Household-Level Spatiotemporal Patterns of Incidence of Cholera, Haiti, 2011

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A cholera outbreak began in Haiti during October, 2010. Spatiotemporal patterns of household-level cholera in Ouest Department showed that the initial clusters tended to follow major roadways; subsequent clusters occurred further inland. Our data highlight transmission pathway complexities and the need for case and household-level analysis to understand disease spread and optimize interventions.

The 2010–2011 Haiti cholera epidemic was one of the largest worldwide in recent history. Before the initial outbreak, cholera had not been reported in Haiti for at least 100 years (*1*). Multiple factors likely contributed to the magnitude and spread of the early outbreak, including lack of prior exposure to cholera among the population, genetic characteristics of the *Vibrio cholerae* strain, and the consequences of the January 2010 earthquake, which included mass destruction of the infrastructure of Haiti and displacement of 1.5 million persons. The water and sanitation infrastructure in Haiti were inadequate before the 2010 earthquake; much of the population had no access to treated drinking water (48%) or sanitation facilities (75%) (*2*). Many of the limited services were destroyed by the 2010 quake (*3*).

As of February 28, 2013, the Ministry of Public Health and Population (MSPP) of Haiti and the National Directorate for Water Supply and Sanitation, working with the Pan American Health Organization, announced an ambitious plan to eradicate cholera from Haiti and Hispaniola: the plan calls for aggressive efforts to improve sanitation and to vaccinate the entire Haitian population (*4*). Designing this plan for optimal operation requires an understanding of cholera transmission within the population, and the development of models that permit assessment of the impact of proposed interventions on disease incidence. However, epidemiologic studies on the Haiti cholera outbreak have focused on the diffusion of the disease by using aggregated data, such as those from arrondissements (*5*) and communes (*6*). To evaluate cholera case clustering and provide a basis for modeling and intervention design, we conducted a spatiotemporal analysis of household-level data in the Ouest Department in Haiti during 2010–2011.

The Study

We used data from the Collaborative Cholera Mapping Project (CCMP), a Web-based dataset (no longer online) of household-level cholera cases captured through the United Nations Children's Fund water, sanitation, and hygiene program in the Leogane/Petit Goave area and Sustainable Aid Supporting Haiti (https://www.facebook.com/SAS-Haiti/info), a private nongovernmental organization (NGO) working in the area. The CCMP contains case data from 4 communities that include 3 urban areas, Petit Goave, Grand Goave, and Leogane (Figure 1, panel A). The fourth community in the CCMP is La Source, a small community in the west on Highway 7 (not mapped). Case data are summarized in the Table; full details on the urban structure of each community are provided in the Detailed Description of the Four Communities in the Collaborative Cholera Mapping Project (online Technical Appendix, http://wwwnc.cdc.gov/EID/article/20/9/13-1882-Techapp1.pdf).

The CCMP compiled global positioning system (GPS) data on household locations of patients who reported to cholera treatment centers during January–August 2011. Households were visited by community health workers employed by NGOs in the region. Persons in each household were educated about cholera, and surfaces in the house were disinfected. The GPS coordinates were entered into the dataset by NGO personnel.

Data were provided by CCMP with exemption from the University of Florida Institutional Review Board. Participants were not identified. We constructed a geographic information system, or GIS, database of household cases by date for each of the 3 communities on Route 2 and evaluated them separately. We plotted CCMP cases against daily case incidence reported to MSPP for the Ouest Department to evaluate the temporality of CCMP data.

We evaluated space-time clustering of cases for each community by season (winter or summer), using the spatial scan statistical tool in SaTScan (http://www.satscan.

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org). We used the retrospective space-time permutation model (*7*), which does not require data for population at risk, a key factor given the lack of reliable post-earthquake population data for Haiti (online Technical Appendix, Geospatial Analyses). Households were used as case locations. Clusters were identified as a maximum cluster size of 50% of case data and a maximum temporal window of 50% of the study period (online Technical Appendix, Geospatial Analyses).

There was close agreement in the trend of daily CCMP and MSPP data (Figure 1, panel B), illustrating 2 seasonal peaks for the epidemic, with fewer total cases in the dryer winter months and very close agreement in the timing of seasonal peaks between CCMP and MSPP cases. Datasets were not complete for all time periods for all sites (Table), reflecting some element of bias in identification of households related to operational factors such as availability of personnel to follow-up cases and enter case data into the dataset. Nonetheless, there was a clear pattern of disease movement from CCMP data, with winter/spring cases seen in La Source, Petit Goave, and Grand Goave, followed by ongoing summer cases in Grand Goave, and movement of the epidemic eastward into Leogane, with some early spring cases in Leogane.

