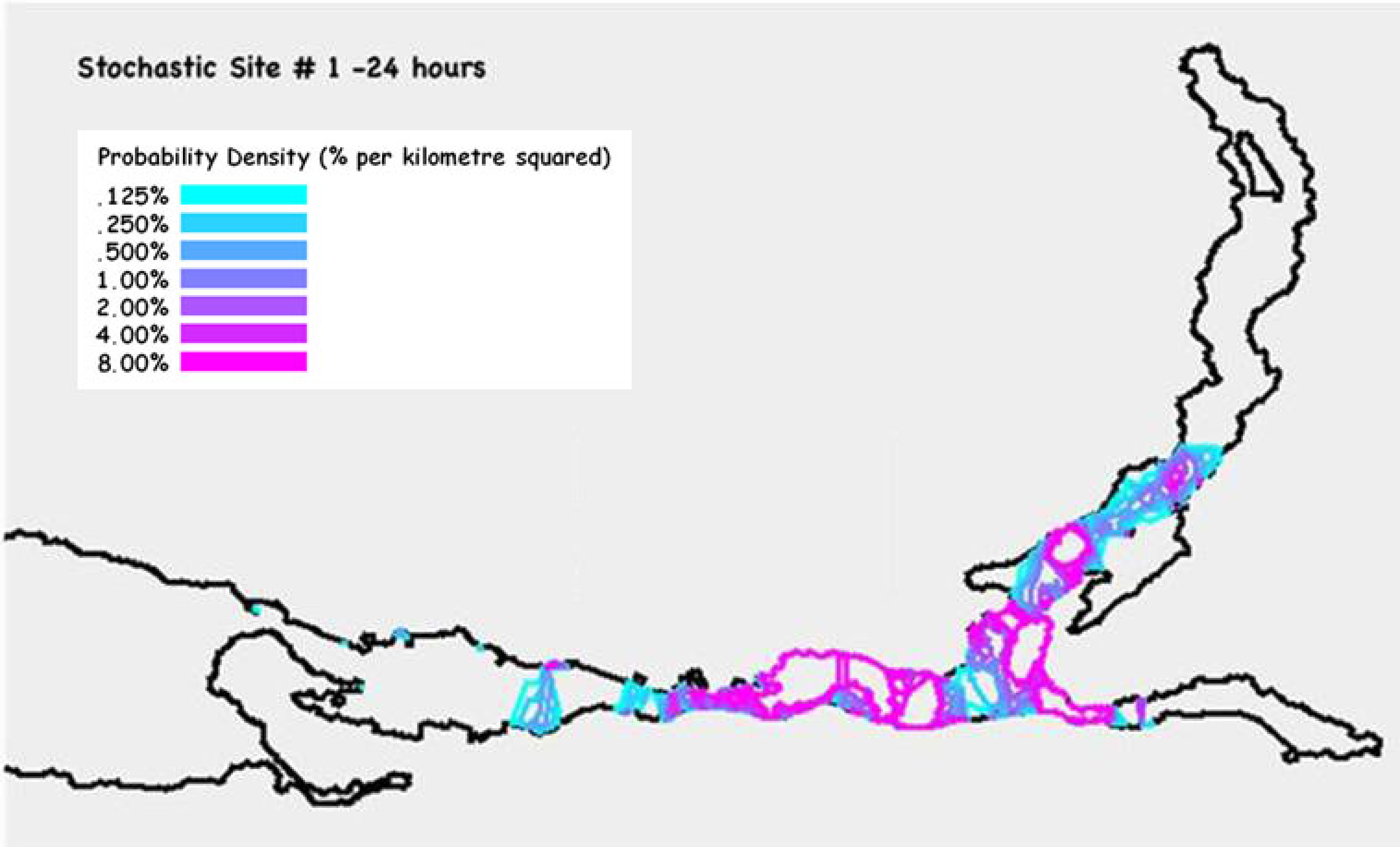

Figure 31: Stochastic Site #1—24 hours

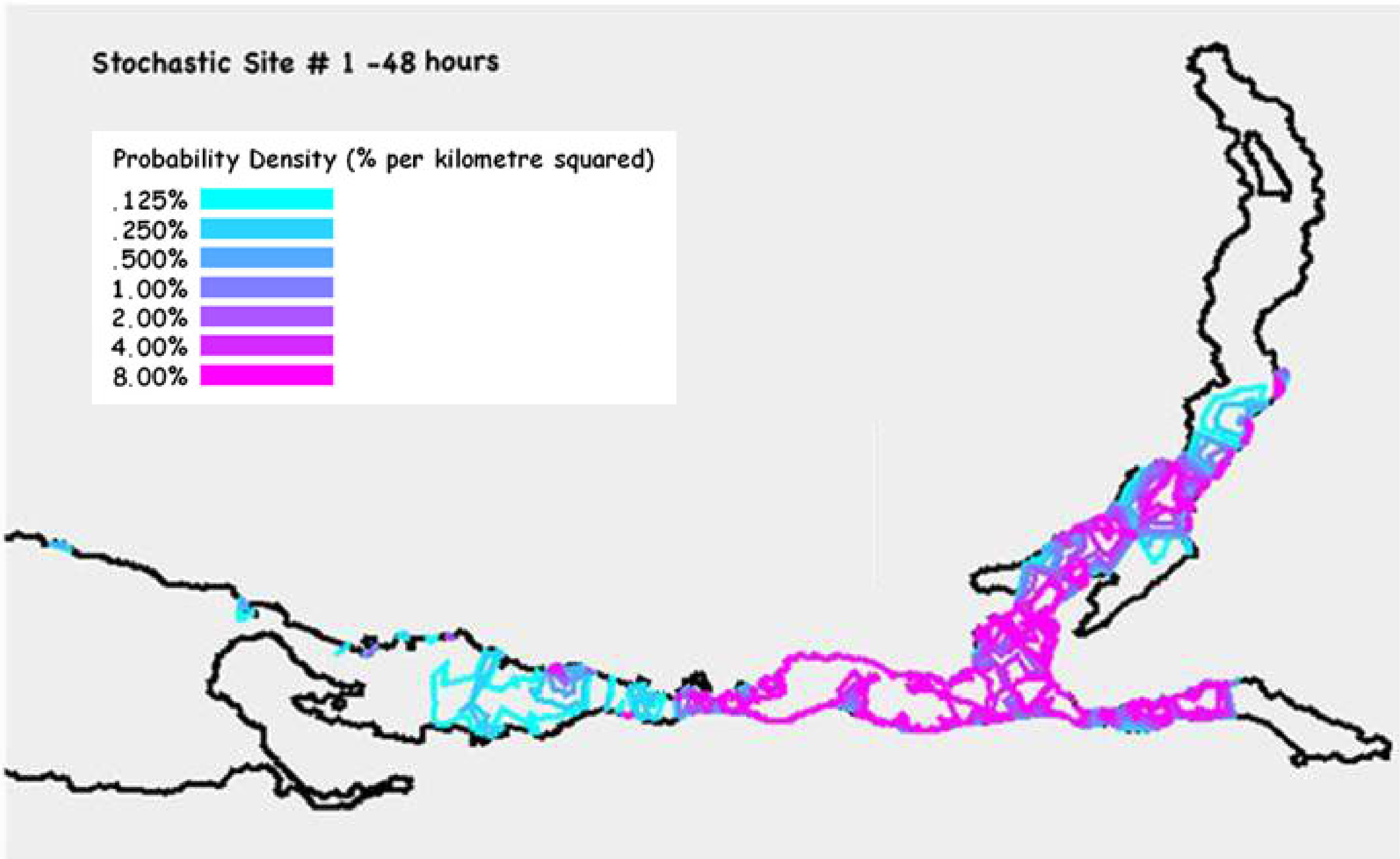

Figure 32: Stochastic Site #1—48 hours

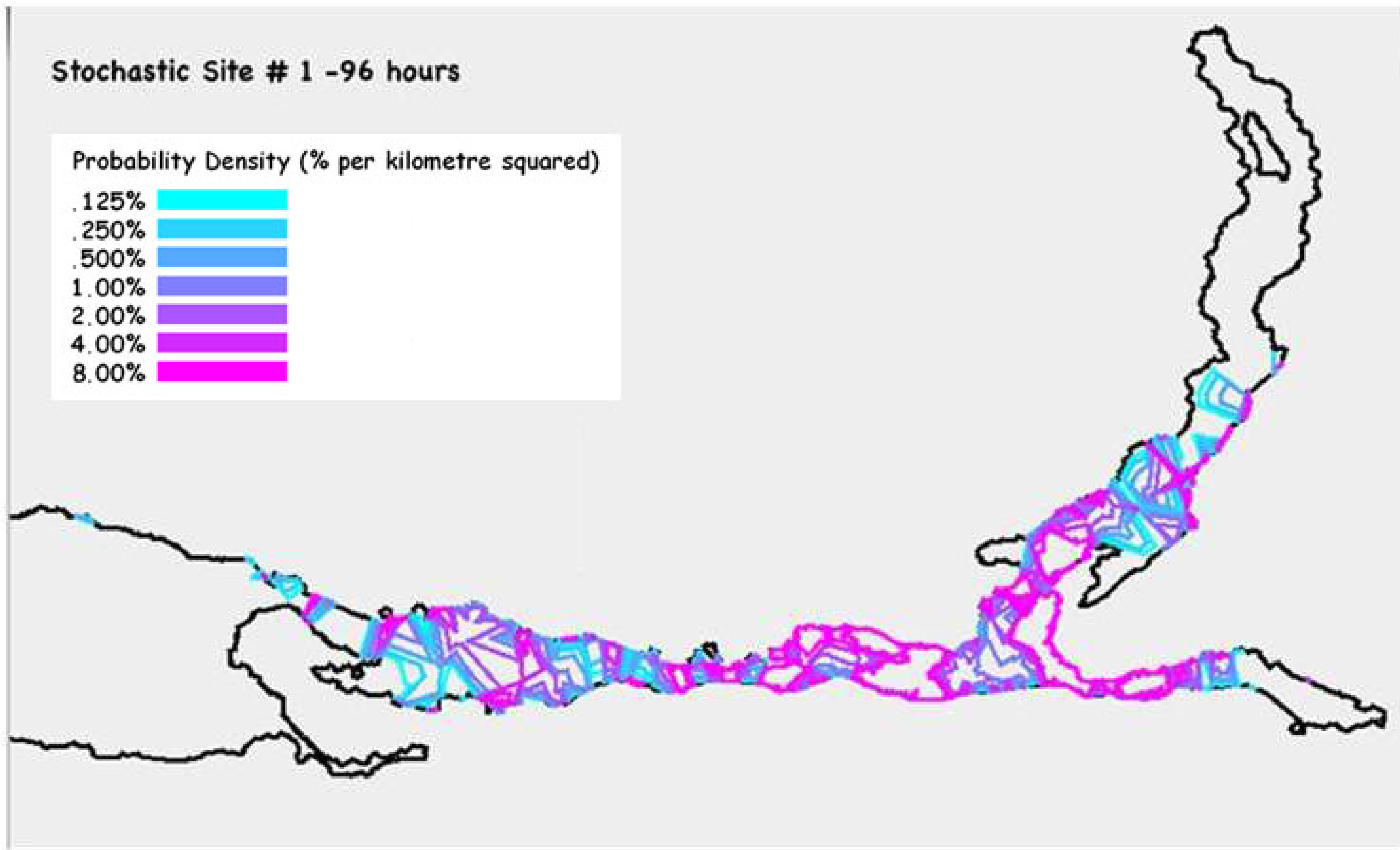

