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Haiti Cholera and a Plethora of Haiti Medical Condition Data

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Abstract
In January 2010, a 7.0 magnitude earthquake struck Haiti, killing over 200,000 people and further disrupting healthcare and sanitation infrastructure in the country. In the aftermath of the earthquake, at the request and direction of UNESCO, international workers from many countries arrived in Haiti to assist in the response and recovery efforts. Nine months following the earthquake, in Week 42 of 2010, cholera broke out and spread across the country. Before the outbreak, no cases of cholera had been identified in Haiti for more than a century, and the Caribbean region as a whole had not been affected by cholera outbreaks. The population's lack of prior exposure and acquired immunity likely contributed to the severity of the outbreak. Following the outbreak of cholera, Doctors Without Borders (DWBs) engaged a Team of environmental epidemiologists, empirical data analysts and statisticians from North Carolina State University (NCSU) and Coastal Carolina University (CCU) to address the circumstances of the outbreak and spread of Cholera across Haiti. The Team quickly reported that the data showed that there were spatial sequential high-density outbreaks at all of the seven Haiti Public Health Centers and that Cholera had been introduced by and was being carried across Haiti by people who suddenly appeared and were infected with and carrying the disease. The Team reported this to DWBs, who determined that Nepalese peacekeepers sent to Haiti by UNESCO were carrying the disease and introduced to Haiti. Moreover, the NCSU-CCU Team correctly forecasted further outbreaks and spreads of the disease over a several year period [1, 2]. In addition to Cholera, other medical condition data were also collected at the seven Haiti Public Health Centers. This report describes temporal and spatial relationships of the Cholera cases across Haiti and also those other medical condition data and their apparent correlations to Cholera or not. As Cholera outbreaks are more common in warmer climates, and as global climate change is advancing, associated medical conditions, as found to be related to the 2010 and subsequent Cholera outbreaks in Haiti, may portend future outbreaks.

Keywords: Haiti Earthquake, Cholera, Medical Conditions

Introduction

The 2010 Haiti Cholera outbreak was the first modern large-scale outbreak of Cholera, a disease once considered beaten back largely due to the invention of modern sanitation. The disease was introduced to Haiti in October 2010, not long after the disastrous earthquake earlier that year, and since then Cholera has spread across the country and become endemic, causing high levels of both morbidity and mortality. Since 2010, nearly 800,000 Haitians have been infected by cholera, and more than 9,000 have died, according to the United Nations (UN). Cholera transmission in Haiti today is largely a function of eradication efforts including water, sanitation, hygiene education, and oral vaccination. Early efforts were made to cover up the source of the epidemic, but revealed the temporal and spatial history of the spread, and reported those findings to DWBs, who in turn focused on a United Nations (UN) Peacekeeping force from Nepal that was responsible for the introduction and spread of the Cholera Further, the investigations of journalist Jonathan M. Katz and epidemiologist Renaud Piarroux, documented the results of contamination by the infected UN peacekeepers deployed from Nepal. In terms of total infections, the outbreak has since been surpassed by the war-fueled 2016–2021 Yemen Cholera outbreak, although the Haiti outbreak is still one of the most deadly modern outbreaks. After a three-year hiatus, new Cholera cases reappeared in October 2022, as predicted that they would [1, 2].

It is of note that Cholera is caused by the bacterium Vibrio cholerae that when ingested can cause diarrhea and vomiting within several hours to 2–3 days. Without proper treatment including oral rehydration, cholera can be fatal. The suspected source of

Vibrio Cholerae in Haiti was the Artibonite River, from which most of the affected people had consumed the water. Each year, tens of thousands of Haitians bathe, wash their clothes and dishes, obtain drinking water, and recreate in this river, therefore resulting in high rates of exposure to Vibrio Cholerae. Figure 1 documents the original outbreak and spread, though the right side of the map has been distorted. In Figures 2 and 3, the cumulative cases

