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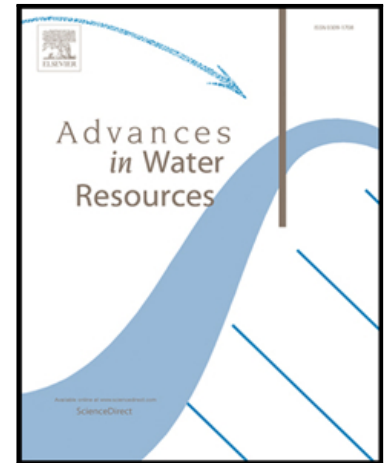
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## Accepted Manuscript

Cholera spatial-temporal patterns in Gonaives, Haiti: from contributing factors to targeted recommendations

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**Highlights**

- Patterns of cholera socio-environmental risk factors were identified in Gonaives City, Haiti.
- Coastal flood plains are high-risk associated with easy access to a contaminated brackish water table.
- Hillside areas are high-risk associated with poverty, poor water availability and open defecation.
- Development of water supply networks and safe sanitation practices must be neighbourhood-specific.

ACCEPTED MANUSCRIPT

## **Cholera spatial-temporal patterns in Gonaives, Haiti: from contributing factors to targeted recommendations**

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**Abstract**

Introduction: Gonaives, in the Artibonite region, is one of the most affected areas by the cholera epidemic in Haiti. Five years on, the epidemic persists and further information is needed to guide water and sanitation strategies for cholera elimination.

Methods: The number of cholera cases, socio-economic and environmental characteristics of Gonaives city neighbourhoods were included in an unsupervised classification approach and a general additive model was used to estimate standardized incidence ratios, adjusted on locations.

Results: Five classes of neighbourhoods were identified in Gonaives. Three classes were defined as high-risk in comparison with the area with the lowest incidence ratio: coastal flood-prone poor neighbourhoods (Class 5) with frequent open defecation and wide access to a shallow water table (Standardised Incidence Ratio - SIR of 3.15 IC95%[1.41; 7.04]); a coastal trade area (Class 3) with good access to a brackish and shallow water table likely contaminated by numerous latrines (SIR of 2.5 IC95%[1.05; 5.95]); and the hillside poor residential neighbourhoods (Class 4) with poor water availability and frequent open defecation (SIR=3.2 IC95%[1.25; 8.18]).

Conclusion: Water and sanitation prevention strategies should not be homogenous. Within an urban area, prevention strategies should be planned according to the specific socio-environmental and geographical context of each neighbourhood.

**Keywords**

Cholera; Socio-economic risk factors; Environmental risk factors; Spatial analysis; Water availability; Sanitation

## 1. Introduction

Since October 2010, Haiti has been affected by the most important cholera epidemic in recent history. A dramatic number of cases were seen with the first phase of the epidemic in October–December 2010, with daily case counts exceeding 4 000 in mid-December (Barzilay et al., 2013). This was followed by further large peaks of cases in mid-2011, late-2011 and in 2012. Despite the overall trend of decreasing number of cases of cholera over the past five years, cholera persists with epidemic waves in the rainy season separated by residual cases in between peaks. As of the 14<sup>th</sup> April 2016, a total of 776 661 cases and 9 287 deaths have been reported in Haiti (MSPP, 2016, p. 2016).

It is now well established that the cholera epidemic originated from a camp of UN Nepalese peacekeepers near Mirebalais, in the Centre Department, and initially spread along the Artibonite river, both the longest river in Haiti and an essential water source for local communities (Piarroux et al., 2011; Cravioto et al., 2011; Hendriksen et al., 2011; Frerichs et al., 2012; Gaudart et al., 2013). The cholera epidemic quickly propagated from the Centre and Artibonite departments, with rapid transmission country wide over several weeks in October–November 2010 (Gaudart et al., 2013; Blackburn et al., 2014; Allan et al., 2016). Not only was the Artibonite department among the first hit, it also continues to be one of the most affected. After the capital, Port-au-Prince, the administrative department of Artibonite saw the highest number of cases (119 519, as of 14<sup>th</sup> April 2016) (MSPP, 2016, p. 2016). Gonaives, with an estimated population of around 356 000 (IHSI (Institut Haitien de Statistique et d'Informatique) et al., 2015, p. 20156), is both the principal town of the Artibonite department and an area severely hit by cholera. A retrospective

community-based survey undertaken by Médecins Sans Frontières, identified Gonaives as one of the main affected towns in 2010-2011, with an estimated crude mortality rate of 19.1 deaths per 1000 person years 95% CI[14.9-24.4], an estimated two-fold increase on previously reported mortality rates (Luquero et al., 2016).

Previous studies of cholera in urban settings have identified patterns in environmental and socio-economic characteristics associated with cholera cases, which include socio-economic status, such as income level (Penrose et al., 2010) and hygiene conditions, such as proximity to refuse dumps (Osei and Duker, 2008). Other studies have analysed the protective effects of improved sanitation, such as safe water supply sources, hand-washing with soap (Kanungo et al., 2012) and water treatment (Dunkle et al., 2011) at the individual level. Environmental characteristics, such as proximity to lakes, have been shown to be significant in a spatial analysis (Bompangue et al., 2009), although few studies use geographical coordinates, especially within an urban area. Studies have highlighted this importance of research at the local level, where there can be large differences of cholera transmission within a city, between different communes or informal settlements (Penrose et al., 2010; Azman et al., 2012). Studies at the city level may hide intra-urban differences in social and environmental conditions (Sur et al., 2004; Sasaki et al., 2008). Furthermore, it is essential to identify the areas of a city most affected, as they may act as drivers of the epidemic across the city and should be targeted first for control strategies and vaccination programmes (Azman et al., 2012). This therefore indicates the need to study the association of environmental and socio-economic

characteristics by commune with the cholera incidence in Gonaives City, taking into account the geographical coordinates of each commune.

In October 2012, the Ministry of Public Health and Population (MSPP) in Haiti launched a National Plan for the elimination of cholera (2013-2022) (Republic of Haiti et al., 2013). It integrates prevention strategies at the short, middle and long term along several themes: water and sanitation, epidemiological surveillance, health promotion and behavioural change, and clinical care of infected patients in healthcare institutions. One of the main aims is to decrease the risk of transmission by rehabilitating existing drinking water supply networks and constructing new waste water collection and treatment systems in the main towns and peri-urban areas. In order to prioritise the areas requiring interventions in Gonaives, it is vital to consider the cholera epidemic in the local infrastructural context. This helps to identify the most vulnerable neighbourhoods at risk of cholera and adapt control and prevention strategies.