Figure 33: Stochastic Site #1—96 hours

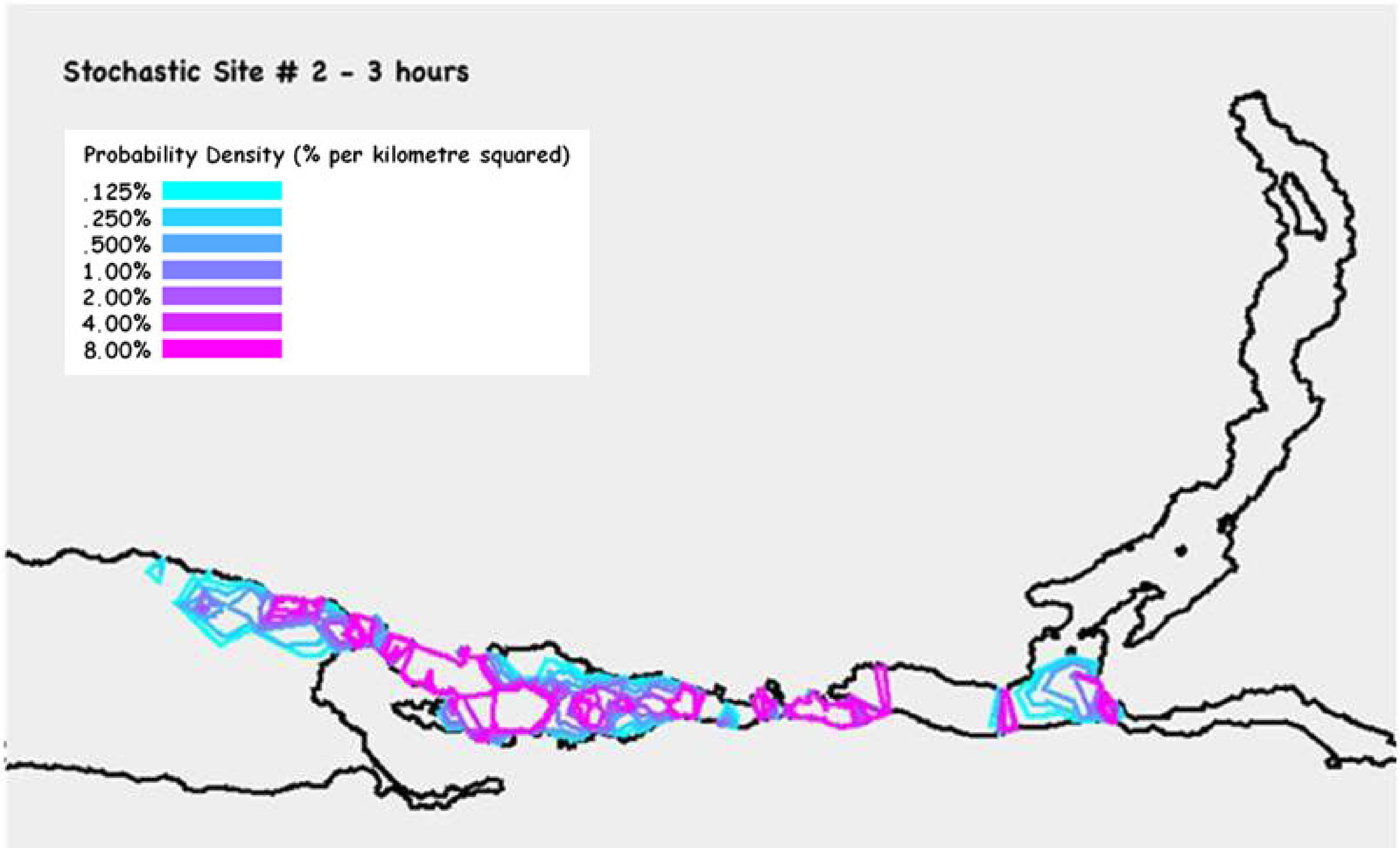

Figure 34: Stochastic Site #2—3 hours

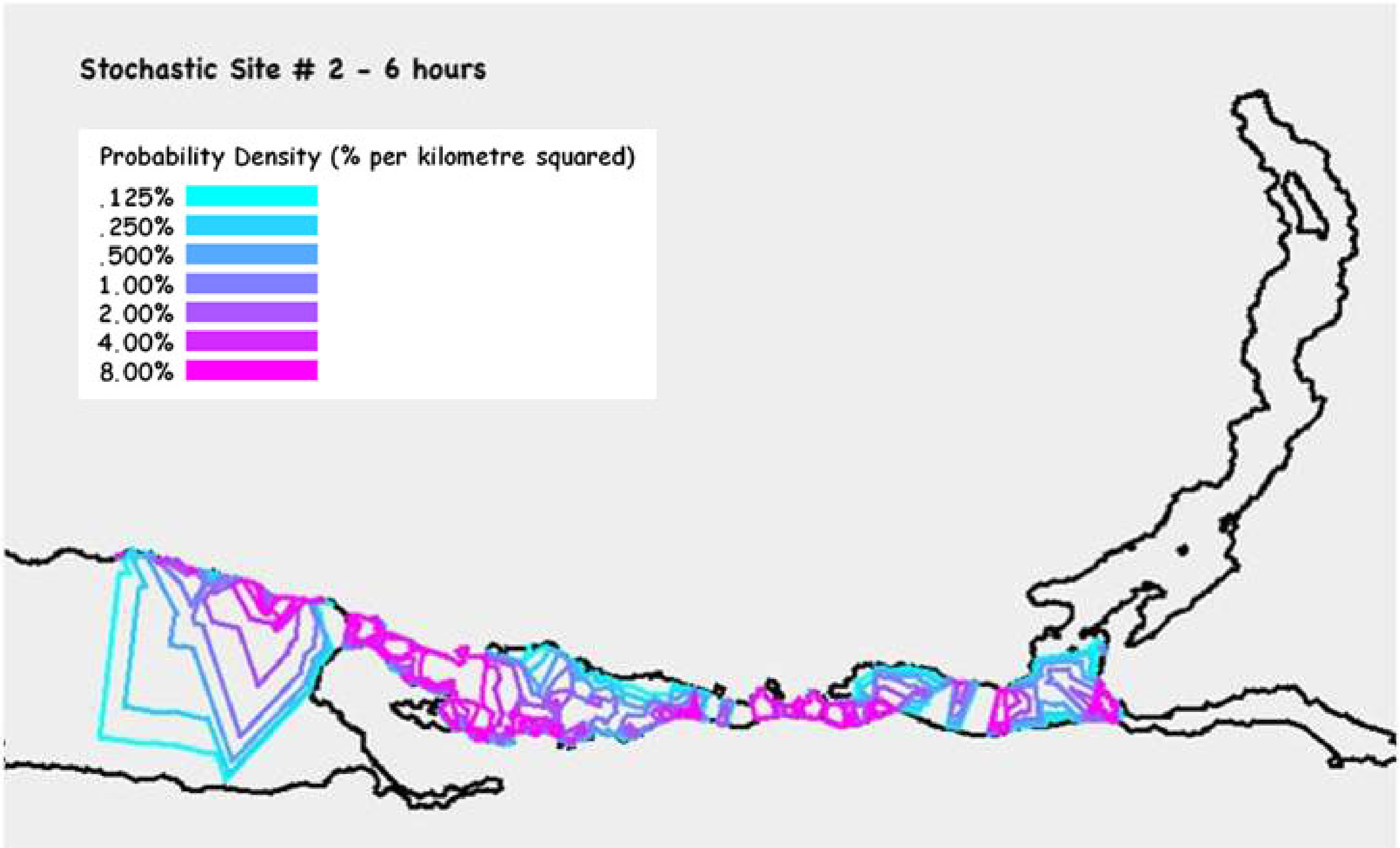

Figure 35: Stochastic Site #2—6 hours

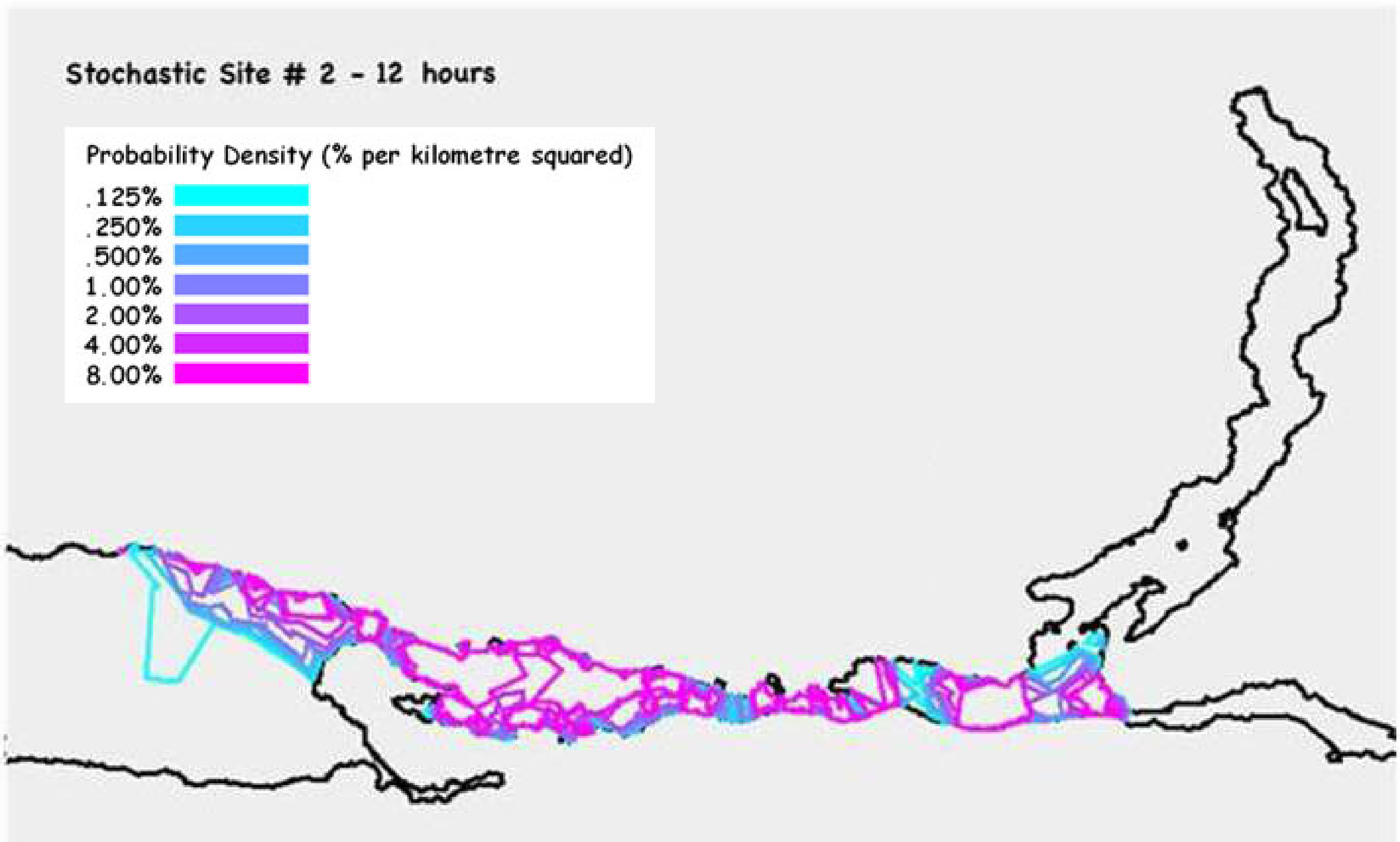

