INVENTORY MANAGEMENT OF CHOLERA VACCINATIONS IN THE EVENT OF COMPLEX NATURAL DISASTERS

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ABSTRACT

The paper explores the considerations and recommendations for mass vaccination campaigns in response to natural disasters and their secondary effects, specifically cholera epidemics and the vaccine stockpile necessary to effectively treat the disease. Cholera is a significant post disaster risk to an already affected population. As one of the first responders to these disasters, the Marine Air Ground Task Force (MAGTF) must consider an epidemic cholera outbreak as a threat to mitigate in the planning process for Humanitarian Aid and Disaster Relief (HADR) scenarios. This project considers these factors based on former HADR events to determine optimized stock pile of vaccinations.

INTRODUCTION

Natural disasters have the ability to change the course of history. Whether it is a 2004 tsunami in Southeast Asia or a 2010 earthquake in Haiti, these events mobilize a global response in a short time in order to assist the local government in saving lives. As one of the first responders to these disasters, the Marine Air Ground Task Force (MAGTF) must consider an epidemic cholera outbreak as a threat to mitigate in the planning process for Humanitarian Aid and Disaster Relief (HADR) scenarios. The logistics associated with HADR are extremely difficult, and planners often do not have the resources to look at the second- and third-order effects of a disaster, which have the potential to endanger hundreds if not thousands of lives.

Endemic and epidemic-prone cholera spreads after natural disasters due to increased contamination of drinking water, austere and unsanitary living conditions, and the malnutrition resulting from lack of food [13]. As a result, the World Health Organization (WHO) reported over 470,000 cases of cholera in the 2010 Haiti earthquake alone and over 6,500 deaths associated with the disease [12]. Since cholera most often occurs in developing countries where water and wastewater mix, the post-natural disaster environment is a breeding ground for this disease. Between 2004 and 2013, The World Disaster Report (2014) states there were 2,021 earthquake or flood disasters, each with the potential to infect hundreds of thousands of people. These disasters and their associated outbreaks have begun to gain global attention.

As of July 2014, the WHO has stated a need for an oral cholera vaccine (OCV) stockpile with at least two million doses. The WHO recommended that this stockpile be used preemptively versus reactively due to the short duration of many cholera outbreaks, advising that an epidemic may be over before the vaccinations can be distributed to the affected population [7]. The use of these vaccines during emergency response situations will provide a short-term intervention against potential cholera outbreaks, while populations affected by disasters are most at-risk.

The goal of any HADR operation is to reduce casualties and human suffering of the population affected by the disaster. The focus of our research is to assist in the decision making process to help mitigate the spread of secondary disasters, such as a cholera epidemic, using optimal inventory levels of vaccines and timing of dispensing at early onset.

NATURAL DISASTERS

The Federal Emergency Management Agency (FEMA) is one the leading sources for disaster information within the United States. FEMA's definition of a natural disaster can be summarized as an event that results "in a minimum of 100 deaths/injuries or result in over $1 million worth of damage" [1][4]. High impact or substantial damage must occur from the disaster in order for federal relief efforts to be authorized. Internationally, disasters are classified and analyzed by the Centre for Research on the Epidemiology of Disasters (CRED). In order to be included in the Emergency Events Database (EM-DAT), it must meet CRED's definition of a disaster. This includes at least one of the following criteria: "10 or more people killed, 100 or more people affected, declaration of a state of emergency, call for international assistance" [3].

The impacts of natural disasters can encompass a broad range; comprehensively they are generally classified as 'direct' and 'indirect' impacts. Direct impacts are caused by the disaster itself, whereas indirect impacts are caused by the consequences of living in a post disaster state [9]. Indirect impacts, or secondary disasters, also referred to as "second web of death and destruction" have the ability to increase human suffering more than the direct impacts from the original disaster [9].These indirect impacts can manifest as secondary disasters when outbreaks or epidemics of transmittable and/or water borne pathogens occur [9]. The severity of outbreak and disease transmission post disaster can be associated with the size of the population displaced from primary residences and basic infrastructure. The severity can also be determined by the overall status of healthcare of the population, to include medical services, vaccination rates, and availability and adequacy of water sanitation [3]. It is not uncommon for the surviving population to continue to dwell in their damaged homes or in temporary camps, which are usually in a high state of insanitation post disaster' these conditionsfacilitate the transmission of disease between households [8].

Cholera, whether epidemic or endemic, is one of the diseases that increases in transmission post natural disaster. This transmission is even more heightened in developing nations. After the December 2004 Indonesian tsunami, health assessments conducted two weeks post disaster found that 85% of the affected population that continued to drink from unprotected wells, reported diarrhea within the same time period [3]. Following the 2005 Pakistan earthquake, a cholera outbreak was reported within a makeshift displaced persons camp. Despite over 750 reported cases, the outbreak was controlled after sufficient water and sanitation facilities were provided to the entire population affected by the earthquake [3].

