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*Chapter 1*

# BIOPHYSICAL ENVIRONMENTS DO RECOVER FROM OIL SPILL EFFECTS

***Walter H. Pearson[1,*] and W. Cody Fleece[2,†]***
[1]Stantec Consulting Services, Suite E, Okemos, MI, US
[2]Stantec Consulting Services, Cincinnati, OH, US

## ABSTRACT

Immediately after oil spills, assertions often arise that "ecosystems do not recover from spill effects." A survey of the literature concerning the recovery of the biophysical components of terrestrial, freshwater and marine environments assessed the scientific support for the notion of no environmental recovery from oil spills. The survey examined 176 Valued Ecosystem Components (VECs) from 48 oil spills in subarctic and cold temperate regions. The scientific literature on recovery from marine oils spills proved voluminous, whereas that for freshwater and terrestrial spills proved sparser.

The outcomes reported by study authors simply do not support the notion that biophysical environments do not recover. Indeed, the environments and their components quite commonly recover. For the studies reviewed, the VECs had recovered or were recovering by study's end in 83%, 67%, and 72% of the cases for marine, freshwater, and terrestrial biophysical environments, respectively. Despite the lack of clean-up in 10 experimental spills, 62% of the VECs were recovering at study's end. Overall, 79% of the total VECs examined from all environments had recovered or were recovering. Cases of no recovery or no apparent recovery were associated with short study duration, inappropriate spill clean-up techniques, experimental spills, or complex interactions with other natural or human-derived factors.

Recovery times vary with the environment, the VEC, and other factors. The average times to recovered status for the biophysical VECs examined were 1.7 and 4.9 years for freshwater and marine environments, respectively. Recovery times for terrestrial VECs were complicated by the fact that seven of the terrestrial spills were experimental spills in which the oil contamination was not cleaned up. Some terrestrial VECs that achieved recovering status appeared to do so in about 2 years, but others were still recovering or

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[*] Phone: 616 -610-4614. E-mail: Walter.Pearson@stantec.com.
[†] E-mail: Cody.Fleece@stantec.com.

showed no recovery after 20 years, especially among those from experimental spills. Fifteen of the terrestrial VECs were from Arctic and Subarctic Zones where cold temperatures decrease biodegradation rates and short growing seasons decrease annual growth rates.

Several factors can slow recovery. First, if oil persists, recovery times may be lengthened. Clean-up is undertaken to remove and lessen the persistence of hydrocarbons; however, while spill clean-up should strive to remove as much oil as is practically possible, it need not completely eliminate contamination before recovery can proceed. Second, inappropriate clean-up techniques, such as the use of heavy equipment in marshes, can substantially lengthen recovery times. The contingency planning and operations in modern spill response carefully selects the most appropriate treatment for the oil type, level of contamination, and the nature of the receiving environment.

Cases exist where recovery may benefit from active human intervention beyond routine clean-up operations. The most protracted recovery in terrestrial environments appears to be where oil reaches groundwater, where cold temperatures decrease biodegradation rates in soil, or when short thaw seasons limit vegetation growth. The state of the art in bioremediation and phytoremediation continually improves and holds promise for spills where natural environmental processes for oil degradation are inhibited.

## INTRODUCTION

Immediately after oil spills, assertions often arise that “ecosystems just do not recover from spill effects.” This notion needs to be confronted with the results of scientific studies of recovery. The purpose of this chapter is to examine what the scientific literature has to say concerning the recovery of the biophysical components of terrestrial, freshwater and marine environments from oil spills. This chapter reports the results of our most recent examination of the scientific literature regarding recovery of ecosystems and their Valued Ecosystem Components (VECs) from spills that have occurred primarily in Cold Temperate and Subarctic Zones. The chapter addresses two sets of questions.

The first set of questions includes:

- How do oil spill characteristics differ among recovery studies for the terrestrial, freshwater, and marine environments?
- How common is recovery?
- How much time does recovery take?
- What factors influence recovery?

A semi-quantitative analysis of our results from the literature survey addresses the above questions.

The second set of questions includes:

- How does recovery from oil spills compare to recovery from other disturbances?
- What factors impede recovery?
- What can be done when recovery lags?
- What implications do the survey results have for oil spill preparedness, prevention and response?

- What implications do the survey results have for defining and measuring recovery?

A literature review approach addresses this second set of questions and provides additional information concerning questions from the first set. Although clean-up is usually the first step to environmental recovery, this chapter examines the course of events after the clean-up phase has ended to assess recovery processes and outcomes for the biophysical environment.

Many scientific papers and books have reviewed oil spills (Clark 1982; Teal and Howarth 1984; Wells et al. 1995; Rice 1996; API 1999; National Research Council 1975, 1985, 2003; Kingston 2002; Wiens 2013), but here we focus on those studies that have followed recovery. Recovery of human environments is not treated here but one example of a study documenting recovery of the human environment from an oil spill can be found in Fall et al. (2006).

This chapter represents the third iteration in our ongoing study of recovery. The first and second iterations were prompted by hearings conducted as part of a review for the proposed Northern Gateway Pipeline between Alberta and British Columbia, Canada. The Canadian National Energy Board and the federal Minister of the Environment established a Joint Review Panel to conduct a review of the project. The specific objective of the initial review was to assess the scientific evidence regarding ecological recovery from oil spills. Initially, about 114 papers were reviewed for the first iteration (Stantec 2012) and assessed for relevance to recovery in support of the hearing process. This chapter is now based on reviews of over 140 publications and builds upon the original report (Stantec 2012) by incorporating information and data developed during the hearings and from subsequent review of the literature following the close of the regulatory hearings. The additional literature corroborates the results of the initial review and lends stronger support to the major conclusions of our initial review.

This introduction includes two short overviews drawn from the literature. The first addresses the behavior of spilled oil, and the second, the various processes involved in recovery.

## Behavior of Spilled Oil in the Environment

The behavior of spilled oil is governed by the characteristics of the environment at the time and place of the spill and by the characteristics of the spilled oil, including type and the rate and duration of spillage. Substantially greater detail appears in reviews by the National Research Council and others (NRC 1975, 1985, 1999, 2003, Whittle et al. 1982, Wiens 2013). The general framework for understanding oil behavior derives primarily from marine spills of crude oil and some refined products, which are the most studied overall. Some observations concerning spilled oil behavior in terrestrial and freshwater environments appear at this section’s end.

Crude oils and refined products such as fuel oils are mixtures of natural chemicals. The modifications to crude oil in refining can significantly alter the products’ behavior and fate in the environment, but the petroleum-based aromatic and aliphatic compounds in the refined products undergo the same degradation processes as the original parent compounds.

Immediately upon being spilled into terrestrial, freshwater, and marine environments, the spilled oil becomes subject to numerous chemical, physical and biological processes that begin to break down, biodegrade and otherwise assimilate the spilled oil (NRC 1975, 1985, 1999, 2003, Whittle et al. 1982). This natural degradation of oil sets the conditions under which the recovery of the biophysical and human environments from oil spills occurs. Ultimately, spilled oil is broken down into carbon dioxide and water by sunlight (photolysis) and microbes (biodegradation). However, the time required depends on the nature and amount of the petroleum product spilled and the characteristics of the receiving environment.

Oil spilled onto water surfaces under calm conditions tends to spread by gravity into a thin layer (about 0.1 mm thick) to cover a relatively large area. However, the actions of wind, tides, and currents often lead to an uneven distribution of oil slicks of various thicknesses. Wind and current can transport the slicks, which then can strand on shorelines. Oil viscosity increases as the slicks weather, and spreading decreases. Under windy conditions, many oils form stable water-in-oil emulsions called mousse - the sticky, dark coagulum that can accumulate along shorelines. Because water becomes incorporated into the mousse, the amount of contaminated material that must be addressed in the spill response also increases. Strong winds increase the rate of evaporation and, along with wave action, can increase the rate of dissolution. Both weathering processes remove the more volatile and soluble hydrocarbons from the oil.

Different weathering processes dominate at different times after spillage. Within hours evaporation transports most of the volatile and toxic oil components into the atmosphere, where sunlight oxidizes the compounds. Evaporation can remove up to 50% of the oil mass from the water surface, depending on oil type and its content of volatile compounds. Dispersion occurs when wind waves or other turbulence drives oil into the water column where it is present as droplets or dissolved hydrocarbon for the more soluble fractions. Oil droplets can coalesce into larger droplets that float back to the water surface when the waves or turbulence abates.

The terms “dispersed,” “sunken,” and “submerged” oil are frequently used interchangeably but are not precisely the same because different processes are involved (NRC 1999). Naturally dispersed oil occurs when turbulence drives oil into the water column. Such conditions as moderate waves in marine and lake environments or high, turbulent flows in rivers can produce this turbulence. Dispersed oil is present as droplets that can coalesce and resurface when the turbulence decreases. Submerged oil can occur when the oil density is greater than that of the receiving water and the oil sinks by gravity. Increased oil density can occur when weathering removes the lighter volatile compounds or, more commonly, when oil comes into contact with sand and incorporates heavy sand particles. Distinguishing the mechanisms that have operated in a given spill can be difficult so that NRC (1999) recommends using the term “non-floating oil.”

Oil spilled into the terrestrial environment spreads by gravity but the spreading rate and pathway is heavily influenced by the terrain, soil types, and vegetation. The tendency of oil to seep into soil and migrate into groundwater is affected by soil characteristics such as grain size and by oil characteristics such as viscosity and weathering state. Oil spreading over land tends to pool in low areas in the terrain. Oil spilled on land can cross the terrain to reach freshwater. In crossing the terrain, spilled oil can incorporate heavy particles.

Oil spilled into freshwater systems, such as streams, rivers, ponds, and lakes, is subject to the same processes of evaporation, dispersion, dilution, dissolution, and transport as oil in marine systems (API 1999, NRC 1999). As noted earlier, the turbulence associated with swift currents in streams and rivers can physically disperse oil into the water column. As in marine systems, the dispersed oil droplets can coalesce when the turbulence decreases and the larger droplets float to water surface. Because of the shallow depths of rivers compared to marine waters, there is greater opportunity for the dispersed oil to reach bottom substrates and sorb particulate matter. Freshwater is less dense than marine waters and the sorption of particulates can increase the density of heavy oils to the point that it sinks by gravity.

Ultimately, most of the oil spilled into terrestrial, freshwater and marine environments is broken down by natural agents. With no clean-up or other treatment, about 75% of crude oil spilled into the marine environment will be broken into carbon dioxide and water (Whittle et al. 1982). Biodegradation rates depend on the oil type and characteristics of the receiving environment, such as temperature and prevailing microbial populations (NRC 2003).

### Processes in Recovery

First, some distinctions concerning terminology are needed. The term “oil spill recovery” can be ambiguous. Here, the term “recovery” refers to the recovery of the biophysical environment from an oil spill, not the recovery or collection of oil during oil spill response and clean-up. The physical collection and removal of oil from the environment is an important first step in enabling recovery and decreasing time to recovery but is not recovery in the sense used here. Also, remediation and restoration are active human interventions that enable or accelerate recovery, but are not recovery itself. Ecological recovery, then, includes the processes and outcomes that return the ecosystem or VEC to a desired functioning state.

Some natural processes that advance ecological recovery include:

- Natural transport – wave action, currents, and other processes physically move the oil from one environmental compartment to another;
- Natural transformation – photolysis and biodegradation break down the oil;
- Natural population growth – the population rebuilds through natural recruitment and growth;
- Immigration, colonization, and recolonization – organisms move into the affected area and re-establish their populations.