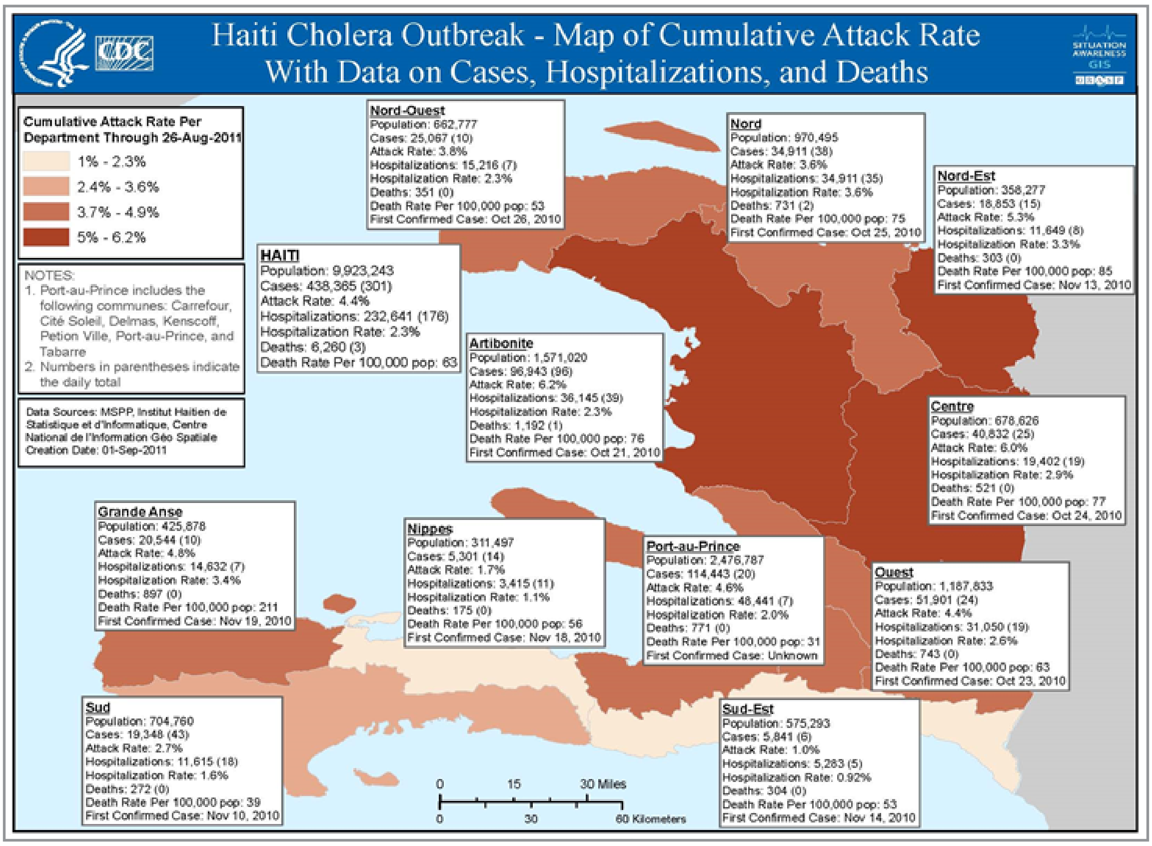


Figure 1: The synopsis of the outbreak and spread of Cholera in and across Haiti in 2010.

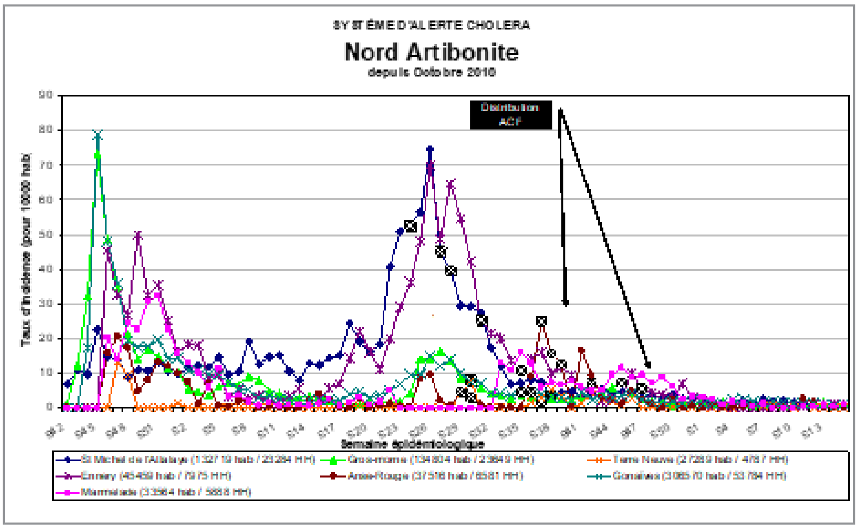


Figure 2: The cumulative cases of cholera at the seven Public Health Centers as provided to the US Centers for Disease Control & Prevention (the US CDC).

In Figure 3, the raw data that was provided in spread sheets by the CDC to us correctly captured the number of cases by the Public Health Centers, as can be ascertained by comparing Figures 2 and 3.

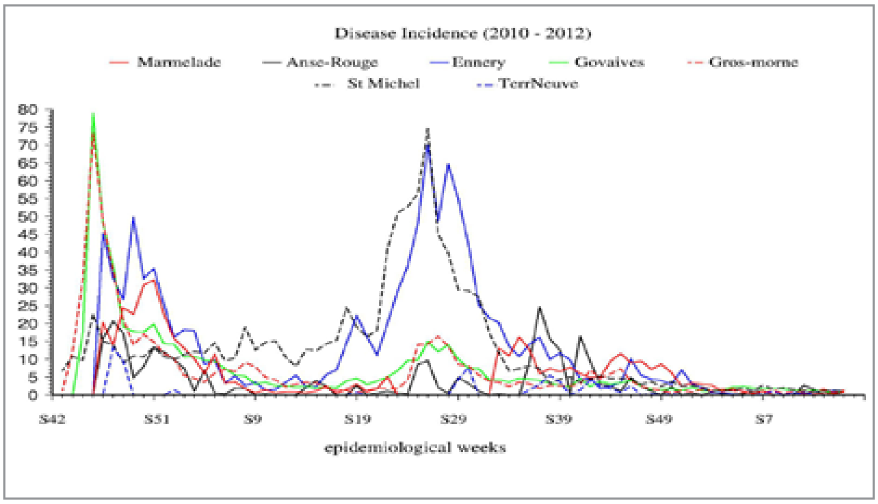


Figure 3: Our plots of the Cholera cases at the seven Public Health Centers across Haiti provided by the CDC and DWBs to our team. Comparing Figure 3 to Figure 2 shows that the documented cases were as documented by the Haiti Public Health record keepers. The Public Health record keepers kept excellent records.

