RESEARCH ARTICLE

Key Points:
- We present a Disaster-Pressure State-Ecosystem Services-Response-Health framework linking disaster-degraded ecosystem services to health
- Damaged ecosystem services produce acute, chronic, and cumulative stress that are associated with adverse health outcomes in humans
- Disaster-related health effects deserve more attention in planning for future disasters and improving response and restoration efforts

Correspondence to:
P. A. Sandifer
sandiferpa@cofc.edu

A conceptual model to assess stress-associated health effects of multiple ecosystem services degraded by disaster events in the Gulf of Mexico and elsewhere

Paul A. Sandifer[1] [iD], Landon C. Knapp[2], Tracy K. Collier[3], Amanda L. Jones[4], Robert-Paul Juster[5], Christopher R. Kelble[6], Richard K. Kwok[7], John V. Miglarese[4], Lawrence A. Palinkas[8], Dwayne E. Porter[4], Geoffrey I. Scott[4], Lisa M. Smith[9] [iD], William C. Sullivan[10], and Ariana E. Sutton-Grier[11] [iD]

[1]School of Sciences and Mathematics, College of Charleston, Charleston, South Carolina, USA, [2]Master's in Environmental Studies, College of Charleston, Charleston, South Carolina, USA, [3]Private, Bainbridge Island, Washington, USA, [4]Department of Environmental Health Sciences, University of South Carolina, Columbia, South Carolina, USA, [5]Department of Psychiatry, Columbia University, New York, New York, USA, [6]Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami, Florida, USA, [7]Epidemiology Branch, National Institute of Environmental Health Science, Research Triangle Park, North Carolina, USA, [8]Department of Children, Youth and Families, University of Southern California, Los Angeles, California, USA, [9]Office of Research and Development, U.S. Environmental Protection Agency, Gulf Breeze, Florida, USA, [10]Department of Landscape Architecture, University of Illinois at Urbana-Champaign, Champaign, Illinois, USA, [11]Earth System Science Interdisciplinary Center, University of Maryland and National Oceanic and Atmospheric Administration, Silver Spring, Maryland, USA

Abstract Few conceptual frameworks attempt to connect disaster-associated environmental injuries to impacts on ecosystem services (the benefits humans derive from nature) and thence to both psychological and physiological human health effects. To our knowledge, this study is one of the first, if not the first, to develop a detailed conceptual model of how degraded ecosystem services affect cumulative stress impacts on the health of individual humans and communities. Our comprehensive Disaster-Pressure State-Ecosystem Services-Response-Health model demonstrates that oil spills, hurricanes, and other disasters can change key ecosystem components resulting in reductions in individual and multiple ecosystem services that support people's livelihoods, health, and way of life. Further, the model elucidates how damage to ecosystem services produces acute, chronic, and cumulative stress in humans which increases risk of adverse psychological and physiological health outcomes. While developed and initially applied within the context of the Gulf of Mexico, it should work equally well in other geographies and for many disasters that cause impairment of ecosystem services. Use of this new tool will improve planning for responses to future disasters and help society more fully account for the costs and benefits of potential management responses. The model also can be used to help direct investments in improving response capabilities of the public health community, biomedical researchers, and environmental scientists. Finally, the model illustrates why the broad range of potential human health effects of disasters should receive equal attention to that accorded environmental damages in assessing restoration and recovery costs and time frames.

1. Introduction

Humans have been coping with disasters for millennia and in doing so helped shape human development and cultural evolution [*Torrence and Grattan*, 2002]. Despite this long history of events, impacts, and reactions, the science of disaster management and response is relatively new [*Lindell*, 2013; *Lurie et al.*, 2013]. While the last several decades have demonstrated rapid advances in our ability to prepare for, respond to, and recover from many kinds of disasters, their occurrences and levels of impacts to humans are increasing at an alarming rate. Since 1990, climate-weather or geophysical natural disasters have impacted about 217 million people per year globally [*Learning and Guha-Sapir*, 2013]. These authors reported a substantial upsurge in such disasters since 1989, with nearly 80% of the overall increase accounted for by a sharp surge in "climate-related events," which have been exacerbated by increasing urbanization, deforestation, and environmental degradation. Moreover, many of the worst technological disasters in recorded history, including oil spills in marine environments, have occurred since the 1970s [*Aguilera et al.*, 2010; *Krejsa*, 1997; *Lurie et al.*, 2013; *Silei*, 2014].

The recent history of disasters in the United States underscores the magnitude of these impacts in terms of both economic damage and human health effects. In 2005, the U.S. saw approximately $160 billion (B) in disaster damages, of which about $85 B and >1800 deaths resulted from Hurricane Katrina alone [*Colgan and Adkins*, 2006; *National Oceanic and Atmospheric Administration (NOAA)*, 2016; *Sutton-Grier et al.*, 2015]. In 2012, there were 11 weather disasters in the U.S. that resulted in 377 deaths and >$110 B in damages, including Hurricane Sandy which accounted for > $70 B in damages in the U.S. [*Sutton-Grier et al.*, 2015; *U.S. Department of Commerce* [*USDOC*], 2013]. The 2010 Deepwater Horizon (DWH) oil catastrophe resulted in 11 deaths and the release of ~5 million barrels of oil into the Gulf of Mexico ecosystem [*McNutt et al.*, 2012]. Payments required of BP and the other responsible parties, including for natural resource damages, previously estimated at ~$54 B, have now approached ~$62 B [*Bomey*, 2016; *Gilbert and Kent*, 2015]. However, even this amount does not account for the majority of already documented and likely additional long-term impacts to human health and well-being nor the overall impact to the Gulf Coast economy. *Adkins* [2015] assessed the impacts to GDP (gross domestic product) in coastal areas of Louisiana, Mississippi, and Alabama a decade after hurricanes Katrina and Rita. While GDP in the shore-adjacent counties and parishes had grown at 3+ % annually from 2000 to 2005, GDP declined in 2006 and 2007 and only reached 2005 levels again in 2010, just before the DWH catastrophe. Since 2010, GDP of the same shore-adjacent counties and parishes has hovered around 2004 levels.

In addition to economic impact, most disaster response efforts focus on acute injury and exposures (e.g., to infectious disease, toxic substances, or toxins). As a result, a considerable body of literature has documented mostly acute and some chronic human health effects from oil spills, hurricanes, and other natural and technological disasters [e.g., *Aguilera et al.*, 2010; *Cheong et al.*, 2011; *Institute of Medicine*, 2007; *Jung et al.*, 2013; *Keim*, 2011; *Laffon et al.*, 2016; *Manuel*, 2013; *Rhodes et al.*, 2010; *Shultz et al.*, 2015]. Here we do not focus on these direct and often significant impacts to human health that can be as severe as death, largely because they are generally well recognized. Chronic effects of disasters on the health of either humans or the environment, in particular, effects that degraded ecosystem services, the benefits humans derive from nature [*Millennium Ecosystem Assessment* [*MEA*], 2005], may have on health, appear to have received less attention than more immediate and direct threats. For example, the 1984 chemical explosion in Bhopal, India, also impacted critical ecosystem services such as clean water, but it is much better known—and rightly so—for the illnesses and massive loss of life it caused [*Broughton*, 2005; *Varma and Varma*, 2005]. Even in cases of extreme oil spills in the U.S., such as the DWH catastrophe or the 1989 Exxon Valdez oil spill in Prince William Sound, Alaska, there has been much less emphasis on acute or chronic human health impacts, likely because these are not covered under the Oil Pollution Act of 1990. This act is the primary legislation that controls how the U.S. manages, responds to, determines responsibility for, and assesses damages resulting from oil spills. Perhaps, even more importantly, the policy for dealing with human health impacts of disasters tends to be primarily focused on reactive, after-the-event responses [*Cutter and Zoback*, 2013; *Lurie et al.*, 2013].