At the request of UNICEF in 2013, the authors have been involved in epidemiological studies of the cholera outbreak, helping to understand the dynamics of cholera by bringing together the environmental context and population characteristics with a spatial-temporal analysis. Here, we present an epidemiological study on cholera in Gonaives, the objective of which is to provide information on the socio-economic and environmental characteristics associated with the number of cases of cholera and describe the profiles of the neighbourhoods most affected by cholera. This will help guide the middle and long-term prevention strategies to reduce the vulnerability of the population and reduce the risk of cholera transmission.



## **2. Material and Methods**

### **2.1 Gonaives: situation and characteristics**

The commune of Gonaives covers an area of 620.5 km<sup>2</sup>. Over three quarters of its 356,000 estimated inhabitants (IHSI (Institut Haitien de Statistique et d'Informatique) et al., 2015) live in the coastal city, which represents the third urban concentration of Haiti, and is located on the main road connecting Port-au-Prince Metropolitan Area to Cap-Haitien. Local rainfall is scarce in the commune, but the city is situated at the bottom of a large watershed, where runoff water collects and drains to the sea. Due to these geographical characteristics, Gonaives presents an increased vulnerability to hydro-meteorological events, such as floods and cyclones in comparison to other surrounding areas. The city of Gonaives is a major transit route for people travelling to and from the south of Haiti. Alongside the cholera epidemic, other recent socio-economic concerns for the city include the displacement of people after the 2010 earthquake, riots, and increasing populations in shantytowns with poor living conditions. The commune of Gonaives is subdivided into Gonaives city plus five communal-sections – 1<sup>st</sup> Pont Tamarin, 2<sup>nd</sup> Bassin, 3<sup>rd</sup> Petite Rivière de Bayonnais, 4<sup>th</sup> Poteaux, 5<sup>th</sup> Labranle (Figure 1 Panel B). Gonaives city has spread rapidly over the past decades, and is currently split into 28 neighbourhoods (Supplementary Database), of which 20 of the neighbourhoods have been partially mapped by Gonaives city council (Supplementary Figure S1).

### **2.2 Data collection**

The remaining eight neighbourhoods that had not been previously mapped were delimited by field investigations, through interviews and confirmation with local habitants (Supplementary Database). Addresses of cholera suspected cases seen

from 11 November 2013 to 22 March 2016 were collected from registry books at the three cholera treatment institutions in Gonaives (Hôpital Secours-Providence in 2013-2015, CDI Raboteau in 2015, then the new Hôpital Secours-Providence in 2015-2016) and surrounding communes of Ennery and L'Estère. The addresses were attributed to the correct neighbourhood with local and experienced staff from ACF non-governmental organization (Action Contre la Faim) and IOM inter-governmental organization (International Organization for Migrations). Neighbourhoods were characterized using the 2008 Local Urbanism Plan of Gonaives provided by the city council; a geographic information system (GIS) analysis; and field studies performed with staff from ACF NGO, who have worked in the city on WASH (water, sanitation and hygiene promotion) and cholera response programs for many years. Based on known risk factors associated with cholera transmission in urban settings, available data and particularities of Gonaives City, the following socio-economic and environmental characteristics were collected for each neighbourhood and are detailed in the supplementary Database: mean and minimum altitude, distance from the sea, flooding risk, water table depth and salinity; population, socio-economic status; drinking water availability (from domestic wells, water pumps or DINEPA water network); prevailing type of sanitation including open defecation practices, unimproved latrines or modern improved toilets; size and cleanliness of markets; presence and traffic activity of motorised taxi stations; main building use and number of floors. Geographical analysis was performed with the use of shapefiles of communes and communal administrative boundaries (obtained from the National geospatial information center, <http://www.cnigs.ht>, accessed 1 August 2016), a shapefile of Gonaives neighbourhoods (drawn for this study),

an altitude raster ([magic.csr.utexas.edu/Event/10Haiti/Elevation.cfm](http://magic.csr.utexas.edu/Event/10Haiti/Elevation.cfm), accessed 1 August 2016) and a raster of the population estimated in 2015 (LandScan, <http://web.ornl.gov/sci/landscan/>, accessed 1 August 2016). Finally, satellite estimates of daily-accumulated rainfall in Gonaives (TRMM\_3B42\_daily v7, on the commune centroid) were extracted from NASA website ([http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance\\_id=daily\\_p\\_comp](http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=daily_p_comp), accessed 1 August 2016).

### 2.3 Statistical analysis

Univariate analysis was performed to analyse the relationships between cholera incidence and the collected socio-economic and environmental characteristics, as listed in the supplementary Database, using the non-parametric Kruskal–Wallis test. Continuous variables were transformed into categorical using quartile discretization. In order to classify neighbourhoods according to their characteristics, hierarchical classification on principal components of a multiple correspondence analysis (MCA) was used, as previously described (Lê et al., 2008; Husson et al., 2010). All the variables were included in this analysis. A multiple correspondence analysis (MCA) was the first pre-processing step to explore the socio-economic and environmental characteristics on the mixed data set, which takes into consideration relationships between variables. Then, the coordinates of each variable in the first 20 principal components, which summarise 99.22% of the information, were used to perform a Hierarchical Ascendant Classification (HAC). This method provides classes according to the socio-economic and environmental profile using an objective non-supervised classification technique, allowing the classification to be independent from the number of cases of cholera. Furthermore, using the first 20 principal components

is a way of removing the noise from the data and therefore renders the classification more stable (Husson et al., 2010). A sensibility analysis was performed in order to evaluate the stability of the classification through different component numbers (15 to 25). A generalized additive model (GAM) was then applied to compare these classes with the number of cholera cases:

$$\text{Log}(\text{CholeraCase}) = \text{Cluster} + s(\text{Lon}, \text{Lat}) + \text{offset}(\log(\text{Pop})) \sim \text{NegBin}$$

A Negative binomial model was performed, taking into account over-dispersion. The log population was used as an offset in order to estimate the standardised incidence ratio associated with each class. A bivariate thin plate spline,  $s(\text{Lon}, \text{Lat})$ , based on geographical coordinates of each neighbourhood centroid was used to take spatial autocorrelation into account, as previously described by Simon Wood (Wood, 2006). The level of significance was fixed at  $\alpha=0.05$ .

