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Water-Based Oil Spill Modeling Software: Benefits, Requirements & Recommendations

Report prepared at the request of YVR's Environmental Specialist Patrick McGuiness in partial fulfillment of UBC GEOG 419: Research in Environmental Geography, for Dr. David Brownstein

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An analysis of water-based oil spill modeling and the available software that predicts, simulates and models the trajectory oil spills incorporating coastal, hydrodynamic and meteorological conditions.

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Paper Terminology

"WOMS" = Water-Based Oil Spill Modeling Software: Computer programs and systems to increase knowledge on the trajectory and fate of oil spills, which enhances oil spill response capabilities. Can be used as a decision support tool to predict the behavior of various oils/fuels in the water column based on hydrodynamic (water forces/motions) and meteorological (weather) data.

YVR: Vancouver International Airport (British Columbia, Canada)

Oil Type → Fuel, Jet A Fuel, Oil Spill: In this study, we are not distinguishing between types of fuel or oil. All disperse in slightly different fashions but within OMS (Water-Based Oil Spill Modeling Software) the user can select an oil type input from the oil type database.

Plume of Fuel: An area in water containing oil/fuel released from an aircraft or tank farm that spreads in the environment due to the action of hydrodynamic forces and meteorological conditions.

Oil Slick: An area on the surface of water caused by the presence of oil.

Catastrophic Oil Spill: Large-scale oil spills greater than 1,000 L.

Oil Spill Trajectory/Simulation: Predicting the route of an oil slick and plume over time, while also describing the path, movement, behavior and time of oil in water.

Data Types: The variables that WOMS must consider and have available for inputs for accuracy - hydrodynamic, meteorological, base maps, oil types, source etc.…

YVR Reference Map: Canada's West Coast in Richmond: Vancouver Lower Mainland, B.C.

Introduction

In 1989 there was a catastrophic oil spill in Alaska's Prince William Sound, known as the Exxon Valdez Spill, where an oil tanker spilled 11 million gallons of crude oil (You & Leyffer, 2011). Without the development or use of an oil spill model to support effective response planning, the spill spread to devastate and contaminate the region - one of the most catastrophic human-caused environmental disasters (Li *et al,* 1998). Following the Exxon Valdez spill, the need for oil spill mapping technology was recognized, and this major event received extensive attention which helped kick-start the development of water-based oil spill modeling software (WOMS).

YVR's Environmental Specialist Patrick McGuiness sponsored my research question for this project regarding water-based oil spill modeling software (WOMS). The central focus of my research is to explore the uses, benefits, requirements and types of WOMS for YVR's specific coastal needs, then to locate and recommend available WOMS that YVR's environmental specialists can integrate into their "Airport Authority Spill Response Plan". This paper is meant to educate and deliver general awareness to the reader regarding all aspects of WOMS, and provide real examples of WOMS that are available for use.

Catastrophic oil spills, such as the Exxon Valdez Spill and the recent BP oil spill in the Gulf of Mexico, have illustrated the extreme importance of developing efficient oil spill response planning strategies (You & Leyffer, 2011). The recent development of oil spill modeling software will further strengthen and improve spill response strategies and actions, while reducing environmental and social impacts.

YVR Background & Rationale

Due to the risks and dangers associated with a potential catastrophic fuel spill (>1,000 L), YVR airport authority wants to locate the appropriate software available to predict the movement and dispersion of fuel in order to deploy their protocol containment measures. YVR is Canada's second largest international airport, and its coastal geographic location is uniquely placed with major waterways immediately beside it. Currently, YVR airport authority does not have the software tools in-house to map, simulate or predict the movement of fuel over time in the case of catastrophic spill. Given the 1.3 billion liters of jet fuel used at YVR annually (SRP, 2010), the Airport Authority is regularly preparing to manage and prevent fuel spills.

The major concern regarding hazardous spills is the possibility of fuel entering the water bodies that are in direct contact with YVR's perimeter - The Fraser River, and The Georgia Straight. These two waterways in contact with YVR are very complex, and oil spill models must be coupled with accurate numerical hydrodynamic and meteorological models that consider the individual coastal characteristics (Li *et al*, 1998). Specifically for YVR, The Georgia Straight forms a deep waterway with strongly modulated estuarine currents, resulting in a complex flow regime dominated by the freshwater plume of The Fraser River (McClintock *et al*, 2010).

