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Review

Recurrence of cholera epidemics in South Africa: inadequate sanitary facilities, poor environmental monitoring practices, and climate change as possible contributing factors

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Cholera is an acute infectious disease caused by two toxin-producing strains, namely *Vibrio cholerae* O1, and *Vibrio cholerae* O139. Its recorded history stretches as far back as 1817, in Bengal, India, yet it continues to be a public health threat to this present day. Although cholera epidemics are now a relatively rare phenomenon in developed countries, frequent epidemics continue to be experienced in sub-Saharan Africa. Africa accounted for 63.33% of the 223 370 cases of and 4 159 deaths from cholera that were reported globally in 2020. Furthermore, of the 342 900 cholera cases and 3 304 cholera deaths reported globally in 2022, 40.28% of the cases and 77.85% of the deaths were in Africa. Inadequate sanitation infrastructure as well as inadequate provision of quality, safe drinking water in South Africa still creates conducive conditions for the transmission of cholera. In addition, climate change is increasingly becoming a risk factor towards the spread of *V. cholerae* pathogens in inland regions. To make recommendations on how South Africa, and potentially the Southern African region as a whole, can minimise the resurgence of cholera, this review addressed the following questions: Does South Africa have adequate sanitation infrastructure to curb the spread of cholera? Is there enough intentional surveillance of environmental water sources for vibrios as a cholera outbreak predictive tool? What is the impact of climate change on the resurgence of cholera in South Africa? And, what needs to be done to curb the resurgence of cholera in South Africa?

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INTRODUCTION

Aetiology and epidemiology of cholera

Cholera is an acute infectious disease whose recorded history stretches as far back as 1817, to Bengal, India (Jensen et al. 2021). It is caused by two toxin-producing strains (serogroups) of the bacterium *Vibrio cholerae*, namely *Vibrio cholerae* O1, and *Vibrio cholerae* O139 (Nelson et al., 2009). While cholera is known to be a disease mostly associated with insanitary conditions and faecal contamination of food and drinking water, its aetiological agent, the toxigenic bacterium *Vibrio cholerae* (as well as the non-cholerae *Vibrio* strains) is endemic as a natural inhabitant of brackish riverine, estuarine, and coastal waters (Almagro-Moreno and Taylor, 2013). It would make a perfect hypothesis, therefore, that the first incidence of cholera must either have been caused by the consumption of contaminated seafood, or by the contamination of freshwater resources resulting from the backflow of ocean currents, or that the bacterium could have been introduced into freshwater resources by migrating seabirds or fish – the options are as many as the possible transmission pathways of the disease. Once vibrios were introduced onto land and freshwater resources, several reservoirs could then have been established for them, including several sea and riverine organisms and creatures such as algae, shellfish, chironomids and their egg masses, fish, waterfowl, amebae, and crustaceans, especially copepods, as is now known (Nelson et al., 2009; Vezzulli et al., 2010). The dissemination of cholera from the Asian sub-continent, where it was first discovered, to the rest of the world has been attributed to four main routes, including human migration (CDC, 1993; Bwire et al., 2016), migratory seabirds like the Great Cormorants which may contract the bacterium from fish prey and then transport it for distances exceeding 1 000 km a day, potentially to other continents (Laviad-Shitrit et al., 2019), food trade across countries and continents (Popovic et al., 1993), and environmental pollution, as from sewage discharges from sea vessels coming from a cholera endemic region (McCarthy and Khambaty, 1994; Cohen et al., 2012; Chen et al., 2022).

There are two distinctive patterns by which cholera occurs as a disease, namely endemic and epidemic cholera. Epidemic cholera is known to take place close to water channels, during suitable weather conditions that support the growth of the bacterium *V. cholerae* (Jutla et al., 2013). Meanwhile, endemic cholera is linked to seasonal climatic patterns and intrusions by tidal seawater (Jutla et al., 2013; Deen et al., 2020). Flies are thought to participate in cholera transmissions since they serve as vectors for the bacteria (Farhana et al., 2016). While in recent years cholera epidemics have become a rare phenomenon in developed countries, sporadic epidemics are still experienced in the Asian sub-continent as well as in sub-Saharan African countries (WHO, 2022). There were 223 370 cases and 4 159 deaths reported worldwide in 2020, of which 36.67% cases and 1.56% deaths were recorded in Asia and 63.33% cases and 98.44% deaths were recorded in Africa (WHO, 2020). Meanwhile, only one case and zero deaths were reported in Australia, and no cases and deaths were reported in both Europe and the Americas (WHO 2020). Furthermore, in 2022 there were 342 900 cholera cases and 3 304 cholera deaths that were reported worldwide, of which 40.28% cases and 77.85% of the deaths were from Africa while 59.09% cases and 22.15% of the deaths were from Asia (WHO 2023).