CHOLERA STOCKPILE

In 2011, the World Health Assembly implemented Resolution 64.15 calling for the reduction of cholera through the use of vaccines [11], but suggested that vaccines would not serve as a substitute for cholera treatment and prevention, but as a parallel effort to help reduce the spread of the disease [5]. It was determined that an appropriate stockpile would alleviate any demand shortfalls that may cause political unrest and potential ethical sensitivities when choosing what portion of an at risk population to vaccinate.

The WHO has determined that the initial stockpile size should be two million doses [5]. Factors used in determining the initial stockpile include a nation's desire for a national vaccination campaign, implementation of a vaccination campaign, the anticipated percentage of the population who will participate in the campaign, vaccine availability, and funding availability [7]. While many variables play a role in stockpile determination, every effort must be made to ensure vaccines are available when needed.

THE MODEL

Our effort in this research is primarily to determine the optimal number of vaccines to store in the national stockpile in order to ensure effective distribution to an affected population during complex disasters. Our model, the Cholera Vaccine Inventory Model (CVIM), takes into account the shelf-life of vaccines, costs of over and under stocking, and any salvage value the vaccine may have after expiration. The CVIM optimizes the number of vaccines to manufacture and hold in the stockpile in order to reduce overall costs or net penalties. However, many other contributing factors affect the results of this model.

In order to determine the factors that influence the CVIM and more accurately calculate optimal quantities, we use simulation. The Natural Disaster and Cholera Simulation Model (NDCSM) incorporates proportions of complex natural disasters occurring in specified regions (continents), the anticipated number of cholera cases, and case fatality rates associated with the disease to attempt to replicate the scenarios. Both these models, CVIM and NDCSM, help us analyze appropriate contributing factors to ensure accuracy in planning for a national cholera stockpile based on associated costs and probability of outbreak occurrence.

NATURAL DISASTER AND CHOLERA SIMULATION MODEL

The NDCSM seeks to forecast the number of cholera causing natural disasters that will occur in the defined regions of the world in any given year. This information is used to predict the number of cholera cases that will result in such a disaster, to assist emergency planners in preparing for a secondary disaster. The simulation model incorporates several factors in relation to natural disasters and cholera. These factors can be seen in Table 1.

Table 1: Factors Incorporated into Simulation Model

1.	Types of disasters that cause a secondary cholera outbreak.
2.	Probability of cholera causing natural disaster occurring in any given region in a given year.
3.	Distribution of cholera cases in a given region given there was a cholera causing natural disaster.
4.	Probability of death given the cholera vaccination was given.
5.	Probability of death given the vaccination was not given.

The research conducted focuses solely on those natural disasters that can result in a secondary natural disaster of cholera infection. The usual source of a cholera epidemic is through the feces contamination of the local water and/or food sources [2]. This implies that cholera-causing natural disasters must enable the mixing of feces and the water/food supply of a community or nation. We, therefore, focus on natural disasters in which this is probable, such as tropical cyclones, ground movement, floods, tsunamis, landslides, and tropical storms.

The inputs needed by NDCSM to obtain the required outputs include region case fatality rates, annual cholera cases in a region per year, vaccine effectiveness, probability of distributions of annual cholera cases, and natural disaster occurrences.

We collected data from the Emergency Events Database (EM-DAT). We sorted the data by the natural disaster types mentioned above, between the years 1915 and 2015, in order to build a more robust data set for the NDCSM. We then sorted disasters with the likelihood of a secondary cholera outbreak by type, including tropical cyclones, ground movement, floods, tsunamis, landslides, and tropical storms. Within each disaster type, we then sorted the data by region and year of occurrence. We aggregated the data by region and occurrence to determine the percentage of disasters that occurred in each region in a given year, and averaged these results over the last 100 years, 40 years, and 20 years.

CHOLERA CASES AND CHOLERA CAUSING NATURAL DISASTERS

The 2014 World Health Organization Cholera Report provided the information required to find a probability distribution of cholera cases in the different regions. We took 20 years (1993–2013) of report data including number of cases per region, deaths associated with cholera, and the case fatality rate (CFR). This data gave us the ability to fit probability distributions and run simulations for each region in order to predict the number of cholera cases per year per region. It was necessary to narrow down the scope of these cases to those associated only with cholera-causing natural disasters as defined earlier in this paper. Therefore, we incorporated the probability of those disasters for accuracy. The simulation outputs provided the number of cholera causing natural disasters that occur in each region, and our assumption was that if a natural disaster occurs in a region, it will result in a cholera outbreak. This allows a conservative estimate from the simulation.

Case Fatality Rate

The World Health Organization Cholera Report provides the CFR for each region by year with some exceptions. This rate is associated with deaths from cholera without vaccinations. In order to determine the impacts of the vaccination and ultimately, how many of the vaccinations should be stocked, we determined the number of deaths irrespective of whether the affected population is vaccinated or not. In order to simulate this data, the CFR for each region was averaged over the 20-year period. This percentage was then used to determine the CFR of the simulated number of cases. We multiplied this rate by the effectiveness of cholera vaccinations (85%) to determine the case fatality rate of epidemic cholera given that the vaccine was available and given to the affected population [3].

