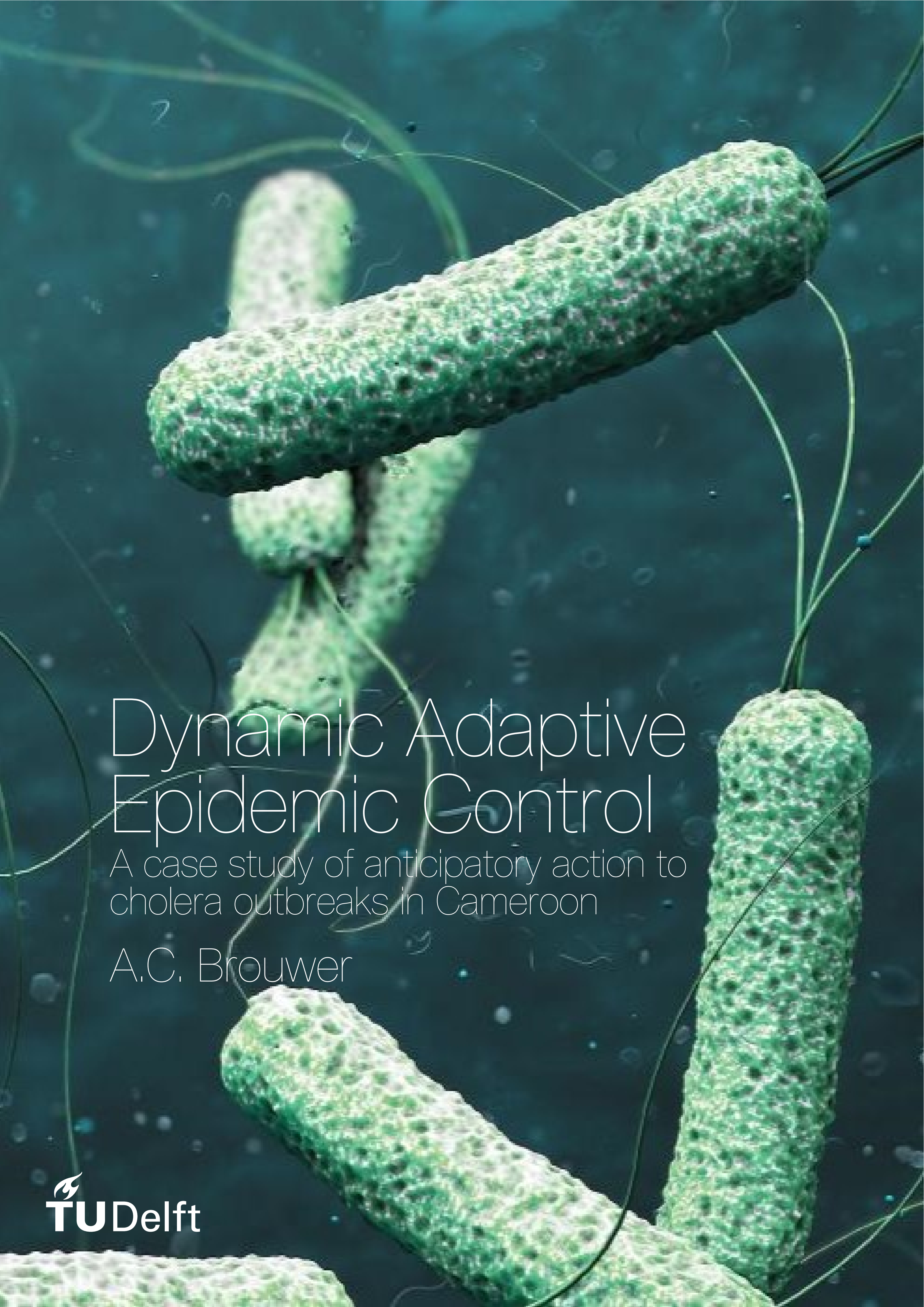

Dynamic Adaptive Epidemic Control

A case study of anticipatory action to cholera outbreaks in Cameroon

A.C. Brouwer

TU Delft

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A case study of anticipatory action to cholera outbreaks in Cameroon

by

A.C. Brouwer

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An initiative of the Netherlands Red Cross

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Executive summary

Cholera, an ancient disease that causes significant morbidity and mortality, remains a global health challenge, particularly affecting the world's most vulnerable populations. Responding rapidly to cholera outbreaks presents significant challenges due to resource, capacity, and time limitations. Anticipatory action (AA) is a newly emerging strategy in the field of humanitarian aid, designed to preemptively address potential crises. By taking impact-reducing actions before a disaster strikes, AA seeks to minimize human loss. However, AA frameworks currently use static prepared-in-advance plans. As a result, AA is not sufficiently able to deal with the uncertainty levels in the onset and spread of epidemics. Effective epidemic control requires flexible plans that can adapt to a constantly changing environment and incoming information, such as the number and location of suspected cases, weather forecasts, and population movement, while balancing flexibility with an effective management approach.

The field of Decision Making under Deep Uncertainty (DMDU) is progressively shifting towards a "monitor and adapt" approach in policymaking, moving away from traditional "predict and act" models. Within this emerging paradigm, the Dynamic Adaptive Policy Pathways (DAPP) method emerges as an efficient strategy for planning in situations characterized by profound uncertainty. The DAPP method integrates adaptation pathways with adaptive policymaking to empower decisionmakers in creating policies that are both robust across various future scenarios and flexible enough to adjust as contextual dynamics evolve.

This thesis explores the DAPP method for decisionmaking under deep uncertainty as an innovative approach to improve AA in epidemic control. More specifically, we explore how DAPP enables the incorporation of newly available data and information to adjust our control strategies to minimize the impact of the outbreak. This research represents the first application of the DAPP approach in the context of epidemic control, introducing a novel challenge in assessing its suitability. As a result, the study is driven by the following main research question.

How can the Dynamic Adaptive Policy Pathways (DAPP) method enhance anticipatory action (AA) approaches in the context of epidemic control?

To answer this question, this research conducts an in-depth investigation into the efficacy of the DAPP approach for the development of flexible control strategies to address the unpredictable nature of epidemic outbreaks. It includes an extensive case study of ongoing cholera issues in Cameroon, where the Cameroon Red Cross, supported by the French and The Netherlands Red Cross and EHESP, is developing an early action protocol for cholera. This case study is coupled with evaluations by field experts and model-based analyses with a stochastic compartmental model. These components collectively assess the performance of DAPP relative to traditional static AA strategies, offering insight into its potential advantages in managing complex, dynamic health crises.

We have tailored the DAPP method to suit the unpredictable nature of epidemic outbreaks. By incorporating specific elements of AA, such as shock-based triggers, and merging these with DAPP's adaptive pathways, regret minimization, and contingency triggers, we have developed a method that supports the creation of dynamic adaptive protocols for epidemic control. In our case study of Cameroon, we demonstrated the formulation of a dynamic adaptive plan for cholera control. This plan outlines a sequence of actions, beginning with low-regret measures and escalating to high-regret actions as necessary, coupled with a weekly review mechanism to adjust the control strategy based on the current outbreak situation. We showed how a tiered control strategy, calibrated to different levels of outbreak risk and uncertainty, can introduce flexibility in the control of epidemics. The method enables a scalable approach, with adjustments informed by outbreak data. The comparative advantage of the DAPP approach, as evidenced through model-based evaluations and expert opinions, lies in its dynamic adaptiveness to evolving outbreaks, which leads to significant potential over traditional control strategies.

This thesis contributes to the field of epidemic control by providing a novel perspective on managing health crises through the application of the DAPP method. It bridges the gap between static planning methods and the need for flexible strategies in the face of epidemic uncertainties. On a societal level, this research directly supports global efforts to combat cholera by offering a robust framework for dynamic adaptive outbreak control strategies. While focused on cholera outbreaks in Cameroon, the findings offer universally applicable insights that can improve early control plans in regions prone to cholera and other infectious diseases.

Future research should focus on various aspects to further improve epidemic control strategies, including assessing geographic and spatial dynamics, scalability of DAPP in resource-limited settings, extension of regret-based action prioritization, integration of preemptive vaccine strategies, and exploration of alternative decisionmaking methodologies for deep uncertainty. These areas represent critical opportunities for advancing our understanding and efficacy in controlling epidemics such as cholera.

This thesis demonstrates the significant potential of the DAPP method to enhance AA approaches in controlling epidemic outbreaks. By offering a structured, flexible approach that adapts to the unpredictable dynamics of epidemics, DAPP improves the effectiveness of outbreak control, contributing toward the broader goal of global health and advancing toward the Sustainable Development Goals.

Acknowledgements

Dear reader,

As I close the chapter on my studies at the Delft University of Technology with the completion of this Master's thesis, I am filled with gratitude for the experiences, challenges and learning opportunities encountered along the way. During this research, I have learned many things, from delving into literature to brainstorming on methods and frameworks, and navigating the complexities of cholera control. I could never have done this without the help of the people around me.

First, I would like to thank my supervisors, Tina Comes and Martijn Warnier, whose guidance and expertise have been invaluable throughout this research process. Your critical questions and research suggestions not only elevated the quality of my work, but also enriched my learning experience. Next, a special thanks goes to my daily supervisor and mentor, Mikhail Sirenko, for your patience, guidance, feedback, and support throughout this process. I greatly enjoyed our collaboration and appreciate your encouragement and belief in pushing the boundaries of this research further.

My gratitude also extends to Marc van den Homberg and Mélanie Droogleever Fortuyn for your contributions to my understanding of humanitarian aid and anticipatory action, as well as for your motivational support. Your continuous input on my work from a humanitarian perspective was immensely valuable. Mélanie, I enjoyed our discussions on early actions, and I appreciate that you showed interest not only in my work, but also in my personal well-being. To Pascal Crépey and Anne Laure Maillard, I thank you for your expertise in epidemiology, your feedback, and your work on the cholera simulation model.

Two years ago, I decided to switch my Master's program from Applied Mathematics to Engineering and Policy Analysis. I thank my fellow EPA students for being incredibly welcoming, which made my start in February very smooth and allowed me to make friends along the way. On a more personal note, this thesis process has not always been easy and I have faced many challenges toward the end of these six months. Continuous support and encouragement throughout this process have been invaluable. I would like to express my appreciation to my family, friends and fellow students. I thank my fellow students at EWI for our shared study sessions. A special thanks goes to Jan for your incredible support during stressful moments, as well as for your feedback on ideas and proofreading parts of my thesis. Jan, I think you would have been a great EPA student.

All of the support I received throughout my years as a student has not only enriched my academic experience, but also prepared me for the next steps in my career and life. As this chapter concludes, I look forward to the adventures that lie ahead, carrying forward the lessons learned.

Enjoy the reading!

Annemieke Brouwer
Rotterdam, March 2024

List of Acronyms

510	Data and digital initiative of the Netherlands Red Cross
AA	Anticipatory action
CATI	Case-Area Targeted Interventions
DAPP	Dynamic Adaptive Policy Pathways
DMDU	Decision Making under Deep Uncertainty
DRC	Democratic Republic of Congo
DREF	Disaster Relief Emergency Fund
EAP	Early Action Protocol
EHESP	École des hautes études en santé publique
F.CFA	Central African CFA franc
FbA	Forecast-based Action
FbF	Forecast-based Financing
GTFCC	Global Task Force on Cholera Control
IDSR	Integrated Disease Surveillance and Response
IFRC	International Federation of Red Cross and Red Crescent Societies
KPI	Key performance indicator
NS	National (Red Cross or Red Crescent) Society
OCHA	(United Nations) Office for the Coordination of Humanitarian Affairs
OCV	Oral cholera vaccines
ORP	Oral Rehydration Point
RCRC	Red Cross Red Crescent
SDG	Sustainable Development Goal
S(E)IR	Susceptible, (Exposed,) Infectious, Recovered
UN	United Nations
WASH	Water, sanitation, and hygiene
WHO	World Health Organization

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1 Introduction

1.1. Societal problem

1.1.1. Cholera outbreaks

The ancient disease cholera still causes 95,000 deaths per year, and is a stark symbol of inequality as it predominantly affects the poorest and most vulnerable populations (Ali et al., 2015). The geographic footprint of cholera mirrors that of poverty itself (Global Task Force on Cholera Control, 2017). Cholera is an infectious disease caused by the Vibrio cholerae bacterium, which is generally transmitted through contaminated water or food (Nelson et al., 2009). Cholera is a treatable illness; however, without prompt treatment, it can turn fatal in a matter of hours (Global Task Force on Cholera Control, 2021). Hence, every death resulting from cholera is preventable with the tools available today, placing the objective of eradicating its public health impact well within our grasp. Controlling cholera requires a comprehensive approach, including fundamental components such as access to clean water, sanitation, and hygiene services, as well as the administration of oral cholera vaccines (Global Task Force on Cholera Control, 2017).

Cholera pathogens can spread rapidly among vulnerable populations, particularly those without access to safe drinking water, adequate sanitation, and hygiene facilities, and those with limited medical resources (Taylor et al., 2015). Although safe drinking water and advanced sanitation systems have ensured that Europe and North America remain cholera-free for decades, the disease continues to infect an estimated 2.9 million people per year (Ali et al., 2015). Cholera persists as a global health challenge, particularly in endemic regions, exacerbated by urbanization and population growth (Global Task Force on Cholera Control, 2017) and climate change (Alcayna et al., 2022; Asadgol et al., 2019). With the wealth of technical knowledge, tools and an expanding global supply of vaccines at our disposal, it is time to accelerate sustainable measures against cholera on regional, national, and international fronts. Ending cholera is not merely a remarkable opportunity, but a moral imperative and a pivotal step toward achieving the Sustainable Development Goals (SDGs) (Global Task Force on Cholera Control, 2017).

1.1.2. Decisionmaking in epidemic control

Decisionmaking during epidemics involves navigating through a maze of uncertainty while aiming to mitigate the health, social, and economic impacts of the epidemic (Hunink et al., 2001). In managing uncertainties, healthcare providers must anticipate the progression of infectious diseases and determine the most beneficial treatments amidst competing priorities and limited information. This is complicated because rapid and accurate decisionmaking is crucial for controlling disease spread and preventing fatalities (Ratnayake et al., 2020), while resources and local capacity are limited (Global Task Force on Cholera Control, 2017). When developing plans[1] to address outbreaks, concepts such as cost-effectiveness analysis (Gold, 1996; Hunink et al., 2001; Mechler, 2016), regret minimization (Haasnoot

[1] In decisionmaking, terms such as plans, policies, strategies, designs, protocols, and actions are often used interchangibly (Marchau et al., 2019). Each chapter of this thesis uses the term that is most appropriate to its content.

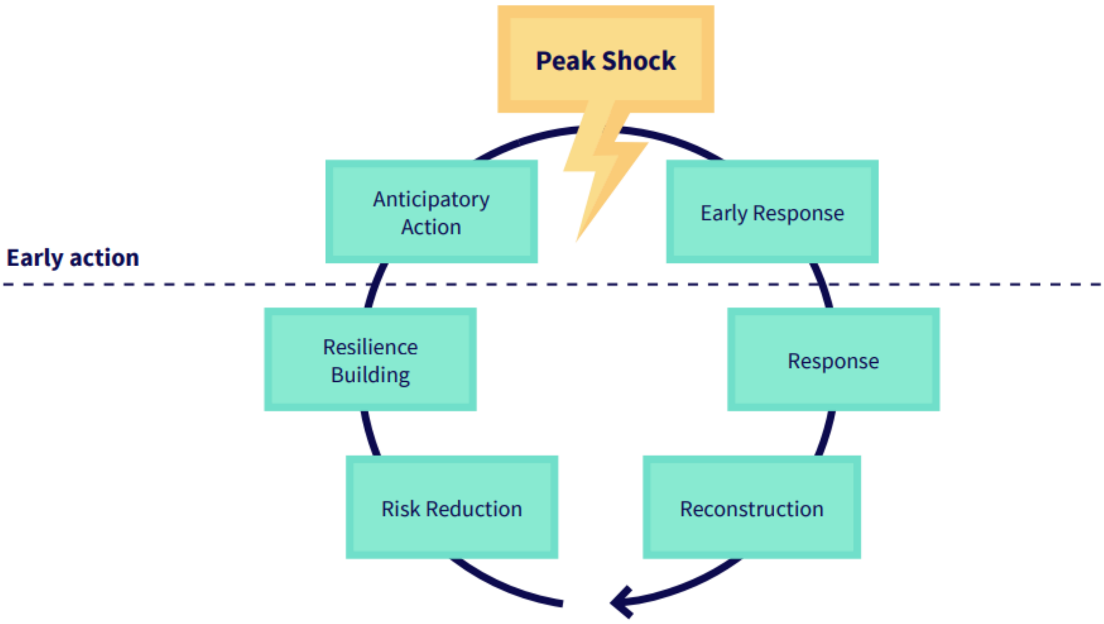


Figure 1.1: Early action as part of a resilience and response continuum (Scott, 2022).

et al., 2018; Walker et al., 2013), and mathematical modeling to investigate disease dynamics and explore effective intervention strategies (Daley & Gani, 2001; Wang, 2022), become instrumental. These approaches help policymakers identify interventions that provide substantial health benefits at a justified cost and make informed decisions that reduce the likelihood of future regret.

Anticipatory action

To effectively control an epidemic, it is vital to respond quickly to the initial cases. However, this is challenging as deliberations on control strategies and the allocation of humanitarian funds can be time-consuming. Thus, there is an imperative shift from predominantly reactive to proactive approaches, which necessitates the commitment of resources in advance. This approach is called 'Anticipatory action' (AA) and follows the stages of disaster response shown in Figure 1.1. AA has emerged in humanitarian aid as an innovative way to minimize the loss caused by hazards (Anticipation Hub, 2022), by bridging the gap between development, disaster risk reduction, and post-disaster humanitarian response (Tozier de la Poterie et al., 2023). Although humanitarian organizations take different approaches to AA, most share three common characteristics: actions to be taken are agreed upon in advance; actions are initiated based on forecasts; and there is pre-agreed funding in place to allow implementation (Anticipation Hub, 2022; Chaves-Gonzalez et al., 2022). AA has previously been applied in climate and disaster risk management where it led to expansion of capacity, more proactive operations, faster humanitarian response, and better collaboration with partners(Tozier de la Poterie et al., 2023). AA initiatives are an increasing part of response plans at the IFRC, UN Agencies, and NGOs such as the World Food Programme (WFP), and the Start Network (United Nations Office for the Coordination of Humanitarian Affairs (OCHA), 2021).

While traditional AA has been centered on extreme climatic and weather phenomena (Gros et al., 2019, 2022; Tozier de la Poterie et al., 2023), there is increasing recognition of the need to preemptively address other significant hazards, such as disease outbreaks and epidemics (Alcayna et al., 2023; Anticipation Hub, 2023). The primary goal of AA in epidemic control is to prevent or mitigate outbreaks. However, the approach's reliance on a predetermined course of action renders the AA framework somewhat static and inflexible, potentially constraining the capacity to adapt to the dynamically changing conditions characteristic of epidemic scenarios. Such rigidity may prove inadequate in the face of epidemics, where the interplay of climatic, environmental, socio-behavioral, and biological factors demands a more versatile AA strategy. Despite these limitations, the implementation of predetermined actions, supported by pre-arranged financing and grounded in evidence-based triggers, has significant potential to improve epidemic AA efforts (Anticipation Hub, 2023). Recent initiatives apply AA to epidemics for the first time in the context of cholera control. The Red Cross is currently developing early action protocols for cholera in Cameroon (Alcayna et al., 2023) and the first AA pilot for cholera in the Democratic Republic of Congo (DRC) was recently implemented by the United Nations (United Nations Office for the Coordination of Humanitarian Affairs, 2022).

When developing AA protocols for epidemic outbreaks, one needs to grapple with the uncertainty present in the problem. During an outbreak, the progression of the disease is unpredictable, as there is a complex interplay with environmental, social, and infrastructural factors. In situations where there are many plausible futures and a wide range of outcomes, we refer to this uncertainty as ‘deep uncertainty’ (Marchau et al., 2019; Walker et al., 2013). This complexity is challenging for conventional AA decision-making frameworks, since actions need to be agreed upon in advance when there is less information available and the uncertainty is high. Hence, application to epidemic control requires modifications to AA that make it robust against uncertainty.

Dynamic Adaptive Policy Pathways

To address the challenge of continuous changes in external factors, the field of Decision Making under Deep Uncertainty (DMDU) is increasingly favoring ”monitor and adapt” policymaking over traditional ”predict and act” policies (Stanton & Roelich, 2021). Within this paradigm, the Dynamic Adaptive Policy Pathways (DAPP) method developed by Haasnoot et al. (2013) stands out as a particularly effective method for planning under conditions of deep uncertainty. By combining adaptation pathways (Haasnoot et al., 2012) with adaptive policymaking (Kwakkel et al., 2010), the DAPP method enables decisionmakers to design policies that are robust in most future evolutions and able to adapt according to the evolution of their context (Kwakkel et al., 2016). The DAPP methodology achieves this dynamic robustness by using (i) a sequence of potential policy pathways (Haasnoot et al., 2013), and (ii) a robust monitoring system that triggers the initiation of a policy adaptation process (Haasnoot et al., 2018). The DAPP method was developed in the context of water management (Haasnoot et al., 2013, 2018), and finds most applications in climate change and flood risk management (Haasnoot et al., 2015; Manocha & Babovic, 2017; Maru et al., 2014; Prober et al., 2017). The use of DAPP in such contexts typically involves analyses on a decadal time scale, differing significantly from the monthly time scale that is more commonly associated with epidemic control protocols.

So far, there is no strong evidence that DMDU approaches, such as DAPP, will work well in epidemic control. However, recent research by Hadjisotiriou et al. (2023) exploring the effectiveness of DMDU strategies during pandemics, including COVID-19, concludes that these approaches are promising. Specifically, they highlight the importance of an immediate response capability in the event of an outbreak, which involves the preliminary execution of policy components, coupled with the capacity for ongoing monitoring and the ability to modify the policy in response to evolving conditions (Hadjisotiriou et al., 2023).

1.2. Case study

This thesis focuses on the challenges associated with controlling cholera in Cameroon. This nation has faced recurrent cholera outbreaks since 1971, rendering the disease endemic (Ateudjieu et al., 2019; Che et al., 2020). The emergence of a political and social crisis in 2016 in the Northwest and Southwest regions resulted in widespread displacement, loss of lives, and the destruction of crucial healthcare infrastructure, and thus potentially exacerbated the cholera epidemic in the Southwest Region by 2018 (Kadia et al., 2023). In 2021, Cameroon experienced a significant cholera outbreak, marked by thousands of suspected cases and fatalities, primarily due to inadequate access to clean water (Musa et al., 2022). The subsequent year posed a new challenge as floods impacted over 314,000 individuals, precipitating another cholera outbreak, particularly in the northern border regions. The proliferation of cholera in these areas has been attributed to insufficient WASH (Water, Sanitation, and Hygiene) conditions, limited access to safe water, and a shortage of adequate healthcare facilities (Musa et al., 2022). Since late March 2023, a concerning surge in cholera cases has been noted, especially in the central region, with official reports by June 2023 documenting 19,087 suspected cases, including 1,880 confirmed cases and 450 deaths, translating to a fatality rate of 2.4% (ACAPS, 2023).

In response to this ongoing crisis, the French Red Cross has incorporated Cameroon into its RIPOSTE program, a comprehensive effort aimed at fortifying pre- and post-epidemic response strategies (Croix-Rouge Française, 2024). 510, the Netherlands Red Cross' data and digital initiative, is working closely with the French Red Cross, the Cameroon Red Cross, and the EHESP School of Public Health to create an early action protocol designed to effectively address cholera outbreaks with AA in Cameroon. This thesis enhances the protocol's development, by proposing a dynamic framework that is able to react to incoming information.

1.3. Knowledge gap

Rapid response to epidemic outbreaks poses considerable challenges, stemming from constraints in resources and operational capabilities, compounded by the unpredictable nature of epidemic progression. AA emerges as an innovative strategy designed to improve humanitarian responses by implementing preemptive actions to mitigate the impact before a disaster occurs, thus reducing human casualties and the scale of response efforts required. However, existing AA frameworks predominantly rely on static, pre-formulated plans triggered by single-dimensional indicators. Such an approach falls short of addressing the complexities and uncertainties inherent in the emergence and spread of epidemics. Effective epidemic control necessitates flexible and adaptive[2] plans capable of evolving in response to dynamic environmental changes and new data. It should take into account updates on suspected case numbers and locations, weather conditions, and population movements. This approach must strike a balance between maintaining flexibility and ensuring efficient management.

The critical knowledge gap centers on how to effectively control epidemics while allowing for flexibility and uncertainty. DAPP's dynamic adaptiveness to evolving information hold the potential to significantly enhance strategies for responding to epidemics. Yet, the methodology for integrating these dynamic approaches within the context of epidemic control remains unexplored. Our approach devises dynamic adaptive policymaking strategies for epidemic control, blending the anticipatory foresight of AA with the dynamic adaptiveness of DAPP to improve outcomes in epidemic control.

1.4. Research questions

Given the identified gaps in our understanding, this thesis is guided by the following main research question:

How can the Dynamic Adaptive Policy Pathways (DAPP) method enhance anticipatory action (AA) approaches in the context of epidemic control?

To comprehensively address this research question, the following sub-questions have been formulated:

1. In what ways can the DAPP method be adapted to manage the dynamic and uncertain nature of epidemic outbreaks within the framework of AA?
2. What are the possible adaptive pathways for epidemic control within the DAPP method, and how do they provide flexibility in response to evolving outbreak scenarios?
3. Which critical signposts and triggers are essential for epidemic control in the DAPP method to enable timely and effective AA?
4. How does the effectiveness of the DAPP method in controlling epidemic outbreaks compare to that of traditional approaches, in terms of response time and outbreak mitigation?

These questions aim to explore the suitability and effectiveness of the DAPP method compared to traditional, static methods in addressing the complex and changing landscape of epidemic outbreaks.

[2]The concepts of flexibility and adaptiveness emphasize different aspects of robustness, although they can overlap. We follow the definitions of Marchau et al. (2019), who define flexibility as the ability to modify policies in real time, which is often useful in recovering from surprise, and adaptiveness as the ability to adjust goals and methods in the mid- to long-term, as information and understanding change. We define dynamic adaptiveness as the combination of adaptiveness over time with dynamic interaction with the system of concern.

1.5. Contribution

This thesis aims to improve our understanding of decisionmaking processes in the context of epidemics by delving into the application of the DAPP method for epidemic control. Through a detailed examination of DAPP and AA concepts and their applicability in epidemics, this thesis provides a new way to bridge the traditional static planning approaches with the dynamic needs of effective epidemic control. These results are relevant in addressing the complex challenges posed by epidemic control. Moreover, the model-based analysis of different epidemic control strategies innovates optimal control research, that typically only compares different intervention measures, discarding the impact of scale and timing.

On a societal level, this thesis directly contributes to the ongoing global efforts to combat cholera, a persistent public health threat that affects millions worldwide. In alignment with the objectives of the Cholera Research Agenda (Global Task Force on Cholera Control, 2021), this research bridges the critical gap between theoretical research and practical implementation. This is achieved by engaging with humanitarian professionals from the Red Cross and using their extensive field documentation. Although the thesis focuses on a case study of cholera outbreaks in Cameroon, its findings provide methods for policymaking that could enhance epidemic control strategies in regions vulnerable to cholera and possibly other infectious diseases. We hope that further applications of the proposed method will illustrate its suitability for other geographical and epidemiological contexts.

2
Background

This chapter aims to provide a comprehensive background on the topics relevant to the research presented in this thesis, offering an extensive review and critical evaluation of both academic literature and gray literature. This will be complemented by the findings of the desk research conducted at the Red Cross. Key areas to be explored include cholera control and decisionmaking, including anticipatory action (AA) and Dynamic Adaptive Policy Pathways (DAPP). This approach ensures a well-rounded understanding of the subject matter, laying a solid foundation for the research.

2.1. Cholera control

Globally, 844 million people still lack access to even the most fundamental sources of drinking water, with more than 2 billion relying on contaminated water sources. Furthermore, 2.4 billion people lack basic sanitation facilities, putting them at risk for various water-related diseases, including cholera (Global Task Force on Cholera Control, 2017). As shown in Figure 2.1, households in countries affected by cholera typically fall below the global average in terms of access to essential water and sanitation services.

2.1.1. Current global situation

The seventh cholera pandemic, which occurred primarily between 1961 and 1975, marks the seventh significant global outbreak of cholera. Despite its historical timeframe, the strain responsible for this pandemic continues to exist today. The World Health Organization (WHO) considers it an ongoing pandemic (World Health Organization, 2023). Since mid-2021, the world has seen a significant resurgence of cholera, marked by outbreaks in new areas, an increase in the number of affected countries, and higher mortality rates. The WHO's disease outbreak news highlights this resurgence, noting further that cholera outbreaks climbed from 23 countries in 2021 to 30 in 2022, underlining the pandemic's expanding scope and severity. (World Health Organization, 2023). Notably, several countries reported their first outbreaks in years, with global case fatality rates reaching the highest levels in over a decade. By early 2023, cholera continued to affect at least 18 countries, with the situation exacerbated by factors like complex humanitarian crises and climate change. The global response capacity is hindered by a lack of resources, including vaccines, and overstretched health personnel. The WHO now assesses the global risk from cholera as very high, reflecting the severity and spread of the ongoing outbreaks (World Health Organization, 2023).

2.1.2. Epidemiology of cholera

The Vibrio cholerae (V. cholerae) bacterium is the cause of cholera, which is generally transmitted through contaminated water or food (Nelson et al., 2009). Only two serogroups, O1 and O139, are associated with outbreaks. The severity of the infection can vary depending on factors such as the amount of bacteria ingested, prior exposure, vaccination, and overall health (World Health Organization, 2017). The most common sign of cholera is profuse watery diarrhea, which is often described

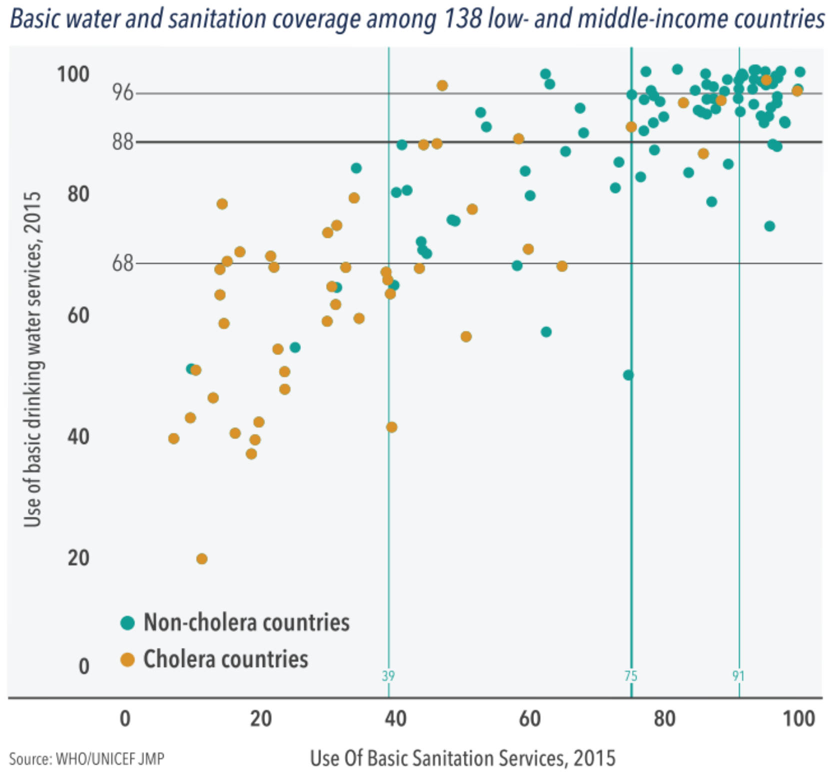


Figure 2.1: Reported access to water and sanitation of 138 low- and middle-income countries, following World Bank Definitions (Global Task Force on Cholera Control, 2017).

as having a consistency of ”rice water”. Abdominal cramps are also common. In more serious cases, people may experience vomiting, dehydration, extreme thirst, leg cramps, and restlessness (Centers for Disease Control and Prevention, 2020). The time between infection and the onset of symptoms can range from 12 hours to 5 days (Azman et al., 2013), and up to half of all infected individuals may not show any symptoms (Nelson et al., 2009). Cholera is a treatable illness; however, without prompt treatment, it can turn fatal in a matter of hours (Global Task Force on Cholera Control, 2021). While high-income countries have been free of cholera for more than a century, it remains a major public health issue in low and middle-income countries in sub-Saharan Africa, the Middle East, and South Asia. Cholera is present in around 47 countries, with periodic devastating outbreaks, such as in Zimbabwe (2008), Haiti (2010), Sierra Leone (2012) and the ongoing outbreak in Yemen (Ali et al., 2015). Cholera disproportionately affects communities already struggling with conflict, inadequate infrastructure, weak health systems, and malnutrition (Global Task Force on Cholera Control, 2017). Humanitarian crises increase the risk of cholera outbreaks, demonstrating its link to social injustice and its heavy toll on the world’s poorest and most vulnerable populations.