There has been as fair amount of effort to develop conceptual models that relate stressor-caused environmental damage, including climate change, to certain human health and well-being outcomes [e.g., *Abramson et al.*, 2015; *Bradley and Yee*, 2015; *Briggs*, 1999; *Hambling et al.*, 2011; *Jackson et al.*, 2013; *Kelble et al.*, 2013; *Oosterbroek et al.*, 2016; *Palinkas*, 2012; *Patterson et al.*, 2010; *Reis et al.*, 2015; *Sandifer and Sutton-Grier*, 2014; *Smith et al.*, 2013; *Summers et al.*, 2014, 2016; *Yee et al.*, 2012]. Many of these models are derived from the general Driver-Pressure-State-Impact-Response (DPSIR) ecological model that has been used for decades and was adopted by the United Nations Commission on Sustainable Development [*Organisation for Economic Co-operation and Development*, 1993].

One widely adopted model is the Driving force-Pressure-State-Exposure-Effect (DPSEEA) framework proposed by *Corvalan et al.* [1996] and *Briggs* [1999]. This model describes health impacts as being influenced by driving forces (e.g., population growth and economic development) that lead to pressures on the environment (e.g., harvesting, mining, and waste release) that result in changes in the state of the environment (e.g., increases in pollution and increased risk from natural hazards). It requires an assessment of the exposure to these pressures (e.g., external exposure and absorbed dose) that lead to potential health effects (e.g., morbidity and mortality). *Hambling et al.* [2011] rated this model as best of those reviewed for application to develop environmental health indicators for the effects of climate change on health. However, the DPSEEA model does not assess the impact of natural or technological disasters on the health and functioning of ecosystem services and thus makes no connection between ecosystem services and human health. In addition, the

authors noted DPSEEA may have limitations for use with regard to disaster impacts. *Reis et al.* [2015] improved the DPSEEA model by offering an ecosystems-enriched or *e*DPSEEA construct. While the model is general in its presentation, it allows for inclusion of complex considerations and connections, although these are not elaborated in the framework diagram. This model was discussed in a workshop format at a scientific meeting where its utility in helping to identify a wide range of implications, including some related to loss of specific ecosystem services, was demonstrated.

Health impact assessment (HIA) is useful for evaluating the potential health impacts of future activities that will affect the environment. An HIA is "a combination of procedures, methods, and tools by which a policy, program, or project may be judged as to its potential effects on the health of a population, and the distribution of those effects within the population" [*Gothenburg Consensus Paper*, 1999]. A major advantage of the HIA process is that it brings public health issues to the attention of decision makers around topics and decisions that fall outside of traditional public health arenas, such as transportation or land use [*Kemm*, 2001]. In the U. S., HIAs may be considered analogous to environmental assessments (EAs), which are required under the National Environmental Policy Act and which assess the impacts of activities on environmental outcomes such as air and water quality. One difference is that HIAs can be voluntary, whereas EAs are required for federally funded projects. Typically, HIAs have not included ecosystem services per se. However, *Horwitz and Finlayson* [2011] have shown how the HIA approach could be used to demonstrate the human health values of maintaining healthy wetlands, and the U.S. Environmental Protection Agency has developed an approach to bringing ecosystem services into HIA via its geospatially enabled EnviroAtlas [*U.S. Environmental Protection Agency [USEPA]*, 2015].

We are not aware of previous models that have connected natural or technological disasters to stress-associated physiological and psychological health outcomes that result from loss of ecosystem services. Although it may not be appropriate or useful in all cases, an ecosystem service framework that lays out the connections between ecosystems and human health is relevant to planning for, and responding to, natural and technological disasters, especially for coastal communities that are heavily dependent on natural resources.

The societal costs of not having a conceptual model for how disasters impact the mental and physical health of nearby residents is that the public dramatically underestimates disaster effects on human health and well-being, local economies, and the resources necessary to effectively prepare for and respond to disasters. This paper begins to fill that gap. We provide one of the first conceptual frameworks that include disaster impacts on environmental conditions and ecosystem services and how impacts to ecosystem services have subsequent negative effects on human physiological, psychological, and community health and well-being. This conceptual model can be used to enhance both predisaster preparation and postdisaster responses by improving our understanding of the full suite of impacts that disasters cause and the wide range of human health outcomes for which we should prepare and be ready to respond.

2. Materials and Methods

This was a conceptual modeling study and thought experiment. We used the broad definitions of human health and well-being developed by the World Health Organization [*World Health Organization*, 1946] and utilized extensively elsewhere [e.g., *MEA*, 2005; *Sandifer et al.*, 2015] and assessed relevant models of environmental and human health effects of disasters via a broad ranging but targeted literature review. This was followed by an iterative design process among the project team which included information from the literature, original ideas, and in-depth discussions with a wide range of experts individually and in two focused workshops.

In addition to conceptual model development, we conducted an extensive data mining initiative that focused on available ecosystem pressure, ecosystem state, ecosystem services, human health, and community characteristics data for the Gulf of Mexico and the affected coastal counties of Texas, Louisiana, Mississippi, Alabama, and Florida. Initial data mining efforts by the investigators identified numerous portals providing access to data related to environmental conditions in the Gulf of Mexico prior to and following the DWH incident. Following this assessment of available data sets, we assembled in workshop format a broad mix of carefully selected experts in biomedical (e.g., stress biomarkers, other indicators of mental and physical health, and human microbiome), clinical (involved in assessing and treating disaster victims), and ecological

(ecosystem services, ecosystem processes, and biodiversity) sciences, as well as health scientists and ecologists with recent experience in or related to the Gulf of Mexico. The primary purposes of the workshop were to (1) review the available data in the context of our conceptual modeling approach, (2) identify existing data sets that likely could be used to assess health effects of disasters, and (3) conduct a preliminary case study of our model within the context of available data and literature. Results from the data mining activities and the workshop will be reported separately.

Although we found a number of useful frameworks during our literature review, none connected disasters to health effects through impacts to ecosystem services. Therefore, we adopted and modified concepts from several existing frameworks and incorporated them into a more comprehensive and novel model that explicitly identifies and emphasizes the human health consequences that are due to the disaster's effects on the environmental benefits on which people and communities depend.

We chose the model of *Kelble et al.* [2013], augmented with information from *Yee et al.* [2012], *Bradley and Yee* [2015], and other sources as the basis for the environmental-ecosystem service components of our framework. Foundation blocks for the human health and well-being elements of our model were the mental health impacts diagram of *Palinkas* [2012, 2015], the Eco-Health DPSIR model of *Bradley and Yee* [2015], and the allostatic load (AL)-chronic stress model of *McEwen and Stellar* [1993] and *McEwen* [1998a, 1998b, 2000]. The literature review was accompanied by two workshops that garnered a wealth of expert opinion from scientists representing diverse disciplines. Similar interdisciplinary expert workshops have produced highly useful results [e.g., see *Bradley and Yee*, 2015; *Foley et al.*, 2010; *Halpern et al.*, 2012; *Kelble et al.*, 2013; *Lovelace et al.*, 2012; *Reis et al.*, 2015].

The origin of the *Kelble et al.* [2013] framework is the general DPSIR model that has been used widely in ecology for decades and more recently to explore some aspects of human health and well-being [*Bradley and Yee*, 2015; *Sekovski et al.*, 2012; *Yee et al.*, 2012]. The DPSIR model illustrates how certain events or changes (termed "drivers") exert specific kinds of "pressures" on the condition or "state" of ecosystem components, resulting in impacts to the ecosystem and responses (human actions taken as a result of the impacts). *Kelble et al.* [2013] modified the DPSIR framework to support ecosystem management approaches to environmental decision-making. They removed impacts per se and replaced them with ecosystem services and allowed for identification of positive as well as negative effects of stressors. Ecosystem services are shown at the top of their model to emphasize priority. Disasters were not explicitly included among the drivers at the base of this model, and human health is incorporated only as one among many ecosystem services.

