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Development of artificial intelligence approach to forecasting oyster norovirus outbreaks along Gulf of Mexico coast

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ABSTRACT

This paper presents an artificial intelligence-based model, called ANN-2Day model, for forecasting, managing and ultimately eliminating the growing risk of oyster norovirus outbreaks. The ANN-2Day model was developed using Artificial Neural Network (ANN) Toolbox in MATLAB Program and 15-years of epidemiological and environmental data for six independent environmental predictors including water temperature, solar radiation, gage height, salinity, wind, and rainfall. It was found that oyster norovirus outbreaks can be forecasted with two-day lead time using the ANN-2Day model and daily data of the six environmental predictors. Forecasting results of the ANN-2Day model indicated that the model was capable of reproducing 19 years of historical oyster norovirus outbreaks along the Northern Gulf of Mexico coast with the positive predictive value of 76.82%, the negative predictive value of 100.00%, the sensitivity of 100.00%, the specificity of 99.84%, and the overall accuracy of 99.83%, respectively, demonstrating the efficacy of the ANN-2Day model in predicting the risk of norovirus outbreaks to human health. The 2-day lead time enables public health agencies and oyster harvesters to plan for management interventions and thus makes it possible to achieve a paradigm shift of their daily management and operation from primarily reacting to epidemic incidents of norovirus infection after they have occurred to eliminating (or at least reducing) the risk of costly incidents.

1. Introduction

Norovirus is a highly contagious virus (Atmar et al., 2008; Hall et al., 2012; Teunis et al., 2008) and a primary cause of gastroenteritis (de Graaf et al., 2016). While norovirus can be transmitted from person to person, foodborne transmission is an important route for the spread of the virus (Verhoef et al., 2015). Many foodborne norovirus outbreaks are attributed to oysters harvested from waters contaminated with sewage (Fitzgerald et al., 2014; Wall et al., 2011). Oyster growing areas are usually located in nearshore shallow waters that are exposed to land-based contaminants and marine source pollution (Campos et al., 2017a). Therefore, primary sewage sources of oyster norovirus are malfunctioning municipal wastewater treatment plants, sanitary sewer overflow, human wastes discharged from marine vessels, and urban or agricultural runoff (Berg et al., 2000; Fitzgerald et al., 2014; Worgan et al., 2008). The filter-feeding behavior of oysters allow them to obtain food by pumping water through gills and concentrate viruses within their edible tissues up to 100 times the level in the growing water depending on the level and source of fecal pollution, hydrographic characteristics, and environmental parameters such as water temperature and salinity (Burkhardt and Calci, 2000; Campos et al., 2015; Nappier et al., 2008). Therefore, oysters are susceptible to norovirus contamination.

In order to protect human health, the National Shellfish Sanitation Program (NSSP)—a cooperative program between the U.S. Food and Drug Administration (FDA), state regulatory agencies, the Interstate Shellfish Sanitation Conference, and the shellfish industry, requires shellfish producing states to monitor shellfish harvesting waters to determine that they are safe before harvesting is permitted (NSSP, 2015). While a study by Pringle et al. (2015) found a strong correlation between the reductions of norovirus and Male-Specific Coliphage (MSC) concentrations in wastewater (Pringle et al., 2015) and suggested that MCS could be used as an indicator for norovirus in wastewater treatment plants, fecal coliform bacteria are commonly monitored by shellfish sanitation programs as an indicator organism for the quality of the oyster growing waters and the end product. Several studies have shown the inadequacy of fecal coliform bacteria as an indicator of shellfish quality because a variety of infectious human pathogens (such as norovirus) were detected in oysters with the acceptable level of fecal coliforms (Atmar, 2010; Le Guyader et al., 2006; DePaola et al., 2010). As a result, oyster norovirus outbreaks have constituted a growing threat to both the public health and the shellfish industry. The

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unprecedented oyster norovirus outbreaks from January – April 2017 in the Pacific Northwest sickened hundreds of oyster consumers in Canada and the U.S.A. (http://www.phac-aspc.gc.ca/phn-asp/2017/outbreak-norovirus-eclosion-20170327-eng.php; http://www.kingcounty.gov/depts/health/communicable-diseases/disease-control/outbreak/oysters.aspx).

Norovirus is commonly detected by using molecular methods, such as Reverse Transcription Polymerase Chain Reaction (RT-PCR) and real-time PCR (Flannery et al., 2013; ISO, 2013; Kageyama et al., 2003; Vinjé et al., 2004; Knight et al., 2013; Vinjé, 2015; Woods et al., 2016), which are currently considered as highly sensitive and specific, and cost-effective methods (Hong et al., 2015; Wyn-Jones and Sellwood, 2001). Woods et al. (2016) presented an efficient detection and characterization of norovirus in several oyster-associated outbreaks using an ultracentrifugation protocol which incorporated extraction controls and real-time RT-qPCR. In addition to PCR methods, recent studies focused on the development of biosensors due to their high sensitivity and short processing time (Hong et al., 2015; Hwang et al., 2017; Velusamy et al., 2010). Biosensors generally involve a bio-recognition element coupled to an appropriate transducer to detect an analyte of interest (Turner et al., 1987). Hong et al. (2015) proposed an electrochemical biosensor for the detection of norovirus. The concentration of norovirus was measured in a realistic environment with high sensitivity ($R^2 = 0.968$), demonstrating a potential of biosensors for norovirus detection. However, there are no reported applications of biosensors for in-situ detection of norovirus in oyster growing waters due partly to the high-cost of biosensors. It might be feasible in the future to deploy biosensors in oyster growing waters for detection of norovirus.