Statistical analysis was performed using the software programmes R v3.3.0 (The R Foundation for Statistical Computing, Vienna, Austria), and the *mgcv* and *FactoMineR* packages. GIS analyses and mapping was performed using QGIS v2.12.1 (QGIS Development Team, 2016. QGIS Geographic Information System. Open Source Geospatial Foundation Project. <http://qgis.osgeo.org>). Background satellite images used in the maps were obtained from Google Maps. Figures were formatted with GIMP v2.8.16 (The GIMP Team, 2016, [www.gimp.org](http://www.gimp.org)).

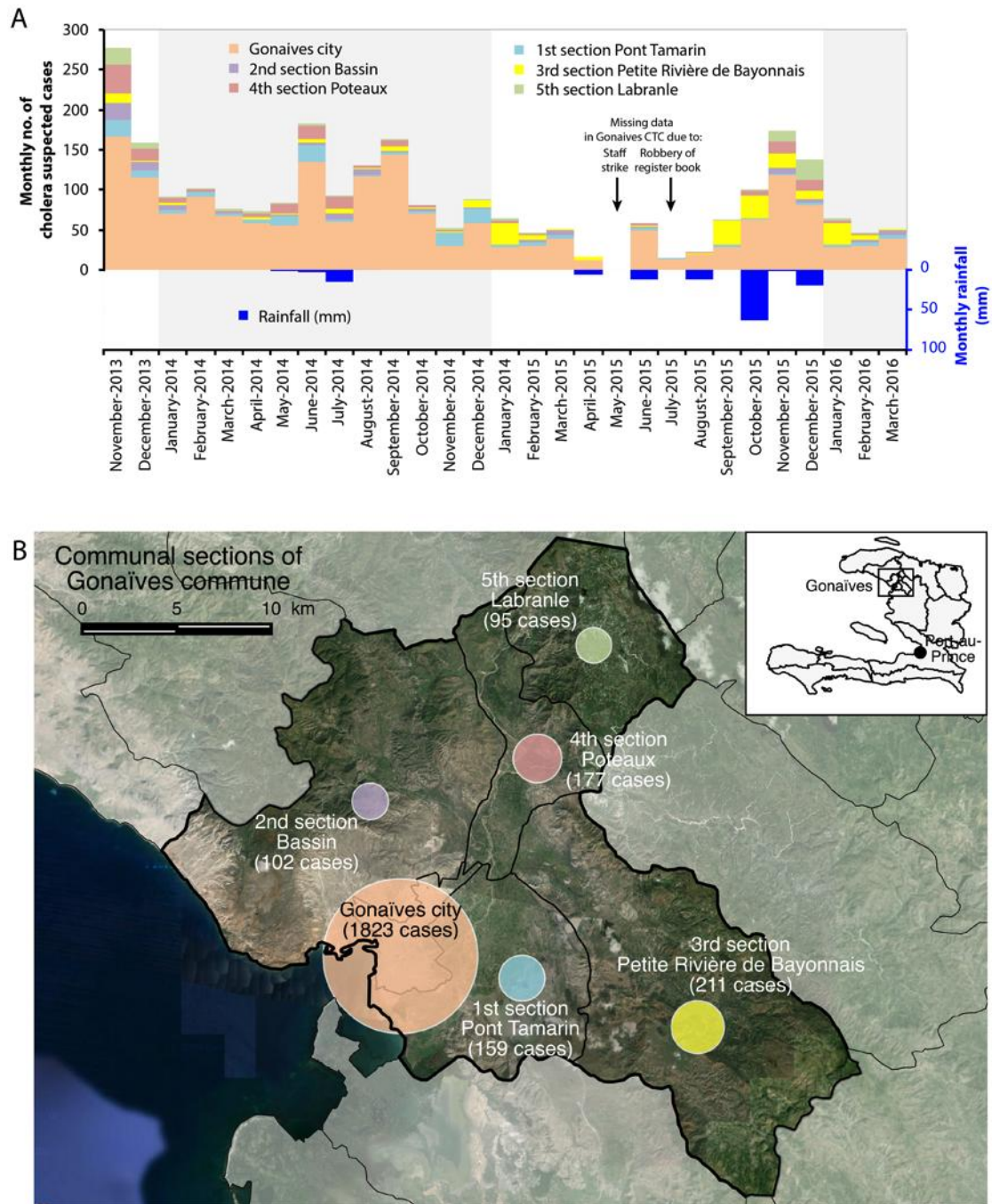
#### **2.4 Ethical considerations**

Cholera counts and addresses were anonymously extracted from registries and aggregated at the neighbourhood scale. This study was approved by the Haitian Ministry of Public Health and Population.

### **3. Results**

From 11 November 2013 to 22 March 2016, 2,567 patients with suspected cholera living in the commune of Gonaives were seen in cholera treatment institutions in Gonaives City or in the surrounding communes. During this period, 268 of these patients were sampled for cholera culture confirmation at the National Laboratory of Public Health, and 51% of these stool cultures were positive for *Vibrio cholera* O1.

Most cases were seen in 2013 and 2014, with two main peaks in November 2013 and September 2014, which did not appear to be related to increase rainfall (Figure 1 Panel A). Conversely, 2015 exhibited a relative lull period from April to August, although staff strikes at the Hôpital Secours-Providence and local riots with the robbery of a register book in CDI Raboteau resulted in missing data during this period. Overall, 71% of these 2,567 suspected cases originated from the city of Gonaives, where the cumulated incidence ratio between November 2013 and March 2016 was 96.8 cases /10,000 inhabitants. The monthly number of total suspected cases per communal section is shown in Figure 1 Panel A and B.



**Figure 1: (A) Epidemic curve of cholera in the commune of Gonaives with concomitant rainfall and (B) Spatial distribution of suspected cases of cholera in each communal section of Gonaives, November 2013 – March 2016.**

Inside the city of Gonaives, there were a median of 41 suspected cases (Interquartile range, 20-104) in each neighbourhood between November 2013 and March 2016 (Supplementary Figure S2). However, spatial distribution of cholera was not homogeneous, as 50% of neighbourhoods provided less than 20, or more than 104 suspected cases (Supplementary Database & Supplementary Figure S2).

At the neighbourhood level, variables significantly associated with cholera incidence in univariate non-parametric analysis included mean altitude (p-value=0.02), drinking water availability (p-value=0.01), prevailing open defecation (p-value=0.008), prevailing use of unimproved latrines (p-value=0.023), socio-economic status (p-value=0.04), water table depth (p-value=0.01) and the presence of a functioning DINEPA water network (p-value=0.005).