Transmission

Vibrio bacteria, including V. Cholerae, are commonly found in aquatic habitats such as estuaries, rivers, and coastal areas (Barua & Greenough, 1992). V. Cholerae, which is linked to human diseases, is widely distributed and can be isolated from a variety of sources, including estuarine waters, surfaces, sewage, seafood, and animals (Barua & Greenough, 1992). Cholera is transmitted when people consume contaminated food or water that contains a contagious dose of V. Cholerae (Nelson et al., 2009). This transmission can be divided into two pathways: short-cycle transmission within households through food or water and long-cycle transmission through contaminated food or water from environmental reservoirs (Nelson et al., 2009; Phelps et al., 2018). Both routes are involved in endemic areas, whereas outbreaks in non-endemic areas usually involve the short-cycle transmission route (Miller et al., 1985). It is essential to comprehend these transmission routes and their interactions due to the complexity of the dynamics of cholera that involves human hosts, the environment, and bacteria (Wang & Liao, 2012).

Asymptomatic infections

It is estimated that between 50 and 75% of people infected with cholera do not show any signs of disease (Menon et al., 2009; Nelson et al., 2009). This poses a problem for the control, surveillance, and prediction of outbreaks of cholera. It is difficult to identify the source of a cholera epidemic, since asymptomatic individuals can spread the bacteria without being noticed (Barua & Greenough, 1992). Furthermore, detecting asymptomatic cases is difficult because it requires an antibody response test, which may not be available in many countries (Nelson et al., 2009). This means that asymptomatic cases are not included in the definition of cholera by the World Health Organization, and thus are excluded from surveillance and research, as many studies follow this definition (Phelps et al., 2018). The ratio between symptomatic and asymptomatic cases can vary greatly, from 1:3 to 1:100, depending on factors such as region, population density, immunity, susceptibility, distribution of blood type and calculation methods (Glass & Black, 1992). Although asymptomatic individuals are less likely to transmit the disease than those with symptoms, they can still spread it to new areas and reservoirs without being noticed (Nelson et al., 2009). Furthermore, their shorter-term immunity makes them more prone to reinfection than those with symptoms (King et al., 2008; Nelson et al., 2009). Immunity in individuals with mild and asymptomatic infections has been found to decrease more quickly than previously thought (King et al., 2008). The role of people who have cholera but do not show any symptoms in causing epidemics is not well understood. However, the ratio of asymptomatic cases to those with symptoms is higher than expected, which implies that more people may have short-term immunity to the disease. This can temporarily reduce the number of vulnerable people and stop the spread of the disease. However, as immunity decreases in a matter of weeks or months, the number of susceptible individuals increases again, creating the conditions for new outbreaks. This hypothesis suggests that the prevalence of asymptomatic cases is a key factor in the dynamics of cholera epidemics (King et al., 2008).

Cholera hotspots

Cholera “hotspots” are specific and relatively compact regions where the concentration of cholera cases is most pronounced (Global Task Force on Cholera Control, 2017). These hotspots serve as central centers for the transmission of the disease to other areas, often coinciding with the rainy season. They have been identified in numerous endemic countries and consistently experience cholera outbreaks. Within these areas, the rates of cholera-related deaths are alarmingly high, healthcare access is limited, and residents contend with poor water quality and sanitation systems. It should be noted that in Africa alone, cholera hotspots are home to 40 to 80 million people (Global Task Force on Cholera Control, 2017).

2.1.3. Current practices in cholera control

The challenges of combating cholera and tracking its progress are numerous and unique due to its variable transmission dynamics and the lack of specific symptoms. Cholera’s transmission can be epidemic, with sporadic outbreaks, or endemic, with regular occurrences and seasonal peaks. This variability, combined with periods when cases significantly drop, complicates surveillance efforts to consistently monitor the disease with precision (Azman et al., 2020). The non-specific nature of cholera symptoms further hampers these efforts. Additionally, there’s a concern that reporting cholera cases can negatively impact a country’s tourism and exports, leading to underreporting or complete non-reporting (Azman et al., 2020). Unlike diseases such as smallpox and polio, for which single, highly effective interventions exist (often referred to as ’silver bullets’), controlling cholera requires a multifaceted approach. While Oral Cholera Vaccines (OCVs) offer moderate effectiveness in the medium term, a comprehensive strategy to manage cholera must also include significant improvements in water and sanitation infrastructure, as well as changes in hygiene behaviors (Azman et al., 2020). These measures are complex and require considerable and sustained investment.

Common actions in cholera control

Efforts to manage cholera focus on two main strategies: preventive measures to avert new outbreaks and medical interventions to lower death rates among those affected. Medical interventions include the use of rehydration therapy, which is a combination of salt, sugar, and clean water, and has been essential in saving lives and reducing the death rate from cholera to below 1% (Ali et al., 2015; World Health Organization, 2021). For more serious cases that require hospitalization, antibiotics such as doxycycline, ciprofloxacin, and azithromycin are prescribed, although this can lead to antibiotic resistance (World Health Organization, 2017). Although it is very important to reduce the mortality rate, this thesis focuses mainly on preventing outbreaks. For measures to mitigate the risk of cholera spread, it is important to note that the cholera bacterium has a free-living cycle outside the human body, with natural reservoirs in the environment. This means that cholera control goes beyond merely identifying cases and managing infected individuals and involves detecting reservoirs of past or future infections and preventing secondary disease spread (Barua & Greenough, 1992). The following measures are commonly used strategies to control the spread of the disease.

- Vaccination is a key approach to combating cholera spread, particularly through the use of inexpensive oral cholear vaccines (OCV). Numerous campaigns and experiments have been carried out in areas where the disease is endemic (Shin et al., 2011; World Health Organization, 2017), and the WHO has granted its approval for vaccines in emergency situations (Martin et al., 2012), as was done during the Haiti cholera outbreak of 2010-2012 (Rouzier et al., 2013). However, OCV is not a long-term solution, as protection is impermanent and bacteria can persist in the environment; therefore, researchers state that it is best used as a complementary measure (Azman et al., 2020; Lessler et al., 2018).
- Traditional hygiene measures and improvements in water and sanitation continue to be the most effective approaches, especially when combined with behavior change interventions (Azman et al., 2020; Menon et al., 2009). Water sanitation techniques, such as chlorination and filtration, can help improve water quality and reduce the number of pathogens. Although the usefulness of this measure in outbreak scenarios can be limited, access to safe water and improved sanitation and behavior change are concluded to be the only long-term solutions (Azman et al., 2020).

2.1.4. Strategies towards cholera control

Published as 'Ending Cholera — A Global Roadmap to 2030,' the Global Task Force on Cholera Control (GTFCC) operationalizes a new global cholera control strategy (Global Task Force on Cholera Control, 2017). The GTFCC is a worldwide network of organizations that promotes a coordinated, multisectoral approach to combat cholera. Since being revitalized in 2014 following a resolution from the World Health Assembly, the GTFCC has played a crucial role in coordinating efforts and partners in the fight against cholera. In their Roadmap, the GTFCC outlines a clear path to a world where cholera is no longer a public health threat. Implementing this strategy by 2030 is expected to reduce cholera deaths by 90%. If cholera-affected countries, technical partners, and donors commit, up to 20 countries could eliminate cholera transmission by 2030. In their publication, the GTFCC defines cholera elimination as any country that reports no confirmed cases for at least three consecutive years and has an epidemiologic and laboratory surveillance system that is able to detect and confirm cases sufficiently. The Roadmap strategy focuses on 47 countries affected by cholera and includes three key approaches.

1. *Swift outbreak containment*: Emphasizing early detection and rapid response, this approach involves robust community involvement, improved laboratory and surveillance capabilities, health system readiness, and rapid response teams.
2. *Targeted prevention in cholera hotspots*: This aspect calls for focused efforts in small areas heavily affected by cholera ("hotspots"), with the aim of stopping transmission through improved water, sanitation, hygiene (WASH) and oral cholera vaccines (OCV). In Africa alone, 40 to 80 million people reside in such hotspots.
3. *Effective Coordination for Support and Resources*: The GTFCC serves as a strong framework for technical assistance, advocacy, and partnerships, both locally and globally. It offers resources to support country-led cholera control programs and fosters collaboration between sectors.

Implementing these strategies involves aligning existing health and WASH resources with the Global Roadmap. This alignment has the potential to significantly reduce the substantial economic burden imposed by cholera, approximately $ 2 billion annually, encompassing healthcare expenditures and productivity losses. The GTFCC cost estimate to control cholera in the Democratic Republic of the Congo shows the potential for up to 50% cost savings compared to ongoing outbreak responses. These investments not only impact cholera, but also positively contribute to reducing other waterborne

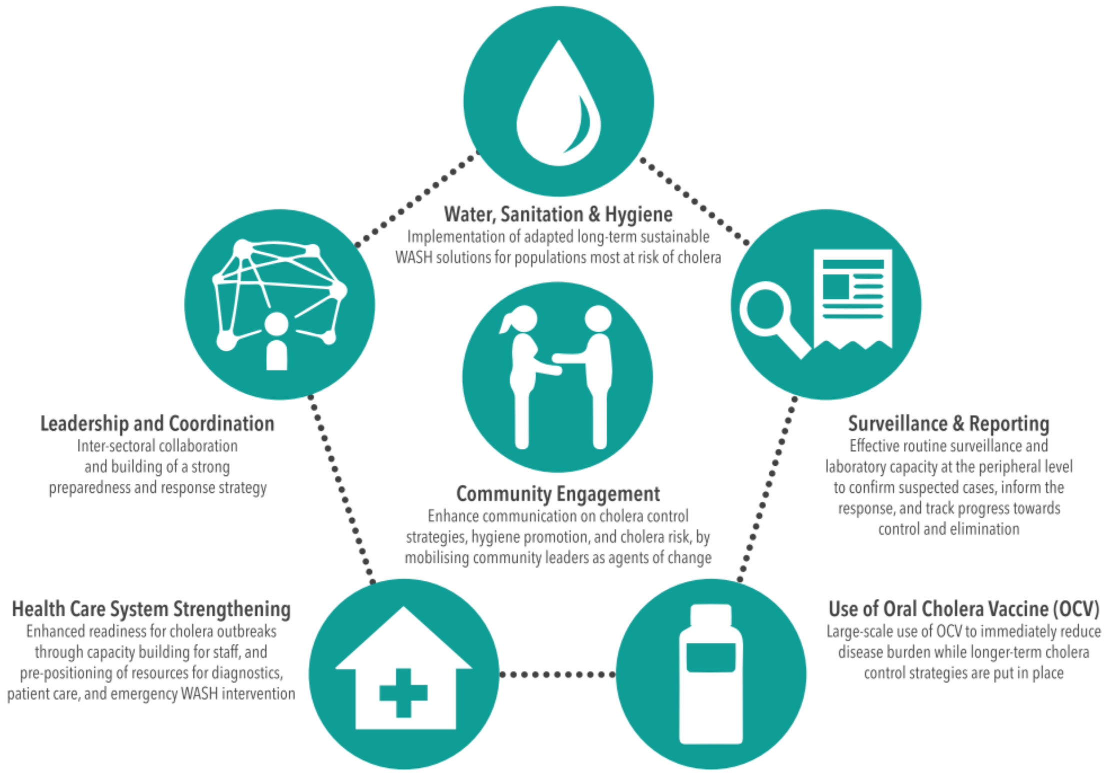


Figure 2.2: Multi-sectoral interventions to control cholera (Global Task Force on Cholera Control, 2017).

diseases. In addition, these investments exhibit a ripple effect by improving poverty, malnutrition, and education. The Global Roadmap aligns with the Sustainable Development Goals, while simultaneously representing an important step toward a cholera-free world.

Cost-effective combinations of interventions
The Global Task Force on Cholera Control (GTFCC) has developed a research agenda to accelerate efforts to combat cholera, with the input of partners, including the Netherlands Red Cross (Global Task Force on Cholera Control, 2021). Its purpose is to bridge the gap between research and implementation, ensuring that research results meet the needs of those affected by cholera, ultimately speeding up progress towards a world without cholera. Based on scores given by more than 100 experts, the 20 research questions with the highest scores were identified as key priorities for the Cholera Roadmap Research Agenda. One of the top 20 priorities of the Cholera Roadmap Research Agenda is to identify the most cost-effective combination of water, sanitation and hygiene (WASH) measures and oral cholera vaccines (OCV) in various contexts, taking into account the transmission dynamics of cholera hotspots (Global Task Force on Cholera Control, 2021). This research question emphasizes the need for research evidence at the country level, as a one-size-fits-all approach is not adequate to combat cholera. By examining the cost effectiveness of integrated interventions, this research priority seeks to provide policymakers and practitioners with the data they need to allocate resources and strategies more effectively, ultimately resulting in more successful cholera control efforts around the world.

Case-Area Targeted Interventions
Case-Area Targeted Interventions (CATIs) offer a strategic approach to curbing infectious disease outbreaks by concentrating efforts in regions with confirmed cases. These interventions, as documented by (Ouamba et al., 2023) and others, aim to rapidly contain the spread of diseases by targeting the areas most at risk with measures such as vaccination campaigns, distribution of medical treatments, health education, and enhanced surveillance activities. CATIs are particularly useful in settings where resources are limited, allowing for efficient allocation to maximize impact on disease control and prevention. (Ouamba et al., 2023) implemented case-area targeted interventions (CATI), including health

promotion, vaccination, antibiotic chemoprophylaxis, water treatment, and active case-finding, which successfully reduced cholera transmission in Kribi district. Further studies, including the prospective observational analysis of Ratnayake et al. (2022) and the CATI review of Sikder et al. (2021), advocate for the systematic application of CATIs, stressing the necessity for consistent case definitions, efficacy assessments, and enhanced collaborative efforts.

Risk classification of areas
Additionally, Azman et al. (2020) have suggested that global efforts to combat cholera should be tailored to the specific needs of high-risk populations. They proposed a two-dimensional classification system to identify areas with different levels of risk, ranging from cholera incidence hotspots to low burden settings. This system takes into account the mean annual incidence rate of cholera cases and the variability in annual incidence rates within subcountry administrative units. They state that in hotspots of cholera incidence, short-term and long-term interventions are necessary, including oral cholera vaccines, case management, and infrastructure improvements. In epidemic-prone areas, the preemptive use of OCV may not be suitable, but rapid reactive OCV plans should be in place to address large outbreaks. In low-burden settings, investments in infrastructure and behavior change are necessary to prevent transmission to neighboring areas and the potential transition to epidemic-prone or incidence-hotspot status. The authors note that local epidemiological knowledge should be used to complement the classification system to address regional nuances.

2.1.5. Challenges in cholera control

This section examines the obstacles that hinder effective cholera control, highlighting surveillance, environmental, and healthcare-related issues. It emphasizes the need for strategic approaches to overcome these barriers for better cholera prevention and control efforts.

Delays in outbreak detection
Ratnayake et al. (2020) investigated challenges and delays in the detection, investigation, response, and laboratory confirmation of cholera outbreaks in fragile and conflict-affected states. They emphasize the crucial need for early intervention and the potential impact of delays on epidemic sizes. This study underscores the importance of improving early detection and rapid control mechanisms to mitigate the spread of cholera, particularly in vulnerable regions, offering valuable insights for public health strategies and policy formulation aimed at controlling infectious diseases in complex environments. Early warning systems, such as the WHO's Integrated Disease Surveillance and Response (IDSR) system (Fall et al., 2019), are essential for disaster response in the African public health sector. However, the IDSR system is not designed for conflict zones, even though many underdeveloped countries rely on it in these settings (Kadia et al., 2023). Kadia et al. (2023) investigated the use of IDSR data to manage cholera outbreaks in conflict-ridden settings in Cameroon. They highlighted the importance of incorporating complementary surveillance systems to improve data quality and timeliness. Furthermore, the research revealed a correlation between conflicts and disease outbreaks, such as cholera and diphtheria, and identified the challenges of poor data timeliness and completeness in the IDSR system, particularly during conflicts. External factors, such as insecurity, were found to hinder data collection and transmission. The lack of disaggregated data was found to have affected early alerts and risk assessments. The study highlighted the need for data validation, even if the data are timely, and criticized the multiple reporting systems used during the cholera outbreak. The preferences of staff for other reporting methods and security concerns further hindered data collection. The authors concluded that more collaborative, purposeful, and context-sensitive data communication strategies are necessary.

Urbanization and climate control
It is essential to recognize the current window of opportunity to act while cholera control remains attainable, with a particular focus on ensuring access to fundamental WASH solutions. Anticipated challenges due to climate change, urbanization, and population growth have the potential to increase the risk of cholera in the foreseeable future (Global Task Force on Cholera Control, 2017). According to UN Habitat, the proportion of Africans living in urban areas is projected to increase from 36% in 2010 to 50% by 2030. Concurrently, the number of residents in slum areas in sub-Saharan Africa is expected to increase with the growth of the urban population. In 2010, a substantial 60% of the urban

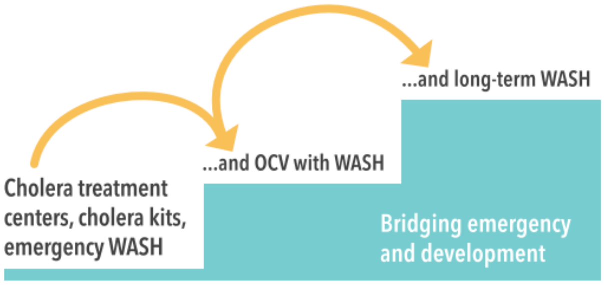


Figure 2.3: From preparedness and response to prevention and control (Global Task Force on Cholera Control, 2017).

population in Sub-Saharan cities lived in slum areas (UN-Habitat, 2016). This upward trend in urbanization is likely to put additional stress on existing infrastructure systems, potentially exacerbating the challenges associated with access to safe water and basic sanitation, especially for the most vulnerable segments of society (Global Task Force on Cholera Control, 2017). Additionally, the environment has a major influence on the spread of infectious diseases, and climate change has a considerable effect on the environment, including higher temperatures, more rain, and extreme weather conditions. These changes are particularly relevant for diseases transmitted by vectors and through water, such as vector-borne and water-borne diseases (Alcayna et al., 2022; Asadgol et al., 2019). Investigating the connection between climate variability and infectious disease transmission is essential for creating risk indices tailored to climate-related diseases.

From response to prevention
The transition from response to prevention in cholera control marks a pivotal shift in strategy, highlighting the importance of preventive measures over reactive ones (Global Task Force on Cholera Control, 2017). This approach advocates for the implementation of early warning systems, improved water and sanitation infrastructure, and community education to prevent outbreaks, rather than just responding to them. By focusing on these preventive measures, public health efforts aim to reduce the incidence of cholera and mitigate its impact on vulnerable populations, ultimately leading to more sustainable and effective control of the disease. With outbreaks occurring frequently, it is challenging to simultaneously build long-term resilience to cholera. At a high level, the Global Task Force on Cholera Control (2017) defines three stages to bridge emergency response and structural developments, as visualized in Figure 2.3. More research is needed to implement these phases into cholera control strategies.

2.2. Decisionmaking

During an epidemic, decisionmakers are faced with choices that range from selecting medical treatments and public health interventions to determining the allocation of resources and implementing policy measures. The primary goal is to minimize the health, social, and economic impacts of the epidemic. Given the urgency and stakes, the decisionmaking process is guided by the principles of uncertainty and the navigation of trade-offs (Hunink et al., 2001).

2.2.1. Managing uncertainty in epidemics

In healthcare, decisionmaking is often complicated by various forms of uncertainty that can significantly impact outcomes. Recognizing and managing these uncertainties is crucial for healthcare providers to make informed decisions that best serve their patients. Hunink et al. (2001) identify three major types of uncertainty in healthcare: diagnostic, prognostic, and treatment uncertainty. These uncertainties are particularly relevant in the context of an epidemic, where rapid and accurate decisionmaking is critical to managing the spread of disease and optimizing patient care outcomes.

- *Diagnostic uncertainty*: This revolves around the challenge of determining the true underlying causes of a patient's illness. Healthcare professionals often rely on a combination of medical history, physical examinations, laboratory tests, and imaging studies to make an accurate diagnosis. However, the interpretation of these data can be complex, with overlapping symptoms among different diseases adding to the uncertainty (Hunink et al., 2001). In particular, in the context of an epidemic, the time required for laboratory tests introduces a trade-off between the urgency of immediate action and the assurance of action based on confirmed information.

- *Prognostic uncertainty*: This involves anticipating the future progression of a patient's illness or condition (Hunink et al., 2001), a challenge that becomes even more complex when applied to predicting the trajectory of an epidemic. Although prognostic models and statistical analyzes offer valuable information, it remains difficult to accurately estimate the course of both individual illnesses and broader epidemic trends.
- *Treatment uncertainty*: This involves questions about the potential benefits and harms of a treatment. It asks: "Does this treatment lead to more benefit than harm?" Even when a diagnosis is clear, the best course of treatment may not be (Hunink et al., 2001). In the context of an epidemic, treatment uncertainty becomes particularly pronounced, focusing on critical questions regarding overall efficacy and potential drawbacks of treatment options at the population level. The consideration of individual patient preferences and conditions, while still important, must be weighed alongside public health objectives and the broader implications of treatment strategies on community health and healthcare resources.

Navigating trade-offs
In the complex landscape of healthcare decisionmaking, particularly within the context of an epidemic, navigating trade-offs becomes an essential but challenging task. These trade-offs often involve balancing the benefits and drawbacks of various interventions, strategies, and resource allocations to optimize outcomes for individuals and the broader population. Two common strategies to navigate such trade-offs are cost-effectiveness analysis and regret minimization.

Cost-effectiveness analysis
Cost-effectiveness analysis (CEA) is a method used to compare the relative costs and outcomes (often measured in quality-adjusted life years or QALYs) of two or more courses of action (Gold, 1996; Hunink et al., 2001). CEA focusses on minimizing project costs, while benefits are predetermined targets such as specific reductions in disaster fatalities and losses (Mechler, 2016). With this approach, CEA omits the need to precisely quantify benefits, which simplifies the analysis. The policymaker can focus on identifying the most cost-effective methods to achieve the set objectives, streamlining decisionmaking processes in scenarios where desired outcomes are established in advance (Mechler, 2016). In the context of an epidemic, CEA helps to identify interventions that provide the best possible health outcomes at the least cost. Specifically, CEA can be used to evaluate various intervention strategies. By comparing the cost per QALY gained from different interventions, policymakers can prioritize strategies that offer the most significant health benefits relative to their costs. Instead of QALY, CEA can also incorporate simpler benefit metrics, such as the extent of population coverage by an intervention (International Federation of Red Cross and Red Crescent Societies, 2023d).

Regret minimization
In decision theory, regret is a measure of the difference between the actual outcome and the best possible outcome had a different decision been made. It involves weighing the risks of false or missed signals, which can lead to either unnecessary actions and overinvestments or insufficient action, underinvestment, and delayed responses with adverse outcomes (Haasnoot et al., 2018). In the context of an epidemic, minimization of regret involves making decisions that are least likely to result in future regret, considering the uncertainty and potential outcomes of different actions. Regret minimization is particularly relevant in the fast-paced and high-stakes environment of an epidemic, where decisions must be made with limited information, and the future course of the epidemic is uncertain. By considering the worst-case scenarios and the potential for regret, decisionmakers can choose strategies that are robust against various future states of the world.

Coordination of efforts
In their examination of the response to the Yemen cholera outbreak between 2016 and 2018, Spiegel et al. (2019) observed that overall preparedness was lacking, with a particular shortfall in harmonized

coordination. This was compounded by the challenges of operating within a complex humanitarian crisis caused by conflict, as is often the case for large epidemics. In the analysed response, the existence of three main coordination systems (health and WASH clusters, cholera task force, and the Incident Management System with its Emergency Operations Centres) operated with limited success and complementarity, leading to inefficiencies and duplicate efforts. The authors conclude that there was a strong need for improved preparedness planning and community-directed response (Spiegel et al., 2019). In another study, Long et al. (2018) highlighted the critical need for spatially coordinated decisionmaking. The study underscores how connectivity between regions significantly influences the spatial dynamics of an epidemic's spread, a factor that is often overlooked in traditional control strategies. The need for policymakers to rapidly distribute limited intervention resources in anticipation of the epidemic's next move is paramount. To address this, the authors proposed a two-stage model designed to optimize the timing and geographical distribution of Ebola treatment units during the initial stages of an outbreak. This model comprises a forecasting stage that uses a dynamic epidemic model to predict the spread, followed by a second stage that employs a methodology to strategically allocate units across affected regions. Through testing various strategies, the study identified the myopic linear program as the most effective. This program allocates resources for the coming week based on an iterative process of estimation and optimization, striking an optimal balance between proactive (anticipating future cases) and reactive (addressing the most affected areas) approaches. This method was shown to be highly effective even with limited data, showcasing its potential as a robust tool in epidemic control planning (Long et al., 2018).

2.2.2. Modelling cholera dynamics

Mathematical modeling of infectious diseases to inform decisionmaking has a long history, beginning with Bernoulli in the 1700s (Bernoulli & Blower, 2004). It has since become an essential part of epidemiological studies (Daley & Gani, 2001). These models are extremely useful, providing information on how infections spread and how epidemics progress, evaluating different intervention tactics, and providing advice on how to effectively manage outbreaks (Hethcote, 2000). There is extensive research activity in the field of cholera dynamics through mathematical modeling. Wang carried out a simple Google Scholar search to identify studies published between 2008 and 2022, using keywords related to cholera and mathematical modeling (Wang, 2022). After eliminating duplicates and irrelevant records, the results showed nearly 500 studies in the last 15 years. In particular, the review indicates a significant increase in the number of articles on cholera modeling, with more than a tenfold increase from 2008 to 2021, demonstrating the growing interest and importance of this research area.

Mathematical cholera models

Most cholera transmission models make use of the typical compartments of susceptible (S), infected (I) and recovered (R) to illustrate the spread of infection in a human population in a so-called SIR model. However, these models usually assume that a person infected with cholera immediately becomes contagious (Wang, 2022). In reality, there is usually a short incubation period for cholera infection, with a median of 1.4 days, according to a systematic review (Azman et al., 2013). To be more precise in considering the effect of the incubation period, mathematical models can include an extra compartment labeled "exposed" (E), forming the so-called SEIR models (Wang, 2022). These models have the potential to improve the precision of forecasts regarding the transmission of cholera and its propagation.

Challenges of spatiotemporal heterogeneities

The transmission of cholera is affected by spatial variability, which is caused by a variety of ecological, geographical, population, mobility, and socio-economic factors (Wang, 2022). The study carried out by Mukandavire et al. (2011) of the 2008–2009 Zimbabwe cholera outbreak demonstrated that the basic reproduction numbers varied significantly between different regions, indicating different transmission patterns within the country. Similarly, research on the 2010 Haiti cholera outbreak and the 2016-17 Yemen cholera outbreak (Tuite et al., 2011) revealed disparities in transmission modes and infection risks in various regions. Although these studies used relatively simple mathematical models, they highlighted the importance of spatial heterogeneity in cholera transmission. Therefore, there is an increasing need for more comprehensive quantitative investigations into how factors such as human mobility and the spread of pathogenic vibrios affect cholera epidemics and endemicity in different geographical areas (Wang, 2022).

The transmission of cholera is strongly associated with environmental conditions, such as floods, droughts, precipitation, water temperature, and salinity, which often vary seasonally and can have a major effect on the dynamics of cholera (Perez-Saez et al., 2022). In many endemic areas, cholera is a seasonal disease, with infection peaks usually occurring during the rainy or monsoon season (Christaki et al., 2020). Climate change, which involves rising sea levels and global temperatures, may also influence the temporal patterns of cholera, potentially increasing the frequency and duration of outbreaks (Asadgol et al., 2019). Traditional cholera models based on ordinary differential equations (ODEs) usually use constant parameters, which may not reflect the seasonal and climatic behavior of cholera dynamics (Wang, 2022). To address this, Wang (2022) states that non-autonomous ODE systems with time-dependent parameters can be used. In this suggested approach, temporal periodicity is introduced into parameters such as the contact rate, the recovery rate, and the pathogen growth rate to represent seasonal oscillations. However, Wang asserts that these periodic models may not fully capture the complex intra- and inter-annual variations in cholera dynamics, particularly in the context of climate change, which does not follow a regular periodic pattern. To better understand cholera's temporal dynamics, he suggests that models with time-dependent but nonperiodic parameters be used. These models, although more difficult to analyze and calibrate, can better represent the influence of climate change and other non-periodic environmental drivers. Wang (2022) argues that, for effective disease control, models must consider both spatial and temporal heterogeneities, to align with a strategic and cost-effective approach.

Real-world applications

Many studies have been conducted to analyze real-world cholera outbreaks, using data from government agencies and public health organizations. These studies mainly used basic transmission models, with a particular focus on the Haiti cholera outbreak from 2010 to 2012 (Wang, 2022). These modeling efforts have been very beneficial in understanding and controlling cholera epidemics. In particular, research on partial differential equation (PDE) studies in cholera modeling improves our understanding of the mathematical aspects of the disease. However, it is important to note that most of these studies are primarily theoretical and face a challenge when it comes to applying reaction-diffusion models to actual data from real-world cholera outbreaks (Wang, 2022). According to Wang's review, a significant hurdle lies in calibrating the diffusion coefficients, which vary between different population groups and spatial locations. As of now, he has found limited published research on simulating outbreaks and fitting practical data using reaction-diffusion cholera models, even in simplified scenarios with one-dimensional spatial domains and constant diffusion coefficients. This challenge is not unique to cholera, but it extends to many other infectious diseases as well. To bridge this gap between theory and practical application, more effort is required to enable real-world use of these epidemic models of PDE and to gain greater recognition and acceptance within the public health community.

Modelling for policy development

In recent years, considerable advances have been made in the field of mathematical modeling of cholera. Despite these challenges, several issues continue to require attention. These include the development of cost-effective health management strategies that can adapt to spatial and temporal variations (Wang, 2022). These modeling issues are applicable not only to cholera but also to a wide range of infectious diseases. Numerous mathematical models have been created to evaluate the effects of cholera control measures on disease transmission and spread (e.g. Collins and Duffy, 2018; Fung, 2014; Miller et al., 1985; Posny et al., 2015; Sun et al., 2017). These models take into account interventions such as antibiotics, vaccinations, water sanitation, and quarantine. They are used to identify cost-effective strategies for controlling cholera outbreaks in different settings. For example, Posny et al. (2015) determined that when it comes to controlling a disease, it is essential to take into account how different interventions interact with each other and the related expenses to shape the optimal strategy. Some models are tailored to particular outbreaks, such as the 2008-2009 cholera outbreak in Zimbabwe (Mukandavire et al., 2011) or the 2010 Haiti cholera outbreak (Andrews & Basu, 2011). These optimal control studies, which consider the costs associated with cholera control measures, attempt to identify the most efficient ways to manage cholera outbreaks while minimizing expenses. These studies often use ordinary differential equation (ODE) models and mathematical principles like Pontryagin's Maximum/Minimum Principle (Pontryagin, 1987). Mathematical models that incorporate cholera control measures can improve our understanding of cholera transmission and help to evaluate different prevention and intervention strategies (Wang, 2022). They can also predict the most effective strategies in terms of balancing impact and cost. However, Wang's findings show that these models face challenges in practical applications. Time-dependent parameters, accurate estimates, and data on the effectiveness of control measures are often difficult to obtain. The assignment of monetary values to reductions in prevalence and mortality can be complex, and the practical utility of some models remains hypothetical. However, these models are nonetheless useful tools to inform policy development and guide the management of the cholera outbreak.