Incidents that could cause a catastrophic spill would be from an aircraft emergency landing in the foreshore or an overflowing spill from a tank farm. The fuel volume of an aircraft spill would range in the thousands of liters, and that of a tank farm would be in the millions of liters. One of YVR's key goals within their annual environmental reports is to reduce spills to zero per year, but this has only been accomplished once. The airport has had several spills over 100 liters, with the largest spill of 18,000 liters in 1998 (SRP, 2010).

Currently, YVR has successfully established an emergency response plan and team, environmental management programs (contaminated sites, hazardous material, environmental impact assessment, water quality, climate change, waste, natural habitat and air quality), coast guard, containment methods and an Airport Authority Spill Response Plan. With all the these great practices already in place, my research is limited to WOMS details and recommendations in which YVR could integrate into their existing Airport Authority plans and teams.

Literature Review & Research Methods

The academic literature research I conducted was primarily to gain insight on the importance and requirements for a WOMS. Before I could search for available software models, I needed to build an educated framework so I could properly judge and recommend specific software models.

An academic search input of "oil spills", "water-based fuel spill models" or "oil spill modeling software" returns a vast literature that is somewhat related, but usually slightly different than the specifics for my research location, type and usage. Much of the academic literature is concerning deep-water (non-coastal) oil spills such as the BP oil spill, or scientific lab experiments unrelated to my desired findings.

Through examining many articles, I soon found studies that evaluated coastal oil spill models and provided great insight on benefits, uses and requirements of the models. I then synthesized my information into a table so I could conduct a proper critique of each WOMS I found in the next step of my project, primarily through grey literature searches. Before a review of the models I found applicable, and my recommendations to YVR, it is important to understand the benefits and requirements of these WOMS.

Model Benefits

Water-based oil spill modeling software (WOMS) has emerged within the 21st century with the increased acceptance and use of computers, technology and electronic communications in the workplace (Chao *et al*, 2000). With this new industrial and commercial use of WOMS, innovative technologies can answer many questions response planners have in regards to an oil spill. Spill models provide information to responders and some example questions that a WOMS can answer for them are:

- ✓ Where is the oil slick directed?
- ✓ What is the speed of movement?
- ✓ What are the weathering and spreading characteristics of the oil under the influences of the present hydrodynamic and meteorological conditions?
- ✓ What coastal environments are likely to be impacted?
- ✓ Where do we place the booms and containment methods?
- ✓ How much time do we have?

WOMS will help answer all of these questions more effectively and accurately than any other method during a spill response. A primary purpose of WOMS is to reduce the environmental impacts of spills through improved selection of spill response planning and strategies (Reed *et al,* 1999). Conducting various spill scenarios and simulations allows for a greater understanding of oil behavior and practices for spill response actions. When spill models are used properly, they mitigate damages to community values, and provide multiple ecological, economic and social benefits.

The Three Pillars: Ecological, Economic & Social

Taking advantage of oil spill models and integrating them into mitigation planning and practice will positively impact the three pillars of sustainability: ecological, economic and social (Chao, 2000). The irreplaceable losses and damages inflicted upon the environment and people within an oil-destructed community are preventable (Delvigne & Sweeney, 1988). With the use of WOMS, we can prepare for such an occurrence, properly mitigate the destruction and sustain a community in danger of oil spill damages. This human-caused catastrophic event is preventable with the use of models to better prepare and protect the three pillars of sustainability. An oil spill accident is extremely harmful to the human health and the ocean environment (Chao, 2000). Coastal locations such as YVR have an increased risk because an oil spill can cause long-term irreversible damage to the marine environment for fishery and wildlife, contaminate the shoreline, create an unsuitable wildlife habitat and kill many organisms that are essential links in the global food chain (Chao, 2000).

YVR values its relationship with their neighboring communities, and as a leader in exceeding environmental standards, integrating a WOMS into their Airport Authority Spill

Response Plan would strengthen their environmental performance. The ecological, economic and social spheres are all interconnected, and taking action to protect them all leads to a more sustainable community (Fig 1) (You, 2011).