The HAC on MCA (Supplementary Results & Figure 2) provided five classes for socio-economic and environmental profile characteristics. The first class (Class 1) was characterized by residential neighbourhoods of intermediate altitude (mean altitude=23m), a higher economic status, the use of latrines and modern toilets and no marketplaces. It corresponded to seven neighbourhoods at the city periphery, with an incidence ratio of 56.1 cases /10,000 inhabitants (min-max, 18.5-144.0) (Figure 3).

The second class (Class 2) was characterized by a lower altitude (mean=9m) but no flooding risk, an intermediate distance to the sea (mean=1,809m), a shallow and fresh water table, an intermediate economic status, a main use of latrines, and a moderate water availability with a functional DINEPA network. It

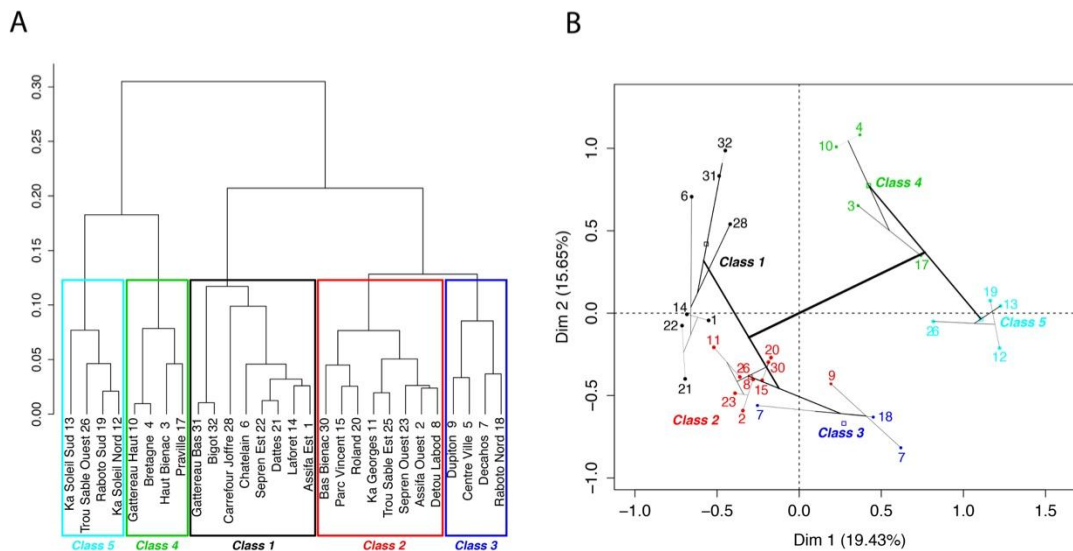
represented 10 neighbourhoods in the middle of the city, with a mean incidence ratio of 61.0 cases /10,000 inhabitants (min-max, 6.9-132.1) (Figure 3).

The third class (Class 3) was characterized by a low altitude (mean=6m), a short distance to sea (mean=614m), a poor sanitation with a major use of open defecation and unimproved latrines, a high water availability with access to a shallow and brackish water table, a residential and commercial use of mainly two floors buildings, and large markets. It represented 3 coastal neighbourhoods at the city centre, with a mean incidence ratio of 104.0 cases/10,000 inhabitants (min-max, 88.2-114.3) (Figure 3).

The fourth class (Class 4) was characterized by a higher altitude (mean=41m), a low water availability with a deep water table, a low socio-economic status, and a prevailing use of open defecation. It represented four hillside neighbourhoods at the city northern periphery, with a mean incidence ratio of 166.9 cases /10,000 inhabitants (min-max, 93.4-546.1) (Figure 3).

The fifth class (Class 5) was a flood-risk area characterized by a low altitude (mean=5m), a short distance to sea (mean=631m), a high water availability with a shallow water table, a poor economic status, a poor sanitation with a major use of open defecation and unimproved latrines. It represented 4 coastal neighbourhoods divided in two part (north and south), with 119.1 cases /10,000 inhabitants (min-max, 99.3-160.3) (Figure 3).