Forecasting models
According to Lauer et al. (2020), forecasting is a technique of predicting an outcome, trend, or event that has yet to be observed, based on existing data. This practice has been used for a long time in areas such as meteorology and economics, to help make decisions about the future. In the last decade, the humanitarian sector has come to understand the importance of being proactive in reducing the long-term effects of crises and disasters (Levine et al., 2020). As a result, forecasting models have become more popular, especially in public health, to provide decisionmakers with the information they need to act quickly (Lessler et al., 2016). Accurate forecasts give people the opportunity to take action before a disaster occurs. The Red Cross Crescent Movement and its partners have developed the concept of forecast-based action and financing (FbA) to create a warning system that will give the humanitarian sector enough time to start early actions, increase preparedness, and strengthen community resilience (Red Cross Red Crescent Climate Centre, 2020). FbA involves taking early steps when forecasts indicate an imminent hazard, with the goal of reducing the negative effects of extreme weather events (Levine et al., 2020; Red Cross Red Crescent Climate Centre, 2020). FbA consists of three main components: triggers, early actions, and financial mechanisms. Both organizations and individuals can take early actions to reduce the effects, such as protecting livelihoods, developing preparedness, and providing assistance (Red Cross Red Crescent Climate Centre, 2020). Examples of these actions include evacuating vulnerable communities, early harvesting, distributing protective items, and providing cash transfers (IFRC, 2020).

FbA has focused mainly on early actions related to extreme weather events, such as droughts, floods, storms, heatwaves, and cold shocks. However, disasters can create conditions that increase the risk of infectious disease outbreaks. Environmental changes, the well-being and behavior of affected populations, and an increased risk of displacement all contribute to the increased risks of disease transmission (Kouadio et al., 2012). Therefore, the next step for FbA is to incorporate early actions for epidemics and diseases. Forecasting of diseases and outbreaks can be used to predict disease transmission, target vulnerable populations before an outbreak occurs, and evaluate the cost-benefit relationship of specific early actions (Chowell & Hyman, 2016; Desai et al., 2019). To be effective in the aftermath of disasters, disease forecasts must be available in near real-time and adapt as more information becomes available (Kahn et al., 2019).

2.2.3. Anticipatory action

Both the Red Cross and OCHA have established methodologies to create Anticipatory action (AA) plans, with their core phases showing significant alignment across both frameworks. Given the detailed guidance available in the Red Cross's FbF Practitioners' Manual (International Federation of Red Cross and Red Crescent Societies, 2023c), this thesis will focus primarily on their framework for a thorough analysis. However, the insights derived are intended to be broadly applicable to AA planning beyond the Red Cross context. For a complete understanding, the OCHA framework, along with a concise reflection on their main differences, is included in Appendix A.

In disaster risk management within the Red Cross, an increasing focus is placed on a proactive but relatively inflexible approach to response protocols. This approach, integrating early warning systems and pre-emptive actions, is critical in minimizing the impact of disasters by mobilizing resources in advance, thereby enhancing community preparedness and resilience (International Federation of Red Cross and Red Crescent Societies, 2023a). This shift towards anticipatory risk management is pivotal in addressing disasters more effectively. The evolving structure of disaster risk management in the Red Cross involves three distinct phases: preparedness, anticipatory action, and emergency response.

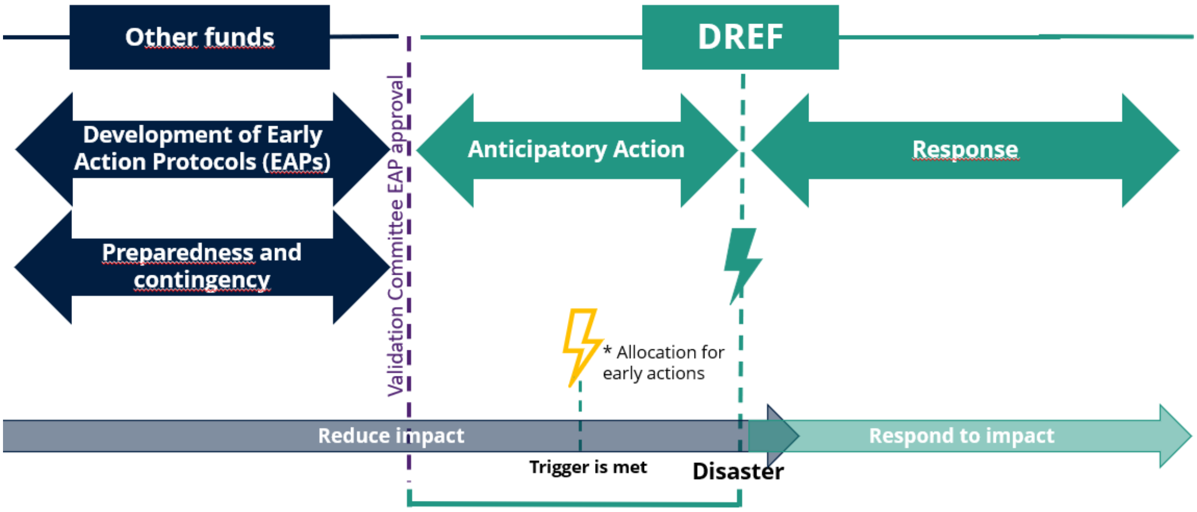


Figure 2.4: Overview of different phases in disaster risk management of the IFRC (International Federation of Red Cross and Red Crescent Societies, 2023b).

- *Preparedness* involves enhancing the capabilities of both institutions and communities to effectively respond before and after a disaster. It includes preparing for anticipatory action and emergency response. Although some preparedness activities are similar for AA and response, such as training staff and volunteers, stock prepositioning, conducting risk monitoring, identifying action triggers and partner coordination, some activities differ. For example, creating Early Action Protocols is specific to AA, whereas contingency planning primarily pertains to emergency response, although it may include limited early actions (International Federation of Red Cross and Red Crescent Societies, 2023a).
- *Anticipatory action*, guided by predictive analysis and early warnings, focuses on implementing measures before a disaster occurs. This stage is important to mitigate potential impacts and ensuring rapid mobilization of resources. AA has three common characteristics: actions to be taken are agreed in advance; actions are chosen based on forecasts; and there is pre-agreed funding in place for implementation (Anticipation Hub, 2022). A more elaborate description of AA can be found in Section 2.2.3.
- *Emergency response*, the final phase, involves the actual deployment of resources and personnel in the aftermath of a disaster, aiming to provide immediate relief and support to affected populations.

An overview of these three stages can be found in Figure 2.4. By clearly delineating these stages, the Red Cross aims for a comprehensive and effective approach to disaster risk management, ultimately aiming to save lives and reduce disaster-induced suffering.

Early action protocols and DREF
An Early Action Protocol (EAP) is a mechanism that brings together a trigger, predefined early actions, and pre-agreed financing (International Federation of Red Cross and Red Crescent Societies, 2023a). EAPs are an important component of the Red Cross's disaster risk management strategy, designed to facilitate proactive, forecast-based responses. These protocols establish predefined actions, activated by specific forecast triggers, to ensure efficient and timely intervention before potential disasters (International Federation of Red Cross and Red Crescent Societies, 2023a, 2023b). By predetermining the course of action, EAPs offer a systematic action framework. However, this predetermined nature also means the framework is relatively inflexible and static, limiting the ability to adjust actions in response to evolving conditions on the ground. The Disaster Relief Emergency Fund (DREF), operated by the International Federation of Red Cross and Red Crescent Societies (IFRC), is a key financial tool that supports the implementation of EAPs. The DREF provides rapid, accessible financial assistance for

disaster response efforts, including both immediate relief activities and anticipatory actions. Its AA Pillar is specifically designed to finance the execution of EAPs based on predefined triggers, allowing for the automatic release of funds.

The concept of lead time is integral to the strategic planning and execution of EAPs. It refers to the period between the identification of a potential disaster (the trigger) and the actual occurrence of the event. This period is crucial because it determines the feasible scope of actions that can be taken in response to an upcoming disaster. The longer the lead time, the broader the range of preparatory and mitigation measures that can be implemented. For example, in the context of flood mitigation, a short lead time can limit actions to those with a short implementation duration, such as the deployment of temporary flood barriers or organizing community evacuations. These are actions that can be implemented relatively quickly and are designed to protect lives and property before the disaster occurs. On the other hand, a longer lead time opens the opportunity for more extensive and preventative measures. This might include reinforcing existing infrastructure to better withstand future floods, or implementing land-use planning strategies that reduce vulnerability over the long term. These actions require more time for planning, funding, and execution, but their benefits are also more enduring. For forecast triggers that provide a lead time of more than three days, it is essential for the EAP to incorporate a stop mechanism. This mechanism is activated if subsequent forecasts, issued before the commencement of early action activities, indicate that the anticipated event is either unlikely to happen, will happen with reduced severity, or will affect a different location than initially predicted. Incorporating such a stop mechanism helps prevent unnecessary expenditure of resources and mitigates the risk of damaging the reputation of the implementing organization by avoiding the distribution of aid in areas where it is not needed.

The concept of action lifetime also plays a vital role in EAPs. It refers to how long an action remains effective in mitigating the impacts of disasters. Some actions, such as stockpiling emergency supplies, have a long action lifetime because they provide benefits that extend well beyond the immediate aftermath of a disaster. On the contrary, other measures, such as emergency broadcasts, offer short-term benefits that are critical in the moment but do not provide long-lasting protection or resilience.

Steps in developing AA plans

An overview of the Red Cross framework for developing EAPs is given in Figure 2.5. This section will provide a description of the steps, based on the analysis of (Tozier de la Poterie et al., 2023) and the Red Cross FbF manual (International Federation of Red Cross and Red Crescent Societies, 2023c). The first step in the process of developing an EAP for AA is to decide which risk should be the priority in the country for which the National Society is creating the EAP. The second step involves identifying available forecasts. It must be verified whether the selected hazards can be accurately predicted by the available forecasts with sufficient lead time. If this is not the case, it must be determined whether the forecasts can be improved. In the third step, a risk analysis is performed. For a complete understanding of risk, an extensive analysis of the impact of previous extreme events, as well as vulnerability and exposure data is required. In step four, the “impact” levels are defined. In the context of FbF, impact levels refer to predefined thresholds of hazard intensity that have historically resulted in significant negative effects on communities, such as damage to property, infrastructure, agriculture, or loss of life. These levels are determined through an analysis of past events, risk assessments, and vulnerability data, allowing to quantify the specific conditions under which an extreme weather event or natural hazard becomes disastrous. Identified impact levels then inform trigger development. Step five is selecting the early actions that have the highest potential to reduce the identified impacts while still feasible to implement in the short lead time that the forecast provides. This is considered one of the most challenging aspects of EAP development (International Federation of Red Cross and Red Crescent Societies, 2023c). In step six, the EAP is developed based on the trigger and early actions, after which , see also Section 2.2.3. After this step, the EAP is submitted to the Forecast-based Action (FbA) of the DREF, which will validate and approve it in step seven to ensure that at the point of the trigger being reached, no further authorizations are needed before the National Society can act. In step eight, the forecast is monitored while the plans are ready to be activated. In this phase, it is important that items are propositioned for distribution, trainings are carried out, and responsibilities are well understood. In step nine, the predetermined trigger threshold is met, triggering the initiation of step ten, where early

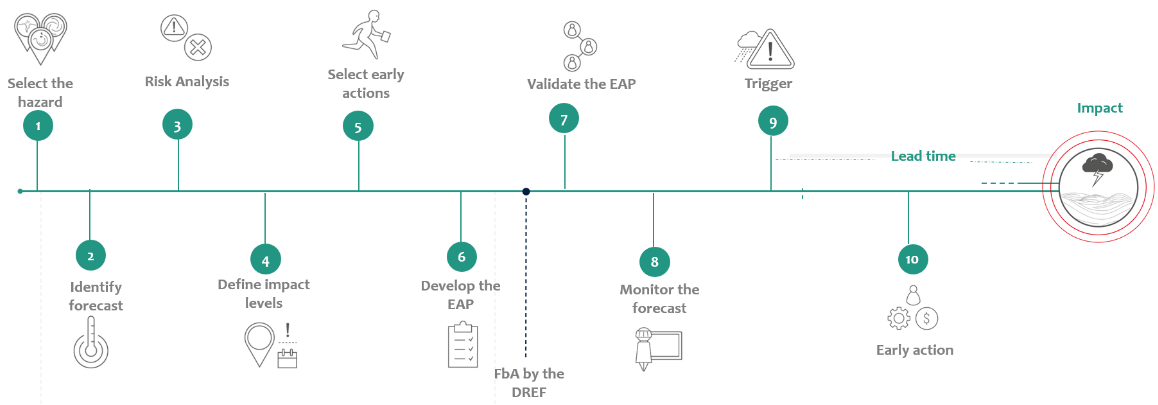


Figure 2.5: Overview of RCRC development and approval process of anticipatory action (based on Tozier de la Poterie et al., 2023).

actions are implemented throughout the available lead time. This period ends with the onset of the disaster. Subsequently, standard disaster response operations, which fall outside the scope of AA and the Early Action Protocol (EAP), are activated to address the aftermath of the event.

Trigger considerations
AA relies on the design of an acceptable and viable trigger, which requires high-quality data to set thresholds that prompt timely and appropriate action. Triggers ideally depend on historical data to understand the specifics of past events, but challenges arise due to data limitations, such as lack of granularity or incompleteness, which can hinder the identification of extraordinary events (Chaves-Gonzalez et al., 2022). The balance between forecast accuracy and lead time is crucial, considering the operational cost of errors (recommended inaction when a shock does occur or recommended action when no shock occurs) (Chaves-Gonzalez et al., 2022). Documenting unknowns and assumptions is key to acknowledging and mitigating built-in tradeoffs. To reduce risks, strategies like phased approaches, budget adjustments, observational (non-forecasted) triggers, and selecting cost-effective or universally beneficial activities are recommended by Chaves-Gonzalez et al. (2022).

Challenges in anticipatory action
In an approach to qualitatively evaluate the RCRC's efforts to develop and implement AA systems, Tozier de la Poterie et al. (2023) identified several challenges in AA in the context of climate risk. The first challenge revolves around uncertainty. One of the main difficulties in establishing AA systems is obtaining access to reliable hazard, impact, and vulnerability data to create reliable forecasts (Tozier de la Poterie et al., 2023). The available data often have gaps, are from various sources, and have not been controlled for quality, making it difficult to establish the trigger for different locations and adding to the already challenging tasks of forecasting and handling uncertainty that is inherent to responding before an event occurs. These issues make it difficult for humanitarians to determine where to initiate AA within a short time window, sometimes resulting in the need to change the location of preparation when more information becomes available (Tozier de la Poterie et al., 2023). Some of the difficulties resulting from forecasting and uncertainty can be overcome by phased triggers and by extending the total activation time by allowing low-cost and low-regret preparations before full activation (Tozier de la Poterie et al., 2023), but this is not yet a standard approach in AA. This provides an opportunity to make policies more adaptive by incorporating adaptation tipping points into protocols, which are conditions under which an action no longer meets the specified objectives (Kwadijk et al., 2010). In particular, there is a need to make an explicit trade-off between how early an action will be and how certain the impact of that action will be. To enable this, the time dimension must be considered throughout the Early Action Protocols. The relevant aspects of the interventions will include the potential delays and uncertainties in the supply chain of the action and the duration of the action.

The second challenge stems from the approach to creating protocols for AA that is often externally driven and top-down, without sufficient involvement at local levels, such as regional offices and community stakeholders. As a result, there is a lack of ownership and capacity at the RCRC's National Societies responsible for implementation (Tozier de la Poterie et al., 2023). The quick and effective implementation of AA protocols depends on the knowledge and ability of regional and local staff and volunteers, which are often lacking. In addition, there is a missed opportunity to integrate AA with existing programs and leverage existing relationships with the broader DRM system. Tozier de la Poterie et al. (2023) found that tensions between AA and the DRM continuum complicate implementation, threaten long-term sustainability, and limit scalability, for example, when the role of AA in overarching systems is unclear or triggers are defined differently. They concluded that future studies should focus on discovering the conditions necessary for successful AA initiatives, so that practitioners can make informed decisions about how to best promote long-term capacity building for humanitarian activities. A more dynamic approach to early action protocols could result in improved contingency planning and in better integration with existing programs.

EAPs for cholera by the Red Cross
Within the Red Cross, the first EAPs for cholera are still in ealy development phases. Meanwhile, in an exploration of the landscape of AA conducted for the Red Cross, three main strategies for AA in disease contexts were identified by (Alcayna et al., 2023).

1. *Identification of Health Impacts Linked to Hydro-Meteorological Hazards*: This approach utilizes weather forecasts to predict extreme weather events and their potential link to outbreaks or increases in endemic diseases. It includes early actions in an early action protocol based on historical data analysis. The trigger is defined depending on the hydro-meteorological hazard and the weather forecast model. The lead time varies, with flood triggers providing 3-10 days, and cyclone early action protocols typically offering 2-3 days. While this approach integrates a combination of triggers and relevant 'amplifying' factors, it's important to note that it does not depend on analyzing statistical correlations between hydro-meteorological events (like floods or cyclones) and disease outbreaks, meaning the certainty of an ensuing outbreak is not quantifiable. Of the three approaches, this one is the most frequently applied within EAPs due to its lower analytical demands. However, it also carries a higher level of uncertainty compared to the others. The Red Cross has applied it to the Mozambique Cyclone EAP to prevent waterborne illnesses (Tozier de la Poterie et al., 2023).

2. *Multi-Stepped Composite Approach (Surveillance & Amplifying Factors)*: This approach integrates various indicators, including surveillance data on diseases and other known drivers of disease transmission, to create a composite trigger or multi-step approach. It helps in coordinating actions with increasing certainty of impacts. For example, a first trigger activates low-cost actions; then a second trigger (e.g., once there is higher certainty of the impact) activates the full range of pre-agreed anticipatory actions. While this approach is already used in drought scenarios by the Red Cross, its adaptation for disease-related scenarios is still largely under development.

3. *Outbreak Risk Prediction Using Mathematical Models*: Progress is being made in academia to combine climate and epidemiological data in statistical models to predict future outbreak probabilities. However, most models currently do not support decisionmaking processes that could turn warnings into early action (S. J. Ryan et al., 2023), hence further model development for this specific puprose is required. In this approach, the trigger is formulated as the probability of a specific caseload threshold being exceeded, which could be weeks to months in advance of an outbreak. This requires access to sufficient real-time data (epidemiological data, climate information, demographic information), in addition to the skills and resources for the maintenance of the system and regular calibration of the model, resulting in some challenges for the realization of these ideas. This approach is not yet operationalized by Red Cross Red Crescent National Societies, although some efforts have been made to develop a prototype dengue early warning system for the Philipines and Barbados, and for malaria in Jonglei State, South Sudan.

All three approaches rely (partially) on historical data, which is often not fully available or of low quality in countries facing waterborne epidemics. For each approach, it will need to be decided if the trigger is based on suspected, probable, or confirmed cases. Following the Red Cross definitions, a suspected case meets clinical criteria (symptoms of a disease), a probable case additionally includes epidemiological criteria, for example close contact of a case, and a confirmed case requires laboratory confirmation of the disease (International Federation of Red Cross and Red Crescent Societies, 2024). This presents a trade-off between quick and lower certainty data (suspected or probable cases) versus slower but higher certainty data. Further data-related problems present themselves in the form of severe under-reporting (e.g. Ali et al. (2015) on cholera cases). Some research accounts for this by correcting for distance to healthcare facilities, e.g. (Hierink et al., 2022).

AA pilots for cholera by OCHA

The United Nations Office for the Coordination of Humanitarian Affairs (OCHA) is developing AA pilot plans for cholera in Mozambique (Government of the Republic of Mozambique, 2023) and the Democratic Republic of Congo (DRC) (United Nations Office for the Coordination of Humanitarian Affairs, 2022). For the DRC, a preliminary version of the ancitipatory action framework has been published (United Nations Office for the Coordination of Humanitarian Affairs, 2022). It operates in three scenarios to prevent large outbreaks, as shown in Figure 2.6. Scenarios 1 and 3 rely on epidemiological data from endemic and non-endemic provinces, that feeds into an alert system. The three indicators that were selected are i) the number of suspected cases, ii) the number of deaths, iii) the weekly incidence of suspected cases (number of new suspected cases relative to the population). For each indicator, they have defined four alert levels (0 to 3) based on the percentile and the increase compared to the previous week. The trigger is reached if a health zone remains on the highest alert level 3 for three weeks and at lease one suspected case is confirmed by laboratories in the previous month. This system of indicators and alert levels covers several situations of interest, although it is not clear from the publication based on what information these specific percentages and levels were chosen. Scenario 2 responds to external shocks such as hydrometeorological hazards. The trigger is reached if a sudden shock (e.g. a flood, a new wave of displacement, a volcanic eruption) affects one or more health zones in an endemic province, and the OCHA Emergency Relief Coordinator endorses the trigger. Each of the three scenarios independently triggers the framework, allowing funding release from the Central Emergency Response Fund for vital WASH and health activities, implemented by UNICEF and WHO. Since the incubation period of cholera is relatively short, the number of cases can increase quickly. Early detection and confirmation of cases require quick action. Therefore, once the trigger threshold for one of the scenarios is reached, UNICEF and WHO will have the flexibility to use CERF funding to intervene in all health areas of concern, not just in the /the health zone(s) in which the trigger was reached (United Nations Office for the Coordination of Humanitarian Affairs, 2022). This pilot is expected to serve as a proof of concept that AA is feasible and can be used to mitigate major cholera epidemics.

2.2.4. Dynamic Adaptive Policy Pathways

In the context of AA for epidemic control, understanding and managing decisionmaking under uncertainty is essential. Quantifying the uncertainty associated with epidemic outbreaks improves this understanding, allowing more informed and effective planning and control strategies. Walker et al. (2013) give five levels of uncertainty, 1 being complete certainty and 5 being total ignorance, with four different dimensions: context, system model, system outcomes and weights on outcomes. To argue that epidemic outbreaks fall under ”uncertainty level 4” based (Walker et al., 2013), we consider the characteristics of level 4 uncertainty, which involves the ability to identify multiple plausible futures without being able to rank them in terms of likelihood due to insufficient knowledge, data, or consensus among decisionmakers. Epidemic outbreaks exemplify this due to their complex and multifactorial nature, influenced by environmental, social, and infrastructural factors, making precise prediction and ranking of outbreak scenarios challenging. This complexity, combined with the variability in certain epidemics's transmission dynamics, the impact of interventions, and the influence of external factors such as climate change, aligns with the criteria for level 4 uncertainty. Furthermore, the range of outcomes and weights is known in the form of a certain number of cases and deaths, which we can assign values to. Following Walker et al. (2013), level 4 falls under *deep uncertainty*.

A method for decisionmaking under uncertain global and regional changes has been developed by Haasnoot et al. (2013): the Dynamic Adaptive Policy Pathways (DAPP) approach. The concept of adaptive policymaking is based on the recognition of deep uncertainty and the need for policies that can evolve (Marchau et al., 2019). These developments mark a paradigm shift from traditional static

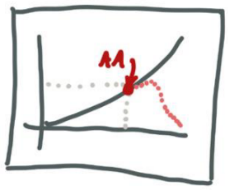
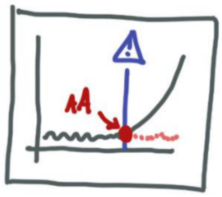
	Trigger threshold: Increased risk of cholera	
	Epidemiological indicators	**From an external factor (for example a flood)**
Provinces endemic	Scénario 1 	Scénario 2 
Non-provinces endemic	Scénario 3 	

Figure 2.6: Representation of the three trigger scenarios in the AA framework for cholera (Translated from United Nations Office for the Coordination of Humanitarian Affairs, 2022).

policymaking toward planning under conditions of deep uncertainty (Haasnoot et al., 2013). The resulting framework encompasses: *transcient scenarios* that capture a range of uncertainties; *actions* to address vulnerabilities and seize opportunities; *Adaptation Pathways* outlining a sequence of potential actions; and a *monitoring system* with corresponding *contingency actions* to ensure that the plan remains aligned with the chosen pathway (Haasnoot et al., 2013). With these components, the DAPP decisionmaking framework allows for sequential decisionmaking in response to changing conditions. The strength of DAPP lies in its ability to integrate a wide range of possible futures, enabling the development of flexible strategies that can evolve as conditions change or new information becomes available.

The steps of developing DAPP

Figure 2.7 provides a schematic representation of the process for developing DAPP. This section describes the steps involved in DAPP, as outlined by Haasnoot et al. (2013).

1. *Describe current situation, objectives, & uncertainties:* The first step of the process involves describing the study area, including the characteristics of the system, its objectives, the current restrictions and possible future restrictions. This is followed by defining what constitutes success by specifying the desired results in terms of indicators and targets. In addition, this description includes the main uncertainties that influence decisionmaking. Beyond uncertainties about the future, these can include uncertainties associated with the data or the models used in the analysis.

2. *Analyze the problem, vulnerabilities & opportunities using transient scenarios:* The second step of the process entails analyzing and comparing the current situation and potential future scenarios with the objectives specified previously to identify any gaps that indicate the need for action. These future scenarios assume no new policies are implemented and are based on the uncertainties identified in the first step. The analysis should consider both opportunities and vulnerabilities.

3. *Identiy actions:* In the third step, the focus is on identifying potential actions that lead to the defined success criteria. These actions are determined based on the opportunities and vulnerabilities identified in the previous step. The objective of this step is to gather a comprehensive range of possible actions. To enhance this process, considering actions from various perspectives can be beneficial.

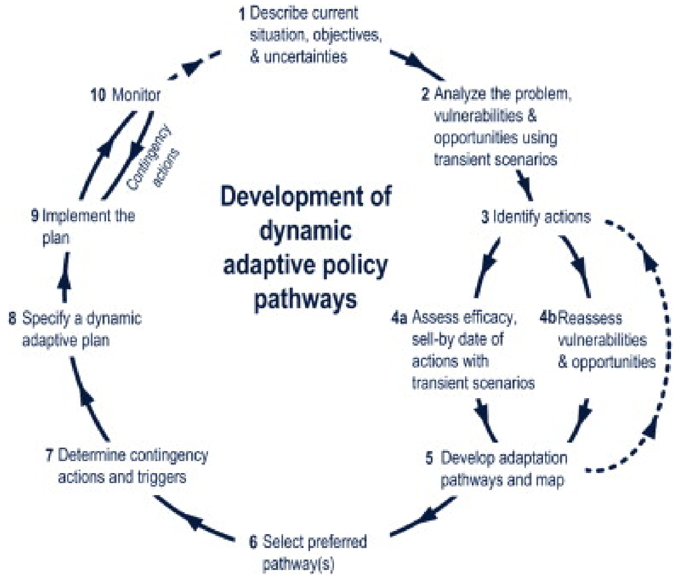


Figure 2.7: The Dynamic Adaptive Policy Pathways approach. (Haasnoot et al., 2013).

4. *Assess efficacy, sell-by date of actions with transient scenarios:* The fourth step involves evaluating the identified actions. This evaluation assesses the impact of each action on outcome indicators in different scenarios, often using scorecards for presentation. The results from this evaluation help determine the 'sell-by date' for each action, indicating its relevance or effectiveness over time.

   Reassess vulnerabilities & opportunities: In addition, the fourth step requires a reassessment of previously identified vulnerabilities and opportunities. It is examined whether an action successfully mitigates a specific vulnerability, utilizes an identified opportunity, or inadvertently creates new vulnerabilities or opportunities. Ineffective actions are eliminated based on this assessment.

5. *Develop adaptation pathways and map:* The fifth step involves constructing Adaptation Pathways using the insights gathered from earlier steps.A pathway is essentially a sequence of actions in which a new action is initiated when the previous one fails to meet the success criteria. Fundamental factors such as urgency, severity of impacts, associated uncertainties, and the preference to maintain flexibility should guide the development of promising pathways. The outcome is an adaptation map that visualizes all feasible pathways that lead to the defined success (2.8).

6. *Select preferred pathway(s):* The sixth step involves narrowing down to a manageable selection of preferred Adaptation Pathways. These preferred pathways are those that align closely with specific perspectives or criteria.

7. *Determine contingency actions and triggers:* The seventh step focuses on improving the robustness of the preferred pathways via contingency planning. This involves defining specific actions to ensure that each pathway remains on track to achieve success. These actions are linked to a monitoring system and associated trigger values. The monitoring system outlines the key factors to be observed, called signposts. Critical values of signpost variables (triggers or signals) indicate the precise moments to activate the contingency actions.

8. *Specify a dynamic adaptive plan:* The eighth step involves consolidating the outcomes of all the previous steps into a dynamic adaptive plan. This plan aims to address a key question: Considering the various pathways and uncertainties about the future, which actions or decisions should be taken immediately, and which can be deferred?

9. *Implement the plans:* In the final stage, the immediate actions are executed, and the monitoring system is set up. Following the implementation of the initial set of actions, the activation of subsequent actions is put on hold until specific trigger events are observed.

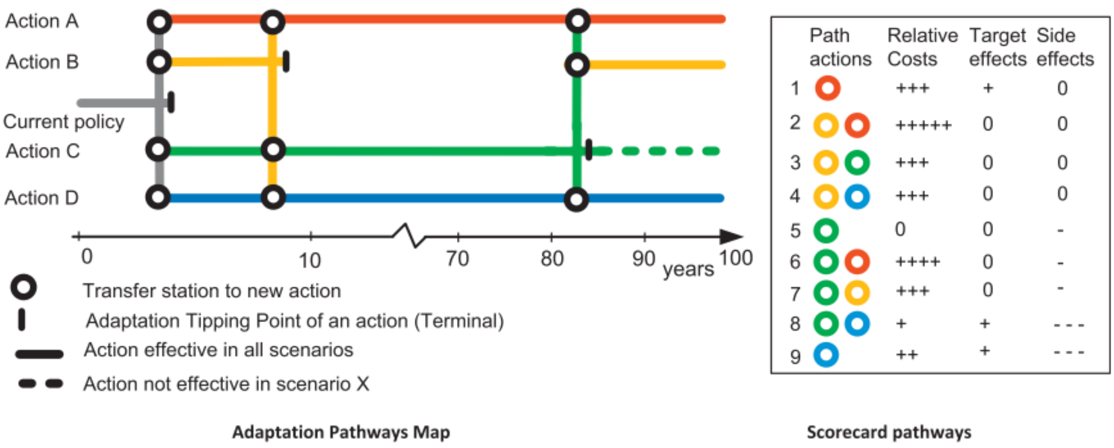


Figure 2.8: An example of an Adaptation Pathways map (left) and a scorecard (Haasnoot et al., 2013). The map illustrates that, starting from the current situation, failure to meet targets begins after four years. The existing policy (indicated by gray lines) offers four different action options. Actions A and D are projected to meet the targets for the next 100 years in all scenarios. Choosing Action B after four years leads to a tipping point in about five years, necessitating a switch to one of the other three actions (indicated by a vertical orange line) to meet the targets. If Action C is implemented after the initial four years, a transition to Actions A, B, or D will be required under some scenarios (as shown by the solid green vertical line), while in other scenarios, the targets will be met for the subsequent 100 years (indicated by dashed green lines). The scorecard details the costs and benefits of the nine potential pathways depicted in the map (Haasnoot et al., 2013).

10. *Monitor:* As time progresses, data pertaining to triggers, collected from various signposts, guide the initiation, modification, cessation, or expansion of actions in response to this incoming information. Over time, there may be a need to revisit and repeat the entire process, ensuring that all plans are current and effectively aligned with evolving conditions.

Designing a monitoring system for DAPP

Building further on DAPP, Haasnoot et al. (2018) have developed a framework for designing and using a monitoring plan as part of the DAPP approach for decisionmaking under uncertainty. They argue that adaptive planning not only involves the execution of current plans but also necessitates anticipatory monitoring. This type of monitoring focuses on determining the optimal timing for implementing actions and assessing their ongoing relevance. The goal is to proactively anticipate future uncertainties that may require the initiation or modification of adaptive plans in response to new information(Haasnoot et al., 2018). A critical aspect of anticipatory monitoring that they identified is recognizing the ‘lead time’ needed for an action to be studied, prepared, and implemented effectively. They conclude that it is crucial to allocate sufficient time between the initial detection of a signal and the anticipated new situation, ensuring that actions are both timely and effective. To develop such an anticipatory monitoring framework, they propose a framework comprising of five steps in the form of answering the following questions (Haasnoot et al., 2018).