Kelble et al. [2013] named their framework the EBM-DPSER (Ecosystem Based Management-Driver-Pressure-State-Ecosystem Service-Response) model because of its focus on supporting ecosystem-based management decision processes. They presented a more detailed version of the EBM-DPSER model as a submodel for the South Florida water column.

We made significant changes in these modified DPSIR frameworks to reflect our three-way focus on disasters as drivers, effects on ecosystem services as avenues through which some environmental consequences of disasters are transmitted to people, and stress-related human health outcomes as the ultimate focus.

Based primarily on work with the Exxon Valdez oil spill, *Palinkas* [2012] separated mental health impacts derived from oil spills into three "tiers": environmental effects (including direct health impacts), community effects (essentially erosion of positive community characteristics that provide support for people), and intrapersonal effects that include a variety of psychological and physiological outcomes. These tiers are interconnected and mediated by the relative risk, vulnerability, and resilience characteristics of individuals and communities. We augmented this framework with additional information gleaned from recent literature particularly relevant to the Gulf of Mexico, hurricanes or oil spills, or to ecosystem service connections to human health and well-being as well as information garnered from our two expert workshops.

Finally, we included psychological and physiological stress as our primary focus for long-term health effects because cumulative stress is associated with many chronic illnesses and related mortality among humans, including a variety of both mental (e.g., depression, anxiety, and posttraumatic stress disorder/posttraumatic stress symptoms (PTSD/PTSS)) and physiological (e.g., cardiovascular disease) disorders [*Juster et al.*, 2010; *Schneiderman et al.*, 2005; *Segerstrom and Miller*, 2004; *Thoits*, 2010]. Because it is linked with such a broad range of health effects, chronic stress is commonly associated with health

problems following traumas of many types, including disasters [*Galea et al.*, 2005; *L. S. King et al.*, 2015; *Mills et al.*, 2007; *Neria et al.*, 2007]. However, chronic stress is generally not well measured via surveys frequently used to assess health status.

Through our literature review and discussions with health researchers, we identified allostatic load (AL) as a powerful concept for understanding impacts of chronic stress on human health [*McEwen and Stellar*, 1993]. The term "allostasis" refers to physiological processes that "maintain stability through change" [*Sterling and Eyer*, 1988] and refers to how organisms adapt to acute stress through the production of stress hormones which act to restore homeostasis. AL is defined as the cumulative "wear and tear" on the human body that increases over time with exposure to repeated or chronic stress and recovery cycles [*McEwen and Stellar*, 1993; *McEwen*, 1998a, 1998b, 2000]. AL represents both the physiological and psychological consequences of chronic exposure to interconnected biological responses to stress, with diminishing opportunity for reset to a "normal" physiological state [*Bizik et al.*, 2013; *Juster et al.*, 2010, 2016; *Logan and Barksdale*, 2008; *McEwen*, 1998a, 1998b, 2000; *McEwen and Gianaros*, 2010; *Picard et al.*, 2014]. Inclusion of AL considerably strengthened our model by providing a specific mechanistic connection between disasters, increasing and cumulative stress, and myriad negative health outcomes.

AL measures the dysregulation of the nonlinear network of multiple physiological systems, and prolonged dysregulation can increase the susceptibility of an individual to stress-related disease [*Berger et al.*, 2015; *Bizik et al.*, 2013; *Juster et al.*, 2010, 2011a; *McEwen*, 1998a, 1998b, 2000]. The severity of AL following a specific event depends on an individual's preexisting AL and a variety of factors that may modify stress effects, such as a person's experiences, environment, genetics, behavior, and relative vulnerability or resilience [*Juster et al.*, 2016]. Overall, the higher the AL, the greater the probability that an individual's health will be negatively impacted. To date, >100 studies have measured AL in order to predict stress-related diseases. Examples of specific health outcomes correlated with or predicted by AL include cardiovascular disease, physical decline, cognitive declines, and all-cause mortality among successful agers [*Gruenewald et al.*, 2006; *Karlamangla et al.*, 2002; *Seeman et al.*, 2001, 2004], PTSD in women [*Glover et al.*, 2006], chronic fatigue syndrome [*Maloney et al.*, 2006], mortality among Taiwanese [*Goldman et al.*, 2006] and poor Americans [*Crimmins et al.*, 2007], Type 2 diabetes among American Samoans [*Crews*, 2007], ischemic heart disease among Americans [*Sabbah et al.*, 2008], and 3 year depressive symptoms among Canadian older adults [*Juster et al.*, 2011b].

AL is typically assessed via biomarkers, which include a variety of endocrine, immunological, metabolic, cardiovascular, respiratory, and anthropometric measures [*Juster et al.*, 2010]. Some of the more readily obtainable include cortisol (from saliva, urine, or hair samples), cholesterol and its lipid components, blood pressure, pulse rate, and body mass index. Cortisol levels can be particularly useful but must be measured multiple times within the same individual because of differences related to diurnal cycles and other natural variation. Biomarker data can be combined via one or several indices [*Juster et al.*, 2010] to provide qualitative and quantitative assessments of AL in individuals or groups. The most commonly employed and potentially useful algorithm for purposes such as the present model is the group AL index which is a "[s]ummary measure representing the number of biomarkers falling within a high risk percentile (i.e., upper or lower 25th percentile based on the sample's distribution of biomarker values" [*Juster et al.*, 2010]. A different and innovative approach that is predictive of AL in youth involves calculating cumulative risk scores from factors such as separation/turmoil, violence, socioeconomic status, single parent, and maternal high school dropout [*Evans*, 2003; *Evans et al.*, 2007]. One or more AL indices and/or the cumulative risk scores can be included in our model to assess AL of the target population. Overall, AL's holistic approach to combining subclinical thresholds for a number of biomarkers allows for a broader biometric approach to assessing the physiological manifestations related to chronic stress and unhealthy behaviors. Its application in the present context is novel.

3. Results

We developed a Disaster-Pressure-State-Ecosystem Service-Response-Health (DPSERH) model that includes both environmental and human health outcomes (Figure 1). The "health" component of this model is the most significant and novel piece that our model adds in connecting disasters to environmental impacts and then to subsequent human health and well-being effects. In this framework, disasters are the drivers
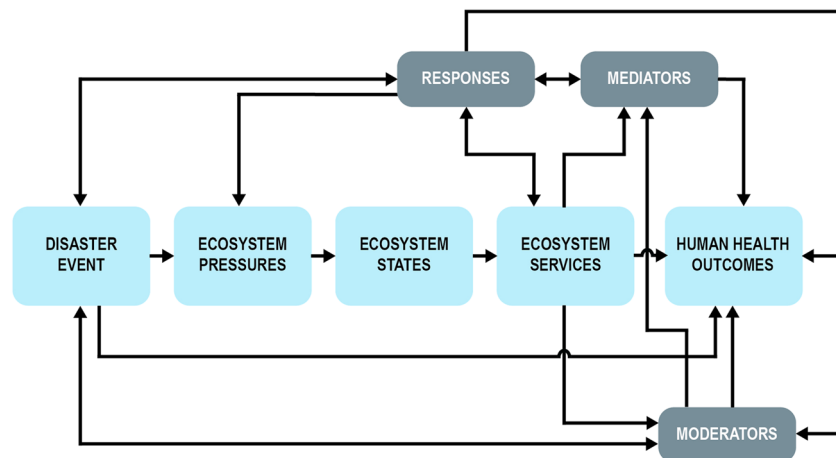
Figure 1. General schema for the overall DPSERH model.