There are benefits to all three pillars of sustainability that could be effectively generated if YVR introduced a WOMS into their Spill Response Plan. Some of which include:

Ecological:

- ✓ YVR showing active involvement in the environment with a proactive approach
- ✓ Minimizing damage and taking action to protect important environmental values
- ✓ Accurate models and mitigation efforts could protect and save local ecosystems, sensitive coastal habitats and biodiversity.

Economic:

- ✓ Accurate predictions for spill trajectory saves time and money during real-time spill response actions
- ✓ With a catastrophic risk event there would be less total impact and loss
- ✓ Avoidance of response costs, fines and market losses
- ✓ Minimizing cost of restoration

Social:

- ✓ Community respect and appreciate to YVR for going above and beyond their required environmental responsibilities
- ✓ Positive and respectable reputation as a leader in environmental protection
- ✓ Minimizing social disruption regarding community health, exposure and concerns

In the case of a catastrophic spill, the cost, losses, time of restoration and clean up greatly exceed monetary costs of integrating a WOMS and training into the YVR spill response plan.

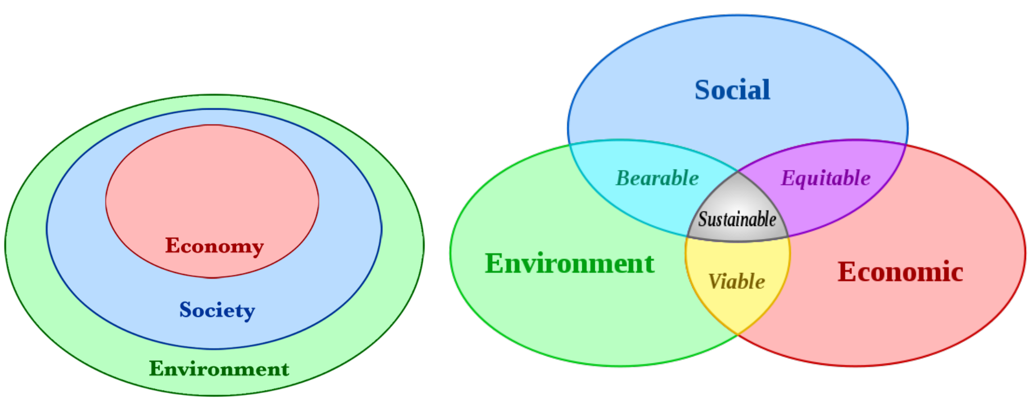


Fig. 1: Representing the interconnected relationship between the three pillars - suggesting that they are all related and sustainability is achieved with the consideration and needs of all three realms (You, 2011).

Model Requirements

I analyzed and took note on the data and calculations in the scientific research, which gave me insight to the most important inputs modeling software must include, being as accurate as possible. Most software models obtain their own basemaps and information via remote sensing and lab investigation (McClintock, 2010). The lab tests I reviewed that predicted water-based oil behavioral characteristics included oil droplet samples, box models and scientific calculations (Li, 1998). Oil behavior is affected by the physical, chemical and biological processes defining the water body (Delvigne, 1988). These processes include spreading, advection, evaporation, dissolution, emulsification, photo-oxidation, sedimentation and biodegradation (Chao, 2000). Oils' natural dispersion computation relies on the sea-state conditions and it is required for assessment of the lifetime of an oil spill (Reed *et al,* 1999).

Modeling software must consider the natural dispersion of oil in its different weathering states and types as a function of time in different hydrodynamic and meteorological conditions (Delvigne, 1988). It is important the software models can generate the necessary calculations but are user friendly and allow for the proper input data fields.

While some models have 3D features, the standard 2D surface simulation is just as effective because more than 90% of oil particles stay in the upper layers (0-16m under the surface), which means the upper waters are the most polluted after a spill (Delvigne, 1988).

I have created a list of key data requirements a WOMS must include for an accurate output and model representation:

- ✓ Hydrodynamic Variables – Tidal & currents. Hydrodynamic data is the most important determinant for oil migration because oil movement is influenced primarily by current patterns (Chao, 2000). Data can be gathered from current meters, drift buoys, ship surveys and remote sensing.
- ✓ Meteorological – Weather – wind, SST, air temperature. Available from weather forecasting services, airports (historic dataset), offshore buoys and the Internet (Salt, 2011). Important to communicate data from the field for "real time" models in an actual response.
- ✓ Oil Type – Modeling systems contain an oil database with oil types and characteristics. Oil types behave differently when spilled on water and it is important to have such a database within the modeling program (Chao, 2000).
- ✓ Appropriate Base Maps– Important to have accurate basemap specific/tailored to their (YVR) environmental setting. Most models have remotely sensed basemaps included in their database.