1. What are key decisions, actions, tipping points and assumptions in the adaptive plan?
2. What developments could trigger implementation of the actions or invalidity of the assumptions? This could be external developments, developments and response of stakeholders, policy decisions, system and impact signposts, and innovations.
3. What (derivative) signposts can be used to monitor these developments and assumptions and give signals that actions need to be implemented or that the plan may need to be reassessed?
4. If these signposts are measurable, are they able to give timely and reliable signals for implementation or reassessment of the plan?
5. What combination of signposts could give timely, reliable and convincing signals and will be selected for the signal system/monitoring plan?

Addressing these questions enables the development of a signal map that presents a set of signposts and corresponding signal values, allowing for anticipatory monitoring (Haasnoot et al., 2018).

2.3. Main findings

Responding rapidly to epidemic outbreaks presents significant challenges, due to resource and capacity limitations. AA is a newly emerging strategy aimed at accelerating humanitarian responses. By taking impact-reducing actions before a disaster strikes, AA seeks to minimize human loss and required response efforts. However, AA frameworks currently use static prepared-in-advance plans with one-dimensional triggers and distinct phases of preparedness, anticipatory action, and response. As a result, AA is not sufficiently able to deal with the levels of uncertainty in the onset and spread of epidemics. Effective epidemic control requires plans that can adapt to a constantly changing environment and incoming information, such as the number and location of suspected cases, weather forecasts and population movement, while balancing flexibility with an effective management approach. The knowledge gap identified in this chapter revolves around the application of DAPP to enhance the AA framework for epidemic control. The dynamic adaptiveness of DAPP to new information could significantly improve epidemic control strategies, yet the knowledge of how to integrate these approaches effectively in the context of epidemic control remains unexplored. This gap underscores the need for research to develop flexible and effective control strategies for epidemic management.

3

Methodology

This thesis aims to adapt the Dynamic Adaptive Policy Pathways (DAPP) method for anticipatory action (AA) in the context of epidemic control, to obtain a deeper understanding of how flexibility and uncertainty management can effectively contribute to epidemic control. This chapter provides the methodology used to arrive at the results in this thesis. It includes the introduction to the case study, an exposition of the conceptual frameworks adopted, the methods applied, and the computational framework including the data used to support the research. This methodological overview ensures a transparent and replicable research process.

3.1. Case study of Cameroon

This thesis uses a case study of cholera preparedness in Cameroon to illustrate the application of the DAPP method for epidemics. In doing so, we apply the insights from Besiou and van Wassenhove (2020), who underscore the importance of bridging the gap between academic research and the practical needs of humanitarian operations, advocating for research that is both relevant and impactful. This serves as a motivation for our exploration of cholera control policies in Cameroon. The research aims to offer valuable recommendations for cholera control that are applicable to the needs of humanitarian practitioners and the communities they support.

3.1.1. RIPOSTE project

In various regions of Africa, epidemic outbreaks such as cholera (Global Task Force on Cholera Control, 2017) and measles (Patel et al., 2020) continue to pose a recurring threat, underscoring the broader challenge faced by many African countries. In particular, cholera has become endemic in numerous countries, resulting in annual outbreaks that last several years (Ali et al., 2015). In response to this ongoing crisis, the French Red Cross has initiated the RIPOSTE program, a comprehensive effort aimed at fortifying pre- and post-epidemic control strategies (Croix-Rouge Française, 2024). This is the first attempt to create early action plans for a disease context within the Red Cross. The selection of participating countries in the program is influenced by persistent challenges of cholera, as well as the presence of other concurrent epidemics. Currently, part of the RIPOSTE program are four sub-Saharan African countries, which are Guinea, Cameroon, the Democratic Republic of Congo, and Chad, as well as two regional intervention platforms of the French Red Cross located in the Indian Ocean (PIROI) and the Caribbean (PIRAC). 510, the Netherlands Red Cross' data and digital initiative, works closely with the French Red Cross and National Societies to create early action protocols designed to effectively address cholera outbreaks with AA. This thesis was conducted under the guidance of 510, in the context of the RIPOSTE project.

3.1.2. Involved actors

This thesis research engages with different stakeholders within the RIPOSTE project, reflecting a collaborative effort across multiple domains.

The International Red Cross and Red Crescent Movement
Our case study is conducted in partnership with the Red Cross. Although the term “The Red Cross” is often used for simplicity, it is important to clarify that this name does not represent a single entity. In reality, the International Red Cross and Red Crescent Movement is a global humanitarian network of organizations that are all dedicated to providing assistance to those in need, particularly in times of disaster and armed conflict (International Federation of Red Cross and Red Crescent Societies, 2022b). It consists of three main components: the International Committee of the Red Cross (ICRC), International Federation of Red Cross and Red Crescent Societies (IFRC), and the National Red Cross and Red Crescent Societies, of which the IFRC and several National Societies were involved in this thesis.

- The IFRC coordinates and directs international assistance following natural and man-made disasters in non-conflict situations. It supports the development of National Red Cross and Red Crescent Societies and assists them in capacity building to improve their local humanitarian responses. In the scope of this thesis, the IFRC plays an important role in the funding and approval of the early action protocols mentioned in Section 2.2.3. In addition, internal documentation of the IFRC has been used.

- The National Societies are individual organizations within each country, often referred to as National Societies. They operate as auxiliaries to the public authorities in the humanitarian field. They play a critical role in their local communities and often serve as the first line of response in times of crisis. This thesis has benefited from the collaboration with the French Red Cross and the Netherlands Red Cross, in particular the latter’s data and digital initiative, 510. Future phases of the RIPOSTE project will see the involvement of the Cameroon Red Cross, which will extend the timeline of this thesis. This involvement will be anticipated by including the Cameroon NS as the stakeholder responsible for the implementation phases in DAPP.

The ICRC, IFRC, and National Societies work in a complementary manner: the National Societies are the main implementers of the movement’s activities in their respective countries, the IFRC coordinates efforts at an international level, especially in non-conflict emergencies, and the ICRC takes the lead in conflict zones (International Federation of Red Cross and Red Crescent Societies, 2022b). There can be overlap in activities and sometimes ambiguous operational boundaries within the International Red Cross and Red Crescent Movement. For simplicity, this thesis will use ”the Red Cross” as a general term to refer to the Movement in contexts where the distinction between specific organizations is not important. However, in sections where details about specific entities are relevant, either the IFRC or the relevant National Society will be explicitly identified.

École des Hautes Études en Santé Publique
The École des Hautes Études en Santé Publique (EHESP), recognized as a leading institution for public health research and education, has an important position within the RIPOSTE program, leveraging its epidemiological expertise to address complex epidemic challenges. EHESP contributes significantly by developing a cholera model specifically designed for the context of Cameroon. This model integrates local data, environmental factors, and socio-economic conditions to predict outbreak patterns and identify potential hotspots for targeted interventions.

3.2. Conceptual framework

To motivate the development of an adapted DAPP method tailored for epidemic control, we first gain a deeper understanding of the relevant concepts by analyzing their conceptual frameworks. A conceptual framework can be defined as a network or “a plane” of interconnected concepts that collectively provide a comprehensive understanding of one or more phenomena (Jabareen, 2009). Unlike quantitative models, which aim to offer theoretical explanations, conceptual frameworks serve to enhance understanding. Following this usage of conceptual analysis, we integrate concepts of AA and DAPP to build a conceptual framework for decisionmaking in epidemic control as a foundation for adapting the DAPP method. We use conceptual framework analysis to determine how DAPP can be adapted to a humanitarian AA context for epidemic control. Subsequently, the focus shifts to updating the method for developing epidemic control protocols.

3.2.1. Building a conceptual framework

In this process, we follow the methodology for conceptual framework analysis as suggested by Jabareen (2009). This section outlines the procedural steps recommended by Jabareen (2009) and details their specific application within the context of this research.

Phase 1 and 2: Mapping data sources and categorizing of the selected data
The first task in the process is to initiate a comprehensive review of multidisciplinary literature and conduct initial interviews with practitioners and scholars. This phase aims to achieve a holistic understanding of the phenomenon under study through extensive data collection. The second phase is to read and categorize the collected data by discipline and significance, ensuring a thorough representation of each field's contributions to the topic. For this thesis research, a literature review was conducted on the topics of epidemic control, AA, DMDU and DAPP. The search methodology for the literature review involved investigating the mentioned research areas. Keyword searches were carried out in databases including the TU Delft Library, Scopus, Web of Science, and Google Scholar. In addition, gray literature has been obtained from the Red Cross, various United Nations departments, and the World Bank. To complement the database search, the snowball technique was used to identify additional sources. To gain a comprehensive understanding of the Red Cross context, this study analyzed internal documents provided by the 510 initiative. To enrich these insights, the research was supplemented with desk research and discussions with 510 employees. The results of these two phases are presented in Chapter 2.

Phase 3 and 4: Identifying, deconstructing and categorizing concepts
Through detailed examination of the data, the third phase prompts to discover key concepts, allowing them to emerge naturally from the literature. This phase acknowledges the importance of inductive reasoning in qualitative inquiry. The fourth step is to break down each concept to understand its attributes, assumptions, and roles, then categorize them according to their significance in various aspects. The main concepts identified in phase 3 are AA and DAPP, with particular interest in their applicability to epidemic control, following the thorough analysis in Chapter 2. For phase 4, they were analyzed on their significance on the following aspects: focus, approach, decisionmaking, desirable plan, consideration of uncertainty, flexibility, and applicability to epidemic control. We have deviated from the aspects suggested by Jabareen (2009), and instead followed the analysis of Haasnoot et al. (2013) and adapted these to fit the context of this thesis. The resulting analysis can be found in Section 3.2.2.

Phase 5: Integrating concepts
The fifth phase consists of combining similar concepts into more comprehensive and unified categories, significantly reducing the total number of concepts to a manageable number. We use this phase for integrating the development processes of the frameworks in question. Through an in-depth comparative analysis of the AA and DAPP development processes, similar phases were identified and similarities and divergences were described. This approach facilitated a reduction in complexity and highlighted the parallels and divergences within the methods of AA and DAPP, providing a clearer framework for understanding their respective applications and efficacies. The results of this phase can be found in Section 3.2.2.

Phase 6: Synthesis, resynthesis, and making it all make sense
This phase consists of iterative synthesizing the identified concepts. This step requires openness and flexibility, continuing until a coherent and meaningful framework emerges. In our research, this framework emerges in the form of an adapted DAPP method for epidemic control. To guide the synthesis approach, we use components of design science as described by Hevner et al. (2004). We identify an environment, in our case, the context of disease control within the Red Cross, that has goals, tasks, problems and needs. The adapted method should be developed within the context of organizational strategies and existing processes. Furthermore, Hevner et al. (2004) identify a knowledge base consisting of foundations, in our case the AA and DAPP frameworks, and methodologies, such as validation criteria. The identified environment and knowledge base have been used for an iterative process of building and evaluating. Based on this and previous phases of conceptual framework analysis, an adapted DAPP method is designed and presented in Section 3.2.3.

Phase 7: Validating the conceptual framework

Phase seven is to assess the validity of the conceptual framework by evaluating its relevance and utility to scholars and practitioners in all disciplines. This may involve presenting the framework in academic settings for feedback. In this thesis, we validate both our conceptual framework and the adapted DAPP method, and we do this in a qualitative and quantitative way. A case study and simulation are chosen as methods of validation, following the suggestions of Hevner et al. (2004), complemented by expert validation, as suggested by (Jabareen, 2009). The computational framework for our simulation is described in Section 3.3, and the case study is introduced in Section 3.1. The expert validation is presented in Sections 4.2.1 and 5.3.1

Phase 8: Rethinking the conceptual framework

The final phase is to recognize that a conceptual framework, especially one that addresses multidisciplinary phenomena, is dynamic. It should evolve based on new insights, literature, and feedback, ensuring that it remains relevant across the disciplines it encompasses. The main part of this phase is done by a discussion of the strengths, weaknesses and limitations of this research, presented in Chapter 5, as well as the identification of future research recommendations in Section 6.3.

3.2.2. Conceptual framework for epidemic control strategies

AA and DAPP are promising approaches in epidemic control, although their integration into a unified conceptual framework has remained unexplored within the existing literature. AA, variably classified as a strategy, approach, and framework, delineates a proactive stance in humanitarian responses (Anticipation Hub, 2023; Chaves-Gonzalez et al., 2022; Tozier de la Poterie et al., 2023). Conversely, DAPP-initially introduced as a method and subsequently regarded as an approach- underscores the imperative of dynamic adaptiveness in policymaking under conditions of profound uncertainty (Haasnoot et al., 2013, 2018; Marchau et al., 2019). By adopting a unified view of AA and DAPP, our aim is to improve our understanding of their combined potential in epidemic control.

Concepts of AA and DAPP

Table 3.1 compares the features of AA and DAPP. Both approaches aim at supporting decisionmakers in responding effectively after preagreed triggers. Both frameworks incorporate a degree of proactiveness, with AA focusing on early action based on forecasts and DAPP on adjusting actions as new information becomes available. However, the way in which the two approaches offer decision support are quite different. AA relies on predefined triggers for action, making decisions based on risk assessments and forecasts. This often leads to a one-dimensional approach to decisionmaking. DAPP, however, employs a more complex decisionmaking process under deep uncertainty, using continuous monitoring to identify when changes in the strategy or actions are necessary. In terms of uncertainty management and flexibility, AA presents a more static model, with limited flexibility once a plan is in place, and does not actively incorporate uncertainty into ongoing decisionmaking other then defining a termination trigger. DAPP, on the contrary, is built around the principle of adaptiveness, with mechanisms to continuously incorporate uncertainty and allow for dynamic shifts between different pathways.

AA and DAPP in a disease context

With AA in the early exploratory stages of disease application and DAPP yet to be applied, our analysis of their effectiveness in epidemic control relies on informed estimations. Reflecting on AA and DAPP in the context of epidemic control suggests a tension between the need for immediate and proactive action and the need for flexibility in the face of evolving challenges and uncertainties. AA offers a straightforward and potentially faster path to intervention based on established forecasts and risk assessments, making it suitable for rapid control protocols. However, its effectiveness may be limited by its rigidity and the static nature of its planning methods. On the other hand, DAPP's strength lies in its ability to navigate uncertainty and adapt to changing circumstances, making it particularly well suited to managing complex, evolving situations like epidemic outbreaks. The inherent flexibility and continuous re-assessment embedded in DAPP could lead to more resilient and sustainable epidemic control strategies. However, the complexity and demands of its adaptive decisionmaking processes require effective coordination among stakeholders, which poses challenges in practical implementation. In conclusion, while both AA and DAPP offer valuable frameworks for epidemic control, a hybrid approach that leverages the proactive, early intervention strengths of AA, combined with the adaptive, flexible planning

Table 3.1: Comparative analysis of anticipatory action (AA) and Dynamic Adaptive Policy Pathways (DAPP) approaches, focusing on their application in epidemic control strategies. Detailed descriptions of frameworks are provided in Section 2.2.3 for AA and Section 2.2.4 for DAPP.

Aspect	**Anticipatory action**	**Dynamic Adaptive Policy Pathways**
Focus	Prioritizes early action based on forecasts and risk assessment to mitigate impact.	Focuses on creating flexible pathways that can adapt over time to changing circumstances.
Approach	Proactive, aiming to anticipate and reduce disaster risk before it occurs.	Adaptive, continuously adjusting policies and actions as new information becomes available.
Decisionmaking	Based on risk assessments and forecasts to implement actions before a crisis. Involves predefined, often one-dimensional triggers for action based on specific thresholds.	Utilizes decisionmaking under deep uncertainty principles to guide policy adjustments. Involves monitoring and identifying signals that indicate the need to switch paths.
Desirable plan	One static prepared-in-advance Early Action Protocol with AA plans, separate of the response and response preparedness actions.	Offers multiple, adaptive pathways, with preferred paths influenced by varying perspectives and emergent conditions.
Consideration of uncertainty	Initially addresses uncertainty through risk assessments, but lacks ongoing incorporation of uncertainty in active decisionmaking.	Actively incorporates uncertainty into planning and execution, allowing dynamic shifts between pathways and the integration of contingency actions.
Flexibility	Limited, with a focus on executing a predefined set of actions.	High, with clear guidelines on when and how to modify policies, enhanced by a robust monitoring and evaluation framework.High, with clear guidelines on when and how to modify policies, enhanced by a robust monitoring and evaluation framework.
Applicability to epidemic control	Initial pilots of the AA framework in epidemic control are still in early phases. Proven effective in early interventions for other hazards, it promises to curb epidemic spread through proactive measures. However, it may be unable to adapt to the unpredictable nature and spread of epidemic outbreaks.	Although DAPP has not yet been implemented in disease control, its adaptive approach is promising for navigating the changing dynamics of epidemic outbreaks and enabling flexible strategy adjustments. The complexity of decisionmaking processes, however, may present challenges in stakeholder coordination and implementation.

capabilities of DAPP, may offer a comprehensive strategy for managing the multifaceted challenges of epidemic control.

The development methods of AA and DAPP

Table 3.2 compares the development methods for AA and DAPP. In principle, these methods show high-level similarities and similar phases can be distinguished. Both AA and DAPP begin with siliar analysis phase: AA involves hazard selection, risk assessment, forecast identification, and impact level definition, aiming for a precise understanding of immediate threats in a specific area, to define objectives and motivate why a certain hazard was chosen. DAPP, similarly, starts with a broad situation description and objectives, incorporating uncertainties and problem analysis with transient scenarios. Furthermore, both approaches incorporate a monitoring step, though with different scopes. AA focuses on continuous monitoring of forecasts to guide immediate action, while DAPP employs systematic monitoring of the environment and policy effectiveness, with the aim of long-term adaptiveness. Certain steps show more pronounced differences between the two methodologies. First, AA selects early actions based on predefined criteria, forming an implicit singular pathway. DAPP also identifies actions through a process involving efficacy assessment, but then continues with the development and mapping of multiple adaptation pathways. This difference is the result of AA's focus on a rapid and fully predefined strategy versus DAPP's emphasis on flexibility and long-term adaptiveness with pathways. Second, AA uses triggers based on shock events, while DAPP focuses on systemic stresses. In AA, triggers for initiating actions are derived from impact levels, part of the risk assessment in the analysis phase. Therefore, in AA, triggers and action initiation are very closely linked. In DAPP, triggers and contingency actions are identified later in the planning cycle. These triggers aim for system robustness, not directly tied to specific policy pathways. Third, the planning phases differ significantly. AA develops and validates an Early Action Protocol (EAP), resulting a more fixed plan until its next revision. DAPP specifies a dynamic adaptive plan which is more flexible and can evolve as conditions change. Last, the implementation of actions in AA is directly tied to the triggers, which continues until the disaster occurs. DAPP's approach to action involves implementing contingency actions as informed by ongoing monitoring and trigger identification, allowing for adjustments based on evolving scenarios. In conclusion, the DAPP method offers a more comprehensive foundation to developing plans. However, there is potential for further enhancement through the integration of AA components. Given the similarities between the frameworks, this integration process is relatively straightforward.

Table 3.2: Comparison of the development methods for anticipatory action (AA) and Dynamic Adaptive Policy Pathways (DAPP). Detailed descriptions of the steps are provided in Section 2.2.3 for AA and Section 2.2.4 for DAPP.

Phase	**Anticipatory action**	**Dynamic Adaptive Policy Pathways**
Analysis	Hazard selection; risk assessment; forecast identification; impact level definition (steps 1-4).	Situation description; objectives and uncertainties clarification; problem analysis with transient scenarios focusing on vulnerabilities and opportunities (steps 1-2).
Actions	Early action selection based on predefined criteria (step 5).	Action identification; efficacy assessment using scenarios; opportunities and vulnerabilities reassessment (steps 3-4).
Pathways	Actions implicitly form a implicit singular pathway.	Development and mapping of multiple adaptation pathways; selection of preferred pathways based on strategic goals (steps 5-6).
Trigger	From impact levels, shock-based triggers for initiating actions are derived (part of step 4).	Identification of triggers for contingency actions based systemic stresses (step 7).
Plan	Development and validation of the EAP (steps 6-7).	Specification of the dynamic adaptive plan (step 8).
Implementation	Implied to occur following plan validation.	Follows the specification of the adaptive plan (step 9).
Monitoring	Continuous monitoring of forecasts to guide action (step 8).	Systematic monitoring of environment and policy effectiveness to inform adjustments (step 10).
Act	Activation of early actions based on triggers; continuous until disaster (steps 9-10).	Implementation of contingency actions as informed by monitoring and trigger identification (between steps 9-10).

Phases in epidemic control

Epidemics evolve both temporally and geospatially, posing significant challenges to effective control efforts. To respond effectively, it is crucial to act quickly and adaptively, incorporating real-time epidemiological data updates and modifying intervention strategies to meet the evolving situation (Long et al., 2018; also discussed in Section 2.2.1). In the context of humanitarian aid, having plans prepared in advance is vital for quick decisionmaking. To enable this, the Red Cross identifies three phases in disaster risk management: preparedness, anticipatory action, and response (as detailed in Section 2.2.3). In their plans, actions are organized within these phases to clarify their timing. This clustering is useful, as there can be a large number of actions. For natural hazards, the occurrence of the event or the peak shock is often used as the moment AA shifts into response. However, for epidemics, the exact boundary between AA and response is not yet defined. The shift could already take place at one confirmed case or only when the shock of an epidemic outbreak occurs. As there is a great difference between these two, we conclude that epidemic control would benefit from a more fluid approach. Indeed, the GTFCC outlines strategic phases for epidemic control: emergency control, outbreak prevention, and long-term control (Global Task Force on Cholera Control, 2017; further explained in Section 2.1.5). These stages are designed to connect emergency actions with development efforts. Building on these concepts, we broaden the scope of this thesis not only to investigate AA, but also to include resilience building and 'early action' as defined by Scott (2022) and visualized in Figure 1.1, which includes both AA and early response. This extension serves as an approach to bridge the gaps between development, preparedness, AA and response. We propose an expanded framework comprising four cumulative phases to streamline decisionmaking. These phases are progressive, with each subsequent phase including the actions and objectives of the previous phase(s) in addition to its own.

1. *Resilience Building and Monitoring*: Focuses on strengthening systems and improving preparedness during non-outbreak periods, especially in light of expected effects of climate change and urbanization. This phase encourages early investment in health infrastructure, training, and community awareness.

2. *Anticipatory Action*: Prioritizes preventive measures and early interventions when there is increased risk or suspicion of an outbreak. This proactive approach ensures that systems are in place before an epidemic occurs, reducing the impact and potentially preventing outbreaks.

3. *Early Response*: Addresses early, small-scale outbreaks through rapid and effective interventions.

4. *Response*: Addresses the complexities and challenges of controlling an active outbreak, including coordination with other NGOs, governments, and health organizations.

Implementing well-defined phases offers organizations and stakeholders a cohesive framework to guide their initiatives. This structured guidance not only aligns efforts and resources with the evolving stages of epidemic control, but also ensures unified progress toward shared goals. The establishment of specific phases clarifies the roles and responsibilities for all involved parties at each epidemic stage, enhancing collaboration between local governments, non-profits, and the private sector. With a clear understanding of the current phase of an epidemic, decisionmakers can better target funding and resources to areas of greatest need. The delineation of phases also allows for a more flexible control of epidemics, allowing organizations to quickly adapt their strategies and actions as the situation evolves, which is key to navigate the unpredictable nature of epidemics. Additionally, distinct phases support more effective communication strategies, both with the public and among stakeholders. Specific messages and actions for each phase ensure that communication is timely and understandable, thereby improving public trust and encouraging adherence to preventive measures and emergency directives.

Triggers for epidemics

In the context of AA for climate-related natural hazards, achieving an optimal balance between the accuracy of forecasts and the lead time available for early action is essential, as discussed in Section 2.2.3. This balance enables stakeholders to make informed decisions before the onset of natural hazards. However, the dynamics of epidemic outbreaks present a different challenge. Unlike singular climate events, epidemics often do not follow a predictable trajectory with a single peak impact. Instead, they can manifest in multiple waves, each potentially varying in intensity and geographical spread.

The initial outbreak of an epidemic can be characterized as a shock event due to its sudden onset and immediate impact on the population. This abrupt beginning typically demands rapid protocol activation and mobilization of resources to mitigate its effects, which is similar to natural hazards. On the other hand, the progression and spread of an epidemic often resemble systemic stress, reflecting prolonged challenges that affect the resilience and capacity of health, social, and economic systems. This dual nature of epidemics, combining elements of both immediate shocks and ongoing systemic stresses, necessitates the integration of trigger mechanisms from both AA and DAPP.

In deploying a multi-phased strategy for epidemic control, establishing precise triggers for the timely transition between control phases is essential. The trigger mechanism of AA is effective for this purpose. Yet, for tracking the disease's progression and adjusting strategies accordingly, the trigger system from DAPP, which incorporates contingency actions, could provide significant additional value following the initial outbreak. Integrating these trigger models enables epidemic control that is both rapid and flexible.

3.2.3. The DAPP method in an epidemic context

Building on the foundation laid out in Chapter 2 and Section 3.2, the DAPP method, as introduced by Haasnoot et al. (2013), has been adjusted to the unique challenges of epidemic control. This section delves into the nuances of the adjusted DAPP method, detailing the modifications made to align with the specific needs of epidemic control. It elaborates on each component of the method, illustrating how it diverges from and builds on the original methodology proposed by Haasnoot et al. (2013), thus offering clear steps for the development of DAPP in the face of the complexities of epidemics.

Main differences with classical DAPP

In the adjusted DAPP method, specific epidemic phases are introduced. This serves to structure the control strategy, allowing for better coordination. These phases also enable incorporation of AA into broader control strategies. The proposed phases are: "Resilience Building and Monitoring" for periods without an outbreak, focusing on strengthening systems and preparedness; "Anticipatory Action" for times when the risk of an outbreak is heightened, emphasizing preventive measures and early interventions; "Early response" to manage the situation during an early outbreak, and "Response" for the management of outbreaks. It is important to note that deviations from this framework may be necessary based on the unique characteristics of specific epidemics, allowing for tailored control strategies that better address the situation at hand.

Additionally, we introduce a step to integrate triggers signaling transitions between various phases of control, drawing inspiration from the AA framework. This step, situated after problem analysis, leverages the scenarios resulting from the analysis to inform trigger development. Subsequent steps include action assessment, followed by the development of adaptation pathways. This adjustment allows triggers to act as initiation points for the pathways, employing the shock-based trigger approach characteristic of AA. To ensure actions remain effective throughout the progression of the disease, identifying contingency actions and triggers remains important. Contingengy planning ensures alignment with the pathways and enhances the overall robustness of the control strategy. To clarify, we will adopt the terms 'early action triggers' for initiating immediate the actions of the Anticipatory Action and Early Response phases and 'contingency triggers' for adjusting strategies as conditions evolve.

As a consequence of the incorporation of these early action triggers, we deviate from the pathways as proposed by Haasnoot et al. (2012), and instead make the pathways for epidemic control more hardcoded to specific scenarios, as is common practice in AA and more generally in humanitarian plans. In addition, we add weekly decision points to the maps to visualize when contingency actions, such as upscaling of actions, can take place.

The DAPP cycle for epidemic control

This section describes the steps involved in developing DAPP for epidemic control. Figure 3.1 provides a schematic representation of this process. The selection of an epidemic for a specific region or country is taken implicitly before entering the DAPP cycle.

1. Describe current situation, objectives, uncertainties

The first step of classical DAPP, which is to develop a complete understanding of the situation at hand, the objectives of the plans, and uncertainties, can be applied directly in the context of epidemics. This step should focus on the epidemiology of the epidemic in the target area, including current incidence rates, transmission dynamics, and healthcare capacity. The objectives would be framed around reducing incidence, improving response times to outbreaks, and increasing community awareness and education. From there, specific success criteria can be formulated. Uncertainties revolve partially around the future, such as the location of a first case, conflict, natural hazards, and climate change

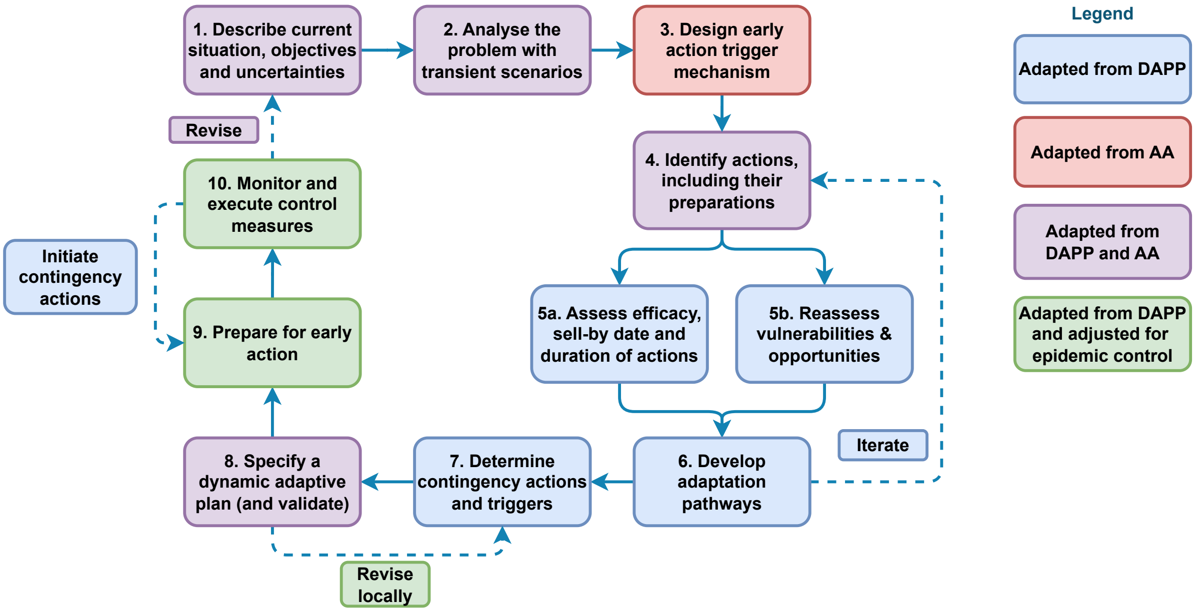


Figure 3.1: DAPP method adapted to fit the context of epidemic control, including AA. The steps outlined in blue originate from the DAPP framework, while those in red are drawn from the AA framework. For steps highlighted in purple, both DAPP and AA frameworks suggest similar actions; in these instances, the descriptions as provided by the DAPP method were selected for consistency. The steps marked in green have been adjusted from DAPP to suit the requirements of epidemic control.

effects. Furthermore, there is uncertainty of the data and models, such as under-reporting, delays in reporting, and forecasting limitations.

2. Analyze the problem with transient scenarios
The second step of classical DAPP, which is the problem analysis, is directly suited in the context of an epidemic. To improve the understanding of the problem, an analysis of previous outbreaks and vulnerability and exposure data can be used to assess the risk of outbreak in different regions. In particular, vulnerabilities resulting from conflict, population movement, natural disasters, and inadequate healthcare infrastructure can be relevant to the spread of the epidemic. Opportunities may exist in the form of epidemiological models that can help forecast outbreaks. With transient outbreak scenarios that span the uncertainties identified in step 1, different courses of an outbreak can be simulated to identify critical intervention points to mitigate the spread of an epidemic.

3. Design early action trigger mechanism
Building on the scenarios outlined in the preceding step, this step focuses on developing an early action trigger mechanism. This mechanism clearly defines "early action triggers," which are specific indicators that pinpoint the exact timing for transitioning between different phases of epidemic control. It is important that the triggers accurately reflect uncertainties specific to the disease and geographic, including underreporting and delays. For the proposed epidemic phases, we propose a trigger framework that can be adapted to local requirements.