This chapter considers the factors in recovery in more detail later.

## APPROACH

The study objective was to examine published studies to discern the broad patterns in ecological recovery following oil spills. Accomplishing the objective required three steps: 1) identification of spills where ecological recovery was studied 2) construction of a database of attributes described in those studies (Appendix), and 3) analysis of the data for patterns regarding ecological recovery.

## Spill Selection

Candidate spills were identified for inclusion in the study using widely available databases including EBSCOhost, ScienceDirect, and Google Scholar. Articles were also identified from the bibliographies of relevant articles. The selection process for literature was not an attempt to randomly sample all oil spills but rather to obtain a list of spills most relevant to recovery of the biophysical environment in Cold Temperate and Subarctic Zones. General criteria for inclusion of literature for a spill were the following:

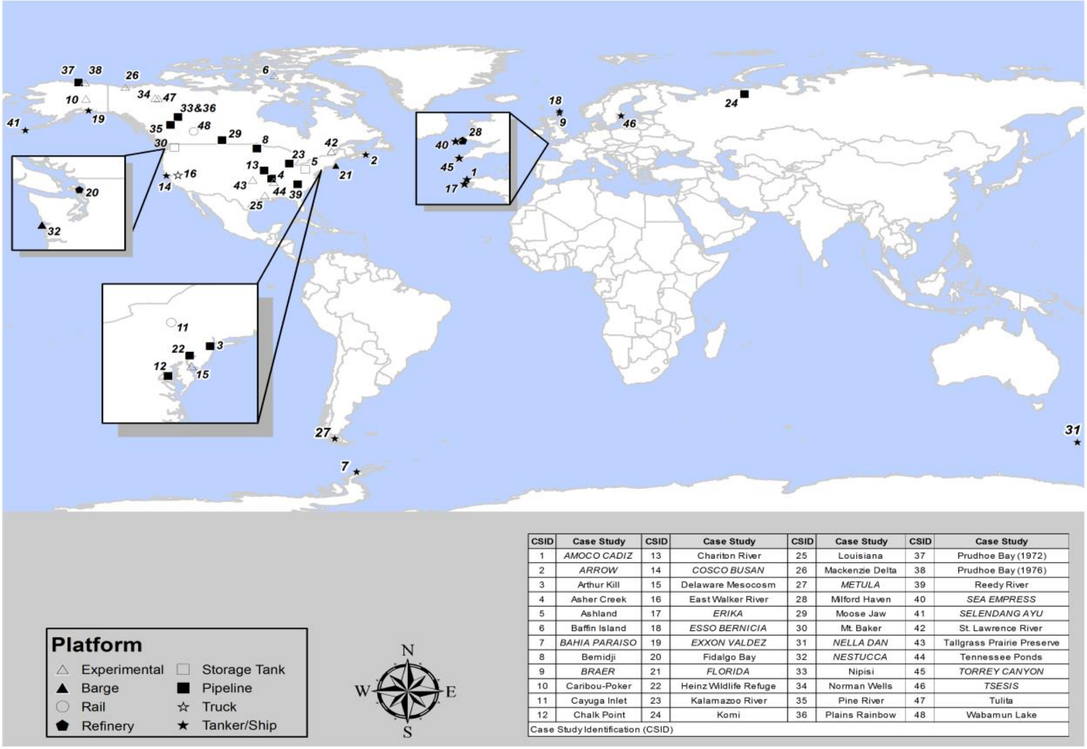
- Only studies that had some explicit mention of recovery were examined in detail and included in the database for assessment.
- Studies examined were those that documented changes in conditions of a particular VEC with time after an oil spill.
- Studies were from cold temperate, subarctic, and temperate ecoregions as a means to narrow the assessment to circumstances most relevant to the Northern Gateway project.
- In a small number of cases, studies were included in the assessment despite having failed to satisfy these criteria if the spill represented the only source of information for a particular topic area.

The largest and most intensively studied oil spills often focused on more than one Valued Ecosystem Component (VEC) while smaller or less intensively studied spills might report on only one VEC. Nine of the 48 spills in the database accounted for 116 VECs while the remaining 39 spills had three or fewer VECs. The majority of the spills examined were from the Northern Hemisphere (Figure 1).

## Information Sought

The following variables were initially identified for inclusion in the database.

- Oil spill name
- Location
- Year of spill
- Oil type
- Volume spilled
- Volume recovered
- Platform (source) for spill
- Environment affected
- Valued Ecosystem Component
- Observed mortality
- Recovery status
- Processes reported
- Measures to accelerate recovery
- Years to recovery
- Study duration



| CSID | Case Study | CSID | Case Study | CSID | Case Study | CSID | Case Study |
|---|---|---|---|---|---|---|---|
| 1 | *AMOCO CADIZ* | 13 | Chariton River | 25 | Louisiana | 37 | Prudhoe Bay (1972) |
| 2 | *ARROW* | 14 | *COSCO BUSAN* | 26 | Mackenzie Delta | 38 | Prudhoe Bay (1976) |
| 3 | Arthur Kill | 15 | Delaware Mesocosm | 27 | *METULA* | 39 | Reedy River |
| 4 | Asher Creek | 16 | East Walker River | 28 | Milford Haven | 40 | *SEA EMPRESS* |
| 5 | Ashland | 17 | *ERIKA* | 29 | Moose Jaw | 41 | *SELENDANG AYU* |
| 6 | Baffin Island | 18 | *ESSO BERNICIA* | 30 | Mt. Baker | 42 | St. Lawrence River |
| 7 | *BAHIA PARAISO* | 19 | *EXXON VALDEZ* | 31 | *NELLA DAN* | 43 | Tallgrass Prairie Preserve |
| 8 | Bemidji | 20 | Fidalgo Bay | 32 | *NESTUCCA* | 44 | Tennessee Ponds |
| 9 | *BRAER* | 21 | *FLORIDA* | 33 | Nipisi | 45 | *TORREY CANYON* |
| 10 | Caribou-Poker | 22 | Heinz Wildlife Refuge | 34 | Norman Wells | 46 | *TSESIS* |
| 11 | Cayuga Inlet | 23 | Kalamazoo River | 35 | Pine River | 47 | Tulita |
| 12 | Chalk Point | 24 | Komi | 36 | Plains Rainbow | 48 | Wabamun Lake |
| Case Study Identification (CSID) | | | | | | | |

Figure 1. Geographic distribution and platform for spills examined in this study.

Very few studies contained comprehensive or complete information for all of the variables of interest. Consequently, sample size varies depending on the completeness of the variables under consideration. Several variables were only sporadically reported in published studies and sample sizes were insufficient for analysis. Variables with insufficient information included volume recovered, observed mortality, processes reported, and measures to accelerate recovery.

## Spill Characteristics

This chapter addresses information from a total of 48 spills. Reviewers recorded information on the spill name, location, the year of spill, volume, and type of product spilled.

Spilled products were described in the literature as crude oil, heavy crude, light crude, Number 2 Fuel Oil, Number 5 Fuel Oil, Number 6 Fuel Oil, Diesel, gasoline, and various mixtures of the aforementioned types (i.e., multiple products were spilled). The product types were consolidated according to shared properties into the following categories: crude oil, fuel oil, or crude and fuel oil. Only one gasoline spill, which accounted for only one VEC, was included in the initial database. This record was omitted from consideration here (Appendix) because of the small sample size and the different properties of gasoline compared to crude and fuel oils. Recovery was studied in accidental spills originating from several platforms (e.g., tankers, pipelines, trains), as well as in experimental studies in which oil was intentionally released or left untreated.

## Environmental Characteristics

Spills were classified as Marine, Terrestrial, or Freshwater according to the environment where the spill occurred. Within these groups, spills were further classified according to the Valued Ecosystem Component affected and for which recovery was studied. The Marine category included estuaries. Information was assembled for 176 VECs grouped into the following categories:

- Algae
- Birds
- Fish
- Macro-invertebrates
- Mammals
- Microbes
- Reptiles
- Vegetation
- Sediment
- Shoreline
- Soil
- Water Quality

VECs in the transition zone between aquatic and terrestrial transition environments (e.g., shorelines and shoreline vegetation) were included in Marine and Freshwater categories. Upland vegetation, soil and groundwater VECs were assigned to Terrestrial ecosystems. VECs most often focused on single species but studies also focused on community or assemblage metrics (e.g., diversity, richness, Index of Biotic Integrity).

In some instances, the same VECs were studied at multiple points in time. For example, Collins et al. (1994) studied product constituents in soils 15 years after an experimental spill and Prince et al. (2003) analyzed product constituents in soils at the same location 10 years later (25 years post-spill). Therefore, although some VECs may appear to be double counted, multiple studies on the same VEC for the same spill provide information on recovery over time.

## Recovery Status

A prerequisite of the recovery evaluation was that sufficient information for each VEC existed that would allow for the detection of injury and for tracking progress toward recovery. Each paper was evaluated for recovery in the form of quantitative data showing temporal change or simply using general keywords such as “recover (or any part of the word), return to natural equilibrium, return to previous historical conditions, return to pristine conditions, and return to baseline.” If substantive data were presented characterizing the status of a VEC, reviewers accepted the author’s conclusions regarding recovery as presented in the paper without assessment of the validity or accuracy of the conclusions.

The Categories of recovery status and criteria used to guide decisions regarding recovery status were the following:

- Insufficient Data: the author stated that insufficient information was found to judge recovery; the author mentioned recovery but did not present sufficient information or data for the reader to discern recovery status; the author presented an assertion concerning recovery or the absence of recovery but offered no data or chain of reasoning to support the conclusion;
- None or none apparent: not showing recovery, long term effects have set in and conditions are not improving or improve very modestly;
- Recovered: full recovery or a return to pre-spill conditions that were equal to non-oil spill base data or baseline conditions;
- Recovering: partial recovery, moving closer to conditions before oil spill, but not yet exhibiting full recovery;
- Uncertain: this category refers to circumstances where some metrics, sample locations, or time periods suggest that some recovery has occurred, while other indicators suggest that recovery has not occurred.

Some spills were studied at multiple points in time. Reviewers tracked each spill through to the most recent, readily available publication. However, it was often observed that when resources were categorized as “recovering,” no additional studies could be found verifying “recovered.”

### Assessment and Analysis

Simple descriptive statistics were generated from the assembled database (Appendix) characterizing the type and number of spills encountered in the literature, the duration of study by ecosystem, the number and volume of spills by environment and other appropriate indicators. A total of 176 VECs from 48 spills formed the base of this analysis. In a few cases, correlation or association tests were used to examine relationships between variables.

## RESULTS

### How Do Oil Spill and Other Characteristics Differ Among Recovery Studies?

Study of recovery from spills was quite uneven among environments (Figure 2a) and VECs (Figure 2b). The spill characteristics in this chapter do not represent those for all spills, but for those for which some study of recovery was found.

Marine spills dominate with the most VECs studied and the most spills with study durations greater than 5 years (Table 1 and Figure 3). Less attention has been given to recovery in freshwater and terrestrial environments. Similarly, macroinvertebrates, shorelines, birds, sediment, and fish have received the most study of recovery, while the rest substantially less (Figure 4).

