High-resolution spatial analysis of cholera patients reported in Artibonite department, Haiti in 2010–2011

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ABSTRACT

Background: Cholera is caused by *Vibrio cholerae*, and is transmitted through fecal-oral contact. Infection occurs after the ingestion of the bacteria and is usually asymptomatic. In a minority of cases, it causes acute diarrhea and vomiting, which can lead to potentially fatal severe dehydration, especially in the absence of appropriate medical care. Immunity occurs after infection and typically lasts 6–36 months.

Cholera is responsible for outbreaks in many African and Asian developing countries, and caused localised and episodic epidemics in South America until the early 1990s. Haiti, despite its low socioeconomic status and poor sanitation, had never reported cholera before the recent outbreak that started in October 2010, with over 720,000 cases and over 8700 deaths (Case fatality rate: 1.2%) through 8 december 2014. So far, this outbreak has seen 3 epidemic peaks, and it is expected that cholera will remain in Haiti for some time.

Methodology/findings: To trace the path of the early epidemic and to identify hot spots and potential transmission hubs during peaks, we examined the spatial distribution of cholera patients during the first two peaks in Artibonite, the second-most populous department of Haiti. We extracted the geographic origin of 84,000 patients treated in local health facilities between October 2010 and December 2011 and mapped these addresses to 63 rural communal sections and 9 urban cities. Spatial and cluster analysis showed that during the first peak, cholera spread along the Artibonite River and the main roads, and sub-communal attack rates ranged from 0.1% to 10.7%. During the second peak, remote mountain areas were most affected, although sometimes to very different degrees even in closely neighboring locations. Sub-communal attack rates during the second peak ranged from 0.2% to 13.7%. The relative risks at the sub-communal level during the second phase showed an inverse pattern compared to the first phase.

Conclusion/significance: These findings demonstrate the value of high-resolution mapping for pinpointing locations most affected by cholera, and in the future could help prioritize the places in need of interventions such as improvement of sanitation and vaccination. The findings also describe spatio-temporal transmission patterns of the epidemic in a cholera-naïve country such as Haiti. By identifying transmission hubs, it is possible to target prevention strategies that, over time, could reduce transmission of the disease and eventually eliminate cholera in Haiti.

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1. Introduction

Cholera is caused by *Vibrio cholerae*, and is transmitted through fecal-oral contact. Infection occurs after the ingestion of the bacteria and is usually asymptomatic. In a minority of cases, it causes acute diarrhea and vomiting, which can lead to potentially fatal severe dehydration, especially in the absence of appropriate medical care. Immunity occurs after infection and typically lasts 6–36 months (Ali et al., 2011; Weil et al., 2012).

In October 2010, cholera unexpectedly arrived in Haiti, affecting a population already devastated by the consequences of the January 2010 earthquake (Bilham, 2010). Since cholera had not been present in Haiti for at least a century (Jenson and Szabo, 2011) the outbreak struck an immunologically naïve population and, within a month, cases were reported throughout the country (MSPP, 2015). To date, the epidemic has seen 3 large peaks—November 2010, June 2011 and June 2012. The overall burden has been vast, with over 720,000 cases and over 8700 deaths (Case fatality rate: 1.2%) through 8 December 2014 (MSPP, 2015).

The first patients were reported in Mirebalais, a small town the Center department. The outbreak spread rapidly along the Artibonite River, presumably due to contamination of the water (Piarroux et al., 2011). Soon thereafter, health centers began reporting large numbers of patients in the communes (subdivisions of departments) along the lower Artibonite River (Petite Rivière, Vérettes, l'Estère and Saint Marc). Artibonite department has reported over 136,000 cases to date, the second highest number after the capital, Port-au-Prince.

Almost immediately after the first reported cases, Haiti's Ministry of Health (MOH) set up a dedicated cholera surveillance system to record cholera patients and deaths. Aggregated data were (and continue to be) reported to the MOH according to the department and the commune in which the patients were treated. These data, regularly updated, have been available online since the beginning of the epidemic. An overview of cases reported in this surveillance system during the first two years of the epidemic was published in February 2013 (Barzilay et al., 2013).

Given the size of the epidemic and relatively weak infrastructure, these data are impressive. Nonetheless, there is little information available at resolutions below the commune level (i.e., by communal section and village). In a few instances during outbreak phases, the MOH, various non-governmental organizations and local health workers would perform ad hoc analyses of the geographic origin of patients at these lower levels in order to better target interventions (prevention measures, awareness-raising activities, water treatment and rapid access to rehydration therapy). This data was used solely for operational purposes and has not been published, to the best of our knowledge. The overall distribution of cases at the level of communal sections and villages therefore remains unknown. However, several authors have pointed out the need for high resolution mapping, in order to show transmission heterogeneities and better target interventions (Mukandavire et al., 2013; Blackburn et al., 2014).

The population of Artibonite is 1.5 million inhabitants (DSDS, 2009). It is the second-most populated department after the Ouest Department which includes the capital, Port-au-Prince. Its topography is varied, with densely populated plains and major cities along the Artibonite River and the Caribbean coast, as well as sparsely populated mountainous areas with remote villages. The department produces many agricultural goods, and is home to some of the country's busiest markets, attracting people both from Port-au-Prince and also the northern departments.

The vast Artibonite estuary is prone to flooding during the rainy season (Tennenbaum et al., 2013). Considering its high population density and poor sanitation (Ecodev, 2013), there is a high risk for continued cholera transmission in the area. The area was also severely affected by hurricanes in 2004 (Franklin et al., 2006) and 2008 (Brown et al., 2010) and is likely to be hit again. All these factors are potential contributors to endemic settling of cholera in the area. This geographical and economic diversity, together with the large number of reported cholera patients, makes the Artibonite a priority region for more detailed spatial analysis of the cholera epidemic (Fig. 1).

We therefore undertook a study to describe the spatial dissemination of cholera in the Artibonite department at a sub-communal level. Our objectives were two-fold: first, to understand the dynamics cholera transmission in Artibonite and second, to demonstrate the feasibility and value of high-resolution spatial mapping for targeting prevention activities and planning outbreak responses.

