The Oil Spill Science Triad: Viewpoint on the Coexistence and Optimization of Models, Laboratory Tests, and Empirical Field Observations and Data for Natural Resource Damage Assessments

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667037 ABSTRACT

This paper provides a viewpoint on ways to blend and optimize the use of various scientific tools to address information needs as part of oil spill natural resource damage assessments (NRDAs). Oil spills are complex events of multidisciplinary interest, requiring the application of a blend of established, generally accepted approaches to answer the many scientific questions related to oil spill response and NRDAs arising during and after each spill. Each spill scenario is unique and demands different information, but central to all assessment strategies are questions around the needs for and the feasibility of collecting adequate representative field data versus (or more productively in concert with) the application of spill models, remembering that models alone can't create facts. Useful information also comes from considering the degree to which the processes and ambient measures in a new spill can be represented by extrapolations of data and information from prior spills. Through a discussion of a three-part "toolkit" or "triad" applied to different types of oil spill NRDAs, this discussion offers insights and suggestions, largely from a strategic scientific perspective, for optimizing the blend of these tools to sufficiently address the assessment of injuries to natural resources so restoration can be appropriately evaluated, scaled, planned, and implemented.

INTRODUCTION AND CONTEXT

In this paper, we aim to provide a perspective on ways to approach the blending and optimization of available groups of scientific tools to generate information that support injury assessments related to ecological components. While specific discussion of technical tools themselves is beyond the scope of this paper, what is clear is that observations, data, laboratory tests, and physical/chemical models acquired or used during and after an oil spill event support the information needs of many scientific, regulatory, and legal issues. Spill response and countermeasures and cleanup decisions, along with natural resource damage assessment (NRDA), civil actions, and public health and safety decisions, all rely to varying extents on scientific information. NRDAs draw on information collected for these other purposes and vice versa. The various component pieces of a NRDA require answers to the many scientific questions arising during the process of assessing injuries to natural resources to determine the scale and types of restoration needed. Given the fast moving complexities of most oil spill events, investigations require a thoughtful and appropriate application of a blend of established, generally accepted approaches, including some consideration of relevant new innovative approaches to injury determinations, and a spill-specific application of these approaches or scientific “tools” used and deployed in balance with the spill event. In previous spill events, NRDA data and information collection efforts have often lacked coordination, failed to consider data uses before data collection, and ignored lessons learned or data collected from previous spills, thus leading to inefficiencies rooted in unusable or indefensible data.

To assess the types and extent of injuries resulting from an oil spill, the NRDA process includes an important set of consistent and logical scientific steps (adapted from Boehm and Ginn 2013) including 1) confirmation and analysis of the oil release(s); 2) confirmation of a pathway from the release to the key potentially affected natural resources; 3) measurement/determination of exposures of these resources to oil and its components; 4) determinations of adverse response of natural resource populations to these exposures; and 5) characterization of the unimpacted environment and the natural resources therein (i.e., baseline conditions). It is important to stress that depending on the size of the spill, the oil characteristics, the release scenario, and other factors, a detailed implementation and analysis of each of these steps is seldom needed. For example, it has been the practice of several states to develop rapid damage assessments for smaller spills through the construction and use of "lookup compensation tables.". For example, the State of Washington's NRDA process[1], is such a process. It should also be noted that in some cases parties can develop early restoration plans in advance of formal injury assessment.

Many challenges exist in applying scientific strategies and methodologies to studying oil spills. Each spill scenario is different and demands different information over differing time frames. The needs for data and actionable information for both spill response decisions and for NRDAs arise quickly during the emergency response, and these data and information not only support early phases of a spill where collection of ephemeral data is important but also help to design further data collection efforts to answer longer-term questions related to ecological recovery trajectories and restoration assessment (Robilliard et al. 1997; Boehm et al. 2013). Central to this initial phase and to subsequent information gathering are the needs for and the feasibility of collecting adequate representative field data versus (or more productively in concert with) the application of spill models. Furthermore, data and information can be extrapolated

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[1] https://apps.leg.wa.gov/WAC/default.aspx?cite=173-183

from other well-studied spills. Ideally, in each NRDA, a balance of data/information collection efficiency and defensibility should be optimized.

So what is the balance to be struck between empirical data needs, extrapolations, and model outputs? How can this blend be optimized in different types of spills, of differing sizes, at differing locations, of differing ecological and political sensitivity? The answer of course varies according to the spill scenario, but what all spills have in common is the need to generate a sufficient quantity of defensible information during the multiple phases of a spill—first days, to months, and in many cases to years. In this paper, we provide a perspective on ways to approach the blending and optimization of available tools using the "NRDA Triad" of methods, scaled and balanced according to the specific oil spill under investigation.

EVOLUTION OF METHODS – THE TRIAD TOOLKIT

For the purposes of this discussion, the triad under consideration (Figure 1) consists of (1) empirical data and observations, (2) use of various types of models that extend or help to analyze the empirical data and observations to gain a more comprehensive perspective of effects, and (3) extrapolation of information from other oil spills.

Empirical data and observations

The multitude of methods that have been developed from the late 1960s to the present for the study of the various abiotic (e.g., chemistry, fate, weathering, and transport) and biological (e.g., chemical exposure, toxicology, individual organism response, and population effects) components of oil spills are too varied and numerous to cover in this paper. Examples can be found in NRC 2003, Robertson 2001, ITOPF 2014, Fingas 2015, Lubchenco et al. 2012, and others. What these methods have in common though is that they consist of measurements (e.g., chemical concentrations and compositions, forensic chemical source identification, fish catch statistics, individual organism measurements, etc.) and expert observations (e.g., aerial overflight photographs and sketches, remote satellite sensing of surface oil, drifter deployments, shoreline oiling distributions [using the Shoreline Cleanup Assessment Technique or SCAT], etc.). Methods for collecting such data and information have been well published and are parts of a "toolkit" that has been generally accepted by the scientific community over time, even as these methods have evolved and expanded. However, empirical data collections obtained during evolving oil spill events can never alone satisfy the needs of a NRDA injury assessment given the spatial and temporal complexities of an actual oil spill. Empirical data and observations typically represent a snapshot of the conditions, concentrations, etc. at a given location and point in time and may not represent average or changing conditions over a wider area and period. Conversely, models can provide a representation of spatially and temporally changing conditions, which in concert with empirical data, better inform injury assessments.

Models

The reference to "models" here includes mathematical or laboratory representations of the actual field conditions (i.e., the "real world"). Such models include 1) spill trajectory, fate, and transport models; 2) oil spill impact/injury models, which employ toxicology and biological information with trajectory/fate information; and 3) dose-response models derived from laboratory tests factoring in chemical/exposure (e.g., weathering, partitioning) and toxicity. Other types of models have been developed and can be used to estimate largely unobservable losses in the acute phases of a spill where, for example, direct contact may lead to post-mortality sinking (e.g., models of marine mammal and bird mortalities; carcass sinking). Additionally, food web/chain and ecosystem models are also available to spill scientists (e.g., Ainsworth et al. 2018) as a means to understand the interconnections between resource components.

All types of models are intended to help users understand the complexities of the “real world” but are essentially only representations, arguably simplifications, of complex processes that may or may not occur only at limited times and/or over highly variable spatial scales during and after the actual incident. Thus, models can help to develop hypotheses of what has actually occurred, but their outputs require sufficient validation through observations and empirical data.

The important dual challenges of understanding measurement and modeling uncertainties can be helped by a blending of the two. A variety of models have been developed for and applied to oil spills and to NRDAs related to those incidents. Models use available environmental conditions and characteristics of the oil to predict and to develop hypotheses related to oil movements, oil “behavior” (e.g., weathering and partitioning), chemical exposures, toxicity, and biological losses. Models of toxicity (i.e., dose/response) to specific or representative species at risk are also developed through lab testing.

Models (fate and transport)

Models of the environment and the movement and transformations of oil on and in the aquatic environment, termed fate and transport/hydrodynamic models, have been evolving since the 1980s. The evolution of these physical and chemical models has been reviewed, and a selection of these well-documented, generally accepted models are available and in widespread use (e.g., Huang 1983; Spaulding 2017; French-McCay 2004; Reed et al. 1999; Afenyo et al. 2016). These models are used in conjunction with observational field data in a forecasting mode during response to determine where the oil is moving to help guide sampling, predict interactions with wildlife, and guide dispersant application strategies offshore and other cleanup efforts; they are used in conjunction with field data in a hindcasting mode as part of NRDA to assess spatially and temporally varying exposure of resources to the surface and subsurface oil and potential injuries. Essentially models assist in the “confirmation of a pathway from the release to the key potentially affected natural resources” (Step #2 above) by identifying the area of impact, slick thicknesses, oil weathering, etc. over time.

Models (injury assessment)

Fate and transport models have been paired with models of exposure/toxicity/production foregone to help estimate and quantify natural resource injuries—i.e., lost biomass and/or services. The injury models began with the development of the NRDAM/CME model (Reed et al. 1989; French et al. 1996) used for Type A (i.e., simplified assessments for smaller spills) of damages to natural resources in coastal and marine environments under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). They evolved further (e.g., French-McCay 2004) after the development of separate regulations and practices under the Oil Pollution Act of 1990 (OPA). In lieu of or augmented by field measurements, these models have been used in many spills over the past 25 years to both forecast the movements of oil during incidents as well as, in support of NRDAs, to couple hindcasting with estimates of biological losses and hence injuries.

While field validation of components of injury models include exposure concentrations and durations leading to actual toxicity in the field, etc., actual losses are difficult or impossible to measure in the field. These injury assessment models help to integrate data to approximate the injuries, thus offering starting points for the consideration of NRDA Steps #3 and 4 above: measurement/determination of exposures of these resources to oil and its components and determinations of adverse response of natural resource populations to these exposures.

Laboratory models - toxicity testing

Though laboratory simulations of oil spill processes have been undertaken for many years, of particular relevance are dose-response or toxicity models derived from laboratory testing. How a specific oil may result in chemical dosing in receiving waters and how that dosing, in turn, may impact aquatic (and other) organisms both acutely and chronically have been central to the field of aquatic toxicology for many years (e.g., NRC 2003; Bejarano et al. 2014; Redman et al. 2012; Redman and Parkerton 2015; Dupuis and Ucan-Marin 2015; NAS 2019; and many others). An abundance of information is available on the sublethal and lethal—chronic and acute—toxicities of various oils, but this information must be applied with great care to actual spill situations in the assessment of injuries. Consideration of the environmental context or relevance for any laboratory toxicity dose-response model is essential. For example, while a toxicity threshold is developed through extended laboratory testing (e.g., acute tests lasting 24–96 hours; chronic test lasting 7 days or more), its applicability in the field over shorter periods in an environmentally relevant area needs to be factored into its use in injury assessment models, lest use of toxicity data may greatly overpredict toxicity, injuries, losses, and damages.

A key question during NRDA efforts is whether additional, oil-specific, organism-specific tests are needed. This is a key question because there is much information already available in the literature to estimate field doses and adverse responses to same and then to develop a range of possible outcomes for new spill events. Further ecotoxicology testing alone should never be used as a sole basis for injury assessment without field verification of such injury and use to evaluate the real-world ecological significance of such tests.

Extrapolations from other spills

The need for empirical information can, in part, be satisfied to varying degrees by extrapolations and use of data and information from prior spills. Depending on the spill situation, such extrapolations can be highly useful and relevant, but they can also be very inappropriate if not aligned carefully. It is quite logical and desirable to bring experience, scientific findings, and even data from previous spills to bear on a specific spill situation. For example, and as mentioned above, there is an abundance of toxicity data on crude and refined oils, as well as on the chemical composition of oils, that have been spilled in other incidents and can be compared to the oil in a spill under study. Furthermore, there is an abundance of information on the range of concentrations of oil and oil components found in the water column during well-studied spills such as the Deepwater Horizon (Wade et al. 2016; Boehm et al. 2016) and the Exxon Valdez (Boehm et al. 2007). While data sets cannot easily or defensibly be extrapolated in their entirety to a spill under investigation, careful application of relevant subsets of data can nevertheless be very useful in informing various aspects of a NRDA, Steps 1–4 above and restoration scaling in particular.

DISCUSSION

The above descriptions suggest an application decision matrix that can guide the mix of empirical data/observations, models, and extrapolations and that can be used and optimized for a given spill situation during various phases of a spill (e.g., Figure 2). Injuries to natural resources cannot be determined solely through measurements, models, or extrapolations from other spills, but tailored blends of these tools can create defensibility and efficiency at the same time.

There is a wealth of information and scientific experience available to NRDA practitioners (trustee and responsible party, managers, scientists, and economists) to be used to develop these blends of tools in any oil spill scenario (e.g., NOAA[2]; IPIECA[3]; Israel et al. 2019; Boehm and Ginn 2013). Aquatic spill scenarios (i.e., those that result in oil entering a water body) are generally divided into offshore/coastal and inland spills. These two broad categories are considered in contingency planning activities and the development of general sampling plans (e.g., ITOPF 2014; IPIECA-IOGP 2014; NAS 2016). Characteristics considered in planning and conducting a NRDA include multiple aspects of the oil release and the receiving environment, collectively called the spill scenario:

- Release: Oil type and amount; rate and duration; location and depth
- Receiving Environment: Prevailing conditions; offshore resources-at-risk; pre-existing exposures to oil; accessibility and logistics.

The National Oceanic and Atmospheric Administration (NOAA) “Raw Incident Data” site is one compilation of information on oil spills around the world.[4] A large number of oil spill events (3,810) have been recorded. Between 1985 and 2019, there were between 15 and 197 oil spill incidents annually in the United States where NOAA was notified by the US Coast Guard. Many more inland spills occur each year, which fall under EPA jurisdiction. Though almost all oil spills require some level of response and information gathering, the number of spills that result in a formal NRDA are relatively few. For those spills that occur at a size or location where a “significant impact” may be of concern, NRD Trustees may initiate steps towards a NRDA under OPA §990.41 if natural resources under the trusteeship of the trustee may have been, or

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[2] https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/resources/fosc-guide.html; https://response.restoration.noaa.gov/environmental-restoration/environmental-assessment-tools/noaa-sampling-guidelines-arctic-oil-spills.html

[3] http://www.ipieca.org/resources/

[4] https://incidentnews.noaa.gov/
https://incidentnews.noaa.gov/raw/index, accessed on 12-16-2019

may be, injured as a result of the incident, thus triggering information gathering. Before any official determination of a formal NRDA is made, with the possible exception of small spills that are quickly cleaned up, initiation of a sampling and monitoring program is prudent, particularly if a large enough spill results in use of chemical dispersants or controlled *in situ* burning (IPIECA-IOGP 2014).

As set forth in the OPA (15 C.F.R. §§ 990.2-.66) and CERCLA (43 C.F.R. §§ 11.10-.93) NRD regulations, all investigations must be able to address, to some extent, 1) a comparison of impacted and unimpacted areas through some evaluation of baseline conditions as well as 2) an evaluation of trends in chemical exposure and or resource changes over time, both before, continuing into, and after the spill event. However, the intensity and scope of any and all NRDA investigations must conform to the realities of the spill scenario. At one end of the scenario-based data collection spectrum are the small reported spills that happen frequently in aquatic waters. At the far end of the data collection spectrum are the examples of the Exxon Valdez (1989) tanker spill and the Deepwater Horizon (2010) oil well blowout.

Fate and transport modeling is universally useful in spill response and NRDA. For small spills, once the location and nature of the spill is known, model results may be all that is needed along with visual observations in lieu of empirical data collections to come to a reasonable agreement on possible range of injuries and restoration project scaling in spite of the uncertainties inherent in modeling. However, for larger, more complex, and environmentally sensitive spills, fate and transport models cannot defensibly carry the data/information burden alone. In these cases, models are used, in conjunction with an appropriate scale and range of empirical data collections used for validation, to fill in the temporal or spatial empirical data gaps. Overreliance on modeling without sufficient empirical validation can lead to scientific overreach. The example of Berenshtein et al. (2020) is one where modeling was used to create new facts when a massive data set was actually available and which casts doubt on the modeling results. Modeling can be used to estimate spill movements, dissolved concentrations, etc. if ephemeral data collection was infeasible or not undertaken, but such estimations must be supported by facts from the spill of information extrapolated from other spills..

Appropriate extrapolation can be very efficient and effective. As an example, while the entire 12,000+ water column chemistry data set (BP Gulf Science at https://data.gulfresearchinitiative.org/pelagos-symfony/data-discovery) from the very large, long-duration, Deepwater Horizon deep sea blowout is not generally applicable in its entirely to another spill, the application of a relevant subset of that data set to a surface oil spill of crude oil is quite plausible, if carefully and expertly done. The entire data set pertains to an ongoing deep sea blowout, but much of the data collected after the release ended (July 15, 2010) relates to samples taken under and around oil floating on the surface. This data set could be applied to estimate surface oil-related water column impacts in the same general area from similar types of crude oils (see Figure 3). Other extrapolations of different data sets, including published oil weathering studies and toxicology test results, are quite feasible without necessarily having to replicate those data collections or laboratory tests entirely for small to medium sized spills.

All spills, regardless of size or resource sensitively require robust observations from the air and from land and water that are already built into all spill response actions to determine the footprint of the oil over time. For aquatic impacts, aerial observations are essential for establishing an accurate time-dependent surface footprint of the oil. Composite surface oil “footprints” (i.e., use of the composite integration of areal coverage at any given time by differing types and thicknesses of the oil during a spill) are technically misleading. For shoreline impacts and injuries to shoreline resources, the use of temporally specific observations and measurements, starting with SCAT shoreline exposures/footprints, form the foundation of any NRDA. Because systematic SCAT observations are generally robust, fate and transport models of shoreline impacts are seldom if ever useful or helpful in this regard. If they are used, they are constrained by actual SCAT observations (i.e., a model cannot logically predict the presence of oil where none was observed through repeated observations over time) (e.g., Nixon et al. 2016).

Balance and optimization

In general, optimization of the oil spill triad to address the questions at hand is at the crux of post Deepwater Horizon spill NRDA science strategy. It is impossible to understand the elements of an injury assessment through measurements, models, or extrapolation alone. Sub-optimization and a loss of scientific defensibility occur with an overreliance on any one tool.

There is no one formula leading to an optimized blend of the scientific tools for oil spill NRDAs. How should data, models, and extrapolations be mixed and applied? To begin this discussion, it is useful to assess when they are out of balance. Beyond the strict need for high-quality data and QA/QC of data and all outputs of models and data analyses, the only absolutes seem to be where scientific defensibility comes up short, through any of the following (i.e., “the 7 deadly oil spill sins”): 1) the lack of sufficient observations/descriptions of the spill scenario; 2) overdependence on any one tool (e.g., results based on modeling or empirical data alone); 3) the overreliance on small local data sets to represent a large spill area; 4) the lack of sufficient empirical data to validate model outputs (i.e., outputs must be linked sufficiently to real-world data/observations); 5) the lack of some degree of modeling to derive adequate representation of empirical data; 6) the reliance on laboratory tests of toxicity to represent real-world impacts/injuries without field validation; and 7) failure to consider the natural baseline (e.g., natural mortalities and alternative stressors/causation factors). Each of these situations may lead to scientific indefensibility.

An optimization sequence leading to an appropriate blending of tools and approaches logically includes the following:

- The development of a conceptual site model (CSM). Based on past experiences, details of the spill scenario, and knowledge of resources potentially affected, what hypotheses can be developed?
- Generation of hypotheses (predictions of what is expected to happen spatially and temporally) to be tested:
  - Assess how and which models can be used to affirm the basic elements of any hypotheses from the CSM;
  - Assess what information is available from other spills and plausibly extrapolatable to the spill scenario;
  - Derive information from appropriate toxicology models from existing information and literature;
  - Integrate these data/information into predictive fate and transport forecasting models to generate hypotheses; and
  - Determine what information is needed to answer questions/test hypotheses.
- Collection of data and information. How much and what types of new data are needed to a) describe the environment and calibrate models; b) describe exposures and validate model outputs, especially those pertaining to time-

  dependent chemical exposures; and c) fill baseline (unimpacted area) data needs and gaps?

- In cases where some level of injury is apparent early on, an evaluation of potential restoration projects either as emergency, early, or compensatory restoration.

These decisions can be guided by considering a matrix of spill and resource complexity. A simplified example is presented in Figure 4. In this matrix the key questions are:

1. What is the nature of the spill scenario?
2. What is the nature of the resources potentially affected by the spill?

Both of the questions provide input into the CSM. In this matrix the relative importance of and emphases on the components of the oil spill triad are shown as examples. Here we provide an example of four basic types of spills based on spill scenario complexity and resource complexity. Admittedly this is an oversimplification of any spill, no two of which are exactly the same. However, experience with a variety of oil spills and with how and to what extent which tools were applied optimally or inefficiently, provides a useful basic conceptual framework.

- Type 4: Represents a range of types of major spill events—large, persistent oil, highly complex and/or sensitive resources at risk. Priorities include:
  - Collection of observational information on slick movement and resources at risk
  - Collection of oil samples
  - Forecast modeling to predict slick movement and guide sampling
  - Large-scale temporal and spatial sampling and analysis of key resources (e.g., water, biota, marshes, etc.)

  - Hindcast modeling to fill in spatial and temporal data gaps
  - Use of appropriate, relevant, existing toxicology information
  - Use of data from other spills used as a “reality check.”
- Type 3: Represents a range of smaller spills, some with more potentially toxic oils and/or occurring in highly sensitive areas. Priorities include:
  - Collection of observational information on slick movement, impact zones, and resources at risk
  - Collection of oil samples
  - Forecast modeling to predict slick movement and guide sampling
  - Hindcast modeling to hypothesize exposure fields – temporal and spatial
  - Limited data collections to validate models
  - Use of appropriate, relevant, existing toxicology information
  - Use of data from other spills used as a “reality check.”
- Type 2: Represents a range of larger spills occurring in urban areas, usually with less sensitive or complex resources, and large spills occurring offshore out of range of highly sensitive resources or potential landfall. Priorities include:
  - Collection of observational information on slick movement, impact zones, and resources at risk
  - Collection of oil samples
  - Forecast modeling to predict slick movement
  - Use of data from other spills to represent exposure fields

  - Hindcast modeling to determine the application of existing, extrapolated data
  - Limited data collections to validate models
  - Use of appropriate, relevant, existing toxicology information
- Type 1: Represents a range of smaller spills that dissipate rapidly, occur in urban areas or areas of less sensitive resources, and are often dealt with through spill compensation tables (like those used in Washington State). Priorities include:
  - Collection of observational information on slick movement, impact zones, and resources at risk
  - Collection of oil samples
  - Use of data from other spills to represent exposure fields
  - Use of appropriate, relevant, existing toxicology information.

CONCLUSION

In the post-Deepwater Horizon era, NRDA lessons learned from that event are still being digested and applied by trustees and responsible parties. The perspective provided here aims to assist with post-DWH NRDA scientific assessment planning. A CSM fed by information on the spill scenario, its size and complexity, and the complexity and sensitivity of the resources at risk sets the stage for planning and executing optimized information collection based on the different generalized categories of the “oil spill triad” in an oil spill NRDA injury assessment.

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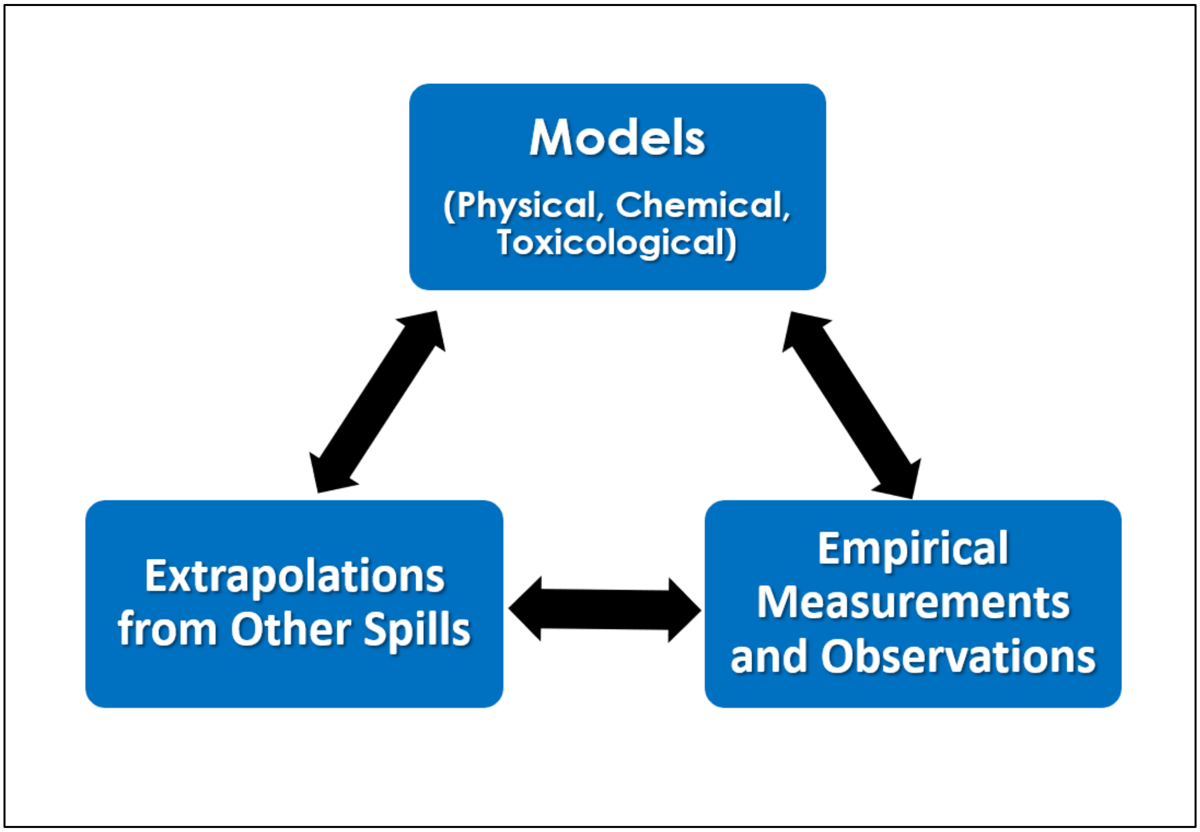

Models

(Physical, Chemical, Toxicological)