- The initial phase, Phase 1: Resilience Building and Monitoring, is suggested to be active under conditions of zero reported cases and an absence of elevated risk factors. This phase is often covered in Red Cross contingency plans, as visualized in Figure 2.4.
- Triggers for Phase 2, Anticipatory Action, are specific signals or indicators that prompt nonprofits, public health authorities, and governments to implement preparedness and low-regret measures to prevent or mitigate the impact of an outbreak. Within the Red Cross, these are covered by the EAP. These triggers are important for early intervention, which can significantly reduce the spread of disease and its associated morbidity and mortality. Triggers for advancing to Phase 2 include a set of specific conditions that indicate an increased risk of an outbreak. These conditions can encompass disease forecasting models, the confirmation of cases in adjacent regions, suspected

cases within the region itself, the occurrence of extreme weather events or other natural disasters, and significant population displacements, for example, due to conflict. These triggers can be further improved with risk assessments derived from the identification of vulnerable locations. The relevance and impact of each condition depend on the disease in question, underlining the need for a tailored approach in control planning. This specified combination of factors serves as an alert to escalate preparedness and intervention efforts for a duration that depends on the trigger involved. For example, in the case of a trigger related to extreme weather events, the period of AA would align with the duration of the weather phenomenon. Conversely, for a trigger resulting from a confirmed case in a neighboring area, the duration of intensified measures would take into account the disease's incubation period, as well as the potential for travel-related spread. This approach ensures that the action taken is both proportionate to the immediate risk and adaptive to the specific circumstances presented by the trigger. If, after this specified duration, there is no further indication of an emerging case or the persisting risk of one, the strategy advises a reversion to Phase 1. However, should additional indicators of increased risk emerge during or after this period, the continuation of Phase 2 is warranted to address these ongoing or new risks.

- Transitioning to Phase 3, Early Response, is triggered by the confirmation of a case within the area under surveillance, following traditional epidemic emergency response triggers. This phase involves a more intensive and prolonged high-regret response efforts to control the outbreak.
- A trigger for Phase 4, Response, activates when the disease exhibits rapid spread or achieves high infection rates in densely populated areas, signaling the need for coordinated intervention. Examples of specific triggers include the surpassing of a predetermined threshold of new cases per day within a province or a certain percentage increase in cases over a short period across multiple regions.
- Equally important is defining triggers for reverting to earlier phases, in the Red Cross terminology called STOP mechanisms. Once the epidemic is deemed under control, a re-assessment is performed. If there remains a high risk of recurrence, a step back to Phase 2 is advised to maintain an elevated level of preparedness. On the contrary, if the risk is significantly reduced, a return to Phase 1 is appropriate, signaling a successful mitigation of the immediate threat and a shift back to building resilience against future outbreaks.

For ease of operation, we recommend activating entire phases through these triggers. Yet, flexibility within a phase should be maintained, allowing for not activating certain actions or other deviations from the phased approach as required. Furthermore, when the action list is relatively short, assigning specific triggers to individual actions could prove more effective than using triggers for phases.

4. Identify actions, including their preparations
The third step of classical DAPP is to identify a wide range of potential actions that lead to the defined success criteria, based on the opportunities and vulnerabilities identified in the previous step. To better fit the needs of epidemic control, this step is updated to explicitly include preparatory steps, such as the pre-positioning of supplies or setting up a cold supply chain for vaccine transport, in the action identification process. This will provide clarity on all necessary measures.

5a. Assess efficacy, sell-by dates, and duration of actions
The fourth step of classical DAPP involves evaluating the actions identified based on the efficacy in different scenarios, to determine the sell-by date for each action. Some actions may be effective for multiple epidemic phases or have long sell-by dates, i.e. action lifetimes, making them more impactful. To enhance understanding, we categorize implementation time into two distinct stages: the post-alert preparation stage and the action stage. The post-alert preparation stage encompasses the steps of planning, mobilizing resources, and sensitizing the community, laying the groundwork for rapid and efficient control. Following this preparatory stage, the action stage begins, marking the period in which the planned activities are actively executed.

5b. Reassess vulnerabilities & opportunities
In addition, the fourth step of classical DAPP requires a reassessment of previously identified vulnerabilities and opportunities. In the context of disease, reevaluate how actions might alter the landscape

of vulnerabilities and opportunities, taking into account potential shifts in the socioeconomic or environmental context that could affect the dynamics of the epidemic. Ineffective actions are eliminated on the basis of this assessment.

6. Develop adaptation pathways
Similar to classical DAPP; the fifth step involves building adaptation pathways using the insights from earlier steps. For an epidemic, a pathway is a sequence of actions in which a new action is initiated when the epidemic (re)enters a different phase, as indicated by early action triggers. As the field of epidemics is funding constrained, cost-effectiveness and regret are both important measures to guide the development of promising pathways. Recall that "regret" denotes the advisability of taking action in the event that the outbreak is averted or does not occur. It serves as a measure of the action's defensibility against the backdrop of a false alarm and is particularly relevant for anticipatory actions. Like in classical DAPP, the outcome of this step is an adaptation map that encapsulates all feasible pathways that lead to the defined success.

As a consequence of the incorporation of early action triggers, we deviate from the pathways in classical DAPP, and instead make the pathways for epidemic control more hardcoded to specific scenarios, as is common practice in AA and more generally in humanitarian plans. In addition, we add weekly decision points to the maps to visualize when contingency actions, such as upscaling of actions, can take place, to allow for flexibility. The current and expected number of cases, potentially aided by a simulation model, are used as input for the decision to increase control efforts. As the preparation time of actions is very important in Anticipatory Action, we include a dotted line to represent the preparation phase, while the solid line represents active actions. The colors of the lines correspond to the different actions, similar to classical DAPP. To be inclusive to color-blind people, we recommend using a color palette such as the one developed in (Wong, 2011).

In classical DAPP, there is an extra step that involves narrowing down to a manageable selection of preferred Adaptation Pathways. These preferred pathways are those that align closely with specific perspectives or criteria. We have chosen to incorporate the selection of prefered pathways in this step and make it optional. For the sake of simplicity and operational feasibility, it may be chosen to develop a singular set of pathways that represent the developed action and trigger strategy. This simplifies the process and enhances operational feasibility, albeit at the expense of later flexibility.

7. Determine contingency actions and triggers
The seventh step of classical DAPP focuses on improving the robustness of the preferred pathways via contingency planning. This involves defining specific actions to ensure that each pathway remains on track to achieve success, and triggers that inform when these actions need to be taken. In the context of controlling an epidemic, these actions might involve ensuring adequate organizational readiness and local familiarity with the strategies, or restocking supplies after an (anticipated) outbreak. Subsequently, these actions are linked to a monitoring system.

8. Specify a dynamic adaptive plan (and validate)
Similar to classic DAPP, the eighth step involves consolidating the results of all previous steps into a dynamic adaptive plan. This involves compiling the selected pathways, actions, and monitoring strategies into a comprehensive plan that outlines immediate and future steps, including who is responsible for each action and how progress will be evaluated. In the context of humanitarian aid, such plans often need validation and approval to secure funding. In the context of the Red Cross, the dynamic adaptive plan will likely be an EAP, that needs streamlining with contingency and response plans, ensuring they are coherent and aligned in terms of triggers and responsibilities. If required, the plans can later be locally adjusted to reflect regional insights and conditions. In such instances, re-approval of the adjusted plans may be necessary.

9. Prepare for early actions
The implementation step in classic DAPP has been divided into a preparation step and an execution step. In this first step of implementation, the groundwork for later action is laid. For the actions in the pathways, all preparations are carried out to ensure readiness for an outbreak.

10. Monitor and execute control measures
The steps of monitoring is combined with the execution of the control strategy, as they take place in parallel. As time progresses, data pertaining to triggers, collected from various signposts, guide the initiation, modification, or expansion of actions in response to this incoming information. Of particular interest are epidemic forecasting and case surveillance. These efforts aim to proactively manage and mitigate the impacts of potential health crises by closely monitoring trends and patterns that may indicate shifts in the trajectory of the epidemic. The monitoring step runs in parallel as a continuous thread throughout all phases of outbreak control.

Preventing outbreaks represents a proactive approach to controlling potential epidemic outbreaks before they escalate. This step consists of taking the actions in the AA plans to mitigate the risk of outbreaks or reduce their impact if they occur. Outbreak control focuses on containing the spread of the disease, providing treatment to those affected, and implementing strategies to prevent further transmission. The strategy is informed by data collected through ongoing monitoring and surveillance, ensuring that actions are evidence-based and tailored to the specifics of the current situation. Over time, or after an outbreak has occured, there may be a need to revisit and repeat the entire DAPP process, ensuring that all plans are current and effectively aligned with evolving conditions.

3.2.4. Evaluation of the DAPP method for epidemic control

We evaluate the effectiveness of the DAPP method for epidemic control by comparing the developed dynamic adaptive cholera control strategy with two classic AA cholera control strategies and the strategy of not taking action. The first classic AA strategy against which we compare is the AA framework used by the Red Cross, which is currently used to develop the first EAP for cholera control in Cameroon. For a detailed description of this framework, we refer to Section 2.2.3. As there is not yet a clear cholera control strategy based on the Red Cross AA framework, we use an expert-based qualitative evaluation that focuses on the application of the DAPP method with requirement engineering. The second classic AA strategy is OCHA's AA protocol for cholera control in the DRC (United Nations Office for the Coordination of Humanitarian Affairs, 2022), detailed in Section 2.2.3. This protocol was chosen because it is currently the only AA protocol developed for an epidemic, and cholera is endemic in both the DRC and Cameroon (Ali et al., 2015). We use a computational framework to conduct a quantitative comparison of our control policy, OCHA's control policy, and the policy of not taking action.

3.3. Computational framework

The quantitative comparison between our proposed policy, the OCHA policy and not taking action, relies on a cholera simulation model. The evaluation's simulation model is developed by researchers from the École des Hautes Études en Santé Publique (EHESP), an institution for public health research and education, and after that extended by us to incorporate dynamic intervention policies. With this setup, it is possible to evaluate a simplified representation of the impact of various intervention strategies outlined in this thesis. Although the model remains unpublished, it is intended for future publication. It represents a significant advance in our understanding of cholera dynamics in Cameroon and provides a vital tool to evaluate the potential efficacy of intervention strategies. We decide to use the model, since its ability to realistically model desease outbreak and population movement greatly enriches our analysis.

3.3.1. Model description

The EHESP researchers have implemented a cholera simulation model that uses the SEIR framework (detailed in Section 2.2.2). It is a stochastic epidemiological metapopulation model designed to simulate the spread of cholera within Cameroon. They have divided Cameroon into several distinct zones, according to administrative boundaries recognized by health authorities. In the model, these zones are interconnected through directed population flows that are estimated using a gravity model, which approximates both the volume and direction of population movements. The EHESP model is set up to simulate the spread of cholera for a predefined number of weeks, during which the population moves between the different compartments of $SEIR$. The model excludes the simulation of mortality. A proportion can initially be placed in $S_{\text{vaccinated}}$, to represent a constant fraction of the population that

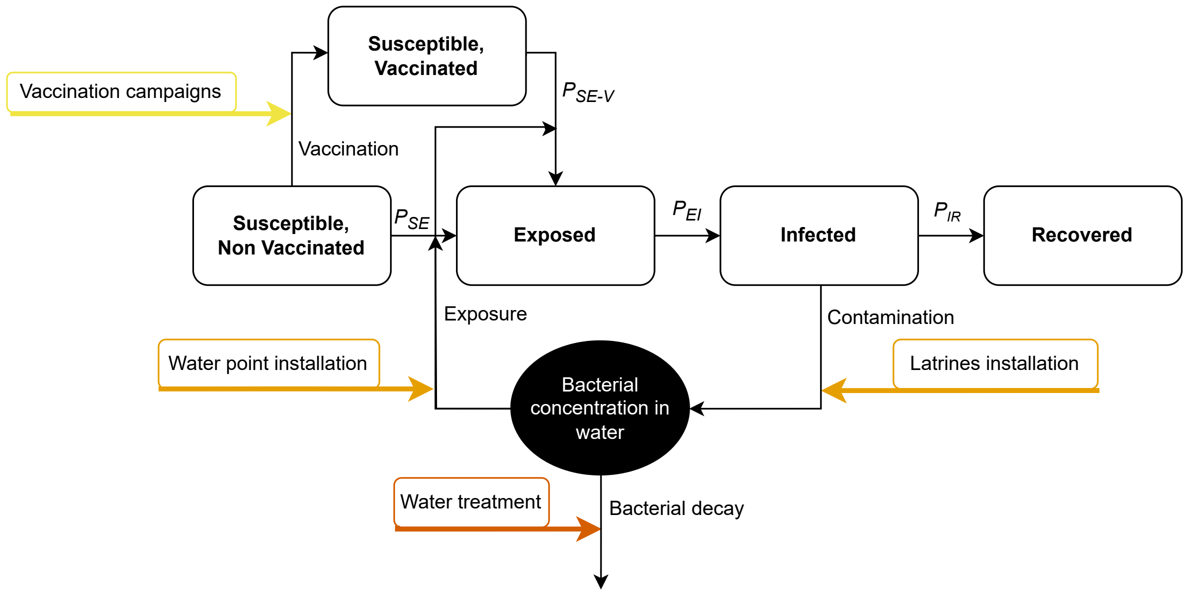


Figure 3.2: Schematic representation of the used SEIR model of cholera transmission dynamics, including the interventions vaccination campaigns, water point installation, water treatment and latrines installation.

is vaccinated. The model reports on the number of cases after the simulation period has ended. This model setup does not allow for a dynamic change in parameters based on the intermediate number of cases, which is required to represent trigger-based intervention policies. Hence, we changed the model to run per week, reporting on all compartments of $SEIR$ and on B. After each week, based on the reporting of the number and location of cases, interventions can be activated or deactivated. Through this extension, it is possible to evaluate the impact of various intervention policies outlined in this thesis. An overview of the model dynamics, including the impacts of the interventions, is shown in Figure 3.2.

Implementation

The model relies on two R libraries to implement state-space models: odin and dust (FitzJohn et al., 2020). With these libraries, R-like code in an odin script that contain the SEIR equations of the cholera model, is automatically transpiled into C++. This C++ code is compiled into a dynamic library with an R interface, which allows computationally efficient simulation (FitzJohn et al., 2020). The model is structured around 58 areas, each with populations distributed across four compartments: susceptible (S), exposed (E), infectious (I), and recovered (R).

Infection dynamics

The dynamics of the compartments S, E, I, R, including mobility between areas, and the spread of the bacterial load (B), are governed by the equations below. We rely on existing research to derive the model parameters that we used in our numerical simulations, as presented in Table 3.3.

The infection rate for area i is given by

$$\text{rate\_SE}[i] = \beta \frac{B[i]}{\kappa + B[i]}, \tag{3.1}$$

which leads to the following probability of transitioning from S to E for area i:

$$p\_SE[i] = 1 - \exp(-\text{rate\_SE}[i]), \tag{3.2}$$

resulting in the following flows for non-vaccinated ($j = 1$) and vaccinated ($j = 2$) individuals:

$$f_{SE}[:, 1] = \text{rbinom}\left(S[i, 1], p_{SE}[i]\right), \tag{3.3}$$
$$f_{SE}[:, 2] = \text{rbinom}\left(S[i, 2], (1 - \text{vaccine\_efficacy}) \times p_{SE}[i]\right). \tag{3.4}$$

Table 3.3: Parameter values used for numerical simulations with reference.

Parameter	Symbol	Value	Reference
Contact rate with V. cholerae in the environment	β	0.1072 day^{-1}	(Collins & Duffy, 2018; Tien & Earn, 2010)
Contribution of each infected person to the population of V. cholerae	ξ	10 cells/ml day^{-1} person^{-1}	(Codeço, 2001)
Rate of leaving the incubation stage	ρ	1/1.4 day^{-1}	(Wang, 2022)
Recovery rate for infected individuals	γ	0.2 day^{-1}	(Codeço, 2001)
Net decay rate of pathogen	δ	0.0333 day^{-1}	(Collins & Duffy, 2018; Hartley et al., 2006; Tien & Earn, 2010)
Half saturation rate of V. cholerae	κ	10^6 cells/ml day^{-1}	(Codeço, 2001; Hartley et al., 2006; Miller Neilan et al., 2010)

To account for infections from other areas, the flows for non-vaccinated (*nv*) and vaccinated (*v*) individuals are defined as:

$$f_{SE\_ext\_nv}[:,] \leftarrow \text{rbinom}\left((S[i,1] - f_{SE}[i,1]) \times \epsilon \times \text{gravity\_matrix}[i,j], p_{SE}[j]\right), \tag{3.5}$$

$$f_{SE\_ext\_v}[:,] \leftarrow \text{rbinom}\left((S[i,2] - f_{SE}[i,2]) \times \epsilon \times \text{gravity\_matrix}[i,j], (1 - \text{vaccine\_efficacy}) \times p_{SE}[j]\right), \tag{3.6}$$

where the *gravity matrix* estimates population flows between areas based on population densities and travel times. The transition rate from E to I, determined by the incubation period, is:

$$p_{EI} = 1 - \exp(-\rho), \tag{3.7}$$

leading to the flow from E to I given by

$$f_{EI}[:,] = \text{rbinom}(E[i,j], p_{EI}). \tag{3.8}$$

Similarly, the transition rate from I to R is given by

$$p_{IR} = 1 - \exp(-\gamma), \tag{3.9}$$

resulting in the flow from I to R given by

$$f_{IR}[:,] \leftarrow \text{rbinom}(I[i,j], p_{IR}). \tag{3.10}$$

These dynamics result in the following transitions for non-vaccinated ($j = 1$) and vaccinated ($j = 2$) individuals:

$$S' = S[i,j] - f_{SE}[i,j] - \begin{cases} \sum f_{SE\_ext\_nv}[i,], & \text{if } j = 1 \\ \sum f_{SE\_ext\_v}[i,], & \text{if } j = 2 \end{cases}, \tag{3.11}$$

$$E' = E[i,j] + f_{SE}[i,j] + f_{EI}[i,j] + \begin{cases} \sum f_{SE\_ext\_nv}[i,], & \text{if } j = 1 \\ \sum f_{SE\_ext\_v}[i,], & \text{if } j = 2 \end{cases}, \tag{3.12}$$

$$I' = I[i,j] + f_{EI}[i,j] - f_{IR}[i,j], \tag{3.13}$$

$$R' = R[i,j] + f_{IR}[i,j], \tag{3.14}$$

$$B' = B[i] - \delta B[i] + \xi \sum I[i,]. \tag{3.15}$$

Data
The model utilizes two key data sets: historical data on cholera cases and population figures, both detailed to the third administrative level. The period covered by the cholera data is 29 October 2021 to 16 July 2023. These data provide a look at where and for how long cholera cases occurred, although under-reporting is suspected. The historic cases were used as a first step in validating the model dynamics. Additionally, population data at the same level of detail help to understand the distribution of the population across these areas. Furthermore, the population density combined with travel times is used to estimate travel flows.

3.3.2. Experimental set-up

We demonstrate the utility of the different policies by examining the results of experimental simulation. In the experiments, all individuals are initially placed in S. One area is randomly selected to introduce the first $1e8$ cholera bacteria. This is an estimate based on historical case data, calibrating the model to recent cholera outbreaks and allowing the generation of realistic epidemiological scenarios. The simulations were conducted across 1,000 iterations, each utilizing a consistent seed to ensure identical outbreak onsets for the tested policies. However, the seed varies between different runs, allowing for a diverse range of scenarios across the tested policies.

Within the experimental framework, certain simplifications have been made. We assume that interventions are implemented at the health zone level, yet in practical scenarios, these actions would occur at a more localized scale, such as within a city. Furthermore, following the findings presented in Table 4.2, we assume that the treatment of individual cases does not influence the overall spread of the disease. As the model does not simulate mortality, treatment has no measurable effect in our experiments. Consequently, our analysis focuses exclusively on the outbreak prevention aspect, and we exclude of oral rehydration points from our simulation, given their association with treatment rather than prevention. To align with the constraints of the simulation model, our experimental framework includes exclusively the scenario that relies on the detection of suspected cases that are indeed cholera, as opposed to climatic events or falsely suspected cases. The model does not simulate observed behaviors, such as the onset of symptoms or the confirmation of the case. Instead, it is designed to simulate the epidemiological dynamics of cholera infections. To bridge this gap and better reflect real-world conditions, we introduce manual adjustments for delay times. These adjustments aim to simulate the observed behaviors that inform our trigger framework. Specifically, while the model initiates simulated control measures at the point of infection, we incorporate a one-week delay to account for the incubation period of the disease and the time required for detection, thereby ensuring a more realistic representation of the disease progression and intervention timeline. Furthermore, we assume that the time between infection and official case confirmation spans two weeks.

Interventions
For the parameter values that simulate the impact of interventions, we rely on existing research, as presented in Table 3.4. Due to limited available local data and limited intervention research, these are estimates that do not take into account local conditions, such as current WASH quality. Due to a model limitation, all actions except water point installation are simulated at the district level, with the installation of water points simulated at the national level. When exploring the effectiveness of vaccination as a preventive measure, we align with the methodology proposed by Mwasa and Tchuenche (2011), which assumes a continuous vaccination campaign. This approach assumes that a predetermined fraction of the population is vaccinated per time frame. We take the same fraction, but we assume a linear progression over 8 weeks to reach their vaccination rate to account for scaling of the vaccination campaign to the district level. For the impact of water treatment on the bacterial decay, we follow Collins and Duffy (2018), and for the impact of water points installation on the exposure rate, we follow the research of Andrews and Basu (2011) and Fung (2014). Evaluation of latrine implementation on the contamination rate presents a more complex task due to the limited quantitative data in existing literature. We base our estimate on research of Bertuzzo et al. (2011), who found a 40% reduction in the contamination rate due to sanitation measures within a month, after which the contamination rate stabilizes. Sanitation measures typically refer to latrines or flush toilets (Fung, 2014). Hence, we use the finding of Bertuzzo et al. (2011) to estimate b. To convert their 40% to a weekly reduction rate, we solve $\xi(1-b)^4 = 0.6\xi$ to $b = 0.12$, and model this decline until achieving a cumulative reduction

Table 3.4: Parameter values used for simulating interventions.

Parameter	Symbol	Value	Reference
Efficacy of vaccine	ϵ	0.58	(Bi et al., 2017)
Vaccination rate	ϕ_i	0.08 week^{-1} up to 0.61 in total	(Collins & Duffy, 2018; Mwasa & Tchuenche, 2011)[b]
Increase in δ due to water treatment	d_i	0.0333	(Collins & Duffy, 2018)
Reduction rate for β due to water points installation[a]	c	0.01 week^{-1}	(Andrews & Basu, 2011; Fung, 2014)
Reduction rate for ξ due to latrines installation	b_i	0.12 week^{-1} up to 0.40 in total	Estimated[c]

[a] Due to model limitations, the installation of water points can only be simulated on the national level, as opposed to the other interventions that can be initiated on the district level, as notated with a subscript in their symbol.
[b] Collins and Duffy (2018) and Mwasa and Tchuenche (2011) use a vaccination rate of 0.07 per day. We use a rate per week, equaling $1.07^7 - 1 = 0.61$.
[c] Bertuzzo et al. (2011) found a 40% reduction in the contamination rate due to sanitation measures within a month, after which the contamination rate stabilizes. Sanitation measures typically refer to latrines or flush toilets (Fung, 2014). Hence, we use the finding of Bertuzzo et al. (2011) to estimate b. To convert their 40% to a weekly reduction rate, we solve $\xi(1-b)^4 = 0.6\xi$ to $b = 0.12$, and model this decline until achieving a cumulative reduction of 0.40.

Table 3.5: Parameter values for simulating scaled-up interventions, based on estimations. We assume that interventions can be escalated every four weeks, with imposed limits to prevent unrealistically high impacts. These estimates, heavily reliant on assumptions, are intended to illustrate the potential effects of dynamically scaling interventions within a cholera control strategy.

Parameter	Symbol	Scaling
Vaccination rate	ϕ_i^s	10% increase per four weeks, up to a rate of 0.80 in total.
Increase in δ due to water treatment	d_i^s	10% increase per four weeks, up to a net decay of 0.1 in total.
Reduction rate for β due to water points installation	c^s	10% increase per four weeks, up to a contact rate of 0.2 in total.
Reduction rate for ξ due to latrines installation	b_i^s	10% increase per four weeks, up to a contamination rate of 5.7 in total.

of 0.40. These impact estimates enable an evaluation of policy strategies, based on both theoretical and empirical foundations.

Furthermore, we explore the option of dynamic upscaling of interventions. To simulate this, we assume that the intervention efforts can be increased every four weeks, with a resulting effect of 10% on the corresponding model parameters, as shown in Table 3.5. To avoid unrealistically high impacts, we impose limits on these effects. Furthermore, for the scaled interventions, we linearly increase the weekly costs. It is important to note that these estimates are largely speculative and are intended to demonstrate the possible impacts of adaptive scaling in a cholera control strategy.

Policy comparison

We analyze the number of cases in each policy, and compare the number of cases averted by the DAPP and OCHA protocols compared to not taking action. In addition to evaluating the number cases averted, a critical aspect of our analysis involves examining the financial cost associated with each strategy. To accurately assess these costs, we refer to the data presented in Table 4.2. Following the action analysis, we assume that the cost associated with the preparation and execution of interventions remains constant on a weekly basis.

Some adjustments to the OCHA protocol have been made to allow for a better comparison. The original OCHA protocol includes 20 low- and high-regret actions, including employee training and mobilization, hygiene promotion, water treatment, and treatment centers similar to oral rehydration points, all of which begin after the protocol is triggered. Our actions vaccinations and the installation of water points and latrines are not part of their protocol, but the total number of their actions is higher, as we limited our research to include only six actions. For the purpose of this comparison, which aims to evaluate the differences between a static and a dynamic adaptive AA protocol, we will proceed under the assumption that both protocols incorporate identical actions. Consequently, we assume that the OCHA strategy uses the actions analyzed in our study and that both the low- and high-regret actions will begin with preparations after reaching OCHA's triggers. Furthermore, the OCHA protocol does not define when the actions are terminated, leading us to assume that the actions are terminated after three weeks without new cases, similar to their initiation period.

4

Results

This chapter outlines the application of the DAPP method specifically for AA strategies in epidemic control, through a case study of cholera in Cameroon. Furthermore, it provides a qualitative, expert-based validation and a quantitative, model-based validation of the adjusted DAPP method and developed protocol.

4.1. Applying DAPP to cholera control in Cameroon

This case study explores the application of the DAPP method adjusted for epidemics to the control and mitigation of cholera outbreaks in Cameroon. Using this method for dynamic adaptive planning, our aim is to improve the resilience of public health systems against the spread of cholera, taking into account the unique environmental, social, and economic challenges faced by the country. We focus the application to the development of AA, but include resilience building and early response for a more fluid approach. The analysis shows how the steps of our adjusted DAPP method, as outlined in Section 3.2.3, were taken to develop a dynamic adaptive control strategy for cholera in Cameroon.

The application of the DAPP framework adjusted for epidemic scenarios aligns with the methodology of the Red Cross for the design of early action protocols aimed at cholera control in Cameroon. However, if our method would be operationalized in the current setup of the RIPOSTE project, the integration of the DAPP approach introduces some complexity due to the various stakeholders involved. During the development phase, the collaboration spans 510 (an initiative of the Netherlands Red Cross), the French Red Cross, the Cameroon Red Cross, and the École des Hautes Études en Santé Publique (EHESP), while the Cameroon Red Cross is responsible for the execution phases of the action plans. This collaborative approach is illustrated in the epidemic DAPP model shown in Figure 4.1.

This case study will focus mainly on the initial seven steps of the framework, in anticipation of a forthcoming field trip to Cameroon. This expedition is expected to provide extensive local information, after which a reiteration of the DAPP cycle is recommended to further refine and enhance cholera control strategies. However, this will exceed the timeline of this thesis.

4.1.1. Current situation and problem analysis

The first two steps of our adjusted DAPP method consist of describing the current situation, objectives, and uncertainties, followed by analyzing the problem with transient scenarios.

Since 1971, Cameroon has experienced recurrent outbreaks of cholera, making cholera endemic (Ateudjieu et al., 2019; Che et al., 2020). In 2016, a political and social crisis unfolded in the Northwest and Southwest regions, leading to widespread displacement, fatalities, and destruction of vital healthcare infrastructure. These challenging conditions may have played a role in the cholera epidemic that afflicted the Southwest Region in 2018 (Kadia et al., 2023). The year 2021 saw another major cholera outbreak in Cameroon, with thousands of suspected cases and deaths, mainly attributed to lack of ac-

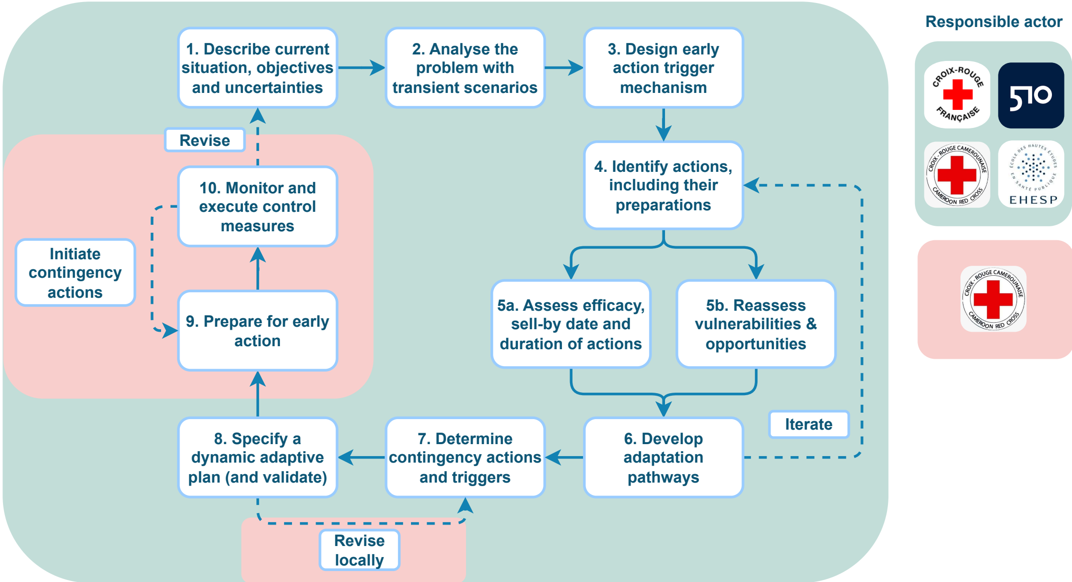


Figure 4.1: DAPP framework adapted to fit the Red Cross framework for developing and implementing an early action protocol for cholera control in Cameroon. The steps in the green box are conducted by the Red Cross France, 510 and EHESP, and the steps in the pink box are conducted by the Red Cross Cameroon.

cess to clean water in affected areas (Musa et al., 2022). The year 2022 brought a different challenge, as floods affected more than 314,000 people in Cameroon, triggering yet another outbreak of cholera, especially in the northern border regions. Contributing to the spread of the cholera-causing agent in these areas are inadequate WASH conditions, limited access to safe water sources, and the lack of adequate healthcare facilities (Musa et al., 2022). A worrying increase in cholera cases has been observed since late March 2023, particularly in the central region. As of June 2023, official reports indicated 19,087 cases, with 1,880 confirmed cases and 450 recorded deaths, indicating a 2.4% fatality rate (ACAPS, 2023). Compounding these challenges, healthcare workers went on strike in June 2023 due to unpaid wages, and a global cholera vaccine shortage has further strained the country's ability to respond effectively to the outbreak. Access restrictions in remote areas also hinder evaluation and containment efforts (ACAPS, 2023).

Cameroon's healthcare system is organized into 179 districts, each serving between 50,000 and 300,000 people (Jarrah et al., 2014). These districts are further divided into 1,673 health zones, known as "aires de santé." Healthcare programs are implemented through district hospitals, with strong support from community participation. The document "Plan National de Réponse à l'Épidémie de Choléra au Cameroun, Août–Octobre 2018" (Ministry of Public Health, Cameroon, 2018) outlines the strategic approach of Cameroon to controlling the outbreak of cholera. The main objective of the plan is to strengthen the coordination of epidemiological surveillance to implement control and prevention measures to better manage epidemic outbreaks. Strategies toward this objective include improved coordination at national and regional levels, capacity building in regions at risk, and mass vaccination. In previous research supervised by 510, it was found that communication disconnect between state and nonstate organizations presents a barrier to effective collaboration (Rachman, 2023). In her research, Rachman found that in the context of an active outbreak, there is a consensus for increased frequency to ensure timely information exchange. The Cameroon government employs dual protocols for surveillance and information sharing, which are dependent on the outbreak status. Variation in frequency is also affected by the organizational level at which information is exchanged (Rachman, 2023). During an outbreak, the Ministry of Health (MoH) of Cameroon anticipates updates from communities and health facilities every three days. However, challenges such as limited capacity, inadequate training, and internet issues often result in the MoH receiving data instead every three days. Combined with a duration of on average 1 week for laboratories to confirm a case (Rachman, 2023), there is a significant delay between the local detection of a suspected case and the official declaration of an outbreak.