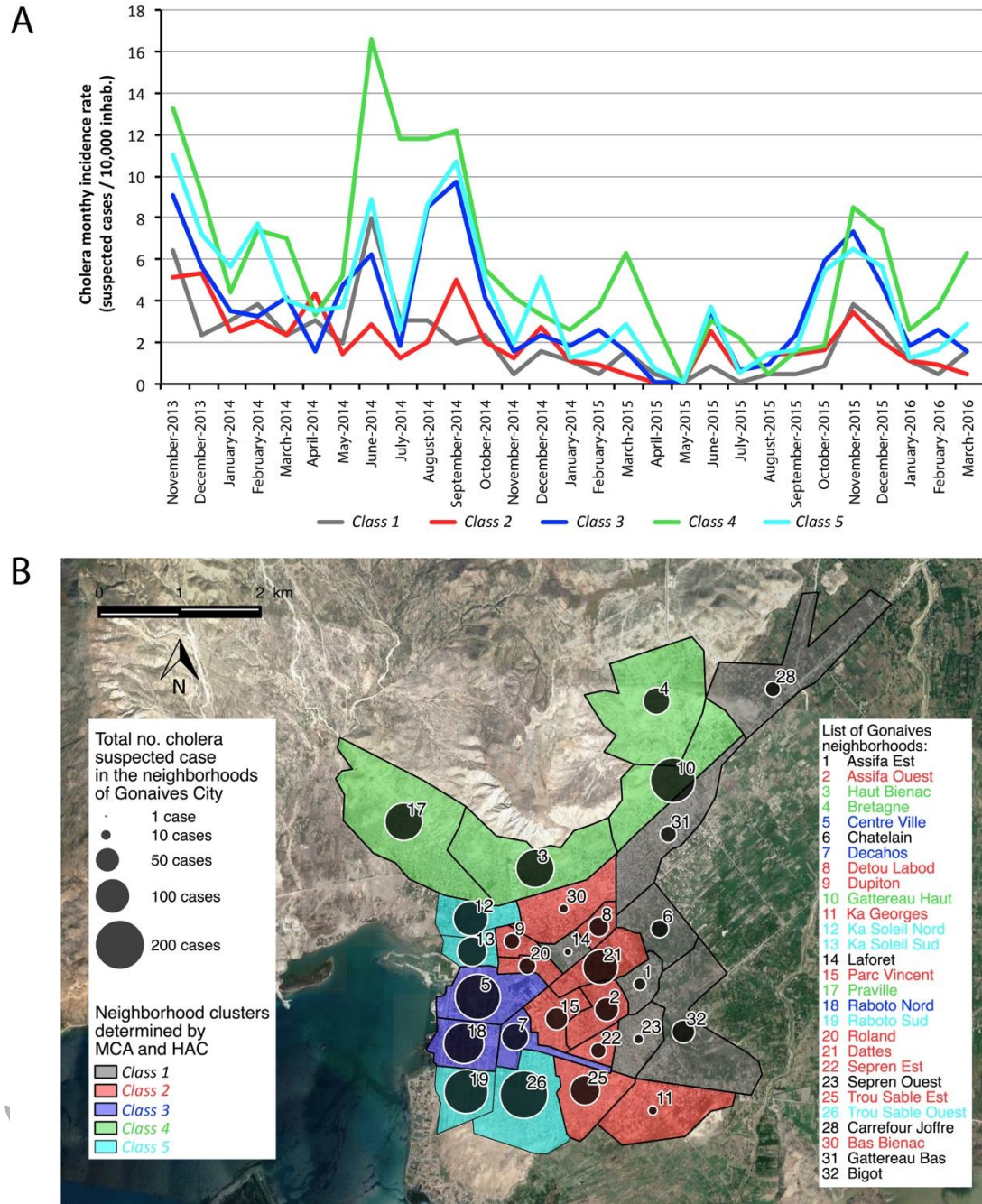




**Figure 2: (A) Hierarchical Ascendant Classification (HAC), and (B) Multiple Correspondence Analysis (MCA) factor map of the 28 neighbourhoods of Gonaives City based on their socio-economic and environmental characteristics.** HAC was performed using the coordinates of each variable in the first 20 principal components of the MCA (Supplementary Results). In the factor map, neighbourhoods were projected on the two first components of the MCA. Colours represent each of the five identified classes. Dots in Panel A represent the 28 neighbourhoods, and lines their relationship.

Compared to Class 2 (the intermediate area with the lowest incidence ratio), the regression analysis (GAM) demonstrated that, adjusting for the geographical location, the peripheral higher economic status class (Class 1) was not significantly different (SIR=0.76 IC95%[0.38; 1.49], p-value=0.43). The hillside poor area with no water availability and open defecation (class 4) was the area most at risk, with a SIR of 3.20 (IC95%[1.25; 8.18], p-value=0.015). The coastal flood-prone and poor area (Class 5), with high access to a shallow water table, was significantly at risk with a SIR of 3.15 (IC95%[1.41; 7.04], p-value=0.005).

The central coastal trading area with good access to a brackish water table and the main use of latrines (class 3), was also at risk with a SIR of 2.49 (IC95%[1.05; 5.95], p-value=0.039).



**Figure 3: (A) Cholera epidemic curve for each of the five classes of neighbourhoods, and (B) spatial distribution of suspected cholera cases in each neighbourhood in Gonaives City, November 2013- March 2016.**

#### 4. Discussion

We highlight the heterogeneity of the mechanisms causing cholera persistence in the city of Gonaives, a major transmission hotspot in the Artibonite department and more generally in Haiti. Amongst the neighbourhoods of Gonaives we identified five different classes based on their socio-economic and environmental profiles. The classes exhibited significantly different cholera incidence rates. Three high-risk classes were identified – poor hillside neighbourhoods, poor neighbourhoods of the coastal floodplain and coastal trade neighbourhoods. Compared to the lowest risk Class 2, the highest risk class (Class 4), incorporated the northern hillside poor neighbourhoods, which have limited access to water and frequent open defecation. There is no functional water supply, and water has to be purchased downhill from private pumps or connections to DINEPA network. There are few latrines, and open-air defecation is the most common practice. The other at-risk classes (Class 3 and 5) are the low-lying coastal neighbourhoods, with increased risk of flooding and a high mainly brackish water table. Due to poor maintenance of limited existing water networks, there is no reliable water supply resulting in the use of uncontrolled water supplies, such as local shallow wells. Their contamination is at higher risk due to their close proximity to numerous porous latrines with poor maintenance and sparse dislodging. The low-lying terrain increases flooding risk, and essential water drains are clogged by rubbish. Whereas Class 5 includes poor residential neighbourhoods, important trading activities are present in the Class 3 neighbourhoods of the coastal centre, with large markets where poor hygiene practices, such as dirty hands and contaminated fruit and vegetables, may

