Towards Integrated Modeling of the Long-term Impacts of Oil Spills

Abstract

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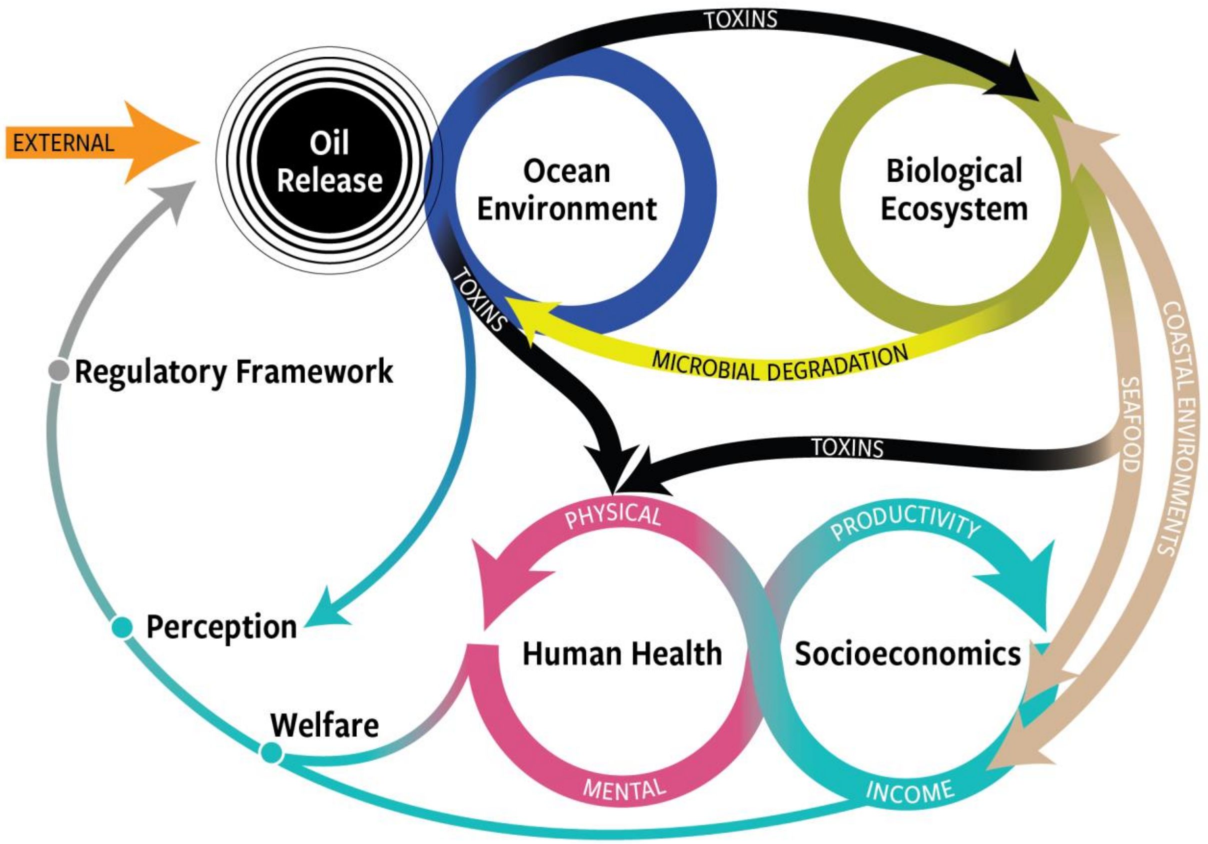
Graphical Abstract



Title Page (with Author Details)

Towards Integrated Modeling of the Long-term Impacts of Oil Spills

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Keywords: Oil Spills, Impact and Damage Assessment, Integrated Assessment Modeling, Systems Dynamics, Causal Loop Diagrams

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1. Introduction

On April 20, 2010, the Deepwater Horizon (DWH) oil drilling platform exploded, killing 11 people and injured 17 others, and causing a deep-sea blowout. This led to one of the largest oil spills in history, releasing natural gas plus an estimated 5 million barrels of oil into the Gulf of Mexico (GoM) before the well was capped 87 days later (McNutt et al. 2012). As part of the response, 2 million gallons of dispersant were applied at the deep sea and at the sea surface (USCGNRT 2011).

The DWH oil spill was notable for its immense impact, and for being the deepest (~1,500 m) major oil spill to date. Despite advances in drilling safety, the likelihood of a range of spills of various sizes is still a danger for which preparation, response, and recovery plans are needed, given the lessons learned from the DWH accident. To this end, a number of tools are available. Models for operational oil spill forecasting, including ocean, wave and weather forecasting for predicting oil movement and concentration (Barker et al. 2020) tend to employ short time horizons, making predictions hours to weeks into the future. They also are typically used to guide emergency response activities and immediate cleanup efforts (e.g., by answering questions such as where to deploy equipment for shoreline removal of oil). These operational models can be quickly configured to investigate tactical questions as new questions arise. In contrast, broader models that estimate the effects of oil spills on society (i.e., integrating ocean environment, biological ecosystems, socioeconomics and human health knowledge domains) can be employed for damage assessment and strategic planning. These models are intended to operate over longer time horizons, from months or years to decades. They tend to be more interdisciplinary in nature, because they require integration across broad knowledge domains. Although environmental assessments depend strongly on quantitative models that can incorporate knowledge from a wide range of disciplines, fully coupled assessment models that consider quantifiable aspects of human dimension are scarce, and while a few quantitative interdisciplinary models have been developed (Paris et al. 2013, Ainsworth et al. 2018, French-McCay et al. 2019, Dukhovskoy et al. 2020, Berenshtein et al 2020a), they have not been connected under a single framework. This paper addresses efforts towards this end and lays out a framework of how the long-term analysis of oil impacts can be integrated and implemented for future strategic planning for optimizing long-term recovery from major oil spills.

System Dynamics (Forrester 1961, 1989, 2010), as an organizing principle, was used to drive the synthesis effort. In simple terms Forrester (2010) described System Dynamics as, “Interpreting real life systems into computer simulation models that allow one to see how the structure and decision-making policies in a system create its behavior.” System Dynamics is a methodology for addressing complex interdependent and non-linear systems that are governed by sequences of interacting causes and effects, also called feedback loops. Ideally, primary determinants of behavior should be endogenous, i.e., there should be few external driving forces. This principle is well suited for our purpose (Pérez-Pérez et al. 2020), given that we wish to consider how the entire GoM (nature and humans) is impacted by an oil spill. The method has proven well suited for policy analysis in general because feedbacks tend to exist at multiple points in the political system (Pagoni and Patroklos 2019, Zhou et al. 2020).

The conceptualization phase of building a System Dynamics model often includes the development of Causal Loop Diagrams (CLDs), which aid in visualizing interconnections among the systems to be linked (Brennan et al. 2019). CLDs are shown as flow diagrams in which the nodes represent variables, and links, including directional arrows, represent causal influences. Specific information about nonlinear functional forms and state variables is neglected in CLDs for simplicity. The CLDs thus provide a high-level qualitative overview of the system, making them ideal for synthesizing complex and interconnected systems in a way that is easily understandable. Because CLDs are simple and visually intuitive, they can be co-developed with experts unfamiliar with the method of System Dynamics.

This paper focuses on the development of the CLD for the GoM system in the context of oil spill impacts. Additionally, the intention is for the CLD to be applicable to oil spills in general, while using DWH as an example to guide its development.

To describe the development of the CLD and its interpretation this paper is organized in the following sections, following the introduction Section (1): Section (2) we present the societal questions and stakeholder needs that helped guide this synthesis; (3) we developed the CLDs; (4) we analyze the CLD in light of the societal questions posed in Section 2; (5) we map existing models onto the CLD, to identify gaps in understanding and model development (based on the stakeholder needs identified in Section 2); (6) we describe a roadmap for future applications, and (7) we summarize and conclude.

2. Societal Questions and Stakeholder Needs

Many questions have been raised by stakeholders and concerned citizens over the years about the long-term impacts of the DWH oil spill. A number of these questions were consolidated by the GoM Sea Grant Oil Spill Science Outreach Team (Hale et al. 2019) who engaged with stakeholders to learn about their oil spill science-related questions and concerns. The team engaged with target audiences (Table 1) and the general public during the first year through one-on-one discourse, small group meetings, and large group input sessions. In 2014 and 2016, the team conducted two Social Network Analyses to understand how credible, relevant, and timely oil spill science information flowed through a network of people from these specific target groups in the GoM. Survey participants used the opportunity to share topics of interest (Sempier et al. 2019a, 2019b, 2019c, See https://gulfseagrant.org/oilspilloutreach). The team also compiled audience feedback data from evaluations completed before and after 30 oil spill science seminars and workshops. All data, surveys, and evaluations represent target audience input between 2014 and 2018. From these efforts, some of the key questions consolidated by Sea Grant were very broad, and included:

- “Is the Gulf seafood safe to eat?”
- “What are the impacts to wildlife?”
- “Where did the oil go and where is it now?”

- “Do dispersants make it unsafe to swim in the water?”

Additional questions (Table 2) are more specific variations of the bulleted questions above that were categorized by experts within each of the knowledge domains. Some of the additional questions, for the socioeconomics domain, expand upon the bulleted questions to include questions about the impacts of the spill on economics, infrastructure, and community resiliency.

To obtain additional feedback from oil spill decision makers representing industry and the oil spill response, restoration, and environmental monitoring communities, a stakeholder panel was coordinated in 2020 by Sea Grant (see supplementary materials for details). Needs identified by this panel included:

- A cross-disciplinary model that can quickly be repurposed for new geographic areas and be applicable on a wide range of scales both nationally and internationally.
- Models that can track the oil transport and fate from the time a spill occurs all the way to and through the damage assessment process and system recovery (NOS 2020).
- Models that look at cleanup strategies and their potential impacts
- Models that could accommodate additional considerations such as air quality components, different oil types, and freshwater-salinity fronts,
- Provide for improved baseline data so that impacts of oil spills can be better assessed.

- Maintenance of data repositories and its accessibility for future modeling needs.