2. Methodology

2.1. Spatial unit of analysis and map sources

Data were analyzed at the communal section level, the smallest administrative division for which population data were available from the last census (in 2003). Population data were also available for several towns in Artibonite but not for villages or hamlets. These data were adjusted using an annual growth rate of 1.64% (DSDS, 2009). Patients originating from outside Artibonite and seeking treatment in Artibonite were excluded.

Artibonite is divided into 15 communes, in turn divided into 63 communal sections. Nine major cities were considered independently, bringing the total number of political subdivisions analyzed to 72. These 9 cities had population census available in the national demographic data (reference), and therefore could be included as separate entities in the analysis. Other smaller cities with unavailable population data where included in their section communales. Lists of village names in each communal section were compiled from several sources (Open Street Maps, Direction Nationale de l'Eau Potable et de l'Assainissement DINEPA, Mission des Nations Unies pour la Stabilisation en Haiti MINUSTAH, MOH sources) as well as direct observation in the field.

Maps designed by MINUSTAH were modified for this study using ArcGIS software.

2.2. Study period

The time unit used for analysis was the epidemiological week, defined from Sunday at 12 a.m. to the following Sunday at 12 a.m.

The study period extended from October 2010 (epidemiological week 42), when the first cholera patients were reported, to the end of 2011 (epidemiological week 52). For these analyses, Phase 1 was considered to run from week 42-2010 to week 12-2011, and Phase 2 from week 13-2011 to week 52-2011. The transition point was set after the minimum number of weekly cases between the first two epidemic peaks during week 12 (Fig. 2).

2.3. Case definition

Following MOH definitions, a suspected cholera case was a patient (including children less than 5 years of age) reporting at least three liquid stools in the previous 24 h.

All patients seen and notified on the health facility registers (hospitalised or treated as out patients) were included in this study.

2.4. Data sources

During the study period, patients with suspected cholera were treated in dedicated health facilities throughout the department. Upon entry, the following information was recorded in admission registers: date of admission, date of first symptoms, age, gender,
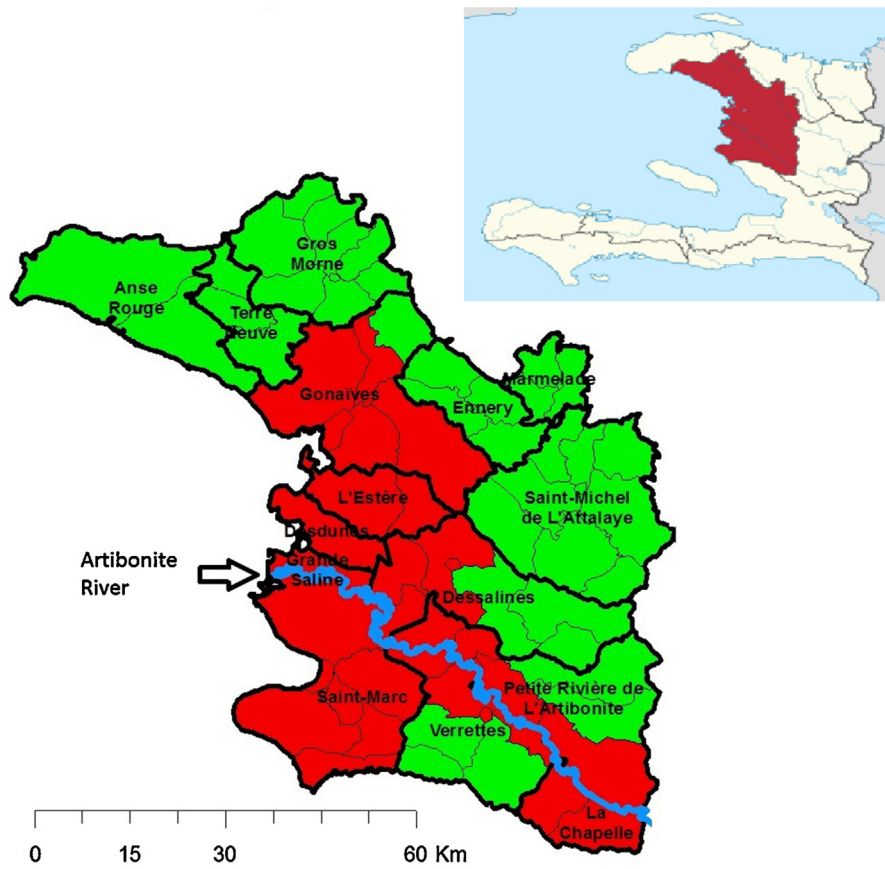
Fig. 1. Location and topography of Artibonite department. Green areas are mountainous, with a population of 526,405 people, i.e., 35% of the population.

origin (i.e., patient address broken down in Commune, Section communale and Village), and state of dehydration. When patients left the facility, the exit date and health status were recorded in the same register. In parallel, individual patient files recorded similar data. Where cases admission registers were incomplete or missing, we collected data from patient files.

The National Cholera Surveillance System recorded 590 community deaths (MSPP, 2015) which had not visited Health facilities prior to their death. Consequently, these were not recorded in health failities, and therefore not included in the data presented here.