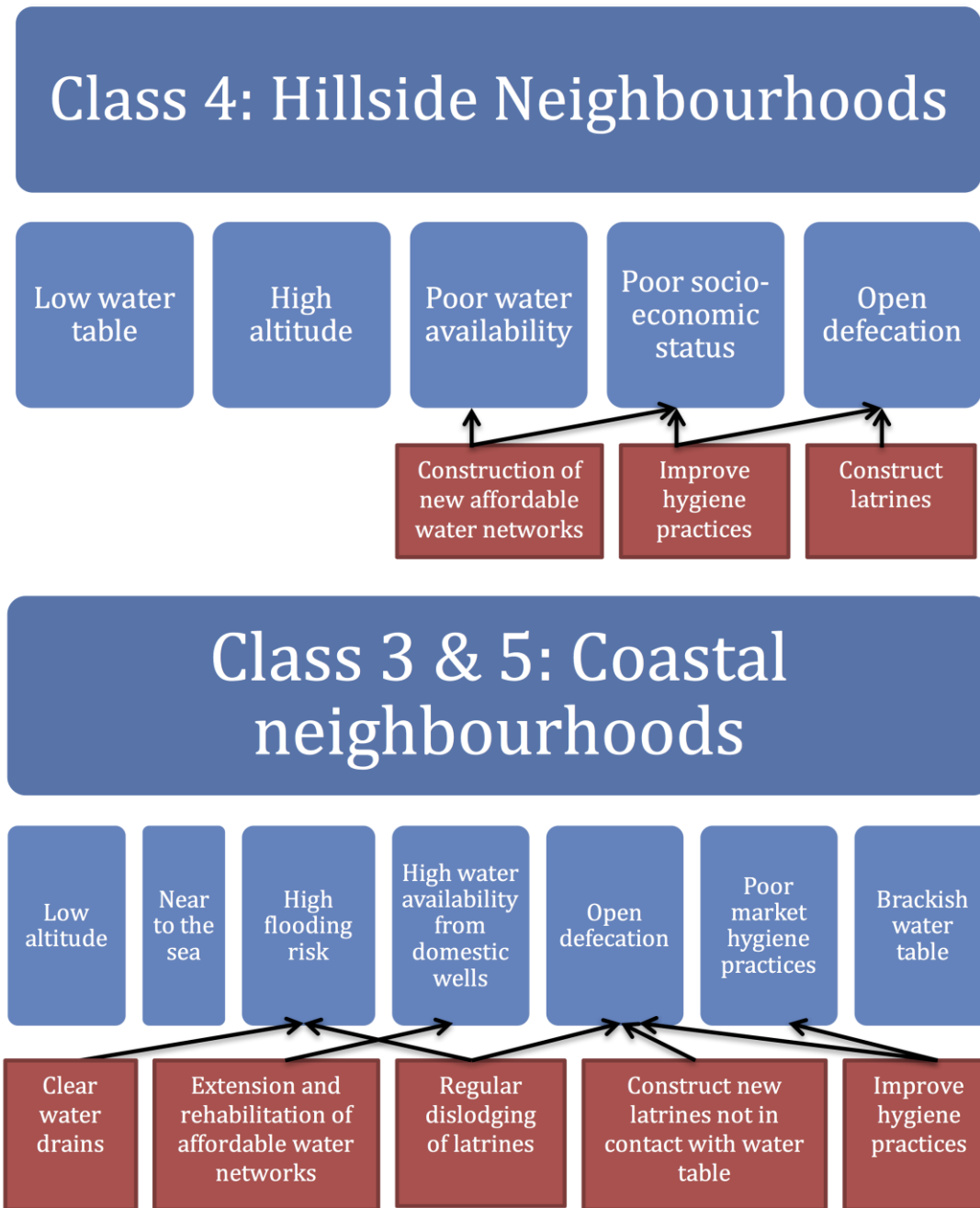
contribute to disease transmission. The relationship with water is complex: our main results showed that cholera risk is significantly concentrated in an area with high water availability and in another area with low water availability. The problem remains the same, poor access to clean drinking water.

To our knowledge, this is the first study that incorporates a statistical spatial analysis of cholera risk factors with various socio-economic and environmental characteristics, obtained from available geographical databases and field studies, in an urban context. This wide-angle approach enables us to have an overall vision of the patterns of cholera socio-environmental risk factors in the city of Gonaives. However, we note several limitations of our study. The number of suspected cases of cholera, rather than confirmed cases, was used in this study, as only 10% of suspected cases were sampled for confirmation culture, which is in accordance with WHO recommendations (World Health Organization (WHO) and Global Task Force on Cholera Control, 2010). Secondly, some of the variables included in the analysis are continuous, such as economic status, functionality of the water network, or drinking water availability. However, due to local constraints, the field investigation was only able to observe qualitative information with no systematic sampling of households. Furthermore, classification methods identify variables that exhibit differences between the neighbourhoods. However, there may be variables that play a relevant role in cholera transmission, but we were unable to identify in the analysis due to homogeneity in each neighbourhood. We performed an ecological study, not an individual population study. This introduces classical ecological fallacy, which therefore means we cannot infer a direct individual risk from these neighbourhood risk profiles (Richardson and Montfort, 2000).

However, our results do not aim to describe individual risk factors of cholera transmission, which have already been assessed by several case control studies (Dubois et al., 2006; Dunkle et al., 2011; Kanungo et al., 2012; Morof et al., 2013) including a study conducted in Gonaives in 2011 (Grandesso et al., 2013). Additionally, our study could not capture important factors associated with the dynamics of cholera transmission, such as population movements (Bengtsson et al., 2015), population immunity (Jackson et al., 2013), rainfall (Eisenberg et al., 2013) or mitigation activities implemented by cholera response teams. We aimed to focus on neighbourhood characteristics associated with cholera incidence. In our univariate analysis, few risk factors seem to be significantly associated with cholera incidence, probably due to the heterogeneity of cholera-associated socio-environmental characteristics in the city and the limited number of neighbourhoods (28). Furthermore, our methods were chosen to take into account possible highly correlated variables, an important risk of biased estimates during the multivariate analysis. We implemented a dimensional reduction through the use of other statistical methods for large numbers of variables, such as multiple correspondence analysis and hierarchical classification. The identified socio-environmental classes were significantly associated with cholera incidence, which highlights the importance of this approach. Rather than describing the individual risk patterns, our results propose a classification of cholera distribution patterns in one of the most affected communes in the country, in order to implement adapted elimination strategies for the specific socio-economic contexts.

These results have already been incorporated into a contingency plan promoted by several governmental and non-governmental stakeholders;

including the local authorities, the Ministry of Public Health and Population, the National directorate for potable water and sanitation (DINEPA), UNICEF and the Pan-American Health Organisation (PAHO). This contingency plan is essential to raise funds from international funding agencies, in order to prioritise the extension and/or rehabilitation of water supply networks, as identified in the National Cholera Elimination Plan. Our results helped to identify the neighbourhoods in which to prioritise these middle and long-term prevention strategies (Figure 4). Within the hillside neighbourhoods, the priority is to construct a new water network, which does not currently exist, with enough pressure to ensure clean water supply uphill. Strategies to improve hygiene practices should focus on the washing of hands and the reduction of open defecation practices by promoting the construction of improved latrines. Within the coastal neighbourhoods, improving water quality should focus on the extension and rehabilitation of existing water supply networks. An efficient chlorination system should be implemented. This water supply has to be affordable, in order to reduce the use of domestic wells that are currently easily contaminated due to the high water table and high flooding risk. Furthermore, new latrines that are not in contact with the water table should be constructed in the flood-risk neighbourhoods, alongside the regular dislodging of excrement. To further limit the risk of flooding, it is important to regularly clear water drains. Education should focus on improving the hygiene practices and conditions in the markets.