However, only 0.03% of the cases and 0% deaths were reported in the Americas, with absolutely no cases and deaths reported in both Europe and Australia (WHO, 2023). The World Health Organisation predicts that approximately 4.1 million cholera cases and 150 000 deaths occur annually (WHO, 2023). Furthermore, the African continent is regarded as a cholera hotspot, with over 141 400 cases and 400 deaths reported annually (WHO, 2023). However, despite the decline in number of deaths, cholera still poses a serious health threat across the globe owing to the lack of adequate laboratories, detection apparatus and government support, which means that only one third of the cases and deaths are reported in most developing countries (WHO, 2023).

Because *Vibrio cholerae* is acutely infectious, with an infectious dose of (ID_{50}) of 40 colony forming units (CFU) (Gillman et al., 2021), cholera infection will most likely be fatal if untreated. Further, there are a number of factors that make people more vulnerable to cholera infections, as well as the severity of the disease (Hartley et al., 2006). These include genetic makeup, such as individuals with blood group O, individuals living in unsanitary and overcrowded conditions, individuals with prior vagotomy, individuals with *Helicobacter pylori* infection as well as those using proton-pump inhibitors and antihistamines (Fanous and King, 2023). Moreover, pregnant women, children below the age of five as well as non-breastfed infants are among those more susceptible to cholera infections (Deen et al., 2008; Kuhlmann et al., 2016; Deen et al., 2020). Also, immunocompromised individuals, such as those living with the human immunodeficiency virus (HIV), tend to be more susceptible to infectious diseases like cholera (Von Seidlein et al., 2008). Moreover, individuals with low vitamin A levels are also regarded as high risk (Harris et al., 2008; Deen et al., 2020).

Of the factors discussed above, however, the most devastating cholera epidemics in recent times have widely been linked to the consumption of contaminated water or food (Vezzulli et al., 2021), living in squalid conditions, as well as sanitation failures, from household to municipal level (Du Plessis, 2023). Once there is as little as a single, usually unidentified, case of cholera, the disease can spread very quickly since faeces of infected person(s) have been identified as a primary source of contamination. The most common symptoms of cholera include leg cramps, nausea and vomiting, dehydration – often associated with kidney failure in severe cases, and diarrhoea (Aborode et al., 2023). However, in regions with poor health infrastructure, these complications are often mistaken to be due to other causes or diseases, such as typhoid (DeRoeck et al., 2005), diarrhoea (Davies et al., 2017), shigellosis (Cash et al., 2014), and campylobacteriosis (Ghosh et al., 2016), making it difficult to correctly diagnose the disease.

While the majority of industrialised countries have, to a large extent, conquered the scourge of cholera by investing in health and sanitary infrastructure such as drinking water and sewage treatment facilities (Conn, 2014), lack and/or poor maintenance of the same in developing countries still creates conducive conditions for the transmission of *Vibrio cholerae* (Cuneo et al., 2017). However, the recent epidemics as well as isolated cases of cholera in South Africa indicate that there are more factors at play in its resurgence than just poor maintenance of infrastructure. Of course, the first question to ask is whether South Africa has adequate and properly maintained sanitation infrastructure, especially considering its growing population. Equally, another, important questions to ask would be: what is the impact of climate change on the resurgence of infectious diseases such as cholera in a setting like South Africa? And, as a way forward, what needs to be done to curb the resurgence of cholera in South Africa? This review is aimed at addressing these questions as well as to make recommendations as to how the country, and potentially the Southern African region as a whole, can minimise the resurgence of cholera for the general good of its citizenry. As a delineation, and to facilitate in-depth scrutiny of the subject while avoiding ambiguity, the use of the term 'sanitation facilities/infrastructure' was restricted to the sewage reticulation system, chiefly the wastewater treatment facilities.

Does South Africa have adequate sanitation infrastructure, both in term of drinking water treatment as well as sewage reticulation facilities?