Objectives for cholera control by the Red Cross
Within the framework of the RIPOSTE initiative (as detailed in Section 3.1.2), the Red Cross is committed to a proactive approach in the fight against cholera in Cameroon, with a clear objective to prevent and manage outbreaks effectively by use of anticipatory action. This commitment will be realized with the development of an EAP. At the core of this strategy is the early anticipation or detection of potential outbreaks. Timely intervention is critical to stopping the spread of cholera, reducing the incidence of new cases, and lowering the fatality rates associated with the disease. The Red Cross acknowledges the effectiveness of simple and actionable measures that not only curb cholera transmission, but also alleviate its impacts and protect lives (International Federation of Red Cross and Red Crescent Societies, 2022a).

Uncertainties in cholera outbreaks
Identifying the initial location of a new cholera outbreak poses a significant challenge, compounded by various local factors such as conflict-induced population movements or natural disasters such as floods. The source of the initial case often remains uncertain, potentially arising from contact with contaminated water sources, travelers from endemic regions, asymptomatic carriers, or previously undetected infections. As a result, it is highly uncertain in which area of Cameroon an outbreak will occur. Another area of uncertainty revolves around the number of outbreaks expected within the EAP time frame and the capacity to manage multiple outbreaks simultaneously, given the constraints on funding and resources. The rate at which an outbreak might escalate also remains unpredictable. In addition to these forward-looking uncertainties, there are also challenges associated with data reliability, including issues of underreporting (Ganesan et al., 2020) and delays in reporting (Ratnayake et al., 2020). These data ambiguities add another layer of complexity to forecasting and responding to cholera outbreaks effectively.

Epidemic phases
The epidemic phases introduced in Section 3.2.2 and recommended within the DAPP framework for epidemic control, as specified in Section 3.2.3, will be employed. These phases are: “Resilience Building and Monitoring” for periods without an outbreak; “Anticipatory Action” for times with increased outbreak risk; “Early Response” for during an early, small-scale outbreak. These structured phases enable dynamic adaptive control strategies for the evolving nature of epidemic threats, ensuring that interventions are both timely and appropriate to the situation at hand.

Vulnerability assessment
Enhancing our understanding of the cholera problem in Cameroon requires a thorough evaluation of vulnerabilities and opportunities. To initiate vulnerability assessment, examining the geographic distribution of historical cholera cases provides valuable information. Consequently, a map with the distribution of suspected cholera cases and deaths in 2022 is presented in Figure 4.2, which offers an overview of the areas most affected. The figure shows that regions across the north, center, south and west are impacted by cholera, with the Sud Ouest, Littoral, Centre, and Sud regions experiencing the most significant outbreaks. Additionally, the Extreme Nord and Nord regions are affected, but to a lesser extent.

A critical step in the process of identifying vulnerabilities involves examining cholera risks. The heightened probability of cholera outbreaks in Cameroon can be attributed to a combination of factors, including substantial population movements between Cameroon and neighboring countries such as Nigeria, the Central African Republic, and Chad (Ateudjieu et al., 2019). Furthermore, persistent cholera incidents in these neighboring regions, coupled with inadequate access to water, sanitation and hygiene (WASH) services within Cameroon, contribute to increased risk (Ateudjieu et al., 2019). Shockingly, approximately one third of households in Cameroon lack adequate sanitation facilities and there is a shortage of healthcare personnel to meet the medical needs of the population, highlighting the multifaceted challenges the country faces (National Institute of Statistics (Cameroon) and ICF, 2020). In their study, Ateudjieu et al. (2019) conducted an assessment of the preparedness of healthcare facilities in four cholera-prone districts in Cameroon to respond effectively to outbreaks of cholera. The results of the assessment revealed significant readiness deficiencies, which led the study to conclude that these inadequacies in the preparedness of healthcare facilities could hinder their ability to respond efficiently to cholera outbreaks, with the potential to worsen the risks of disease transmission if not addressed.

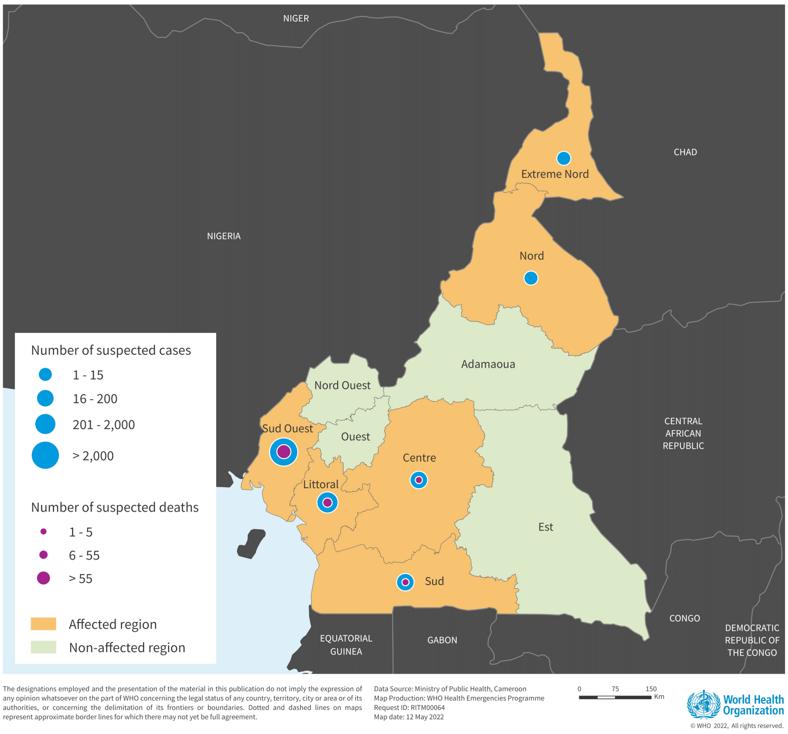


Figure 4.2: Distribution of cholera cases in Cameroon, from 29 October 2021 to 30 April 2022 (World Health Organization, 2022).

In previous research conducted in collaboration with 510, a risk assessment was performed for the Cameroon regions (Ifejube et al., 2023), the results of which are shown in Figure 4.3. The assessment examined the influence of climatic, environmental and socioeconomic factors on a cholera outbreak in Cameroon. The risk factors that were found to be more closely correlated with cholera in Cameroon were precipitation, the amount of surface water in the area, the availability of WASH facilities, and the ratio of population to healthcare facilities.

Opportunity assessment

Part of the problem analysis in DAPP is an opportunity assessment. In our case study, an opportunity emerges with the development of a cholera simulation model by the EHESP. This model, based on the SEIR framework, is specifically designed to reflect the conditions in Cameroon and will serve as a tool for forecasting cholera outbreaks. Subsequently, the model can assess the impact of various prevention strategies, from targeted vaccination to water chlorination. This work lays the groundwork for new approaches that enable real-time epidemiological modeling to inform public health decisionmaking, and can be integrated into the trigger framework in a later stage, outside of the scope of this thesis.

Scenarios of cholera outbreaks

Based on the uncertainties identified in Section 4.1.1, transient scenarios can be developed. These scenarios serve as a basis for understanding the potential variability and dynamics of cholera outbreaks, enabling a more informed approach to planning and control. By examining a range of possible outbreak patterns, including variations in intensity, geographic spread, and timing, stakeholders can better prepare for and mitigate the impact of cholera in affected communities. To streamline the analysis, this thesis builds on the scenario framework established by OCHA for their cholera pilot program in the DRC (United Nations Office for the Coordination of Humanitarian Affairs, 2022), as shown in Figure 2.6 and elaborated in Section 2.2.3. This decision is informed by the endemic nature of cholera in both the DRC and Cameroon (Ali et al., 2015). OCHA's framework distinguishes between cholera-endemic and non-endemic provinces through an examination of high-risk areas. Using this methodology and building on the insights from Section 4.1.1, this study identifies the provinces of Sud Ouest, Littoral, and Centre in Cameroon as cholera-endemic due to their high or very high risk of cholera, as visualized by

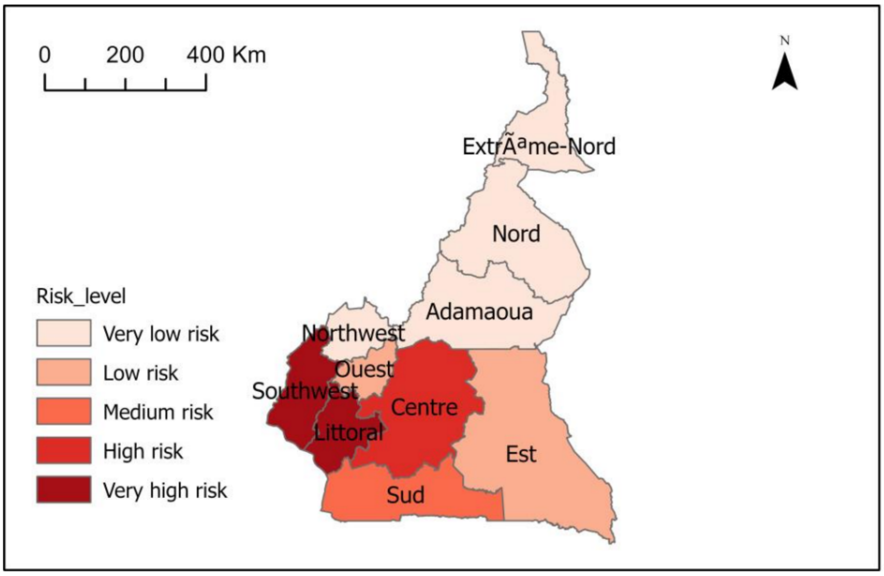


Figure 4.3: Risk map of cholera in Cameroon (Ifejube et al., 2023).

Figure 4.3. Additionally, the provinces of Extreme Nord, Nord, and Sud are classified as endemic due to recent outbreaks, as shown in Figure 4.2. Consequently, the provinces of Nord Ouest, Ouest, Est, and Adamaoua are determined to be non-endemic. We build upon the scenarios outlined by OCHA and introduce sub-scenarios involving a falsely suspected cholera case or the absence of cases in an at-risk area. Consequently, the scenarios we explore are as follows:

1. The identification of a suspected cholera case in a province previously classified as non-endemic leads to two possibilities: (i) the suspected case is tested positive for cholera, and (ii) the suspected case is tested negative. Within Scenario 1.i, the outbreak can vary in size and duration.
2. A forecasted occurrence of an external disruptive event, such as flooding, within an endemic region presents three potential outcomes: (i) a flood, followed by the detection of a suspected and later confirmed (or negated) cholera case, (ii) a flood but the absence of any cholera cases in the area considered at risk, and (iii) the flood does not take place. Within Scenario 2.i, the outbreak can vary in size and duration.

4.1.2. Signposts and triggers

The third step of our adjusted DAPP method is to design an early action trigger mechanism.

Key signs to monitor during the implementation of control plans include case data (such as suspected, confirmed, and negated cholera cases) and flood alerts. These elements will be consistently observed throughout the control efforts. We have chosen for these triggers as they correspond to our previously identified scenarios. Future expansions of this monitoring strategy may incorporate additional external variables, such as warnings of other natural hazards such as heavy rainfall, predictions from the cholera forecasting model developed by EHESP, observed population movement patterns and instances of conflict, to improve the trigger accuracy.

The plan in principle starts in Phase 1: Resilience Building and Monitoring, under conditions of zero reported cases and an absence of elevated risk factors. Note that in places with an active outbreak and reported cases, the plan will start in a later phase.

Triggers for Phase 2: Anticipatory Action
The transition from Phase 1 (resilience building and monitoring) to Phase 2 (outbreak prevention with anticipatory action) is prompted by any one of the following signals:

1. The identification of a suspected cholera case, indicating a potential outbreak.

2. A flood warning or comparable environmental hazard, such as significant rainfall, in an endemic area, which could increase the risk of a cholera outbreak due to water contamination.

Triggers for Phase 3: Early Response
Upon reaching Phase 2, further escalation to Phase 3 can be triggered by:

1. The confirmation of a cholera case, which shifts the response from anticipatory actions to targeted outbreak prevention and case treatment.
2. The identification of a suspected case following a flood, which requires immediate attention due to the heightened risk of cholera transmission in post-flood conditions.

Triggers for transitioning back to Phase 1: Resilience Building and Monitoring
The shift back to Phase 1, focusing on resilience building and ongoing monitoring, is warranted under any of the following conditions. It is important to note that a cautious approach may involve a temporary downscaling to Phase 2 before fully returning to Phase 1.

1. Confirmation that the suspected cholera case was a false alarm, effectively negating the initial cause for concern.
2. The anticipated flood does not materialize, thereby reducing the immediate risk of waterborne disease outbreaks.
3. Post-flood conditions where no new cholera cases have been detected and WASH infrastructure has been fully rehabilitated, indicating the absence of an elevated risk.
4. The absence of new cholera reports over a defined period, such as three weeks, which suggests that the outbreak has been contained. The specific duration should be informed by current conditions and epidemiological insights.

This trigger framework serves as a guideline for making informed decisions. Circumstances may warrant deviations from these suggested triggers. For example, in scenarios where Cameroon is grappling with several outbreaks at once and resources are constrained, prioritizing the management of outbreaks that pose the greatest risk or have the largest number of cases may become necessary.

4.1.3. Action assessment

The fourth and fifth steps of our adjusted DAPP method are identifying actions, including their preparations, and assessing and reassessing the efficacy, sell-by date and duration of actions, with use of vulnerabilities and opportunities.

Action identification
To maintain conciseness, our analysis focuses on a select number of actions, deferring the exploration of a wider set of actions to future studies. 510 and EHESP have identified 18 early post-alert actions for cholera control. From this pool, we have selected five actions that are often used in cholera control. The pre and post-alert preparation needs for each selected action are informed by insights from the Global Task Force (Global Task Force on Cholera Control, 2017, 2019). A summary of these findings is presented in Table 4.1.

Action assessment
Table 4.2 presents an evaluation of the interventions identified in Step 3, detailing their post-alert preparation duration, execution timeline, impact on attack rate and fatatilty rate, sell-by date, and costs. The following section describes the motivation to arrive at these assessments. To simplify the analysis, it is assumed that the interventions have uniform relevance across all three scenarios delineated in Step 2.

The preparation times are derived from the detailed preparatory actions specified in Table 4.1. In particular, the preparation time for vaccinations is subject to the highest level of uncertainty, due to the global shortage of vaccines, which could prolong supply times (Gulumbe & Danlami, 2022). Execution time estimates are informed by internal Red Cross documentation (International Federation of Red Cross and Red Crescent Societies et al., 2023) and assessments carried out by the 510 initiative. Volunteer training, including task allocation and deployment, is expected to last approximately one week. The execution time of the other interventions is ongoing, depending on the scale and available resources.

Table 4.1: Identified actions for the outbreak prevention with AA phase, detailing the sector, action and a description of the action and the corresponding preparation. The actions are selected from an action analysis conducted by 510 and EHESP. The preparations are derived from (Global Task Force on Cholera Control, 2017) and (Global Task Force on Cholera Control, 2019).

Sector	**Action**	**Description of action and preparation**
Strengthening the NS	Volunteer training	*Action:* Conduct identification, briefing, and hands-on training sessions for volunteers, followed by deployment in vulnerable areas. *Preparation:* Before the alert, develop training materials and modules on outbreak prevention before the alert.
Health	Vaccination campaigns	*Action:* Support the execution of preventive and reactive vaccination campaigns, ensuring adequate coverage. *Preparation:* Before the alert, conduct a thorough inventory of existing vaccine stocks and order additional quantities according to projected needs before the alert. Establish cold chain logistics (from 2 °C to 8 °C) in anticipation of the arrival of the vaccine. Following the alert, train volunteers, relocate the vaccines, sensitize the community, and set up a vaccination site.
WASH	Water points and latrines installation	*Action:* Install emergency drinking water sources and latrines, ensuring they meet sanitation and hygiene standards to prevent the spread of disease. *Preparation:* Before the alert, make an inventory of the necessary materials for emergency latrines and water point installation. Following the alert, train volunteers, select strategic locations based on population density and accessibility to reduce transmission risk, and re-locate the supplies for the installations.
WASH	Water treatment	*Action:* Implement water treatment methods at all community and emergency water points, regularly monitor water quality to ensure safety standards are met. *Preparation:* Before the alert, secure a supply of water disinfection technologies (chlorine tablets, filtration units). Following the alert, train volunteers and relocate the supplies.
Health, WASH	Oral Rehydration Points	*Action:* Implement and support Oral Rehydration Points (ORPs) to provide immediate treatment to cholera patients and prevent severe dehydration. *Preparation:* Before the alert, acquire and pre-position supplies, including oral rehydration salts, safe water, cups, and spoons. Following the alert, train volunteers, identify strategic locations and set up the ORPs.

Table 4.2: Assessment of actions including post-alert preparation and execution time, their impact on reducing the attack rate, and associated costs in Central African CFA franc, based on preliminary expert knowledge at 510, internal documentation (e.g. International Federation of Red Cross and Red Crescent Societies et al., 2023), and literature.

Action	Preparation time [weeks]	Execution time [weeks]	Impact on attack rate[a]	Impact on case fatality rate[a]	Sell-by date [years]	Costs [F.CFA]
Volunteer training	0	1	0[b]	0[b]	0	25M
Vaccination campaigns	1	Ongoing[d]	++	++	3[c]	13.5M
Water points and latrines installation	1	Ongoing[d]	+	0	1	18M
Water treatment	0.5	Ongoing[d]	++	0	0	18M
Oral Rehydration Points	1	Ongoing[d]	0	+++	0	12M

[a] 0 no impact, + positive impact, ++ large positive impact, +++ very large positive impact

[b] While volunteer training does not have a direct impact, it is a prerequisite for the implementation of all other interventions.

[c] At least 3 years for two doses, while one dose offers only short-term protection (Bi et al., 2017).

[d] The exact execution time depends on the required scale of the intervention, the available staff, and the severity of the outbreak.

The impact metric is focused on the influence on the attack rate and the case fatality rate, reflecting the primary objectives of the outbreak control strategy. Impact is assessed on a graduated scale, categorized as follows: ‘no impact’ signifies the absence of a measurable effect; ‘positive impact’ indicates a measurable, positive influence; ‘large positive impact’ denotes a significant, positive effect; and ‘very large positive impact’ highlights an exceptionally substantial positive impact. Although volunteer training plays a vital role, its impact on the attack rate and fatality rate is considered 0, as this action by itself does not directly contribute to cholera control. For the other interventions, impact estimates are informed by the literature. Collins and Duffy (2018) indicate that among singular interventions, water purification was found to be the most effective method of reducing infection rates, followed by vaccination efforts. Accordingly, for attack rate we assign a rating of *very large positive impact* for water treatment and *large positive impact* for vaccination. Moreover, Miller Neilan et al. (2010) showed that, within the assessed interventions, vaccines demonstrated the greatest efficacy in reducing infections, closely followed by sanitation measures. Therefore, we deduce that sanitation measures, including the installation of water points and latrines, achieve a *very large positive impact* attack rate score, similar to vaccines. Oral Rehydration Points (ORPs) only impact the fatality rate and not spread of the disease (Guerrant et al., 2003), therefore achieving a *0 positive impact* score on attack rate.

Concerning the case fatality rate, both vaccination and rehydration significantly influence outcomes, although to varying degrees. Rehydration efforts are particularly effective, producing a substantial positive impact on survival rates (E. T. Ryan et al., 2000; Sousa et al., 2020), resulting in a *very large positive impact* rating. Vaccinations also play an important role in reducing fatalities (Sousa et al., 2020), resulting in a *large positive impact* rating.

Furthermore, the interactions between these interventions can be mutually reinforcing, with certain combinations exhibiting a synergistic effect that improves overall efficacy. For example, research by Collins and Duffy (2018) demonstrated that integrating vaccines with water purification efforts significantly amplifies positive effects on the infection rate. However, the exploration of such synergistic relationships remains underexplored in existing literature. Identifying the most effective combinations of interventions for varying contexts is a priority on the Global Cholera Research Agenda (Global Task Force on Cholera Control, 2021), highlighting the need for further research on these dynamic interactions. Given the limited data available on the synergistic impacts of combined interventions, this thesis will analyze each action in isolation.

The concept of a 'sell-by date' is applied to assess the durability and relevance of various interventions in outbreak control. For volunteer training, the sell-by date is effectively immediate (0) due to the need for specific briefing and relocation with each new outbreak. In contrast, vaccination campaigns have a considerably longer sell-by date, extending to more than 3 years. This duration is attributed to the protection conferred by a two-dose vaccination regimen, administered 14 days apart (Bi et al., 2017). Alternatively, a single dose provides short-term immunity, offering an estimated 69% effectiveness within the first year. Therefore, for rapid mass vaccination strategies that use one dose, the sell-by date is shorter. The lifespan of emergency water points such as durable tanks and latrines is estimated at 1 year, although variations may occur based on the quality and durability of the installations. Water treatment interventions are assigned a sell-by date of 0, reflecting the persistent risk of recontamination and the need for ongoing monitoring and treatment to maintain water safety. Similarly, Oral Rehydration Points (ORPs) carry a sell-by date of 0, reflecting that the termination of operation marks the end of treatment provision.

Lastly, the cost assessment of the interventions draws upon recorded expenditure data from a documented cholera outbreak in Cameroon in 2015, as outlined in the 2015 DREF report (International Federation of Red Cross and Red Crescent Societies, 2015), and insights from the cholera contingency planning documents developed by the IFRC and the Canadian Red Cross (International Federation of Red Cross and Red Crescent Societies et al., 2023). This financial analysis is further refined through collaboration with the expertise provided by 510. However, it is important to note that the specific scope and duration of the interventions, which influence these cost estimates, are not fully detailed in the documentation used. In addition, cost variations are anticipated due to fluctuations in the prices of materials. For the purposes of this analysis, we assume that the presented costs represent weekly expenditure, and we approximate the initial setup or preparation costs to be similar to the ongoing weekly costs. It is important to acknowledge the provisional nature of these cost estimates, emphasizing the need for a more comprehensive cost analysis and adjustments based on localized cost assessments and empirical data.

Regret classification and cost-effectiveness

The interventions can divided into low- and high-regret categories based on their operational lifespan, as indicated by their sell-by dates, shown in Table 4.3. Actions with non-zero sell-by dates, such as vaccination campaigns and the installation of water points and latrines, are categorized as relatively low-regret measures. This classification stems from their potential to confer lasting advantages that could extend into subsequent outbreak scenarios. However, it is important to acknowledge that these actions are not entirely devoid of regret. If a cholera outbreak does not materialize before the sell-by date, the efforts and resources invested in these actions would have been spend in vain. Conversely, water treatment and oral rehydration points, due to their immediate and discontinuous nature, fall into the category of high-regret, particularly in scenarios where an anticipated outbreak does not materialize, rendering their impact negligible. For these actions, the resources had better be used elsewhere, where there are infections. An exception to this line of reasoning is volunteer training. Despite its rapidly diminishing effectiveness, it remains a critical prerequisite for subsequent initiatives. Consequently, it is categorized as a low-regret action.

The efficacy assessment can be further informed by comparing the estimated impacts with the costs. As shown in Table 4.2, of the low-regret actions vaccination campaigns stand out for their higher cost-effectiveness, attributed to their larger impact and relatively lower costs compared to the installation of water points and latrines. The efficacy analysis of high-regret actions depends on the deemed importance of attack rate reduction versus case fatality rate reduction. If these impacts are considered equally important, then oral rehydration points are more efficacious due to their significant effect on reducing fatalities. These insights are important in guiding decisionmaking in subsequent steps, particularly when prioritizing interventions. Moreover, it may be relevant to recall the synergistic effect observed between water treatment and vaccination efforts (Collins & Duffy, 2018), which may influence the action selection.

Reassessment of vulnerabilities and opportunities

For future studies, or following the field visit to Cameroon, exploring the distinct requirements of local regions becomes relevant, especially in contexts marked by conflict or inadequate health infrastructure.

Table 4.3: Regret classification of the actions based on their sell-by date.

Action	Sell-by date	Regret classification
Volunteer training	0	Very low[a]
Vaccination campaigns	3	Very low
Water points and latrines installation	1	Low
Water treatment	0	High
Oral Rehydration Points	0	High

[a]Although the effectiveness of volunteer training diminishes quickly, it serves as an essential foundation for subsequent actions. Therefore, it will be treated as a low-regret action.

This inquiry aims to refine the selection of actions to better align with the unique challenges faced, as reflected by vulnerabilities and opportunities. In particular, the regret classification may change based on local vulnerabilities. However, the current selection of proposed actions shows positive outcomes in both impact metrics, eliminating the need for immediate reassessment of vulnerabilities in response to these measures. Furthermore, the implementation of these actions does not alter or negate the previously identified opportunities, maintaining the strategic landscape as initially assessed.

4.1.4. Pathways

The sixth step of our adjusted DAPP method is to develop adaptation pathways.

Following the steps outlined previously, we develop adaptation pathways. As a first step in this process, we identify actions for Phase 1: Resilience Building and Monitoring, Phase 2: Anticipatory Action, and Phase 3: Early Response, according to how regrettable they might be if not needed. Given its high potential for regret, the treatment of water sources and the setup of ORPs are allocated solely to Phase 3. Conversely, vaccination campaigns and the establishment of water points and latrines, which carry relatively lower-regret risks, are deemed suitable for both Phase 2 and Phase 3. Within the scope of actions examined, none are identified as completely no-regret and could be included in Phase 1. Hence, we define a pathway consisting of unspecified resilience building activities, combined with monitoring.

The subsequent step involves constructing an adaptation pathways map for the scenarios outlined in Section 4.1.1. These maps are visual tools designed to clarify and guide the complex process of planning and executing actions in the face of potential cholera outbreak scenarios. On the map, each ‘line’ delineates the progression of an action, segmented into a dotted line for its preparatory phase and a solid line for its active implementation phase. ‘Triangles’ on the map signal the input of case data, indicating the moment when a case is suspected, confirmed, or negated. Actions are vertically organized by their associated level of regret, which evaluates their suitability in circumstances where an outbreak does not materialize. The timeline is marked in weeks, with the emergence of a suspected case marking week 1. Following the initial preparation for each action, a weekly review is conducted to consider scaling down actions as the situation stabilizes or resolves.

The duration of the preparation of actions is informed by the analysis presented in Table 4.2. The estimated median incubation period for cholera is a brief 1.4 days (Azman et al., 2013; Wang, 2022). However, there is expected delay before the case is reported to health facilities, whether by Red Cross volunteers, through community surveillance, or by patients themselves. In three reported cholera outbreaks in Cameroon, Ratnayake et al. (2020) observed an average delay of 5 days from symptom onset to detection, aligning with the median delay in all outbreaks studied. Consequently, we assume that infection occurs in week 0, with the identification of a suspected case designated as the start of week 1, from which we measure epidemic weeks. The interval from suspected to confirmed case is projected to be about 1 week. This is conservative compared to the rapid 2-day confirmation time seen in the studied Cameroonian outbreaks, but it accounts for a median 6-day delay reported across multiple outbreaks (Ratnayake et al., 2020). We estimate a lead time of 1 week from flood warning to occurrence, as analyzed by Coughlan de Perez et al. (2016). However, this estimate should be updated to reflect the latest forecasting models available for Cameroon. Lastly, actual events may unfold more rapidly or slowly than estimated in this thesis. To accommodate this variability, the adaptation pathways must be reviewed and potentially revised during weekly evaluations.

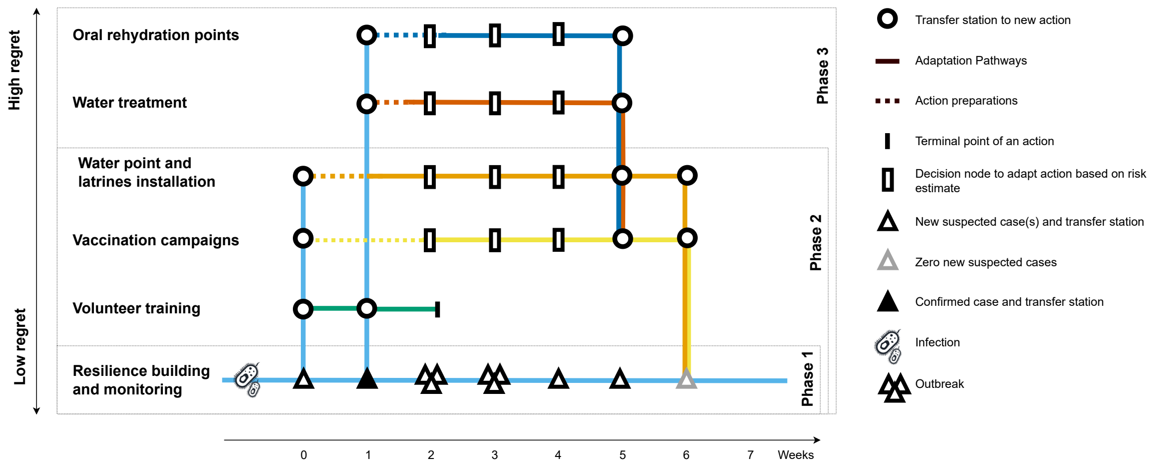


Figure 4.4: Adaptation pathways map corresponding to Scenario 1.i., which begins with the identification of a suspected cholera case and is followed by the laboratory confirmation of the case. Actions are sorted according to their level of regret and organized into three distinct phases of epidemic response: Phase 1 encompasses resilience building and monitoring; Phase 2 involves anticipatory action; and Phase 3 is dedicated to early response measures. Color-coded lines delineate the progression of actions within each phase. Dotted lines indicate the preparatory stages of actions, while solid lines denote the active implementation of measures. Transfer stations, marked by circles, triangles and rectangles, allow for adjustments in control strategies, either escalating or de-escalating actions across phases, contingent on risk estimates and evolving data such as new suspected or confirmed cases.

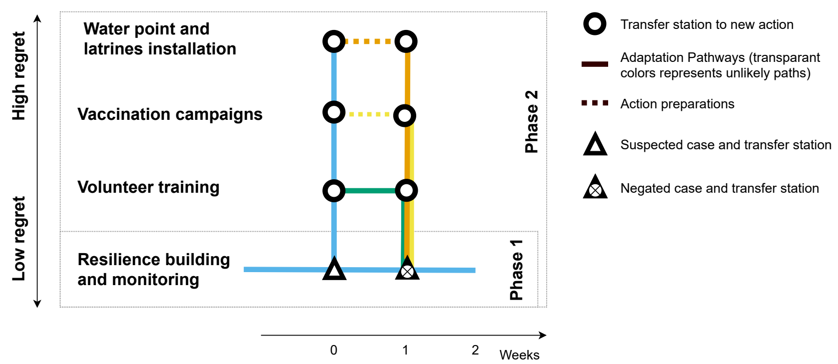


Figure 4.5: Adaptation pathways map corresponding to Scenario 1.ii., that starts with the detection of a potential cholera case. It further depicts the process flow where the initial suspicion is subsequently disproven by laboratory testing, resulting in the negation of the case and termination of preparations.

Scenario 1: Identification of a suspected case

The first scenario outlined in Section 4.1.1, Scenario 1.i, unfolds with the detection of a potential cholera case in the first week, progressing to the laboratory's confirmation of the case by the second week. This sequence is depicted in the adaptation pathways map (Figure 4.4), showcasing the strategic control strategy. The scenario begins in Phase 1 with the detection of a suspected case, triggering immediate volunteer mobilization and setting up for Phase 2 activities. Concurrently, the groundwork for Phase 3 actions is started as soon as the case is confirmed, which may coincide with ongoing Phase 2 preparations and activities. Overlapping of tasks is anticipated; for example, while volunteers are being trained, resources are being assembled for installing water points and latrines to ensure readiness for installation in the following week. Vaccination preparations follow a similar pattern, with vaccines being transported during volunteer training sessions, allowing trained volunteers to assist with finalizing the campaign setup once finished with their training. Decision points from week 4 onwards provide opportunities to scale down the actions or adjust the pathways to accommodate any unforeseen delays in preparation.