In Grand Goave, long lasting (≈20 days) winter case clusters appeared in early January at the confluence of a natural waterway and Route 2, the major highway into the southern peninsula (Figure 2, panel A). This was followed by springtime cases further inland/upland in rural areas and along waterways (Figure 2, panel B). Summer clusters that followed were in rural, inland/upland areas, with no clusters identified in the urban center. In Leogane (summer), clusters were again identified along Route 2, beginning south of the city and in the urban center (Figure 2, panel C). Later clusters appeared the mountains, in communities along the Momance River, with subsequent clusters following the river toward the Caribbean Sea. Four of 6 clusters in Petit Goave were situated between 2 major highways with 2 clusters near the urban center (clusters 5, 6) (Figure 2, panel D). The first 2 clusters appeared east (cluster 1) and west (cluster 2) of the urban center in semirural regions along natural waterways.

Table. Case count and date ranges of cholera case reports by community, Haiti, 2011

Community	Total no. cases	Date range of cases (no.)
Petit Goave	612	Jan 1–May 6 (612)
Grand Goave	549	Jan 1–Apr 7 (348); May 1–Aug 15 (201)
Leogane*	344	Feb 7–May 7 (61); Jun 7–Jul 26 (283)
La Source	25	Jan 10–Feb 22 (23); Apr 23 (2)

*Cases in Leogane were few for the reporting period of Feb 7–May 7; related data were not included in further space-time analysis.

Conclusions

Here we provide an initial spatiotemporal assessment of household-level cholera following the introduction of *V. cholerae* to Haiti. Our 2011 winter/spring cases occurred in the initial larger epidemic wave, followed by additional peaks in cases in summer, with the onset of the rainy season. Our data support the hypothesis that initial case transmission followed roadways, particularly Route 2. In Petit and Grand Goave, transmission along roadways was followed by disease movement into rural/inland areas. After initial urban case clusters occurred in Leogane, cases appeared in the mountains, with clusters then appearing along the Momance River, consistent with the hypothesis that the river provided a transmission route for *V. cholerae*. Supporting this observation, toxigenic *V. cholerae* O1 was recently recovered from the Momance River (*8*).

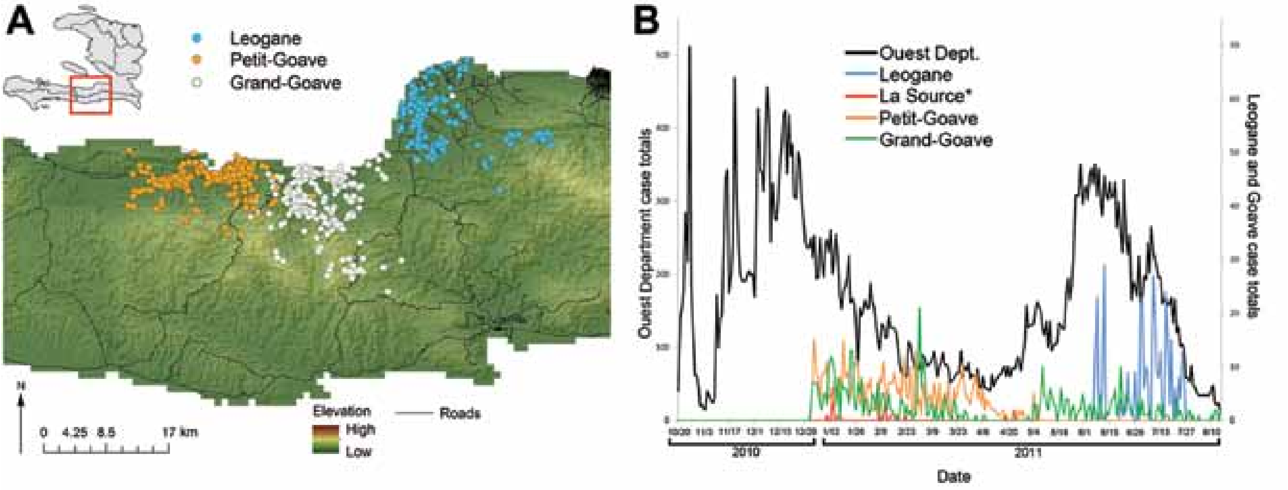

Figure 1. Findings of the Cooperative Cholera Mapping Project in Haiti, 2011. A) Geographic distribution of household cholera cases per day. B) Temporal pattern, color-coded by community, compared with reported cases in the Ouest Department (black). Color coding of map symbols in A correspond to line colors in B. La Source cases (n = 25) are plotted but not mapped.