**Figure 4: Profile characteristics (blue boxes) of the three high-risk classes identified by hierarchical classification (hillside neighbourhoods and the two coastal neighbourhoods), and corresponding specific control and prevention strategies for the elimination of cholera (red boxes).**

## 5. Conclusions

In conclusion, factors associated with the cholera spatial distribution are heterogeneous across neighbourhoods of the city of Gonaives, Haiti. Therefore, prevention strategies should not be homogenous. We provide an important example of the need to adapt prevention strategies according to the specific socio-environmental context of each neighbourhood within the city. Not only will these strategies help mitigate and eliminate cholera transmission in Gonaives and the surrounding communes, they will also have an impact on other diseases sharing the same mode of transmission, such as shigellosis, typhoid fever, hepatitis A etc. More generally, this will help improve the livelihood of the population in the third largest city in Haiti. A similar approach is currently being implemented by UNICEF and its partners in other cities affected by cholera in Haiti, such as Cap-Haitien and Saint-Marc. Harnessing the information from spatial analysis, observational field studies and geographical databases provides an adaptive contextualised approach that may be generalised to other urban areas affected by cholera worldwide.

**Declaration of interest**

S Rebaudet, Anne-Gaelle Lebeau, Aaron A Abedi, Gregory Bulit and R Piarroux declare a scientific relationship with UNICEF.

All other authors declare no conflict of interest.

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### **References**

- Allan, M., Grandesso, F., Pierre, R., Magloire, R., Coldiron, M., Martinez-Pino, I., Goffeau, T., Gitenet, R., François, G., Olson, D., Porten, K., Luquero, F.J., 2016. High-resolution spatial analysis of cholera patients reported in Artibonite department, Haiti in 2010–2011. *Epidemics* 14, 1–10. doi:10.1016/j.epidem.2015.08.001
- Azman, A.S., Luquero, F.J., Rodrigues, A., Palma, P.P., Grais, R.F., Banga, C.N., Grenfell, B.T., Lessler, J., 2012. Urban cholera transmission hotspots and their implications for reactive vaccination: evidence from bissau city, Guinea bissau. *PLoS Negl Trop Dis* 6, e1901. doi:10.1371/journal.pntd.0001901
- Barzilay, E.J., Schaad, N., Magloire, R., Mung, K.S., Boncy, J., Dahourou, G.A., Mintz, E.D., Steenland, M.W., Vertefeuille, J.F., Tappero, J.W., 2013. Cholera Surveillance during the Haiti Epidemic - The First 2 Years. *N. Engl. J. Med.* 368, 599–609. doi:10.1056/NEJMoa1204927
- Bengtsson, L., Gaudart, J., Lu, X., Moore, S., Wetter, E., Sallah, K., Rebaudet, S., Piarroux, R., 2015. Using mobile phone data to predict the spatial spread of cholera. *Sci Rep* 5, 8923. doi:10.1038/srep08923
- Blackburn, J.K., Diamond, U., Kracalik, I.T., Widmer, J., Brown, W., Morrissey, B.D., Alexander, K.A., Curtis, A.J., Ali, A., Morris, J.G., 2014. Household-Level Spatiotemporal Patterns of Incidence of Cholera, Haiti, 2011. *Emerging Infectious Diseases* 20, 1516–1519. doi:10.3201/eid2009.131882

- Bompangue, D., Giraudoux, P., Piarroux, M., Mutombo, G., Shamavu, R., Sudre, B., Mutombo, A., Mondonge, V., Piarroux, R., 2009. Cholera epidemics, war and disasters around Goma and Lake Kivu: an eight-year survey. *PLoS Negl Trop Dis* 3, e436. doi:10.1371/journal.pntd.0000436
- Cravioto, A., Lanata, C.F., Lantagne, Daniele S, Nair, G.B., 2011. Final Report of the Independent Panel of Experts on the Cholera Outbreak in Haiti. United Nations, New York, NY. URL: <http://www.un.org/News/dh/infocus/haiti/UN-cholera-report-final.pdf> (accessed 8.1.16)
- Dubois, A.E., Sinkala, M., Kalluri, P., Makasa-Chikoya, M., Quick, R.E., 2006. Epidemic cholera in urban Zambia: hand soap and dried fish as protective factors. *Epidemiol Infect* 134, 1226–1230. doi:10.1017/S0950268806006273
- Dunkle, S.E., Mba-Jonas, A., Loharikar, A., Fouché, B., Peck, M., Ayers, T., Archer, W.R., De Rochars, V.M.B., Bender, T., Moffett, D.B., Tappero, J.W., Dahourou, G., Roels, T., Quick, R., 2011. Epidemic cholera in a crowded urban environment, Port-au-Prince, Haiti. *Emerg Infect Dis* 17, 2143–2146. doi:10.3201/eid1711.110772
- Eisenberg, M.C., Kujbida, G., Tuite, A.R., Fisman, D.N., Tien, J.H., 2013. Examining rainfall and cholera dynamics in Haiti using statistical and dynamic modeling approaches. *Epidemics* 5, 197–207. doi:10.1016/j.epidem.2013.09.004
- Frerichs, R.R., Keim, P.S., Barraï, R., Piarroux, R., 2012. Nepalese origin of cholera epidemic in Haiti. *Clin Microbiol Infect* 18, E158-163. doi:10.1111/j.1469-0691.2012.03841.x

- Gaudart, J., Rebaudet, S., Barraïis, R., Boncy, J., Faucher, B., Piarroux, M., Magloire, R., Thimothe, G., Piarroux, R., 2013. Spatio-Temporal Dynamics of Cholera during the First Year of the Epidemic in Haiti. *PLoS Negl Trop Dis* 7, e2145. doi:10.1371/journal.pntd.0002145
- Grandesso, F., Allan, M., Jean-Simon, P.S.J., Boncy, J., Blake, A., Pierre, R., Alberti, K.P., Munger, A., Elder, G., Olson, D., Porten, K., Luquero, F.J., 2013. Risk factors for cholera transmission in Haiti during inter-peak periods: insights to improve current control strategies from two case-control studies. *Epidemiol. Infect.* 1–11. doi:10.1017/S0950268813002562
- Hendriksen, R.S., Price, L.B., Schupp, J.M., Gillece, J.D., Kaas, R.S., Engelthaler, D.M., Bortolaia, V., Pearson, T., Waters, A.E., Upadhyay, B.P., Shrestha, S.D., Adhikari, S., Shakya, G., Keim, P.S., Aarestrup, F.M., 2011. Population genetics of *Vibrio cholerae* from Nepal in 2010: evidence on the origin of the Haitian outbreak. *MBio* 2, e00157-00111. doi:10.1128/mBio.00157-11
- Husson, F., Josse, J., Pagès, J., 2010. Principal component methods - hierarchical clustering - partitional clustering: why would we need to choose for visualizing data? Technical Report – Agrocampus. Agro Campus Ouest, Applied Mathematics Department. URL: [http://factominer.free.fr/docs/HCPC\\_husson\\_josse.pdf](http://factominer.free.fr/docs/HCPC_husson_josse.pdf) (accessed 10.1.16)
- IHSI (Institut Haïtien de Statistique et d'Informatique), Direction des Statistiques Démographiques et Sociales, Ministère de l'Économie et des Finances, République d'Haïti, 2015. Population totale, population de 18 ans et plus, Ménages et densités estimés en 2015. Port-au-Prince, Haiti. URL: [www.ihsi.ht/pdf/projection/Estimat\\_PopTotal\\_18ans\\_Menag2015.pdf](http://www.ihsi.ht/pdf/projection/Estimat_PopTotal_18ans_Menag2015.pdf) (accessed 10.1.16)