- ✓ <u>Spill Source/Volume</u> – In our case, it would be known/estimated depending on plane size or tank farm volume, and location of emergency landing/spill would be determined easily in the case of an actual incident.

For YVR's specific coastal location, there is a need for the modeling software to include a level of dynamic representation of oil in the coastal zone. Coastal consideration includes representation of oil-sediment interactions, wave propagation, tides, surf and variations in the shoreline. Modeling oil in a coastal environment is more complex and requires explicit descriptions of the processes active at the coastline (You, 2011)

Model Types

A large number of oil spill models are in use today, ranging in capability and function. From "simple trajectory, or particle-tracking models, to three-dimensional trajectory and fate models that include simulation of response actions and estimation of biological effects" (Reed *et al*, 1999). All of the ranging functions can be narrowed down into five model types (four of the models can be seen below – 3D model type is missing because it is an extension on the application of trajectory models), and it is important to ensure the type being used incorporates the appropriate processes required for each individual model (Fig. 2).

Use of Modelling Functions

	Weathering	Trajectory	Stochastic	Backtrack
Contingency Planning	☑☑	☑	☑☑	☒
Exercises	☑☑	☑☑	☑☑	☑
Response Operations	☑☑	☑☑	☑	☑☑

☑☑ Extremely useful

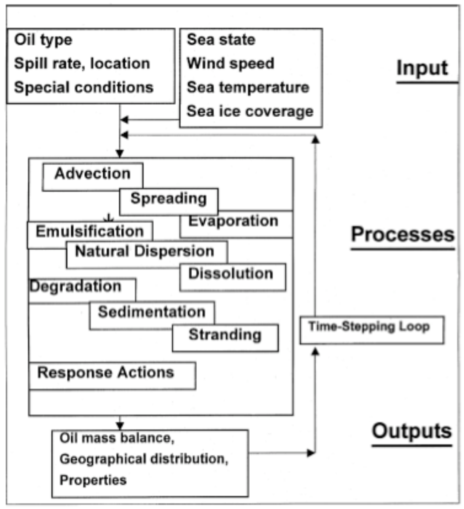
☑ Some use

☒ Limited / no use

Fig. 2: Different uses of modeling functions for mitigation spill drills and spill response (Salt, 2011)

The five model types include oil weathering, stochastic, trajectory, hind-cast, and 3D models. For YVR's specific use, I focused my research on four of the five models (excluding hind-cast models).

1. The Oil Weathering model predicts the changes in oil characteristics that can occur to the oil slick over a function of time, while under the influence of specific environmental conditions (Salt, 2011). The environmental conditions that influence the properties of oil include water temperature, sea-state (waves, salinity, sediment) and wind speed, all of which are closely interlinked (Reed *et al*, 1999) (Fig. 3).



Reed *et al*, 1999

Fig. 3: General layout of oil weathering models. (Reed *et al*, 1999)

2. The Stochastic Model acts as a probability model that includes a series of potential trajectories, which is very useful for mitigation planning and spill drill exercises (Salt, 2011). Using a series of different hydrodynamic and meteorological conditions, the user will have a better understanding of oil behaviors and characteristics during seasonal variations, and how oil properties change over time. Historical records can be used as example inputs to produce a simulation of where an oil slick might travel over a defined time period.

3. The Trajectory/Deterministic Model is the most useful in the occurrence of real-time oil spill response. It is used to illustrate the predicted route of an oil slick over time, and it commonly includes an estimate weathering profile (the first model described) under the hydrodynamic and meteorological conditions (Salt, 2011). The information this model tells the user includes:
    - ✓ Predicted slick trajectory and volume
    - ✓ Dispersion, emulsification and evaporation over time
    - ✓ Coastlines impacted
    - ✓ Time estimate and duration

    All of the above allow for the proper placement of YVR's containment procedures to be put in action, with an accurate estimate of slick destination and time allowance.