of the changes that cascade through the ecosystem and ultimately end up causing or contributing to human health effects. Pressures are the immediate physical, chemical, and biological effects of disasters that cause changes in the ecosystem. State refers to the condition of the physical, chemical, and biological attributes of the ecosystem that contribute to production, quality, or delivery of ecosystem services. These conditions can be measured objectively and are often changed through pressures exerted by disasters. Ecosystem services are the benefits that people derive from nature and that make human life on Earth possible [*Cairns and Pratt*, 1995; *Daily*, 1997; *MEA*, 2005; *Rapport et al.*, 1998; *Yoskowitz et al.*, 2010, 2016]. These definitions are in accordance with recent standardization recommendations of *Oesterwind et al.* [2016] for consistent usage. They define driver as "superior complex phenomena governing the direction of the ecosystem change, which could be both of human and nature origin"; pressure as "a result of a driver-initiated mechanism (human activity/natural process) causing an effect on any part of an ecosystem that may alter the environmental state"; state as "the actual condition of the ecosystem and its components established in a certain area at a specific time frame, that can be quantitatively-qualitatively described based on physical (e.g., temperature, light), biological (e.g., genetic-, species-, community-, and habitat- levels), and chemical (e.g., nitrogen level and atmospheric gas concentration) characteristics"; and impacts as "consequences of environmental state change in terms of substantial environmental and/or socioeconomic effects which can be both, positive or negative." They also defined response as "all management actions seeking to reduce or prevent an unwanted change or to develop a positive (desirable) change in the ecosystem." While we include management actions in responses in our model, we followed *Kelble et al.* [2013] and *Bradley and Yee* [2015] in using a broader definition, that is, the range of human reactions to disasters. These reactions can have negative and positive consequences and can include anything from first-responder emergency efforts to long-term changes in policy and preparedness, how formal and informal institutions and leaders perform and communities respond, media coverage, and how people react to media reports and institutional actions.

This basic schema (Figure 1) illustrates how disasters create environmental pressures on the state or condition (e.g., contamination) of ecosystem components (e.g., fish stocks), resulting in degradation of ecosystem services (e.g., reduced water quality and loss of fishery harvest and associated income), which in turn produces acute and chronic stress (e.g., through anticipated or realized loss of income and family disruption) that then results in negative health outcomes for individuals, groups, and communities. Moreover, responses taken to mitigate risks after a disaster may affect the flow of ecosystem services, thereby increasing or decreasing stress through lost or improved opportunities to benefit from ecosystem services. Disasters may also have short-term and chronic effects on health outcomes via traumatic injury and exposure to infectious disease and toxic substances as indicated by a direct arrow from disasters to health. Roles of mediators, moderators, and responses are detailed below.

For the present case, we chose two kinds of disasters, major hurricanes and large oil spills, due to our project's focus on the Gulf of Mexico (Figure 2). However, this model would work equally well for assessing human health effects of loss of ecosystem services caused by other natural and technological disasters, such as
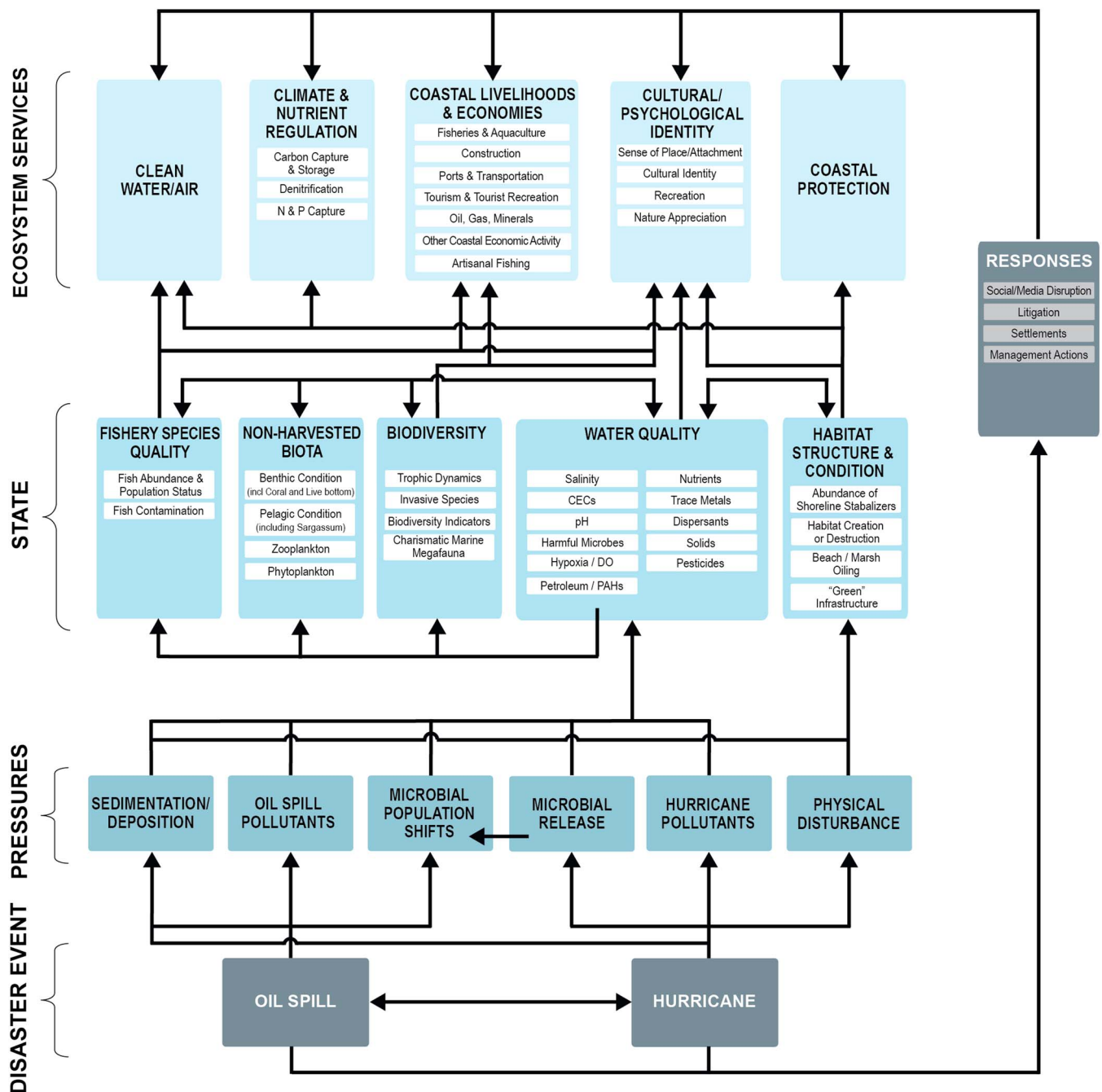
Figure 2. The detailed environmental/ecosystem services module of the DPSERH model.

extreme weather events, chemical spills, industrial accidents, tsunamis, earthquakes, major harmful algae blooms, and even some terrorism incidents where there is significant environmental damage.

The pressures we include represent major effects of both hurricanes and oil spills, including physical disturbance and destruction, changes in sedimentation and deposition (increases, decreases, resuspension, redistribution, and accumulation of oil), chemical and other pollution, and changes in microbial community composition and function. Depending on the type of disaster and its proximal effects, other pressures could be added or one or more of these removed, similar to the way *Kelble et al.* [2013] and *Cook et al.* [2014] have done in their submodels. However, based on the literature for hurricanes and oil spills, we considered these pressures among the most important [*Joye*, 2015; *Sheikh*, 2005; *USEPA*, 2007].
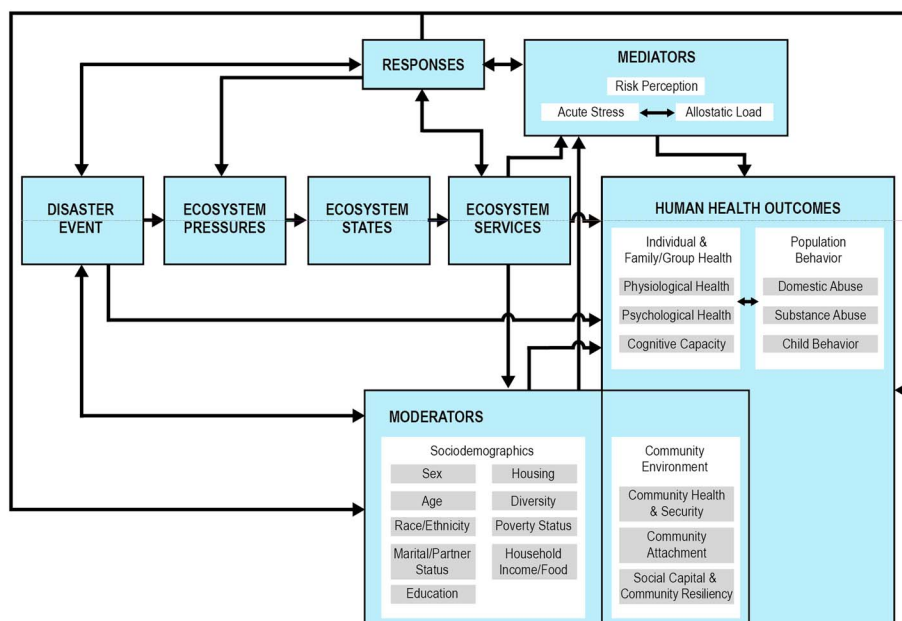
Figure 3. The DPSERH model schema with elaboration of the human health module.