There is increasing recognition that cholera has 2 routes of transmission, one involving movement through waterways (e.g., surface waters, rivers) and the other related to more direct transmission from person to person (*9*,*10*). In keeping with recent mathematical models (*11*), our data support the hypothesis that both routes are important to transmission in Haiti. The inland/river movement in both Petit Goave and Leogane occurred during the summer rainy season, consistent with a link between transmission involving surface waters and seasonal rainfall. These data were collected early in the course of the epidemic and limited to a small proportion of the total reported cases. Multiple years of observation are necessary to confirm these patterns; however, models in this and other regions already suggest the development of a seasonal pattern of illness linked with rainfall (*12*).

Generally, human mobility, such as urban/rural or rural/urban migrations can influence disease patterns (*13*).

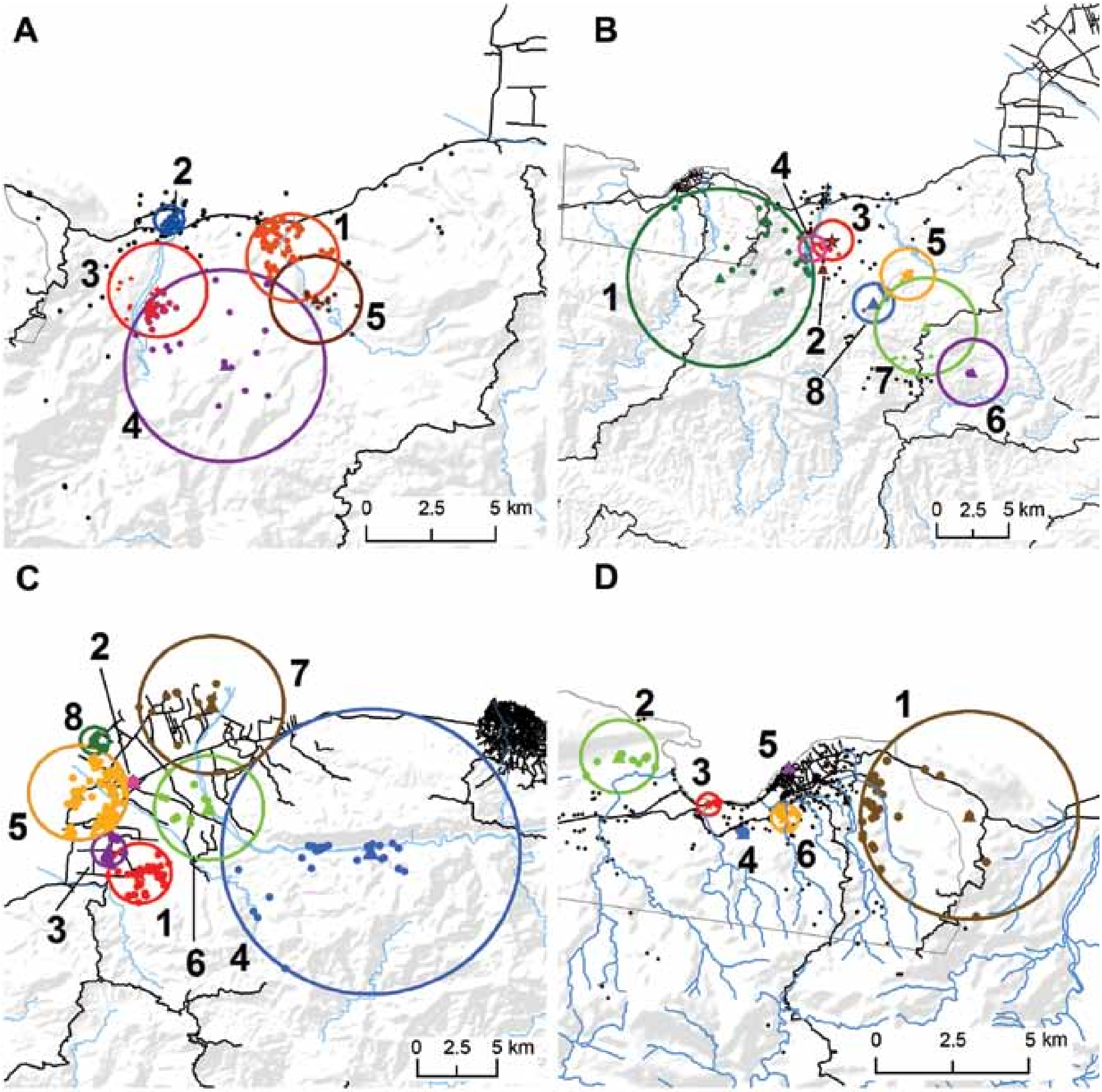

Figure 2. Space-time clusters of cholera in 4 communities in Haiti, 2011. A) Grand Goave, winter; B) Grand Goave, summer; C) Leogane, summer; and D) Petit Goave, summer. Stars represent primary cluster centers and triangles, secondary cluster centers. Dots represent approximate locations of households within clusters. Clusters are numbered sequentially by order of date of occurrence.

Our results suggest that such mobility is a factor of epidemic cholera transmission in Haiti. Recent models suggested human movevent out of damaged areas was substantial, but ultimately, persons attempt to return to the areas that formed the basis of their predisaster social networks (*14*). This study identifies key geographic areas for improved data collection. It also highlights the need for careful targeting of interventions that are shaped by ongoing data collection and analysis at local levels. Transmission routes can differ across space and time, and only by understanding these local differences can cost-effective disease control methods be identified and implemented.

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Dr Blackburn is an assistant professor of geography and principal investigator at the Emerging Pathogens Institute, University of Florida. His research interests are focused on the spatiotemporal patterns and ecology of pathogens found in environmental reservoirs; particularly, those that cause zoonoses.

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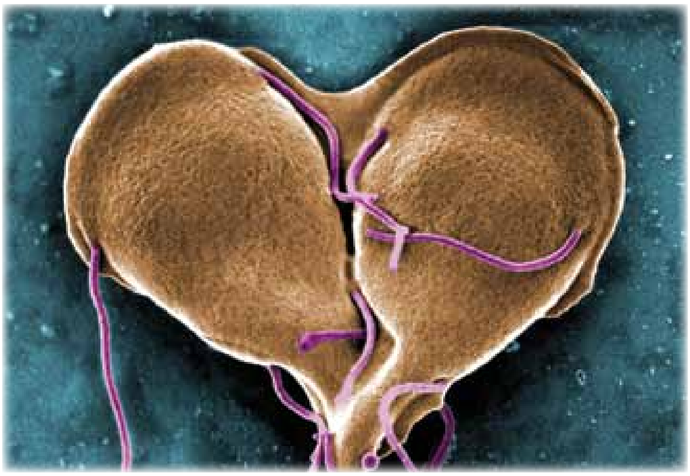