Extrapolations from Other Spills

Empirical Measurements and Observations

Figure 1. The Oil Spill Triad: Sources of data and information

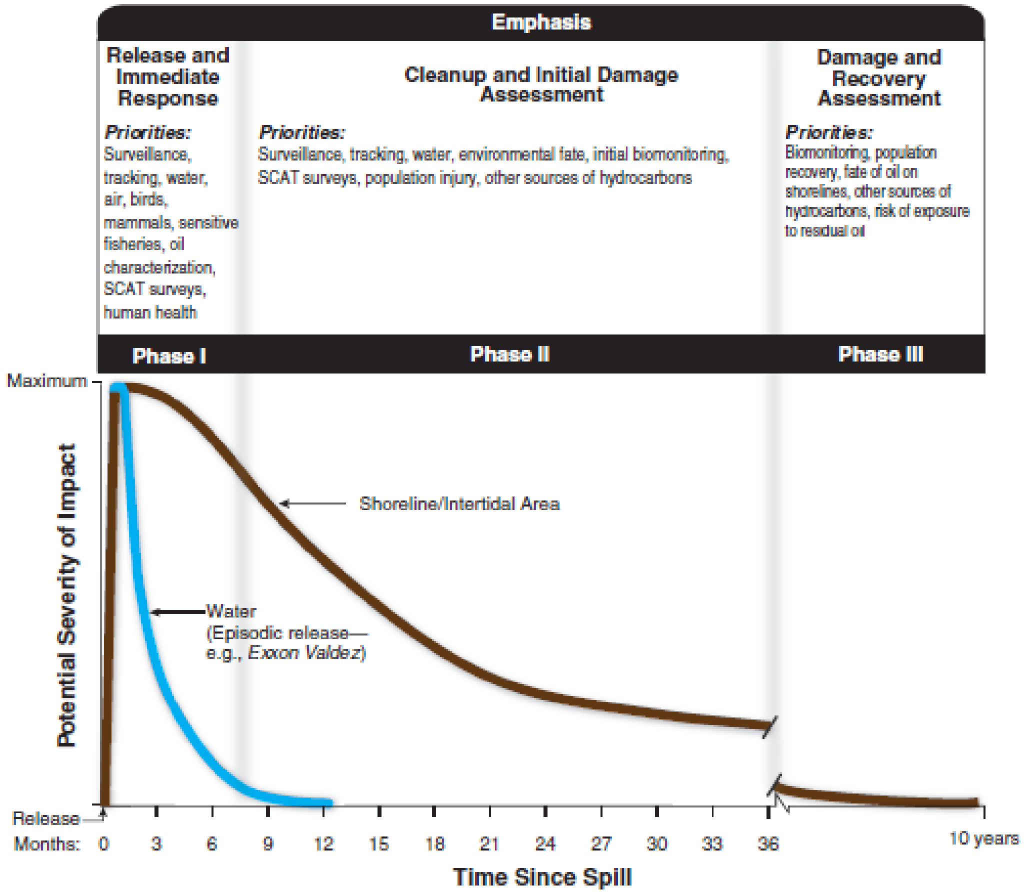


Figure 2. Phases of a spill: Information needs vary over time. Example shown is for a short-term, large release in a complex resource-intensive area (from Boehm et al. 2013).