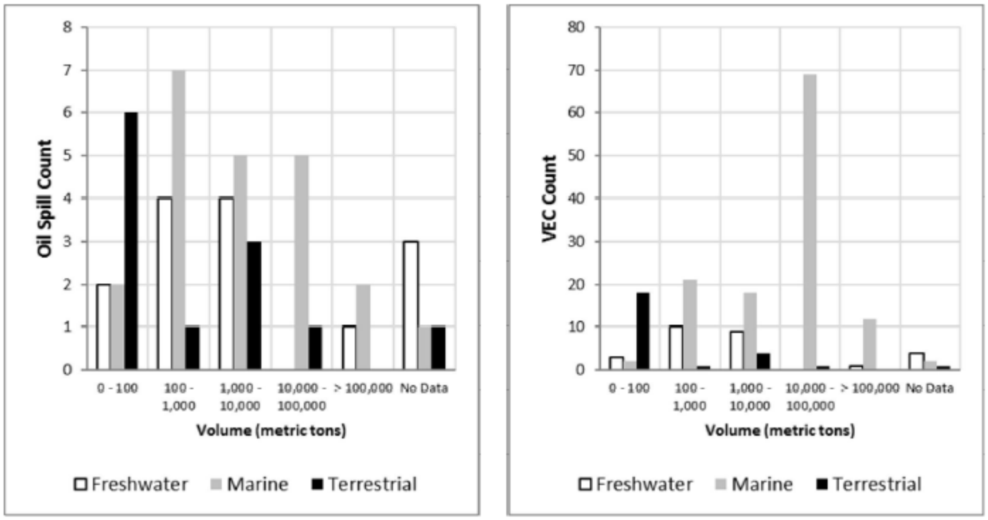


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Figure 2. (a) Spill frequency by environment and volume and (b) VEC frequency by environment and spill volume.

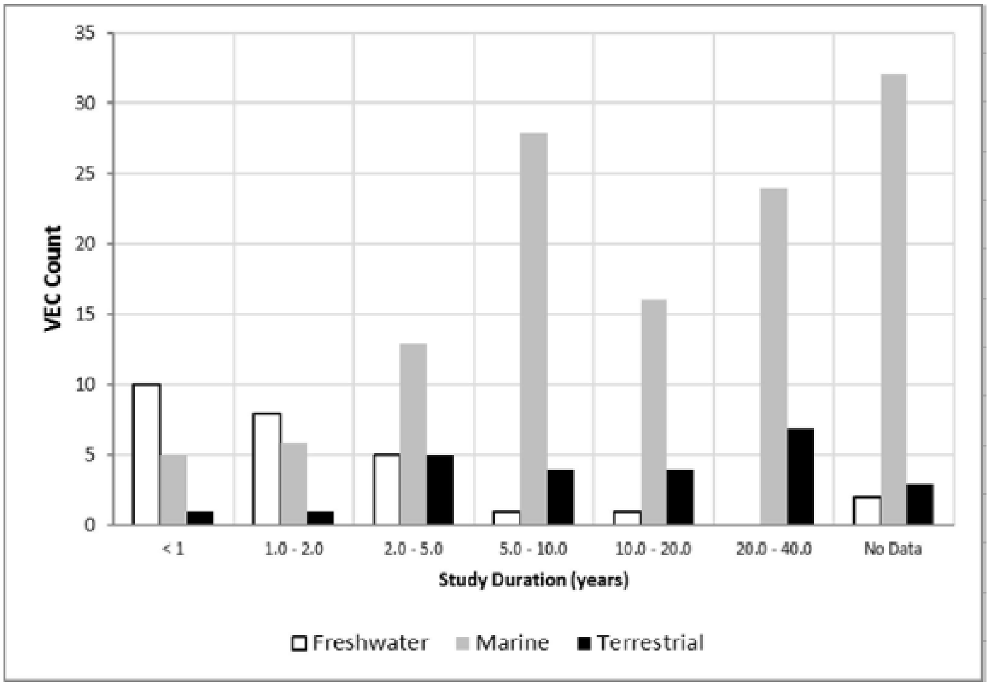


Figure 3. VEC count by environment and study duration.

Crude oils were by far the most common oil type for which recovery was studied (Figure 5). Fuel oils of various types were the second most common oil types studied. Some spills involved release of both crude oil from the cargo and a fuel oil from the fuel tanks.

Crude oils have been studied in all three environments and crude oil spills from tanker ships have received the most attention (Figures 5 and 6 and Table 2). The largest spill volumes were also associated with tankers and ships (Table 2).

**Table 1. Spill volume and study duration by environment**

| | Volume (metric tons) | | | Study Duration (years) | | |
|---|---|---|---|---|---|---|
| Environment | Spill Count | Average | Standard Deviation | Count | Average | Standard Deviation |
| Freshwater | 11 | 13434 | 40790 | 25 | 1.9 | 2.8 |
| Marine | 21 | 30839 | 58641 | 92 | 12.1 | 9.9 |
| Terrestrial | 11 | 8785 | 25245 | 22 | 12.9 | 10.6 |
| Grand Total | 43 | 20745 | 47831 | 139 | 10.4 | 10.0 |

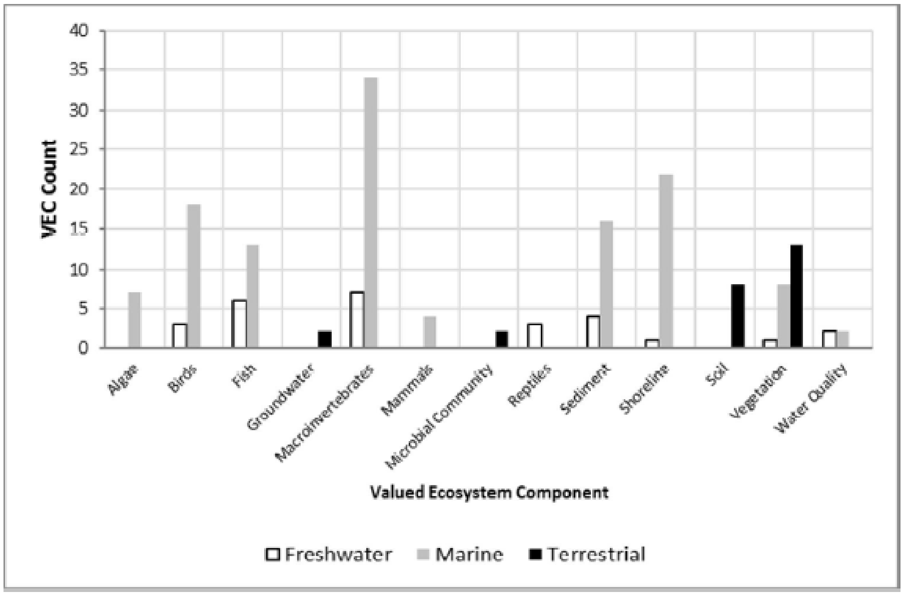


Figure 4. VEC count by VEC group and environment.

Terrestrial spills reported in the recovery literature tend to be from pipelines, refinery storage tanks, and railway accidents. Freshwater spills are primarily from barges and pipelines. Most VECs came from large marine spills (Figure 6) and the EXXON VALDEZ oil spill (EVOS) had the largest VEC count (n=54) of any spill.

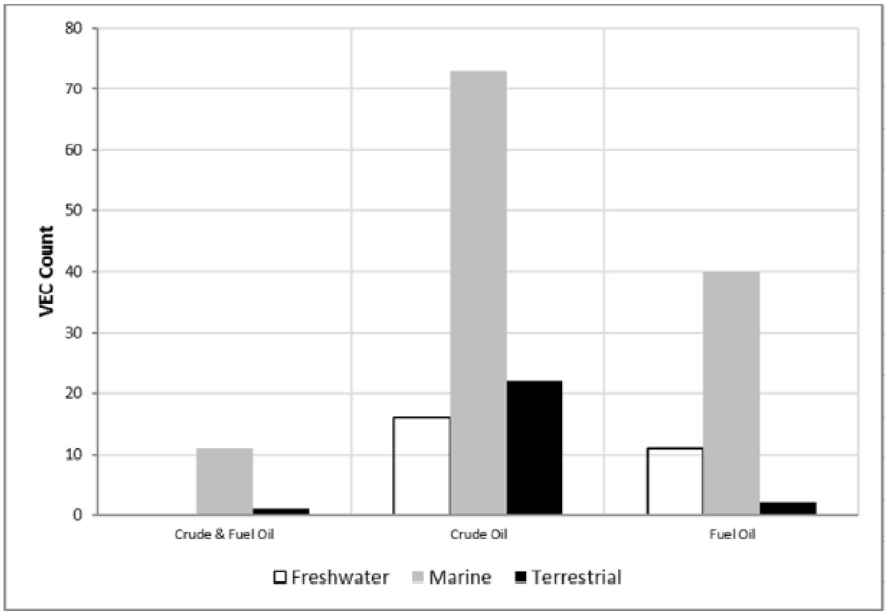


Figure 5. VEC count by product type and environment.

## How Common Is Recovery?

The sum of the study outcomes as reported by study authors simply does not support the notion that ecosystems do not recover from oil spills (Table 3, Figure 7).

Indeed, not only do ecosystem components recover, and they do so quite commonly. For the 48 oil spills reviewed, the VECs had recovered or were recovering by study's end in 83%, 67%, and 72% of the cases for marine, freshwater, and terrestrial biophysical environments (n=124, 27, and 25), respectively. The ten experimental spills had 21 VECs subject to either intentional release or intentional lack of clean-up. Despite this lack of clean-up, 62% were recovering at study's end (Appendix). Overall, 79% of the total VECs examined from all environments and platforms (n=176) had recovered or were recovering.

**Table 2. Spill volume and study duration by spill source**

| | Volume (metric tons) | | | Study Duration (years) | | |
|---|---|---|---|---|---|---|
| Platform | Spill Count | Average | Standard Deviation | Count | Average | Standard Deviation |
| Barge | 2 | 646 | 125 | 10 | 19.9 | 14.9 |
| Experimental | 7 | 12121 | 31938 | 19 | 8.9 | 9.2 |
| Pipeline | 14 | 11560 | 35991 | 24 | 8.2 | 9.8 |
| Rail | 2 | 75 | 73 | 6 | 0.9 | 0.7 |
| Refinery | 1 | 670 | NA | 4 | 11.7 | 12.0 |
| Storage Tank | 2 | 1128 | 1564 | 3 | 3.7 | 2.9 |
| Tanker/Ship | 14 | 45785 | 67585 | 71 | 11.4 | 8.8 |
| Truck | 1 | 11 | NA | 2 | 0.4 | 0.0 |
| Grand Total | 43 | 20745 | 47831 | 139 | 10.4 | 10.0 |

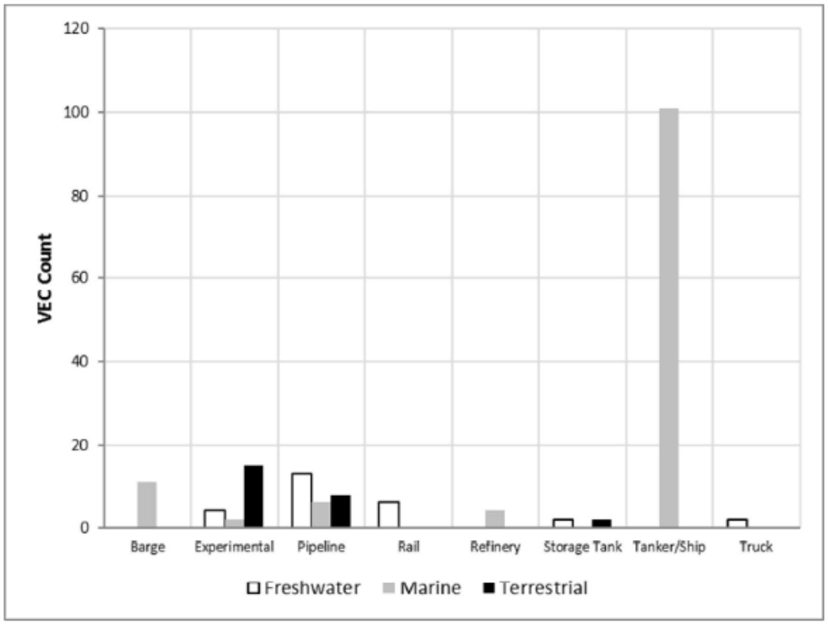


Figure 6. VEC count by spill source and environment.