Provision of adequate, reliable, and safe drinking water is vital for human health as it reduces the burden of waterborne infectious diseases (Edokpayi et al., 2018). Clean water provision therefore ceases to be a privilege but a fundamental right to the existence of humanity. The Government of South Africa, through the South African Constitution, Act 108 of 1996, Chapter 2 (Bill of Rights) and section 24 states that, "Everyone has a right to an environment that is not harmful to their health or well-being" while section 27.1 (b) states that, "Everyone has the right to have access to sufficient food and water" (RSA, 1996). Further, the South African Water Services Act and Regulations (1997–2001) stipulates that everyone has a right of access to basic water supply and basic sanitation (Hay et al., 2012).

In efforts to comply with the Constitution, the South African Government has set up drinking water and wastewater treatment infrastructure at municipal level throughout the country's regions for the provision of both sewage reticulation as well as safe drinking water services to the public. While this has been a huge success story in some settings, with a claimed 92.5% South African households having access to improved drinking water sources (Statistics SA, 2016), there are many South African households, both in urban and rural areas, which still do not have access to both safe and reliable drinking water as well as sanitation services (Edokpayi et al., 2018; Bwapwa, 2019).

In Limpopo Province, for example, Edokpayi et al. (2018) conducted a survey involving 405 households in some rural communities to determine their water-use practices, perceptions of water quality, and household water-treatment methods. They found that while the supplied drinking water was microbiologically safe, not all residents had access to treated drinking water. At the same time, they found that all available surface water sources had traces of faecal contamination, which becomes a hazard to those who, due to lack of access to treated drinking water, will opt for surface water sources as an alternative. This is especially as some studies suggest that most urban regions within South Africa have lower infectious waterborne diseases outbreaks in comparison to the rural regions (Wang et al., 2014; Ajibade et al., 2021; Murei et al., 2022) as urban centres have almost adequate water treatment facilities which enable access to quality and safe water (Ajibade et al., 2021; Bazaanah and Mothapo, 2023; Ibangha et al., 2023). With Limpopo included, 6 out of South Africa's 9 provinces (Free State, Eastern Cape, KwaZulu-Natal, Mpumalanga, North West, Limpopo) have been reported to experience either poor access or no access to safe and quality water resulting in constant outbreaks of waterborne diseases (Okoh et al., 2015; Edokpayi et al., 2017; Dureab et al., 2019).

According to a report by Molobela and Sinha (2011), there are challenges pertaining to water management in South Africa. For instance, the decline in availability and access to quality, clean water stems from many problems such as water mismanagement, political squabbles, as well as economic barriers. Consequently, citizens have become victims of mismanagement of water, with the rural regions suffering the most severe effects (Schulze et al., 2001; Edokpayi et al., 2017). So, while water accessibility challenges can be resolved through the natural availability of water sources, it is factors such as government authorities, supply management, private and government service points, availability of funds, among others, which ultimately provide water security (Molobela and Sinha, 2011). However, despite all these unit factors working together, the rapid rise in population increases water demand in the face of other, militating factors, such as an increasingly drier climate, a drop in groundwater levels, aging water treatment facilities, and a rise in surface water contamination (Molobela and Sinha, 2011). Furthermore, water scarcity and poverty are associated with various infectious disease outbreaks, the deadliest and most frequent of which is cholera, as observed in both sub-Saharan Africa and the Asian subcontinent (Adagbada et al., 2012; Musa et al., 2022). South Africa's rural municipal agencies, in particular, experience difficulties in resource management as there is usually no coordination in balancing community needs against the availability and capacity of water resources (Dungeni et al., 2010; Odeku, 2022). These management constraints tend to hinder the development of new water treatment facilities, as well as the expansion of supply systems to provide access to everyone.

With regards to wastewater treatment plants (WWTPs), the South African Government has, through the Department of Water and Sanitation (DWS), introduced an incentive-based system called the Green Drop Certification to encourage municipalities across the country to treat their sewage effluents to the maximum acceptable standards (Manus, 2022). Two problems exist where wastewater treatment facilities are concerned: the treatment efficiency of existing WWTPs as well as the total unavailability of wastewater treatment facilities in some areas of the country. Regarding the treatment efficiency of the existing WWTPs, it has been observed that, despite the Green Drop initiative, treatment at most of the country's municipal WWTPs is characterised by incomplete removal of pathogens before the release of the wastewater effluents into environmental water bodies (Dungeni et al., 2010; Adefisoye and Okoh, 2017).