Admission registers and patient files of all 79 cholera treatment facilities of the department were searched. (The health facilities included in this study were not supported by MSF at the time of the retrospective data collection, and only 20 of them had been supported by MSF during the first or the second phase). Data clerks from the Artibonite Health Department recorded the place of residence (village, neighborhood) of all suspected cholera patients admitted during the study period. The only data extracted were the patient's origin. These places of residence were assigned to one of the 72 sub-communal locations, using different mapping sources cited above. In cases when the patient adress was not available on
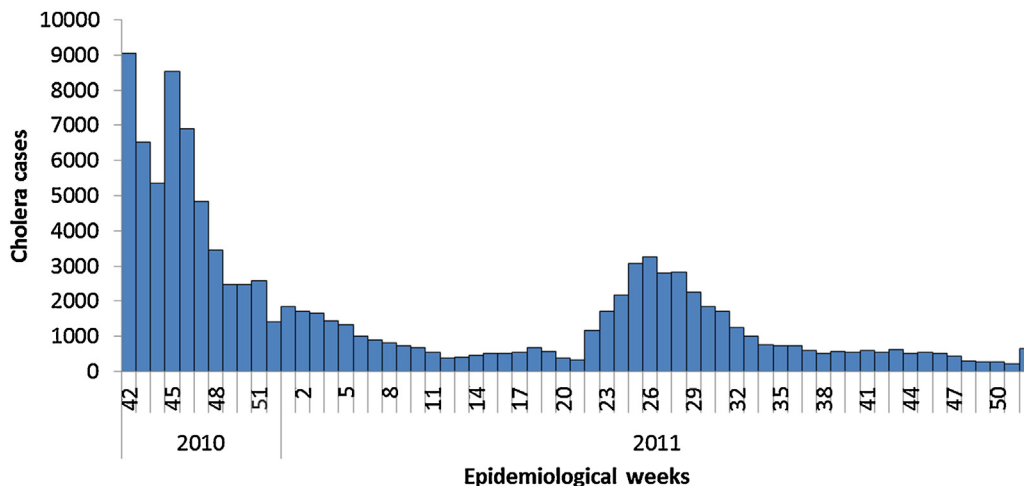

Fig. 2. Number of cholera cases per week from October 2010 to December 2011, Artibonite, Haiti. (*Source:* DSA).
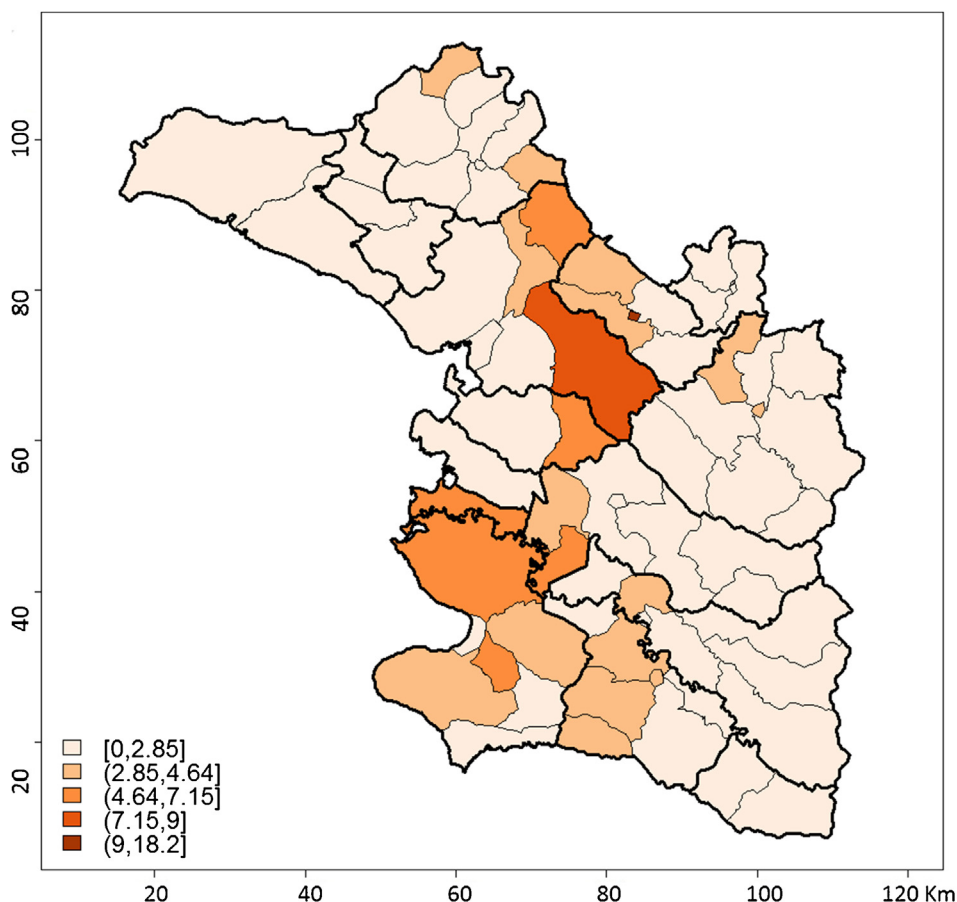
Fig. 3. Cholera Attack Rates by section communale, Artibonite, Haiti: Phase 1 (2010—Week 42 to 2011—Week 12).

maps, the knowledge of the local dataclerks was put at use, providing that at leat 2 dataclerks agreed on the location (commune and section communale) of the adress. If no agreement was found, the patient adress was recorded as unknown. Locations were all administratively linked to a single section communale since the patient origin recorded in the register mentioned Commune, Section communale and village. Information about deaths was not collected, as it was not consistently reported in the registers and patient files. Data was entered into Excel (Windows Corp) and analyzed with Excel and R software.

2.5. Analysis

The spatial analysis was conducted in 3 steps. First, we drew the global epidemiological curve, which showed 2 clear peaks: one at the beginning of the outbreak in October/November 2010 and another in June 2011. Second, we calculated attack rates for each of the 72 communal sections and city during both phases, comparing them to the overall attack rate of the department, using the formula: $RR = \frac{\text{Attack Rate of Communal Section or city of Origin}}{\text{Attack Rate of Department}}$

RR: Relative risk

A communal section or city with a relative risk greater than 1 indicates an attack rate higher than the overall department attack rate. Confidence intervals were calculated using a Bayesian Poisson Gamma model (Wolpert and Ickstadt, 1998).