The Empirical Methodology of Cholera Spread Across Haiti

Employing the Ensemble Empirical Mode Decomposition (EEMD) documented their predictions of future outbreaks and spreads of Cholera in Haiti; which turned out to be highly correct as reported by the DWBs back to our team [1-3]. Figure 4 provides a visualized overview of the EEMD correlations in a "scatter plot matrix" in a grid of bivariate plots for a graph in one of the cells, the label for the vertical axis is the one in that same row of cells and the label for the horizontal axis is the one in that column of cells [4]. The labels run down the diagonal of the matrix. Basically, the seven different time series of EEMD forecasts of the outbreak and spread of cholera was highly correlated across the seven Public Health Centers (PHCs) of Haiti. Empirically these results confirm that the internal modes of variability as functions of space and time were well correlated across the seven PHCs. Basically, the higher the positive correlation between stations, the closer to a 45-degree line, or an ellipse particularly one that is elongated, from lower left to upper right, in each of the Scatter Plot Squares; such as St. Michel with Ennery and Gros-morne and Govaives with Ennery and Anse-Rouge.

Medical condition data were also collected at each of the Public Health Centers and showed some remarkable results. Those are presented in the next section.

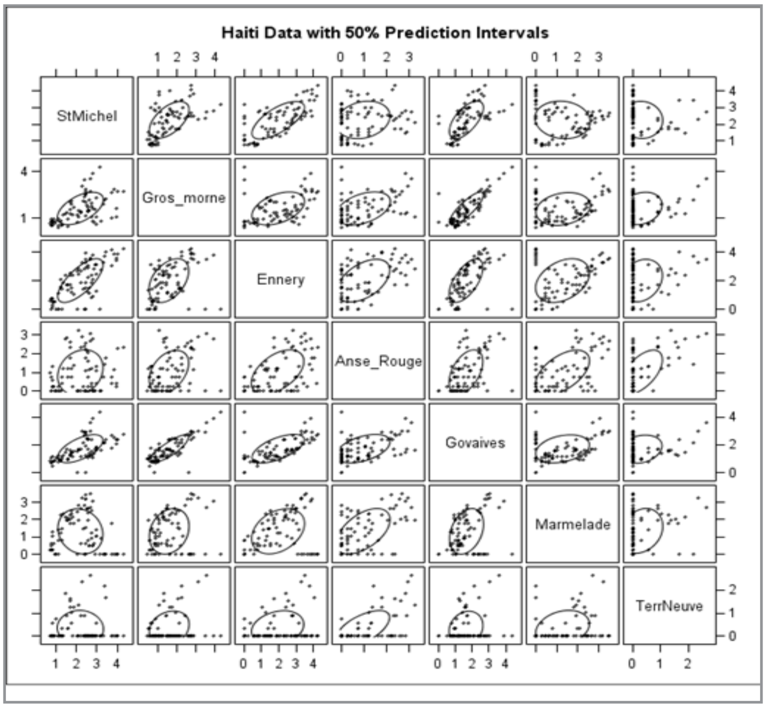


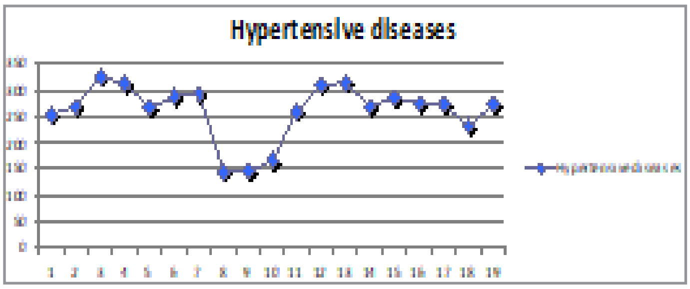
Figure 4: The scatter plot shown has 50% confidence forecast ellipses drawn in using a multivariate normal assumption [4]. The visuals generally display ellipses tilted at about 45 degrees indicating a high degree of correlation; of the prediction of Cholera at each of the seven PHCs with other stations.