For simplicity, we grouped ecosystem states into five large categories of ecosystem attributes: water quality, habitat structure and function, biodiversity, nonharvested biota, and fishery (harvested) species. Each of these major component groups is further subdivided into subgroups, which in turn can be subdivided more and more finely as needed for a particular exercise. Fishery states represent all harvested living resources including, but not limited to, finfish, shellfish, and crustaceans. These state groups and subgroups all represent major ecosystem components and attributes that are known to be influenced by hurricanes and oil spills [*Barron*, 2012; *Incardona et al.*, 2014; *Joye*, 2015; *G. M. King et al.*, 2015; *Kostka et al.*, 2011; *Lee et al.*, 2015; *Mendelssohn et al.*, 2012; *Sheikh*, 2005; *USEPA*, 2007; *Venn-Watson et al.*, 2015].

While there are many ecosystem services that people derive from the Gulf of Mexico [e.g., *Farber et al.*, 2006; *Yoskowitz et al.*, 2010, 2016], we chose five broad groups of ecosystem services that are known to be particularly important in the gulf: these are clean water and air, climate and nutrient regulation, coastal livelihoods and economies, coastal protection, and cultural/psychological identity. Other ecosystem services could be substituted in the model as needed for a particular scenario. Most of the ecosystem service groups included here are also subdivided into smaller (but still large) component services, and as we point out below, we used a subset of particularly important ecosystem services in the overall model. Arrows, each of which is supported by literature or data, indicate connections between drivers and specific pressures, states, ecosystem services, responses, and eventually human health outcomes. While efforts continue to define individual and cascading connections among the myriad components of the socioecological system in the gulf, it is neither feasible nor practical to include every known interaction. Rather, these connections were selected to represent some of the most well-documented and pertinent relationships in the study area.

The human health component of our model (Figure 3) includes physiological and psychological health outcomes such as physical illnesses (e.g., cardiovascular disease) and psychological disorders (depression and PTSS), in addition to cognitive and behavioral outcomes and a variety of community environment variables such as community health and security, community attachment, social capital, and community resilience. We also incorporated risk perception, which can be affected by previous disaster experience and social and community factors and can substantially influence actions people take and their levels of anxiety and stress [*Eisenham et al.*, 2007; *Levine and Picou*, 2012; *Slovic and Peters*, 2006; *Wachinger et al.*, 2013].

The health module also includes moderators and mediators [*Baron and Kenny*, 1986]. A moderator is a qualitative or quantitative factor that specifies when or to whom something may happen, while a mediator is a mechanism by which effects occur. Moderators can be considered as predisposing conditions and may include a range of socioeconomic variables such as sex, age, race/ethnicity, diversity, marital status,

educational level, housing, poverty status, and income and food availability. The importance of each of these in moderating the health effects caused by disasters is well established [*Noji*, 1997]. Community variables also can be moderating factors in some situations or they can be health and well-being outcomes, or both, in a given situation. This duality is illustrated by having the Community Environment measures encompassed in both the Human Health Outcomes and Moderators boxes.

Mediators can include a variety of mechanisms of action. We used acute stress and AL as the primary mediators since we are specifically targeting human health effects associated with stress caused by disasters, although risk perception may also serve a mediating role. As noted previously, we indicate direct effects of disasters, such as traumatic injury, toxicity, or exposure to infectious disease, with an arrow connecting the disaster directly to health outcomes. People's responses in reaction to a disaster and its effects may be positive, negative, or neutral in terms of health effects. Adverse or damaging responses that may increase AL and exacerbate mental and physical distress include negative media reports, litigation, or systematic failure of leaders and social institutions to cope or inspire confidence and trust [*Freudenberg*, 1997; *Juster et al.*, 2011a; *Palinkas*, 2012; *Vasterman et al.*, 2005; *Weems et al.*, 2012; *Xu et al.*, 2016]. Positive responses that may ameliorate stress include effective predisaster planning, warnings, and recovery actions, improved building construction requirements, disaster-focused training and capacity building among public health workers, an emphasis on coastal resilience, and strong community organizations [*Adger et al.*, 2005; *Miller et al.*, 2016; *Norris et al.*, 2008; *Qureshi et al.*, 2004; *Shultz et al.*, 2005].

The entire detailed model is illustrated in Figure 4. We chose to emphasize the following ecosystem services based on literature and expert opinion concerning their linkages to human health and well-being in the Gulf: commercial fishing and aquaculture, artisanal or subsistence fishing, tourism (including tourist-associated recreation), nontourist recreation (e.g., the recreational activities local people take part in that help renew and restore their feelings of well-being), coastal protection, sense of place, and clean water and air. We also included climate and nutrient regulation to represent their importance as ecosystem services, since they may exert additional pressures concurrent with those associated with disasters. However, their effects are likely to take place over much larger temporal and spatial scales that are harder to define than the others. While our choices of ecosystem services were made independently, it is noteworthy that a broad range of Gulf ocean users ranked food (e.g., fisheries), raw materials (including hydrocarbons), and recreation as the top three ecosystem services in a recent relative valuation exercise [*Yoskowitz et al.*, 2016].