The frequency of recovering VECs was higher in fuel oil spills than in crude oil spills relative to other recovery states (Figure 8a). However, these differences were not significant at the 0.05 significance level ($\chi^2 = 4.969$, df = 2, p = 0.083). Observed frequencies for recovery states in freshwater and marine environments (Figure 8a) did not differ significantly ($\chi^2 = 3.915$, df = 2, p = 0.141).

Spills with insufficient information were primarily those with study durations less than 2 years (Table 3). VECs showed no recovery or no apparent recovery in 6%, 11%, and 28% of the cases for marine, freshwater, and terrestrial spills, respectively.

**Table 3. Recovery status by environment and study duration**

| | Proportion | | | Study Duration | | | Years to Recover | | |
|---|---|---|---|---|---|---|---|---|---|
| Recovery State | VEC Count | Proportion | 95% Confidence Interval | Count | Mean | 95% Confidence Interval | Count | Mean | 95% Confidence Interval |
| Insufficient Data | 4 | 0.15 | 0.13 | 3 | 1.1 | 1.0 | | | |
| None or none apparent | 3 | 0.11 | 0.12 | 3 | 1.3 | 1.7 | | | |
| Recovered | 5 | 0.19 | 0.15 | 5 | 2.9 | 3.2 | 5 | 1.7 | 1.4 |
| Recovering | 13 | 0.48 | 0.19 | 12 | 2.0 | 1.8 | | | |
| Uncertain | 2 | 0.07 | 0.10 | 2 | 0.3 | 0.4 | | | |
| Freshwater Total | 27 | 0.15 | | 25 | 1.9 | | | | |
| Insufficient Data | 4 | 0.03 | 0.03 | 4 | 1.3 | 1.2 | | | |
| None or none apparent | 8 | 0.06 | 0.04 | 7 | 14.6 | 6.8 | | | |
| Recovered | 51 | 0.41 | 0.09 | 28 | 12.3 | 2.7 | 48 | 4.9 | 1.4 |
| Recovering | 52 | 0.42 | 0.09 | 46 | 13.3 | 3.3 | | | |
| Uncertain | 9 | 0.07 | 0.05 | 7 | 6.9 | 5.1 | | | |
| Marine Total | 124 | 0.70 | | 92 | 12.1 | | | | |
| Insufficient Data | 0 | | | 0 | | | | | |
| None or none apparent | 7 | 0.28 | 0.18 | 6 | 9.6 | 6.2 | | | |
| Recovering | 18 | 0.72 | 0.18 | 16 | 14.1 | 5.6 | | | |
| Recovered | 0 | | | 0 | | | | | |
| Uncertain | 0 | | | 0 | | | | | |
| Terrestrial Total | 25 | 0.14 | | 22 | 12.9 | | | | |
| Grand Total | 176 | 1.00 | | 139 | 10.4 | 1.7 | 53 | 4.6 | 1.3 |

Cases of no recovery or no apparent recovery were associated with short study duration, inappropriate spill removal and clean-up techniques, lack of clean-up in experimental spills, or complex interactions with other natural or human-derived factors.

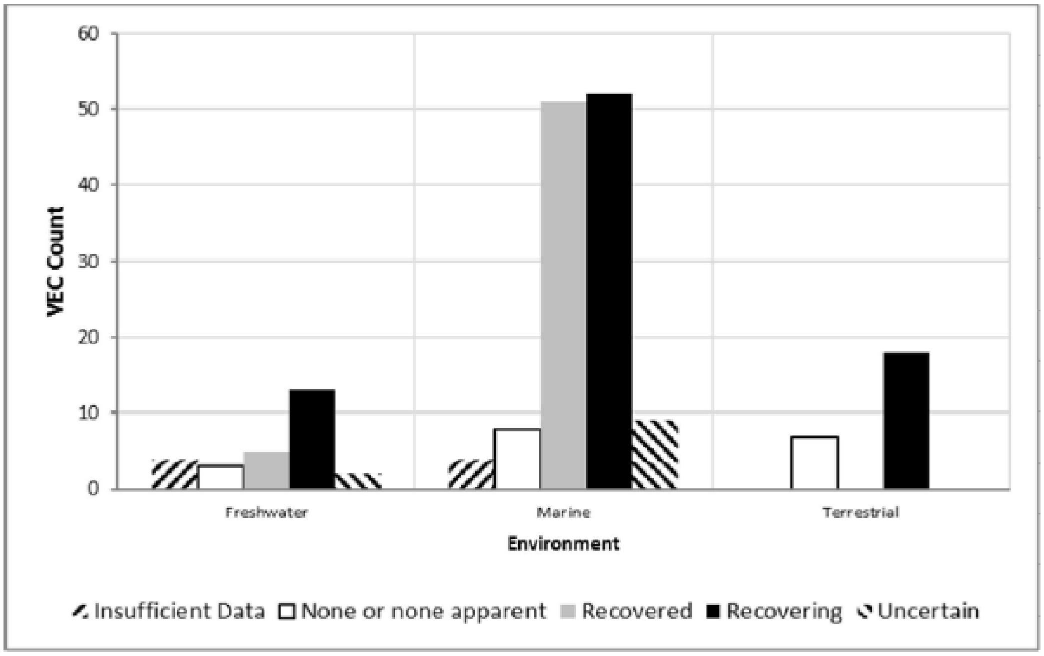


Figure 7. Recovery status by environment.

## How Much Time Does Recovery Take?

The environment, the VEC, and other factors influence recovery times (Table 3, Figure 8). The average times to recovered status for the biophysical VECs examined here (n=176) were 1.7 and 4.9 years for freshwater and marine environments, respectively.

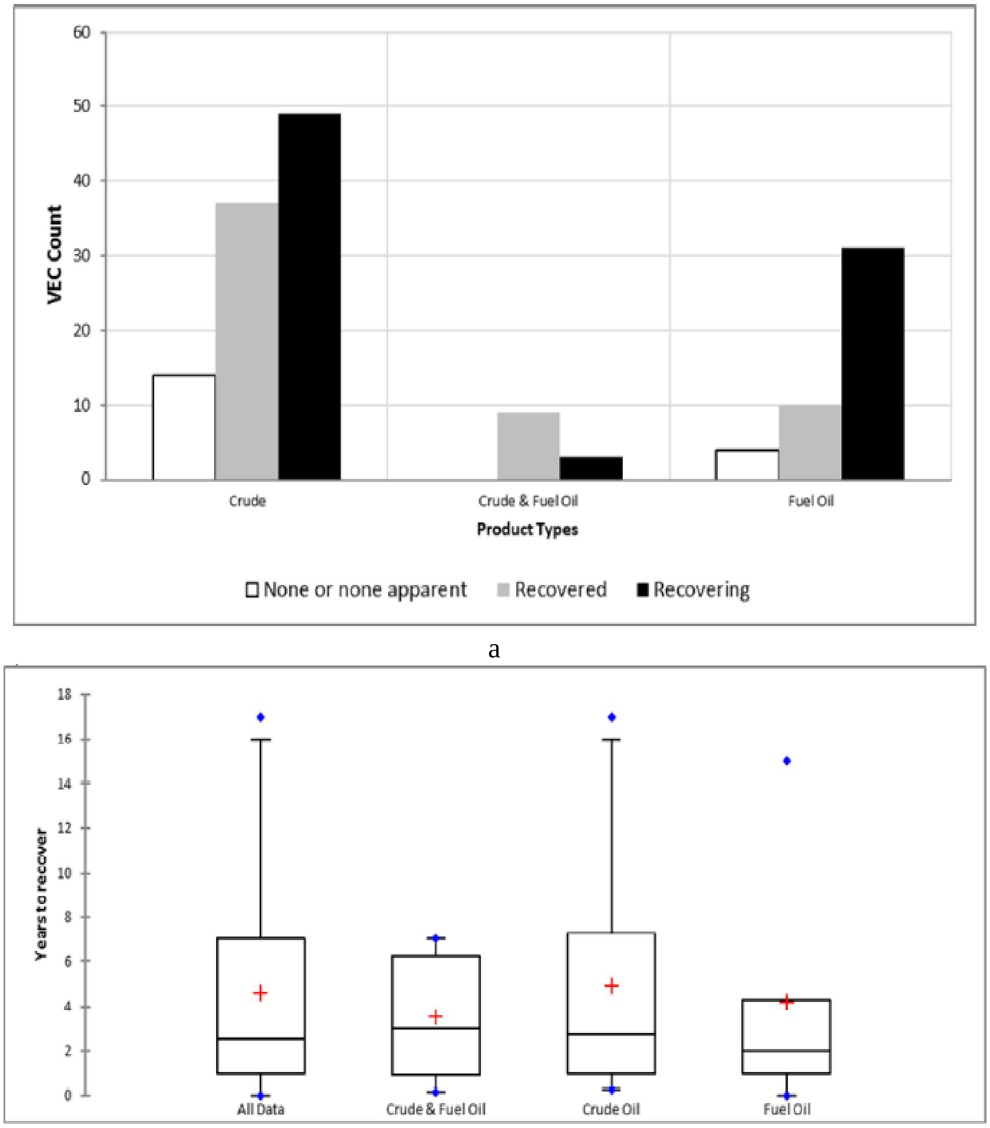
The time for the VECs (n=21) in the experimental spills to achieve a recovering status ranged from 1 to 25 years with a mean of 8.9 years (Appendix). Over all environments and platforms (n=53), average recovery time was 4.6 years.

Recovery times for terrestrial VECs were complicated by the fact that seven of the terrestrial spills were experimental spills in which the oil contamination was deliberately not cleaned up. Terrestrial VECs that achieved recovering status appeared to do so in about 2 years, but some terrestrial VECs were still recovering or showed no recovery after 20 years, especially among those from experimental spills.

Fifteen of the terrestrial VECs were from Arctic and Subarctic Zones where cold temperatures decrease biodegradation rates and short growing seasons decrease annual growth rates.

Over all environments, time to recovery varied little with oil type (Figure 8b) or platform except for one instance from a refinery spill (Figure 9). Recovery time was shortest (less than a year) for spill volumes less than 1,000 metric tons (Figure 10). Recovery time was greatest (about 4 years) for spill volumes between 10,000 and 100,000 metric tons.