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Technical Appendix

Detailed Description of the Four Communities in the Collaborative Cholera Mapping Project

Petit Goave

The urban center Petit Goave suffered significant damage from the 12 January 2010 earthquake and was subsequently damaged by a 5.9 aftershock which had an epicenter that was almost directly under this urban center on 20 January 2012. This damage was significant on a regional scale, as the urban center of Petit Goave services not only populations in the western portion of Ouest, but also communities significantly west of the urban center along Route Nationale 2. As a result, there was a sizable NGO presence immediately following the 2010 earthquake. That presence has since been reduced to only a few satellite offices of NGOs still working in the Leogane area.

While much of the urban infrastructure was damaged as a result of this seismic activity, there remains a strong urban pattern that continues to define settlement patterns and population densities. The urban pattern is largely confined by a complex surface water system comprised of canals and natural seasonal streams and rivers. There are two dominant urban nodes in Petite Goave, one predominantly dedicated to commercial and civic activities along Route Nationale 2 and spreading northwest toward the formally-planned, historic urban center. The second urban node is dedicated largely to residential land use, where more formal settlement patterns are found adjacent to the commercial urban node and transition into more informal settlement patterns as this residential area moves northwest toward the coast.

Grand Goave

While Grand Goave has a distinct and formally-gridded urban pattern, this urban center is far less populated than Petit Goave, particularly in terms of its urban population. Grand Goave is characterized by a confined urban center with most roads running north toward the coast from

Route Nationale 2. Grand Goave quickly transitions away from a formally-planned urban center toward a more rural area to the south of Route Nationale 2. While Grand Goave is a compact and well-defined urban environment, the urban center does not support a significant residential population. Grand Goave’s housing density is concentrated to the south of the urban center and Route Nationale 2 heading toward the mountains. Of the three urban centers included in the Collaborative Cholera Mapping Project (CCMP), Grand Goave is smallest in population, as well as succumbed to the least amount of damage from the 2010 earthquake.