In spite of the extensive efforts made in the detection of oyster norovirus outbreaks and the implementation of sanitation control plans for oyster growing areas, effective and efficient prediction tools that are able to detect oyster norovirus outbreaks on a daily base are still lacking particularly for field-scale detection and management of norovirus. The development of a robust predictive tool for oyster norovirus outbreaks requires a sound understanding of environmental factors affecting the abundance and distribution of norovirus in the coastal water environment. As a result, increasing efforts have been made in the identification of environmental factors and the development of modeling tools for predicting oyster norovirus outbreaks (Wang and Deng, 2012, 2016; Chenar and Deng, 2017). Wang and Deng (2016) developed a novel probability-based Artificial Neural Network model using environmental and norovirus outbreak data collected from Louisiana oyster harvesting areas along the Gulf of Mexico coast, USA, demonstrating the great promise of Artificial Intelligence (AI) techniques (particularly Artificial Neural Networks) in predicting infectious disease outbreaks by learning from the data associated with historical incidents.

The overall goal of this paper is to present an effective and efficient modeling tool for proactively managing and ultimately eliminating oyster norovirus outbreaks. To that end, the specific objective of this paper is to develop an AI-based forecasting model for predicting oyster norovirus outbreaks in advance with sufficient lead time to allow management interventions.

2. Material and methods

2.1. Study area

The Northern Gulf of Mexico coast is the largest oyster-producing body of water in the world. Therefore, this study focuses on the most important oyster harvesting areas along the Gulf Coast of Texas, Louisiana, and Mississippi, including 30 areas in Louisiana, the Copano Bay and the San Antonio Bay in Texas, and Area 2C in Mississippi, as shown in Fig. 1.

The swamp and marsh regions along the oyster growing waters are popular recreational places for camps and houseboats. Some of the recreational facilities have poorly functioning or even failing septic systems, releasing sewage directly to the waters or wetlands connected to oyster harvesting areas (Corkern and Bankston, 2002). In addition, some small towns in the coastal regions have limited sanitary sewer systems and wastewater treatment capacities, producing sanitary sewer overflow (SSO) during heavy storm events and releasing the SSO to oyster growing waters (EPA, 2009; Tetra Tech, 2012). Due to the distributed and uncertain nature of the potential sewage and norovirus sources and the lack of published reports documenting the connection of a specific norovirus source to any reported oyster norovirus outbreaks, it is challenging to directly include the potential sources in a predictive model.

2.2. Data collection and processing

Two types of time series data were collected, including epidemiological data for historical oyster norovirus outbreaks and environmental data for environmental predictors or indicators of oyster norovirus outbreaks. The epidemiological data were obtained from various online data sources. Specifically, historical norovirus outbreaks in Louisiana oyster harvest areas were collected from Louisiana Morbidity Reports released by Louisiana Department of Health and Hospitals (http://www.dhh.la.gov/index.cfm/newsroom/category/126). Four clusters of norovirus outbreaks were reported for Areas 6 and 7 for the periods of January 25–February 23, 1996 (involving 233 cases), December 22, 1996–January 3, 1997 (involving 493 cases), March 12–28, 2002, and March 6–24, 2010, respectively. Another reported outbreak took place from March 1–31, 2002 in Area 1. Two clusters of norovirus outbreaks were reported for Area 3. Oysters harvested from December 10–21, 2007 and from March 20–25, 2010 were recalled due to reported norovirus outbreaks in this area. It was reported that Area 7 was closed on March 24, 2010 after 14 people became ill due to the consumption of norovirus contaminated raw oysters harvested inferably between March 6 and 24, 2010 (LDHH, 2010). Area 13 was closed on March 30, 2010 after 19 people were infected by norovirus due to eating raw oysters harvested from this area between March 27 and 30, 2010 (LDHH, 2010). There was another reported norovirus outbreak in May 2012 in Areas 23, forcing the closure of Areas 23 on May 8, 2012 and the recall of all oysters harvested from this area since April 26, 2012 (http://new.dhh.louisiana.gov/index.cfm/newsroom/detail/2484). Moreover, Area 30 was closed on January 4, 2013 after 12 people were infected with norovirus due to consumption of raw oysters harvested between December 28, 2012 and January 4, 2013 from this area (http://www.dhh.louisiana.gov/index.cfm/newsroom/detail/2732). In Mississippi, two outbreaks, associated with the consumption of norovirus-contaminated raw oysters harvested from Area IIC located in the Mississippi Sound, occurred on January 5 and February 24, 2009 (http://www.issc.org/msoysterrecall). In Texas, the U.S. Food and Drug Administration (FDA) advised consumers to avoid eating raw oysters harvested in the period of February 1–24, 2007 from the San Antonio Bay due to a reported norovirus outbreak. Oyster growing areas in the San Antonio Bay were closed by the Texas Department of Health Services on February 24, 2007 (http://www.outbreakdatabase.com/details/bull-and-oyster-san-antonio-bay-oysters-2007/?). Moreover, all oysters, harvested from the San Antonio Bay between November 16 and 25, 2009, were recalled again by the Texas Department of State Health Services due to another reported norovirus outbreak in this area. It was reported that approximately 12 people became ill with norovirus after eating oysters harvested from this area (http://outbreakdatabase.com/details/san-antonio-bay-oysters-2009/?vehicle=oyster&country=US). The U.S. Food and Drug Administration (FDA) further warned consumers not to eat oysters harvested between 26 December 2013 and 9 January 2014 from Copano Bay, Texas, after they were linked to a norovirus outbreak that caused six norovirus illnesses in Louisiana residents (https://wayback.archive-it.org/7993/20170112222925/http://www.fda.gov/NewsEvents/Newsroom/PressAnnouncements/ucm382247.htm).

The environmental data from 1996 to 2014 were downloaded for six