This has the sum of creating reservoirs of infectious disease pathogens like *Vibrio cholerae* and *Salmonella typhimurium*, among others, in receiving water bodies (Dungeni et al., 2010; Osunla et al., 2021). The release of wastewater effluents post-treatment to contiguous water bodies significantly changes their microbial community abundance as demonstrated by the survival of *Vibrio* species in treated wastewater as either free cell or plankton-associated entities (Igbinosa et al., 2011; Okoh et al., 2015). Several factors have been blamed for the inefficiency of the WWTPs, among them an astronomical rise in the population of major urban centres of the country, fuelled by immigration and semigration (Nkabinde et al., 2018; PMG, 2022), resulting in capacity overload which, in extreme cases, forces engineers to direct some of the raw effluents into by-pass flow (Oksiutycz and Azionya, 2022; Pocock and Joubert, 2018). Another of the factors is the lack of proper maintenance of the WWTPs, resulting in reduced capacity and efficiency (Raghab et al., 2013). These occurrences increase the probability of waterborne disease outbreaks. Of particular concern is the finding by Okoh et al. (2015) that seasonal changes do not affect the survival of *Vibrio* species in post treated waste sludge, implying that we cannot bank on the natural elimination of these pathogens in receiving surface water systems because of unfavourable conditions as seasons change.

Moreover, there are other methods (thermophilic anaerobic digestion, sedimentation and composting) which are applied parallel to WWTPs to treat waste sludges (Samie et al., 2009). This is despite these methods having been proven to not be effective in eradicating other strains of *Vibrio* found in sludges (Samie et al., 2009; Okoh et al., 2015). Lending credence to this observation are multiple reports of cholera outbreaks caused by the discharging of post-treated waste sludge that had active *V. cholera* into water bodies by local WWTPs in the Mpumalanga and KwaZulu-Natal Provinces of South Africa (Samie et al., 2009). Furthermore, WWTPs in both provinces, in addition to the Eastern Cape Province, were found not to comply with the regulatory standards around the discharging of effluents to the environment, as the effluents were not properly disinfected (Wang et al., 2014). These inadequacies of the WWTPs have been fingered as one of the primary sources of the frequent cholera outbreaks the country has been experiencing (Bartone, 2011), as these effluent sludges are frequently used by local farms as manure, which spikes the spread of cholera (Noor et al., 2021). The use of partially disinfected sludges on farms not only contaminates the crops but causes transient damage to groundwater sources.

Unless the situation of WWTPs is expediently remedied, the continued discharge of inadequately treated sewage effluents remains an ongoing source of surface water pollution, making these resources environmental reservoirs of aetiological agents of infectious diseases, including *V. cholerae* (Edokpayi et al., 2015). Therefore, the continued use of water resources impacted by inadequately treated effluents for domestic and agricultural purposes has been linked with a rise in parasitic infections, as well as increasing incidences of diarrhoea, that may be due to the direct consumption of water or raw vegetables from farms that use polluted water for irrigation.

The need for expansion and maintenance of the current active urban WWTPs due to the rapidly rising population is not in question, as it is evident that there is not enough wastewater treatment capacity to handle the high volume of effluents. According to a report by Edokpayi et al. (2015), only 7% of WWTPs in South Africa are deemed adequate in accordance with international standards. What is more concerning is the fact that there is an imbalance in distribution regarding the WWTPs between rural and urban areas, as some WWTPs located in urban regions are well developed whereas those in rural regions are either undeveloped or non-existent (Long et al., 2022; Montwedi et al., 2021).

Consequently, people who dwell in rural areas as well as in informal peri-urban settlements with no access to sewage reticulation systems have resorted to the use of pit latrine systems (Graham and Polizzotto, 2013; Gudda et al., 2019). In this regard, a total of 2 236 schools distributed in six of South Africa's nine provinces, i.e. Free State, Eastern Cape, Limpopo, KwaZulu-Natal, Mpumalanga, and North West, still rely on pit toilets, with 199 schools being without access to sanitary facilities and a further 121 schools being without access to quality water on their premises (Odeku, 2022; Bazaanah and Mothapo, 2023). The complete lack of access to clean water supply in schools presents a challenge in practicing basic hygiene such as washing hands before food consumption, exposing learners and staff members to the possibility of exposure to infectious diseases like cholera (Malakoane et al., 2020). While the use of pit toilets is deemed an alternative basic hygiene provision in comparison to open defaecation practices, pit toilets result in the contamination of groundwater resources, which may potentially result in negative public health outcomes in the course of time (Murei et al., 2022). Moreover, pit toilets are considered neither adequate sanitary facilities nor safe, as they are often linked to multiple outbreaks of infectious diseases (Murei et al., 2022; Odeku, 2022; Bazaanah and Mothapo, 2023). Without a doubt, therefore, provision of safe and quality water is directly linked with adequate provision of adequate and efficient sewage reticulation facilities (Bazaanah and Mothapo, 2023; Budeli et al., 2020).