For the 10,000 simulations we conducted the mean was 260,527 cases of cholera in any given year. The 95th percentile was at 521,010 cases. While the mean is low considering the number of natural disasters that occur, the standard deviation of the mean is extremely high at 3.1 million cases which are shown in the disparity between the 95th percentile (521,010) and 100th percentile (315,000,000). The variability in the simulation demonstrates the stochastic nature of both natural disasters and the appearance of cholera. This amount of variability makes predicting the outcome difficult. Therefore, we used the Bootstrap Tool to increase the accuracy of the simulation.

Bootstrapping is a tool within Crystal Ball that estimates the accuracy of statistics [8]. It "works by randomly sampling the forecast data and then creating distributions of the statistics from each sampling" [8].We then use these distributions to execute the simulation for 200 trials 1000 times each in order to get a good sampling from the simulation. The results show the mean total cases of cholera remains about the same showing 316,868, a difference of approximately 56,000 cases from the original simulation. However, the standard deviation of the mean of means dropped by over 2.6 million.

Table 2. Comparative statistics between 10,000 trial simulation and bootstrap

	Simulation	Bootstrap
Mean	260,527 cases	316,868 cases
Standard Deviation	3.1 million cases	483,808 cases
95% certainty	521,101 cases	415,858 cases

Comparative statistics between the simulation and the bootstrap are shown in Table 2. This data shows that while the overall mean has increased by over 50,000 cases, the standard deviation or variability in the data has decreased significantly. While the standard deviation is still high compared to the mean, it gives a better analysis of the situation than simulation alone.

CHOLERA VACCINE INVENTORY MODEL

The CVIM, or newsvendor model, is an analytical optimization model that seeks to estimate the optimal number of cholera vaccines to manufacture and store in order to reduce penalties or costs.
This newsvendor optimization model incorporates several factors in relation to optimal stocking of cholera vaccines. The inputs to this model are given in Table 3.

Table 3: Factors Incorporated in the Inventory Model

1. Random demand of cholera vaccines.
2. Shelf-life of vaccines.
3. Distribution of cholera cases in a given region give there was a cholera causing natural disaster.
4. Overstock and under stock penalties associated with the cholera vaccine.
5. Salvage value of the vaccine, if any.

In order to determine the penalty associated with having too much of the vaccine, it was necessary to determine the costs associated with making, storing, and transporting the vaccinations required for each affected individual. The cost to produce each dose of OCV is $10.00 and each person requires two doses [10].

For the purpose of military distributed vaccination campaigns, we first took known operating costs of a United States Air Force (USAF) C-17 transport aircraft of just over $23,000 per hour, with the longest trip taking approximately five hours, resulting in an estimate of the cost of delivery to be approximately $115,000.

In order to determine the cost associated for not having a vaccine we determine the value of statistical life (VSL). Since cholera is deadly, the cost of not having the vaccine is the loss of life with the disease. We use the data from health and life insurance companies to associate monetary value of life. This is the "international standard most private and government-run health insurance plans worldwide use to determine whether to cover a new medical procedure. More simply, insurance companies calculate that to make a treatment worth its cost, it must guarantee one year of 'quality life' for $50,000 or less" [6] Since this is the international standard, we use the cost of human life for not having the vaccine in stock to be $50,000 per person.

Our computational experiment estimates the optimized inventory level was 3,205,536 vaccines. This number is derived from 200 years of future demand based on the LogNormal distribution and the over stocking and under stocking penalty. The high under stocking penalty compared to the low overstocking penalty results in the optimization model ensuring that all demand is met in each of the 200 scenarios. As the number of vaccines increase in the stockpile, the average net penalty continues to decline until it reaches 3,205,536. Once it goes over this optimal number, the average net penalty begins to increase slightly as can be seen in Figure 1. This increase is due to the cost of over stocking.

Figure 1: Average net penalty associated with given number of cholera vaccinations

CONCLUSION

This study concludes that with the increasing frequency of natural disasters, outbreaks of secondary epidemics such as cholera are extremely likely. In the most recent case of the 2010 Haitian earthquake, cholera affected more people than were killed in the earthquake itself. If the United States government and military are to continue to participate in humanitarian aid and disaster relief operations across the globe, proper planning and prepositioning of assets or an increase in national stockpile of OCV needs to be addressed. Epidemic prevention is far easier than fighting an epidemic that is already spreading through an affected population. The use of the USMC MAGTF for initial operations can assist HADR planners in mitigating potential outbreaks in order to minimize human suffering. This study also recognizes the cost of such a stockpile has its limitations, but recognizes the number of lives saved through the use of a stockpile outweighs associated inventory and supply chain costs.

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