4. Hind-Cast Models are produced when the source of an oil spill is unknown. This model can backtrack the route of an oil slick and illustrate a reverse trajectory (Salt, 2011), but for our concerns with YVR the source of the spill is known.

5. 3D Models are similar to the trajectory model but include a more sophisticated approach. This approach includes how oil components are behaving in the vertical portion of the water column subsurface, with illustrations of oil characteristics migrating at depth (Salt, 2011).

Available Software Comparison

There are many different forms of oil spill models ranging in complexity, price and function. Some commonly used commercial oil spill models today are OILMAP (Chao, 2000), GNOME (Beegle-Krause, 2001), WOSM, NOAA and COZOIL. All these models have the same purpose of determining the oil movement and distribution in the water body.

Within my research, tailored to YVR's needs and location, I have narrowed my recommended oil models down to OILMAP and GNOME. These two models have the same use and function, but range highly in complexity, cost and detail. I constructed a comparison table of the two models that check the software model capabilities and data input options. Below the model comparison table, I created a cost table including quantitative data I received directed from contacting both OILMAP and GNOME business representatives.

Model:	Literature Content, Industry Use, Popularity & Date	Hydrodynamic (wave & tidal)	Meteorological (weather) & Oil Type	2D - Surface Water model	3D - Plume - Depth - Vertical Model	Interactions with shoreline and coast
OILMAP	👍	👍 More Detailed	👍 More Detailed	👍 More Detailed	👍	👍 More Detailed
GNOME	👍	👍	👍	👍	👎	👎 Coast only acts as concrete barriers

Model:	*Initial Computer Model Cost* USD$	*Training Cost* USD$	*Data Collection for Input*
OILMAP	~ $20,000	~ $4,000 - 2 days	Provided & Minimal $
GNOME	FREE	- Free online - 2 or 4 day course offered by NOAA	Provided & Minimal $

OILMAP

ASA (applied science associates) is a global science and technology solutions company who develops, consult, train, and upgrade the OILMAP software. OILMAP provides rapid predictions of the movement of spilled oil via simple graphical procedures for entering all required data - hydrodynamic, meteorological, oil type, volume etc.… OILMAP can predict all five models mentioned above and it contains an oil database of nearly 1,000 oils. This modeling application is in use by some of the largest oil and gas companies worldwide and goes above and beyond meeting all the requirements for an accurate model.

OILMAP can be used with an online subscription to access data and weather station information required to run the oil spill trajectories. This application is known as OilmapWeb, which is used on a monthly/yearly subscription online fee instead of the one-time fee for the standalone OILMAP version. The standard OILMAP version can only run under Windows (Vista, XP, 7 etc.) and it is not available for mobile applications.

The ASA professionals are easy to contact and offer an incredible amount of helpful information tailored to the needs of the user. OILMAP licensing, cost, version, and use will vary among users because it depends on the functionalities of the modules. Web conference calls can easily be arranged and YVR can take the initiative if they are seeking this model.

Below are output examples of OILMAP:

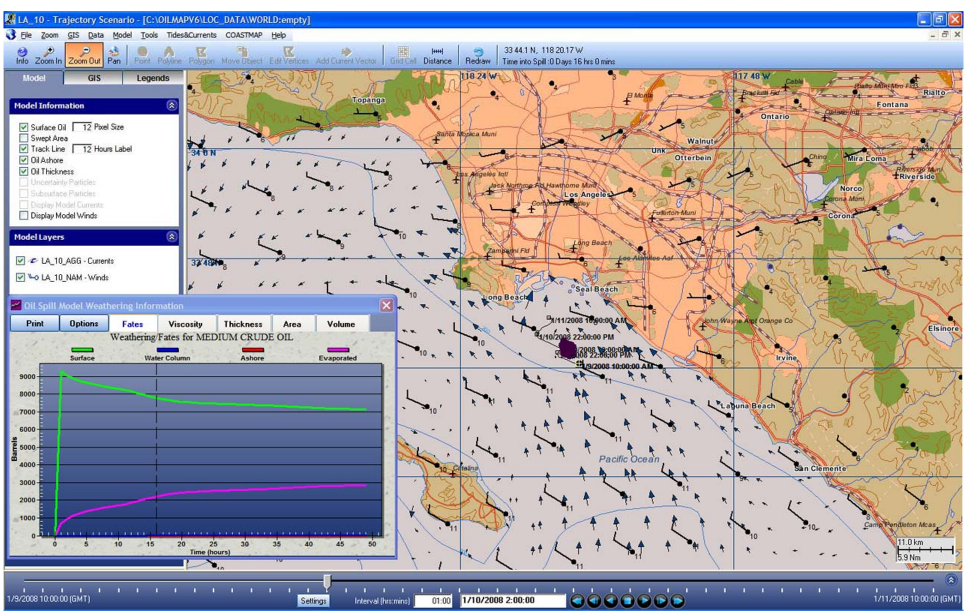


Fig. 4: Screen shot of OILMAP in use, showing the time line and time controls on the bottom, wind direction arrows throughout the image, weathering over time graph on the left, and the input values for hydrodynamic and meteorological conditions in the upper left box. The spill source is the dark purple area in the center, and as the simulation model runs over time, we can observe the movement, spread and weathering of the slick.

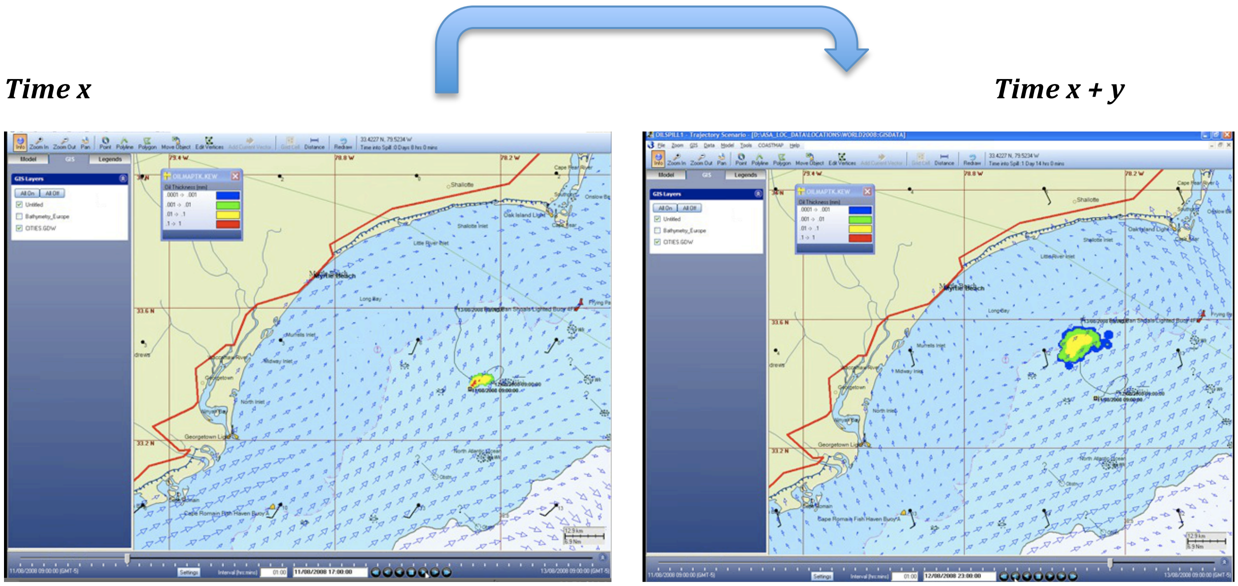


Fig. 5: Screen shot of OILMAP in use, showing the same features as above with a progression on the time scale. We see the spread and depth (represented by the color and legend) of the oil with the chosen input conditions.

Fig. 6: Screen shot of the new OILMAP version 6, in partnership with Google Earth, to provide a more sophisticated model of a surface oil slick over time. Software update additions such as this are available.

GNOME

GNOME (General NOAA Oil Modeling Environment) is a tool developed by the National Oceanic and Atmospheric Administration (NOAA) for oil-spill response (Beegle-Krause, 2001). GNOME is a multi-purpose trajectory model with three different modes: Standard, GIS Output, and Diagnostic (Beegle-Krause, 2001). The GNOME models are more simplistic than the OILMAP model, but this free program can output fairly accurate trajectories for a variety of users ranging in oil mapping skills. From my own research, I found GNOME more applicable for non-complex coastal regions at a smaller scale. The model does not take into consideration the coastal characteristics on a large scale for a localized region such as YVR, and its surrounding unique coastline properties.