Finally, Kulldorff's analysis was performed using SaTScan software [Kulldorff and Information Management Services, Inc. 2005]. This identified clusters of the most vulnerable communal sections

during each phase of the outbreak. The geographical entities are analysed as centroids, not as areas, therefore both rural (low density) and urban (high density) are analysed at the same time, without creating a higher risk of clustering in and around cities. This analysis was limited to the spatial dimension in each phase; time was included in a further analysis where we identified clusters considering both the spatial and time (week) dimensions. The software allowed us to analyze the distribution between each communal section according to a theoretical distribution (Poisson distribution). The null hypothesis was that attack rates were distributed following a Poisson distribution for which the parameter is constant between communal sections; the alternative hypothesis was that attack rates are distributed following a Poisson distribution for which the parameter is not constant through the spatial area, meaning that distributions differed inside and outside the ellipse. To estimate the significance of each identified cluster, we ran 999 iterations of the Monte Carlo test.

2.6. Ethics

Data collected from the registers were aggregated prior to analysis. No identifying information was collected, and no individual data were used for the analysis. The data was recorded as part of the National Cholera Surveillance System prior to the design of this study. The aggregation and analysis of origin of patients on a smaller scale than that available publicly (Commune and Department) was approved and conducted in collaboration with Haiti's MOH.
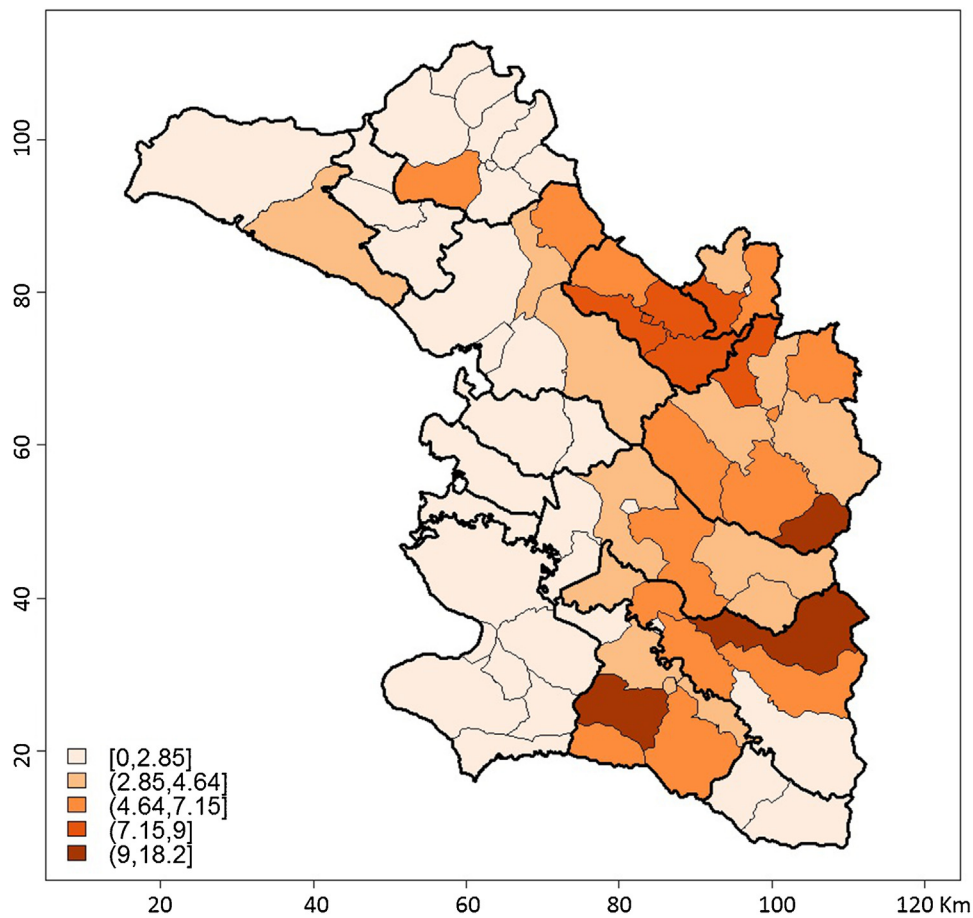
Fig. 4. Cholera Attack Rates by section communale, Artibonite, Haiti: Phase 2 (2011—Week 13 to 2011—Week 52).

3. Results

3.1. Availability of data

Data were collected between October 2010 and February 2012. In 73 facilities, data were available throughout the study period. In six other facilities, origin information was available only between January 2011 and December 2011, thus the first epidemic peak was not captured in these facilities' data. However, patients from these 6 facilities were reported to the National Cholera Surveillance System at the time of their admission (from October 2010 to February 2012), and their numbers are included in the aggregated numbers at the national level.

A total of 84,030 patients with suspected cholera residing in Artibonite were captured in this retrospective data collection (This represents 79.4% of all declared cases in the department over the same time period). 654 Cases residing outside Artibonite were recorded, but excluded from the analysis. 1527 patients (1.82%) did not have a place of residence recorded, or had a residence which could not be assigned to a sub-communal level, and were not included in the spatial and spatio-temporal analyses.

3.2. Evolution of the epidemic and spatial clustering

The epidemiological curve for Artibonite department overall (Fig. 2) shows two peaks. The first occurred during week 46-2010, when 4477 cases were reported, only 4 weeks after the first reported patient. National Cholera Surveillance System data at that time reported 8543 patients(the majority of our missing data patients came from this period.) The number of patients gradually declined to a first minimum of 253 during week 12-2011, before reaching a second peak of 3798 cases during week 26-2011, coinciding with the rainy season. After week 26, case numbers decreased continuously.

3.2.1. Phase 1 (week 42-2010 through week 12-2011)

During the first weeks of the epidemic (week 42-2010 to week 46-2010), patients were concentrated along the Artibonite River and the nearby plains. Thereafter, an increase was seen to the south in Saint Marc city and the surrounding sections. Finally, during week 46, the first cases were seen in the northern and eastern parts of the department, following the main road network, and cases have been reported each week since.

Communal section attack rates ranged from 0.1% to 10.7% during the first phase (Fig. 3). Relative risks were >1 in the eastern part of the department, in the Artibonite River plain and the Gonaives plain, and were <1 in the mountainous areas of the department's northern and eastern regions. Communal section relative risks were heterogeneous, ranging from 0.1 to 4.3. (Fig. 5).