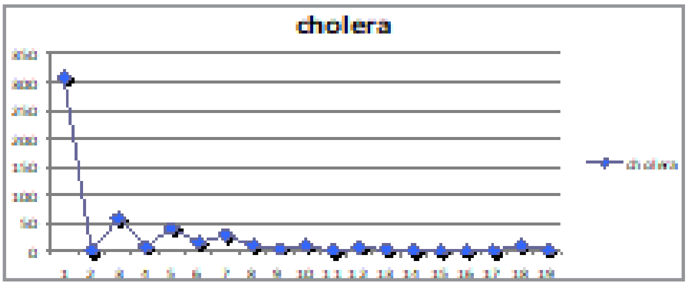
The Statistical Methodology of Medical Conditions

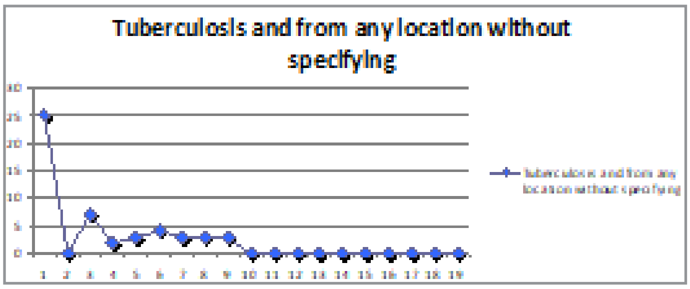
Next, we present the numbers of Medical Conditions of the patients who were tested positive for Cholera at the seven PHCs. Those numbers and the conditions are shown in the compilations in Figure 5. Statistical Analyses of the above diseases and medical conditions will be presented in Table 1. First, we eliminate all diseases with no or zero occurrences. These are: Leprosy, Diphtheria, Dengue, Leishmaniosis, Chagas Disease, Schistosomiasis (Bilharzia), and Onchocerciasis. Next, we label the remaining diseases. They are:

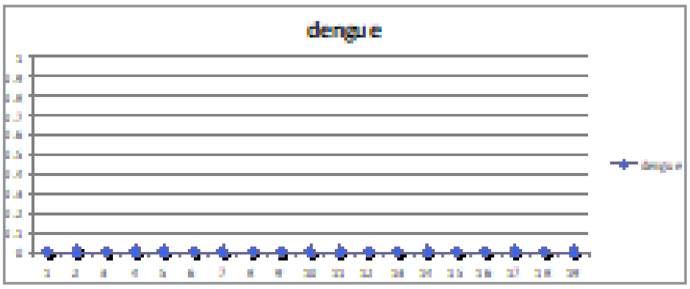
<u>**String**</u> <u>**Label**</u>

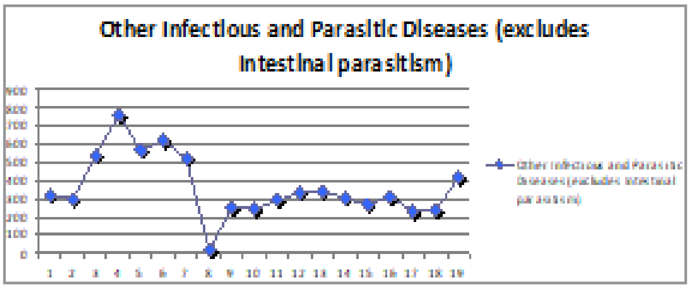
- D1 Cholera
- D2 Typhoid and Paratyphoid (Suspected)
- D3 Other Diarrhea and Gastroenteritis of infectious origin
- D4 Tuberculosis and from any location without specifying
- D5 Meningitis any
- D6 Sexually Transmitted Diseases (excluding HIV / AIDS)
- D7 HIV-AIDS
- D8 Malaria
- D9 Intestinal Parasitism not otherwise specified
- D10 Respiratory Tract infections
- D11 Other Infectious and Parasitic Diseases
- D12 Tumors of all types and locations
- D13 Niagara
- D14 Other visual disorders and unspecified
- D15 Ear Diseases
- D16 Hypertensive diseases
- D17 Other diseases of the circulatory
- D18 Asthma, Chronic Bronchitis, Emphysema and COPD
- D19 Complications of Pregnancy, Childbirth and Puerperium
- D20 Trauma and Polytrauma
- D21 Other causes

