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The spatiotemporal characteristics of environmental hazards caused by offshore oil and gas operations in the Gulf of Mexico

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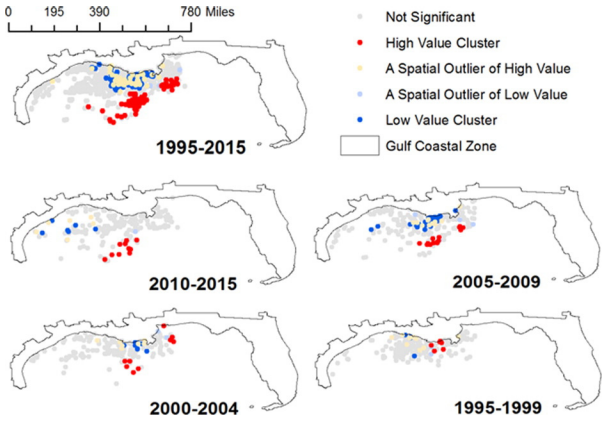
HIGHLIGHTS

- There is currently high interest in exploring and understanding environmental hazards caused by oil and gas operations in the Gulf of Mexico.
- Spatial and temporal clusters of the environmental hazards in the Gulf of Mexico are identified, analyzed, and mapped using spatial statistical and cross variogram models.
- A spatial correlation matrix is designed based on the codispersion coefficient in order to quantify the spatial correlation among different environmental hazards.
- The identified and assessed spatial clusters provide insight to hazard management, environmental protection, and ecosystem conservation.

GRAPHICAL ABSTRACT



Spatiotemporal clustering of twelve types of environmental hazards caused by offshore oil and gas operations in the Gulf of Mexico is analyzed using local Moran's *I*, Getis-Ord G, and a designed spatial correlation coefficient matrix.

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ABSTRACT

Marine ecosystems are home to a host of numerous species ranging from tiny planktonic organisms, fishes, and birds, to large mammals such as the whales, manatees, and seals. However, human activities such as offshore oil and gas operations increasingly threaten marine and coastal ecosystems, for which there has been little exploration into the spatial and temporal risks of offshore oil operations. Using the Gulf of Mexico, one of the world's hottest spots of offshore oil and gas mining, as the study area, we propose a spatiotemporal approach that integrates spatial statistics and geostatistics in a geographic information system environment to provide insight to environmental management and decision making for oil and gas operators, coastal communities, local governments, and the federal government. We use the records from 1995 to 2015 of twelve types of hazards caused by offshore oil and gas operations, and analyze them spatially over a five year period. The spatial clusters of these hazards are analyzed and mapped using Getis-Ord Gi and local Moran's *I* statistics. We then design a spatial correlation coefficient matrix for multivariate spatial correlation, which is the ratio of the cross variogram of two types of hazards to the product of the variograms of the two hazards, showing a primary understanding of the degrees of spatial correlation among the twelve types hazards. To the best of our knowledge, it is the first application of spatiotemporal analysis methods to environmental hazards caused by offshore oil and gas operations; the proposed

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methods can be applied to other regions for the management and monitoring of environmental hazards caused by offshore oil operations.

1. Introduction

Coastal and marine ecosystems are the main support for social wellbeing and economic prosperity, and continually more population are living in coastal regions (de Groot et al., 2012; Folke et al., 2002; Osterblom et al., 2011). At the same time, coastal and marine environment is experiencing significantly increasing threats from human activities, such as oil and gas drilling incidents, runoff from agricultural lands, and climate change, among others (NGS, National Geographic Society, 2013). One of the most challenging topics of the current world is how can people have sustainable development in the environment, resources, and society. The maintenance of a sustainable functioning of coastal and marine ecosystems depends on societies' and governments' decisions on how to monitor, change, and balance the supply of marine ecosystems (Costanza et al., 2014; Halpern et al., 2012; Worm et al., 2006).

Oil and gas operations are a main source of environmental pollution to ocean ecosystems and the environment (Islam and Tanaka, 2004). Besides agricultural land runoff, oil and gas drilling increasingly causes environmental threats to the Gulf of Mexico. There are >51,000 oil and gas wells aggregated in the northwestern Gulf, and among them about 27,000 abandoned oil and gas wells have not been checked for any potential environmental problems (Donn, 2010). According to the World Offshore Accident Dataset (DNVGL.com), one of the most reliable databases of offshore oil and gas failures and incidents, there are 6451 official records of incidents; geographically there have been 3505 in the North Sea, 1685 in the Gulf of Mexico, 45 in the Mediterranean, and another 1216 in all other regions across the world; the Gulf of Mexico ranks the second among the list of offshore oil incidents. Furthermore, offshore oil and gas incidents both directly and indirectly result in significant environmental hazards with huge amount of oil spills and gas blowouts in the ocean, which puts ocean ecosystems and coastal environments at severe risks.