Figure 36: Stochastic Site #2—12 hours

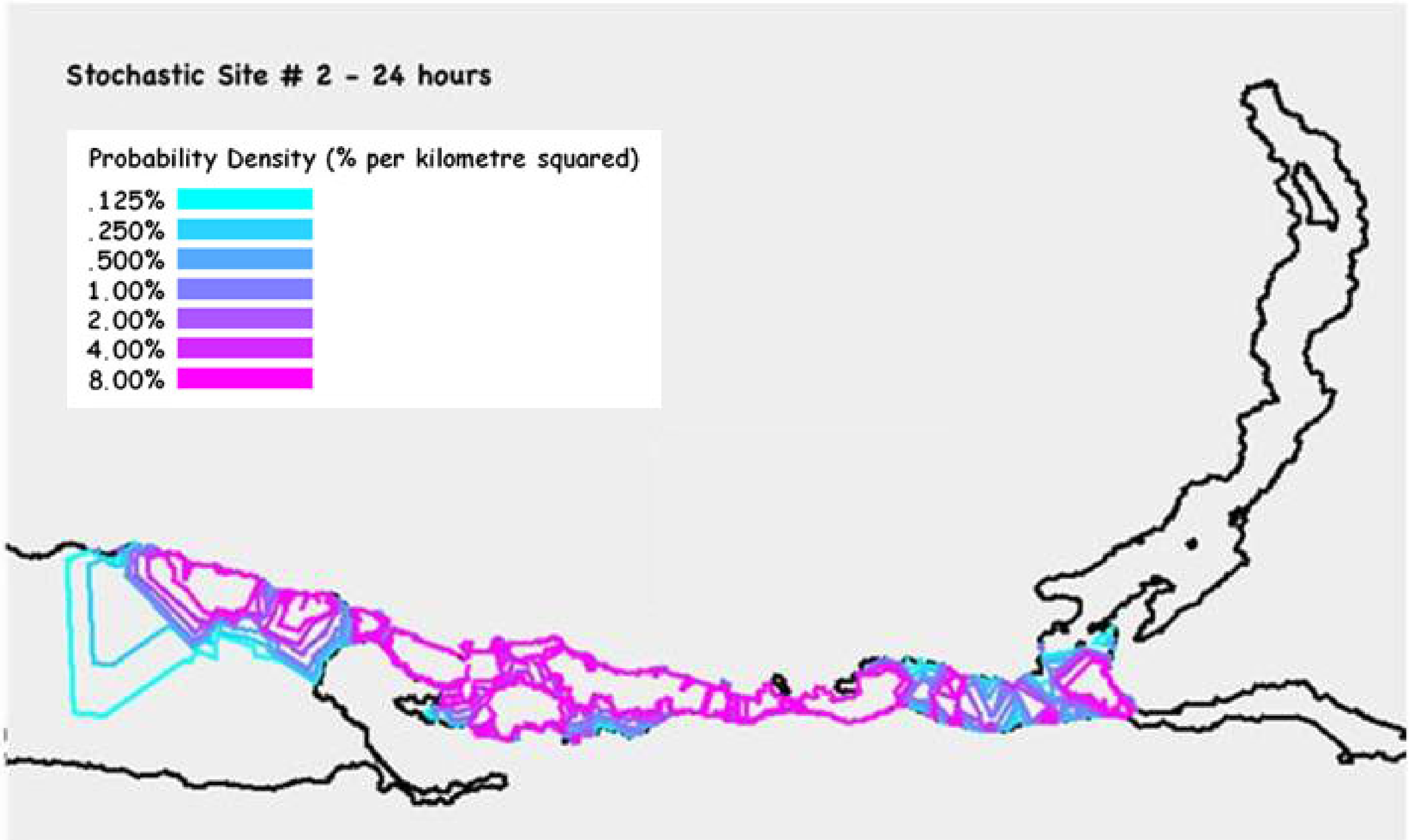

Figure 37: Stochastic Site #2—24 hours

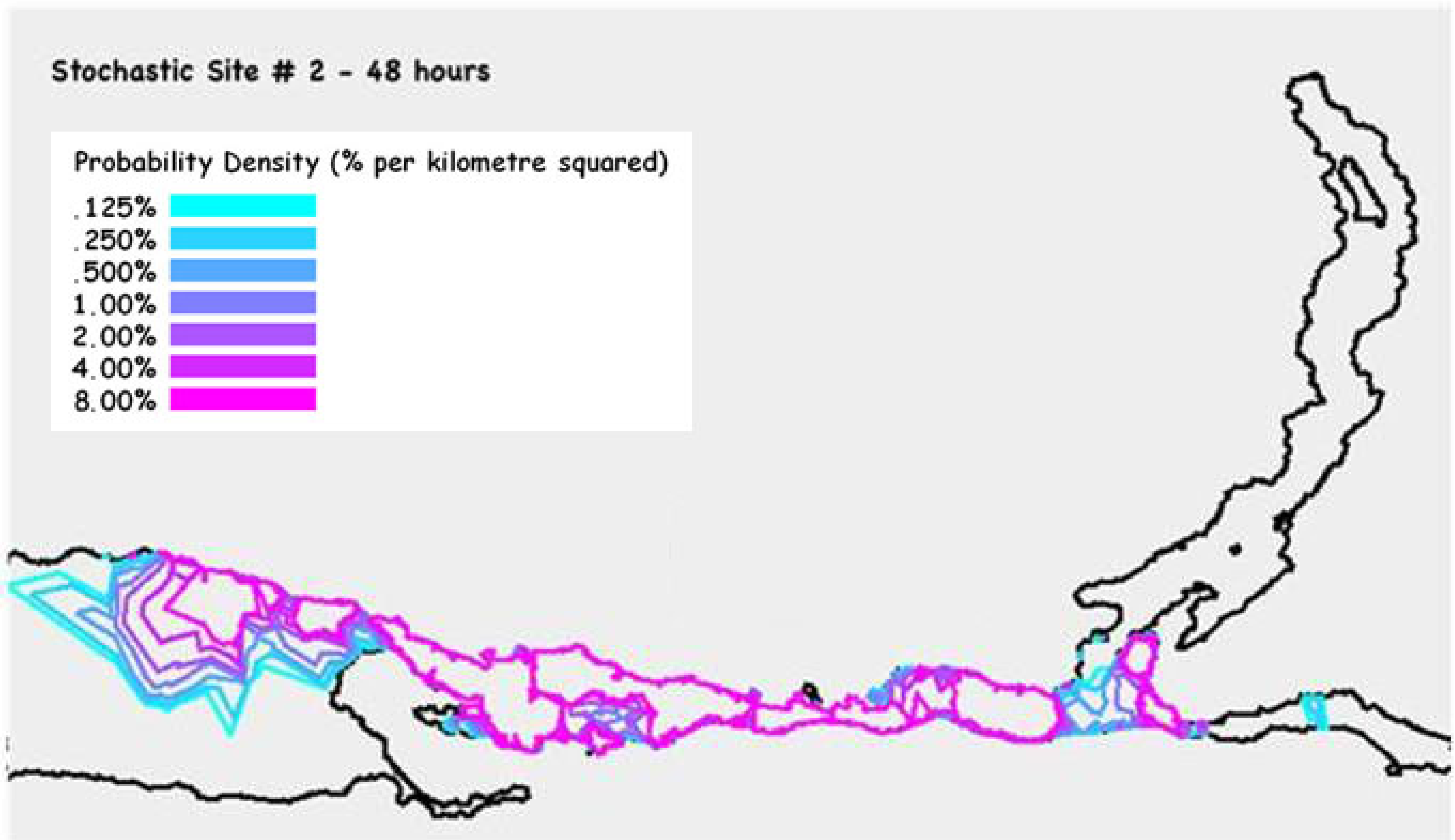

Figure 38: Stochastic Site #2—48 hours