3.1. Case Study: DWH Disaster, Human Health Impacts of Fishery Closures

Using this new conceptual model, one can trace the potential for stress-related health effects from a disaster through impacts on one or multiple ecosystem services and then on to specific individual, group, and community health outcomes (Figure 4). Here we apply our new DPSERH model to briefly examine both environmental and human health/well-being effects of pollution from the DWH oil catastrophe and subsequent management and other responses. The spill resulted in substantial impacts to water and air quality through contamination by crude oil and its components, dispersants, and compounds formed as a result of burning of surface oil and flaring of natural gas, among other things. These pollutants entered the Gulf of Mexico food web, with resulting major concerns about potential for accumulation of contaminants in seafood at sufficiently high levels to cause health problems for other animals consuming them, including humans and marine mammals [*Wilson et al.*, 2015; *Ylitalo et al.*, 2012]. Even months and years after the incident, when the weight of scientific evidence clearly demonstrated that there were no significant levels of oil- and dispersant-related contaminants in commercially or recreationally harvested seafood, there remained widespread distrust and concern among the public, including seafood harvesters and purveyors [*McKendree et al.*, 2013; *Morgan et al.*, 2016; *Sandifer et al.*, 2012]. Both the immediate and longer-term concerns were widely reported in the media, further raising levels of public anxiety. The near-term effect was the action by the NOAA to close all federal waters of the Gulf to fishing where oil had been sighted or was expected to be found. Following the first fishery closure on 2 May 2010, the area of closure expanded to a peak of ∼229,215 sq km (37%) of gulf federal waters by 2 June. After that point, waters that met all test criteria were systematically reopened, with one third of the total closure reopened on 22 July 2010 and all but 0.4% of Gulf federal waters reopened to fishing by 15 November. The final federal fisheries area was reopened 1 day before the first anniversary of the DWH explosion, 19 April 2011 [*Lubchenco et al.*, 2012; *Ylitalo et al.*, 2012].
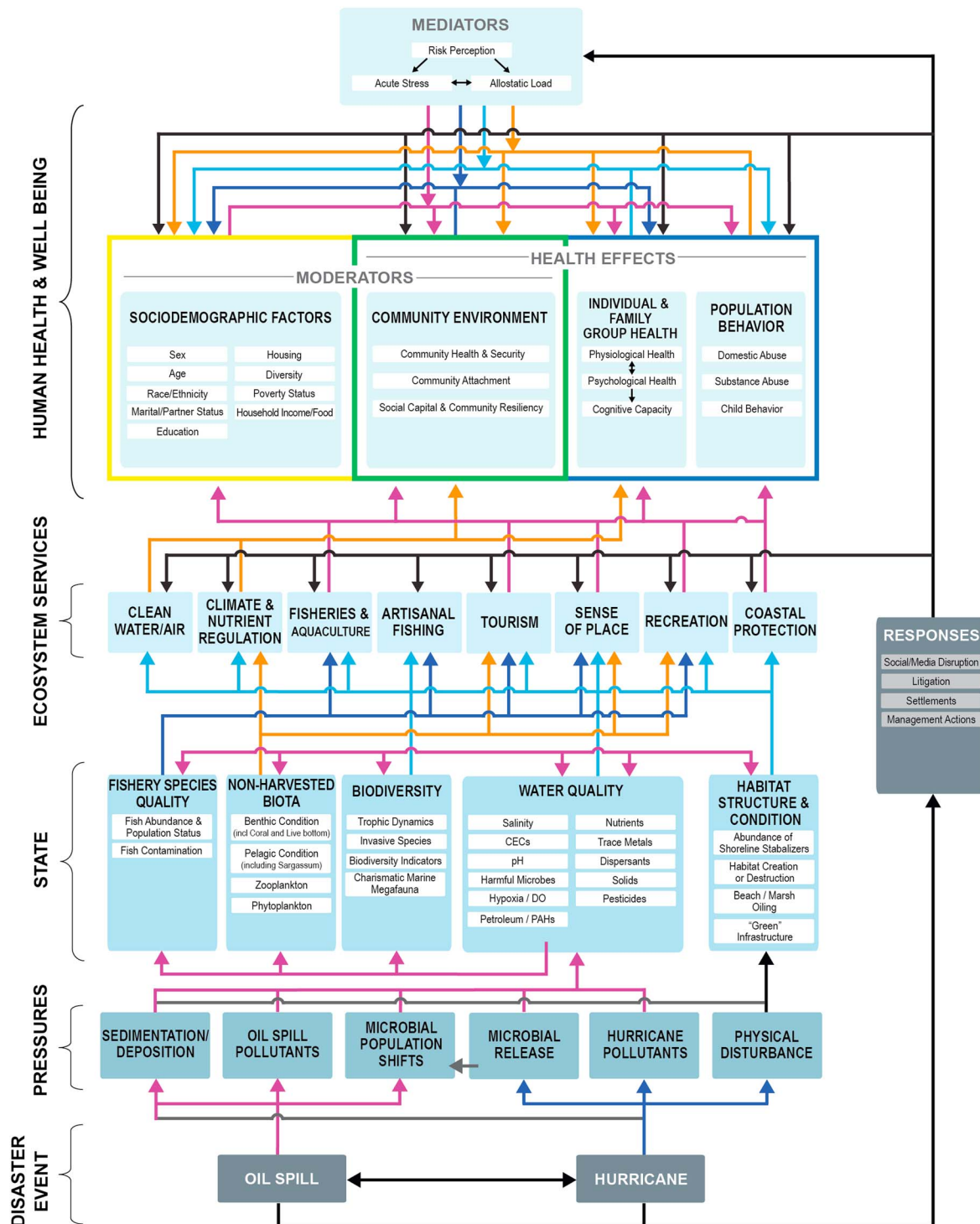
Figure 4. The overall DPSERH model, showing connections among various components. These connections are not meant to be all inclusive but rather illustrative. All arrows shown are based on existing literature or data. Different colors used for arrows have no significance other than to increase ease of following specific connections among model elements.

The closures resulted in the complete loss of fishery ecosystem services in these areas during the periods that they were closed, including commercial, recreational, and tourist-related fishing, even though there were relatively little observed impacts, especially from contamination, to the underlying resources. In addition, the specter of oil-coated marshes, beaches, and wildlife caused major disruptions in tourism. The loss of

Table 1. Examples of Health Effects of Hurricane Katrina and the Deepwater Horizon Oil Catastrophe

Health Effects	Catastrophe (Hurricane/Oil Spill)	Reference
Elevated anxiety mood disorder and PTSD in New Orleans residents across broad sociodemographic range after hurricane	Katrina	*Galea et al.* [2007]
Persistent PTSS, especially among the disadvantaged	Katrina	*Paxson et al.* [2012]
Persistent depression and stress, especially among females, African Americans, less educated, and those affected by separation and severe home and financial damage	Katrina	*Picou and Hudson* [2010]
Threefold increase in hospital admissions for myocardial infarctions during 6 years after event	Katrina	*Peters et al.* [2014]
Increased blood pressure, headaches, stomach and respiratory problems, irregular heartbeat; depression and PTSS; especially among females, African Americans, poor, and lacking strong social connections	Katrina	*Adeola and Picou* [2012, 2014]
Increased interpersonal violence	Katrina	*Schumacher et al.* [2010]
High levels of PTSS in children	Katrina	*Jaycox et al.* [2010]
2.7 times higher than national incidence for severe emotional distress in children	Katrina	*McLaughlin et al.* [2010]
>50% of children still reported mental distress 2 years after event	Katrina	*Abramson et al.* [2008]
Nearly 30% of pediatric patients presented with mental health problems 3 years after event	Katrina	*Olteanu et al.* [2011]
High levels of tension, anxiety, depression, fatigue, confusion, and less able to cope related to loss of income	DWH	*Grattan et al.* [2011]
High psychological stress related to economic and health concerns	DWH	*Gill et al.* [2012, 2014]
Increased and persistent anxiety, depression, and PTSS especially among those previously affected by Katrina	DWH/Katrina	*Osofsky et al.* [2011]
Stress effects most associated with low income and low social support	DWH	*Laffon et al.* [2016]
Negative mental and physical health effects were greater in fishing households, among coastal residents, Cajuns, lower socioeconomic status, and less among those with stronger community attachments; effects declined over time	DWH	*Cope et al.* [2013]
Spill-related income loss was strong driver of mental health problems, including those related to corrosive community issues and media reporting	DWH	*Morris et al.* [2013]
High levels of stress, anxiety, depression, and behavioral problems among Vietnamese American fishers especially about economic concerns	DWH	*Ngo et al.* [2014]
PTSD in children in affected LA parishes; most pronounced for those with previous hurricane exposure and some other personal factors; mental and physical effects connected	DWH	*J. D. Osofsky et al.* [2014], and *H. J. Osofsky et al.* [2014]
Nearly 50% of participants affected by DWH; high percentages concerned about wildlife, seafood safety, loss of way of life, and reduced job opportunities; high levels of depression, anxiety, and PTSS	DWH	*H. J. Osofsky et al.* [2014]
Drug, marijuana, and alcohol use increased among those >12 and young adults experienced depression and increased thoughts of suicide	DWH	*Gould et al.* [2015]
Negative health indicators of physical and mental distress and depression, with women and children most susceptible; related to loss of income, jobs	DWH	*Fan et al.* [2015]
Stress, PTSS, anxiety, and serious mental illness in LA coastal residents still high after 2 years; mostly related to disruption of lives, work, family and social engagement	DWH	*Hansel et al.* [2015]
Children and adolescents highly vulnerable to trauma; cumulative risk of mental health problems increases with multiple traumatic events	DWH	*L. S. King et al.* [2015]
Economic impact related to increased depression and PTSD symptoms, somewhat alleviated by individual resiliency	DWH	*Shenesey and Langhinrichsen-Rohling* [2015]
At large geographic scale, no severe and persistent behavioral effects	DWH	*Shultz et al.* [2015]
Fishers reported elevated concerns about economic and financial impacts, health, and threat to cultural heritage	DWH	*Cherry et al.* [2015]
Among oil spill cleanup workers, having prespill mental health concerns associated with postspill counseling and medication	DWH	*Lowe et al.* [2015]
Study included >2000 women. Physical exposure to spill associated with burning and soreness of nose, throat, and lungs, dizziness, and wheezing; economic exposure associated with wheezing, headaches, stuffy/running nose	DWH	*Peres et al.* [2016]
Women exposed both economically and physically to the oil spill experienced increased depressive symptoms and domestic violence while physical exposure alone was related to mental distress.	DWH	*Rung et al.* [2016]