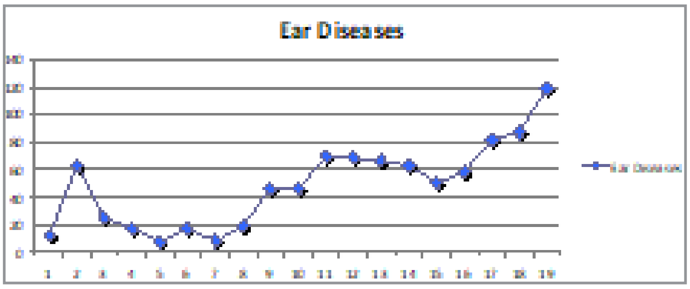


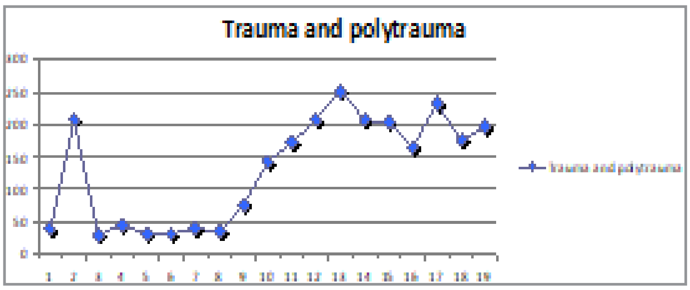


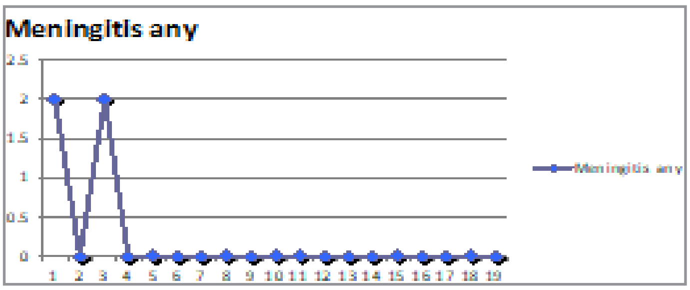


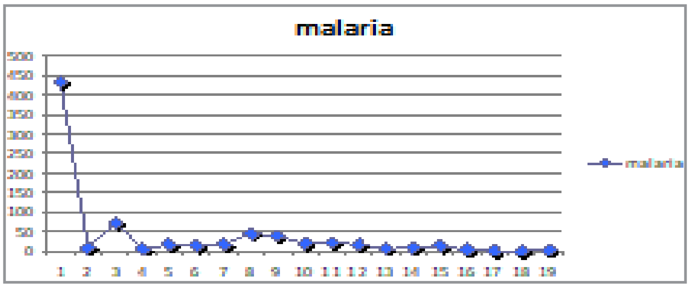


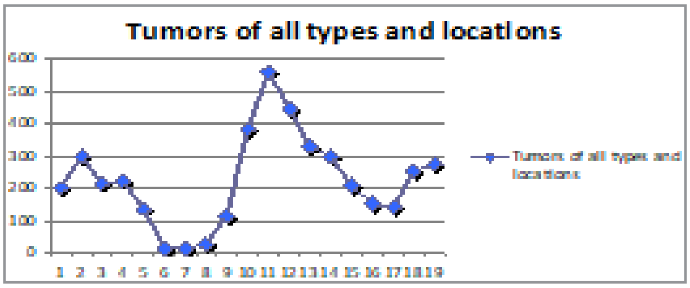


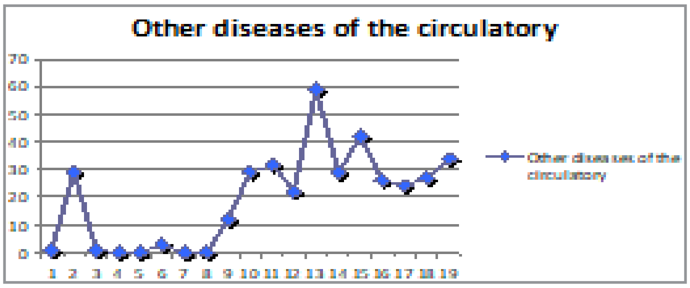


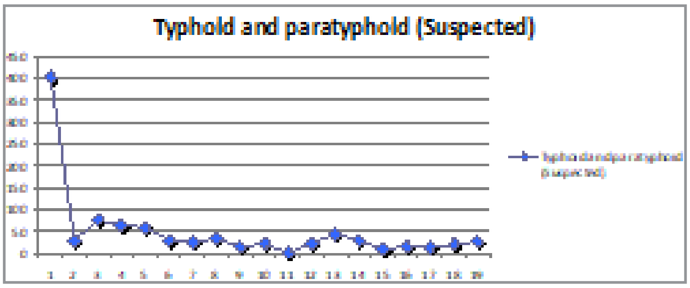


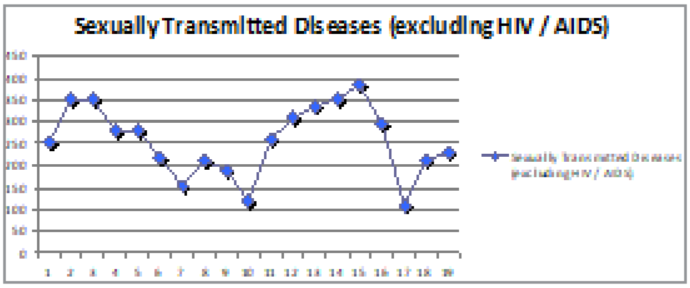


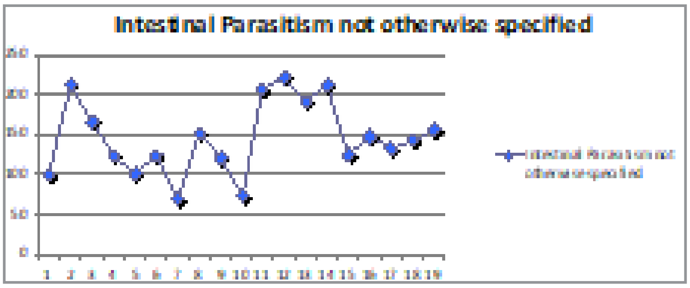

malaria
malaria