To identify clusters (i.e., groups of neighboring communal sections) with statistically significant higher relative risks than the overall department, we performed a Kulldorff's spatio-temporal analysis. All significantly high-risk clusters reported here have a p-value below 10^{-10}. During the first phase, 3 high-risk clusters were seen: the lower Artibonite/Gonaives plain, the area along the Artibonite River and the sections located on the main roads leading to the northern departments of Haiti. These clusters encompass 17 communal sections (Fig. 7 and Table 1). An additional 3 smaller clusters, encompassing 4 communal sections, were identified within the same areas.
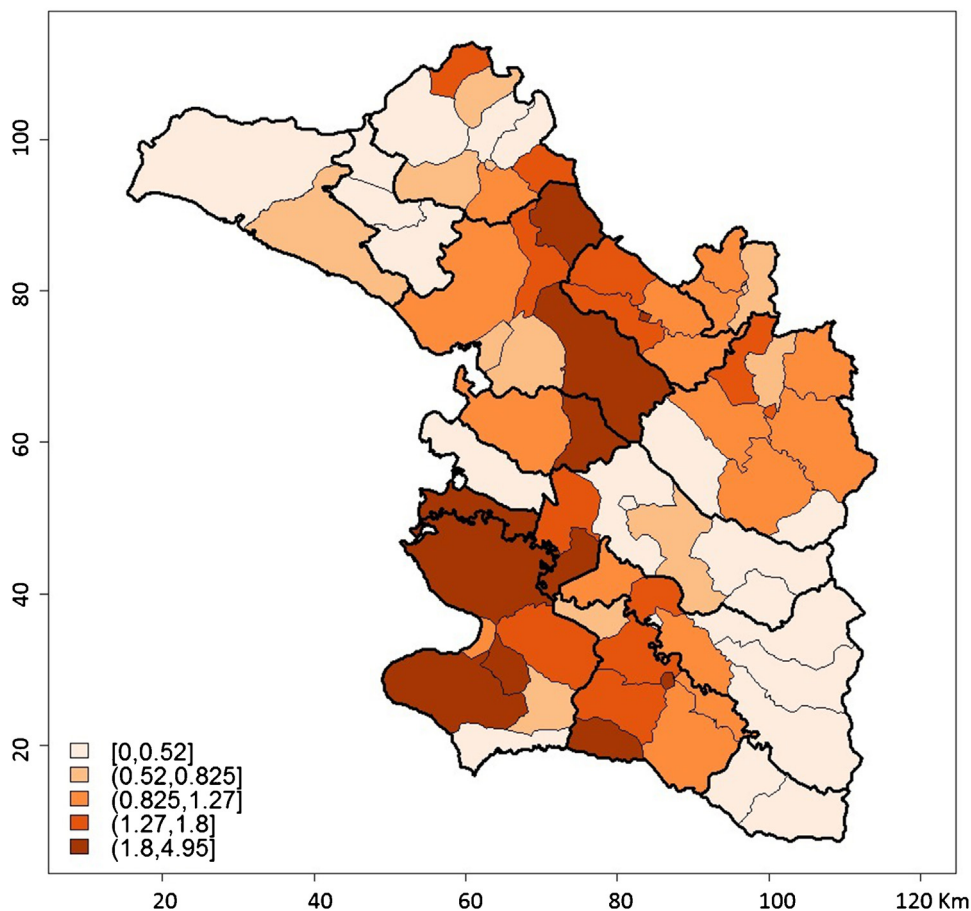
Fig. 5. Relative risk of cholera during Phase 1 and Phase 2: Phase 1 (2010—Week 42 to 2011—Week 12).

To further pinpoint the time and place(s) of the highest risk, we performed a spatiotemporal analysis for each week in order to identify, on a small scale, the location of any initial increase (i.e., potential transmission hubs). A high-risk cluster was seen (RR: 23.46) during week 42-2010 in the area of St Marc city and 6 nearby communal sections. This area, with a population of 162,295 individuals, is located on the Artibonite River, and contains a major market on the road linking Port-au-Prince to Gonaives and the north of the country.

Between the 2 peaks (week 46-2010 to week 26-2011), occasional clusters were seen in remote areas, such as the communes of St Michel, Anse Rouge, Gonaives, Ennery, and Marmelade, resulting in a slow increase in overall cases in the department. But these small flares never led to a continuous increase in patients lasting longer than one week.

3.2.2. Phase 2 (week 13-2011 through week 52-2011)

During this second phase, sub-communal attack rates ranged from 0.2% to 13.7% throughout the 63 rural communal sections and

9 urban entities (Fig. 4). The relative risks (range 0.09–4.5) seen at the sub-communal level during this phase showed an inverse pattern compared to the first phase, with relative risks >1 in the mountainous areas of eastern Artibonite and lower RRs in the plains and along the main roads (Fig. 6).

Kulldorff's analysis of this phase showed only 2 significant high-risk clusters, one of which encompassed 34 entities and over half the department's population (719,491 individuals) with a RR of 2.65 ($p < 0.05$) (Fig. 8, Table 2). Spatiotemporal analysis showed a cluster occurring during week 26-2011, coinciding with the rainy season in Artibonite. This cluster included 27 of the 72 sub-communal entities (population 404,016), and had a relative risk of 5.67 ($p < 0.05$). Both clusters were located in the more remote, mountainous eastern part of the department.

4. Discussion

We present the highest-resolution maps published to date of the spatial and temporal evolution of the cholera epidemic in Artibonite. These maps are based on a retrospective analysis of the geographic origin of cholera patients between October 2010 and December 2011. The analysis was performed at the sub-communal

Table 1
Relative risk and population information for significantly high risk clusters during the first phase (2010—week 42 to 2011—week 12).

Cluster	Population	Expected cases	Reported cases	Relative risk
1	64,980	1511	4192	3.00
2	439,996	10,231	14,794	1.75
3	43,324	1007	1836	1.87
4	30,349	706	1043	1.49
5	5525	128	200	1.56
6	14,813	344	383	1.11

Table 2
Relative risk and population information for significantly high risk clusters during the second phase (2011—week 13 to 2011—week 52).