fishery and tourism ecosystem services—compounded by heavy media coverage, growing uncertainty over the magnitude and duration of the spill and the related moratorium on new oil and gas activities, differences of opinion within the engaged scientific community, and a host of sociodemographic and community factors —caused high levels of anxiety, depression, and other indicators of increased stress among people who were dependent on fisheries and tourism for income, food, and a treasured way of life (Table 1) [*Levine and Picou*, 2012; *Shenesey and Langhinrichsen-Rohling*, 2015; *Shultz et al.*, 2015], and also among oil and gas industry workers and their families, as well as the oil spill cleanup workers [*Kwok et al.*, 2017]. Using existing information from the literature (Table 1) and available data sets, we can trace the path of the disaster's effects beginning with the DWH catastrophe through impacts to water quality and then on to concerns for seafood safety, the loss of fishery and tourism ecosystem services through fishery closures, the consequent loss of livelihoods, food and treasured ways of life, the accumulation of stress in individuals and communities caused by the loss of ecosystem services, and the manifestation of the accumulated stress (AL) in mental and physical disorders and social disruption.

4. Discussion

To a significant extent, human health and well-being depend upon the condition of the environments in which we live and the goods and services they provide. This relationship has been explored in detail in the Millennium Ecosystem Assessments [*MEA*, 2005] and more recently by the National Academy of Sciences specifically for the Gulf of Mexico [*National Academy of Sciences*, 2013]. The concept of ecosystem services is explicitly human centric, and human health and well-being can be considered the cumulative or ultimate ecosystem service [*Sandifer and Sutton-Grier*, 2014]. Degraded environments which can no longer produce or deliver high-quality ecosystem services may have a variety of negative ramifications for human health and well-being, including poor nutrition and starvation, inadequate shelter, increased incidences of infectious diseases, loss of livelihood and cultural identity, diminished availability of potable water, reduced opportunities for recreation and relaxation, and reduction in climate modulation and nutrient regulation [*MEA*, 2005; *Sandifer and Sutton-Grier*, 2014].

Environmental disasters substantially affect the well-being of hundreds of millions of people annually [*Learning and Guha-Sapir*, 2013]. Yet despite substantial efforts to increase understanding of linkages between ecosystem health and human health via ecosystem services, the pathways and mechanisms through which disasters damage ecosystems and then how those ecological injuries are translated into long-term and widespread negative effects on human health for the most part are poorly understood. The novel conceptual model presented here is, to our knowledge, the first attempt to elucidate how disaster-impacted ecosystem services feed into psychological and physiological mechanisms that are associated with specific health problems in humans. Additionally, the model makes possible exploration of health effects of one degraded ecosystem service at a time or simultaneous consideration of several affected ecosystem services. This is important because in the Gulf of Mexico and elsewhere crucially important ecosystem services such as commercial and recreational fisheries, tourism, and cultural identity/sense of place are strongly interlinked, and concerns related to the relative condition of these services may persist long after disaster events.

The model also allows for assessment of interactive effects (synergistic, antagonistic, or additive) of two or more disasters that may affect one another (e.g., hurricane impacts on a recent or ongoing oil spill) and may affect both the environment and human health and well-being. For example, hurricanes may cause oil spills (there were >130 oil spills associated with Hurricane Katrina [*Sever*, 2006]) or exacerbate recent or ongoing spills. Additionally, the stress produced by Katrina was a major factor affecting many people who 5 years later were impacted by the DWH catastrophe [*H. J. Osofsky et al.*, 2011, 2014]. Incorporation of AL in the model provides the opportunity to evaluate cumulative stress effects from multiple disaster events and environmental cascades, providing a needed common health and well-being indicator that transcends disasters and other life changing events.

Development of this model is particularly important for the Gulf of Mexico, a Large Marine Ecosystem with a well-documented history of major environmental disasters and impacts. The Gulf has been affected by massive modifications to support the offshore oil industry: ongoing subsidence and loss of wetlands associated with flood control, navigation improvements, and sea level rise; annual hypoxic "dead zones" caused principally by anthropogenic eutrophication; invasive species; repeated effects of major storms such as

Hurricanes Katrina and Rita; and ongoing oil pollution from both natural seeps and small to massive accidents including the 1979 Ixtoc and more recent DWH catastrophes [*Committee on Environment and Natural Resources*, 2010; *Gulf Coast Restoration Task Force*, 2011; *Gundlach et al.*, 1981; *McCallum and Heming*, 2006; *Mississippi River Gulf of Mexico Nutrient Task Force*, 2013; *Natural Resources Defense Council*, 2015; *U.S. Fish and Wildlife Service*, 2013]. Similarly, most coastal areas in the U.S. and around the world are impacted by multiple stressors, often acting simultaneously and synergistically [*Sandifer and Sutton-Grier*, 2014], and this model should be useful for assessing disaster threats and impacts to coastal ecosystems and communities globally.

The DWH catastrophe resulted in the largest marine oil spill in the U.S. and one of the largest ever globally [*McNutt et al.*, 2012]. Environmental impacts of the DWH disaster are being investigated in great detail [*Lubchenco et al.*, 2012], with hundreds of scientific papers reporting effects of the oil, dispersants, and cleanup efforts on the Gulf ecosystem and its component habitats and organisms, from the coast to deep water and including vulnerable species such as sea birds, sea turtles, and marine mammals (e.g., see *Beyer et al.* [2016] and programs and reports from Deepwater Horizon research workshops held in 2010–2012 and of the Gulf of Mexico Oil Spill and Ecosystem Science Conferences for 2013–2016).

Even though long-term human health effects of oil spills have received less attention and research funding than the environmental damages, the literature dealing with mental and physical health impacts is growing rapidly [e.g., *Aguilera et al.*, 2010; *Kwok et al.*, 2017; *Laffon et al.*, 2016; *Peres et al.*, 2016; *Rung et al.*, 2016] (Table 1). What is often not recognized is that the two impacts, to ecosystems and human health, are often directly related [*H. J. Osofsky et al.*, 2014]. Even though some previous studies have relied on volunteered, self-reported health status, behaviors, and risk factors that are subject to bias [*McCoy and Salerno*, 2010], the overall weight of evidence concerning health impacts is substantial. Even though there remains a comparative paucity of information on effects on physical health, some physical and mental health outcomes are now being assessed in long-term, cohort-based studies [*Kwok et al.*, 2017; *Peres et al.*, 2016; *Rung et al.*, 2016].