- Jackson, B.R., Talkington, D.F., Pruckler, J.M., Fouché, M.D.B., Lafosse, E., Nygren, B., Gómez, G.A., Dahourou, G.A., Archer, W.R., Payne, A.B., Hooper, W.C., Tappero, J.W., Derado, G., Magloire, R., Gerner-Smidt, P., Freeman, N., Boncy, J., Mintz, E.D., 2013. Seroepidemiologic Survey of Epidemic Cholera in Haiti to Assess Spectrum of Illness and Risk Factors for Severe Disease. *Am J Trop Med Hyg* 89, 654–664. doi:10.4269/ajtmh.13-0208
- Kanungo, S., Sur, D., Ali, M., You, Y.A., Pal, D., Manna, B., Niyogi, S.K., Sarkar, B., Bhattacharya, S.K., Clemens, J.D., Nair, G.B., 2012. Clinical, epidemiological, and spatial characteristics of *Vibrio parahaemolyticus* diarrhea and cholera in the urban slums of Kolkata, India. *BMC Public Health* 12, 830. doi:10.1186/1471-2458-12-830
- Lê, S., Josse, J., Husson, F., 2008. FactoMineR: An R Package for Multivariate Analysis. *Journal of Statistical Software* 25.
- Luquero, F.J., Rondy, M., Boncy, J., Munger, A., Mekaoui, H., Rymshaw, E., Page, A.-L., Toure, B., Degail, M.A., Nicolas, S., Grandesso, F., Ginsbourger, M., Polonsky, J., Alberti, K.P., Terzian, M., Olson, D., Porten, K., Ciglencecki, I., 2016. Mortality Rates during Cholera Epidemic, Haiti, 2010–2011. *Emerging Infectious Diseases* 22, 410–416. doi:10.3201/eid2203.141970
- Morof, D., Cookson, S.T., Laver, S., Chirundu, D., Desai, S., Mathenge, P., Shambare, D., Charimari, L., Midzi, S., Blanton, C., Handzel, T., 2013. Community Mortality from Cholera: Urban and Rural Districts in Zimbabwe. *Am. J. Trop. Med. Hyg.* doi:10.4269/ajtmh.11-0696
- MSPP, 2016. Ministère de la Santé Publique et de la Population de la République d’Haïti. Centre de Documentation. URL <http://mspp.gouv.ht/newsite/documentation.php> (accessed 4.23.16).

- Osei, F.B., Duker, A.A., 2008. Spatial dependency of *V. cholera* prevalence on open space refuse dumps in Kumasi, Ghana: a spatial statistical modelling. *Int J Health Geogr* 7, 62. doi:10.1186/1476-072X-7-62
- Penrose, K., de Castro, M.C., Werema, J., Ryan, E.T., 2010. Informal urban settlements and cholera risk in Dar es Salaam, Tanzania. *PLoS Negl Trop Dis* 4, e631. doi:10.1371/journal.pntd.0000631
- Piarroux, R., Barraï, R., Faucher, B., Haus, R., Piarroux, M., Gaudart, J., Magloire, R., Raoult, D., 2011. Understanding the cholera epidemic, Haiti. *Emerg Infect Dis* 17, 1161–1168. doi:10.3201/eid1707.110059
- Republic of Haiti, Ministry of Public Health and Population, National Directorate for Water Supply and Sanitation, 2013. National Plan for the Elimination of Cholera in Haiti 2013-2022. Port-au-Prince, Haïti. URL: <http://reliefweb.int/report/haiti/national-plan-elimination-cholera-haiti-2013-2022> (accessed 10.1.16)
- Richardson, S., Montfort, C., 2000. Ecological correlation studies, in: *Spatial Epidemiology. Methods and Applications*. P. Elliott, Jon Wakefield, Nicola Best, and David Briggs, Oxford, pp. 205–220.
- Sasaki, S., Suzuki, H., Igarashi, K., Tambatamba, B., Mulenga, P., 2008. Spatial analysis of risk factor of cholera outbreak for 2003-2004 in a peri-urban area of Lusaka, Zambia. *Am J Trop Med Hyg* 79, 414–421.
- Sur, D., Manna, B., Deb, A.K., Deen, J.L., Danovaro-Holliday, M.C., von Seidlein, L., Clemens, J.D., Bhattacharya, S.K., 2004. Factors associated with reported diarrhoea episodes and treatment-seeking in an urban slum of Kolkata, India. *J Health Popul Nutr* 22, 130–138.
- Wood, N.S., 2006. *Generalized Additive Models: An Introduction with R*,

Chapman & Hall/CRC Texts in Statistical Science. Chapman and Hall/CRC.

World Health Organization (WHO), Global Task Force on Cholera Control, 2010.

Cholera outbreak: assessing the outbreak response and improving

preparedness. World Health Organization (WHO), Geneva. URL:

<http://www.who.int/cholera/publications/OutbreakAssessment/en/>

(accessed 10.1.16)

**Supplementary Database: Excel spreadsheet of variables collected and included in the analysis**

**Figure S1: Map of the 28 neighbourhoods of Gonaives City.** (Background satellite image obtained from Google Maps)

**Figure S2: Total number of cholera suspected cases seen from the 28 neighbourhoods of Gonaives City**

**Supplementary Results: Excel spreadsheet with results of the Multiple Correspondence Analysis (MCA) factor map of the 28 neighbourhoods of Gonaives City based on their socio-economic and environmental characteristics.** Coordinates of each variable in the first 20 principal components of the MCA. Eigenvalues, Percentages of variances and Cumulative percentages of variances of each component. Main characteristics of neighbourhood classes identified after the Hierarchical Ascendant Classification (HAC) using the 20 first components of the MCA.