The GNOME model, regional location files and documentation are available online, and training is offered in a few different formats by the NOAA professionals who developed this model (Beegle-Krause, 2001). The images below are screen shots of the "oil spill movie" output provided from GNOME, simulating a 49,000 Gallon oil spill in the San Juan Islands over a 72 hour time period.

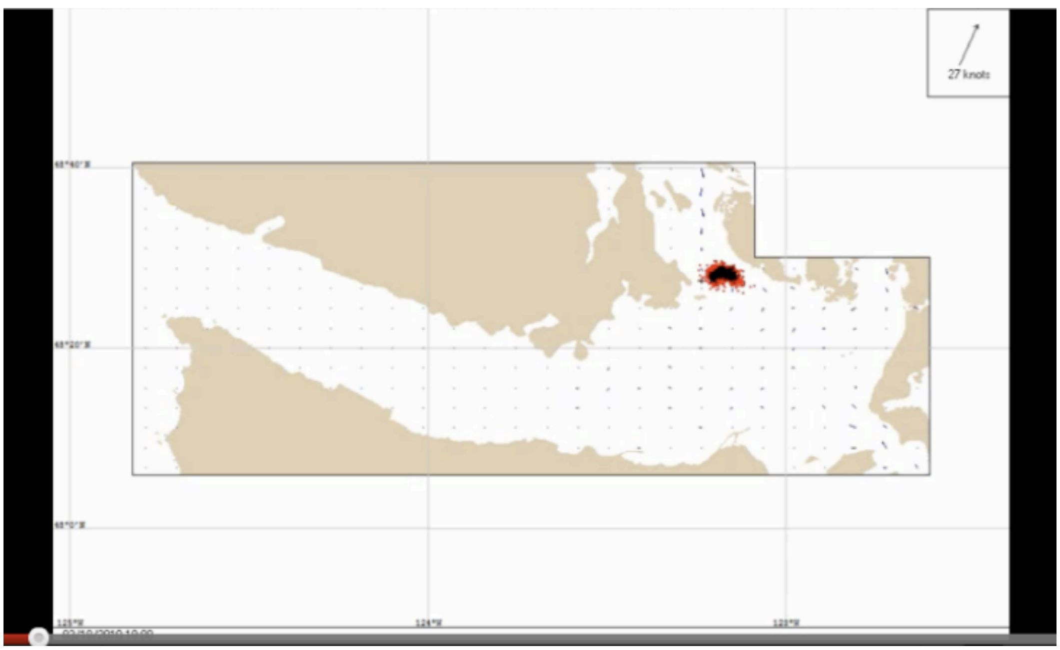


Fig. 7: Time x - Screen shot series of time x, y z of the GNOME model output. We can see the wind speed and direction in the top right corner, but it shows one direction representative throughout the entire simulation, which does not take into consideration of coastal features. A very simple version compared to OILMAP.