Oil affects most components of marine ecosystems. Some components are more vulnerable to physical impacts, and some are sensitive to chemical toxicity, but others are relatively resilient to both. The main effects of oil include: (1) large quantity oil coats the feathers of seabirds and fur of some marine mammals. Oil can be ingested by mammals and turtles therefore resulting in potentially toxic effects. Mammalian and avian breeding failure can be exacerbated by some tissue hydrocarbons. (2) Fish eggs and larvae are more likely to be harmed by toxic effects than adults. Furthermore, the Polycyclic Aromatic Hydrocarbons (PAHs) can be mutagenic and carcinogenic. (3) Invertebrates' sensitivity to oil varies significantly. Some barnacles and limpets can withstand a degree of oiling, but corals are often the most sensitive. Accumulated oil residues may cause secondary health effects on shellfish. (4) Individual planktonic organisms may experience toxic effects from oil, but the plankton might be relatively unaffected by oil with an increasing population of plankton after certain periods; oil does not always stick to seaweeds because of their mucilaginous coating. Seagrasses may be affected, and the species may shift from perennial species to more rapidly growing annual ones. Detailed effects on marine wildlife and habitats are discussed by USFWS (2010).

The incidents of offshore oil and gas drilling are a significant anthropogenic source of gas hydrocarbons in the marine environment and can cause very hazardous environmental consequences. For example, the severe situations developed in the Gulf of Mexico caused by the Deepwater Horizontal oil spill occurred in 2010. The levels of methane in surface waters can exceed over 100 times the normal concentrations. These type of accidents in fact typically cause long-term releases of large amounts of natural oil and gas into ocean and coastal ecosystems. NOAA reported: “Obviously the Gulf is not as healthy as it was”, and many surveyed scientists agreed that the Gulf of Mexico was at 73 on a 0 to 100 healthy scale, which has now dropped to 65 (AL.com, 2015). These accidents drastically changed the composition and biomass of the water fauna and caused mass mortality of many organisms, including fish and seabirds. Patin (1999) summarized the detailed effects of natural gas on marine life. Medical toxicology typically distinguishes three levels of intoxication by methane effects on vertebrates: (1) light, causing reversible temporary impacts on the central nervous (CNS) and cardiovascular systems' functions, (2) medium, resulting in increasing number of leukocytes in the peripheral blood and deep functional changes in the cardiovascular systems and CNS, and (3) irreversible disturbances of the cerebrum, alimentary canal, and heart tissues are typically caused by heavy level intoxication of methane.

Although scientists, communities, and governments have done extensive studies of the ecosystem and environmental threats due to offshore oil operations, little has been explored about spatial and temporal characteristics of the environmental hazards caused by offshore oil and gas operations. Offshore oil and gas drilling entails potential severe consequences to the pollution of the environment, direct and indirect threats to ocean and coastal ecosystems, and deterioration of the security of energy supply. There are urgent needs for operators, communities, and governments to understand the spatiotemporal properties of the consequences of offshore oil and gas drilling, which typically result in significant risks and damage to both ocean and coastal environment and ecosystems.

In order to fill the knowledge gap, we propose a regional study of offshore oil and gas operation incidents and provide insight for spatial and temporal decision making for hazard management and monitoring. The organization of this study includes the introduction of the study area within the Gulf of Mexico in Section 2, the spatial analysis methods in Section 3, a summary of the results in Section 4, discussions in Section 5, and in Section 6 a concise conclusion.

2. Study area and data

The Gulf of Mexico (Fig. 1) is one of the most attractive US oilfields due to its geopolitical stability, established and increasing oil operation infrastructure, and proximity to refineries. The US Federal offshore region of the Gulf of Mexico provides about 17% of total US crude oil production and about 5% of total dry gas production; along the Gulf coast, there is located >45% of US petroleum refining capacity and about 51% of total US natural gas processing plant capacity (US EIA). It has been a hot spot for oil and gas companies, and many large oilfield service firms have experience in increases of revenues.

According to the US EIA, total US oil production will increase by 48% in 2019 compared to 2012 (US EIA, 2014). This rise will be mainly driven by unconventional oil and gas production from shale and tight oil fields. However, shale oil output is expected to decline after 2020 since oil companies have exhausted production from their most prosperous areas. On the other hands, the Gulf of Mexico is very likely to provide more stability to US oil production in the long run given the vast reserves and strong infrastructure in the region. Oil product from the Gulf is expected to rise from around 1.5 million barrels a day to over 1.9 million barrels a day in the year 2019. The oil output will be from significantly increasing deep-water operators in the Gulf, because more oil are produced by drilling fewer wells as compared to onshore producers.

The US Bureau of Safety and Environmental Enforcement (BSEE) has detailed reports of offshore oil drilling incidents from 1995 to 2015