Available literature demonstrates that disaster-related impacts to ecosystem services result in significant, long-lasting, and debilitating stress-related health effects among human survivors (Table 1). This is particularly true for those ecosystem services that affect (1) jobs, income, and way of life (e.g., natural resource-based employment such as fishing, many kinds of tourism, and oil and gas extraction); (2) individual, family, and community health (e.g., water and air quality, food safety and supply, housing, and community security); and (3) sense of identity and social connection (e.g., local recreation and sense of place and community). It is also clear that stress is a common and dominant risk factor for long-term human health effects of disasters in the Gulf of Mexico and in other settings and that cumulative stress may lead to a wide range of negative health effects [*Atwoli et al.*, 2016; *Mathur et al.*, 2016]. Similar to findings about Hurricane Katrina and the DWH catastrophe, stress effects are still observed multiple years after the 2011 Indonesian tsunami and the Fukushima tsunami and nuclear reactor accident, including significant impacts of economic losses, family disruption, concerns about compensation, and social disturbance [*Irwantol and Zulfa*, 2015; *Tsujiuchi*, 2015]. *Albrecht* [2005] coined the word "solastalgia" to encompass the feelings of distress and other mental health effects associated with loss of identity and damage to or loss of home, treasured places, and way of life. *Warsini et al.* [2014] were apparently the first to use the term to describe the mental anguish, depression, PTSS, and other psychological issues that people may experience following losses of home, livelihood, and other environmental damage due to natural disasters. Some of the impacts of both natural and technological disasters reviewed here also could be classified as solastalgia.

Certain human populations are more vulnerable to effects of disasters and disaster-associated stress, such as those who have experienced previous trauma (e.g., exposure to Hurricane Katrina in 2005 followed by the DWH in 2010), women, children, the elderly, minorities and those who are economically or socially disadvantaged (Table 1). In addition, recent research on dolphins in areas affected by the DWH oil catastrophe clearly showed negative physiological effects, particularly to adrenal glands (which are involved in stress responses) and lungs [*Schwacke et al.*, 2014; *Venn-Watson et al.*, 2015; *Smith et al.*, 2017], suggesting that such physiological impacts could occur in exposed people as well. All of this information supports our focus on chronic psychological and physiological stress as a valuable indicator of negative human health outcomes and the use of AL as a mediator of stress pathophysiology.

In contrast to other available frameworks, the DPSERH model presented here deals specifically and in detail with disasters and health impacts related to degradation of ecosystem services. Overall, DPSERH offers a number of important benefits not explicitly incorporated in other frameworks related to disasters.

1. It elaborates environmental and health connections, includes sociodemographic and community moderators, and identifies potential physiological mechanisms that may result in a variety of stress-associated negative health outcomes. If supplemented with appropriate environmental, psychological, and physiological data and information from biomarkers and other indicators, DPSERH could be employed to identify specific disaster impacts to one or more critical ecosystem services, possibly measure the associated ALs in affected populations, and assess apparent linkages between increased acute and chronic stress and specific behavioral and physical human health outcomes.

2. The DPSERH model can help policy makers identify which populations are most vulnerable, who may need more help to recover from specific disasters, and what types of health impacts are likely to result from the disaster. For example, children, women, those who are socially, educationally, and economically disadvantaged, the elderly, and men and women who depend directly on specific ecosystem services (e.g., fisheries and tourism) for their livelihoods are most likely to be impacted (Table 1). Long-term effects of chronic and cumulative stress and associated negative health outcomes (e.g., PTSS, anxiety, depression, substance abuse, domestic disturbances, and increased cardiovascular and other inflammatory-based diseases), as well as direct physical and mental traumatic injury, will need both immediate and continuing medical attention following disasters. These populations and health challenges are not the traditional ones considered immediately after a technological disaster such as an oil spill that tends to focus most attention on the direct impacts of oil and toxins on first responders and communities while overlooking or placing less emphasis on other impacts to communities dependent on fisheries and natural resources.

3. DPSERH can help provide a more realistic cost estimate of disasters. DPSERH shows that there are many effects on humans beyond the initial potential for acute injuries or disease and that, therefore, all of these human health effects should receive at least equal attention to that accorded environmental damages in assessing restoration and recovery costs and time frames. The model helps identify additional impacts of disasters that are not currently accounted for in disaster response or planning. Society is currently grossly underestimating the societal costs of disasters such as the DWH. None of the estimates of economic impact due to Hurricane Katrina or the DWH catastrophe nor those of other similar disasters like Hurricane Sandy [*USDOC*, 2013] included realistic assessments of costs incurred due to physical and mental illness and diminished well-being, or for treatment of both short- and long-term health consequences among infants, children, adolescents, adults, and vulnerable subpopulations. To prevent this situation from happening in the future, policy makers should ensure that costs for assessment, treatment, recovery, and monitoring of the health of humans and communities affected by disasters, and the subsequent loss of ecosystem services, are included in calculations of penalties and recovery of damages from responsible parties and in government-supported recovery efforts.

4. Disaster preparedness and recovery planning should incorporate the DPSERH framework to account for human health and well-being requirements. This includes monitoring of selected health and well-being parameters from individual to community levels in order to determine when damage and recovery have occurred and to what extent.

5. In conjunction with other tools, the model could be used to direct investments in improving capabilities of the public health community, biomedical researchers, and environmental scientists and to help guide development and implementation of an integrated, rapid disaster research response capacity [*Lurie et al.*, 2013; *Miller et al.*, 2016; *Sandifer et al.*, 2007]. Special emphasis should be placed on predisaster and postdisaster collection of clinically and diagnostically relevant biomarkers, mental health indices, and other data on psychological and physiological conditions of individuals and groups and monitoring of these indicators over time to quantify stress-related human health impacts and their long-term recovery. Such data could be used in conjunction with the model described here to help attribute causes of observed effects and to assess and document overall recovery and specifically that related to restoration of the full suite and quality of ecosystem services.

6. For future disasters including extreme climate events such as drought, forest fires, heat waves, and floods, this model can help fill the gap between our understanding of immediate human health impacts and the

longer-term impacts to human health and well-being that develop and may persist for extended periods of time due to disaster impacts on ecosystem services on which human communities depend.

5. Conclusions

The DPSERH model described here is among the first to connect damage to ecosystem services from environmental disasters (e.g., hurricanes and major oil spills) to a broad range of human health effects within a comprehensive conceptual framework. To our knowledge, it is the first to connect negative health outcomes associated with acute, chronic, and cumulative stress to disaster-linked degradation of individual and multiple ecosystem services. In addition to elements of the well known and often modified DPSIR (Driver-Pressure-State-Impacts-Response) environmental model, our DPSERH model incorporates the allostatic load concept of cumulative stress and the associated physiological mechanisms of action that result in mental and physical disorders. The framework illustrates how disasters have much broader impacts on human health and well-being at individual to community levels than just direct bodily and property injury. The model allows one to visualize and tease apart the myriad ways by which oil spills, hurricanes, and other disasters cause changes in key ecosystem components and thereby reduce individual and aggregate ecosystem services that support people's livelihoods, health, and way of life. Further, the model elucidates how damage to ecosystem services produces acute, chronic, and cumulative stress in humans and at least some of the physiological mechanisms by which cumulative stress increases risk of adverse psychological and physiological health outcomes. This new and innovative DPSERH tool can be used to improve disaster preparedness and recovery planning for hurricanes, oil spills, and many other kinds of environmental and technological disasters, help target investments in key areas for disaster-focused public health and research capacity building, including predisaster and postdisaster data collection and analysis, and support development and implementation of policies to identify disaster-related human health impacts and include human health response and recovery in damage assessments.

Fundamental requirements for community planning include identifying vulnerabilities, risks, priorities, and information gaps and developing courses of action based on available information. Our DPSERH model helps demonstrate the interconnectedness of cascading incidents across the full spectrum of the community that includes ecosystem services. In addition, it provides an ecosystem framework for holistic community planning related to disasters, such as development of community HIAs and the community-specific emergency support function that addresses public health and medical services. Using this conceptual model, a community can analyze the critical connections among key environmental criteria of "community health," for example, clean air, water, and natural and open spaces.

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