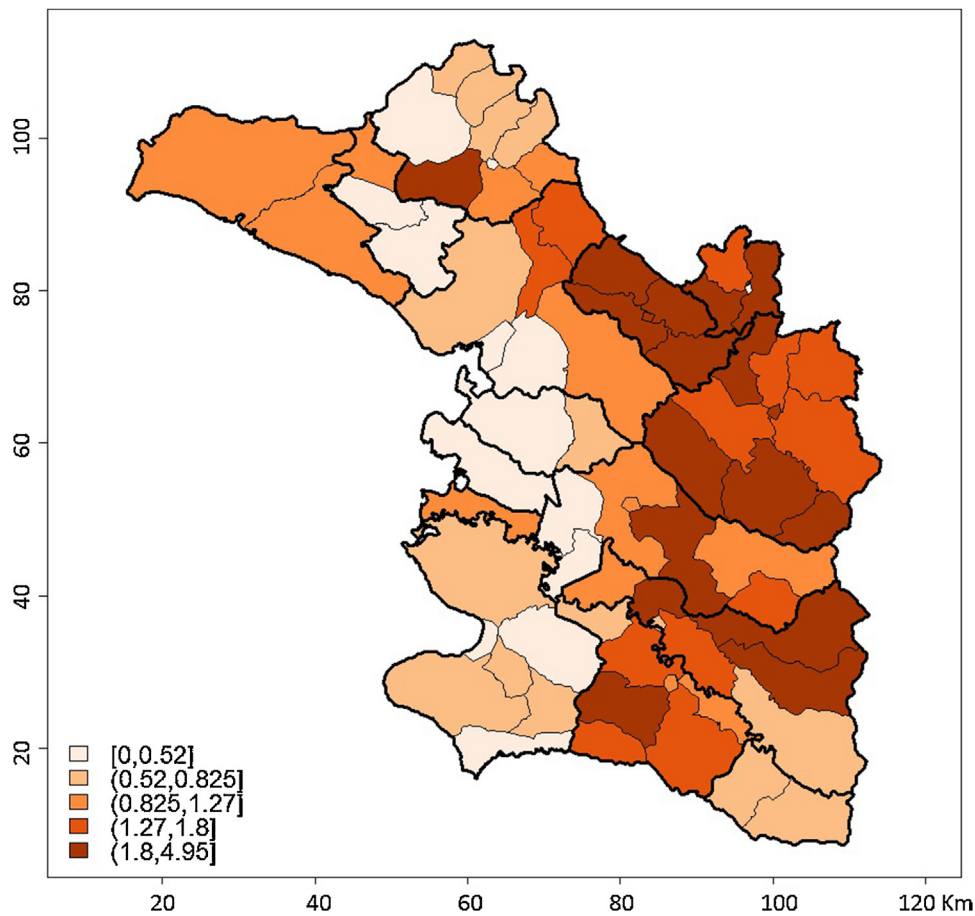| Cluster	Population	Expected cases	Reported cases	Relative risk
1	719,491	19,940	30,088	2.65
2	31,133	863	1412	1.64

Fig. 6. Relative risk of cholera during Phase 1 and Phase 2: Phase 2 (2011–Week 13 to 2011–Week 52).

level, adding detail to previous work at the department and commune level (Barzilay et al., 2013; Gaudart et al., 2013; Rebaudet et al., 2013). The maps illustrate that cholera ARs and RRs can vary widely across small geographic distances (<20 km), underscoring the importance of fine-scale mapping for identifying hot spots and in turn targeting these areas with preventive measures.

The first phase of the epidemic showed a strong concentration of cholera patients in the Artibonite plain, with a rapid increase in number of patients during the first weeks after the initial case was reported. We showed a very high-risk cluster in the densely populated areas along the Artibonite River. This finding is consistent with the hypothesis that the disease was artificially introduced upstream (Piarroux et al., 2011; Frerichs et al., 2012), in turn contaminating the river downstream with a large amount of infectious fecal matter (Fernández and Mason, 2011; Dowell and Braden, 2011) and leading to high ARs in certain areas in the immunologically Haitian naïve population.

Spatiotemporal analysis also confirmed that Saint Marc was a hot spot during this early phase. Its high population density, busy markets, and location along the main road between Port-au-Prince and the north of the country likely contributed to Saint Marc's role as a major transmission hub at the epidemic's beginning. In the first few days, reported cases, spread north to Gonaives and south to Port-au-Prince, presumably following the road network. This spread along roads is consistent with transmission patterns observed in previous epidemics (Médecins Sans Frontières-France, 2011; Mhalu, 1984; Mentambanar, 1998; Forbes, 1968; Pyle, 1969). As shown in other outbreaks, markets could have also played a role in the rapid dissemination throughout the department, (Fernández and Mason, 2011; Frontières-France, 2011; Quick, 1995; Chevallier,

2004; Weber and Mintz, 1994). The population's immunological naïveté, lack of knowledge about cholera and overall poor sanitary conditions with less than 20% of people having access to sanitation and over half the rural population defecating in the open (UNICEF, 2010), are likely to have exacerbated the situation.

The beginning of phase 2 showed only sporadic case increases in certain areas, without a persistent epicenter. This lack of clustering suggests a low association between environmental and demographic factors and an increase in numbers of reported patients.

The second major peak occurred simultaneously in a large part of eastern Artibonite. During the same time, reported cases remained relatively low in the areas most affected at the beginning of the epidemic. The low caseload reported in the low plains of the Artibonite River could reflect natural immunity resulting from the high case load there during the first phase (Tacket and Losonsky, 1992; Mosley, 1969; Ali et al., 2005).