Scenario 1.ii starts in the same manner as Scenario 1.i, with the initial identification of what is believed to be a cholera case (Figure 4.5). However, this scenario diverges when laboratory results later reveal that the suspicion was unfounded. In such an event, the preparatory actions for Phase 2 activities are rendered unnecessary and are therefore terminated. Time and effort must then be allocated to efficiently conclude any unfinished tasks and redistribute the resources that were allocated for the anticipated outbreak control efforts.

Scenario 2: Flood warning

Scenario 2.i is initiated by a flood warning in an endemic region, prompting the immediate commencement of volunteer training, as depicted in Figure 4.6. As the flood unfolds, early preventive measures, including the installation of water points and latrines, are set in motion to mitigate potential health risks. Concurrently, around the time of the first signs of infection, vaccination campaigns are ready to be launched. In this scenario, the first infections are illustrated to appear within the first days after the flood, although the timing could vary depending on the region's endemic levels. Given the elevated risk of an outbreak, preparations for Phase 3 actions begin at the first sign of a suspected case, rather than awaiting confirmation. Should this suspicion later be disproved, Phase 2 measures may either persist in anticipation of future cases or conclude as outlined in Scenario 2.ii. Upon activation, the interventions follow a similar course to Scenario 1.i, with a similar flexibility for adjustments based on the changing dynamics of the situation.

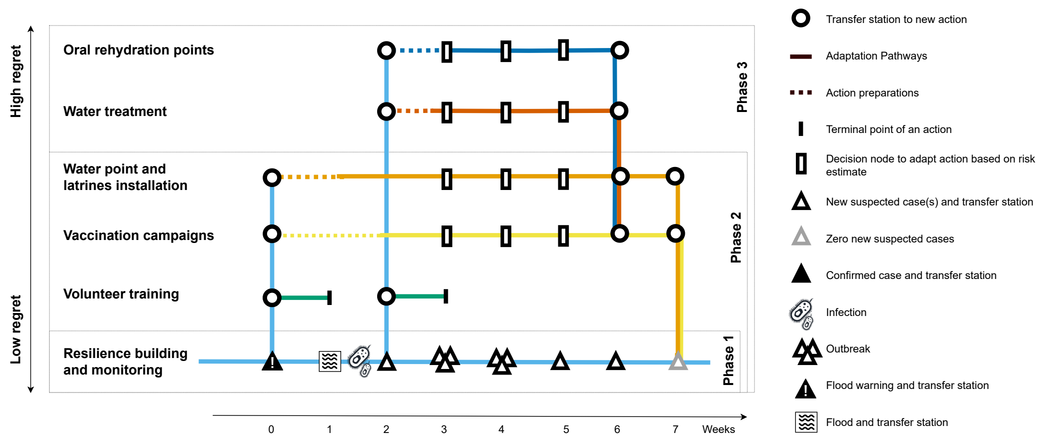


Figure 4.6: Adaptation pathways map outlining the sequential events and pathways for Scenario 2.i, initiated by a flood warning. It details the subsequent stages including the occurrence of the flood, detection of a cholera infection, and the confirmation of the case. The map visually represents the structured control timeline, indicating the critical interventions and decision points following each event in the scenario.

In Scenario 2.ii, although a flood occurs, it is not followed by a cholera outbreak (Figure 4.7). Initially, the absence of infection in the aftermath of the flood is uncertain, as historical data indicate that post-flood cholera outbreaks can manifest several weeks later. Jutla et al. (2017) highlight that while the immediate risk of cholera post-natural disaster is generally low, it will escalate without sufficient control measures, namely access to clean water, improved sanitation, and hygiene practices. Therefore, it is recommended to maintain Phase 2 interventions for an extended period after flood, even in the absence of reported cases, until WASH facilities are adequately restored. This scenario underscores the possibility that diligent execution of Phase 2 actions could effectively prevent an outbreak.

In Scenario 2.iii, the expected flood does not materialize. Although this scenario is not depicted visually, the control strategy aligns closely with that of Scenario 1.ii.

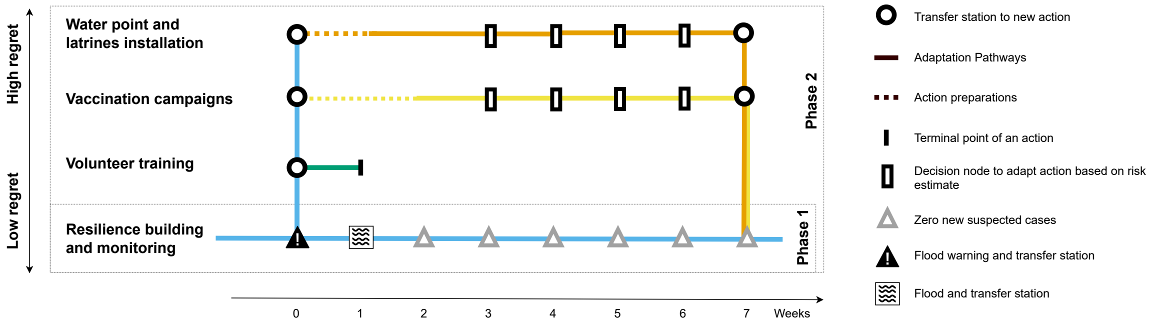


Figure 4.7: Adaptation pathways map outlining the control strategy for Scenario 2.ii, initiated by a flood forecast and followed by the flood's materialization. The scenario culminates without the outbreak of a cholera infection, illustrating the termination of proactive and reactive measures undertaken due to the non-occurrence of a cholera outbreak post-flood.

4.1.5. Contingency actions and triggers

The seventh step of our adjusted DAPP method is to determine contingency actions and triggers.

Contingency actions serve as an integral component of the DAPP framework, designed to provide flexible and rapid control when faced with unexpected developments or when initial strategies prove insufficient. Given the unpredictability of cholera outbreaks and the dynamic nature of environmental and societal factors in Cameroon, developing a robust set of contingency measures is essential for ensuring the resilience and effectiveness of the overall cholera control strategy. On a weekly basis through the decision-points, it can be chosen to activate contingency actions. These actions may be triggered by various challenges, such as an unexpected rise, stagnation, or persistent increase in cholera cases, complications in logistics and supply chains, environmental and political instability, natural disasters and famine, as well as issues with underreporting and public resistance to implemented measures. Given these potential challenges, the following contingency actions are proposed, guided by insights from Global Task Force on Cholera Control (2017) and informed by the analytical groundwork laid in earlier sections of this study.

1. *Upscaling of Actions*: Increase the efforts of actions through upscaled volunteer employment, supply provision and other necessary resources. Trigger: This measure is initiated based on the discrepancy between targeted and actual case reduction outcomes.

2. *Stockpile and Pre-position Supplies:* Establish strategic stockpiles of critical supplies, including cholera vaccines, rehydration solutions, and water purification materials, in key locations. Trigger: Initiate this action when monitoring indicates a supply shortage or when consumption rates accelerate, suggesting potential supply depletion.

3. *Enhanced Surveillance and Data Analysis:* Intensify surveillance efforts to detect and analyze cholera case trends in real-time. Leverage mobile technology and community reporting to enhance data collection and dissemination. Trigger: This measure becomes necessary when there is evidence of significant underreporting or when unusual patterns in transmission are detected, indicating a potential outbreak escalation.

4. *Community Engagement and Education Campaigns:* Amplify community engagement efforts, focusing on educating the population about cholera prevention, symptoms, and the importance of seeking early treatment. Trigger: Activate this approach upon identifying areas of resistance towards recommended preventive actions or health guidelines, to ensure community-level compliance and support.

5. *Enhanced Collaboration*: Strengthen response efforts through increased coordination among organizations, leveraging shared resources, knowledge, and expertise. Trigger: Activated in situations of logistical challenges, supply shortages, or when facing environmental, political, or societal crises that impede standard intervention strategies. Climate change, urbanization and population growth could be additional triggers, as these are anticipated to increase the risk on cholera.

4.1.6. Planning, implementation and monitoring

The eighth, ninth and tenth steps of our adjusted DAPP method are the specification and validation of a dynamic adaptive plan, the preparation for early action, and the monitoring and executing control measures. If necessary, contingency measures are taken.

Following the exploratory mission to Cameroon, a dynamic adaptive plan will be developed, synthesizing insights from all preceding phases. This comprehensive plan will guide the preparations and subsequent enactment of the protocol's directives. In addition, it is vital to monitor cholera incidences alongside flood alerts, allowing proactive measures to emerging threats. In the final stage, it is imperative to assess the suitability of initial strategies. Should these strategies prove insufficient, the implementation of contingency measures will be crucial for enhancing control effectiveness and ensuring adaptive improvements.

4.1.7. Recommendations for revisiting the DAPP Cycle

The scheduled field trip to Cameroon represents a critical opportunity to gather nuanced understandings of the challenges and strengths within local health systems, community resilience, and the effectiveness of existing cholera control measures. In light of this, the following recommendations are made for the Red Cross upon returning:

1. *Evaluation of initial assumptions*: The assumptions and conditions that underpinned the initial adaptation pathways and actions should be reassessed in the context of observations and data collected from the field. This may involve validating the effectiveness of identified actions, the accuracy of risk assessments, and the perceived levels of community engagement and awareness.
2. *Incorporation of local insights:* Insights regarding local healthcare infrastructure, community behaviors, water and sanitation practices, and logistical challenges encountered in the field should be directly incorporated into the DAPP cycle. This may lead to the identification of new actions, modification of existing ones, or reprioritization of interventions based on their feasibility and potential impact.
3. *Adjustment of pathways and triggers:* Based on updated insights, the adaptation pathways, early action trigger mechanism, and contingency plans should be reviewed and adjusted as necessary. This may involve refining the criteria for early action triggers, introducing new signposts based on local risk factors, and updating contingency plans to address unforeseen challenges.
4. *Enhanced focus on resilience building:* Special attention should be given to strengthening the resilience-building phase of the DAPP cycle, leveraging local capacities, and addressing identified gaps in infrastructure, knowledge, and resources. This could involve targeted investments in WASH infrastructure, community health education programs, and capacity-building for local health workers.

4.2. Evaluating the effectiveness of DAPP compared to classic AA

In this section, we evaluate the effectiveness of the DAPP method for epidemic control and the protocol for cholera control proposed in this thesis. Our evaluation contrasts the DAPP approach with classic AA strategies. This comparison aims to test the ability of DAPP in helpin develop a more efficient and effective control strategy to the evolving challenges posed by cholera. We first present a qualitative expert-based comparison where we compare our method and protocol to the conceptual Red Cross AA framework for cholera, followed by a model-based comparison where we compare the DAPP-informed cholera protocol to OCHA's cholera protocol.

4.2.1. Qualitative comparison

To validate our proposed method for decisionmaking in cholera control, we have evaluated our problem analysis, solution requirements, and proposed solution with two humanitarian experts from 510. Notably, one expert, having recently returned from a field mission in Cameroon, provided valuable insights into the practical applicability and potential local adaptation of our approach. In the evaluation, the humanitarians compared the proposed DAPP method and results with the AA framework used by the Red Cross to develop an EAP for cholera control. To facilitate expert dialogue, we first presented the adjusted DAPP method, and then discussed our problem analysis, solution requirements, and proposed solution. In this section, the main findings of the expert validation are presented. The setup of the validation and the questions used to guide the expert dialogue are shown in Appendix B.

Problem analysis
The following two findings of the problem analysis were discussed.

- *Predicting and controlling cholera outbreaks is difficult because we can not foresee when, where, or how quickly they will happen. Static, rigid plans that set out actions too strictly do not offer enough flexibility to adjust as needed.*
- *At the start of a potential outbreak, when someone shows symptoms of cholera but it has not been confirmed, there is uncertainty about whether it is actually cholera. To avoid misusing resources, no steps are taken yet, other than laboratory testing. However, during this waiting period, valuable time is lost. Furthermore, there remains uncertainty about the size of the outbreak, as there is under-reporting.*

They agree with the first statement. There are very limited data or indicators that can be used to design trigger models that do not trigger too often and that do not give many false triggers. As funds are limited, it is challenging to trigger only for the most severe outbreaks, but to do so while it is still in a very early stage. Ideally, they would like to include climate and seasonal data, such as weather patterns and temperature, to inform triggers. There is a high uncertainty involved, which does not fit the current setup of AA planning at the Red Cross, which tries to avoid acting in vain. Regarding the second statement, indeed, the Red Cross often reacts too late, waiting for a confirmation while the outbreak is already growing. In Cameroon, the Ministry of Health reports official case numbers quite late. Sometimes, the local NS has community-based surveillance information from their own Red Cross volunteers earlier than from the government, but then they still wait for official numbers. They raise the additional problem that the Ministry of Health is currently the initiator of action for the Cameroon NS, through an official letter. Then, after that, funding has to be requested from the IFRC. These structural approvals result in further delays. However, the humanitarians estimate that it is possible to do some regional and smaller activities with volunteers already in the area, but a coordinated response or a request for funds from the DREF requires government approval.

Solution requirements
The following two solution requirements were discussed.

- *We need a flexible cholera control plan that can easily adjust to the situation. This means doing more or less depending on the outbreak's severity.*
- *The plan should also include actions that we can take even when we are not sure if it is a cholera outbreak yet. These early actions can be advantageous regardless of the outbreak's confirmation.*

They strongly agree with the solution requirements. There is a need for flexibility, as there is a risk involved with triggering correctly. This has not yet been incorporated into the Red Cross AA framework. They also recognize the value of low-regret actions. Typically, in AA protocols at the Red Cross, there is a strong focus on actions that are quick to implement. However, they agree that low-regret actions should be prioritized when there is still a high level of uncertainty about the size of the outbreak. As an additional requirement, they name the operational requirement of distinguishing anticipatory action from response, because for response there are different stakeholders involved. In particular, during the outbreak response, other NGOs are also taking action. More generally, stakeholder involvement during the DAPP cycle was listed as an important requirement, as it is common practice in humanitarian aid to collaborate on the response.

Proposed solution
The proposed solution was discussed, which includes the adjusted DAPP method and the resulting plan, complemented by the pathway maps as shown in Figures 4.4 and 4.6.

We have adjusted the DAPP method to fit the context of epidemic control. By following the steps of the method, we developed a flexible plan for dealing with cholera outbreaks that looks like a map. It lists out steps we can take as the situation changes, starting with low-regret actions and moving to high-regret actions if needed. The plan includes how long each step will take to set up. Every week in the plan, shown as squares on the map, we can decide whether to do more or less, based on what is actually happening with the cholera outbreak.

We first discussed whether, reflecting on the DAPP method and application, any steps, uncertainties, or actions were overlooked. A limitation of this research is that we analyze a limited number of actions, but it was confirmed that the chosen actions were indeed all mentioned as important in by Cameroonian humanitarians. They mentioned that the preparation durations depend on the local situation, such as the local vaccine stockpile, and might need to be updated. Regarding triggers, in this work, suspected case and flood triggers have been analyzed. 510 is also considering triggering when a neighboring district is facing cases, and at a later stage, also seasonality and climate events. The weekly decision points were considered useful, but they thought that in reality these might be more frequent than weekly in the midst of an outbreak, such as every one or two days, and weekly in periods without an active outbreak. Hence, a varied spacing between the decision points would be more realistic. Lastly, more focus could be given to the starting points of the actions, after the preparation is finished, as this represents a very important moment in time for AA.

Regarding the complexity and utility of the pathways, they think that the pathway maps are not very intuitive and are not convinced that they are currently clear enough to be used by the Cameroon NS. Furthermore, they expect the pathways to become more complicated with a larger number of actions. In the AA framework of the Red Cross, the simplicity of diagrams is very important because protocols are often developed by humanitarians who are different from those who execute them on the ground. A suggestion they had was not to have all the information in one diagram, but instead to break it down into smaller parts and build up the scenarios in a storytelling approach. In addition, they would like to see more clearly what informs the decision points. Operationally, concerns were expressed that making flexibility and weekly decision points mandatory could increase workload rather than providing clear tasks, as is the aim of the Red Cross AA protocols. The suggested approach could also be perceived as restrictive if it diverges from their existing workflow. We agreed that the pathways should be tailored to the current organizational processes of the end users and support their way of working rather than making it more complicated. To do this, close stakeholder involvement is required during the development of the pathways. In Cameroon, the ongoing evaluation of the control strategy is considered very important. This is something the Red Cross AA framework does not currently facilitate, as the Red Cross only evaluates the protocol after the plan is fully implemented. Hence, if framed as such, the weekly decision points in the DAPP approach as evaluation points are expected to be well received. They concluded that if the pathways were adequately tailored to local support needs, they would help in decisionmaking for cholera control. In particular, they think the pathways would be useful for training people for outbreak control and to show how they can be flexible in that.

Fulfillment of requirements

They fully agree that the plan developed with the DAPP method meets the flexibility requirement and they believe that the decision points encourage to consider frequently whether things need to be changed. Furthermore, they consider low-regret actions very valuable for anticipatory action planning at the Red Cross. However, the additional requirement of strong stakeholder involvement was not met in the scope of this research. Although the French NS, the Dutch NS, 510, and EHESP were involved, the Cameroon NS was not. The humanitarians think that this would be needed to apply the DAPP method and the pathways in real life. As a consequence, they view this research as a strong exploration and development of DAPP for epidemic control, but not yet fully ready for practical operationalization.

Future applications

The presented pathways focus on the onset and the first weeks of the cholera control strategy, to inform the EAP and connect to the early response stage. However, the humanitarians also showed interest in combining anticipatory action, response plans, and contingency plans more broadly in the pathway maps. This would create an overview of all the actions that are carried out, although by different stakeholders and from different budgets, allowing for synergy between these actions. The humanitarian sector is thinking about ways to integrate disaster risk reduction with response and development, as these are currently very siloed approaches in terms of planning, responsibility, and finances. They expect that adaptation pathways could help guide this process. They added that the pathways could also help in technical discussions with funding agencies to negotiate the combining of funds and to be more flexible with that.

Reflecting on the DAPP process and its usefulness within 510, they see value in following this process for the development of EAPs. During the past few months, DAPP has prompted them to think more critically and broadly about uncertainties and scenarios. In particular, they would include the concept of check points, low-regret actions, and the flexibility to change the approach in their EAPs. However, they cannot be completely free in these changes because they have to comply with the requirements of the IFRC for EAPs. Furthermore, they see opportunities to apply DAPP in their product development. They have developed an impact-based forecasting model that now relies on a single trigger, which they want to integrate with more general risk assessments. They expect the pathways to guide streamlining preparatory actions, risk-based triggers, and actions. On a more general note, they were interested in an internal presentation to further introduce the DAPP method within 510 and learn from its principles. They consider the method and pathways clear enough for their colleagues to understand, who can then apply it in their work when advising humanitarians on the ground.

Main findings
The evaluation of our DAPP method against the AA framework by humanitarian experts from the Red Cross highlighted its potential to improve cholera control, but also showed where refinements are needed. The experts agreed on the need for a flexible control plan, appreciating the DAPP method's focus on dynamic adaptiveness and low-regret actions in uncertain stages, recognizing that the current AA protocols are very static. However, they expressed concerns about the complexity of the pathway maps and suggested simplifying them for better field applicability. The experts emphasized the importance of closely involving stakeholders, particularly local ones such as the Cameroon NS, to ensure that the DAPP approach is practical and aligned with real-world needs. Looking ahead, there is interest in broadening the application of the DAPP method to integrate disaster risk reduction with response and development strategies. This could facilitate more flexible AA strategies and improve the efficiency of humanitarian interventions. In summary, while the DAPP method was seen as a promising tool for cholera control, refining its usability and ensuring stakeholder involvement are important steps for its practical deployment and effectiveness in humanitarian settings.

4.2.2. Model-based comparison

To compare the effectiveness of the two policy approaches quantitatively, we use a simulation model developed by EHESP researchers, which we extended to allow testing of dynamic interventions. It is a stochastic epidemiological metapopulation model that uses the SEIR framework, designed to simulate the spread of cholera within Cameroon. The model parameters can be found in Table 3.3, the intervention parameters in Table 3.4, and the conceptual framework, including the description of the model and the experimental setup, can be found in Section 3.3. The simulations ran for a span of 26 weeks, with findings averaged over 1,000 iterations.

Policies
As a comparative policy, the OCHA AA protocol for cholera control in the DRC was chosen (United Nations Office for the Coordination of Humanitarian Affairs, 2022), as well as the protocol of not taking action. The OCHA protocol's pathway for the scenario of a suspected case that is later confirmed, is illustrated in Figure 4.8, while the pathway for the DAPP protocol under the same scenario is depicted in Figure 4.4. Although depicted in these diagrams, Oral Rehydration Points are not simulated as an intervention because we assume that they do not affect the dynamics of our simulation model (refer to Section 3.3.2). A comparative analysis between the protocol proposed in this thesis and the OCHA protocol is summarized in Table 4.4.

For the implementation of our DAPP-informed cholera control strategy, we employ a trigger mechanism as detailed in Section 4.1 and summarized in Table 4.4, and weekly decision points that follow the four-weekly upscaling of parameters as outlined in Table 3.5. The observations in the model serve as triggers for starting certain actions. Once an individual has been infected, it is assumed that one week later the case is detected, at which point the volunteer training and preparations for the low-regret actions start. It is assumed that one week later the case will be confirmed. At this point, preparations begin for the high-regret actions. As soon as the preparations are finished, the action is 'active', and starts affecting the model dynamics with an additional one-week delay, reflecting the necessary time for the impact to fully materialize. From this point forward, the situation is monitored weekly. We assume that it is operationally possible to increase the scale and intensity of an intervention every four weeks. Consequently, once an intervention has been in effect for four weeks, the need for escalation is evaluated weekly. For the sake of simplification, the occurrence of new cases serves as the only criterion for scaling up. To simulate this upscaling, we alter the intervention parameters as detailed in Table 3.5. If there are no new cases for a period of one week, the interventions are stopped and the model reverts to monitoring, remaining in a state of readiness for the next trigger.

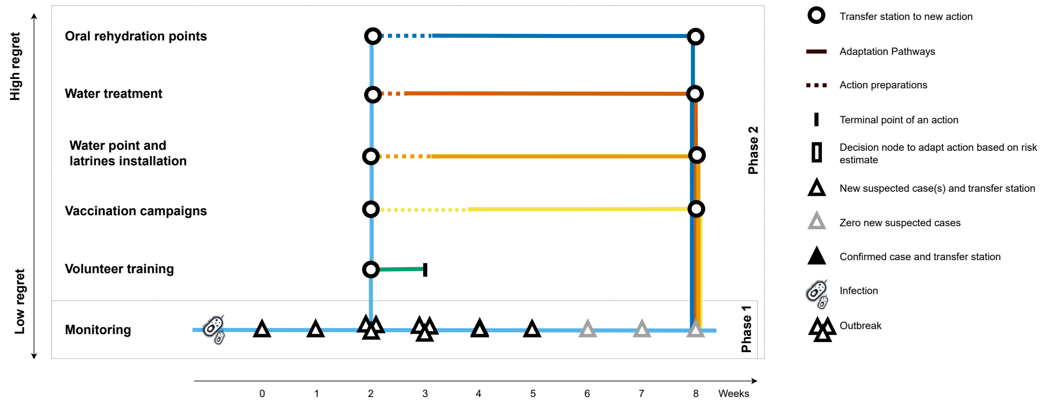


Figure 4.8: Pathways map corresponding to OCHA's protocol to scenario 1.i., that starts with the detection of a potential cholera case. After an increase in cases for three weeks, the volunteer training and action preparations are started. In week 8, no new cases have been reported for three weeks and all actions have been terminated.

We use the static protocol for cholera control of OCHA as a benchmark in our analysis, summarized in Table 4.4 and visualized in Figure 4.8. Unlike our dynamic protocol, which differentiates between actions based on their level of regret, the OCHA framework applies uniform delay times to accommodate uncertainties inherent in epidemic control. In this framework, the trigger for action is activated upon detection of new cases in a health zone for three successive weeks. Consequently, training and preparatory activities begin three weeks after the first infection. The termination of the strategy follows a three-week period without new cases.

Comparison of the policies

Our simulation results offer a comparative analysis of three distinct approaches: the DAPP protocol, the OCHA protocol, and a no-action protocol. The main performance metrics, shown in Table 4.5, illustrate the effectiveness of each protocol in mitigating the impact of the simulated scenario on various key performance indicators (KPIs). The analysis shows that implementing the DAPP protocol results in a significantly reduced number of cases compared to scenarios without any protocol. Although the OCHA framework also decreases the incidence of cases compared to having no protocol, it still results in 1.7 times more cases than the DAPP protocol. Additionally, the DAPP protocol achieves higher vaccination rates in fewer weeks. This efficiency comes from the ability of the protocol for up-scaled vaccination, resulting from the flexibility at weekly decision points to adjust the scaling as needed. When analyzing the costs of the interventions, we see that the costs of the DAPP protocol are 27% higher compared to the OCHA protocol. This can be explained by the more effective, but also more expensive upscaled interventions. In summary, the implementation of the DAPP protocol results in the lowest number of overall cases, paired with the highest overall cost.

Table 4.4: Comparative analysis of the DAPP-informed AA protocol for cholera in Cameroon and OCHA's AA protocol for cholera in DRC for the scenario of a suspected case. This comparison assumes a three-week termination trigger in OCHA's protocol and an identical set of actions for both protocols.

Aspect	**AA protocol informed by DAPP**	**OCHA's AA protocol**
Trigger for suspected cases[a]	Soft trigger upon the report of a single suspected case; escalates to a hard trigger with a confirmed case.	Triggered after observing a 4x increase in suspected cases over three consecutive weeks.
Strategy	Initiates Anticipatory Action phase with low-regret actions upon a soft trigger; initiates Early Response phase with low- and high-regret actions following a hard trigger. Scaling or terminating actions based on weekly assessments.	Upon triggering the protocol, a combination of low- and high-regret interventions is deployed.
Actions	Low-regret actions: vaccination campaigns, installation of water points and latrines; High-regret actions: water treatment.	Vaccination campaigns, installation of water points and latrines, and water treatment.
Termination of actions	After one week without cases, the protocol reverts back to Resilience Building and Monitoring.	All efforts end after three weeks without cases.
Flexibility	Incorporates weekly decision points to scale interventions up or down or to cease actions entirely.	Allows intervention across all concerned health areas, not limited by the trigger's location, but does not allow for dynamic scaling of actions.
Uncertainty management	Utilizes a tiered trigger system to manage uncertainty, aligning action intensity with emerging risks through low- and high-regret actions and weekly decision-points to adjust the strategy.	Employs a 'wait and see' approach, initiating actions after a three-week trend of increasing suspected cases.

[a] In the simulation comparison, we exclusively focus on the scenario that initiates with a suspected case and do not assess the flood scenario.

Table 4.5: Performance metrics per protocol, averaged over 1,000 runs of a 26-week simulation. The duration of the interventions represents the total number of weeks during which the interventions were active, aggregated across all districts. The cost is in F.CFA (Central African CFA franc).

KPI	DAPP protocol	OCHA protocol	No protocol
Average Overall Cases	469,069.55	801,049.56	1,305,439.80
Average Overall Vaccinated	6,756,534.36	6,312,696.38	0.00
Average Weeks with Vaccination	47.12	55.98	0.00
Average Weeks with Water Treatment	47.12	62.40	0.00
Average Weeks with Water Points[a]	23.75	22.00	0.00
Average Weeks with Latrines	54.23	62.40	0.00
Average Overall Costs (F.CFA)	5674.26 M	4470.41 M	0.00
Average Costs of Training (F.CFA)	754.52 M	1207.17 M	0.00
Average Costs of Vaccination (F.CFA)	1515.39 M	1101.38 M	0.00
Average Costs of Water Treatment (F.CFA)	1477.26 M	1468.51 M	0.00
Average Costs of Water Points[a] (F.CFA)	597.14 M	432.00 M	0.00
Average Costs of Latrines (F.CFA)	2084.47 M	1468.51 M	0.00

[a] Although the durations for most interventions are compiled from all districts, the installation of water points was simulated at the national level due to a model constraint. As a result, this metric shows the number of active weeks on a national level without correctly reflecting the scale of the action through the number of districts affected by cases. Similarly, the cost estimate for water points is an underestimate. This constraint applies equally to both policies, thereby having a minimal impact on our comparative analysis.

If we zoom in further, and analyze the cost per case averted and the cost per death averted (Table 4.6), it becomes clear that DAPP strongly outperforms the OCHA protocol on effectiveness and cost-effectiveness. Note that we did not directly simulate mortality, but assume the number of deaths based on an estimated case fatality rate in Cameroon of (Ali et al., 2015).

Table 4.6: Analysis of the policies' performances.

KPI	DAPP protocol	OCHA protocol
Cases averted	836,370.25	504,390.24
Cost per case averted (F.CFA)	6784	8862
Estimated deaths averted[a]	31,782.06	19,166.82
Cost per deaths averted (F.CFA)	178,528.39	233,215.53

[a] Based on the estimated cholera fatality rate in Cameroon of 3.8% (Ali et al., 2015).

Figure 4.9 illustrates the weekly incidence of new cholera cases in the three scenarios: implementation of the DAPP protocol, the OCHA protocol, and in the absence of any intervention protocol. The DAPP protocol starts earlier, in particular with the low-regret actions. This visualization clearly demonstrates the superior performance of the DAPP protocol, not only in its capacity to initiate control efforts earlier than the OCHA protocol but also in its ability to bring the number of new cases down to zero through the flexible escalation of intervention measures. The initial sharp decline in case numbers can be attributed to the impactful role of vaccinations in preventing outbreaks. While other measures play a significant role in containing the disease, their effectiveness is notably enhanced through strategic escalation, underscoring the critical importance of flexibility in the control strategy.

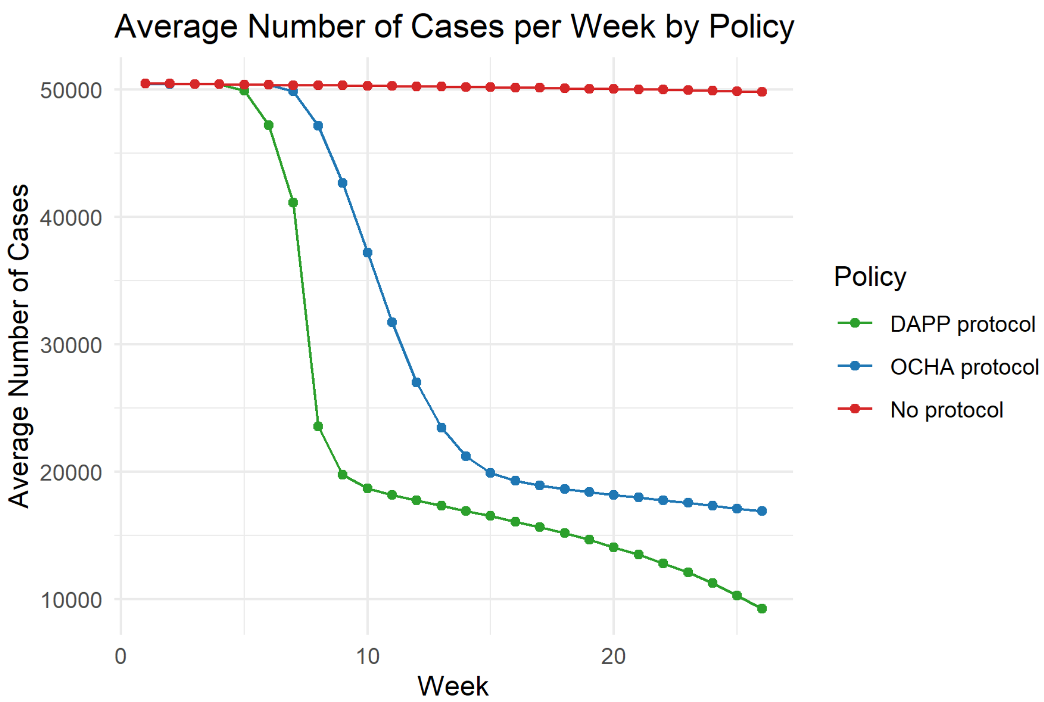


Figure 4.9: Weekly number of new cases averaged over 1000 simulations for the DAPP protocol, the OCHA protocol, and without any protocol.