Poor monitoring of South Africa's aquatic environments as reservoirs of infectious disease agents

Environmental aquatic ecosystems are often regarded as reservoirs of waterborne infectious disease agents such as *V. cholerae*, *Salmonella typhi*, and *Escherichia coli* O157:H7, among others

(Olsen et al., 2002; Ntema et al., 2014; Liu et al., 2018). Consistent, intentional surveillance of these environmental water bodies is a critical mitigation strategy that may go a long way towards helping health authorities to anticipate and prevent possible future cholera outbreaks. As an example, a surveillance study conducted in 2010 within Haiti by Alam et al. (2014) showed the presence of both *V. cholerae O1* in environmental aquatic reservoirs, only to be followed by a cholera outbreak that resulted in over 600 000 cases and over 7 000 deaths within a span of 2 months after this detection. This raises a number of questions: the first being around the seriousness with which health and government authorities perceive the work that is done by research scientists. The second ponders on the disconnect between research and policy, while the third addresses the issue of competency on the part of government departments/ministries. It is time that governments the world over begin to appreciate the role of scientific research in policy development, and in the day-to-day running of governments. Besides this case, there have been various reports in which the presence of both lethal and non-lethal *V. cholerae* strains was reported in different aquatic environments, and in varying concentrations (Baron et al., 2013; Gaudart et al., 2013; Alam et al., 2014). Furthermore, the findings of Alam et al. (2014) demonstrate that fluctuations in environmental temperatures trigger the proliferation of *V. cholerae* strains, driven by changes in certain environmental conditions such as salinity, phytoplankton abundance, chlorophyll concentration, and sea levels.

Therefore, monitoring of environmental parameters that are known to be adequate physiological stimuli for the proliferation of *V. cholerae* can also aid in forecasting the probability of outbreaks (Jutla et al., 2010). For instance, a surveillance of the ocean colour as a biogeological signature of *V. cholerae* colonies by Racault et al. (2019) linked areas with higher levels of both phytoplankton and zooplankton with the presence of *V. cholerae.* This is because phytoplankton and zooplankton are known to contain chitin, which acts as chemotactic attractant, enhancing the production of biofilms (Racault et al., 2019). The approach by Racault et al. proves to be reliable as it shows the correlation between both phytoplankton and zooplankton and *V. cholerae* in previous outbreaks dating from 1950 to 2019. However, the limitation with the use of this model is that it is expensive as it requires access to satellite data.

Natural waterbodies are often interconnected via a series of streams and rivers. These streams may have negative health impacts as they may serve as conduits for waterborne infectious disease agents. For instance, due to the frequent cholera outbreaks occurring in the Great Lakes Region in Uganda (Alajo et al., 2006; Bwire et al., 2013; Bwire et al., 2018), the five largest environmental reservoirs responsible for water supply throughout Uganda were examined for the presence of *V. cholerae* (Bwire et al., 2018). The findings indicated the presence of *V. cholerae* O1 and *V. cholerae* O139 in all of the five largest lakes as well as in other surface water bodies, causing the lakes to be reservoirs of both *V. cholerae* O1 and *V. cholerae* O139 (Bwire et al., 2018). As a result, there are several explanations for the spread of *V. cholerae* outbreaks in the region: the abstraction of drinking water from contaminated lakes; contamination of surface waters through both animal and human interactions, as well as the change in climate pattens which results in some or all of the following: abnormally high rates of rainfall (and hence flooding), movement of contaminated fish from polluted waters to unpolluted local waterbodies, as well as the influx of travellers and refugees from active cholera endemic countries or communities to cholera-free regions (Alajo et al., 2006; Bwire et al., 2018). In yet another surveillance study carried out by Du Preez et al. (2010) in Pungwe Estuary in Mozambique, toxigenic *V. cholerae* O1 and O139 strains were detected. Considering that the Pungwe River empties into the Indian Ocean, this case presents further evidence that the backflow caused by ocean high swells can be a major source of *V. cholerae* in inland coastal regions. South Africa is a coastal country, with its rivers flowing either into the Indian Ocean on its eastern and southern coast or into the Atlantic Ocean on its western coast. The question then is: how frequently are surveillance studies done to assess the presence of *V. cholerae* in these particular rivers? And whose responsibility is it to conduct these intentional surveillance studies? Asking such questions lays bare the pivotal role played by research institutions such as universities in providing ongoing data on which government authorities can rely to inform policy and decision making. However, the disconnect between academic-led research on the one hand and government ministries on the other hand needs to be addressed for the war against infectious disease outbreaks to be won.