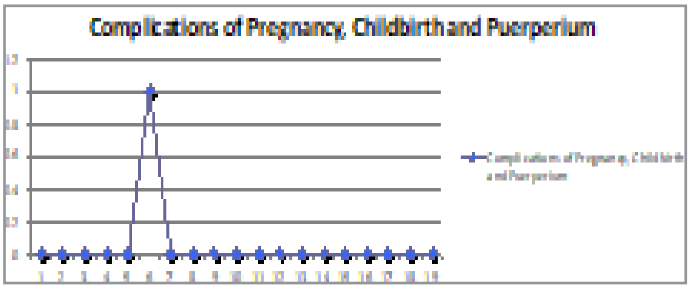

Tumors of all types and locations
Tumors of all types and locations

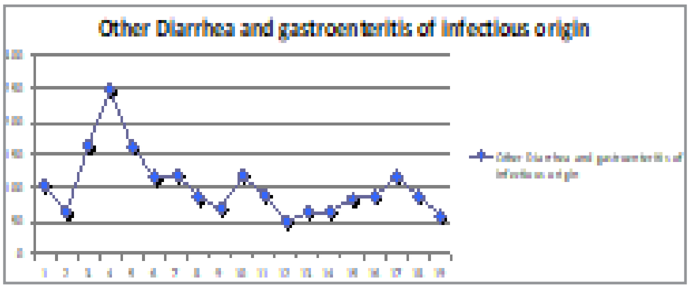

Other diseases of the circulatory
Other diseases of the circulatory

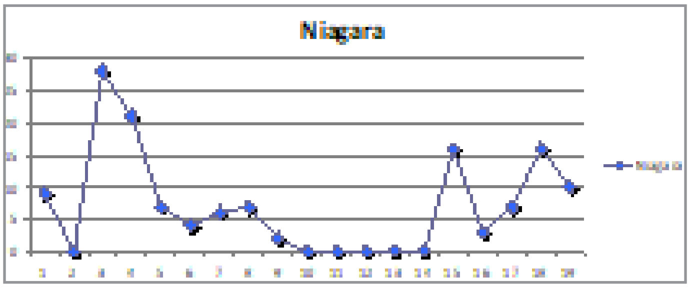

Typhoid and paratyphoid (Suspected)

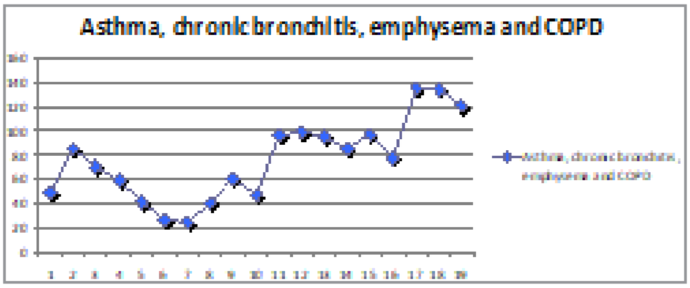

Sexually Transmitted Diseases (excluding HIV / AIDS)