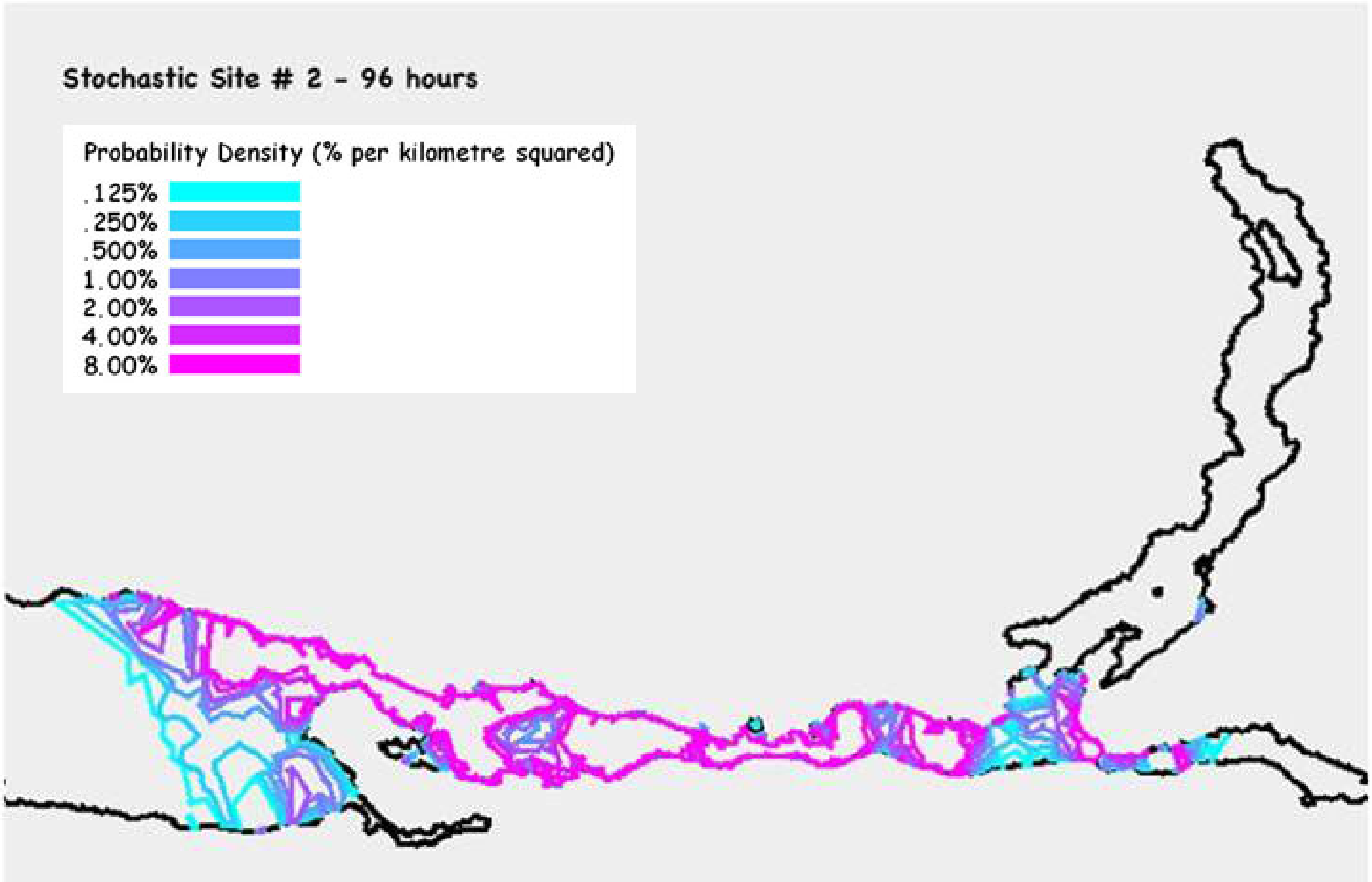

Figure 39: Stochastic Site #2—96 hours

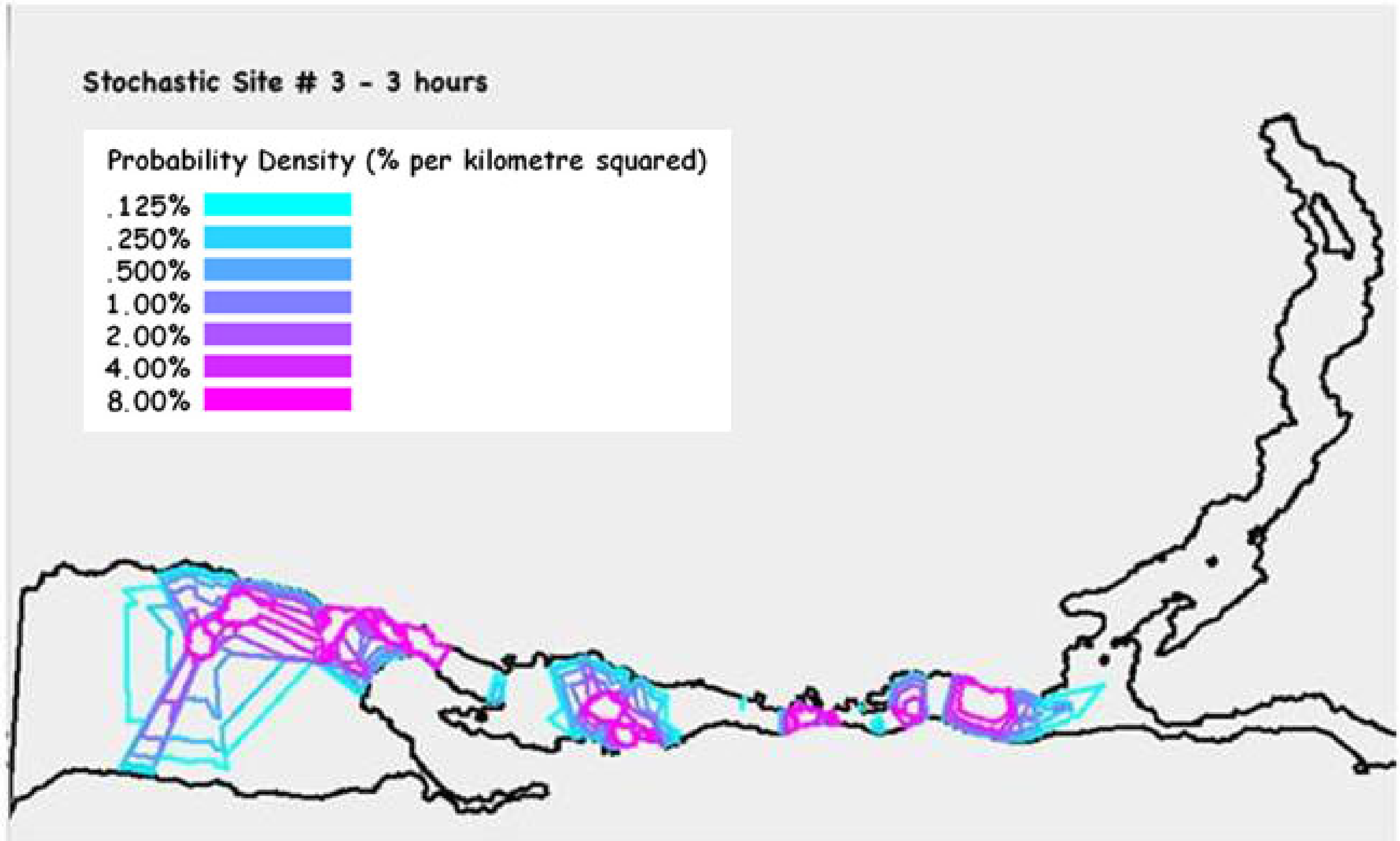

Figure 40: Stochastic Site #3—3 hours

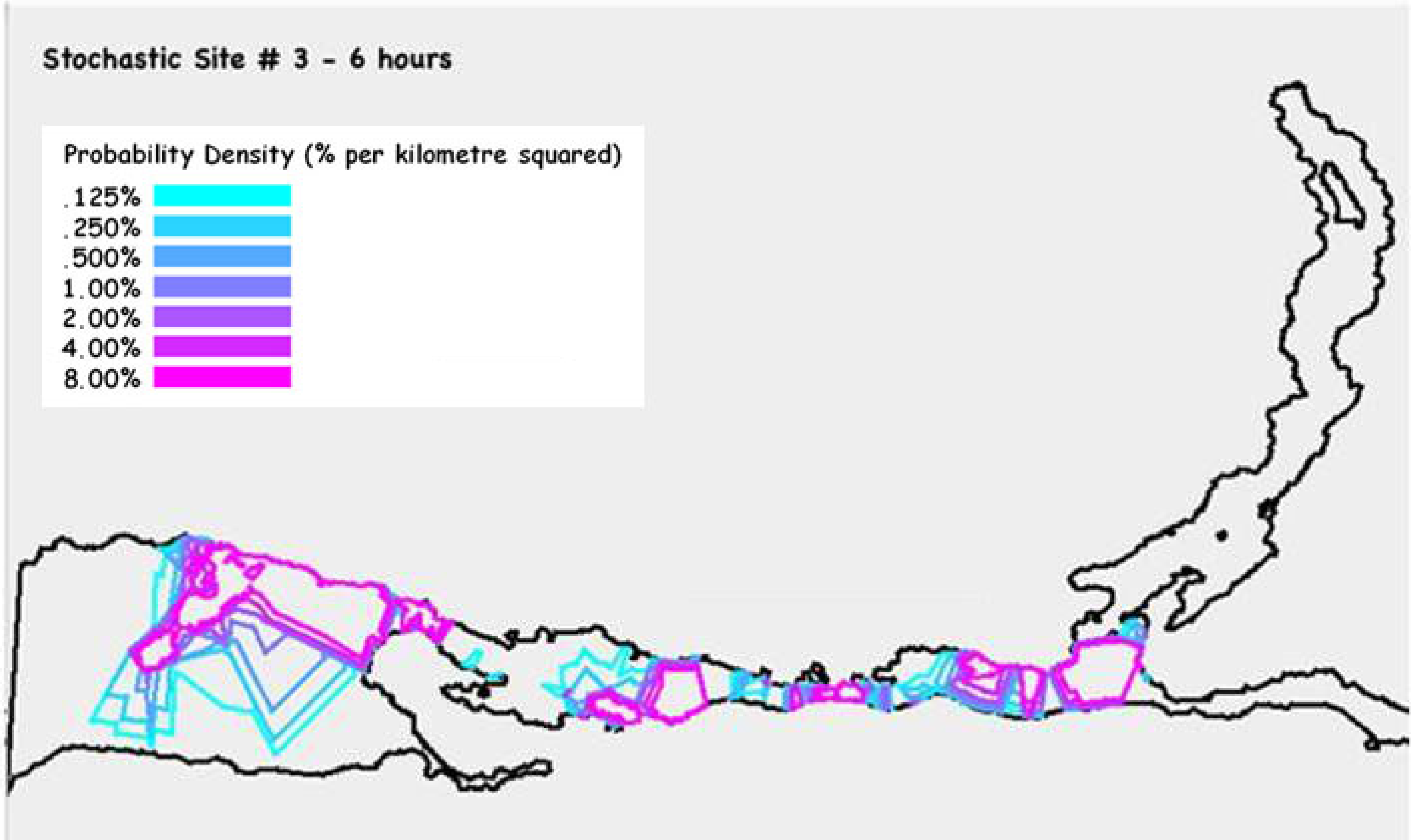

Figure 41: Stochastic Site #3—6 hours