It is worth noting that the intentional monitoring of environmental reservoirs for the presence of *V. cholerae* pathogens in most developing countries such as South Africa remains a challenge due to financial constraints, low research budgets and other economic barriers. Therefore, as long as a research gap remains in the surveillance of aquatic reservoirs, the number of *V. cholerae* outbreaks in Africa will remain high. In a study that presents another angle, Vezzulli et al. (2021) revealed a co-interaction between clinical and environmental *V. cholerae* pathogens, emphasising the need to strengthen research focus on wastewater treatment (WWT) facilities as primary sources for the contamination of environmental waterbodies with clinical *V. cholerae* pathogens and antibiotic resistance genes (ARGs) in inland areas. This further increases the risk of integrative genetic polymorphism between known *V. cholerae* strains and other bacterial species, especially those possessing antibiotic-resistance genes, which may subsequently lead to uncontrollable *V. cholerae* super-pathogens (Abia Akebe et al., 2022). Various South African environmental reservoirs are also reported to be associated with antimicrobial-resistant species, which raises serious health concerns (LaVanchy et al., 2019; Fadare and Okoh, 2021; Abia Akebe et al., 2022). Surveillance of environmental water bodies therefore goes beyond investigating their microbial quality and must function in parallel with environmental waste management. Environmental waste management involves hygiene practices which have a high impact towards mitigating the spread of various infectious diseases. For adequate mitigation, the surveillance of environmental water bodies should be coupled with adequate hygiene practices and environmental waste management.

CLIMATE CHANGE AND THE RESURGENCE OF CHOLERA IN SOUTH AFRICA

Climate change is considered a risk factor for outbreaks of cholera and other infectious diseases, especially in developing countries (Constantin de Magny et al., 2008; Collins, 2003). Globally, the effects of climate change are more pronounced in sub-Saharan Africa in the form of rising temperatures. South Africa is located in the subtropical region and is known to have warm temperatures that are optimal for the proliferation of infectious disease agents such as *Vibrio cholerae* (Hunter, 2003; Mendelsohn and Dawson, 2008; Dudley et al., 2015). Some researchers have made links between geographical locations and climate conditions and the proliferation of *V. cholerae* pathogens (Bompangue et al., 2008; Vezzulli et al., 2021). Data emanating from the use of climate models, satellite data, and known patterns in the spread of disease show that with warmer temperatures and increased rainfall, cholera spreads more readily inland, especially in areas of denser populations (Fig. 1). As the figure shows, the inner core of South Africa is at a heightened risk of climate change–induced sporadic outbreaks of cholera. It can also be seen that the whole country in general has a higher risk of cholera outbreaks if compared to the rest of the African continent.