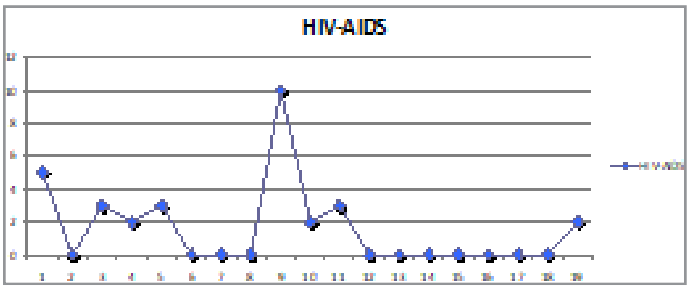

Intestinal Parasitism not otherwise specified

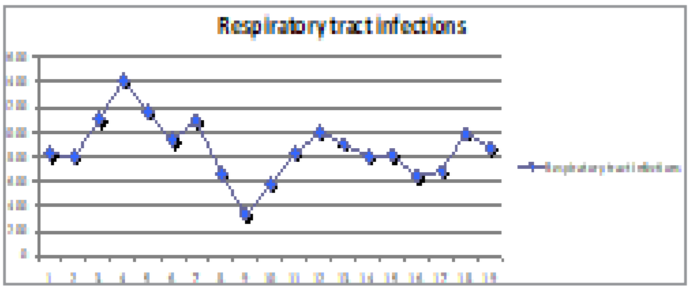

Complications of Pregnancy, Childbirth and Puerperium

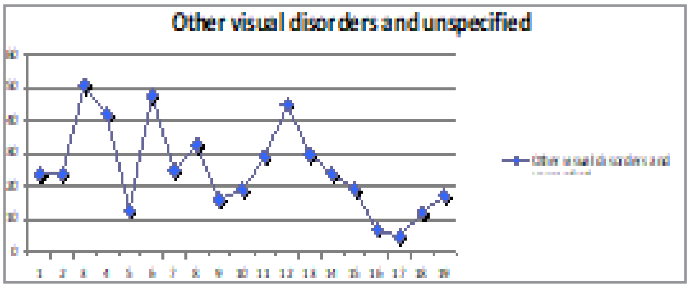

Other Diarrhea and gastroenteritis of infectious origin


Niagara


Asthma, chronic bronchitis, emphysema and COPD


HIV-AIDS


Respiratory tract infections



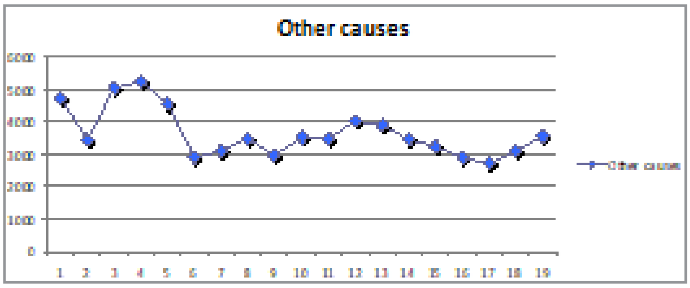


Figure 5: Medical condition data collected at the seven PHCs in Haiti for patients with confirmed cases of Cholera.

To conduct our statistical analyses, we run a correlation matrix on these showing only those with correlations greater than 0.75 in Table 1. While there is no a priori statistical reason to choose the 75% of probability, we note that this is a very strong %. In any case, omitting correlations less than 0.75, we get, Table1, below.

Table 1

Variable	D1	D2	D3	D4	D5	D6	D8	D9	D10	D11	D13	D15	D16	D17	D18	D20	D21
D1	**.**	**99**	**.**	**98**	**79**	**.**	**98**	.	.	.	.	.	.	.	.	.	.
D2	99	.	.	96	76	.	97	.	.	.	.	.	.	.	.	.	.
D3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D4	98	96	.	.	82	.	97	.	.	.	.	.	.	.	.	.	.
D5	79	76	.	82	.	.	77	.	.	.	.	.	.	.	.	.	.
D6	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D8	98	97		97	77	.	.	.	.	.	.	.	.	.	.	.	.
D9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D10	.	.	.	.	.	.	.	.	.	76	.	.	.	.	.	.	.
D11	.	.	.	.	.	.	.	.	76	.	.	.	.	.	.	.	.
D12	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D13	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D14	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D15	.	.	.	.	.	.	.	.	.	.	.	.	.	75	89	85	.
D16	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.		.
D17	.	.	.	.	.	.	.	.	.	.	.	75	.	.	.	91	.
D18	.	.	.	.	.	.	.	.	.	.	.	89	.	.	.	81	.
D19	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D21	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Here we note that there are 99% correlation relationships which are highly unlikely, statistically speaking [4]. So, revisiting the data sets we note some apparent singularities at the onset of the data time series. These suggest that individuals entered with the medical condition as opposed to developing the medical condition after having contracted Cholera. So, we next take the liberty of eliminating those and redo the Correlation Matrix as shown in Table 2. When we take away the first observations and recalculate the correlation matrix, a very different story emerges, as presented in Table 2 below.

Table 2

Variable	D1	D2	D3	D4	D5	D6	D8	D9	D10	D11	D13	D15	D16	D17	D18	D20	D21
D1	.	.	.	83	.	.	.	.	.	.	.	.	.	.	.	.	.
D2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	84
D3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D4	83	.	.	.	.	.	78	.	.	.	.	.	.	8	.	9	.
D5	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D6	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D8	.	.	.	78	.	.	.	.	.	.	.	.	.	.	.	.	.

D9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D10	.	.	.	.	.	.	.	.	.	76	.	.	.	.	.	.	.
D11	.	.	.	.	.	.	.	.	76	.	.	.	.	.	.	.	.
D13	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D15	.	.	.	.	.	.	.	.	.	.	.	.	.	.	89	84	.
D16	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
D17	.	.	.	8	.	.	.	.	.	.	.	.	.	.	.	91	.
D18	.	.	.	.	.	.	.	.	.	.	.	89	.	.	.	81	.
D20	.	.	.	9	.	.	.	.	.	.	.	84	.	91	81	.	.
D21	.	84	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Next, eliminating variables that have no correlations exceeding 0.75 with others we get Table 3, below.

Table 3

Variable	(D1	D4	D8)	(D10	D11)	(D17	D20	D15	D18)	(D2	D21)
D1	.	83	.	.	.	.	.	.	.	.	.
D4	83	.	78	.	.	-.8	-.9	.	.	.	.
D8	.	.	.	.	.	.	.	.	.	.	.
D10	.	.	.	.	76	.	.	.	.	.	.
D11	.	.	.	76	.	.	.	.	.	.	.
D17	.	-.8	.	.	.	.	91	.	.	.	.
D20	.	-.9	.	.	.	91	.	84	81	.	.
D15	.	.	.	.	.	.	84	.	89	.	.
D18	.	.	.	.	.	.	81	89	.	.	.
D2	.	.	.	.	.	.	.	.	.	.	84
D21	.	.	.	.	.	.	.	.	.	84	.