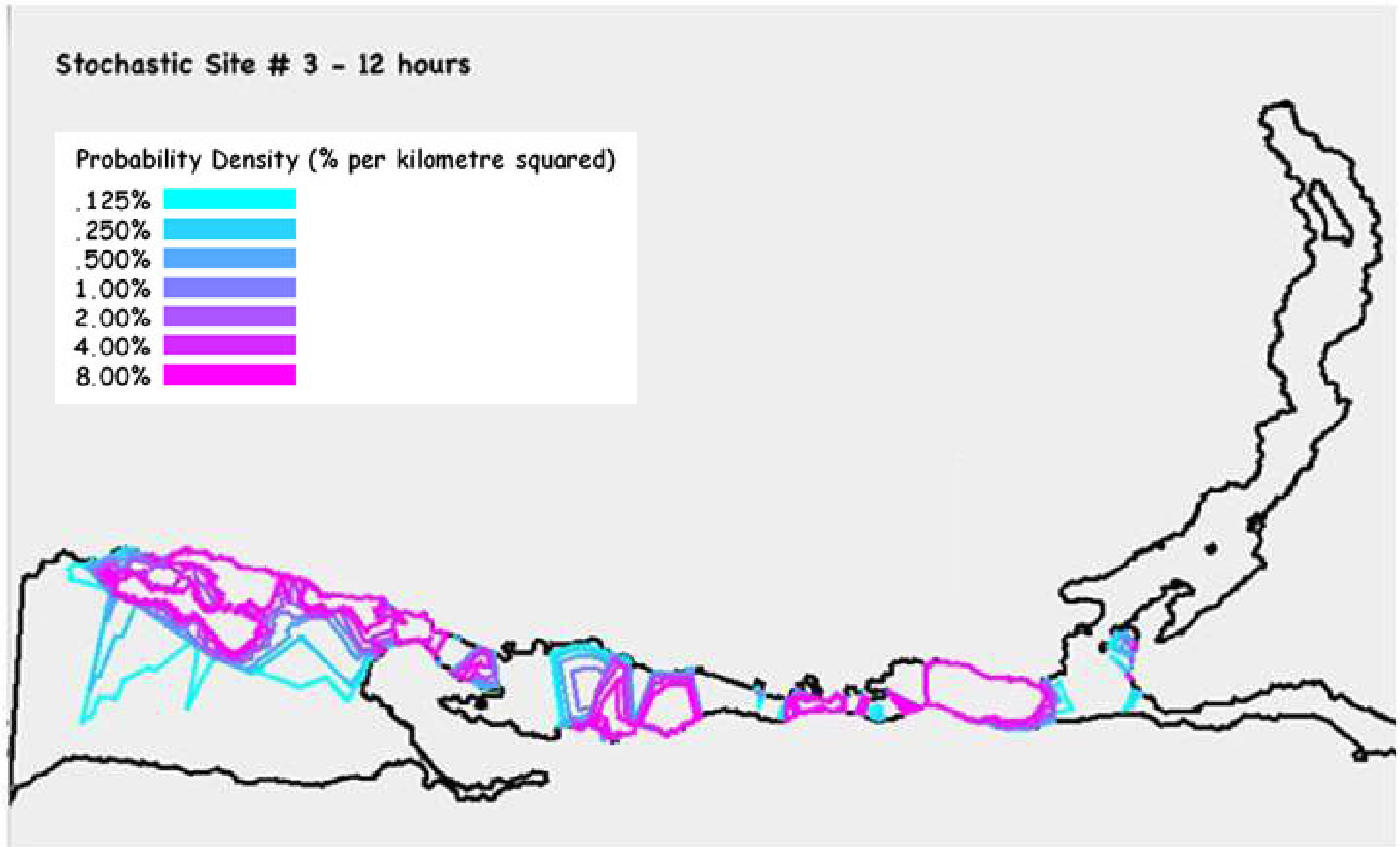

Figure 42: Stochastic Site #3—12 hours

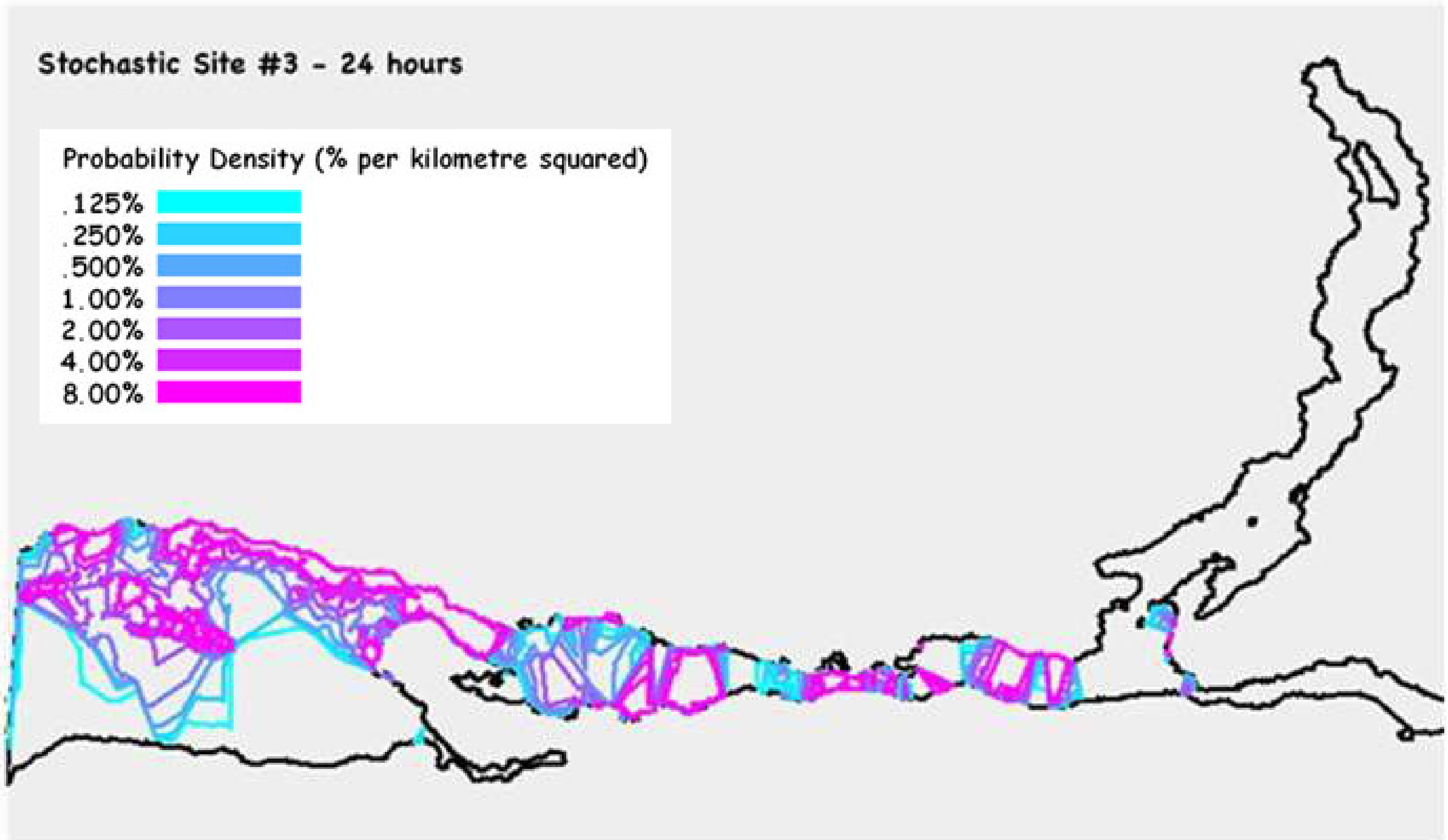

Figure 43: Stochastic Site #3—24 hours

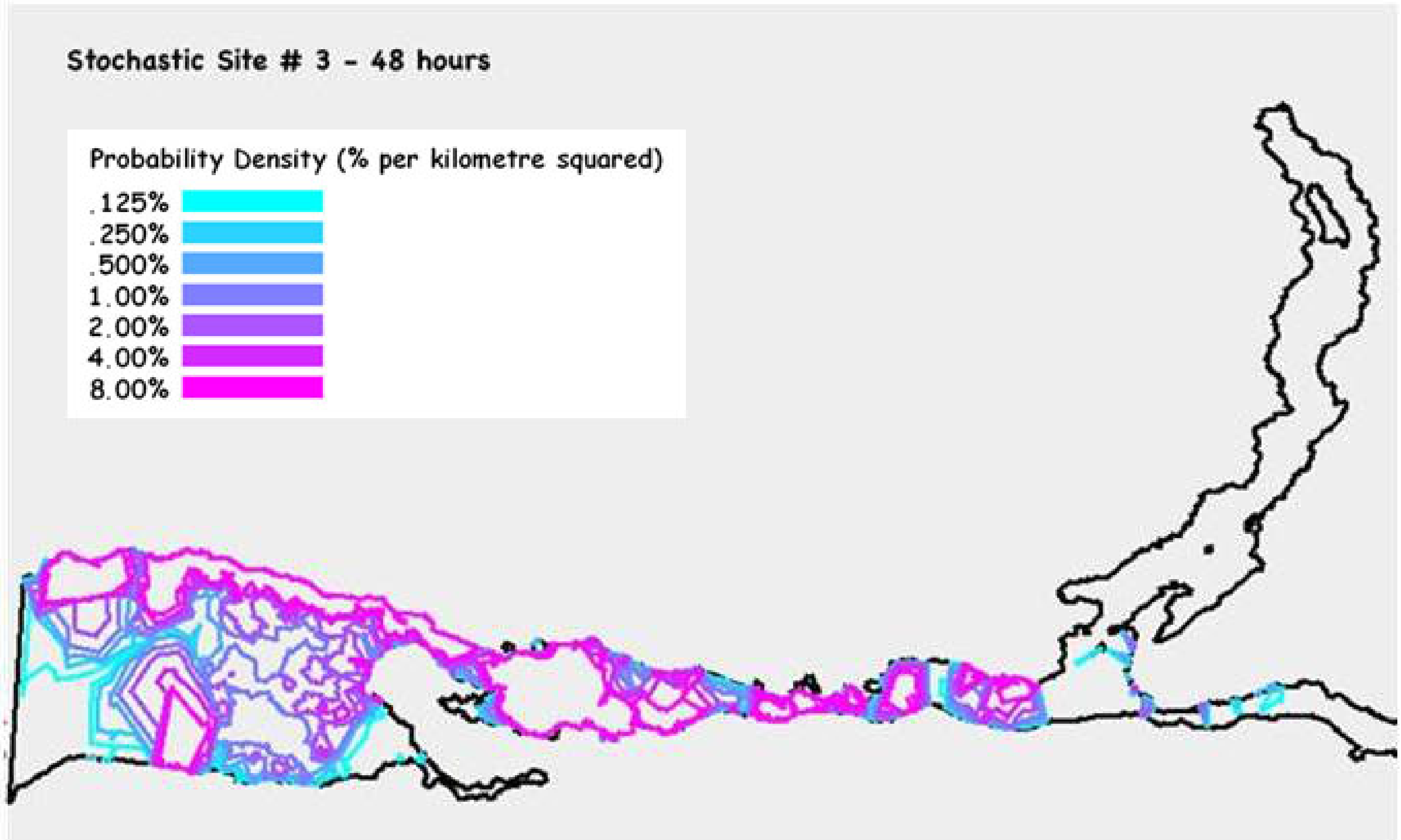

Figure 44: Stochastic Site #3—48 hours

Figure 45: Stochastic Site #3—96 hours

Appendix “L”: Probability Density Distributions for Three Statistically Independent Estimates of the 12 Hour Distribution of a Spill at the Terminal