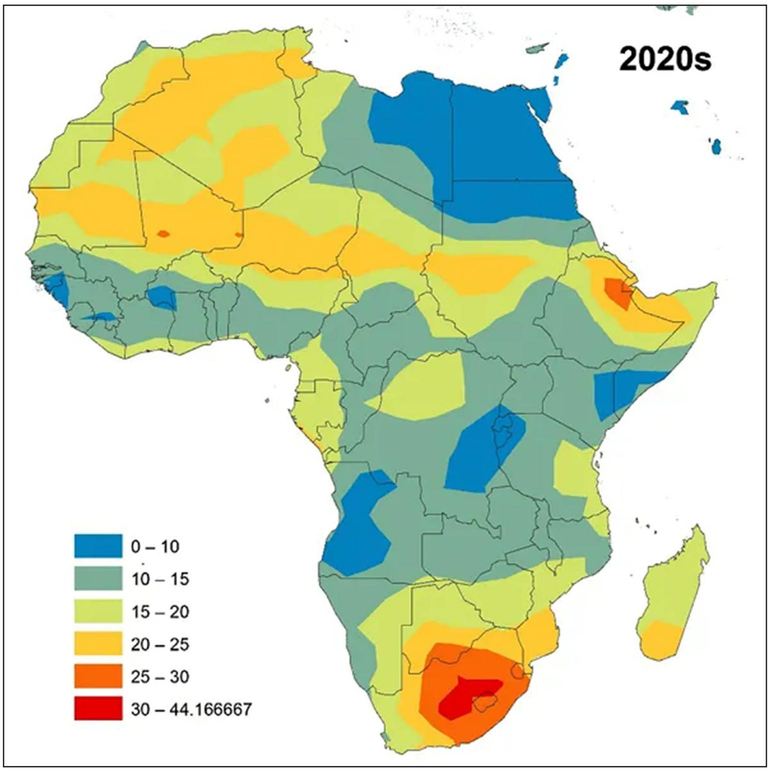

Figure 1. Map published by Wendel (2015, reproduced with permission) presenting the findings of research using a numerical simulation based on epidemic cholera hypothesis, and showing the strength (in per cent) of the combination of temperature and precipitation that may amplify the prevalence of cholera in Africa in the 2020s as climate changes. Red areas may see a sharp increase in cholera outbreaks.

The observations in Fig. 1 can be supported by the findings of Kruger et al. (2022) who used spatial models to show that geographical regions in close proximity to oceans as well as regions with low altitude are at increased risk of cholera outbreaks. Further, the South African coastline can act as a gateway for distribution of *V. cholerae* to inland water bodies through estuaries, especially in the context of climate change–induced tsunamis or heavy rainfall which may raise ocean levels leading to large backflows. Moreover, low-lying regions have a higher risk of flooding during heavy rainfall or tsunami events, which may damage sewerage systems and compromise WWTP facilities by spreading infectious waterborne pathogens (Kruger et al., 2022). Climate change effects may be viewed as a risk towards distribution of *V. cholerae* pathogens in inland regions while at the same time constricting access to quality drinking water (Kruger et al., 2022; Semenza et al., 2022), leading to cholera epidemics.

In another study, Mendelsohn and Dawson (2008) predicted a correlation between sea surface temperature fluctuations and South African cholera outbreaks in the KwaZulu-Natal Province of South Africa in the early 2000s. Also, the country periodically experiences severe droughts, particularly in the Western Cape and Eastern Cape provinces, which have led to a decrease in the availability of clean water (Otto et al., 2018), thereby exposing people to the vulnerability of resorting to microbiologically uncertified water sources. Drought is also known to create adverse conditions such as increased hunger, poor hygiene practice, and marginalization of refugees and nomadic populations (Charnley et al., 2022). These conditions increase the risk of outbreaks of infectious diseases. South Africa is susceptible to drought as a result of high evaporation levels and limited permanent surface water sources (Corwin, 2021). Therefore, the country is projected to face water scarcity with anticipated future climate change (Kephe et al., 2021). Lack of access to quality water is known to be a limiting factor to hygiene practices, which may induce the spread of various infectious diseases (Vezzulli et al., 2020).

Higher ambient temperatures associated with climate change will support proliferation of various pathogens, prolong the transmission seasons of infectious agents or, consequently, their incubation periods within the host (Semenza et al., 2022). Warmer sea surface temperatures, for example, provide highly conducive conditions for the proliferation of various microorganisms, including cyanobacteria, whose blooms are associated with the presence of *V. cholerae*, acting as their reservoir (Islam et al., 2020). Furthermore, the rise in temperature may increase evaporation rates in inland water bodies, thereby increasing the concentration of waterborne infectious agents within them (Nel and Richards, 2022). As an example, the drought that took place in 1992 in Zimbabwe has been implicated in the spiking of cholera outbreaks within that country, limiting both access to safe drinking water, as well as putting a strain on hygiene practices (Baker-Austin et al., 2017; Nel and Richards, 2022).

Besides the lack of adequate WWTPs, environmental waste management, sanitary facilities and access to safe water, as described in the above sections, we need to understand the interaction/relationship between *V. cholerae* and physiological and environmental conditions. *V. cholerae* exhibits fascinating adaptation abilities to survive in freshwater, estuarine and marine ecosystems. Further, *V. cholerae* has developed a commensal relationship with planktons (especial zooplankton copepods) (Iacob et al., 2019; Islam et al., 2020; Kruger et al., 2022) which it has established as an epibiotic niche. *V. cholerae* obtains its nutrition by breaking down the chitin which forms the exoskeleton of copepods (Sun et al., 2015). Furthermore, *V. cholerae* pathogens not only use the chitin as a nutrition source, but also utilise it to produce biofilm lawns that protect them against adverse aqua-physiological conditions (salinity, surface temperature, pH) (Kruger et al., 2022). Moreover, when the environmental physiological conditions are not suitable for *V. cholerae* pathogen proliferation, they enter into viable but non-culturable (VBNC) states while lowering their metabolic rate, especially in regions of endemicity (Wu et al., 2016).