Recovery times varied the most across VEC categories (Figure 11). Marine mammals had the longest recovery time (about 16 years) followed by vegetation (about 10 years) and birds (about 9 years). Fish, macroinvertebrates, shorelines, and sediments had recovery times between 3 and 4 years. Algae and water quality had the shortest average recovery times of approximately 1 year.



b

Figure 8. a) VEC counts by recovery status and product type, b) Recovery time by product type. Plus signs represent the mean, the boxes represent the 25th, 50th, and 75th percentiles. Minimums and maximums are represented by dots above the whiskers. This convention applies to all box plots presented in subsequent figures.

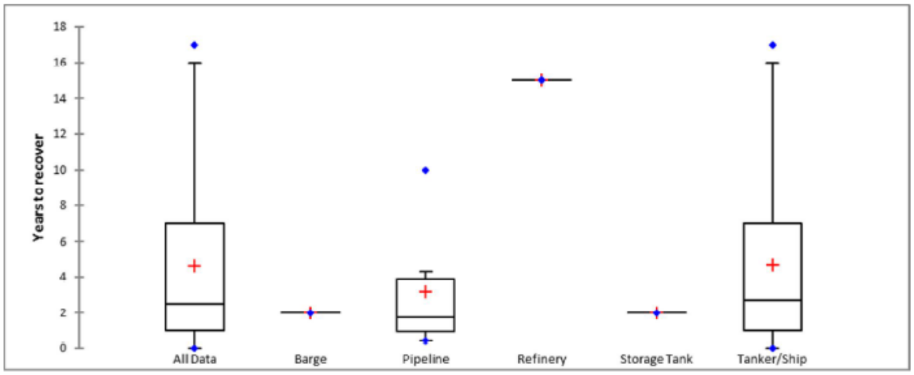


Figure 9. Recovery time by spill source.

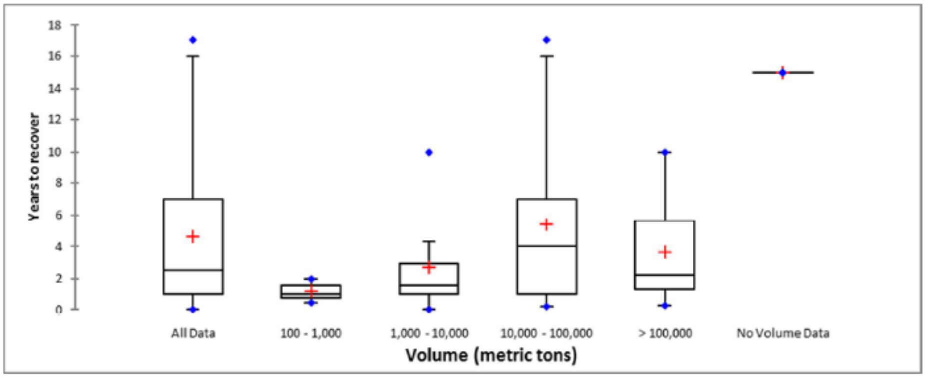


Figure 10. Recovery time by spill volume.

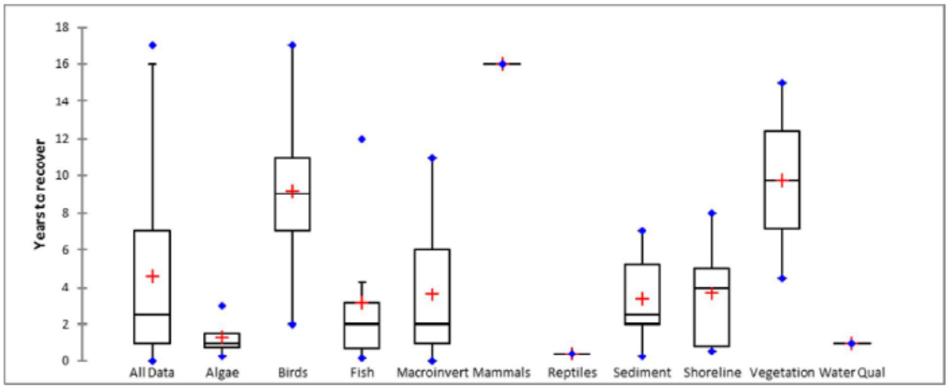


Figure 11. Recovery time by VEC.

## What Processes Influence Recovery?

Any consideration of the processes in recovery from oil spills must point out the crucial role played by clean-up in enabling and accelerating recovery. One lesson learned in case studies of the recovery of estuarine and coastal ecosystems from environmental degradation is that the stressor or disturbance agent needs to be reduced to some extent before recovery can progress (Borja et al. 2010). A corollary is that both human interventions such as oil spill clean-up and natural processes such as biodegradation do not need to fully eliminate all contamination before recovery can progress. Recovery from marine spills is influenced by the degree to which the system is sheltered from physical oceanographic processes (Clark 1982, Teal and Howarth 1984). At one extreme are open marine waters that recover rapidly in weeks or months, and at the other are sheltered, soft-sediment marshes that recover slowly over two or more decades (Teal and Howarth 1984). In the middle are headlands and exposed rocky shores that take 1 to 4 years to recover (Baker 1999). Similarly, oil will persist longer in freshwater habitats, such as marshes, that are sheltered from physical processes or which sequester oil. Because of the longer recovery times for sheltered systems, modern spill response gives high priority to preventing oil from entering marshes and other similar systems.

Recovery is also influenced by several factors related to the life history of the organisms involved. First, recovery proceeds more rapidly when there is an abundant supply of propagules close to the affected area. Pelagic larvae in marine and freshwater environments enable recruitment from adjacent non-oiled areas. Kubach et al. (2010) found that recovery in a riverine environment occurred rapidly near the spill point but required longer further downstream. The differing recovery rates may be partially explained by the proximity of propagules from nearby unaffected areas. Second, the season when the spill occurred can influence the nature of the effect and the time course of recovery. For example, when a spill occurs during or after the season for colonization of invertebrates on an oiled rocky intertidal substrate, recovery may be delayed for another cycle (i.e., the next period of colonization). Third, a long life span generally leads to a long recovery time. Long-lived birds and mammals have longer recovery times than fish (Figure 11). Recovery can be longer when population growth by local reproduction rather than by immigration from other areas is the primary process in recovery.

## What Factors Impede Recovery and What Can Be Done When Recovery Lags?

Several factors can slow recovery. First, if substantial levels of oil persist, recovery times may be lengthened. Clean-up is undertaken to remove and lessen the persistence of hydrocarbons. When clean-up reduces the level of contamination, a point may be reached where the environmental cost of further clean-up exceeds the benefit. In such cases, a Net Environmental Benefit Assessment (NEBA) is now often applied.

Second, inappropriate clean-up techniques can substantially lengthen recovery times. For example, Baker (1999) found that rocky shores typically recover between 1 to 4 years. However, two exceptions, *Esso Bernicia* and *Torrey Canyon,* required at least 10 years (Baker 1999). These longer recovery times were associated with bull-dozing of the shore in the *Esso Bernicia* and the use of first generation dispersants in the *Torrey Canyon*. Another example derives from the *Amoco Cadiz,* in which removal of oiled sediment from salt marshes with heavy earth-moving equipment lowered the level of the marshes and changed the patterns of sediment deposition and conditions for the growth of marsh plants. Ideally, modern spill response includes procedures to carefully select the most appropriate treatment for the oil type, level of contamination, and the nature of the shoreline.

Although the experimental spills make clear that lack of clean-up will substantially lengthen recovery times, the experimental outcomes also make clear that the most protracted recoveries in terrestrial environments appear to be where oil reaches groundwater, where cold temperatures decrease biodegradation rates in soil, or when short thaw seasons limit vegetation growth.

For such cases, recovery may benefit from active human intervention beyond routine clean-up operations. The state of the art in bioremediation and phytoremediation continually improves and holds promise for spills where natural environmental processes for oil degradation are inhibited.

## How Does Recovery from Oil Spills Compare to Recovery from Other Disturbances?

Other reviews of ecosystem recovery found frequencies of recovery similar to those presented in this chapter (79% recovered and recovering overall). Jones and Schmitz (2009) examined 240 studies concerning a broad range of human disturbances and events for evidence of ecosystem recovery. For all types of disturbances, 34% of the indicator variables had recovered and 38% were recovering. For oil spills, about 60% of the indicator variables examined showed recovery. For disturbances, such as overfishing, logging, mining, eutrophication, and invasive species, recovery frequencies of indicator variables were less than 50%.

Borja et al. (2010) reviewed 53 degraded environments to compare the time course of recoveries for different types of stressors. Oils spills have moderate recovery rates. About a half of the stressor categories show recovery in less than five years, some in less than two years. Oil spills showed recovery in two to ten years. More extensive or intensive disturbances, such as disposal of sewage sludge and mine tailings, land reclamation, and long-term wastewater discharge, have shown recovery times over ten to twenty years. A widespread observation among investigators studying the effects oil spills and other disturbances is that the longer the time taken for a VEC to recover, the greater the risk that some natural event or other man-made factor will influence the course of recovery or active restoration (Parker and Wiens 2005; Jackson and Hobbs 2009; Borja 2010; Pearson et al. 2012, 2013).

## What Implications Do the Survey Results Have for Oil Spill Preparedness, Prevention and Response?

Modern spill response has a much different character than in the times of the AMOCO CADIZ (1976) and the later EVOS (1989). Since the EVOS and the passage of Oil Pollution Act of 1990 in the United States, modern spill response has evolved to be able to produce more effective clean-up and meet other objectives. Built on lessons learned, the improved aspects include but are not limited to the following:

- Better state of preparedness;
- Response teams that are trained and then kept ready by regular training and drills;
- Contingency plans and maps identify and locate important resources and indicate both appropriate and inappropriate treatment options;
- Equipment deployed on a distributed basis, often on the basis of potential risk;
- Better equipment and procedures;
- Improvements in remote sensing and other instrumentation and more accurate oil spill trajectory models enable more effective allocation of response personnel and equipment;
- Incident Command Structure - a major improvement in organization and operations during a spill.

A response to a spill today would be better managed and better informed in the application of improved equipment and procedures by trained personnel than for these earlier spill events.

## What Implications Do the Survey Results Have for Defining and Measuring Recovery

Any definition of recovery needs to take into account the dynamic, ever-changing and highly variable character of natural systems. Jackson and Hobbs (2009) offer a perspective:

> "First, environmental and ecological changes are normal; perhaps the most natural feature of the world in which we find ourselves is its continual flux."

Oil spills occur within these continuously changing environments. Further, it is within this continual change leading to alternate ecosystem states along multiple possible pathways that recovery of the environment from oil spills runs its course.

Recovery status and recovery time depend on how recovery is defined; this relationship has been observed in reviews of oil spills since the early 1980s through the present day (Teal and Howarth 1984; Kingston 2002; Jones and Schmitz 2009; Borja et al. 2010). These cited reviews all identify problems with defining recovery as a return to historical conditions. Again, Jackson and Hobbs (2009) offer a perspective:

> "In the long run, no inherent [particular] natural ecosystem or landscape configuration exists for any region."

Defining recovery as a return to a functioning state that provides valuable ecological goods and services is becoming increasingly seen as more appropriate.

### *Definitions of Recovery*

Definitions of ecological (biophysical) recovery occur in both regulatory and scientific contexts. The core element in most definitions in both contexts is a return of an ecosystem or a VEC to some desirable system state following a disturbance. The details of the definitions have changed substantially over the decades as understanding of the dynamics of natural systems has increased. Generally, the changes involve the state to which the system is to return. Jackson and Hobbs (2009) offer more detail on how these changes have been influenced by advances in ecological knowledge derived from the success and failures of ecological restoration.