Appendix "L": Probability Density Distributions For Three Statistically Independent Estimates Of The 12 Hour Distribution Of A Spill At The Terminal

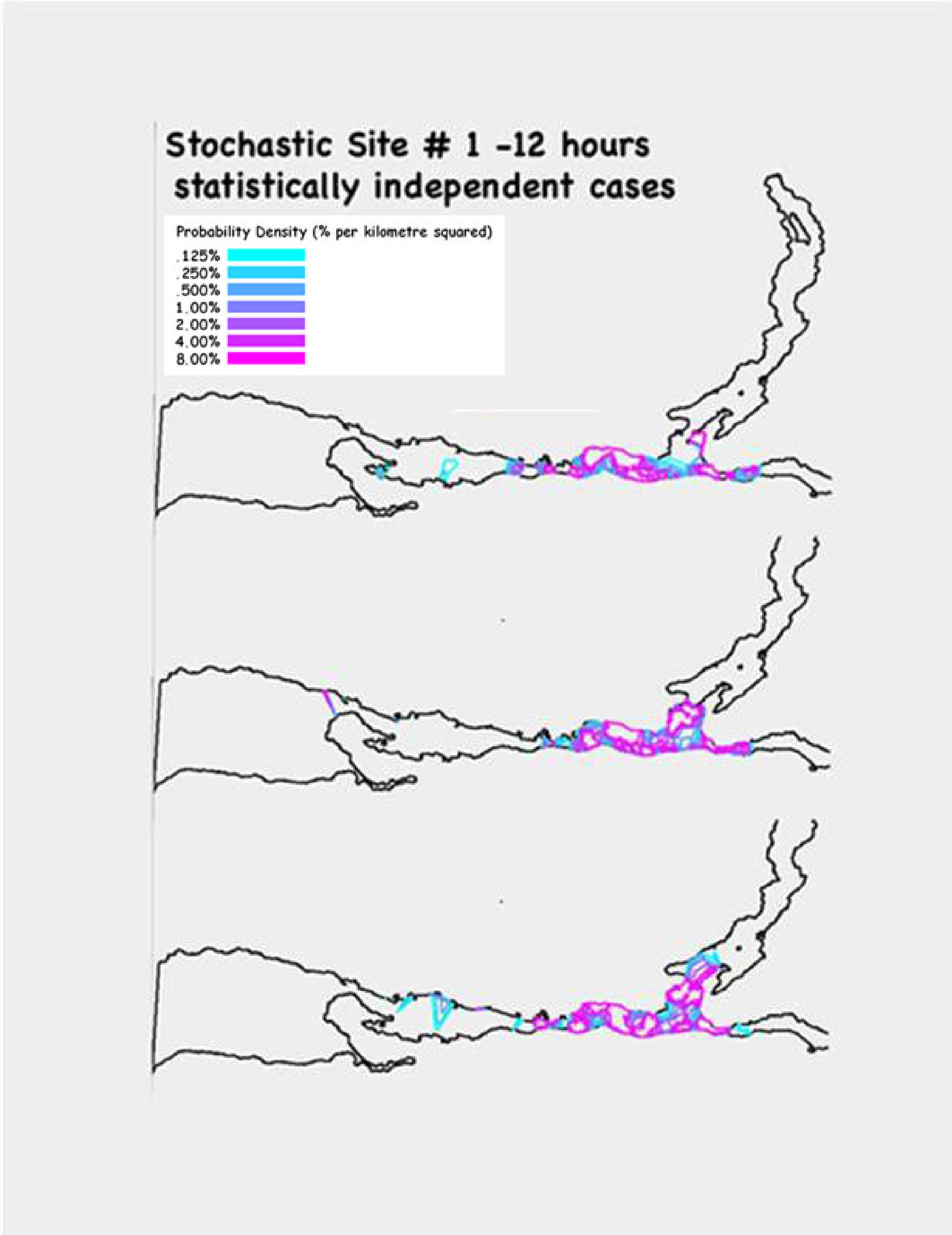

Figure 46: Stochastic Site #1—12 hours: Statistically Independent Cases

Appendix “M”: Stochastic Summary Graphs

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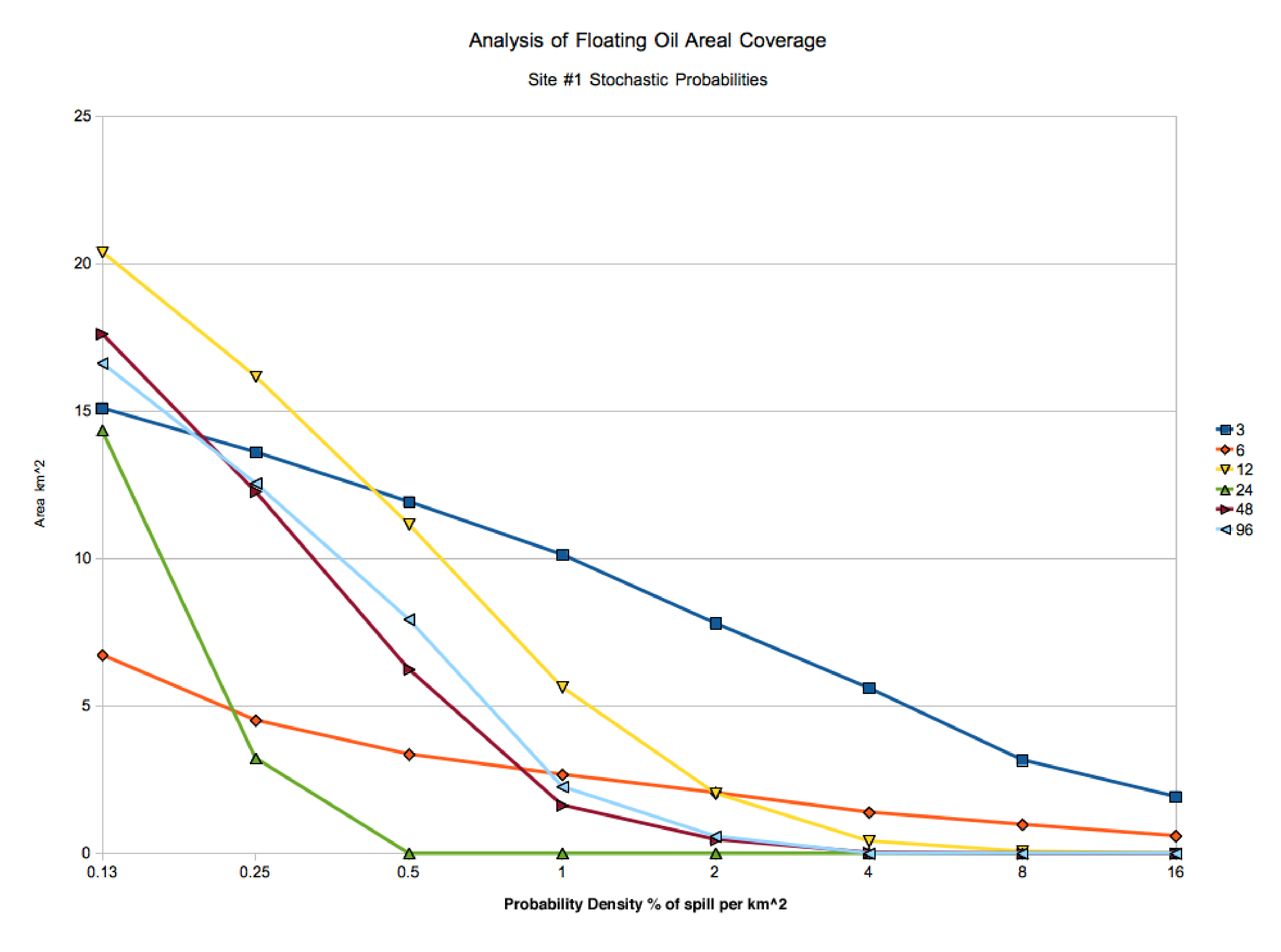

Figure 47: Analysis off Floating Oil Areal Coverage: Site #1 Stochastic Probabilities