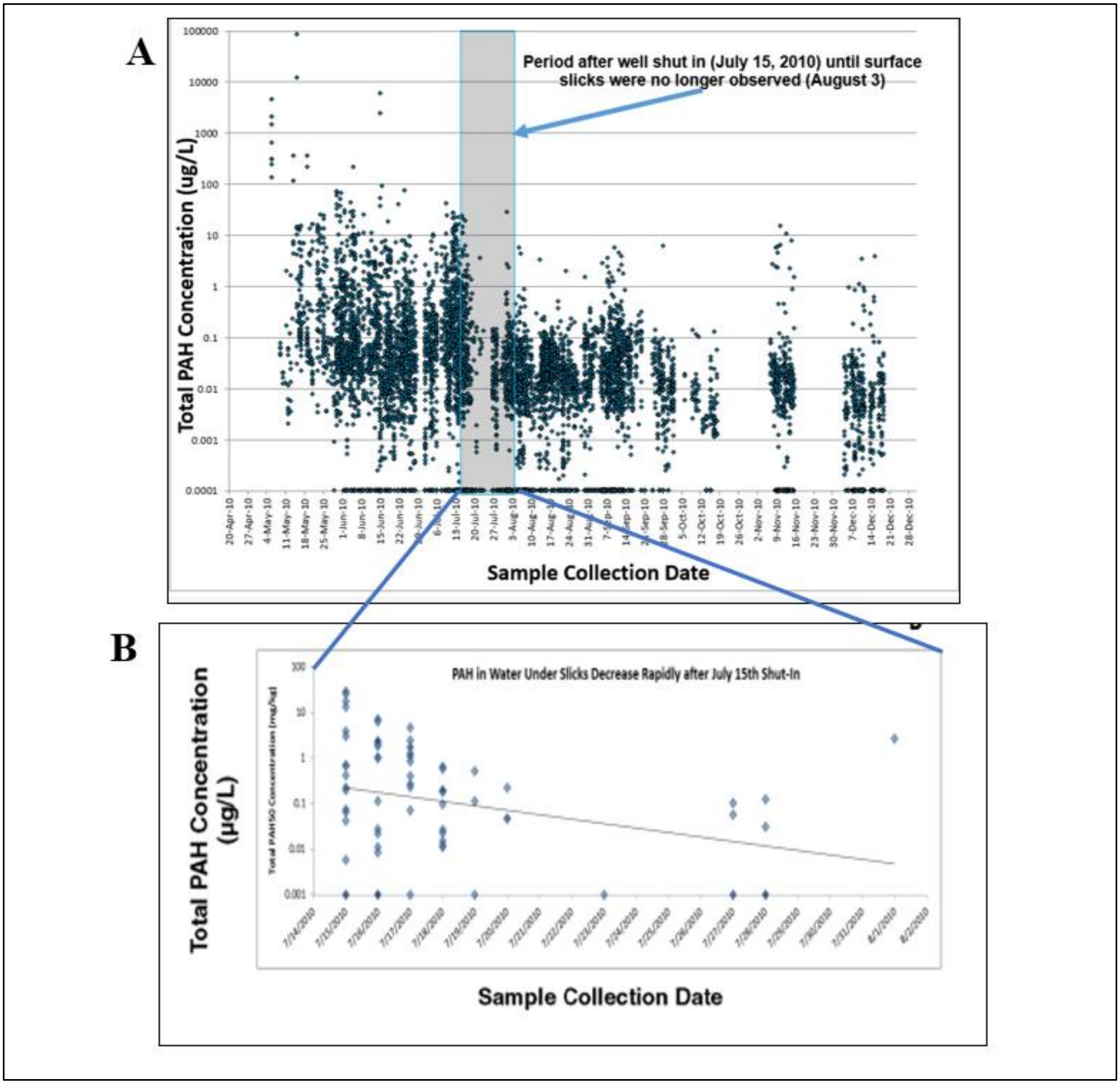
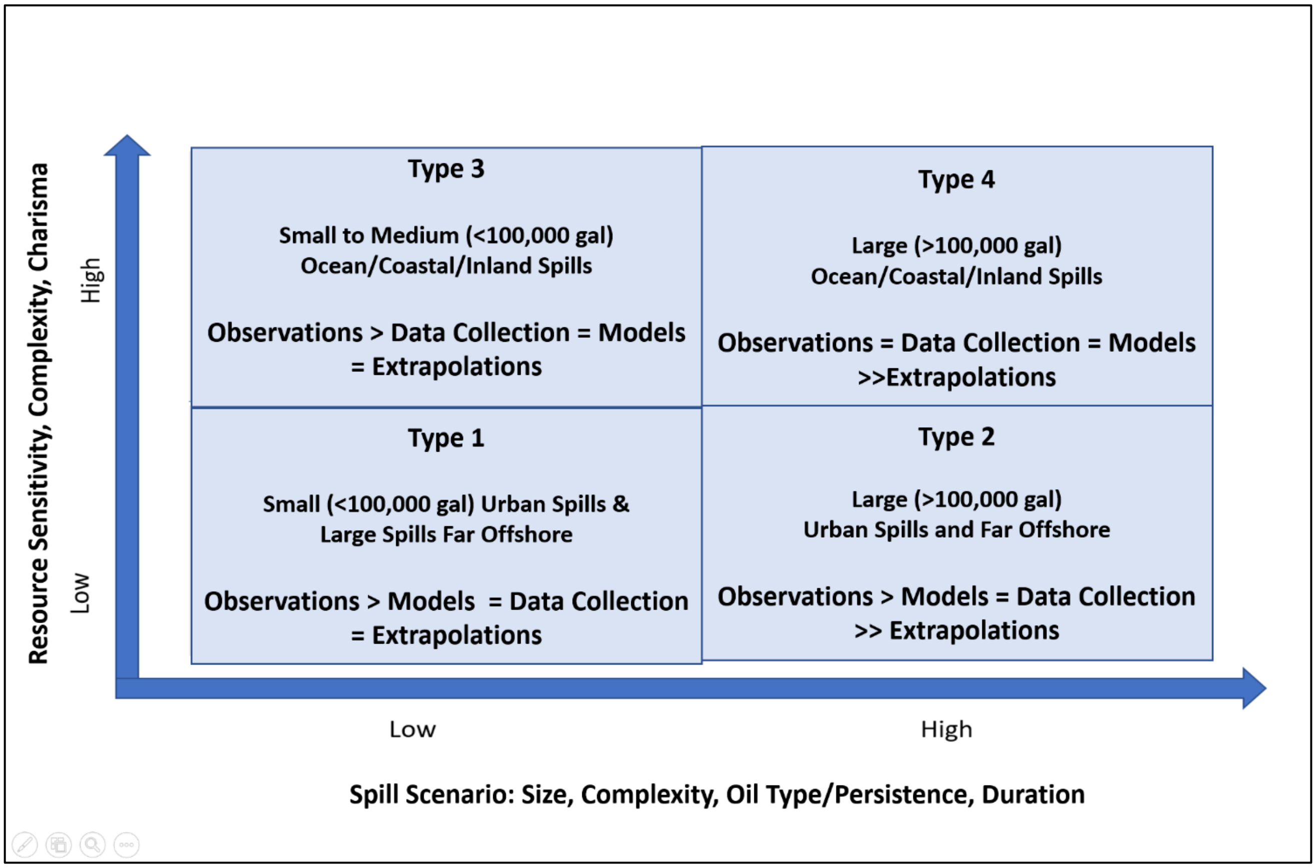


Figure 3. Example of Use of Data from One Spill Applied to Another Spill (adapted from Boehm et al., 2016); A- Entire data set; B- Data set after cessation of release, at 0–4.5 m beneath remaining surface oil slicks (June 15-August 3, 2010).



	Low	High
High	**Type 3** Small to Medium (<100,000 gal) Ocean/Coastal/Inland Spills Observations > Data Collection = Models = Extrapolations	**Type 4** Large (>100,000 gal) Ocean/Coastal/Inland Spills Observations = Data Collection = Models >>Extrapolations
Low	**Type 1** Small (<100,000 gal) Urban Spills & Large Spills Far Offshore Observations > Models = Data Collection = Extrapolations	**Type 2** Large (>100,000 gal) Urban Spills and Far Offshore Observations > Models = Data Collection >> Extrapolations

Figure 4. Example Matrix: The Triad balance varies by spill scenario, which includes the nature of the spill and the complexity of the natural resources at risk.