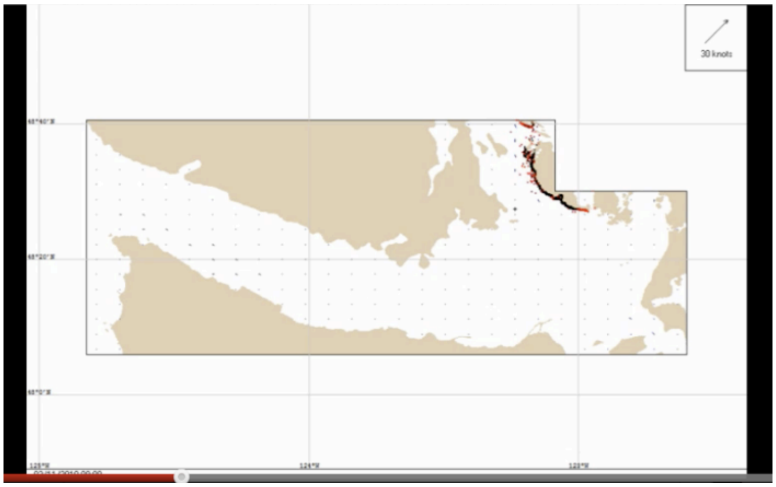


Fig. 8: GNOME output at **Time y**

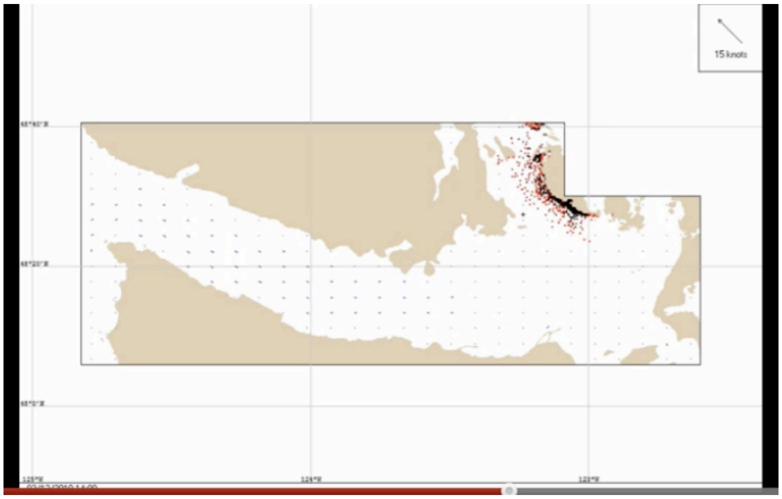


Fig. 9: GNOME output at **Time z**

Limitations & Future Work

Through my findings, I found there were areas that were limited and require future work. It appears most WOMS are only run under windows computer software and have no sophisticated mobile functions yet. Mobile options for WOMS on phones and emergency response DEVS (Drivers Enhanced Vision System) are very limited, and the best option for mobile applications is the use of OilmapWeb using the safari iPhone application until new apps are released. Technology systems and software are constantly improving and when the fundamental data additions become available they can be added.

Future directions with oil spill models include increasing computational power to strengthen oil spill models, allowing more chemical and physical detail, and more direct coupling to hydrodynamic and meteorological models (Reed *et al,* 1999).

Recommendations

After conducting research on oil spill models and searching for an appropriate model for YVR, I have several recommendations for my community partner, Patrick McGuiness.

With my first recommendation, I suggest with great confidence that YVR implements a WOMS into the already present Airport Authority Spill Response Plan. As a leader in our community and the largest airport in Western Canada, YVR has taken the extra steps to invest in the environment, and this preparation technology allows YVR to be active in protecting their valuably shared environment. Also, I believe the time and money already invested in the YVR spill response plan needs to be secured and strengthened with the additional investment in an oil spill modeling system. With the hydrological and meteorological complexities influencing the fate of an oil spill, we have learned that every spill behaves differently, which makes predicting locations of containment and response actions very difficult. There is no better way to predict the trajectory and fate of an oil slick than to have a modeling system in practice such as OILMAP.

My next recommendations for implementing a Water-Based Oil Spill Modeling Software:

- ✓ Purchase the desired software (there are many different commercially available oil spill modeling programs ranging in price)
- ✓ Attend professional training (~2-4 days)
- ✓ Integrate the new software model in the already established Spill Response Plan
- ✓ Attain the necessary data (included in training course)
- ✓ Conduct "spill drill" exercises within the Stochastic Model option of the program
- ✓ Practice running "real-time" trajectories from field data input sources
- ✓ Check the appropriate containment methods and spill response actions are working in unison with the software - proper communication is key
- ✓ Check regularly for technological version updates (mobile applications coming soon)
- ✓ Do not solely rely upon the program. It should be used in conjunction to strengthen the information and plan in place to benefit YVR's response team
- ✓ Remember, the outputs from any model is dependent on the quality of inputted data

My last recommendations are to communicate and partner with provincial support and ministry roles because the province also has their own emergency spill response plan called "The BC Marine Oil Spill Response Plan". This plan uses software that includes extremely useful functions and uses to many levels of government and industries, who share similar goals, values and concerns with protecting B.C's coastal communities and environment. The more sectors involved in implementing a new water-based oil spill modeling software, the greater protection of our coastal waters from oil spill contamination.

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