Lastly, the raincloud plot in Figure 4.10 shows how the number of cases was divided over the simulation runs. It becomes apparent that simulation outcomes contain outliers for the number of cases, and the median values of the three policies are significantly less far apart. Further analysis is required to see whether these outliers still represent realistic outbreak scenarios.

Main findings

The comparative analysis of cholera control policies in Cameroon, grounded in a simulation model, reveals compelling evidence in favor of the superior efficacy of the DAPP protocol over both the OCHA protocol and a scenario without intervention. The DAPP protocol, distinguished by its proactive and flexible approach, significantly reduced the overall incidence of cholera, with a significantly lower number of cases than those observed for the OCHA protocol. This reduction is the result of the protocol's capacity to mobilize and execute low-regret interventions rapidly. However, the financial analysis showed that the DAPP protocol incurs higher overall costs. Yet, when these expenses are analyzed for the cost per case and death averted, the DAPP protocol demonstrates a higher cost-efficiency. This nuanced understanding of cost-effectiveness underscores the importance of evaluating public health interventions not just by their upfront costs but by their long-term impact on public health and economic burden.

Operational flexibility is an important feature of the DAPP protocol. Its design incorporates weekly decision points, allowing the scaling of interventions in response to the evolving dynamics of an outbreak. This dynamic adaptiveness facilitates a more nuanced and responsive approach to epidemic control, allowing timely adjustments to intervention strategies based on real-time assessments of the situation on the ground. In addition, the analysis of weekly incidence rates highlights the capacity of the DAPP protocol to initiate actions more rapidly and effectively reduce new cholera cases compared to alternatives. This rapid reaction is crucial in outbreak situations, where time is of the essence to prevent the spread of the disease.

The variability in outcomes, as illustrated by the raincloud plot, suggests the presence of outliers, indicating that while the DAPP protocol generally outperforms its counterparts, there remains a spectrum of potential scenarios. This variability calls for further investigation to fully understand the implications of these findings and to ensure that the DAPP protocol's strategies are robust across different outbreak scenarios.

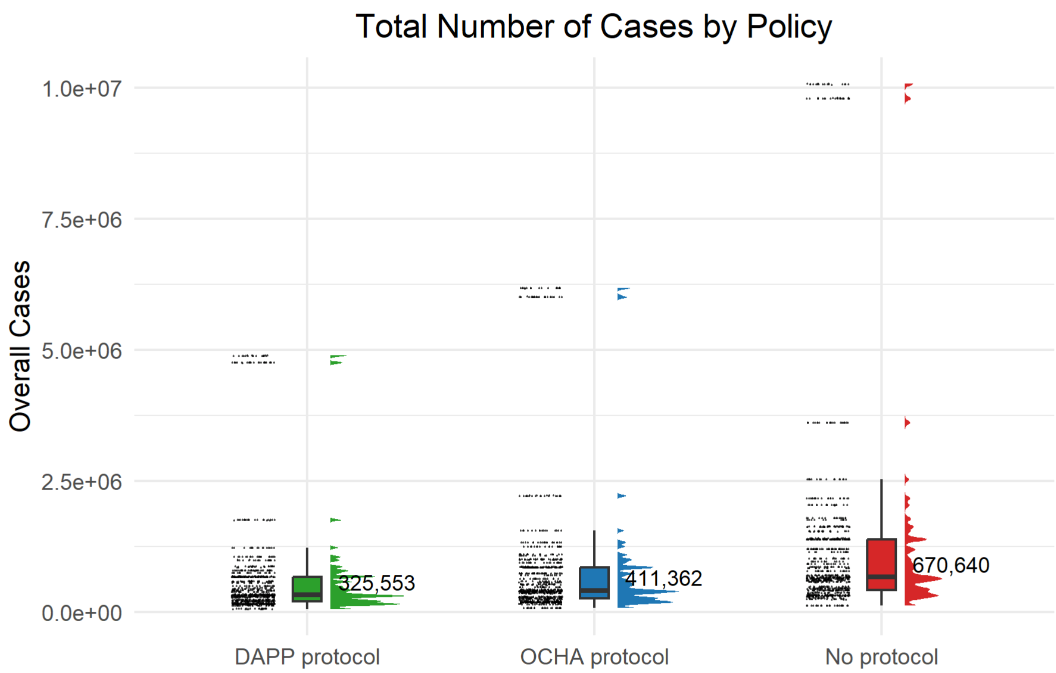


Figure 4.10: Raincloud plot of the total number of cases of the 1,000 experiments. The plot visualizes the jittered raw data, a boxplot including the median, and the data distribution.

5 Discussion

This chapter interprets the results and evaluates the study's limitations. Initially, we analyze the trigger mechanism and the policy pathways formulated during the research and reflect on their potential implications for policymakers. Following this, we examine the limitations of our study, address the assumptions, and evaluate the scope and constraints of our methodology. Furthermore, we evaluate the research approach adopted, particularly the use of Dynamic Adaptive Policy Pathways (DAPP) within a humanitarian anticipatory action (AA) framework, aimed at epidemic control. This evaluation includes an exploration of the methodological strengths and challenges, offering insights into the applicability and effectiveness of DAPP in the design of strategic control strategies for epidemic outbreaks.

5.1. Adapted DAPP method

After a thorough analysis of the concepts of AA and DAPP, we found how the DAPP method can be adapted to epidemic control. For DAPP to be effective in this context, it is essential to integrate AA principles. It was especially critical to extend the framework's trigger mechanism to be able to react to both sudden shocks with early action triggers and to prolonged stresses with contingency triggers. This adjustment is not only critical for its application in epidemic control, but also enhances DAPP's potential in other disaster risk management scenarios with shocks. We grouped measures in epidemic control into clusters of actions, called phases. This simplifies the decisionmaking process and thus streamlines the activation of actions. The pathway map can either visualize the actions with the paths or only the phases. Furthermore, we advance epidemic control by introducing a strategy to prioritize actions based on their regret potential. This enables the formulation of pathways tailored to varying degrees of uncertainty. This approach marks a departure from traditional AA methods, which typically adopt a passive 'wait and see' stance during uncertain times. By categorizing actions into 'low-' and 'high-regret' options, the framework fosters a flexible control strategy. This innovation may also be promising for managing other complex, evolving disaster situations where flexibility is needed.

Adhering to the five conceptual proxies for robustness outlined by Marchau et al. (2019)—namely resilience, redundancy, flexibility, adaptiveness, and comprehensiveness—our proposed method demonstrates a high degree of robustness in the face of uncertainty, as it is strong in at least three of these attributes: (1) resilience, as the Resilience Building phase allows for rapid recovery when outbreaks emerge, (2) flexibility, as the weekly decision-points allow for modification of the policy in real time, and (3) adaptiveness, as our contingency plans allow us to adjust methods in the mid- to long-term. Furthermore, it could be argued that our method achieves (4) comprehensiveness, by integrating interdisciplinary insights into a cohesive approach.

5.2. Application to case study

The case study demonstrates the efficacy of the adjusted DAPP method in facilitating the development of dynamic adaptive strategies for cholera control. The initial phase, comprising a detailed assessment of the current situation and problem analysis, offered a comprehensive understanding of the prevailing conditions. This foundational analysis was instrumental in setting the stage for subsequent action planning.

Action analysis
We evaluated five actions for cholera control in a structured and evidence-based assessment according to well-defined metrics. This approach for selecting actions was time-intensive and rigorous. Although conventional approaches based on expert judgment are more efficient, our comprehensive analysis is more solidly grounded in scientific research and thus lends more credibility to the proposed policy pathways.

Pathways
The visual representation of the pathways through the pathways map helps to communicate epidemic control strategies, although some training might be required. These maps provide a comprehensive overview, illustrating the timeline of incoming information, along with the initiation, preparation, execution, and conclusion of actions across various scenarios. This graphical approach enhances the understanding of the strategic process, offering a visual timeline that is both informative and accessible.

5.3. Effectiveness of DAPP method in epidemic control

5.3.1. Validation through expert engagement

The validation of a conceptual framework is a crucial step that involves determining its logical coherence and applicability not only from the researcher's perspective, but also from the viewpoints of other academicians and practitioners in the field (Jabareen, 2009). To achieve this, consultations were sought from experts across various domains: humanitarian professionals from the Red Cross and 510 initiative, along with epidemiological researchers from EHESP, at different stages of the study.

Input throughout the research
From the humanitarian standpoint, the study generated significant interest for its potential to improve anticipatory actions in the face of epidemics—marking a pioneering effort in developing epidemic Early Action Plans (EAPs). Although EAPs traditionally incorporate singular, phased or seasonal triggers, the introduction of a more sophisticated trigger framework as proposed in this study was deemed particularly suitable for controlling epidemic scenarios. However, caution was raised regarding the standardized process of EAP development within the Red Cross framework. Given that EAPs tailored to epidemics are a relatively new venture, there was an openness to integrating DAPP concepts into the EAPs, recognizing it as an opportunity to enhance their effectiveness. Nonetheless, the operationalization of such a framework presents its own set of challenges, particularly in terms of the local capacities of the National Society in Cameroon. The feasibility of implementing the proposed policy framework with its adaptive pathways depends on local capabilities, indicating a need for careful consideration in its application.

From the perspective of epidemiological researchers at EHESP, the exploration of dynamic adaptive strategies for epidemic control elicited considerable interest. Traditional humanitarian approaches often rely on a 'wait and see' methodology, delaying action until after the confirmation of a case amidst uncertainties. The proposition of initiating low-regret measures during periods of uncertainty—complemented by dynamic adaptive decisionmaking throughout the outbreak—was met with enthusiasm. The experts recommended broadening the scope of considerations beyond flood warnings to include factors such as seasonality and the risks associated with population movements. However, concerns were raised about the challenges in assessing the regret and impact associated with certain actions, given their heavy reliance on specific local contexts. Furthermore, the feasibility of implementing vaccination campaigns was questioned, highlighting potential administrative hurdles. In addition, the campaigns could lead to higher-regret scenarios if individuals fail to receive two doses, if coverage rates are insufficient, or if there is a lack of compliance due to the public's underestimation of epidemic risks. The researchers agreed with the identification of high-regret actions, noting that treatments would indeed be futile in the absence of actual cases. They also proposed modifications to certain interventions. For example, while water purification might be unnecessary for uncontaminated water sources, thereby constituting a potentially high-regret action, the implementation of water testing could serve as a low-regret measure, effectively balancing precaution with practicality.

Formal expert-based validation

At the final stage of this research, a structured validation based on the principles of the engineering of requirements was conducted with humanitarian experts of 510. Through qualitative comparisons with the conceptual framework for AA used by the Red Cross, and feedback from humanitarian experts, the validation revealed the advantages of DAPP over traditional AA strategies. These include the ability to adjust the control strategy in real time based on the latest epidemiological and environmental information, and the emphasis on low-regret actions during uncertain stages of an outbreak. This flexibility is typically not incorporated into the Red Cross AA framework, highlighting a significant area for improvement in traditional approaches. However, the discussion also brought to light challenges in operationalizing the DAPP method, particularly with respect to the complexity of pathway maps and the need for stakeholder involvement. Simplifying these maps for field applicability and ensuring the engagement of local stakeholders like the Cameroon National Society are essential steps toward making the DAPP approach more practical and aligned with real-world needs. Looking forward, the discussion suggested the potential for broadening the application of the DAPP method to integrate disaster risk reduction with response and development strategies, facilitating more flexible and efficient humanitarian interventions. This aligns with the sector's interest in overcoming the siloed approaches of planning, responsibility, and finances in disaster management.

5.3.2. Validation through simulation

This study compared cholera control strategies in Cameroon, demonstrating the DAPP protocol's effectiveness over the OCHA protocol and no intervention. The DAPP protocol notably reduces cholera cases through its quick, flexible approach. This advantage results from DAPP's strategy to take low-regret actions during periods of high uncertainty, instead of taking no actions and waiting for more certainty, as is OCHA's approach to navigating uncertainty. Additionally, we have seen that the flexibility in the control strategy informed by DAPP has a significant effect in reducing the number of cases. This difference allows the DAPP protocol to eliminate all cases, while the OCHA protocol does not.

The DAPP protocol has higher costs, however, its cost-efficiency is superior when evaluating the cost per case and death averted. The protocol's operational flexibility, with weekly decision points, allows for timely interventions that adapt to outbreak dynamics, leading to more effective disease control. Despite its advantages, variability in outcomes suggests some scenarios where DAPP might not outperform alternatives, indicating the need for further analysis to confirm its robustness across different outbreak conditions. Moreover, the scaled intervention modeling is based heavily on assumptions, leading to uncertainty in its outcomes. It is probable that expanding the scale will enhance the effectiveness of interventions, but the extent of this improvement is not precisely understood at present. This underlines the DAPP protocol's potential while highlighting the importance of continuous evaluation.

5.4. Limitations of the study

5.4.1. Action assessment

Prioritization methods

Our approach predominantly leans on regret analysis to determine the precedence of actions. However, this reliance may not always yield the most effective strategy, particularly in environments where data is scarce or unreliable, or when timelines are short. Furthermore, local conditions have a large impact on the effectiveness of actions, which makes it challenging to assess the regret used for action prioritization. Shifting focus towards the implementation of low-cost interventions could offer a more pragmatic alternative, despite the difficulties in accurately evaluating costs. Furthermore, giving preference to actions that require minimal preparation time could enhance the responsiveness of the framework, especially during the initial phases of a crisis. In addition, if the period of uncertainty is only one week, such as the time between a suspected and confirmed case, the preparation time may provide more information in short-term action prioritization.

Vaccinations
In the context of cholera outbreaks, the current protocol necessitates the requisition of vaccines from the global OCV stockpile (Shaikh et al., 2020). However, the strategic shift towards employing vaccines not just as an emergency response but as a preemptive measure to build resilience against cholera is gaining traction (Global Task Force on Cholera Control, 2021). This approach aligns with advancements in AA and pre-agreed financing mechanisms, suggesting the potential need for predetermined vaccine allocations based on specific early-warning triggers. To bolster the rapid availability of vaccines, particularly in cholera-endemic regions, maintaining a localized vaccine reserve could prove beneficial. Given that certain vaccines remain viable for up to three years (Shaikh et al., 2020), such a strategy could significantly reduce response times in initiating vaccination campaigns. This proactive stance, however, introduces logistical and strategic challenges, including considerations of vaccine shelf life, storage conditions, and the dynamics of vaccine immunity within populations. These aspects, while crucial to the development of an effective cholera control and prevention strategy, were deemed beyond the scope of this research. Consequently, simplifications regarding vaccine preparation and deployment times were necessary due to the current uncertainties surrounding these factors. Addressing these challenges through future research could greatly enhance the effectiveness and efficiency of vaccination strategies, particularly in regions where cholera poses a recurrent threat.

5.4.2. Reflection on the adopted approach

To effectively showcase potential strategies for epidemic control over time we employed the DAPP approach, which stands out for its visualization of pathways. The visual nature of DAPP facilitates a clearer understanding of how various pathways unfold in response to different scenarios, enabling stakeholders to anticipate and adapt to future uncertainties more effectively.

However, the applicability and scalability of the DAPP approach for complex policymaking processes, especially to design epidemic protocols over short, medium, and long term horizons, may be limited. This is particularly true within the context of organizations operating under significant resource constraints, such as those in the humanitarian sector. While DAPP has been successfully applied in large-scale, well-funded planning projects—such as the Dutch Delta Programme and the Bangladesh Delta Plan (Lawrence et al., 2019), the transition of this approach to more localized, resource-limited settings remains less explored. Lawrence et al. (2019) particularly stress the need for further exploration in the domains of implementation and monitoring of plans derived from the DAPP method. Furthermore, this investigation did not explore the geographic aspects and spatial dynamics, which are integral to the implementation and effectiveness of epidemic control strategies. This results in a significant gap in our understanding of the strategies required to navigate these spatial complexities effectively.

5.4.3. Scope limitations

The case analysis focused on steps 1 to 7 of the DAPP cycle, since an impending field trip to Cameroon was anticipated to provide new information that would require a reevaluation of the initial steps of the cycle. Thus, it was deemed preferable to delay steps 8 to 10. To further streamline our analysis within the available timeframe, we opted to utilize pre-existing scenarios developed by OCHA instead of investing time in crafting bespoke scenarios. This approach enabled us to efficiently allocate our resources and attention to the critical components of the study. However, this might lead to an incomplete illustration of DAPP in epidemic control.

5.4.4. Funding mechanisms

The funding structure of AA makes it stand out among other response mechanisms in the humanitarian sector since it ensures rapid fund allocation immediately following the onset of an outbreak. For organizations such as the Red Cross, funding for AA is often secured through specialized requests within frameworks like the DREF, a process known as anticipatory financing or pre-agreed financing. However, the pursuit of improved resilience and improved monitoring systems entails significant costs, with benefits that are more indirect and manifest over the long term. To establish funding mechanisms that are well-suited to the advanced approach proposed here, a thorough investigation is required. Such research would explore viable models for financing both immediate and prolonged intervention strategies, ensuring that resources are available when needed yet also support sustainable development and resilience enhancement. This exploration was beyond the scope of the current study, highlighting a gap in our understanding and an opportunity for future research.

5.4.5. Evaluation of effectiveness

A complete evaluation that captures all the benefits and costs of dynamic adaptive epidemic control is very challenging. We reflect on real-life evaluation, policy evaluation, and simulation evaluation separately.

Real-life evaluation
An important component of the DAPP method involves revising strategies, a practice widely adopted both in policymaking circles and within the humanitarian sector. However, this process poses specific challenges, especially when assessing the effectiveness of AAs designed to preemptively mitigate potential outbreaks. If there is no outbreak after ancitipatory actions were taken, it is hard to determine whether the actions counterfactually averted an epidemic. It can be ambiguous whether the lack of an outbreak post-trigger is due to effective mitigation or if the trigger was a false alarm. In addition, low-regret actions still enhance resilience against future epidemics, even if they do not directly prevent an outbreak, which makes it harder to estimate their long-term impacts. This study does not provide a direct solution to the evaluation challenges associated with anticipatory actions within the context of epidemic outbreaks.

Policy evaluation
We have evaluated our proposed DAPP-informed protocol against protocols that are still in development phases of the Red Cross, and an AA protocol of OCHA. The DAPP approach aims to connect AA with regular response, while that is not currently a practice in the humnanitarian field. As a consequence, it is very challenging to have an informative comparison. A limitation is that the regular response that would follow up the AA of the Red Cross or OCHA, has not been evaluated. There are two reasons for this: first, the precise division between AA and response is not yet clearly defined for epidemics, as the incorproation of AA in epidemics is still in very early development phases. Second, there is very limited documentation on the regular response on the ground, both in Cameroon by the Cameroon NS and in the DRC by OCHA. The field of response is much more fragmented, with multiple NGOs and governments involved. It would be very challenging to capture these combined efforts in a simulation.

Moreover, the expenses associated with the activities are largely based on assumptions. We take one time-dependent cost estimate per action to account for the preparation weeks and execution weeks, without considering the size of the district in terms of area, population and number of cases. We do raise the expense of scaled interventions, but we do so in a linear manner, which is not reflective of reality. Consequently, the cost comparison serves as a rough estimate of which policy may be more cost-effective, but it does not accurately reflect the actual cost of effectively controlling an epidemic.

Model-based evaluation
Our methodology uses simulations to assess the effectiveness of strategies through counterfactual scenarios, those that involve alternative policies or the absence of any actions. However, a model is necessarily an imperfect representation of reality and thus misses some important complexities. For example, our model does not accurately represent the intricate interplay among interventions, resilience (both short-term and long-term), specific local conditions, changes in human behavior, and information limitations such as under-reporting and falsely suspected cases. These challenges are amplified in data-scarce regions where cholera is endemic. Furthermore, there has been very limited scientific research on the exact effects of cholera interventions. For example, coverage, timing, and intensity are often not taken into account, although they are highly influential on the intervention's impact. Consequently, the precise effects of these interventions remain uncertain, necessitating further on-site measurements and data gathering. Furthermore, we assumed that actions were taken at the health district level, due to model limitations. However, interventions at a smaller scale would be more realistic. Lastly, the number of deaths was not included in the model, hence, the effect of actions on the mortality rate was not analyzed.

As a result of these limitations, the effect of false triggers on the performance of the protocols has not been measured, as well as the positive effects of low-regret actions in the form of longer term resilience. Furthermore, our simulation was limited to the country of Cameroon, and specific to cholera. To accurately test the efficacy and impact of various policy choices, such as DAPP, on epidemic control, a model would need to be based on a nuanced understanding of many factors interacting over long timeframes. Such advanced modeling was outside the scope of this study. Moreover, additional research is needed on the scaling of interventions to advance the study of dynamic adaptive strategies for controlling epidemics.

6 Conclusion

This thesis presents a comprehensive exploration of the Dynamic Adaptive Policy Pathways (DAPP) method as a novel approach to enhance anticipatory action (AA) in epidemic control. It delved into the complexities of cholera control, particularly focusing on the endemic challenge of the disease that disproportionately affects the world's most vulnerable populations. By examining the multifaceted nature of cholera outbreaks and the inherent uncertainties in their management, this study has aimed to bridge the gap between static, pre-formulated AA plans and the dynamic, evolving nature of epidemics. Through the case study of Cameroon, which has been recurrently plagued by cholera outbreaks, this research has explored the potential of DAPP to offer a flexible framework capable of responding to the unpredictable dynamics of epidemics. This concluding chapter aims to synthesize the findings, discussing how integrating DAPP within AA approaches can significantly improve our capacity to manage epidemic outbreaks more effectively, thereby contributing to the broader goal of enhancing public health strategies and advancing toward the Sustainable Development Goals.

6.1. Answers to research questions

6.1.1. Answer to the main research question

The main research question of this thesis was formulated as follows:

How can the Dynamic Adaptive Policy Pathways (DAPP) method enhance anticipatory action (AA) approaches in the context of epidemic control?

Findings from this research demonstrate that the DAPP method significantly enhances AA approaches by introducing a robust and flexible strategy that notably improves the efficacy of epidemic control measures. Through a model-based comparison, the DAPP-informed protocol has shown to not only reduce response times but also to effectively reduce the incidence of outbreaks more efficiently than traditional AA strategies. This superiority is attributed to its dynamic adaptiveness, use of low-regret interventions, and scalability, allowing for real-time adjustments to the evolving landscape of an epidemic. However, the complexity of the pathway maps has been identified as a potential barrier to widespread adoption, suggesting that further simplification or additional training for humanitarian practitioners may be necessary to fully leverage the benefits of the DAPP method. The need for closer stakeholder involvement, particularly with local entities has also been highlighted as important to ensuring the practicality and real-world alignment of the DAPP approach. Despite this, the positive reception from humanitarian experts, coupled with the method's demonstrated cost-efficiency and operational flexibility, underscores the DAPP method's potential to significantly improve current AA approaches in epidemic control.

We have explored the potential of the DAPP method to transform the landscape of AA in epidemic control through a case study of cholera in Cameroon. Through a comprehensive analysis, this research has showed how DAPP can be tailored to navigate the complex and uncertain terrain of epidemic outbreaks, offering a significant improvement over traditional control strategies. DAPP's dynamic adaptiveness to the changing nature of epidemics lies in its ability to incorporate specific epidemic phases and integrate shock triggers. This tailored approach allows for flexible transitions between phases of epidemic control, ranging from resilience building to anticipatory action and early response, ensuring that actions are both timely and contextually relevant. The introduction of shock-based triggers, informed by an analysis of potential scenarios, underpins an adaptive strategy that dynamically adjusts to the evolving landscape of an outbreak. We demonstrated the flexibility of adaptive pathways within the DAPP method, showcasing how scenarios ranging from suspected cholera cases to flood-related outbreaks can inform staged control efforts. This strategy ensures that interventions are scalable, which allows for increased control efforts when uncertainty decreases or when the situation gets worse. The inclusion of weekly data assessments further refines this flexibility, allowing real-time adjustments to the control strategy based on the latest epidemiological and environmental information. Signposts and triggers play a crucial role in enabling timely and effective AA. By monitoring a set of predefined indicators, the DAPP method facilitates a proactive strategy in response to the signs of an emerging outbreak, ensuring that interventions are not only timely but also precisely targeted to mitigate the spread of cholera. This structured approach to monitoring and control underscores the importance of adaptiveness in the face of uncertainty, allowing for a fluid transition between different phases of epidemic control based on real-time data.

In conclusion, the DAPP method offers a promising advancement in AA for epidemic control, advocating for a shift towards more adaptable and responsive epidemic control strategies. Our findings advocate for the integration of DAPP into broader AA and epidemic management frameworks, emphasizing the importance of flexibility, stakeholder engagement, and the strategic deployment of resources in the face of epidemic threats.

6.1.2. Answers to the sub-questions

The primary research question was dissected into four investigative sub-questions, which are answered in this section.

SQ1: In what ways can the DAPP method be adapted to manage the dynamic and uncertain nature of epidemic outbreaks within the framework of AA?

The DAPP method can be adapted to manage the dynamic and uncertain nature of epidemic outbreaks through several strategies and modifications tailored to the unique challenges of epidemic control. The adaptation includes the following components.

- *Introduction of specific epidemic phases:* The adapted DAPP method incorporates distinct phases tailored to epidemic control. These phases include (1) Resilience Building and Monitoring, which focuses on strengthening systems and preparedness during periods without an outbreak; (2) Anticipatory Action, which emphasizes preventive measures and early interventions when the risk of an outbreak is heightened; (3) Early Response, which manages the situation during an early, small-scale outbreak; and (4) Response, which handles the management of active outbreaks. These phases allow for better coordination and the incorporation of AA into the broader control strategy, ensuring that efforts are tailored to the unique characteristics of specific epidemics.
- *Integration of shock triggers*: The framework introduces triggers to signal transitions between various phases of control, drawing inspiration from the AA framework, called early action triggers. These triggers are developed after the problem analysis, leveraging scenarios resulting from the analysis to inform their development. The subsequent steps include action assessment and the development of adaptation pathways, employing a shock-based trigger approach characteristic of AA. This ensures that actions remain effective throughout the progression of the disease and enhances the overall robustness of the control strategy.

SQ2: What are the possible adaptive pathways for epidemic control within the DAPP method, and how do they provide flexibility in response to evolving outbreak scenarios?

The DAPP method has been used to develop adaptive pathways for cholera control, structured around four distinct scenarios that reflect varying degrees of outbreak risk and environmental triggers. These scenarios encompass: (1.i) the initial identification of a suspected cholera case with subsequent laboratory confirmation; (1.ii) a situation where the suspected cholera case is negated; (2.i) a sequence of events starting with a flood warning, followed by an actual flood and a cholera outbreak; and (2.ii) a scenario where, despite a flood, a cholera outbreak does not occur. At the core of these pathways is the concept of staged responses, initiated by the first indication of risk, in our case either a suspected case of cholera or a flood warning. This initial stage is characterized by a degree of uncertainty, prompting the implementation of lower-regret actions, such as vaccination campaigns and the installation of water points and latrines. These measures are designed to mitigate the risk of cholera spread while having a longer-lasting impact. As the situation evolves and certainty increases, either through the confirmation of cholera cases or the occurrence of a flood accompanied by suspected cases, the control efforts escalate to include more definitive, higher-regret actions. This includes the deployment of water treatment facilities and the establishment of oral rehydration points, which are critical in controlling cholera outbreaks.

The pathways are dynamic, incorporating weekly data assessments to inform decisionmaking. This iterative process allows for adjustments based on the progression of cholera spread. This makes it possible to scale the control measures up or down when the conditions become worse or the situation stabilizes. This approach gives policymakers a significant degree of flexibility, enabling them to respond effectively to the changing landscape of a cholera outbreak. Moreover, the pathways include preparation timelines, offering a tool for monitoring policy implementation against planned schedules. Should significant delays be identified, decisionmakers have the option to alter strategies, ensuring that control measures are timely and effective. This aspect of the DAPP method provides a mechanism for adjusting strategies in real-time, enhancing the overall responsiveness and effectiveness of cholera control efforts.

SQ3: Which critical signposts and triggers are essential for epidemic control in the DAPP method to enable timely and effective AA?

Integration of critical signposts and triggers within the DAPP method is essential for the timely and effective cholera control. This framework delineates a structured approach for transitioning through various phases, by closely monitoring key indicators such as suspected, confirmed, and negated cholera cases, alongside environmental cues like flood alerts. The flexibility to adapt to evolving scenarios is further enhanced by the potential inclusion of additional variables in the future, such as natural hazard warnings, cholera forecast models, and population movement patterns, to refine trigger accuracy. The transition between the framework's phases is designed to respond to the dynamic nature of cholera outbreaks. The shift from resilience building to outbreak prevention is triggered by the identification of a suspected cholera case or environmental hazards that increase outbreak risks. Escalation to emergency response is warranted upon case confirmation or the heightened risk post-flood, emphasizing the need for immediate, targeted interventions. Conversely, the criteria for reverting to the resilience-building phase include the negation of suspected cases, the non-occurrence of anticipated floods, the absence of new cases post-flood, and a period without new cases, indicating outbreak containment.

This approach reflects the importance of flexibility and adaptiveness in epidemic control, acknowledging that deviations from the planned triggers may be necessary under specific circumstances, such as concurrent outbreaks. Such adaptiveness ensures that control efforts are not only preemptive and responsive but also tailored to the unique challenges presented by each outbreak scenario. Ultimately, the DAPP method, with its emphasis on critical signposts and triggers, offers a robust mechanism for epidemic control, enabling policymakers and responders to navigate the complexities of epidemic control with informed, anticipatory actions.

SQ4: How does the effectiveness of the DAPP method in controlling epidemic outbreaks compare to that of traditional approaches, in terms of response time and outbreak mitigation?

This research question is addressed through a detailed evaluation of the DAPP method against traditional AA strategies, specifically those used by the Red Cross and OCHA. The DAPP method's effectiveness in cholera control was compared against classical AA methods through both expert-based and model-based comparisons.

- The qualitative comparison involved discussions with humanitarian experts from 510, highlighting the need for flexibility in cholera control plans and the value of low-regret actions that can be initiated even before an outbreak is confirmed. These discussions emphasized the challenges of responding to cholera outbreaks due to uncertainties in predicting outbreak dynamics and the bureaucratic delays that can hinder timely action. An additional use of the DAPP pathways was identified in technical discussions with funding agencies.
- The model-based comparison used a simulation model developed by EHESP researchers, which was extended to test dynamic intervention strategies. This comparison directly pitted the DAPP method against OCHA's AA protocol for cholera control. The simulation outcomes underscored the DAPP method's ability to initiate actions earlier, particularly low-regret actions, which in turn led to a significant reduction in the average overall cases of cholera. Although implementing the DAPP protocol incurred higher costs, the investment yielded a lower number of cholera cases, demonstrating the protocol's enhanced effectiveness in outbreak mitigation.

The qualitative expert feedback and quantitative simulation results collectively affirm the DAPP method's potential in offering a more efficient and effective control strategy to cholera outbreaks, compared to traditional AA strategies. The DAPP's emphasis on flexibility, early low-regret actions, and dynamic adaptation to changing outbreak scenarios positions it as a valuable approach in the field of epidemic control, particularly in the face of uncertainties and resource constraints.

6.2. Contribution

6.2.1. Scientific contribution

This research addresses a critical knowledge gap: the enhancement of the AA framework for epidemic control through the innovative application of the DAPP approach. The core scientific contribution of this thesis lies in its novel integration of the AA framework with the DAPP method (Haasnoot et al., 2013, 2018), specifically tailored for epidemic control. By incorporating AA concepts, such as shock-based triggers, into the DAPP approach, this research marks a step forward in applying adaptive strategies to humanitarian control strategies for epidemics. This integration makes AA protocols more flexible, enabling them to navigate the complexities and uncertainties inherent in epidemic outbreaks. This advancement addresses the need for increased flexibility in AA strategies, a challenge highlighted by Tozier de la Poterie et al. (2023). Through the application of the adjusted DAPP method to a case study of cholera control in Cameroon, we have developed a dynamic adaptive protocol, capable of dynamically adapting the plan over time in response to the unpredictable unfolding of disease outbreaks. This approach bridges the gap between traditional static planning methods and the flexibility requirement of effective epidemic control.

In demonstrating the proposed adaptive protocol through model-based analysis, we compared the impact of various control strategies on the progression of cholera outbreaks. Previous modeling studies have evaluated the effectiveness of different intervention measures for cholera control (e.g. Collins and Duffy, 2018; Fung, 2014; Miller et al., 1985; Posny et al., 2015; