Supporting information for

Minimizing risks from spilled oil to ecosystem services using influence diagrams: The *Deepwater Horizon* spill response

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19 pages, 11 figures

Additional Information

For: Carriger and Barron, Minimizing risks from spilled oil to ecosystem services using influence diagrams: The *Deepwater Horizon* spill response

Although both had differing development trajectories (Pearl 2005), influence diagrams (IDs) can be regarded as an extension of Bayesian belief networks (BBNs) (Shachter 2007). Whereas the latter only contain nodes related to random variables, IDs contain nodes related to decisions and the utility for evaluating the potential decision outcomes. Both modeling environments have a qualitative and a quantitative component. The qualitative component consists of the directed acyclic graph containing nodes (for random variables, value scales, decisions) and their relationships. The quantitative component consists of the conditional probabilities that measure the uncertainty in the relationships between nodes and the value scales representing the preferences for outcomes.

Consider an initial diagram to examine the influence of natural attenuation through biodegradation of offshore oil and the impact of offshore oil on ecological features of concern. Figure S1 displays an initial structuring of this problem with three chance nodes. Relationships between nodes are explained by the presence of arcs. Arcs are the arrows in Figure S1 that indicate a probabilistic dependency such as a cause and effect or other conditional relationship between two chance nodes.

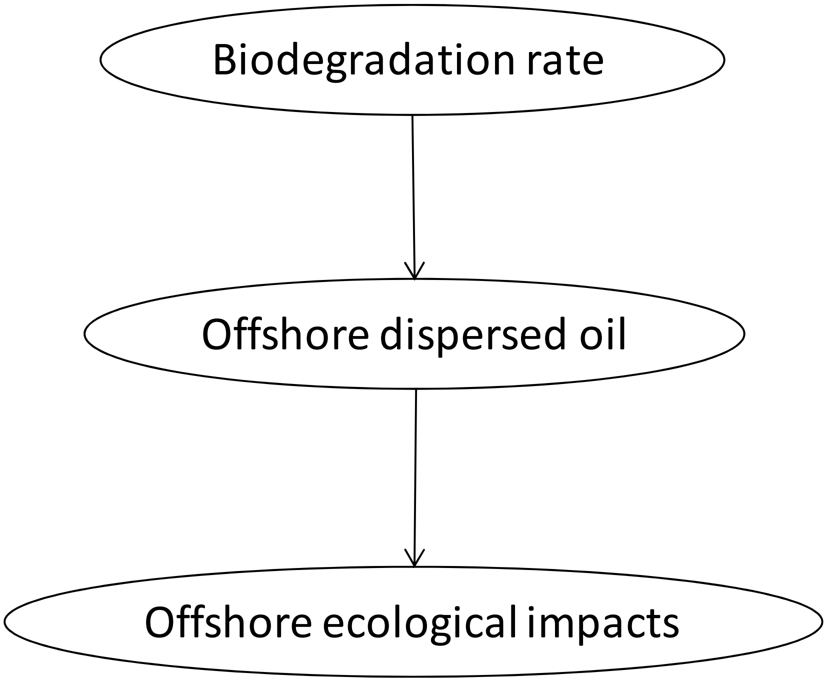

Figure S1. Directed acyclic graph displaying the conditional relationships between biodegradation rate on offshore dispersed oil, and offshore dispersed oil on offshore ecological impacts.

A conditional independence relationship is exhibited in Figure S1. The effects of biodegradation only cause offshore ecological impacts through changes on offshore dispersed oil. If we know the value of offshore dispersed oil for certain, than nothing about biodegradation rates will give additional information on offshore ecological impacts. This relationship is known as a serial connection (Kjaerulff and Madsen 2010). Additional information about conditional independence in BBN structures can be found in Korb and Nicholson (2011). The arcs between the chance nodes in Figure S1 contain probabilistic relationships for each state of the child node dependent on each state of the parents. The absence of an arc between any two chance nodes indicates conditional independence between the variables given the additional relationships in the graph (Kjaerulff and Madsen 2010).

Nodes in an ID are used to represent random variables, decisions, or the utility of outcomes for a problem domain. In Figure S2, decision and utility nodes are added, effectively turning the BBN into an ID. Decision nodes are discrete and represent the actions available to a decision-maker that are under her control. The utility nodes specify the value scale for the attributes important to the decisions. An arc entering a decision node does not indicate that the decision will be probabilistically influenced by the preceding decision or chance node but explicitly indicates that the information in the predecessor node is available before the successive decision is made and is known for certain (Clemen and Reilly 2001). If we knew the biodegradation rate prior to making our response decision, an informational arc can be drawn to the decision variable to indicate that. Utility nodes that have arcs entering from decision nodes or chance nodes contain functions that relate the value of outcomes to each of the states of the parent nodes. Arcs from decision nodes to chance nodes indicate some type of change on a variable dependent on a decision or series of decisions. The arc from the ecological impacts node to the utility node indicates that the value in the decision problem in Figure S2 is dependent on the change in offshore ecological impacts.

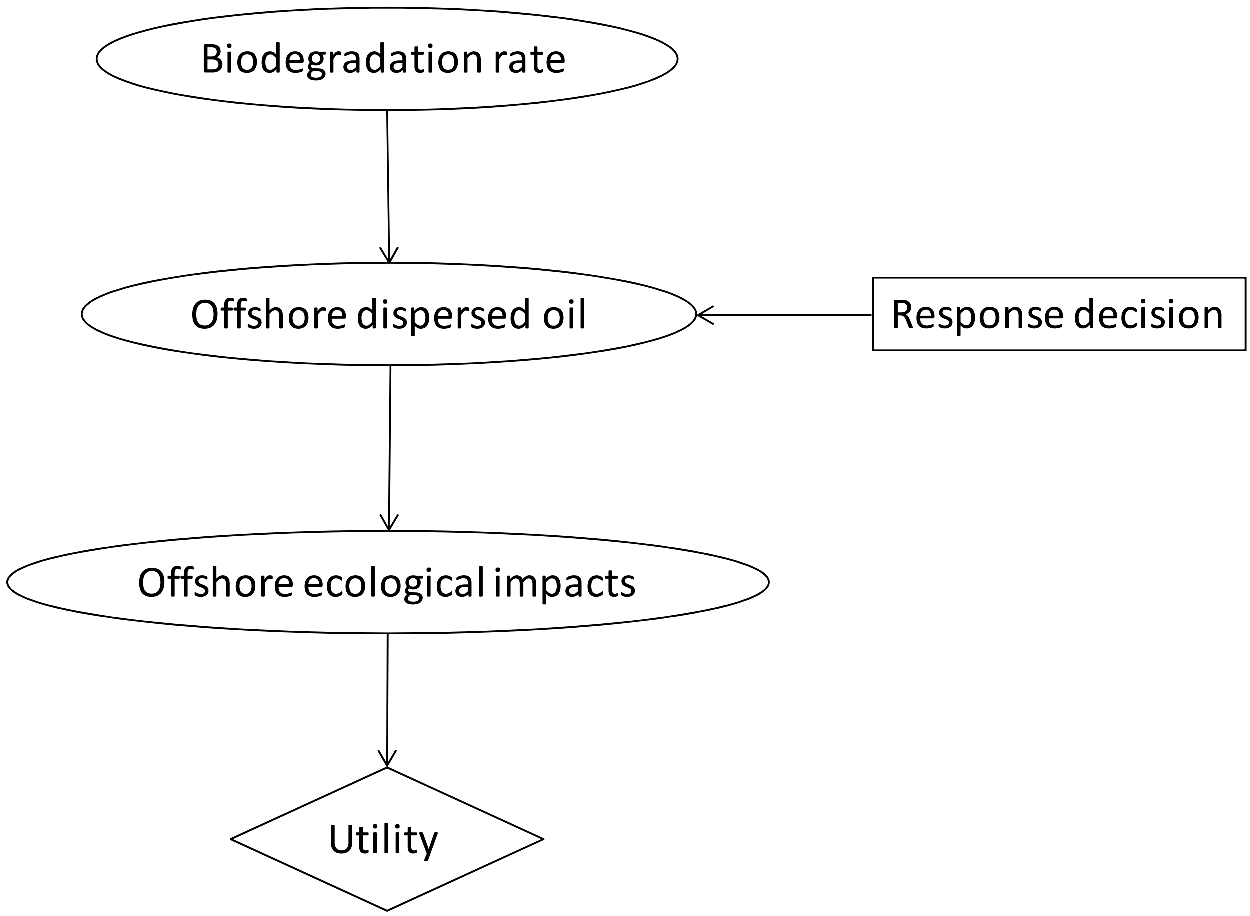

Figure S2. Relationship between risk management intervention responses on offshore dispersed oil and the utility gained from mitigating offshore ecological impacts.

In addition to identifying the variables in a problem, the states they can realize must be included in the nodes of an ID (Kjaerulff and Madsen 2010). A chance node will represent an exhaustive set of mutually exclusive events. The next step in the ID for Figure S2 is to determine these states for each of the variables. States are given next to each node in Figure S3. For continuous variables with categorical states, the states should be tied to explicit levels and discretization should be done carefully. The chance nodes representing continuous variables in the ID can be discretized as numerical ranges instead of categorical variables.

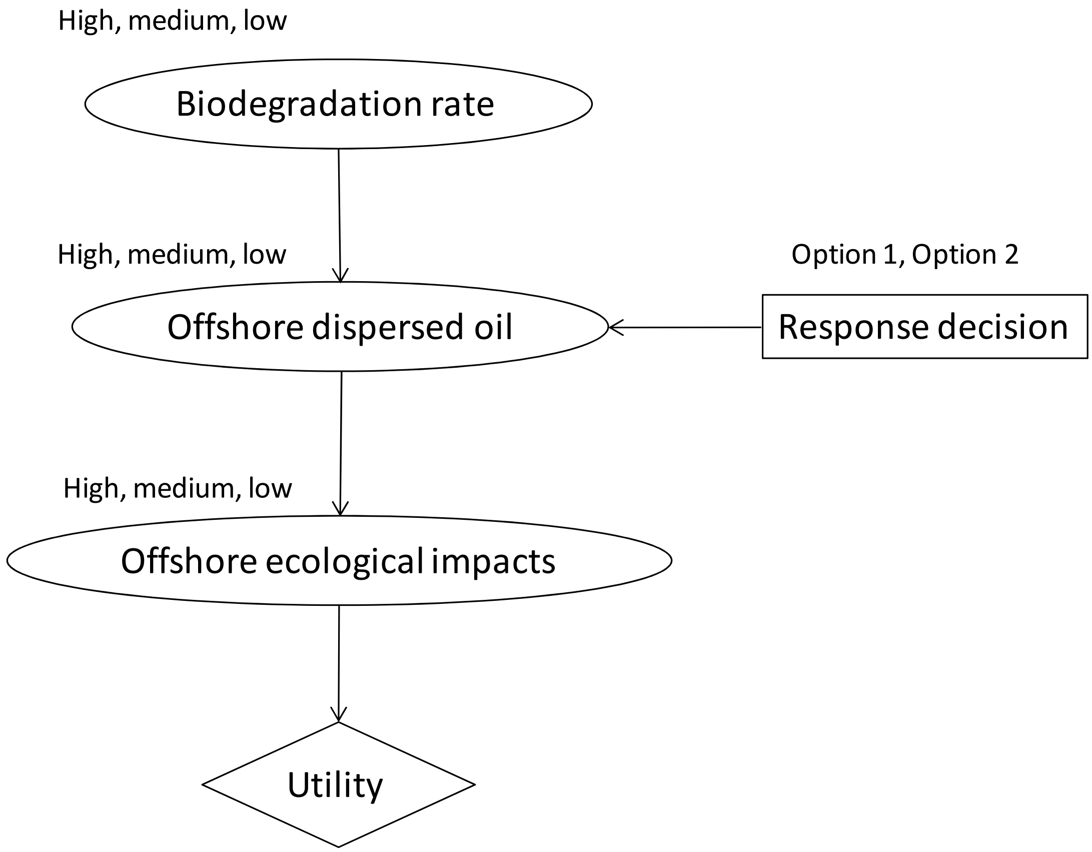

Figure S3. Decision and chance nodes with categorical states for examining the effectiveness of offshore response decisions in preventing offshore dispersed oil from causing ecological impacts.

The relationships between the variables are then quantified in Figure S4. A marginal prior probability distribution is given to biodegradation rate and conditional probabilities are specified for the offshore dispersed oil and offshore ecological impacts nodes. These conditional probabilities are indicated in the conditional probability tables next to each chance node. A table with utility values for each ecological impact outcome is used to measure the preferences for ecological impact changes. These utilities will be probability weighted by the likelihood of the different ecological impacts that might occur for each action. Evaluating the diagram in Figure S4 can be done using steps or procedures that solve the diagram such as through node absorption if the ID contains one utility node (Norsys 1997).

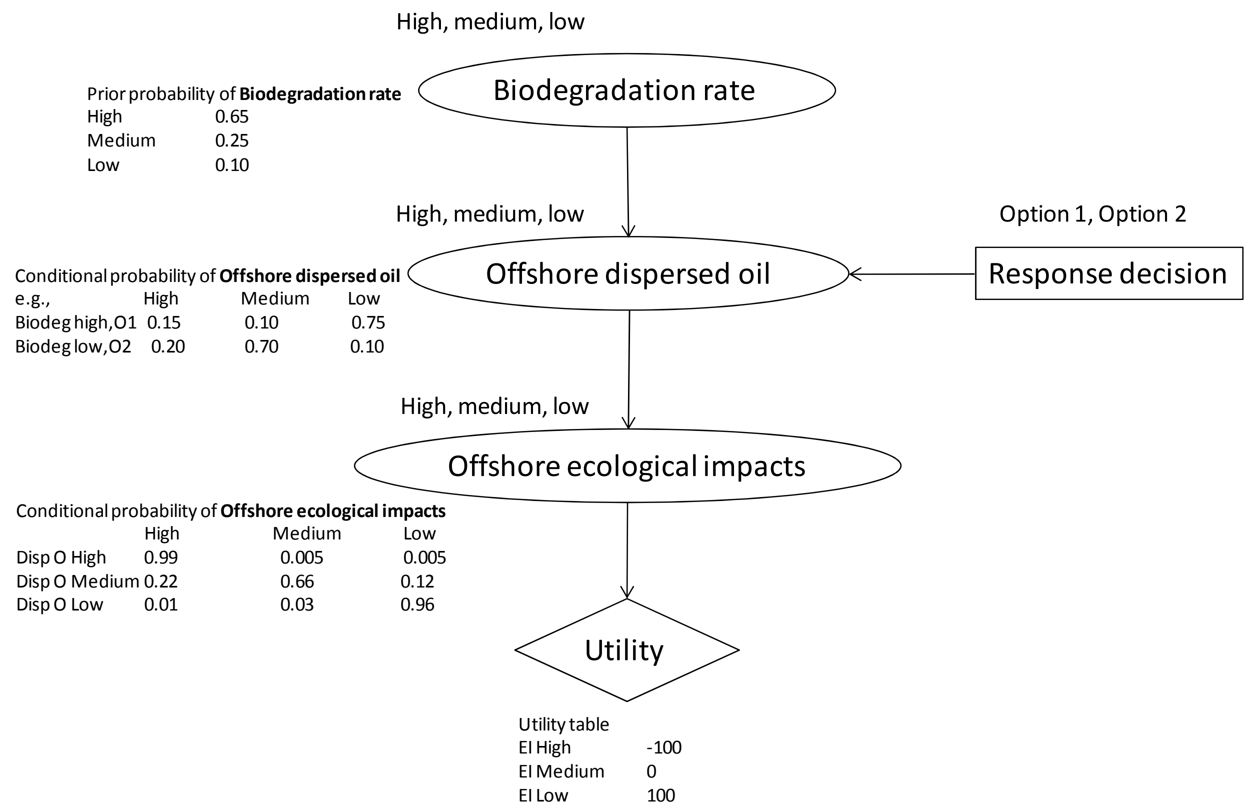

Figure S4. Example of a fully specified influence diagram with conditional probability relationships and utility values for outcomes due to offshore ecological impacts.

Once the model is properly structured, populated, and compiled, the ID can be solved by finding the decision(s) that maximize the expected utility in the utility node(s). We can also extract useful knowledge like the probability distributions for variables under different decision scenarios. This can be done in Netica^{TM} (Norsys 2010) through the examination of how inferences are modified based on different findings about states of the problem domain. Taking the model from Carriger and Barron (2011), a decision-maker or expert can examine scenarios or manually input observations in nodes and study how decision recommendations might change. The graphical nature of the model and its inference engine allow for easy updating.

The prior network (without any decisions or observed states indicated) is displayed in Figure S5. This network does not contain initial knowledge about which of the well release states is more likely. With this ID, the recommendation for the deep ocean response is to apply dispersants as indicated by the higher expected utility next to Deep dispersant application vs. No action. One can also examine the downstream node prior probabilities such as for potential offshore dispersed oil and onshore oil states. As indicated, the probabilities for lower oil states and lower ecological and ecological system service (ES) impacts increases as the oil potentially moves from the deep ocean to the offshore to the onshore region. Decision nodes have a temporal component such that any decision made in the past is known in the future and chance nodes can be connected to decision nodes to indicate that the information in that node is observed prior to the decision. Nothing from a decision window in the future can be observed by a prior decision (Shachter 2007). This can be observed in Figure S5 by the arrows connecting deep ocean to offshore and onshore decisions in a no forgetting sequence.

A second ID is shown in Figure S6 where the well release is observed to be off. The model recommends no action as the best response in the deep ocean so that was selected. Next the sea state was found to be calm-slight and offshore fishery closures were reported to be low. Once again, the higher expected utility indicates that no action is the best offshore response so that decision was selected. For the onshore decision, the trajectory was offshore and the final recommended decision was no action. As the node states and decisions were selected, changes to the probability distributions of other nodes were witnessed instantaneously. In this scenario, risks were almost always low but low offshore fisheries closures created greater risk to offshore ES impacts than would potentially occur to ES in the deep ocean and onshore regions.

In Figures S7-S11, the same ID is used but findings for the nodes are input in different combinations to examine how the ID can be used to make inferences and examine the recommended decisions in different scenarios. Figure S7 displays how updating the ID can be used to select decisions and examine impacts in more detail. In Figure S7, the well release is observed to be fully on. Based on expected utilities, the recommended decision for the deep ocean response is deep dispersant application. This is selected in Figure S8 and evidence is input for a rough sea state and no offshore fishery closures. In Figure S8, the recommended offshore response is no action. We can also examine what the recommended decisions are with different findings.

Figure S9 differs from Figure S8 in that an alternate scenario is displayed where offshore fishery closure is found to be high. In Figure S9, the recommended decision becomes surface dispersant application. This might alleviate some of the loss of ES from a high fishery closure in contrast to the no action recommendation in Figure S8 when no fishery closures occurred. Dispersant application offshore would be the most feasible action when sea state is rough which would hinder burning and mechanical recovery.

Figures S10 and S11 build on Figure S9 but with surface dispersants applied offshore. In Figure S10, the trajectory is observed to be offshore and the recommended decision is no action. The onshore impacts have a greater probability of being low prior to an onshore decision. In Figure S11, the trajectory is nearshore and the booming/berming response becomes the recommended decision. The resulting model has lower expected utilities than if the oil trajectory was offshore and the onshore ecological and ES impacts are higher. The onshore dispersed oil is predicted to be more likely to be high in comparison with surface slick, mousse, and tarballs.

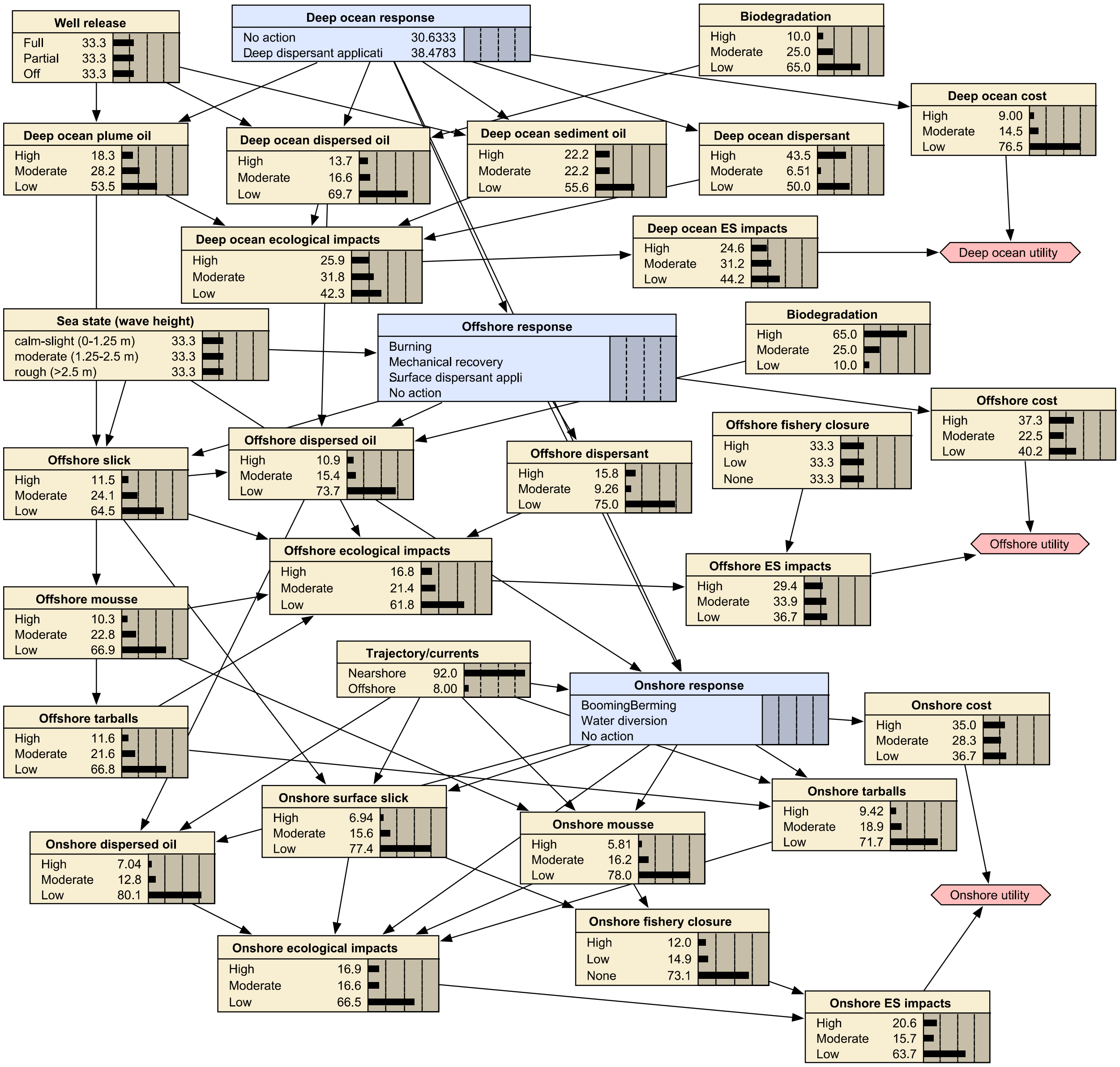

Figure S5. Initial influence diagram for the Deepwater Horizon oil spill.