Climate change may not only lead to the resurgence of infectious disease outbreaks but has the potential to also trigger the emergence of other, less known, or altogether unknown infectious diseases. Importantly, climate change may not always support the proliferation or resurgence of *V. cholerae*. Therefore, it is important to understand the survival tactics of *V. cholerae* during stressing events, which is outside the scope of this review.

NEED FOR NEW INTEGRATED INFECTIOUS DISEASE MANAGEMENT SYSTEMS

South Africa, and indeed the world at large, is witnessing a rise in the number of infectious diseases with the worsening effects of climate change. This calls for the adoption of an integrated disease management system. Disease management systems (DMS) are often confused with data storage or data handling. However, DMS refers to a network of various systems that are linked with their particular purpose. Usually, these systems are interconnected to other systems serving various other purposes. DMS use sophisticated computational software packages to manage and analyse data to provide an integrated healthcare response, and to manage the escalation of epidemics across small-scale and large-scale environments (Hunter, 2000). Mathematical models are used to assess the effects of an infectious disease outbreak throughout a population at a given time (Gent et al., 2013). The system relies on previous archived data of outbreaks, distribution patterns, disease transmission mechanisms, disease origin, high-level decision making, control strategies, as well as the utilisation of biotechnology approaches or tools used to conduct tests (Jeger, 2004; Gent et al., 2013). In other instances, the cause or the origin of the disease may not be of greater importance than precautionary approaches to contain the spread of the disease (Jeger 2004).

Both government and private agencies that manage or deliver services to the public, such as hospital or health services, waste management, water services, pharmaceuticals, laboratories, adequate sanitation and more, are all part of the DMS (Jamison et al., 2006). Most developing countries have poorly developed DMS, making it more challenging to prevent or control epidemics. Therefore, this poses a threat to public healthcare in these countries, including South Africa. Furthermore, lack of adequate tools such as test kits, medical facilities, and medicine stocks, among other necessities, has a detrimental impact on the DMS of any country. There is no denying that collection of reliable data serves as a fundamental core to inform the management system in order to devise precautionary strategies for the containment of the disease, while giving the necessary aid to researchers and healthcare departments to provide solutions towards eradication. Infectious DMS need to be constantly updated to enable them to anticipate any future disease resurgence or development, which is where intentional surveillance of the environment comes in.

While the South African infectious DMS is considered adequate compared to other African countries (Joshi et al., 2014), neglecting to maintain and update it and its subsystems may have detrimental effects on the country's ability to respond to a full-blown cholera pandemic. The inadequate maintenance and monitoring of DMS subsystems such as waste management services, environmental reservoirs, inadequate medical facilities, inadequate access to quality drinking water and poor hygiene practices by the public are suggested to have contributed to the recent (2022–2023) cholera outbreak in South Africa. Therefore, there is need to develop a new integrated and regularly updated infectious disease management system.

CONCLUSION

South Africa remains a cholera hotspot due to its geographical location, the immigration crisis, rapidly growing population, and changing climate. South Africa is water-scarce, and its environmental temperatures are conducive to the growth of *Vibrio cholerae* in its inland surface water systems, while its coastline serves as a natural reservoir of cholera pathogens and other waterborne infectious agents. Further, the inadequate and erratic provision of safe and quality drinking water to the public, coupled with the overwhelmed and altogether insufficient wastewater treatment facilities leaves a sizeable chunk of the South African population vulnerable to cholera and other waterborne diseases. Moreover, the lack of adequate resources and maintenance of WWTPs has been fingered as the primary source of contamination of inland waterbodies, both with *V. cholerae* and other infectious pathogens, as well as the spread of antibiotic-resistance genes. Addressing gaps in intentional surveillance of surface water sources, as well as in the implementation of a regularly updated disease management system (DMS) is recommended as a way forward in the anticipation and containment of future cholera and other infectious disease outbreaks.

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