The second peak started during week 21, coinciding with the start of the rainy season, which could have created ecological conditions sufficient to trigger increased dissemination. Rainfall possibly increased surface water prone to infection (possibly through open defecation) and dissemination through runoff. The mountainous eastern areas identified in the second phase cluster are prone to both, as sanitation conditions are extremely poor and the topography increases the risk of transmission through runoff. Several previous studies ((Rinaldo et al., 2012; Fernández, 2009; Codeço and Lele, 2008; Pascual, 2002; Koelle and Pascual, 2004) have associated rainfall with increased cholera risk, perhaps resulting from an increase of surface water harboring *V. cholerae* (possibly due to open defecation) and dissemination through runoff. Close examination in one communal section (1ère Savane Carrée) in Ennery
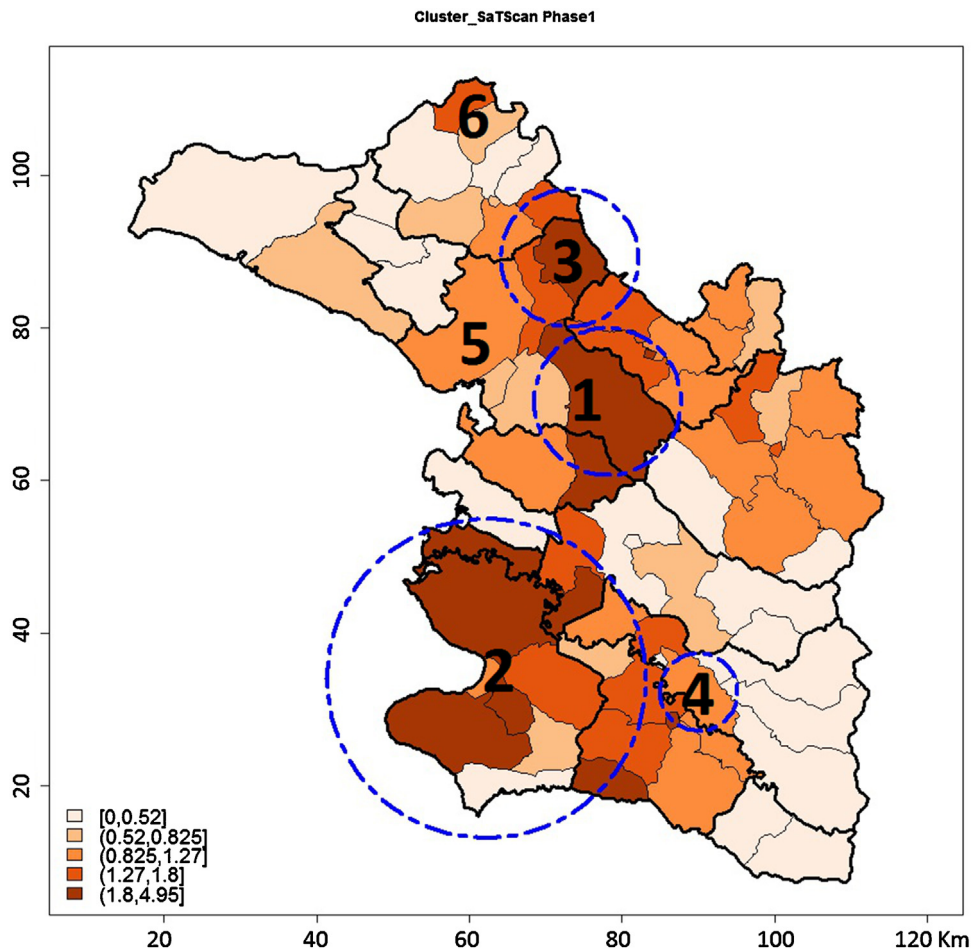
Fig. 7. Significantly high-risk clusters ($p < 0.05$): Phase 1 (2010—Week 42 to 2011—Week 12).

(North–East) showed initial caseloads primarily in urban areas (presumably contaminated through markets and travel), followed by an increase in more mountainous locations (probably villagers contaminated through markets subsequently contaminating their communities) and finally, patients downstream from these mountainous areas (contaminated through the river). Indeed, a year later, in 2012, the beginning of the rainy season again coincided with an increase in patients (MSPP, 2012).

The cluster seen during this second phase was very large, including almost half the population of Artibonite, and centered in remote mountain villages with poor access to sanitation and latrines. Sub-communal level analysis provided us detailed insight into this large cluster, revealing clear differences in relative risk among sections within several communes (e.g., Gros Morne, Dessalines, Petite Rivière de l'Artibonite and Vérettes). Further investigation of the local environment, social determinants, population density at locality scale and other risk factors for cholera transmission would help to explain these differences and to define and target preventive strategies.

Small-scale spatial analysis on patients reported in 2012 should help to further define the seasonality and the spatial distribution pattern. This data collection was implemented with the DSA in 2012, and other non-governmental actors were involved in similar activities. However, to the best of our knowledge, retrospective analysis of these collected data has not been done.

Our analyses have several limitations. Most importantly, missing data at the epidemic's beginning led to a difference of over 20,000 patients compared with the number of patients reported by the MOH (MSPP, 2012) over the same period. Therefore, the cluster analysis of the first phase of the epidemic should be considered with caution. In addition, approximately 2% of registered patients had no geographic information, or had geographic information that could not be traced. The classification of localities of patients required many sources (cited above), since the mapping of localities especially in rural areas is scarce in Haiti. This could have lead to misclassifications. The diagnosis of cholera was based almost exclusively on history and clinical examination, with very few cases confirmed by laboratory diagnosis, which may have led to an overestimation of ARs, especially in the first phase, when medical staff unfamiliar with the disease were confronted to panicked patients, potentially including non cholera patients in the registers. On the other hand, these data are facility-based, and patients who did not seek care were not included, which would have led to an underestimation of ARs. This would be particularly important in the remote mountains regions where access to care is the most limited. The inclusion of mortality data would have been helpful in further identifying priority areas for prevention and treatment interventions. Nonetheless, given the state of shock to the Haitian health care system in the wake of the earthquake and cholera epidemic, the detailed information collected in this study is very valuable.