Appendix “M”: Stochastic Summary Graphs

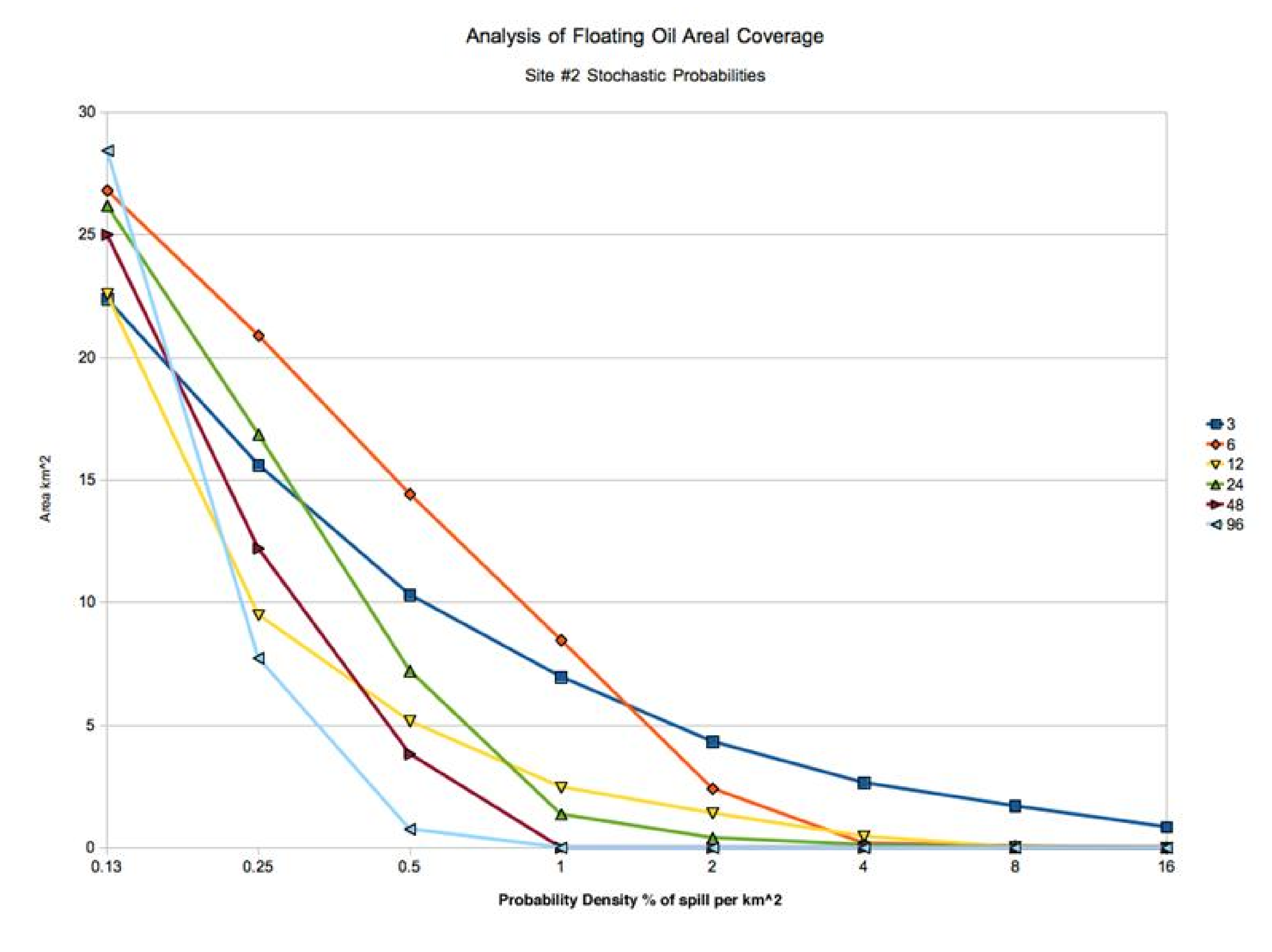

Figure 48: Analysis of Floating Oil Areal Coverage: Site #2 Stochastic Probabilities

Appendix "M": Stochastic Summary Graphs

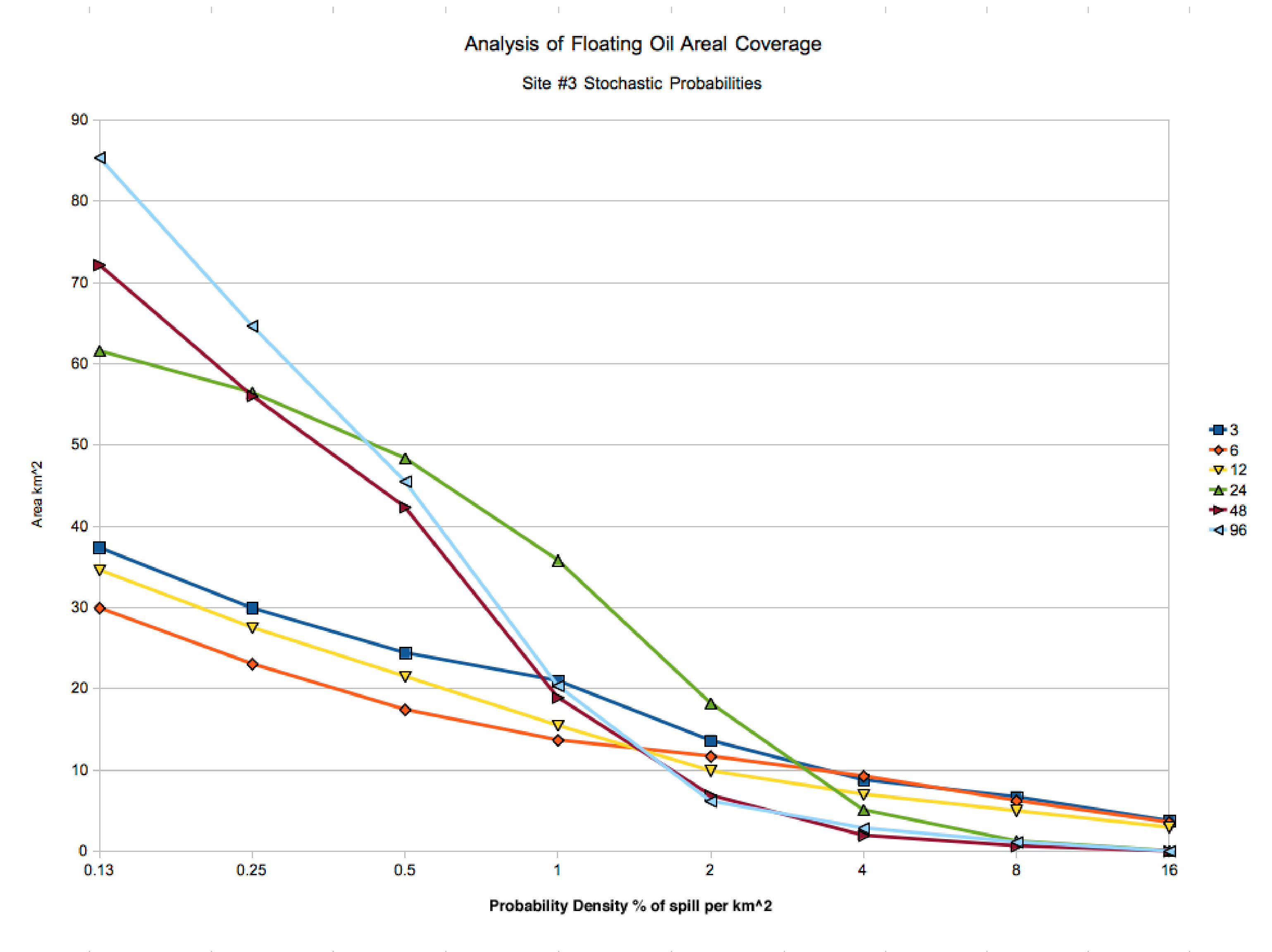

Figure 49: Analysis of Floating Oil Areal Coverage: Site #3 Stochastic Probabilities

Appendix “N”: Instructions Provided to the Partners to Further Model Oil Spill Trajectories in Burrard Inlet

Appendix "N": Instructions Provided to the Partners to Further Model Oil Spill Trajectories In Burrard Inlet

1. Use Burrard Inlet Model B to model spill scenarios in calendar year 2005 at Westridge Terminal, Second Narrows and First Narrows.

2. Create a series of at least 10 runs across the calendar year with the day and time randomly selected using the table provided by Genwest to the Partners.

3. Select elapsed times of interest for the scenario.

4. Combine all the runs for each elapsed time of interest into a single map.

5. In GIS, define polygons of interest.

6. Calculate the percentage of total splots in each polygon of interest.

7. The percentage provides the portion of a spill likely to be present in the polygon under environmental conditions in calendar year 2005.

8. In GIS, define shorelines of interest.

9. Buffer the beached splots to account for the spread of the oil. Very conservative values are a 7 meter diameter buffer for an 8,000 m^3 spill and a 10 meter diameter buffer for a 16,000 m^3 spill.

10. Calculate the km of oiled shoreline.