The ways in which recovery has been defined include return to:

- a natural equilibrium
- previous historical conditions
- pristine conditions
- some notional baseline state
- natural variability derived from comparisons of affected and reference areas
- those conditions that “might have been but for the spill”
- a functional ecosystem state that provides valuable ecological goods and services.

Ecologists have moved away from using such recovery end states such as return to equilibrium because of the increasing recognition of the natural dynamics that lead to ecosystem change, rather than any equilibrium (Landis 2007; Wu and Loucks 1995; Kapustka and Landis 1998; Jackson and Hobbs 2009). For many, any equilibrium in the ecological realm now appears to be only remotely possible, if at all. Return to a previous historical state has also proved problematic and impractical because our understanding of past historical system states is inadequate (Jackson and Hobbs 2009). Also, achieving restoration to previous historical states has frequently failed because other historical natural and man-made events have produced fundamental changes in the system.

Similarly, the notion of a return to pristine conditions is problematic and impractical because pristine conditions are too often an assumption rather than a reality. For example, the Prince William Sound (PWS) ecosystem, despite prevailing beliefs, was not pristine at the time of the EVOS (Wooley 2002). Human activities such as commercial harvesting of fur, fish, and timber, as well as mining and the introduction of non-indigenous species, had already produced extensive ecosystem transformations in the PWS ecosystems. Also, just prior to the EVOS, substantial declines were evident in harbor seal and Steller sea lion populations (Braham et al. 1980; Calkins et al. 1994; Frost et al. 1994), and hatcheries were adding over 500 million juvenile pink salmon to PWS each year (Pearson et al. 2012).

Return to baseline often involves a comparison of post-spill conditions with “baseline” conditions measured usually for a single VEC species or species guild during some pre-project phase of development. Where such baselines have been based on only a year or two of study, they have proven to be inadequate, because basic system dynamics can require years to fully assess. Also, the baseline sampling often proves to be in the “wrong” place to provide “before” data.

Defining recovery as a return to the natural variability of the resource was intended to address some of the shortcomings of the comparison-to-baseline approach. This definition assumes that recovery occurs when the resource in the affected area is “tracking” (i.e., changing in parallel with) the changes in the resource in an unaffected reference area. The subsection below on measuring recovery gives more details on the ways in which this definition can be assessed.

Recently, recovery has been defined as a return to the conditions that would have prevailed had the oil spill not occurred. This definition recognizes the need to account for natural variability and for the influence of natural and man-made factors other than the spill.

Jackson and Hobbs (2009) also argue that the goal of recovery and of active restoration of damaged environments should be to recover or restore the ecosystem to a functional state that provides valuable ecological goods and services. This perspective is also emerging in the regulatory context in North America.

### *Measuring Recovery*

Several reviews compare study designs and ways to measure recovery following oil spills (Wiens and Parker 1995; Parker and Wiens 2005; Wiens 2013), including:

- comparison to baseline
- single-year comparison of affected versus reference area
- multi-year comparisons of affected versus reference areas
- Before-After-Control-Impact (BACI) studies
- weight of evidence

Parker and Wiens (2005) conclude that there is no one "best" way to assess recovery and urge future oil spill investigators to discern how the ecosystem to be studied functions, and determine which set of assumptions prevail for that ecosystem before selecting an appropriate study approach. However, the BACI approach appears to be increasingly favored for assessing oil spill recovery (Parker and Wiens 2005). Where "before" is lacking, the investigator has to fall back a Control – Impact design and wrestle with locating an appropriate control area to compare with the affected area (Parker et al. 2013, Pearson 2013).

One example from EVOS provides some vivid illustrations of how recovery definition influence study outcomes. Landis (2007) compares the different conclusions about recovery from the EVOS in two prominent papers (Peterson et al. 2003, Harwell and Gentile 2006) and seeks to understand why the conclusions differ so much. Landis finds in part that the differences between the two papers derive from "the infusion of social values or policy goals into each." However, the more important source of the differences for Landis (2007) is how the two papers approach the definition of recovery and the role of indirect effects and effect cascades. Indeed, Peterson et al. (2003) do not offer an explicit definition of recovery and appear to imply that recovery is the return to some undefined previous state. In contrast, Harwell and Gentile (2006) do offer a recovery definition – return to an acceptable range of variability in the resource of interest – but one that includes a policy statement ("acceptable") and one for which the outcome rests on a judgment of acceptability rather than on a scientific operation such as a statistical comparison of the attributes of two areas or populations. Landis (2007) recommends that researchers achieve and communicate clearly expressed operational definitions and goal statements in scientific assessments of effects and recovery.

Another aspect of measuring recovery emerges from the assessment here. The review of the studies often observed that when resources were categorized as "recovering," no additional studies could be found verifying "recovered." One plausible explanation for this observation is that the participating parties were sufficiently comfortable with the likelihood of recovery that funding was re-allocated and full recovery was never actually documented.

## CONCLUSION

The scientific literature on recovery is uneven, with marine oils spills and certain VECs receiving the bulk of the studies. We suggest that this condition derives from the fact that tanker and ship accidents spill substantially larger volumes of oil that lead to effects over larger areas and for more VECs. Also, the freshwater studies show substantially less time to recovery than marine spills. We further suggest that the literature does not provide a full understanding of recovery following terrestrial spills. For some presumably large but unknown number of terrestrial spills, oiled soil and vegetation is removed for treatment elsewhere and the areas replanted. In such cases, it appears that recovery is simply not monitored. Clearly, improved response and remediation would benefit from greater study of recovery from oils spills in freshwater and terrestrial systems.

Although adverse effects of oil spills on biophysical environments cannot be denied, the scientific literature is clear that ecosystems and their components do recover. Cases of no or no apparent recovery were associated with short study duration, inappropriate spill response procedures, experimental spills, and complex interactions with other natural or human-derived factors. Recovery times proved to vary with the environment, the VEC, and other factors. The literature is also clear that although recovery can occur in some circumstances with little or no clean-up, appropriate clean-up does enable and can accelerate recovery.

Our overall observation that biophysical environments do recover should not be taken to indicate spill response can be foregone. Spill response is most definitely needed and the capacity for such response needs to be established beforehand and kept in a state of readiness. Such effort will lead to timely and appropriate response that will enable and accelerate recovery.

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# APPENDIX

| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
|---|---|---|---|---|---|---|---|---|---|---|
| *AMOCO CADIZ* | 1978 | Light crude | 240,000 | Tanker/Ship | Marine | ALG | Recovered | 0.25 | UNK | Spooner 1978 |
| *AMOCO CADIZ* | 1978 | Light crude | 240,000 | Tanker/Ship | Marine | FSH | Recovered | 0.5 | UNK | Seymour and Geyer 1992 |
| *AMOCO CADIZ* | 1978 | Light crude | 240,000 | Tanker/Ship | Marine | MCR | Recovered | 1 | UNK | Seymour and Geyer 1992 |
| *AMOCO CADIZ* | 1978 | Light crude | 240,000 | Tanker/Ship | Marine | MCR | Recovered | 2 | 6 | Seymour and Geyer 1992 |
| *AMOCO CADIZ* | 1978 | Light crude | 240,000 | Tanker/Ship | Marine | MCR | Recovered | 2 | 18 | Kingston 2002<br>Dauvin 1998 |
| *AMOCO CADIZ* | 1978 | Light crude | 240,000 | Tanker/Ship | Marine | MCR | Recovered | 2.5 | UNK | Seymour and Geyer 1992 |
| *AMOCO CADIZ* | 1978 | Light crude | 240,000 | Tanker/Ship | Marine | MCR | Recovered | 6 | 18 | Kingston 2002 |
| *AMOCO CADIZ* | 1978 | Light crude | 240,000 | Tanker/Ship | Marine | MCR | Recovered | 10 | 19 | Kingston 2002,<br>Dauvin 1998,<br>Dauvin 2000 |
| *AMOCO CADIZ* | 1978 | Light crude | 240,000 | Tanker/Ship | Marine | MCR | Recovering | UNK | UNK | Glemarec and Hussenot 1982 |
| *AMOCO CADIZ* | 1978 | Light crude | 240,000 | Tanker/Ship | Marine | SHR | Recovered | 8 | 18 | Kingston 2002 |
| *AMOCO CADIZ* | 1978 | Light crude | 240,000 | Tanker/Ship | Marine | VEG | Recovered | 4.5 | 8 | Baca et al. 1987 |
| *ARROW* | 1970 | No. 6 Fuel Oil | 7,980 | Tanker/Ship | Marine | ALG | Recovering | N/A | 7 | Thomas 1978 |
| *ARROW* | 1970 | No. 6 Fuel Oil | 7,980 | Tanker/Ship | Marine | FSH | Recovering | N/A | 30 | Lee et al. 2003 |
| *ARROW* | 1970 | No. 6 Fuel Oil | 7,980 | Tanker/Ship | Marine | MCR | Recovering | N/A | 6 | Gilfillan 1978 |

| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
|---|---|---|---|---|---|---|---|---|---|---|
| *ARROW* | 1970 | No. 6 Fuel Oil | 7,980 | Tanker/Ship | Marine | MCR | Recovering | N/A | 30 | Lee et al. 2003 |
| *ARROW* | 1970 | No. 6 Fuel Oil | 7,980 | Tanker/Ship | Marine | MCR | Recovered | UNK | 30 | Lee et al. 2003 |
| *ARROW* | 1970 | No. 6 Fuel Oil | 7,980 | Tanker/Ship | Marine | SED | Recovering | N/A | 30 | Lee et al. 2003 |
| *ARROW* | 1970 | No. 6 Fuel Oil | 7,980 | Tanker/Ship | Marine | SHR | Recovering | N/A | 7 | Thomas 1978 |
| *ARROW* | 1970 | No. 6 Fuel Oil | 7,980 | Tanker/Ship | Marine | SHR | Recovering | N/A | 27 | Lee et al 1999 |
| *ARROW* | 1970 | No. 6 Fuel Oil | 7,980 | Tanker/Ship | Marine | SHR | Recovering | N/A | 33 | Owens et al. 1978, Owens et al. 2008, Prince et al. 2003 |
| *ARROW* | 1970 | No. 6 Fuel Oil | 7,980 | Tanker/Ship | Marine | SHR | None | N/A | UNK | Kingston 2002 |
| Arthur Kill | 1990 | No. 6 Fuel Oil & No. 2 Fuel Oil | 4,216 | Pipeline | Marine | BRD | Recovered | 2.5 | UNK | Parsons 1996 |
| Arthur Kill | 1990 | No. 6 Fuel Oil & No. 2 Fuel Oil | 4,216 | Pipeline | Marine | BRD | Recovered | 10 | 10 | Maccarone and Brzorad 2000 |
| Asher Creek | 1979 | Crude | 1,000 | Pipeline | Freshwater | MCR | Recovered | 0.92 | 1.46 | Crunkilton and Duchrow 1990;<br>Seymour and Geyer 1992 |
| Ashland Spill | 1988 | No. 2 Fuel Oil | 2,234 | Storage Tank | Freshwater | BRD | Recovered | 2 | 2 | University of Pittsburgh 1990 |
| Ashland Spill | 1988 | No. 2 Fuel Oil | 2,234 | Storage Tank | Freshwater | SED | Recovering | N/A | 2 | University of Pittsburgh 1990 |
| Baffin Island (BIOS) | 1981 | Crude | 15 | Experimental | Marine | SHR | Recovering | N/A | 20 | Owens et al. 1987, Owens et al. 2008, Humphrey et al. 1991, Prince et al. 2002, Prince et al. 2003 |
| *BAHIA PARAISO* | 1989 | No. 2 Fuel Oil | 500 | Tanker/Ship | Marine | MCR | Recovering | N/A | 1 | Seymour and Geyer 1992 |
| Bemidji | 1979 | Crude | 1459 | Pipeline | Terrestrial | GWR | Recovering | N/A | 30 | Revesz et al. 1995,<br>Essaid et al. 2011 |
| Bemidji | 1979 | Crude | 1459 | Pipeline | Terrestrial | GWR | Recovering | N/A | 33 | USGS 2012 |

## Appendix (Continued)

| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
|---|---|---|---|---|---|---|---|---|---|---|
| *BRAER* | 1993 | Crude & No. 6 Fuel Oil | 85,475 | Tanker/Ship | Marine | FSH | Recovered | 0.17 | UNK | Kingston 1999 |
| *BRAER* | 1993 | Crude & No. 6 Fuel Oil | 85,475 | Tanker/Ship | Marine | FSH | Recovering | N/A | UNK | Stagg et al. 1998 |
| *BRAER* | 1993 | Crude & No. 6 Fuel Oil | 85,475 | Tanker/Ship | Marine | MCR | Recovered | 1 | UNK | Kingston 1999 |
| *BRAER* | 1993 | Crude & No. 6 Fuel Oil | 85,475 | Tanker/Ship | Marine | MCR | Recovered | 7 | UNK | Webster et al. 2005 |
| *BRAER* | 1993 | Crude & No. 6 Fuel Oil | 85,475 | Tanker/Ship | Marine | MCR | Recovering | N/A | UNK | Kingston 1999 |
| *BRAER* | 1993 | Crude & No. 6 Fuel Oil | 85,475 | Tanker/Ship | Marine | SED | Recovered | 7 | UNK | Webster et al. 2005 |
| *BRAER* | 1993 | Crude & No. 6 Fuel Oil | 85,475 | Tanker/Ship | Marine | SHR | Recovered | 0.83 | UNK | Kingston 1999 |
| *BRAER* | 1993 | Crude & No. 6 Fuel Oil | 85,475 | Tanker/Ship | Marine | SHR | Recovered | UNK | UNK | Kingston 2002 |
| Caribou-Poker | 1976 | Crude | 7 | Experimental | Terrestrial | MCB | None | N/A | 0.42 | Sparrow et al. 1978 |
| Caribou-Poker | 1976 | Crude | 7 | Experimental | Terrestrial | MCB | None | N/A | 19 | Lindstrom et al. 1999 |
| Caribou-Poker | 1976 | Crude | 7 | Experimental | Terrestrial | SOI | Recovering | N/A | 10 | Sparrow and Sparrow 1988 |
| Caribou-Poker | 1976 | Crude | 7 | Experimental | Terrestrial | SOI | None | N/A | 15 | Collins et al. 1994, Prince et al. 2003 |
| Caribou-Poker | 1976 | Crude | 7 | Experimental | Terrestrial | SOI | Recovering | N/A | 25 | Braddock et al. 2003 |
| Caribou-Poker | 1976 | Crude | 7 | Experimental | Terrestrial | SOI | Recovering | N/A | 25 | Prince et al. 2003 |
| Caribou-Poker | 1976 | Crude | 7 | Experimental | Terrestrial | SOI | None | N/A | UNK | Fitzgerald 2007-2008 |
| Caribou-Poker | 1976 | Crude | 7 | Experimental | Terrestrial | VEG | None | N/A | 2 | Jenkins et al. 1978 |
| Caribou-Poker | 1976 | Crude | 7 | Experimental | Terrestrial | VEG | None | N/A | 15 | Collins et al. 1994 |
| Caribou-Poker | 1976 | Crude | 7 | Experimental | Terrestrial | VEG | Recovering | N/A | 20 | Racine 1994 |

| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Cayuga Inlet | 1997 | No. 2 Fuel Oil | 23 | Rail | Freshwater | MCR | Recovering | N/A | 1.25 | Lytle and Peckarsky 2001 |
| Chalk Point | 2000 | No. 6 Fuel Oil & No. 2 Fuel Oil | 447 | Pipeline | Marine | MCR | Insufficient Data | N/A | 0.5 | Versar 2001 |
| Chalk Point | 2000 | No. 6 Fuel Oil & No. 2 Fuel Oil | 447 | Pipeline | Marine | MCR | Recovering | N/A | 7 | Michel et al. 2009 |
| Chalk Point | 2000 | No. 6 Fuel Oil & No. 2 Fuel Oil | 447 | Pipeline | Marine | SED | Recovering | N/A | 7 | Michel et al. 2009 |
| Chalk Point | 2000 | No. 6 Fuel Oil & No. 2 Fuel Oil | 447 | Pipeline | Marine | VEG | Uncertain | N/A | 7 | Michel et al. 2009 |
| Chariton River | 1990 | Light crude | 356 | Pipeline | Freshwater | MCR | Recovering | N/A | 1 | Poulton et al. 1998 |
| *COSCO BUSCAN* | 2007 | No. 6 Fuel Oil | 184 | Tanker/Ship | Marine | FSH | Uncertain | N/A | UNK | California Department of Fish and Game 2009, California Department of Fish and Game 2010, California Department of Fish and Game 2011 |
| Delaware Mesocosm | 1994 | Crude | 0.1 | Experimental | Marine | SHR | Insufficient Data | N/A | 1.23 | Venosa and Zhu 2003 |
| East Walker River | 2000 | No. 6 Fuel Oil | 11 | Truck | Freshwater | SED | Recovering | N/A | 0.41 | Higgins et al. 2002, Hampton et al. 2002 |
| East Walker River | 2000 | No. 6 Fuel Oil | 11 | Truck | Freshwater | WQL | Recovering | N/A | 0.41 | Higgins et al. 2002 |
| *ERIKA* | 1999 | No. 6 Fuel Oil | 28,000 | Tanker/Ship | Marine | SHR | Recovering | N/A | 0.3 | Prince et al. 2003 |
| *ESSO BERNICIA* | 1978 | No. 6 Fuel Oil | 1,174 | Tanker/Ship | Marine | ALG | Recovered | 1 | 16 | Moore et al. 1995 |
| *ESSO BERNICIA* | 1978 | No. 6 Fuel Oil | 1,174 | Tanker/Ship | Marine | MCR | Recovered | 1 | 16 | Moore et al. 1995 |

## Appendix (Continued)

| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Experimental Study, LA | 1973 | Light crude | ND | Experimental | Freshwater | BRD | Uncertain | N/A | 0.5 | Chabreck 1973 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | ALG | Recovered | 3 | 8 | Kingston 2002,<br>Hoff & Shigenaka 1999 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | ALG | Recovering | N/A | 7 | Houghton et al. 1997 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | Recovered | 7 | UNK | Bowman 1999 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | Recovered | 7 | UNK | Wiens et al. 2001 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | Recovered | 9 | 9 | Murphy and Mabee 2000 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | Recovered | 11 | 14 | Esler and Iverson 2010 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | Recovered | 17 | 21 | Exxon Valdez Oil Spill Trustee Council 2010 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | Recovered | 17 | 21 | Exxon Valdez Oil Spill Trustee Council 2010 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | None | N/A | 9 | Kingston 2002, Lance et al. 2001 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | None | N/A | 9 | Lance et al. 2001 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | Recovering | N/A | 10 | Trust et al. 2000 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | None | N/A | 20 | Exxon Valdez Oil Spill Trustee Council 2010 |

| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
|---|---|---|---|---|---|---|---|---|---|---|
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | Recovering | N/A | 20 | Esler et al. 2010 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | Recovering | N/A | UNK | Exxon Valdez Oil Spill Trustee Council 2010 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | Recovering | N/A | UNK | Exxon Valdez Oil Spill Trustee Council 2010 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | Uncertain | N/A | UNK | Exxon Valdez Oil Spill Trustee Council 2010 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | BRD | Recovered | UNK | UNK | Kingston 2002 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | FSH | Recovered | 1 | 2 | Pearson et al. 1995 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | FSH | Recovered | 2 | UNK | Lee and Page 1997 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | FSH | Recovered | 12 | UNK | Exxon Valdez Oil Spill Trustee Council 2002 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | FSH | Insufficient Data | N/A | 3 | Collier et al. 1993 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | FSH | Recovering | N/A | 10 | Jewett et al. 2002 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | MCR | Recovered | 2 | UNK | Hoff and Shigenaka 1999 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | MCR | Recovered | 4 | 8 | Hoff and Shigenaka 1999 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | MCR | Recovered | 11 | 12 | Page et al. 2005 |

## Appendix (Continued)

| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
|---|---|---|---|---|---|---|---|---|---|---|
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | MCR | Recovering | N/A | 1 | Brown et al. 1996 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | MCR | Recovering | N/A | 2 | Driskell et al. 1993 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | MCR | Uncertain | N/A | 3 | Lee and Page 1997 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | MCR | Uncertain | N/A | 6 | Fukuyama et al. 2000 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | MCR | Recovering | N/A | 8 | Hoff and Shigenaka 1999 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | MML | Recovered | 16 | 21 | Exxon Valdez Oil Spill Trustee Council 2010 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | MML | Uncertain | N/A | 11 | Bodkin et al. 2002 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | MML | None | N/A | 21 | Exxon Valdez Oil Spill Trustee Council 2010 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | MML | Recovering | N/A | 21 | Exxon Valdez Oil Spill Trustee Council 2010 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SED | Recovered | 0.25 | 8 | Hoff and Shigenaka 1999 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SED | Recovered | 2 | 8 | Hayes and Michel 1999 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SED | Recovered | 2 | UNK | Lee and Page 1997 |

| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
|---|---|---|---|---|---|---|---|---|---|---|
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SED | Recovered | 3 | 8 | Hayes and Michel 1999 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SED | Recovered | 6 | 8 | Hoff and Shigenaka 1999 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SED | None | N/A | 8 | Hayes and Michel. 1999 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SED | Recovering | N/A | 12 | Short et al. 2003 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SED | Recovering | N/A | 18 | Michel et al. 2010 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SHR | Recovered | 0.6 | UNK | Lee and Page 1997 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SHR | Recovered | 4 | 8 | Kingston 2002 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SHR | Recovering | N/A | 2 | Lee and Page 1997 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SHR | Recovering | N/A | 3 | Neff et al. 1995 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SHR | Recovering | N/A | 3 | Stoker et al. 1993 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SHR | Recovering | N/A | 3.5 | Michel and Hayes 1993 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SHR | None | N/A | 4.9 | Irvine et al. 1999 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SHR | Recovering | N/A | 8 | Hoff and Shigenaka 1999 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | SHR | Recovering | N/A | 16 | Owens et al. 2008 |

## Appendix (Continued)

| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
|---|---|---|---|---|---|---|---|---|---|---|
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | VEG | Uncertain | N/A | 1 | Dean et al. 1998 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | WQL | Recovered | 1 | 3 | Neff and Burns 1996 |
| *EXXON VALDEZ* | 1989 | Crude | 33,000 | Tanker/Ship | Marine | WQL | Recovered | 1 | 4 | Boehm et al. 2007. |
| Fidalgo Bay | 1991 | Crude | 670 | Refinery | Marine | SED | Recovering | N/A | 1.3 | Hoff et al. 1993 |
| Fidalgo Bay | 1991 | Crude | 670 | Refinery | Marine | VEG | Recovering | N/A | 1.3 | Hoff et al. 1993 |
| *FLORIDA* | 1969 | No. 2 Fuel Oil | 557 | Barge | Marine | FSH | Recovering | N/A | 20 | Teal et al. 1992 |
| *FLORIDA* | 1969 | No. 2 Fuel Oil | 557 | Barge | Marine | MCR | Recovering | N/A | 5 | Michael et al. 1975, Sanders et al. 1980 |
| *FLORIDA* | 1969 | No. 2 Fuel Oil | 557 | Barge | Marine | MCR | Recovering | N/A | 7 | Krebs and Burns 1977 |
| *FLORIDA* | 1969 | No. 2 Fuel Oil | 557 | Barge | Marine | MCR | Recovering | N/A | 37 | Culbertson et al. 2007 |
| *FLORIDA* | 1969 | No. 2 Fuel Oil | 557 | Barge | Marine | MCR | Recovering | N/A | 38 | Culbertson et al. 2008a |
| *FLORIDA* | 1969 | No. 2 Fuel Oil | 557 | Barge | Marine | SED | Recovering | N/A | 5 | Michael et al. 1975, Sanders et al. 1980 |
| *FLORIDA* | 1969 | No. 2 Fuel Oil | 557 | Barge | Marine | SED | Uncertain | N/A | 20 | Teal et al. 1992 |
| *FLORIDA* | 1969 | No. 2 Fuel Oil | 557 | Barge | Marine | SED | None | N/A | 30 | Reddy et al. 2002 |
| *FLORIDA* | 1969 | No. 2 Fuel Oil | 557 | Barge | Marine | VEG | Recovering | N/A | 37 | Culbertson et al. 2008b |
| John Heinz Wildlife Refuge | 2000 | Crude | 650 | Pipeline | Freshwater | REP | Recovered | 0.4166 | 0.833 | Saba and Spotila 2003 |
| John Heinz Wildlife Refuge | 2000 | Crude | 650 | Pipeline | Freshwater | REP | None | N/A | 3 | Bell et al. 2006 |

| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Kalamazoo River | 2010 | Heavy crude | 3,247 | Pipeline | Freshwater | BRD | Insufficient Data | N/A | UNK | Enbridge Energy (In Prep) |
| Kalamazoo River | 2010 | Heavy crude | 3,247 | Pipeline | Freshwater | FSH | Recovering | N/A | UNK | Michigan DNR |
| Kalamazoo River | 2010 | Heavy crude | 3,247 | Pipeline | Freshwater | MCR | Insufficient Data | N/A | 0.25 | Badra 2011 |
| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
| Kalamazoo River | 2010 | Heavy crude | 3,247 | Pipeline | Freshwater | MCR | Recovering | N/A | 1 | MDEQ 2012 |
| Kalamazoo River | 2010 | Heavy crude | 3,247 | Pipeline | Freshwater | REP | Recovering | N/A | 1 | Enbridge Energy (In Prep) |
| Komi | 1995 | Crude | 136,370 | Pipeline | Freshwater | SHR | Insufficient Data | N/A | 2 | Owens et al. 1999 |
| Mackenzie Delta | 1972 | Crude | 266 | Experimental | Terrestrial | VEG | Recovering | N/A | 1 | Bliss and Wein 1972, Wein and Bliss 1973, Ross et al. 1977 |
| *METULA* | 1974 | Light crude | 52,000 | Tanker/Ship | Marine | SHR | Recovering | N/A | 12 | Owens et al. 1999 |
| *METULA* | 1974 | Light crude | 52,000 | Tanker/Ship | Marine | SHR | Recovering | N/A | 30.5 | Owens et al. 2008 |
| *METULA* | 1974 | Light crude | 52,000 | Tanker/Ship | Marine | VEG | Recovering | N/A | 23 | Owens et al. 1999 |
| Milford Haven | 1969 | No. 6 Fuel Oil | ND | Refinery | Marine | SED | Recovering | N/A | 22 | Baker et al. 1993 |
| Milford Haven | 1969 | No. 6 Fuel Oil | ND | Refinery | Marine | VEG | Recovered | 15 | 22 | Baker et al. 1993 |
| Moose Jaw | 1974 | Crude | 2,143 | Pipeline | Terrestrial | VEG | Recovering | N/A | 4 | De Jong 1980 |
| Mt. Baker | 1972 | No. 2 Fuel Oil | 22 | Storage Tank | Terrestrial | VEG | Recovering | N/A | 7 | Belsky 1982 |
| Mt. Baker | 1972 | No. 2 Fuel Oil | 22 | Storage Tank | Terrestrial | VEG | Recovering | N/A | UNK | Belsky, 1975 |

## Appendix (Continued)

| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
|---|---|---|---|---|---|---|---|---|---|---|
| *NELLA DAN* | 1987 | No. 2 Fuel Oil & Lubricating Oil | 125.00 | Tanker/Ship | Marine | ALG | Recovering | N/A | 7 | Smith and Simpson 1998 |
| *NELLA DAN* | 1987 | No. 2 Fuel Oil & Lubricating Oil | 125.00 | Tanker/Ship | Marine | MCR | Recovering | N/A | 7 | Smith and Simpson 1998 |
| *NESTUCCA* | 1988 | No. 6 Fuel Oil | 734 | Barge | Marine | FSH | Recovered | 2 | UNK | Hay and McCarter 2012 |
| *NESTUCCA* | 1988 | No. 6 Fuel Oil | 734 | Barge | Marine | FSH | Uncertain | N/A | 0.4 | Hay et al. 1995 |
| Nipisi | 1970 - 1972 | Crude | 8,182 | Pipeline | Terrestrial | SOI | Recovering | N/A | 25 | Wang et al. 1998 |
| Norman Wells | 1972 | Crude | 7 | Experimental | Terrestrial | VEG | Recovering | N/A | 4 | Hutchinson and Freeedman 1978, Belsky 1982 |
| Norman Wells | 1972 | Crude | 7 | Experimental | Terrestrial | VEG | Recovering | N/A | 5 | Hutchinson and Freeedman 1978 |
| Pine River | 2000 | Light crude | 704 | Pipeline | Freshwater | FSH | Recovering | N/A | 12 | Goldberg 2011 |
| Pine River | 2000 | Light crude | 704 | Pipeline | Freshwater | MCR | Recovered | 1 | 1 | DePennart 2004 |
| Plains Rainbow | 1970-1972 | Crude | ND | Pipeline | Terrestrial | SOI | Recovering | N/A | 25 | Wang et al. 1998 |
| Prudhoe Bay 1972 | 1972 | Crude | 1.185 | Pipeline | Terrestrial | VEG | None | N/A | 6 | McKendrick and Mitchell 1978 |
| Prudhoe Bay 1972 | 1972 | Crude | 1.185 | Pipeline | Terrestrial | VEG | Recovering | N/A | 6 | McKendrick and Mitchell 1978 |
| Prudhoe Bay 1976 | 1976 | Crude & No. 2 Fuel Oil | 0.01 | Experimental | Terrestrial | VEG | Recovering | N/A | UNK | Walker et al. 1978 |
| Reedy River | 1996 | No. 2 Fuel Oil | 3,057 | Pipeline | Freshwater | FSH | Recovered | 4.3 | 9.3 | Kubach et al. 2011 |
| *SEA EMPRESS* | 1996 | Crude & No. 6 Fuel Oil | 72,480 | Tanker/Ship | Marine | ALG | Recovered | 1 | UNK | Moore 2006 |
| *SEA EMPRESS* | 1996 | Crude & No. 6 Fuel Oil | 72,480 | Tanker/Ship | Marine | MCR | Recovered | 6 | UNK | Moore 2006; Nikitik and Robinson 2003, Rutt et al. 1998 |

| Oil Spill Name | Year | Product Type (general) | Volume (metric tons) total | Platform | Environments | VEC * | Recovery Status | Years to recover | Study Duration | References |
|---|---|---|---|---|---|---|---|---|---|---|
| *SEA EMPRESS* | 1996 | Crude & No. 6 Fuel Oil | 72,480 | Tanker/Ship | Marine | SHR | Recovered | 5 | UNK | Moore 2006 |
| Selendang Ayu | 2004 | No. 6 Fuel Oil Diesel | 1,072 | Tanker/Ship | Marine | BRD | Insufficient Data | N/A | 0.33 | Brewer et al. 2005 |
| St. Lawrence River | 1999 | Crude | ND | Experimental | Freshwater | FSH | Recovering | N/A | 1.25 | Hodson et al. 2002 |
| St. Lawrence River | 1999 | Crude | ND | Experimental | Freshwater | SED | Recovering | N/A | 1.25 | Hodson et al. 2002 |
| Tallgrass Prairie | 1993 - 2002 | Crude | 84,549 | Experimental | Terrestrial | SOI | Recovering | N/A | 2.3 | Sublette et al. 2007 |
| Tennessee Ponds | 1981 | Crude | ND | Experimental | Freshwater | MCR | Recovering | N/A | 0.91 | Cushman and Goyart 1984 |
| *TORREY CANYON* | 1967 | Light crude | 118,000 | Tanker/Ship | Marine | VEG | Recovering | N/A | 4 | Burk 1977 |
| *TSESIS* | 1977 | No. 5 Fuel Oil & No. 6 Fuel Oil | 1,000 | Tanker/Ship | Marine | MCR | Recovered | 0.01 | 0.1 | Johansson et al. 1980 |
| *TSESIS* | 1977 | No. 5 Fuel Oil & No. 6 Fuel Oil | 1,000 | Tanker/Ship | Marine | MCR | Recovering | N/A | 3 | Fukuyama et al. 2000 |
| *TSESIS* | 1977 | No. 5 Fuel Oil & No. 6 Fuel Oil | 1,000 | Tanker/Ship | Marine | MCR | Recovering | N/A | UNK | Linden et al. 1979 |
| Tulita | 1988 | Crude Oil | 3 | Pipeline | Terrestrial | VEG | Recovering | N/A | 3 | Seburn et al. 1996 |
| Wabamun Lake | 2005 | No. 6 Fuel Oil | 126 | Rail | Freshwater | FSH | None | N/A | 0.75 | Debruyn et al. 2007 |
| Wabamun Lake | 2005 | No. 6 Fuel Oil | 126 | Rail | Freshwater | FSH | Insufficient Data | N/A | 0.91 | Transport Safety Board of Canada 2007 |
| Wabamun Lake | 2005 | No. 6 Fuel Oil | 126 | Rail | Freshwater | SED | None | N/A | 0.15 | Zrum and Sergy 2006 |
| Wabamun Lake | 2005 | No. 6 Fuel Oil | 126 | Rail | Freshwater | VEG | Recovering | N/A | 2 | Wernick et al. 2009 |
| Wabamun Lake | 2005 | No. 6 Fuel Oil | 126 | Rail | Freshwater | WQL | Uncertain | N/A | 0.11 | Anderson 2006 |

* ALG = Algae, BRD = Birds, FSH = Fish, GWR = Groundwater, MCR = Macroinvertebrates, MML = Mammals, MCB = Microbial Community, REP = Reptiles, SED = Sediment, SHR = Shoreline, SOI = Soil, VEG = Vegetation, WQL = Water quality

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