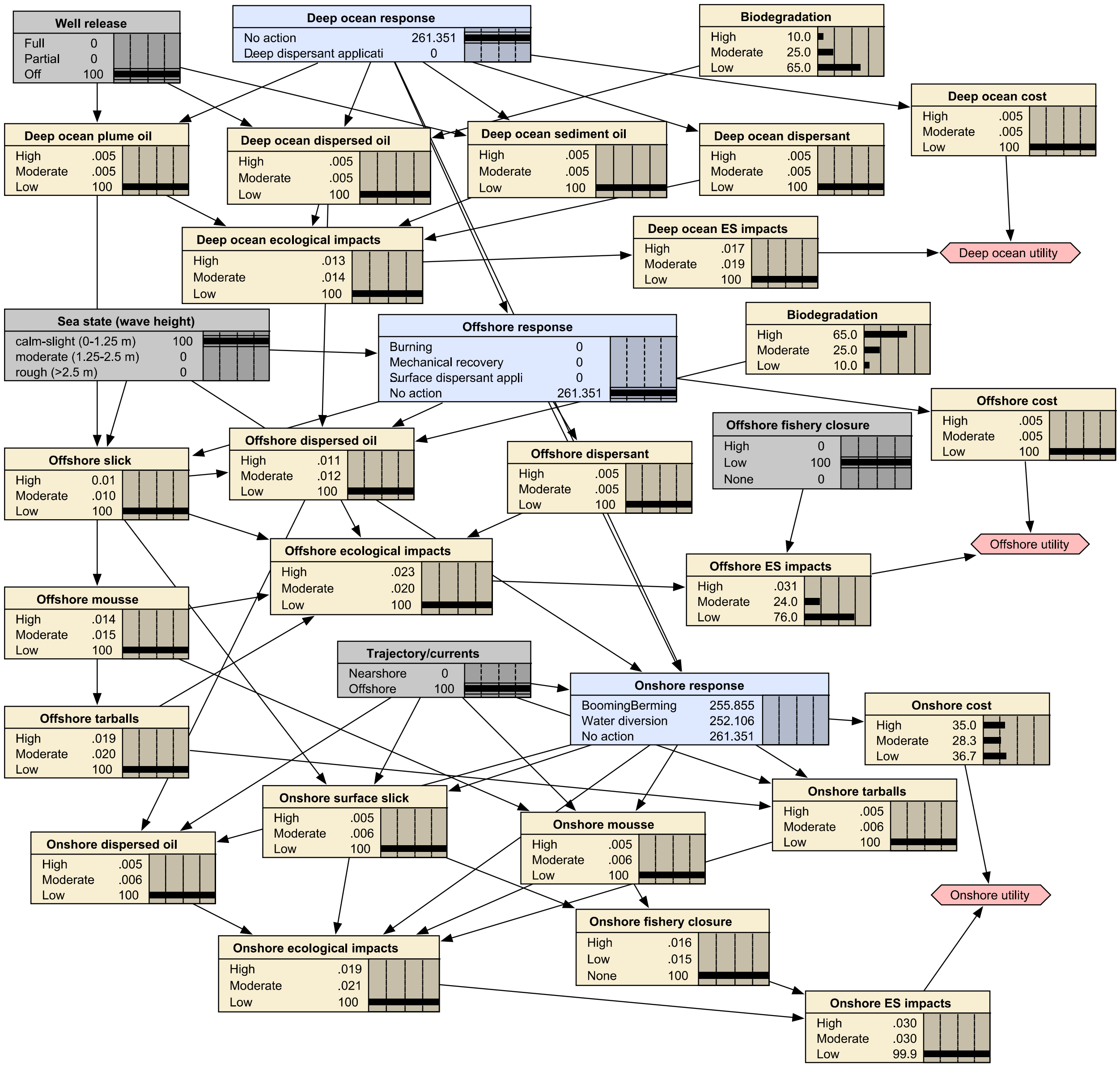

Figure S6. Influence diagram for the Deepwater Horizon oil spill displaying a decision scenario with the well release off.

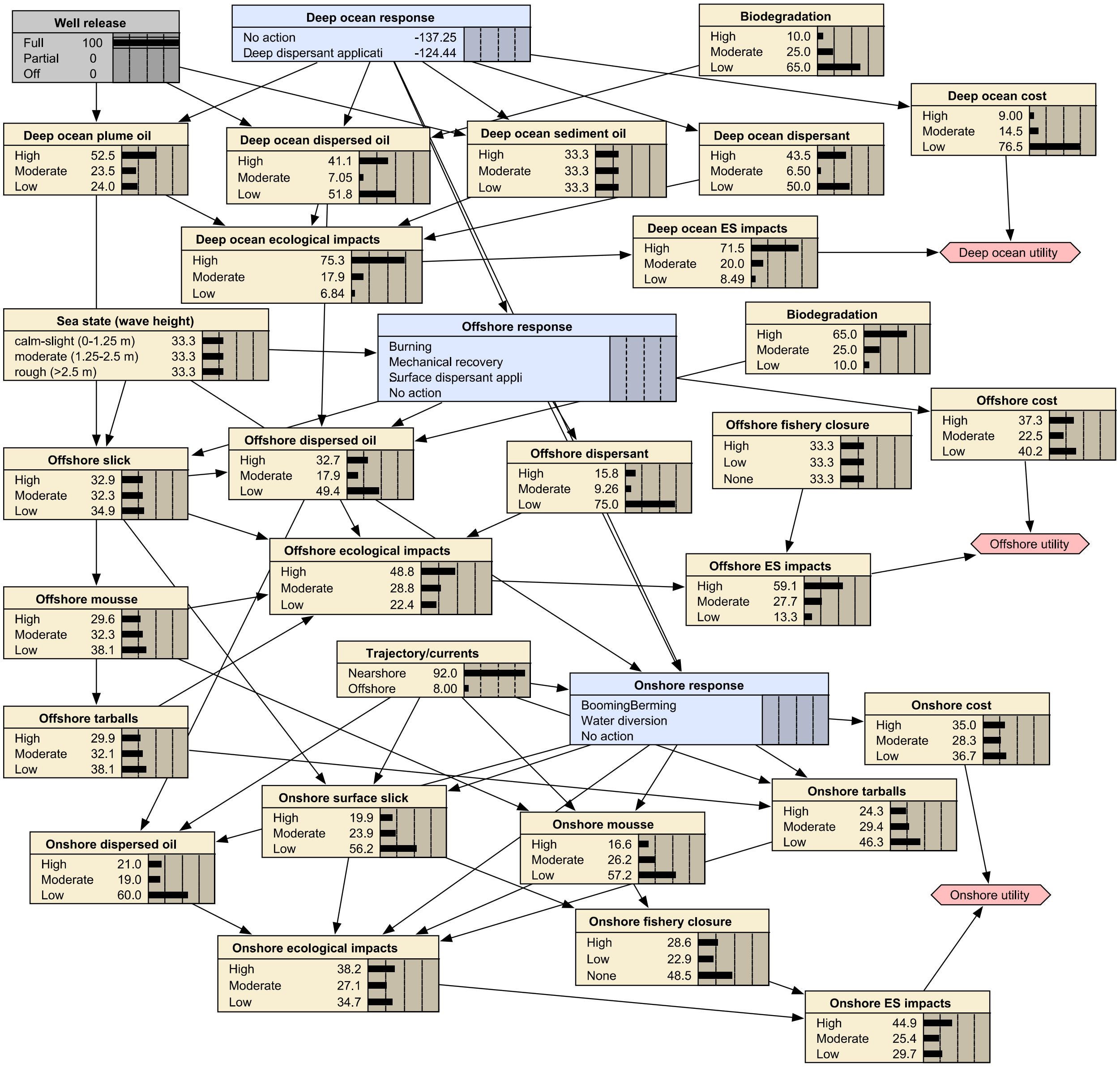

Figure S7. Influence diagram for the Deepwater Horizon oil spill displaying the deep ocean recommended response with the well release fully on.

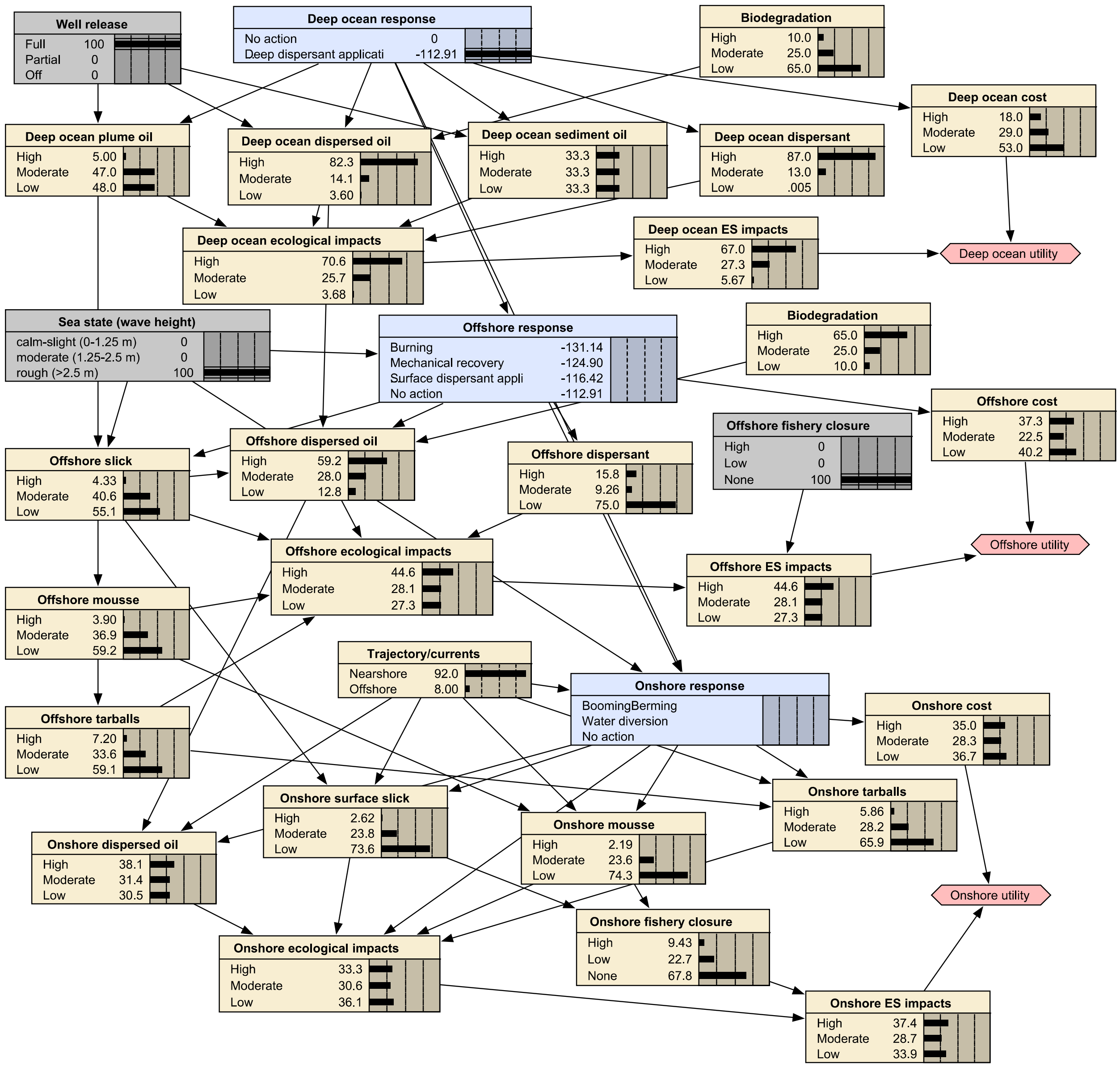

Figure S8. Influence diagram for the Deepwater Horizon oil spill with well fully on, deep dispersant application, rough sea state and no offshore fishery closure.

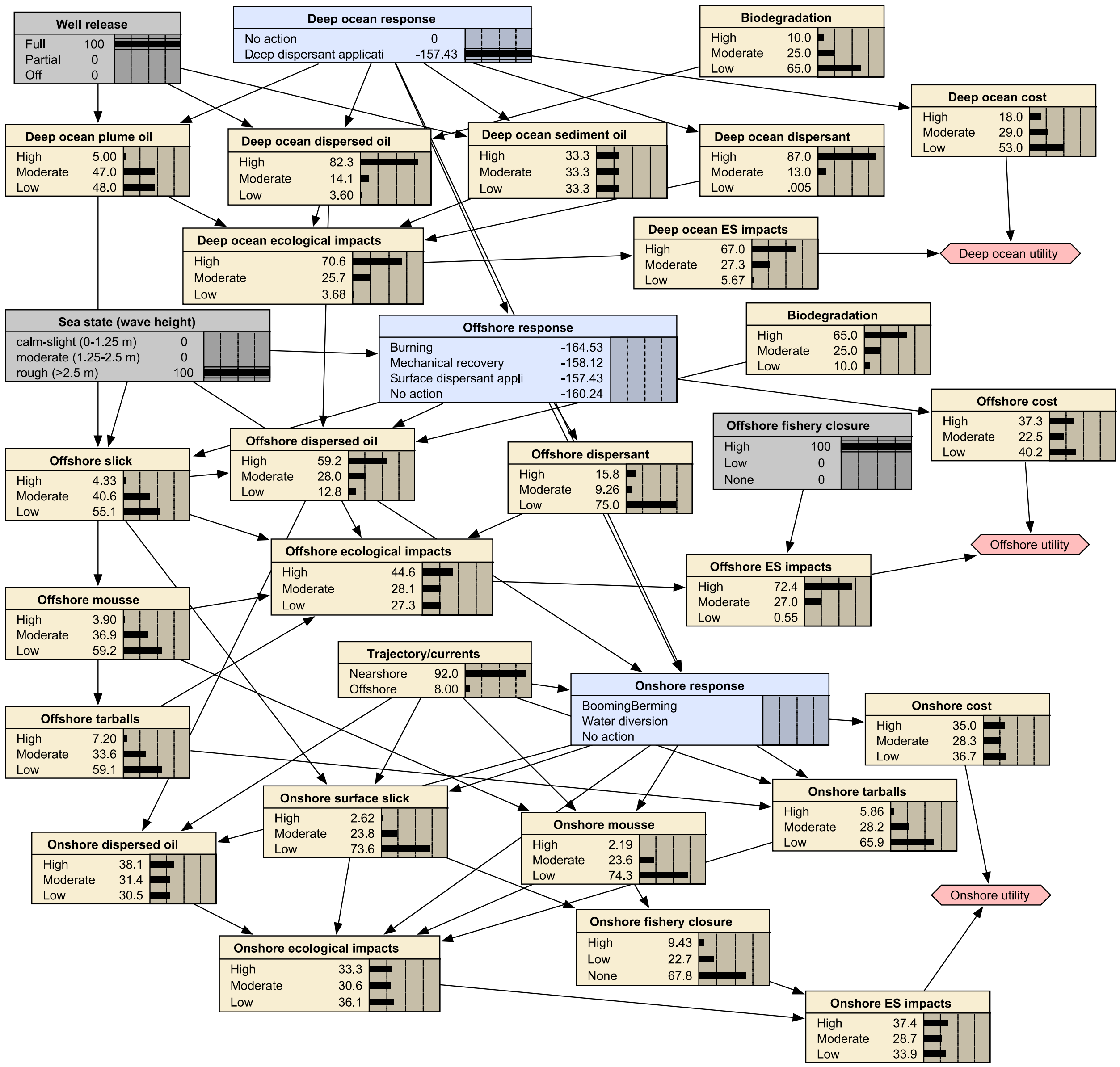

Figure S9. Influence diagram for the Deepwater Horizon oil spill with well fully on, deep dispersant application, rough sea state and high offshore fishery closure.

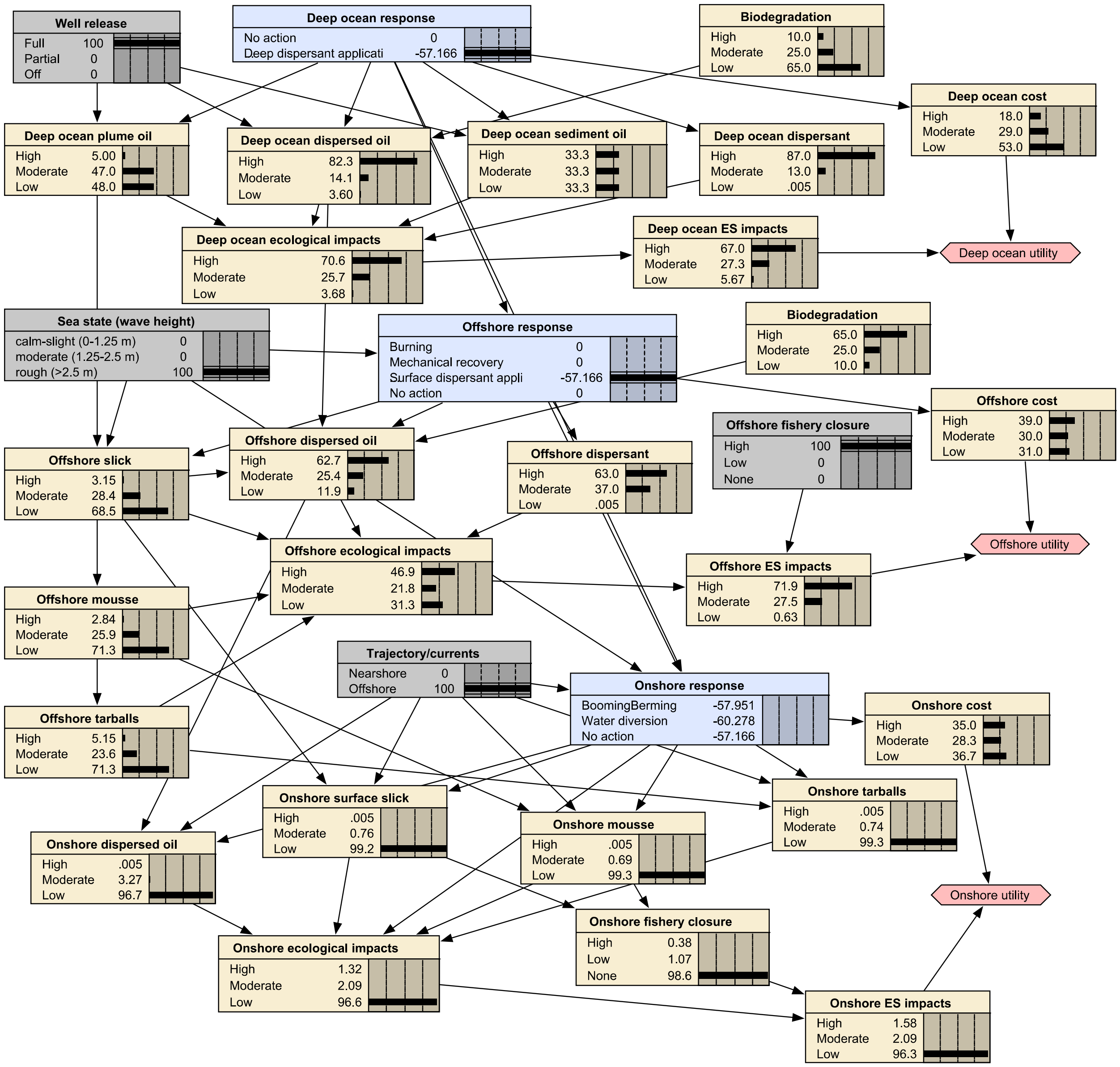

Figure S10. Influence diagram for the Deepwater Horizon oil spill with well fully on, deep dispersant application, rough sea state, high offshore fishery closure, offshore dispersant application, and offshore trajectory.

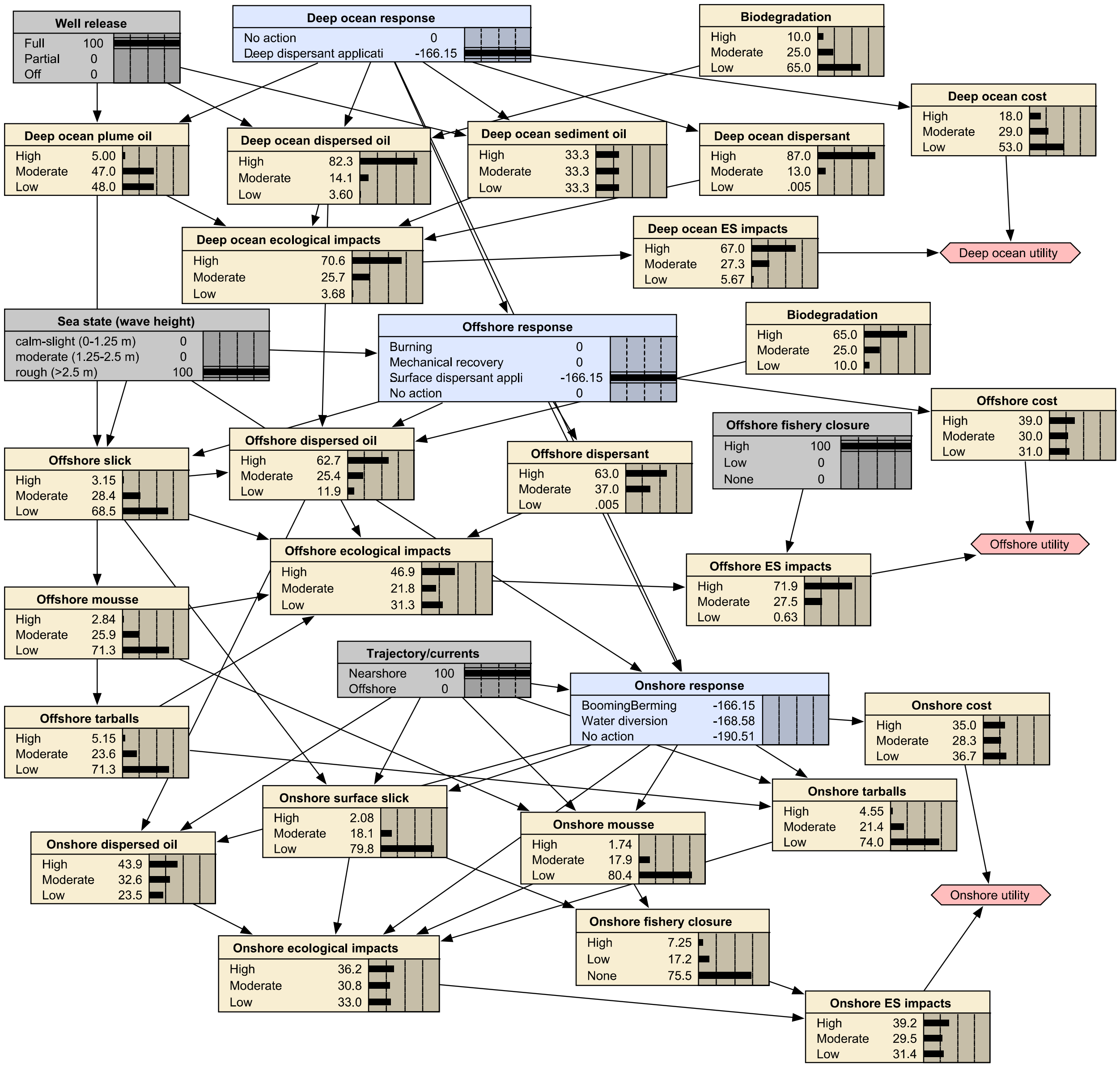

Figure S11. Influence diagram for the Deepwater Horizon oil spill with well fully on, deep dispersant application, rough sea state, high offshore fishery closure, offshore dispersant application, and nearshore trajectory.

In order to ensure that the nodes in a graph are proper representations of the problem at hand, the clarity test should be used (Clemen and Reilly 2001; Howard 1988). This basically consists of examining each chance, decision, and utility node and contemplating if each is sufficient for describing the outcomes without additional explanation. One way of doing this is to envision having perfect future information on the consequences from the decision(s). Can the qualitative ID structure including the nodes and their state outcomes be exactly predicted given this and alternate futures? This test can prevent any confusion about what a node is describing and the ability of the node to predict outcomes. The clarity test should be given for each chance node to ensure that they can properly and clearly explain the consequences they describe, for each decision node and state to ensure that each option clearly describes what it is supposed to describe for any observer, and to each consequence for their interpretation and assessment capabilities (Clemen and Reilly 2001). Some issues that might be observed with the ID in the article include what constitutes high, moderate or low; what does each response event entail; and what ecosystem services or ecological features are being described in deep water, offshore, and onshore regions? As discussed in Carriger and Barron (2011), these processes would require additional modeling with stakeholders, decision-makers, and analysts outside of the example ID to fully elucidate them. Ultimately, the model building process should be iterative through such essential steps as objective and alternative identification, preference model construction, uncertainty analysis and sensitivity analysis until a proper analytic structure (e.g., ID) is built (Clemen and Reilly 2001). In an ID, sensitivity analysis would be useful for evaluating how the range of potential outcomes for chance nodes might change recommended decisions. A requisite decision model should be setup which is one in which no new information is required to work out the decision problem (Clemen and Reilly 2001).

As illustrated above, an ID can be a useful tool for simplifying a complex risk management problem. If recommendations do not appear to be correct, the probabilistic or qualitative reasoning behind the model can be examined but analysts and decision-makers should be open to decision recommendations that are unexpected (Norsys 1997). One consideration that should be made with this and any other risk management model is calibration and evaluation. Additional information on this can be found in Carey et al. (2006) and Korb and Nicholson (2011). Clemen (2008) also discusses a framework for judging the effectiveness of a decision analysis method including whether the process improved the ability of stakeholders to better achieve objectives (i.e., a strongly effective decision analysis).

Influence diagrams give many opportunities for communicating the knowledge and causal interactions behind an environmental management problem. They are also useful for capturing expert or stakeholder beliefs and for examining the data available or needed to make decisions. Some issues for BBNs (or IDs) include the inability to tractably measure continuous temporal processes, the considerations of temporal or spatial scales when integrating processes within a model, and the frequent lack of measurements for establishing conditional probabilities (Leidloff and Smith 2010). Additional decision analytic structures and their functional relevance to different decision problems are discussed in von Winterfeldt and Edwards (2007). One should be open to the assumptions and limitations of models and aspects of IDs may be restrictive for some problems. However, the ability to intuitively display the important factors influenced by the decisions and the information needed to examine prospects from decisions in a transparent causal structure give IDs powerful and broad capabilities for formulating and characterizing problems.

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