- D1 cholera
- D2 Typhoid and paratyphoid (Suspected)
- D3 Other Diarrhea and gastroenteritis of infectious origin
- D4 Tuberculosis and from any location without specifying
- D5 Meningitis any
- D6 Sexually Transmitted Diseases (excluding HIV / AIDS)
- D7 HIV-AIDS
- D8 malaria
- D9 Intestinal Parasitism not otherwise specified
- D10 Respiratory tract infections
- D11 Other Infectious and Parasitic Diseases
- D12 Tumors of all types and locations
- D13 Niagara
- D14 Other visual disorders and unspecified
- D15 Ear Diseases
- D16 Hypertensive diseases
- D17 Other diseases of the circulatory
- D18 Asthma, chronic bronchitis, emphysema and COPD
- D19 Complications of Pregnancy, Childbirth and Puerperium
- D20 Trauma and polytrauma
- D21 Other causes

These are remarkable groupings. While they do not indicate "causality" or "attribution", they do indicate very highly correlated relationships which are either medical in nature or socio-economic or other. Those conclusions are beyond the scope of this study; which simply provides the mathematical relationships. In particular in Table 4, we note several strong clusters.

Table 4

1)	D1, D4 and D8 (Red) with strong Positive Correlations.
2)	D10 and D11 (Green) with strong Positive Correlations.
3)	D15, D17, D18 and D20 (Purple) with strong Positive Correlations.
4)	D2 and D21 with strong Positive Correlations.
5)	D17 and D20 with strong Negative Correlations.

As summarized in Table 4, strong statistical Positive Correlations imply that if you know one disease or medical condition is present and increasing (or decreasing) then the other disease or medical condition will also be present and be increasing (or decreasing). Alternatively, strong Negative Correlations imply that if you know one disease or medial condition is present and increasing (or decreasing) then the other disease or medical condition will also be present and be decreasing (or increasing). Again, this does not prove "causality" or "attribution" but it does show powerful correlative connectivity. To wit, if you know one, then you know the other; again, statistically speaking [4].

Discussion

The first challenge to the eradication of Cholera in Haiti is the country's vulnerability to disasters, putting it in a state of protracted crises. The climax of cholera incidence in Haiti was in 2011 with 352,000 new cases following the introduction of cholera in Haiti in late 2010. Incidence rates gradually declined until 2016 when there was another spike in the transmission and incidence of cholera following Hurricane Matthew's destruction in Haiti from 2–5 October 2016. There was a rise in cholera incidence from 32,000 new cases in 2015 to 42,000 new cases in 2016. By re-damaging Haiti's fragile water and sanitation infrastructure, Hurricane Matthew allowed Cholera to rear its head yet again. These figures demonstrate that the fight against Cholera in Haiti is on unstable ground. This indicates that while eradication efforts have largely been focused on vaccination and community education to prevent transmission, and oral rehydration to reduce mortality, the underlying vulnerabilities that perpetuate the disaster remain, particularly insufficient and unequal access to improved water and sanitation.

Rainy seasons and hurricanes continue to cause a temporary spike in incident cases and deaths. Moreover, as a result of global warming and climate change, Haiti is at an increased risk of cholera transmission. The Intergovernmental Panel on Climate Change (IPCC) advances that global warming between 1.5–2 degrees Celsius will very likely lead to an increase in frequency and intensity of natural disasters and extreme weather events. Resource-poor countries are poised to be affected more so than more developed and economically secure countries.

Environmental factors such as temperature increases, severe weather events, and natural disasters have a two-fold impact on the transmission potential of cholera in Haiti: 1) they present conditions favorable to the persistence and growth of Vibrio Cholerae in the environment, and 2) they devastate a country's infrastructure and strain public health and health care resources. looked into environmental factors influencing the spread of Cholera in Haiti and cites above average air temperatures following the earthquake, and anomalously high rainfall from September to October 2010, long with damage to the limited water and sanitation infrastructure as likely converging to create conditions favorable to a Cholera outbreak [1, 2].

Conclusions

Our empirical and statistical analyses show highly complementary and revealing results. Moreover, both suggest that the peaks in the outbreak and spread of Cholera in Haiti following the Earthquake of 20010, were related to each other but were in fact, singular events caused by sudden introductions of the diseases in the regions of the seven PHCs. The persistent outbreaks are likely related to a combination of environmental and socio-economic factors and other circumstances following the Earthquake. Ancillary medical conditions, documented by Cholera patients at the seven PHCs, produced statistically revealing relationships that are noteworthy.

More advanced mathematical and statistical analyses of the Cholera and Medical Condition data would incorporate a consideration of environmental factors such as precipitation, water and air temperatures, geophysical locales, and oceanic, hydrologic and atmospheric factors. Longer term factors such as atmospheric temperatures, precipitation, water quality, various climate factors, along with public health variables such as hospital size, road access, dedicated medical teams, especially potable water, and infra-structure, would need to be considered as well. The environmental factors would be coupled to socio-economic factors and then decomposed both statistically and empirically, with the cross correlations. A more revealing retrospective, diagnostic analysis could result and it is possible that prognostic capabilities could be created; one more sophisticated then that which we presented.

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