While we have posited several hypotheses about risk factors for transmission, this study does not provide evidence of causal association between risk factors and probability of infection. This should be investigated through further studies in the high-risk areas, ideally identified by new spatial analyses of data collected during the next peak phase.
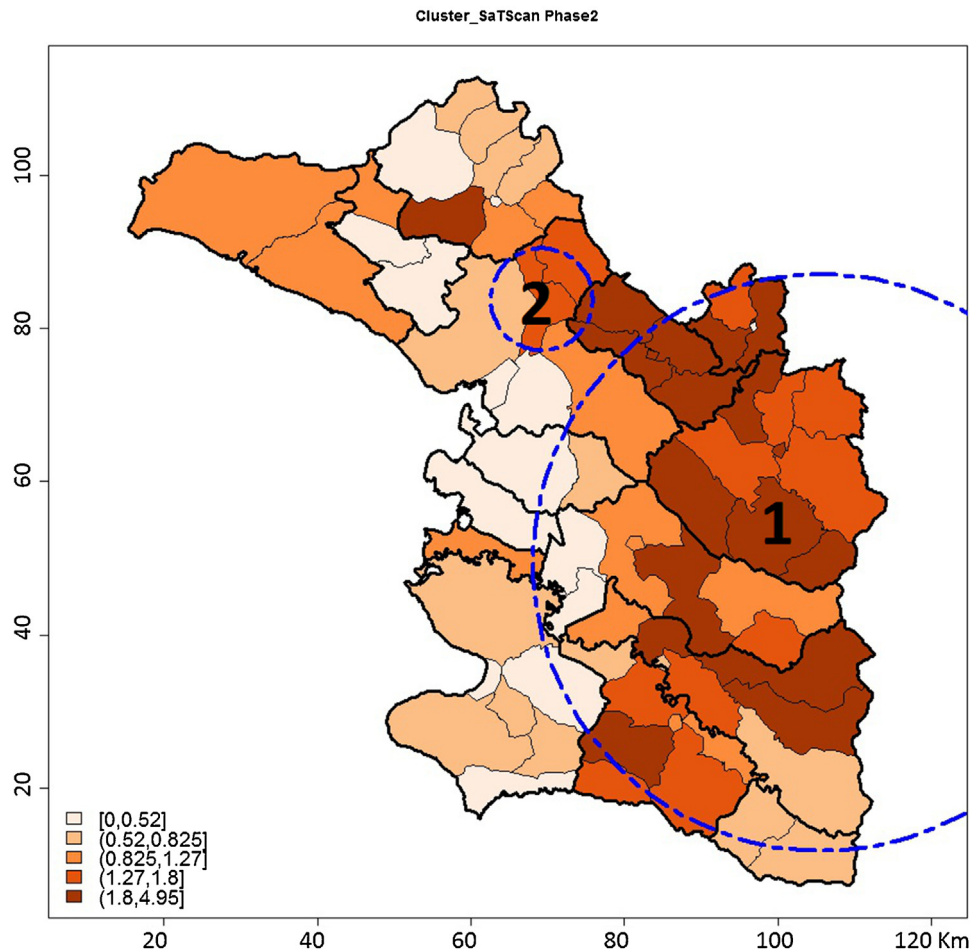
Cluster_SaTScan Phase2

Fig. 8. Significantly high-risk clusters (*p* < 0.05): Phase 2 (2011—Week 13 to 2011—Week 52).

This description of the first stages of a cholera epidemic in a naïve population helps to understand the dynamics of the disease, revealing two phases with very distinct geographical patterns of attack rate distribution at the sub-communal level. Trends during the first phase provided insight into the epidemic's origin and its spread in a vulnerable and immunologically naïve population. The dynamics during the second phase (in the rainy season) are more likely to be a model for transmission patterns in the coming years of cholera in Haiti, with high heterogeneity of transmission rates between communal sections, depending on the hydrographic, topographic and road network. To our knowledge, the latest data has not been analyzed in order to show the latest spatial trends.

Several articles describe the use of models to describe the patterns of spatial distribution of the disease (Tuite and Tien, 2011; Bertuzzo et al., 2011; Rinaldo and Bertuzzo, 2012). However, these are constructed at departmental level, as per the case data available. Thus comparison with the finer scale data depicted in this article is not possible. These articles describe interesting models designed to predict the number of cases, as well as the impact of timely response (vaccination, sanitation) on the dynamic and number of cases. These models could be used at a finer level in order to allow a closer insight on the epidemics dynamic which depends very much on micro factors specific to each setting. The heterogeneity of the Artibonite department setting, between mountains, coast line, river, as well as active human activity and movement impacts the number of cases and attack rates, which also show great heterogeneity in their distribution among neighboring locations. Thus this department would be an interesting entity in which to design a model.

Endemicity of cholera in Haiti depends on the environmental settlement of toxigenic V cholera in Haiti. This spatial analysis does not suggest a pattern of infection consistent with environmental presence of cholera. However, there are discrepancies in the literature concerning the presence of toxigenic stains of the bacteria. Hill et al. (2011) showed evidence of toxigenic cholera in sea water collected in 2010, whereas Baron et al. (2013) did not show evidence of toxigenic cholera. It was argued that the toxigenic strain found in the environment in 2010 was due to fecal contamination, not to an environmental settlement of the disease along the coasts of Haiti. Should this become a reality, a close monitoring of mapping of cases would help identify potential environmental presence of the bacteria.

Given the topographical diversity of Artibonite and the inaccessibility of its remote regions, performing similar analyses during future epidemics would offer a powerful tool for response planning, especially for identifying areas with recurrent outbreaks and that consequently have the greatest need for preventive interventions to interrupt transmission. Increasing the sensitivity and geographic detail of the surveillance systems would result in more accurate mapping of cholera transmission, and in turn make interventions, particularly regarding sanitation and vaccination, more efficient. This would enable better predictions of the most at-risk populations and areas of impact, and in turn facilitate a strategically planned, well-targeted response. Preventive strategies focused on previously identified transmission hubs as well as community-based efforts in specific cholera-vulnerable areas could reduce transmission of the disease and eventually help eliminate cholera in Haiti.

Acknowledgements

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