Leogane

Leogane is a formally-planned, well-confined urban center that lies inland from the coast and northwest of Route Nationale 2. The 2010 earthquake damaged approximately 80–90% of the built environment in Leogane. In response to the significant damage to housing in the area coupled with the lack of basic resources and services in the area, a large concentration of NGOs established relief and rebuilding efforts in the area. Despite the significant and sustained damage to the area following the 2010 earthquake, Leogane continues to be the commercial hub for many communities west of Port-au-Prince, as well as a major thoroughfare for individuals traveling to and from Port-au-Prince to western and southern regions of Haiti.

The urban center of Leogane lies along Route Nationale 2 at the confluence of alluvial plains to the north and mountains to the south. While there is a rapid rural to urban gradient from Route Nationale 2 into the mountains to the south and toward the coast to the north, a lack of roads and transportation services limits the exchange between the rural and urban dynamics, in addition to limiting access to services that are located in the urban center of Leogane. Thus, there is a stark contrast between conditions in the rural outskirts of Leogane and the urban corridor along and to the north of Route Nationale 2, where infrastructure related to water, sanitation, storm drainage and electricity are most robust.

The urban center of Leogane is serviced by a series of ancillary roads that feed into the formal grid pattern of the city. Route Nationale 2 bypasses the formal city center of Leogane. Informal development along the highway (and away from the urban center of Leogane) is the resulting urban phenomenon. This development lies to the south of Leogane and spreads southeast toward smaller urban centers. This is significant as dwelling patterns are also following the urban sprawl away from and to the northeast of Leogane.

One major highway connects the communities represented in the CCMP. Highway Nationale 2 runs from west to east through Petit Goave, Grand Goave and the rural area of Carrefour Fouche to the east of Grand Goave before turning north towards Leogane, continuing on as the major thoroughfare into the capital city of Port-au-Prince.

La Source

La Source is a small community in western Haiti along Highway 7. It sustained heavy damage during the earthquake, with reports of up to 50% of all structures sustaining damage or being destroyed. This community is the western most community in the CCMP and disjunct from the other communities.

Geospatial Analyses

In this study, we were limited to human cholera case data and lacked human population data at a comparable resolution to derive a population at risk for either the Bernoulli or Poisson implementations of the space-time statistics in SaTScan. Given that those cases were recorded at the GPS unit of each household, we had a rare opportunity to map the cholera outbreak at high spatio-temporal resolution. We used the space-time permutation model described in detail by Kulldorff et al. (*1*). Briefly, the space-time permutation model derives case expectation under the assumption that all case dates and locations are independent of any spatial interaction. Next varying sized cylinders are placed over the study area, with the diameter of the circle representing the spatial area scanned and the height of the cylinder representing time. This procedure matches other population-at-risk models available in SaTScan. To determine if case-only data are clustering in space and time, the number of cases in a cylinder is compared to case expectations outside of the cylinder and evaluated using a Poisson generalized linear ratio (GLR). The full mathematics of this are reported in Kulldorff et al. (*1*). Across a large number of cylinders evaluated across the landscape and over the study period, the cylinder that maximizes the GLR is considered the cluster least likely to be random, or the most likely cluster. Additional significant clusters are defined as secondary clusters.

For this study, we used SaTScan v9.1.1 (www.satscan.org) to run the spatial scan statistic. Each case was assigned the geographic location of the household from the CCMP field efforts and the day of the case was determined relative to the first day of reporting in the CCMP.

We set the spatial window at 50% of the household distribution and the time window at 50% of the total days cases were reported. We used the natural break in case reported between the winter time months and later rainy summer months (see Figure 1, panel B in the main text) to divide the study into two time periods (winter/dry, summer/wet). SaTScan models were constructed for each of the three communities, Leogane, Petit Goave, and Grand Goave, separately for each season. Clusters were mapped in ArcGIS v10 (ESRI, Redlands, CA, USA) by mapping cluster centers from SaTScan and placing a buffer around each center using the size of the cluster. Here we considered both primary and secondary, so long as each was statistically significant at $p < 0.05$. SaTScan identifies cluster members (here households) for each clusters. We mapped those and color coded them with the cluster center and buffer. Clusters were identified sequentially by the initial date of cluster appearance.

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