Stakeholder questions consolidated by Sea Grant during its early outreach efforts were generally focused on practical issues, including topics related to impacts on human and ecological health and a desire to understand the ultimate disposition of the oil. Similarly, but in a broader sense, stakeholders from the 2020 Sea Grant outreach effort emphasized the need for practical models that can be quickly repurposed to answer questions associated with specific scenarios once they occur. The need for baseline data and data repositories to be used for model development was also emphasized. In the end the stakeholders underscored the need to understand the extent of damages caused by the spill, including impacts of oil spills on seafood resources, impacts on ecosystems, the ultimate disposition of the oil, and also the safety of recreational resources. With this concept in mind, the CLD was developed to address assessment of damages to the environment, ecosystems, and human health, in addition to their socioeconomic consequences.

3. Development of the Causal Loop Diagram (CLD)

3.1. Creating the CLD

Many of the stakeholder questions focused on the impacts of the spill and needs for interventions to reduce or prevent impacts. Interventions mentioned included dispersant use, clean up to protect wildlife and natural resources, freshwater diversions to influence the movement of the oil, and fishery closures to control seafood safety. Four knowledge domains (Figure 1) were recognized as a starting point to identify the fields of science needed to address both spill impacts and effects of interventions. These knowledge domains include the following:

- Ocean Environment: oceanic and atmospheric transport and biogeochemical and thermodynamic transport and fate processes.
- Biological Ecosystems: interconnectivity of organisms geographically and within and between trophic levels.
- Socioeconomics: evaluating market impacts across different economic sectors as well as non-market societal impacts.
- Human Health: acute and chronic physical and mental health impacts, including physiological and psychological consequences of protracted and cumulative stress.

These four domains served as the starting point for initializing the CLD. They roughly separate the subject of oil spill impact modeling into a distinct set of related and overlapping disciplines. For example, ocean environment modeling requires expertise from oceanography, climate science, and contaminant transport, plus contributions from the physical, geological, chemical, and biological sciences. Biological ecosystems involve a core expertise from the biological sciences including the sub-disciplines of ecology, microbiology, marine sciences, zoology, botany, fisheries, and veterinary sciences, with cross-over to the physical, geological, and chemical sciences. Socioeconomics include the sub-disciplines of economics, anthropology, sociology, psychology, and communication studies. Human health includes the sub-disciplines of environmental health science, public health, medicine, physiology, applications of genomics and other “omic” sciences, biostatistics/bioinformatics. All domains require the application of rigorous mathematical and statistical methods and computer science. The complexity of the impacts of an oil spill is thus demonstrated by the knowledge needs from many different disciplines.

While recognizing the interconnectedness among disciplines, information was consolidated about the latest models by reviewing the literature and gathering input from experts representing each of the four domains of knowledge. Pre-existing review articles that discussed recent advances in oil-spill research were focused on ocean environment (Spaulding 2017), biological ecosystems (Ainsworth et al. 202X, Beyer et al. 2016) and human health (Laffon et al. 2016, Eklund et al. 2019, Sandifer et al. 2020b). Among these Spaulding (2017) and Ainsworth et al. (202X) provided in-depth reviews of available models describing advances in ocean environment models, and how ocean environment models have been interfaced with biological ecosystem models. Ainsworth et al. (202X) emphasizes the lack of quantitative models available in the human health and socioeconomics domains.

Given that modeling in human health and socioeconomics domains are characterized by larger gaps and fewer linkages within existing quantitative models, below we focus on representative modeling capacities within these two domains which expand upon the descriptions from the above-mentioned literature reviews. An extensive review of modeling capabilities in the ocean environment and biological ecosystem domains is described in Ainsworth et al. 202X.

3.2. Current models in human health and socioeconomics

Although considerable evidence has been collected to link human health impacts (both physical and mental) to oil spills (Aguilera et al. 2010, Rusiecki et al. 2018, Kwok et al. 2017a,b, Afshar-Mohajer et al. 2019, Wickliffe et al. 2018, Wilson et al. 2015, Goldstein et al. 2011, Osofsky et al. 2015, Lowe et al. 2019, Tasch and Larcher 2012, Carroll et al. 2002, Pan et al. 2019, Drakeford et al. 2020, Sandifer et al. 2020b, McKendree et al. 2013, Morgan et al. 2016, Wilson et al. 2015, Ylitalo et al. 2012, Farrington 2020), quantification of the links has been limited. Exceptions include a few physical health models based upon risk assessment approaches or Bayesian statistics. For example, the Beach Exposure And Child HEalth Study (BEACHES) evaluated risks to children from oil-contaminated beaches where the hazard was identified as the chemical constituents of oil (Ferguson et al. 2019, 2020a, Tomenchok et al. 2020). Once the concentrations were established through oceanographic models or empirical evidence (Montas et al. 2020, Xia et al. 2020), then the beach play activities of the children were simulated as scenarios for possible exposure (Ferguson et al. 2019, 2020b) and used to compute health risk (Black et al. 2016). In the context of seafood, risk assessments evaluated levels of the more toxic component of oil, polycyclic aromatic hydrocarbons (PAHs), but recognized that toxicological data is missing for alkylated PAH forms limiting the strength of risk assessment approaches due to lack of toxicological data (Farrington 2020, Wickliffe et al.

2014,2018). Groth et al. (2017) utilized a Bayesian hierarchical linear model to estimate exposures to oil spill workers to specific volatile oil components based upon measured levels of total hydrocarbons. They conclude that correlations between total hydrocarbon levels and volatile chemical components may be useful for estimating worker exposure.

In the context of mental health, conceptual and semi-quantitative models have been established to evaluate cause (direct and secondary disaster effects) and effect (resilience and recovery within a community as measured by economic and housing stability, physical and mental well-being, and social role adaptation) (McEwen 2000, Palinkas 2012, Abramson et al. 2010,2015, Hansel et al. 2015). For example, Guo et al. (2018) have utilized structural equation modeling to evaluate hypotheses between place attachment and community resiliency. Indices have been developed to relate community well-being and resilience to environmental, economic, and social factors (Smith et al. 2013, Summers et al. 2016, 2018). A critical area of study in the context of mental health impacts is the potential cumulative nature of stress (Osofsky et al. 2016). Within the literature, the term allostatic load has been used to define the cumulative impacts of repeated and multiple mental health stressors in a person’s life that results in adverse mental and physical health outcomes (McEwen and Stellar 1993, McEwen 2000, Seeman et al. 2001, Galen Buckwalter et al. 2016, Rodriguez et al. 2019, Forrester et al. 2019, Harville et al. 2018). Models that integrate mental health consequences should consider the allostatic load experienced by a community (Chandra et al. 2019, Finucane et al. 2020), especially if impacted by multiple disasters. Koliou et al. (2018) emphasize, in the context of community resilience to natural hazards, the need to integrate physical, social, and economic aspects of community resilience. They further emphasize the need to include interdependencies and system recovery which are yet to be quantified. One of the few conceptual models that integrates physical and mental health outcomes, including considerations for allostatic loads, is the Disaster-Pressure State-Ecosystem Services-Response-Health (DPSERH) model that describes the interdependencies between ecosystem services, individual and community health, and the cumulative stress impacts after disasters (Sandifer et al. 2017).

Like human health, socioeconomics lag in depth and breadth of quantitative models as compared to those available in ocean environment and biological ecosystems, in part due to a lack of high-resolution, longitudinal socioeconomic monitoring and data collection. Challenges exist in matching the spatial and temporal scales of these data sets with those used in biogeophysical modeling. For integrated modeling results to be useful, researchers should consider "decision-making relevant scale (DMRS)" (Yoskowitz et al. 2017, Verburg et al. 2016) whether they are for assessing jurisdictional, institutional, management, and local impacts (Cash et al. 2006). Extensive social and economic datasets exist and are available for use and incorporation into models (NASEM 2017, UNDRR 2017, Sharifi 2016, Miles 2015, Frazier et al. 2014). For example, existing datasets include: the Census data (census.gov) as well as its produced American Community Survey (ACS) Public Use Microdata Sample (PUMS) files, Electronic Medical Records (https://digital.ahrq.gov/key-topics/electronic-medical-record-systems), and marine surveys available through the National Oceanographic and Atmospheric Administration (NOAA) (fisheries.noaa.gov). However, use of these aggregated datasets to fully understand social resilience or vulnerability at the local, sub-county or neighborhood scale is difficult (Patel et al. 2017). Community resilience is inherently local, with high degrees of variability across communities just a few miles (or blocks) apart. Existing available datasets do not capture spatial or temporal variability within counties or census tracts, nor do they differentially weigh socioeconomic factors by local community prioritizations and needs (Frazier 2012).

Traditionally, efforts to estimate economic losses associated with oil spills have focused on assessing lost passive use values using contingent valuation methods (Arrow et al. 1993, Grigalunas et al. 1986, Mazzotta et al. 1994, Hausman et al. 1995, Carson et al. 2003, Loureiro et al. 2009, Loureiro and Loomis 2013). Alternatively, input-output analysis methods can be implemented using current software tools and databases (IMPLAN Group LLC 2020, EconAlyze LLC 2020, U.S. Bureau of Economic Analysis 2020).

Studies related to the economic impacts of the DWH oil spill employed a wider variety of methodologies (Petrolia 2014, Larkin et al. 2013). For example, Sumaila et al. (2012) and Carroll et al. (2016) evaluated the negative economic impacts of DWH on commercial and recreational fishing and marine aquaculture through the seafood value chain using economic impact models for the entire Gulf Coast region. The former study estimated total economic losses for all sectors to be $8.7 billion and the latter study estimated that the short-run impacts on the Gulf seafood industry from the DWH oil spill resulted in reduced income ranging from $22 to $310 million. Another study used spatial databases of annual reported commercial catch prior to the spill to estimate impacts of the oil spill on commercial fisheries in the Gulf Coast region resulting in an estimated minimum loss in annual landed value of $247 million for U.S. Gulf fisheries (McCrea-Stub et al. 2011). Another example employed estimates from the Atlantis ecosystem model to evaluate the short- to medium-term shifts in commercial and recreational fishing activity due to fishery closures resulting from the DWH spill, and input-output analysis to determine the economic impacts of these changes (Court et al. 2019). Another study developed a multi-modal predictive framework integrating (1) blowout simulations (2) data of fishing fleets targeting benthic and pelagic ecosystems, and (3) a social vulnerability index derived from U.S. Census Bureau data. This framework was used to anticipate the relative revenue loss between coastal communities in the GoM (Berenshtein et al. 2019).

In terms of tourism- and recreation-related losses, one example estimates the economic impacts of cancelled recreational trips to Northwest Florida after the DWH spill. A survey process was used to determine average lost visitor spending per household, which allowed researchers to calculate estimated total foregone spending. These figures were then used to model broader regional economic losses of U.S.$ 1.3 billion for the region due to canceled visitor trips (Court et al. 2017). Others developed a series of random utility models for site choice among saltwater anglers in the Southeastern U.S. to estimate recreational user losses resulting from the DWH oil spill (Alvarez et al. 2014, 2015) with results suggesting that total monetary loss from recreational anglers was $585 million.

The wide range of estimated impacts in the examples listed above suggests a high degree of uncertainty and the effect of varying approaches. In the next phase of development socioeconomic modeling efforts should focus on a better understanding of the social dynamics that drive the wide variety of socioeconomic impacts associated with oil spills, the development of best practices related to socioeconomics data collection/use and methodological approaches, and the implementation of dynamic regional economic modeling frameworks to fully integrate the simulation of the broad range of community health and socioeconomic impacts, given their reliance upon another (Ritchie et al. 2013, Whitehead et al. 2018).

Given the limitations in quantitative modeling in human health and socioeconomics, there are major challenges to understanding human health and social dynamics in order to model them in a credible way, to constructing such models, and then to coupling them to existing models of the ocean environment and biological ecosystem dynamics (Buckingham-Howes et al. 2019, Nelson and Grubesic 2020).

3.3. Converting the concepts within the four domains of knowledge into a CLD

Expert-participant input was sought to supplement the information from literature reviews and Sea Grant outreach efforts. Input was facilitated through a sequence of webinars, virtual workshops, and two conference sessions where experts were invited to participate in discussing modeling needs and linkages necessary to answer long-term societal level questions. (See supplemental material for details). These sessions supported an iterative and shared development of the CLD (Figure 2). The process began with researchers' presentations of their work in a series of public webinars, one for each of the four domains. Each webinar was followed by a private working session, typically with 10-20 participants, which used the presented research as a starting point for a structured questioning process designed to identify the causal structure implied by the work as well as linkages to other domains. Some diagram elements were constructed or marked up live, and others were added later based upon participant comments. A subsequent series of workshop sessions reviewed and refined the diagrams and added elements from a more focused exploration of phenomena that cross the four domains.

The CLD developed from these efforts reflect the four primary domains of knowledge (1) the ocean environment (upper center quadrant); (2) biological-ecosystems (upper right quadrant), this quadrant also includes ecosystem services; (3) socioeconomics (bottom right quadrant); and (4) human health (bottom left quadrant) and their associated linkages represented by colored-coded arrows (Figure 2). The transport modeling components of the ocean environment that rely on hydrodynamic, atmospheric, and oil behavior and fate are represented by blue arrows. The components highlighted with gray arrows represent the response linkages necessary for establishing short-term operational models needed for response and the political and governance drivers that mandate the establishment of these short-term models. The interlinkages associated with biological ecosystems as illustrated by different organism biomasses and habitats are represented by the green arrows in the upper right quadrant. Significant connections between the upper half of the CLD and the lower half include seafood, ecosystem services, and interlinkages between oiled shorelines and tourism. The teal and pink arrows along the bottom of the diagram focus on the interlinkages with socioeconomics and human health components including income & employment, physical health, mental health, and productivity. The CLD illustrates the influence of the human systems on the regulatory framework and the linkages to response efforts.

3.4. Observations from the CLD within each domain of knowledge

Ocean Environment: The CLD emphasizes that ocean environment models (upper center, blue circles and arrows) are interlinked with response planning which is highlighted within the upper left quadrant of the diagram (gray circles and arrows, Figure 2). This includes several short-term loops that represent responses to the spill in terms of immediate preparedness and cleanup efforts. The CLD also emphasizes the interlinkages of the ocean environment model with longer term feedback loops that are part of the integrated socio-ecological model, emphasizing that effects captured in operational models can ultimately influence individual health status, productivity and community health. Through perceptions of oil spills on welfare and risk, these longer-term impacts, influence the regulatory framework through which the operational models are mandated. Consequently, outputs from the short-term operational models not only influence how society responds rapidly to protect resources that are sensitive in the short term, but they also influence the longer term socioeconomics and human health domains, which in turn feedback to the regulatory framework through public perceptions of oil spill effects, and hence affect operational responses. The CLD further emphasizes that perceptions are also influenced by the media coverage and the quality of information that is disseminated. The affected perceptions can then drive the regulatory framework which impacts planning, response capacity, and cleanup efforts, which then impacts the amount of oil remaining in the ocean. Thus the ocean environment domain influences the entire range of decision-making time scales, from the short-term, immediate response on the order of hours to days, to the longer term decadal scales through which official policy requires that ocean environment models be established in the interest of public welfare (Walker et al. 2021).

Biological Ecosystems: The biological ecosystem submodel (Figure 2, upper right quadrant, green circles and arrows) is highly simplified (as are several other causal loops). Oversimplifications include the lack of trophic levels and species interdependencies thereby omitting an explicit accounting of ecosystem diversity. In its current simplified form, the CLD emphasizes the interlinkages between oil and impacts on living organisms (e.g., Berenshtein et al. 2020b). It also emphasizes the interconnections of biological ecosystems with socioeconomics through perceived safety of seafood for human consumption and through contact with oil in beach sediments and marshes. Additionally, socioeconomic factors impact biological ecosystems through coastal development and its impacts on coastal habitats and the impacts of fisheries on foodwebs. The CLD also emphasizes that the contamination of biological ecosystems can be on-going due to the circulation of toxins in the water column and their release from buried material. These are all important messages for stakeholders to understand the cascade of effects triggered after a spill. It is important for injury assessment and restoration planning (NOS 2020) to measure the persistent impacts in addition to the immediate acute toxicity and mortality effects. The diagram further emphasizes that the biological system provides important non-market ecosystem services such as protection from storm surges and access to recreation. This is an important part of welfare given that people rely on these non-market services and have an intrinsic interest in the existence value of species and landscapes.

Socioeconomics: The socioeconomic components (teal circles and arrows) tend to be clustered to the bottom right quadrant of Figure 2 with linkages with ecosystem services, seafood harvest, seafood prices, seafood industry capacity, and income & employment. Additionally, oiled shorelines influence beach closures, which have impacts on tourism, income & employment. The diagram also emphasizes that income & employment rely indirectly on many other components of the socioeconomic system, including from the human health domain, for example the influence of human physical and mental health on productivity. Additionally, the diagram emphasizes the intrinsic value of knowledge and information that can be produced through education. Education level can affect perceptions of safety, consumer confidence, people's behavior in response to a spill, and ultimately can impact community welfare. The CLD emphasizes that the socioeconomics components and their linkages to human health and other components of the integrated system can be very complex and intricate.

Human Health: The translation of the models and concepts described above into a CLD (Figure 2) shows links between the oil release and its transport/degradation (blue arrows), and ultimately a connection to human health through the exposure of toxins to human populations (pink circles and arrows). Exposures can occur through cleanup efforts and through contaminated seafood and beaches. The exposure to human populations can result in physical health impacts, which affects society through productivity, and income & employment. The cycle is closed through the links between income & employment to healthcare affordability. Mental health is an important contributor to physical health. Mental health can manifest from toxic exposures through the fear of exposure and loss of use of treasured places, loss of recreational values, and others (Parker et al. 2019, Ramchand et al. 2019, Thomas et al. 2018). Mental health is strongly influenced by income & employment which is linked to fishing and non-fishing economies. Mental health is also influenced by community health. Community health is dependent upon the social network of people, which help maintain the mental health of the people who rely on those networks. The analysis of human health systems emphasizes its strong interlinkages between socioeconomics and physical and mental health.

4. Analysis of the Causal Loop: Key Societal Questions

The unifying theme of stakeholder questions was, “damage assessment in the context of environment, ecosystems, and human health.” In terms of damage assessment, and using DWH as an example, large spills send an immediate shockwave through the system described by the CLD. The physical spill of oil occurred, for example, in the deep ocean, marked by the oil release circle shown in Figure 2. Within 24 hours the information of the spill and the fear of its consequences spread across the human domains. Then a slower set of physical, chemical, and biological effects and information waves occurred, and these slower set of effects were more thoroughly discussed amongst experts and synthesized in the CLD. To track this “damage” through the CLD, we begin by tracking toxins originating from oil (herein, referred to as “toxins”) and their impacts on ecosystems, socioeconomics, and human health. Toxins are defined as chemicals capable of causing lethal effects or sub-lethal effects including acute illnesses, chronic illnesses, and cancer.

Impact to the ocean environment: A portion of the spilled oil rose to the sea surface and was transported from the spill site by wind and surface currents partly to settle into the sediments and partly into the water column (Paris et al. 2012; Le Hénaff et al. 2012). However, the fastest oil to reach shore was the oil that rose to the sea surface and was carried by the surface currents and wind to shore (lower blue circle in Figure 3A). At the surface, oil was removed or converted to new chemicals through several natural processes including photooxidation, photodegradation, evaporation, and biodegradation (DeGouw et al. 2010, Vaz et al. 202X). As a result of the DWH oil spill, Marine Oil Snow Sedimentation and Flocculent Accumulation (MOSSFA) was found to be an important removal pathway (Burd et al. 2020; Quigg et al. 2020, Bracco et al. 2020). Eventually, some of the weathered oil slicks become beached, after which they were influenced further through natural onshore degradation processes. Throughout the water column and seabed, natural microbial communities also played important roles in degrading different compounds in the oil. Humans intervene to mitigate the damages caused to the ocean environment through addition of dispersants and active clean up offshore and onshore. Cleanup methods can lead to additional environmental and human health risks (Figure 3B), such as through the use of dispersants, other cleanup chemicals, burning of surface oil, capture and subsequent disposal of oiled water, sediments, and capture devices.

Impact to the biological ecosystem: The toxic components of the oil spilled in the ocean environment influence the biological ecosystems. The level of impacts on aquatic plants, animal species, and microbial communities are dependent upon the frequency and duration of exposure, and the concentration of toxins that are found at the sea surface, water column, and bottom sediments. In the model, there is a circular ecosystem that represents the biomass of many species (from microbes to fish and corals) (Figure 3A). This ecosystem is naturally regenerating and degrading, but human actions may also have a negative influence on both regeneration and degradation. The steady-state biomass of the system is dependent upon habitat quality which dictates the carrying capacity and is influenced by oiling and coastal development. The biomass of many commercially important species can also be reduced by harvesting through fishing. The influence of biological ecosystems on socioeconomics and ultimately human health is dependent upon the impacts to commercial and recreational fisheries species and to some secondary and tertiary food web consumers such as corals, sea turtles and marine mammals that have intrinsic value to humans, in addition to many other taxa that play critical roles in ecosystem functions (e.g. algae and carbon dioxide sequestration or mangroves and coastal protection).

Interlinkages between ocean environment and biological ecosystems: Although the ocean environment and biological ecosystems have numerous significant feedback loops within their respective domains, processes within these two domains rely on feedback between them. The distribution of toxic substances in the ocean environment is influenced by the environmentally controlled hydrodynamics, and especially ocean currents that play a major role on transport and fate processes. Biological ecosystems are highly influenced by the distribution of toxins and species sensitivity within various trophic levels. The key interlinkages between the two domains, the biodegradation of oil by microbes (counterclockwise green arrow from microbes at the top of Figure 3A) and the uptake of oil spill toxins by marine organisms (clockwise blue arrows in the center of Figure 3A), emphasize the dependence of processes between these two domains. Toxin concentrations are transferred from the ocean environment system into biological systems, then circulate within the ecosystems domain. Damage within the ecosystem domain can include acute and chronic impacts to organisms as well as long-term impacts to their populations via reduction in reproductive capacity and/or genetic damage. Microbial degradation of oil, a key biological process (e.g., MOSSFA), is seen as a major feedback process from the biological ecosystem towards the ocean environment. Although the distribution of toxic substances within the residual oil following a spill can be reasonably simulated through the ocean environment system, it does rely heavily upon the microbial component of the ecosystems processes. These microbes can not only remove oil from the system, but also (by preferentially degrading different molecules) potentially alter its buoyancy and transport. In summary, processes within the upper half of the CLD (between ocean environment and biological ecosystems) are inextricably linked, requiring coupling of the two systems to simulate major mechanisms that invoke damage (e.g., spread of toxins and loss of biomass and diversity) through the system.

Impact to socioeconomics: The spill impacted the seafood industry most immediately through the closure of fishing zones, but also through possible reduction in the quality of the seafood and through reductions in price (as represented by tan arrows in Figure 2). Recreational fisheries are another source of economic value in the GoM, a sector that suffered damages for the same reasons as the commercial seafood industry. More generally, the tourism industry was damaged, due to the impression (real and perceived) of a damaged environment. Income & employment were also affected by loss of jobs and income associated with reduced fishing activity and reductions in demand across the hospitality industries. This impacted the productivity of the labor force that depends on health status (Figure 3B, teal arrows). Human welfare (Figure 3B, bottom teal circle) is closely tied to income & employment. Human welfare also increases by reinvesting a fraction of economic value in education (teal arrows). But if there are excess healthcare costs due to spill effects and toxins then there is an added burden of illness and fewer resources to spend on education. Health also affects productivity directly. So, there are economic and health feedbacks that represent the ways in which economic impacts diminish the accumulation of human welfare, which diminishes productivity and that propagates through the health system.

Impact to health: There are two components to the damages in the health system. First, there are direct physical toxic health effects, where toxic exposures create acute, short- and long-term health effects. The long-term health effects typically appear a few years or decades after the exposure onset or may continue as a chronic condition from the time of exposure. Second, are the indirect mental effects, which can be caused by a number of stressors including the physical health effects or worries about them, the socioeconomic damages, the environmental damages, and a degrading trust in a "system" that allows such a spill to happen. Degradation of mental health might accelerate the degradation of physical health and vice versa. This is probably the most uncertain piece of the system, the interconnectedness of mental and physical health. In general, degradation of human health can affect socioeconomics by changing productivity directly.

Interlinkages between socioeconomics and human health: Unlike the ocean environment and biological ecosystem domains, which have tight circular feedback loops within their respective domains, the feedback loops for socioeconomics include human health and vice versa (Figure 3B) where complete separation of feedback loops between domains is not possible. A major stressor on mental health is employment status and income (which in turn are also affected by the toxins as described above through indirect routes). When the economy is below a long-term trend, psychological and physical stress levels increase and impact health. For mental health and productivity feedbacks, there are more persistent effects on the economy based upon erosion of long-term community resources in the community, social capital and support networks, increased costs for health care, and reduced investment in human capital. There are many economic and health feedbacks that represent the ways in which an oil spill causes damage to the accumulation and use of the six forms of capital affecting community resilience. These capitals are 1) human and cultural, 2) social, 3) political, 4) natural, 5) infrastructure, and 6) financial (NASEM 2019). Although this is an over simplified model and the linkage parameterizations are far more complex than illustrated, the proposed structure emphasizes that socioeconomics and human health are strongly dependent upon each other. The processes in each of these domains cannot easily be separated as the major feedback loops go back and forth through these domains. As such, models developed for the lower half of the CLD need to be tightly and intimately coupled due to the close dependencies between human health and socioeconomics.

Interlinkages between the ocean environment and biological ecosystems (top half) and the socioeconomics and human health domains (bottom half, Figure 2): Interlinkages between the natural domains (top half) and the human-focused domains (bottom half) generally proceed in primarily top down pathways, in particular in the shorter (monthly to yearly) time frames. These top down processes include toxin impacts on seafood harvest, and on physical health through exposure during clean up, seafood consumption, or recreational uses. These impacts from the oil spill help address stakeholder questions focused on damage assessment, with damages operating at the monthly to yearly time scales. Thus, on the time scale of months to years, the system naturally separates where information from the natural domain (top half) is transmitted to the human-focused domain (bottom half). It is recognized, however, that human activities do have feedback towards the natural systems and that the dominance of the top down flow of information is not absolute.

At the much longer time scales (on the order of years to decades) the dominant flow of information is reversed with outer loops that illustrate feedback from the human systems back to the natural systems (Figure 2). These longer-term feedbacks are observed towards the far right of the CLD where coastal development influences shoreline stability and coastal habitats. This feedback directly influences biological ecosystems by impacting ecosystem health and diversity, habitat quality, and carrying capacity. Similarly, another very significant outer loop is shown by the teal arrows found towards the bottom and left of the CLD (Figure 2). These loops represent feedback towards human systems that influence the regulatory framework (upper left), which ultimately impacts the probabilities and response preparedness of future oil spills. These feedback loops connect these systems together and span very long-time scales. A model that addresses these outer loops of the CLD would be capable of answering questions associated with the tradeoffs of prevention and preparedness for future spills.

5. Mapping Existing Models to the CLD: Identifying Gaps in Model Development to Address Stakeholder Needs

To identify gaps in current modeling efforts and methods for linking models, existing state-of-the-art models were consolidated from expert input during virtual workshops. From the virtual workshops, the expert input resulted in a list of 33 models (Table 3) that were developed between 2010 and 2020 within each of the domains of knowledge. The capabilities of these existing models were then super-imposed on the CLD (Figure 4). The results from this superimposition are described for ocean environment and biological ecosystem models (Section 5.1) and for human health and socioeconomic models (Section 5.2). Additional detailed feedback on modeling needs from experts is provided in the supplemental text.

5.1. Ocean environment and biological ecosystem domain models

The super-imposition of existing models on the CLD emphasized the larger expanse and depth of quantitative models currently developed for the ocean environment and biological ecosystem domains (Figure 4, highlighted by the blue, green, light purple and gray shapes). These include models that are designed to be discretized in space and time including a model that integrates atmospheric with oceanic processes (Chen et al. 2013, Curcic et al. 2016). The level of resolution is dependent upon the phase of the oil spill, whether resulting in acute or chronic ecosystem effects. For acute effects, time scales between oceanographic and ecosystem models would be more similar given that the effects of physical smothering and acute toxicity occur within a short period. Whereas for chronic ecosystem impacts, the time scales would be extended to account for growth and expanded habitat of aquatic organisms which generally exceed the time and spatial scales of hydrodynamic processes that affect oil distribution and degradation. The discrepancies between spatial and temporal scales expand as the focus of assessment transition from short-term to long-term ecological impacts.

These discrepancies have been addressed in some existing integrated models (light purple shape). Examples of fully integrated quantitative models that cross-over these two domains of knowledge include Atlantis, the bio-physical Connectivity Modeling System (CMS) and its oil module (oil-CMA), Spill Impact Model Application Package (SIMAP), and Consortium for Simulation of Oil-Microbial Interactions in the Ocean (CSOMIO) (Table 3). The CSOMIO model offers an example of the complexity in combining simulations across these two domains of knowledge, by integrating the simulations of oil with microbial degradation and sedimentation using different computational schemes. The modeling system dynamically couples components for simulating ocean hydrodynamics, oil transport, dispersion and weathering, oil-mineral aggregate (OMA) formation, flocculation and settling, and the lower trophic level marine ecosystem. It is an adaptation and extension of the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system (Warner et al. 2010). A biogeochemical modeling component incorporating a microbial model (Genome-based EmergeNt Ocean Microbial Ecosystem (GENOME); Coles et al. 2017) is implemented in the system and adapted for the presence of hydrocarbons. The sediment transport component of COAWST (Community Sediment Transport Modeling System, CSTMS) is modified to include computationally efficient flocculation parameterizations for OMAs developed from laboratory experiments. The ocean modeling component of COAWST (Regional Ocean Modeling System, ROMS) is modified to simulate three-dimensional oil transport and compositional changes (weathering). These modeling components are linked together using a two-way Lagrangian-Eulerian mapping technique, enabling interaction between all the modeling components for tracking of hydrocarbons from a source blowout to deposition in sediment, microbial degradation, and evaporation while being transported through the ocean.

5.2. Socioeconomic and health domain models

Full integration of models across the socioeconomics and health domains has not yet occurred for oil spill models, although some progress has been made in the integration of ocean environment, ecosystems, and subsets of the socioeconomics realm. The oil-CMS model simulates toxic oil transport, fate and dispersion, impacts to the subsea and to fisheries (Paris et al. 2012, Berenshtein et al. 2019, Perlin et al. 2020), and has expanded into the socioeconomics knowledge domain through its use to evaluate the economic impacts of fishery closures (Berenshtein et al. 2020a,b). SIMAP, a proprietary model (French et al. 1996), crosses over the ocean environment domain, the ecosystem domain, and because of its use in the National Resource Damage Assessment (NRDA) process, also includes estimates of ecosystem valuation by providing input to another proprietary model, the Offshore Environmental Cost Model (OECM, BOEM 2016).

Although there have been extensions of quantitative and discretized models into portions of the socioeconomic domain, there are no models that are fully quantitative and discretized that address the entirety of socioeconomics and human health. As a result, two new categories of models are defined in Figure 4 that differ in level of development compared to models that simulate the ocean environment and ecosystems. These categories include “quantitative modeling frameworks” and “conceptual models.” “Quantitative modeling frameworks” include equations that quantitatively describe relationships between variables but are yet to be integrated in time and space with the more well developed spatially and temporally discretized oceanographic and ecosystem models (e.g., pink, tan, and teal shapes in Figure 4). “Conceptual models” (represented by the dotted gray lines in Figure 4) include flow charts and the development of indices to quantify human health and socioeconomic vulnerabilities. The limitation to integration is disaggregation. But in the case of socioeconomics and human health, the relevant types of disaggregation (other than space and time) are needed. For example, a fisheries valuation model would require information about impacts of oil on fish species and on different sectors of the fishing economy. Impacts will be different for the specific species or groups of species of fish that is/are the focus of commercial and recreational fishing. Therefore, information should be disaggregated to the fish species level by fishing sector for input to socioeconomic models. Such disaggregation is rare for longer-term ecosystem models and so there is generally a mismatch (or impedance) between what ecosystem models provide and the information needed to quantify economic impacts. For physical human health, various chemicals can cause diseases in humans and so integration with physical human health would require that ocean environment models separate chemical data. Oil (crude oil or its products such as fuel oil) is a complex mixture of thousands of individual chemicals. Modeling each chemical would be extremely difficult. For this reason, most oil transport models simulate chemistry by splitting the oil into pseudocomponents (Beegle-Krause et al. 2001, Paris et al. 2012, NOAA 2014, Dagestad et al. 2018). Some go farther to simulate selected PAHs (Berenshtein et al. 2020a, French-McCay et al. 2019, Vaz et al. 2020). Very few, if any, simulate multiple individual chemical concentrations within water, air, and sediments which is a starting point for human health and ecosystem risk assessments. Similarly, here in terms of disaggregation of chemical concentrations there is a disconnect between ocean environment models and physical human health modeling needs that require chemical species disaggregation. And this discussion only considers physical health consequences of some oil components for humans.

The super-imposition of existing models emphasizes that no single quantitative model incorporates the entire range of model components and processes needed to address societal impacts of oil spills, and to our knowledge, there have been no advancements made to quantitatively couple existing models across all four domains, although very broad conceptual non-quantitative models such as DPSERH (section 3.2) are available. Within socioeconomics and human health, the development of quantitative physical health and ecosystem valuation will require that the ocean environment and ecosystem models overcome impedance by providing the outputs needed for quantification in the lower half of the CLD. In the area of mental health and the psycho-social effects of oil spills, although conceptual models for mental health frameworks exist (Figure 4, lower portion of figure), these are generally not quantitatively modeled at this time. Within the middle of the CLD where consumer education, knowledge and consumer confidence intersect, there are no overlapping shapes. The missing components of a model are the non-monetary variables in the community such as how individuals and populations respond to changes in quality of life, what are the quality of life implications of health status, education, and equity, and others. Socioeconomics models need to integrate these variables in addition to traditional monetary metrics. Similarly, perceptions of welfare, community and risk and their influence on regulatory frameworks and their adoption, as shown on the left side of the CLD (Figure 2), are completely lacking from existing modeling frameworks.

6. Roadmap for Future Applications

A CLD is by design qualitative. The next step of a System Dynamics project would be to convert the CLD to a formal simulation model by identifying stocks and flows (Sterman 2002), quantifying linear and nonlinear relationships, and adding time series data for comparison and representation of features outside the model scope. Each variable could then evolve according to an underlying equation that describes the rate of increase or decrease of that variable (as a consequence of all the linkages between domains and impacts in the diagram). With such a general high-level understanding of how the system interacts, key dynamics can then be represented and integrated into a fully coupled model. It is recognized that identifying the underlying equations will be a challenge and will require considerable future research to validate.

One limitation of the CLD in its current form is the lack of spatial discretization and disaggregation of different population groups and different economic sectors. Various spatial domains can however be represented in suitably elaborated and disaggregated sub-models within the same overall conceptual framework. A useful next step would be to attempt the construction of more complex sub-models, especially for the socioeconomic and human health domains, where quantitative models are less well-developed. In addition, it is possible that the existing complex models of the ocean environment and biological ecosystem dynamics could usefully be emulated by less complex systems dynamics models, or even included directly by careful definition and representation of the crucial interconnections.

Rather than building a System Dynamics model, the CLD can be also used for defining and developing connections between models (Zolfagharian et al. 2018). Pathways to integrating models can include a portfolio approach (organize a family of independent models without attempting to link them mathematically), loosely coupled models (where the output from one model is used as the input to the next), fully coupled models (combine multiple large-scale models where information is transferred at each time step), and metamodels (a large holistic and fully-integrated model that simulates details within all systems). Given the large differences in time and spatial scales between the ocean environment/ecosystems and socioeconomics/human health domains, directly linking all modeling efforts into a large metamodel model does not appear to be practical at this time for addressing stakeholder questions. One can envision taking the portfolio of already developed models and augmenting and coupling (federating) them. This will lead to larger models which, at some point, are likely to become intractably difficult and expensive to run as the socioeconomic domain is integrated. The strategy to federate models might be possible for the ocean environment and ecosystem models. For the socioeconomic and human health domains, given the interlinkages between these domains, it would likely be best to further integrate and elaborate the models within these domains.

Given the observations from the CLD, the most practicable path forward appears to be the development of a highly integrated dynamic model that represents the socioeconomic and human health spaces, with rich feedback processes between them. This highly integrated model would be capable of receiving inputs from models that simulate the ocean environment and biological ecosystem domains. This approach, however, does not capture the even less explored decadal scale processes whereby the human dimensions (e.g., change in policies) impact the frequency and magnitude of oil spills, the ability to respond to these spills, and ultimately impact the natural ocean environment and biological ecosystems. Future developments should also integrate these larger term processes that feedback from the human and socioeconomics domains back towards governance aspects that provide some controls on the potential for a spill.

For the health and socioeconomics domains, a crucial requirement is to define suitable disaggregation of the whole population and economy, both spatially and sectorally, and to obtain the data needed to characterize their interactions and evolution. While the level and types of detail needed for these sub-models will be different than that needed for the natural systems models of the ocean environment and ecosystems, there is a paucity of data available to substantiate the human domains. Though there are gaps, in the biophysical realm broad-based monitoring efforts have been organized into formal systems from the global scale, for instance, NASA's Earth Observing System or the Global Ocean Observing System (GOOS), to more regional efforts like the GoM Coastal Ocean Observing System (GCOOS) and Fisheries Information Network (FIN). There is no equivalent monitoring or observing system of a robust suite of socioeconomic variables that can help us assess the value of non-market resources or cultural attributes for example. Data is gathered for various uses (e.g., recreational and commercial fishing, employment in shipping) but there is no concerted effort to aggregate existing data, identify and fill longitudinal data collection gaps, and make it available in a value-added process. An improved human health observing system has been proposed that consists of a six layered approach that includes an already existing three-layered set of large-scale surveys and studies with the addition of three new nested, longitudinal cohort studies (Sandifer et al. 2020a). The conceptual framework under this proposal for an integrated socioecological model for long-term impacts of oil spills that includes improved human health observing systems would provide data to calibrate quantitative models that integrate physical health, mental health, and socioeconomics.

For the immediate future, for expediency purposes, future directions could involve adding socioeconomics and human health functionalities to the operational models for use during an active spill (Brandeau et al. 2009), for prospective impact assessment (Nelson and Grubesic 2017, Grubesic et al. 2019), or for retrospective damage assessment. During an active oil spill, operational models can potentially provide considerable insights regarding the transport of the oil and possible impacts of mitigation measures. Coupling this information with human dimensions would allow for more informed and educated decisions that can prevent irreversible effects on an ecosystem. Knowledge of conditions that may cause irreversible effects could be used to constrain short-term mitigation decisions and help ensure desirable long-term outcomes.

Finally, we must recognize that the deterministic nature of any simple model limits its ability to represent and propagate errors and uncertainty. Uncertainty propagation can, in principle, be addressed by putting probability distributions on each input parameter of the future integrated socioecological model, and then running the model in a Monte Carlo formulation to evaluate how error and uncertainty propagates. In practice, deciding which variables and rates to randomize is a non-trivial problem, and the cost of running many instances of the model will limit the level of detail that can be incorporated in the individual sub-models. Uncertainty issues for operational oil spill models is discussed in Barker et al. (2020) and can be used to help guide approaches for assessing uncertainties in longer scale models capable of answering societal level questions.

7. Summary and Conclusions

The original four box diagram, used to initiate the conceptual modeling framework (Figure 1), was found to effectively serve the System Dynamics approach well as the initial organizing principle for oil spills. The CLD developed emphasized the components and interconnections of a conceptual model that can be used to evaluate the many questions related to damage assessments. The analysis of the CLD emphasized, at time scales of months to years, that the system naturally separates into two tiers: ocean environment and biological ecosystems versus socioeconomics and human health. The top tier requires spatial detail of physical and biological systems. The bottom tier is about human populations, and therefore needs to be disaggregated by individuals (or socioeconomic groups), economic sectors, and health aspects. These tiers therefore work in fundamentally different spaces. This difference in variable measurements may serve as a simplifying approach where the top tier processes (ocean environment and biological ecosystems), which are already interlinked through existing models serve as inputs to the lower tier processes (socioeconomics and health). Efforts are needed to develop a more fully integrated dynamic model that simulates the linkages of the lower tier processes of socioeconomics and human health and one that also accepts, as input, the outputs from the upper tier processes of ocean environment and biological ecosystems.

The CLD also demonstrated that at the much longer decadal time scales, governance or regulatory processes influence the probabilities and possible scenarios associated with future spills. These regulatory processes, whether associated with shoreline development or oil drilling permitting and procedures, represent the primary feedback loops from socioeconomics and human health domains back towards ocean environment and biological ecosystems. In order to incorporate the entire system inclusive of regulatory processes, these longer scale feedback processes should be captured through a secondary set of models (or possibly boundary conditions) that consider changing laws and regulations to mitigate damages from oil spills and which consider levels of oil spill preparation, response, and recovery planning capacity. The consideration of boundary conditions for processes that function at decadal time scales would depend upon whether governance and preparation processes remain constant during the target periods for assessing impacts to socioeconomics and human health.

Improved long-term outcomes would demonstrate the value of integrating models into the decision-making process. Even without quantitation, the CLD can serve as a platform for managers to have a “big picture” view on oil spill effects, and consider indirect effects, which might not have been considered otherwise. For example, the CLD emphasizes that short-term oil-based toxin inputs to the system can have long lasting repercussions on the community as shown by the linkages. Ideally, a fully developed System Dynamics model should be available to evaluate possible long-term outcomes from shorter-term decisions for immediate mitigation. Ultimately there would be utility to linking short-term operational models (Barker et al. 2020) to a System Dynamics model designed to evaluate long-term societal outcomes inclusive of socioeconomics and health, the beginnings of which are described herein. Practical application of the findings and insights of this model is critical as its application supports multiple aspects of human communities.

This exercise would not have been possible without the input from experts and stakeholders (See supplemental text for list). The work emphasized the importance of building a professional network (Rouwette et al. 2002), that can be used to reconfirm key stakeholder questions at the time of a disaster (Walker et al. 2015, Bostrom et al. 2015) and refine linkages since the CLD is not necessarily static. It will change over time as knowledge is gained, and as society structure and values change. These changes can only be implemented in any model through continuous input and updates developed from those with expertise and interests in the impact of oil spills and other disasters. Although emerging from DWH and its focus in the GoM, results from this synthesis study are expected to be valuable for other marine environments that are subject to oil exploration and to other potential contamination events (e.g., harmful algal blooms, floods, chemical plant releases along the coast). The known interlinkages and the knowledge gaps identified through this effort have applicability to the development of fully integrated models capable of assessing holistic societal impacts that incorporate knowledge from ocean environment, biological ecosystems, socioeconomics and human health.

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Table 1: Target audiences engaged by GoM Sea Grant Oil Spill Science Outreach Team

Elected officials	Port and harbor employees
Emergency responders or managers	Tribal communities
Environmental non-profit staff members	Health professionals
Fishers (commercial, for-hire, recreational)	Tourism staff
Natural resource managers	University and college researchers
Oil industry	Sea Grant Extension and GoMRI outreach specialists

Table 2: List of Selected Stakeholder Questions from within Each Knowledge Domain and Consolidated by the GoM Sea Grant Oil Spill Science Outreach Team

Ocean Environment

1. Where did the oil go? What are the biggest deposits today?
2. How long did the oil take to reach the deposits?
3. Which beaches are affected?
4. How much is buried on the sea floor?
5. Could a big storm bring the oil on the sea floor up into the water column and start the process all over?
6. Did any oil make it into the organisms living in the water column or on the seafloor?
7. What happens to the oil over time when dispersants are applied?
8. What are the natural organisms that decompose hydrocarbons (crude oil) and how can we increase this process?
9. Was it possible to track the oil with numerical models? If not, can we do it better now?

Biological Ecosystems

1. Within ecosystems there were 48 questions that related to the following topics
    a. Food webs
    b. Benthic/pelagic/infaunal organisms
    c. Mammals
    d. Juvenile fishes
    e. Inshore/deep-sea habitats
    f. Sub-lethal effects
    g. Dispersants
    h. Fisheries and stock assessment

   Examples of specific questions include
    A. We need to solve the [tradeoff] of short-term effects of oil vs. long recovery [to better understand] actions like dispersant use that may cause short-term negative effects but are beneficial in the long term.
    B. How does food web and ecosystem connectivity affect injury assessment?

Socioeconomics

1. How can vulnerable communities with subsistence economy become resilient to incessant oil spillages?
2. Very interested in impacts to the economy and infrastructure.
3. What are the long-term expert consensus prognosis and predictions for any continued significant health risk or resource effects or community structure changes in the affected areas?
4. What was done most effectively to ensure that the economic concerns of those impacted were met in a sustainable fashion?
5. Short and long-term economic impacts of the BP oil spill on GoM fisheries.
6. Socioeconomic impacts of spill (true costs of closures, lost tourism and fishing income, etc.).
7. Economic impact on areas due to habitat destruction.
8. Impact on coastal communities.

Human Health

1. How are humans affected by eating contaminated fish?
2. Effects of airborne dispersants on community health.
3. Inhalation hazards from aerosol oil spray or burning of oil.
4. What are the potential health risks for the people responding for clean ups?
5. Health impacts on anglers, people working during/in the area of the spill.
6. What health impacts did the spill have on residents?
7. Dispersant effects on human/animal health.
8. Impacts of stress to mental health.
9. Are our citizens safe and healthy living in a region where "big oil" exists?

Table 3: List of Representative Models and Summary of Their Capabilities for Simulating Ocean Environment, Ecosystem, Socioeconomic, and Human Health Impacts of an Oil Spill. For a more complete list please see Ainsworth et al. 202X.

Model Name	**Description**	**Reference**
Ocean Environment - **Operational** Ocean Current Models Relevant to GoM		
HYCOM	HYbrid Coordinate Ocean Model. Oceanic hydrodynamic and general circulation model. Global ocean circulation model.	Chassignet et al. (2007, 2009)
HYCOM (GoM 1/25)	HYbrid Coordinate Ocean Model. Oceanic hydrodynamic and general circulation model. GoM regional model at $1/25^0$ resolution (Naval Research Lab – SSC)	Prasad and Hogan (2007)
HYCOM (GoM 1/50)	HYbrid Coordinate Ocean Model. Oceanic hydrodynamic and general circulation model. GoM regional model at $1/50^0$ resolution (Univ. of Miami)	Le Hénaff and Kourafalou (2016)
HYCOM (FKEYS)	HYbrid Coordinate Ocean Model. Oceanic hydrodynamic and general circulation model. Southeastern Gulfof Mexico and Straits of Florida regional model at $1/100^0$ resolution (Univ. of Miami)	Kourafalou and Kang (2012)
TBCOM	Tampa Bay Coastal Ocean Model (TBCOM) Nowcast/Forecast System	Chen et al. (2018, 2019)
WFCOM	West Florida Coastal Ocean Model (WFCOM) Nowcast/Forecast System	Zheng and Weisberg (2012), Weisberg et al. (2014,2016)
Ocean Environment - **Integrated** Models		
CMS	Connectivity Modeling System. Probabilistic Lagrangian model platform that tracks the movement of biotic and abiotic particles.	Paris et al. (2013), Faillettaz et al. (202X)
oil-CMS	CMS Module that tracks the oil concentration and fate from the deep-sea blowout to the sea surface with an ensemble of boundary conditions for gas to oil ration (GOR), dispersant to oil ratio (DOR), and initial droplet size distribution (iDSD). Couples NOGAPS winds and NAVGEM irradiance for photooxidation.	Paris et al. (2012), Perlin et al. (2020), Vaz et al. (2020)
oil-CMS-TAMOC	Couples oil-CMS with the Texas A&M Oil Spill Calculator (TAMOC) that provides equation of state of oil and gas in the nearfield plume and their time-variable droplet and bubble size distributions.	Vaz et al. (2019)
COAWST-ROMS	Coupled Ocean-Atmosphere-Wave-Sediment Transport - Regional Ocean Modeling Systems. Oceanic hydrodynamic and general circulation model.	Warner et al. (2010)
DwH Oil Spill Trajectory Model	Lagrangian trajectory modeling system in rapid response to the *Deepwater Horizon* oil spill that combines satellite-inferred oil slicks with an ensemble of six different ocean circulation models.	Liu et al. (2011a,b,c), Weisberg et al. (2011)
GNOME	General NOAA Operational Modeling Environment. Oil transport model with fate capabilities that include dissolution and evaporation.	Beegle-Krause (2001), NOAA (2014)
MITgcm-spoil	MITgcm ocean and atmospheric model with a multiphase package called 'spoil'. Simulates a nearfield multiphase plume.	Fabregat et al. (2016, 2017), Deremble (2016)
UWIN-CM	Unified Wave Interface – Coupled Model, coupled atmosphere-wave-ocean-land model for prediction of transport, weathering, mixing, and coastal impacts.	Chen et al. (2013), Chen and Curcic (2016) Curcic et al. 2016

Table 3 (continued)

Model Name	Description	Reference
Ocean Environment - Integrated Models (continued)		
NRDAM/CME	Natural Resource Damage Assessment Model for Coastal and Marine Environments. Oil transport and fate, biological effects, and economic damages model for use in simplified natural resource damage assessments.	Reed et al. (1989), French et al. (1996)
OSCAR	Oil Spill Contingency And Response. Oil transport and fate model	Reed et al. (2000)
SIMAP	Spill Impact Model Application Package. Proprietary model that evaluates oil transport and fate; environmental resource exposures; toxic effects; fish, invertebrate and wildlife mortalities; lower trophic level production losses, food web losses; and population losses of wildlife species. Compensatory restoration scaling based on production gains and resource equivalency analysis (REA)	French-McCay et al. (2019)
Biological Ecosystems		
Atlantis	Modular modeling framework that simulates food webs and capable of evaluating climate scenarios, human impacts on the environment including fisheries, changes in land use, non-point source pollution, and the effect of wind and wave farms. Applied to GoM fisheries.	Fulton et al. (2005), Ainsworth et al. (2015, 2018)
oil-CMS-Atlantis	Couples CMS oil Module with Atlantis model to simulate biomass loss and recovery.	Ainsworth et al. (2018), Berenshtein et al. (2020a)
CSOMIO	Consortium for Simulation of Oil-Microbial Interactions in the Ocean. Nearfield and far-field oil transport and fate, including sediment transport and an emphasis on microbial processes including marine snow and enzymatic processes and evolution of microbial populations through a genomics functional group model. Couples COAWST-ROMS and GENOME.	Dukhovskoy et al. (2020)
DEEPEND	Provides new data for tracking water column organismal abundance and biomass over time (2010-2029) and quantifying vertical connections in ecosystem processes.	Hopkins et al. (1996), Sutton et al. (2017)
EwE	Ecopath with Ecosim models the marine food-web comprising major clades of marine organisms using a mass balance approach. The model simulates marine fishes, birds, reptiles, invertebrates, and mammals allowing for a better understanding of the complex dynamics occurring in the marine ecosystem. Can be used to evaluate policies.	Christensen et al. (1992, 2004)
GENOME	Genome-based EmergeNt Ocean Microbial Ecosystem Model. Simulates the microbial genes responsible for different metabolic functions, including hydrocarbon degradation.	Coles et al. (2017)
GoMex-ECOTRAN	Vertically resolved food web model for the oceanic north central section of the GoM. Expands upon the Ecopath model by simulating vertical migration of organisms, detritus sinking, and physical mixing of nutrients.	Steele and Ruzicka (2011)

Table 3 (continued)

Model Name	Description	Reference
Socioeconomics		
Atlantis and Input-output Analysis (IMPLAN)	Used output from Atlantis model to evaluate temporal distribution of changes in commercial species catch by species and recreational fishing efforts and used this to estimate economic impacts for the northern GoM region.	Court et al. (2019)
oil-CMS-Fisheries	oil-CMS computes fisheries closure based on toxic oil concentration and couples a fisheries socioeconomics module that estimated vulnerability of impacted fishing areas and counties.	Berenshtein et al. (2019, 2020b)
Gulf STREAM	GoM Space-Time Regional Economic Analysis Model. Proposed model that will forecast economic impacts associated with trends and variability in living and coastal marine resources.	Court, C.D., personal communication
OECM	Offshore Environmental Cost Model. Calculates the environmental and social costs resulting from the impact of activities associated with Outer Continental Shelf oil production. Evaluates six environmental and social cost categories: air quality, ecological, recreation, property values, subsistence harvests, and commercial fisheries. Used by the Bureau Ocean Energy Management to estimate the impacts from routine activities.	BOEM (2016)
Travel cost method and Input-output Analysis (IMPLAN)	Economic impacts of cancelled recreational trips to NW Florida after the DWH oil spill.	Court et al. (2017)
Human Health		
Bayesian model	A Bayesian hierarchical linear model was developed to estimate exposures to specific volatile oil components (benzene, toluene, ethylbenzene, xylene, and hexane) to oil drill workers charged with drilling a relief well.	Groth et al. (2017)
BEACHES	Beach Exposure and Child Health Study. Risk assessment platform that uses Monte Carlo simulations to evaluate chemical concentration distributions and child activities to estimate probabilities of physical health outcomes.	Black et al. (2016)
Resilience Activation Conceptual Framework	Analysis of multiple observational disaster cohorts, supplemented with hierarchical secondary data on hazards, risks, infrastructure, vulnerability, and resiliency. Used to develop Z scores as measures of resiliency.	Abramson et al. (2015)
DPSERH	Disaster-Pressure State-Ecosystem Services-Response-Health Model. Conceptual non-quantitative model that evaluates the link between disasters and human physical and mental health, including allostatic load.	Sandifer et al. (2017)

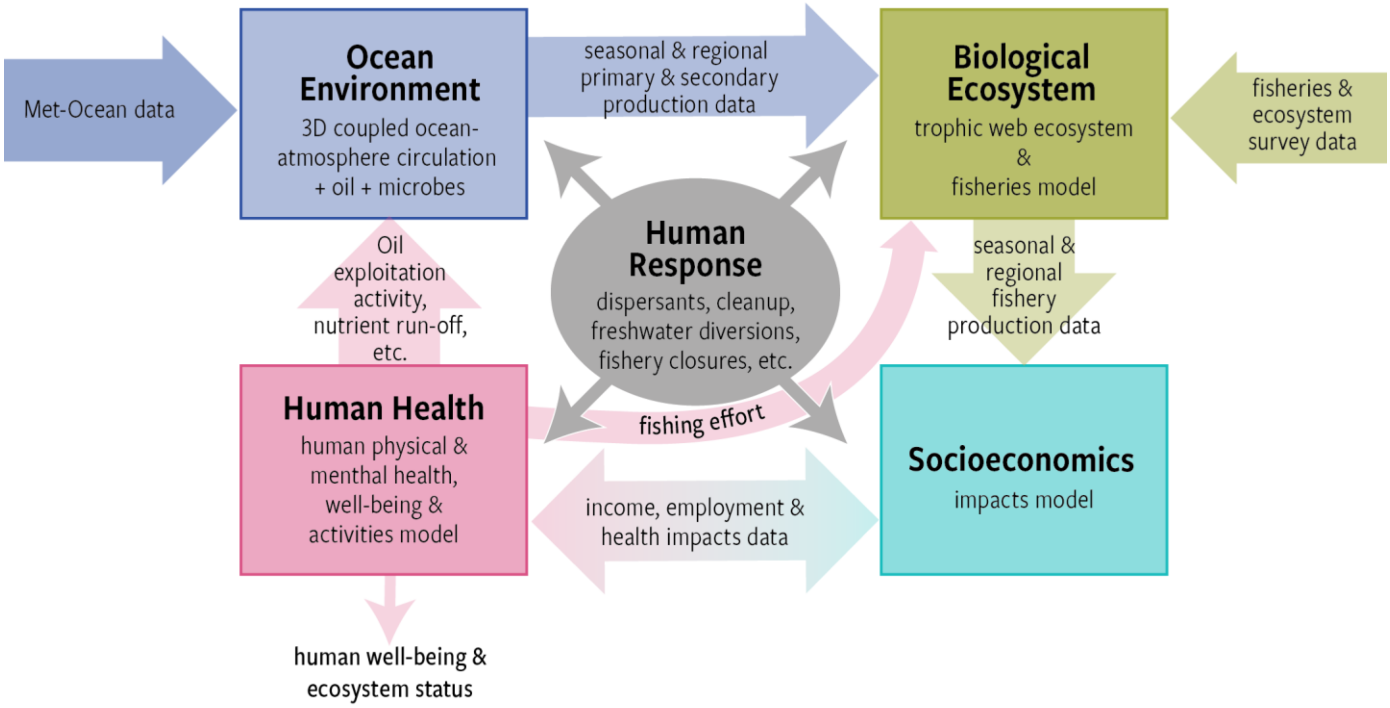

Figure 1. Integrated model structure of the four knowledge domains that were used to first address key stakeholder and societal questions pertaining to oil spill science, and secondly serve as a basis to develop the Causal Loop Diagram (see Figure 2).

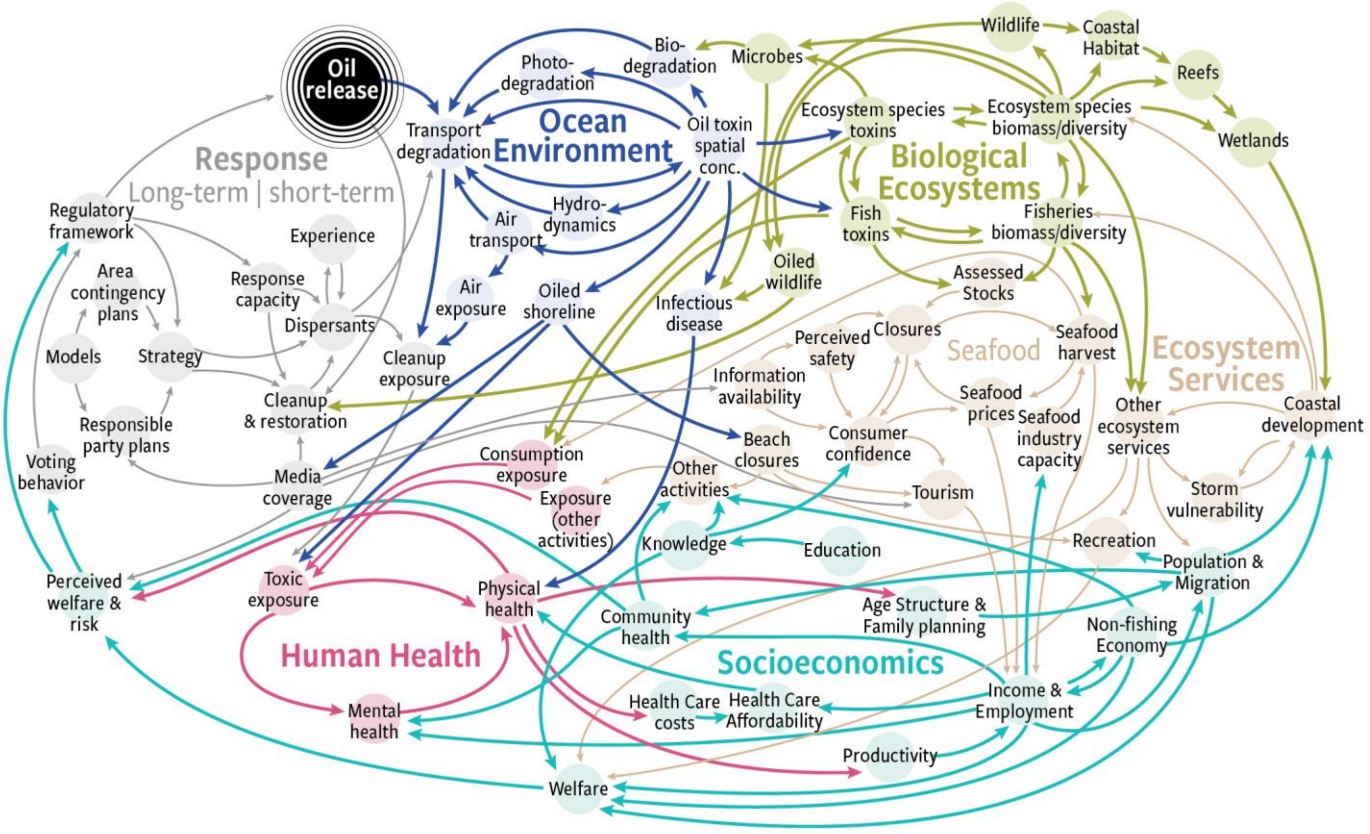

Figure 2. Causal Loop Diagram (CLD) for Conceptual System Structure for Evaluating Oil Spill Impacts. This diagram is intended to be of general use describing the interlinkages of oil spills, although DWH was the primary example used in developing this diagram.

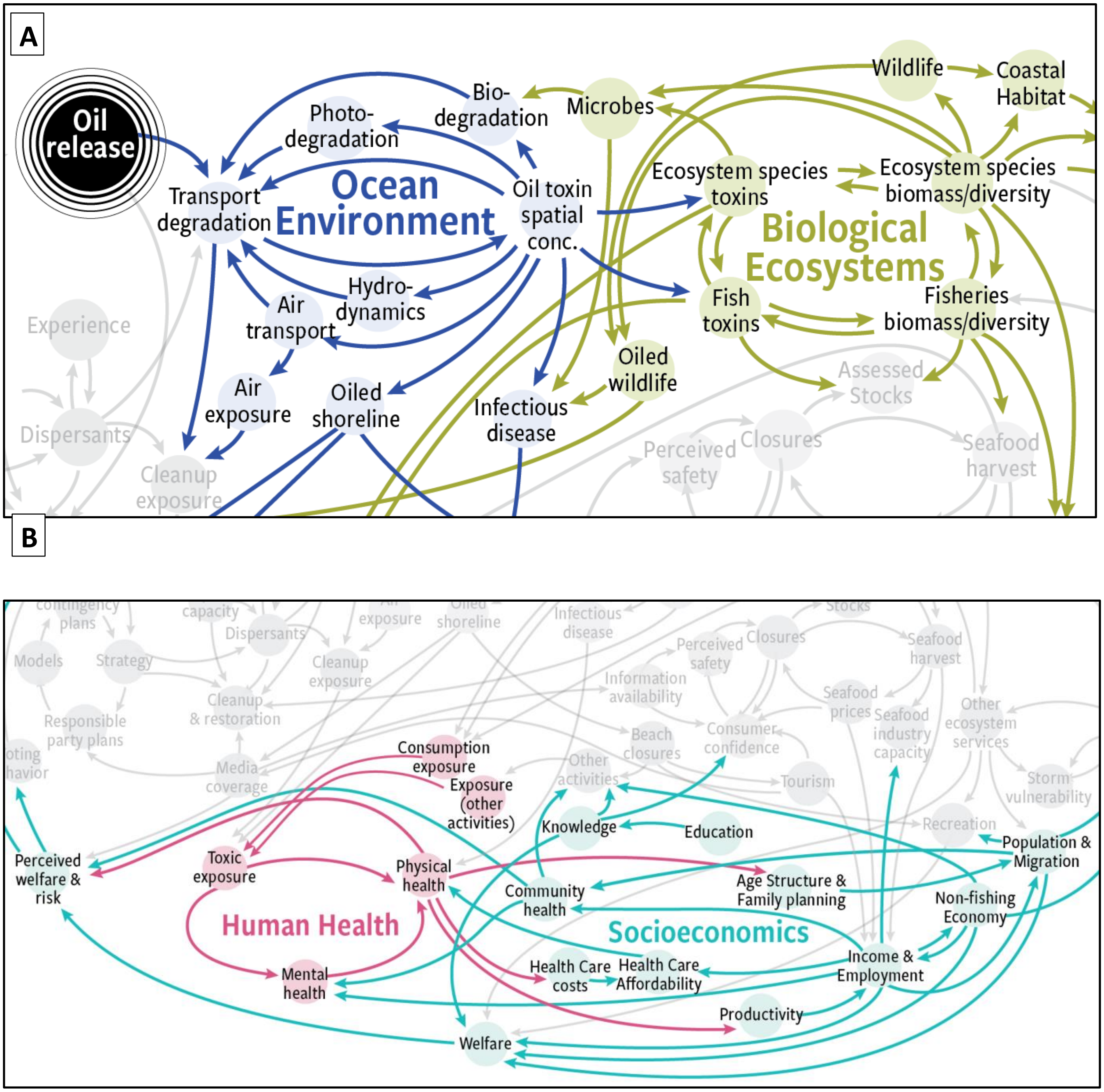

Figure 3: Evaluation of primary feedback loops within and between domains identified from expert group assessments. Upper panel, 3A, emphasizes the main causal consequences of oil spill damage to the ocean environment (blue) and biological ecosystems (green). Lower panel, 3B, emphasizes causal consequences of oil spill damage to the socioeconomics and human health systems (teal and pink) with ultimate impacts to community welfare. Background shows portion of the full causal loop diagram.

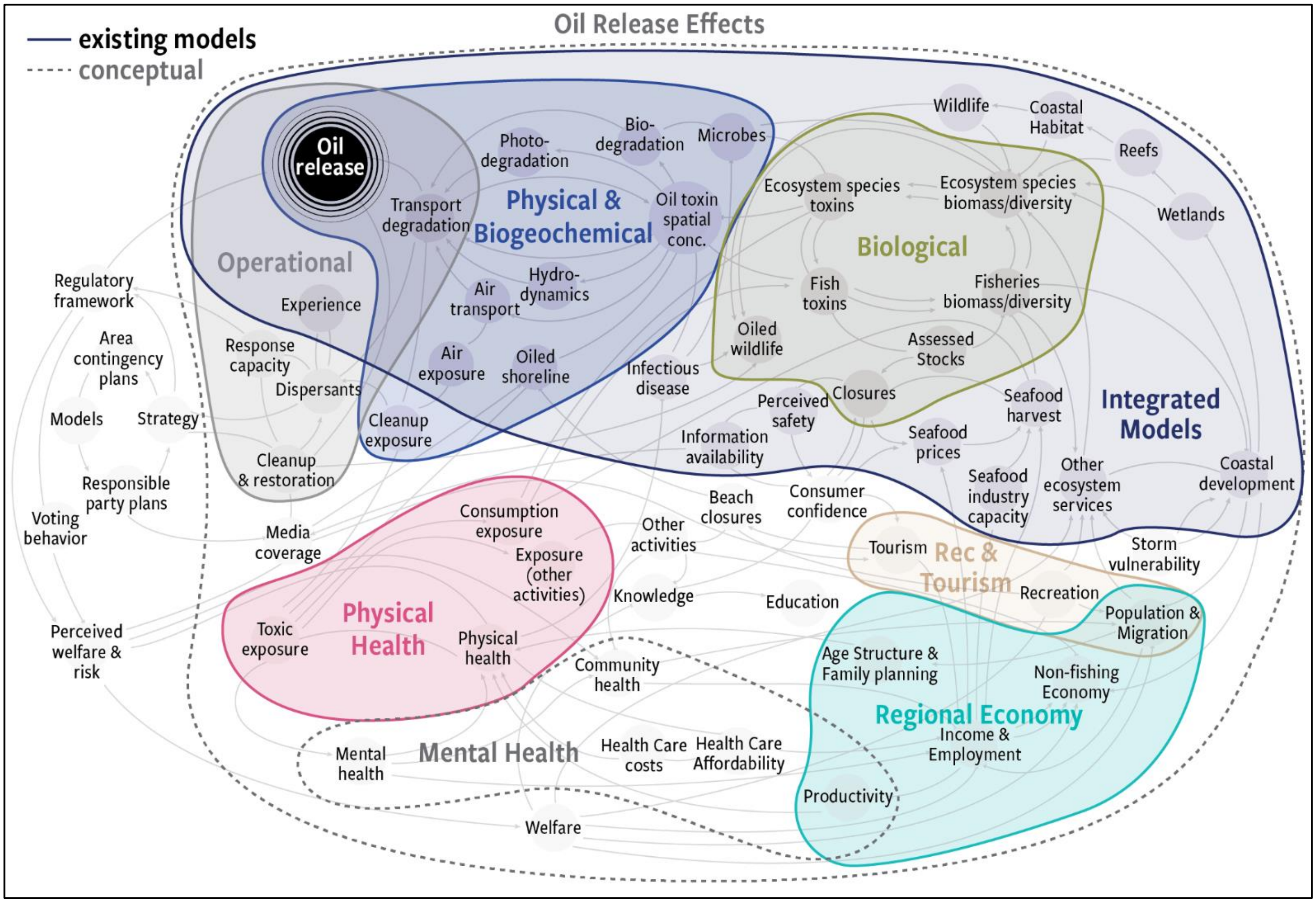

Figure 4. The Causal Loop Diagram with the superimposition of existing models. Blue and green shapes correspond to open source quantitative models that are currently available. Light purple shape corresponds to the few models that integrate the ocean environment, biological ecosystems and some components of the socio-economics domains. The pink, tan and teal shapes show the realm of existing quantitative model frameworks. These quantitative frameworks are yet to be fully developed for integration with the more developed oceanographic and ecosystem models. Dotted shapes correspond to existing conceptual models that are non-quantitative.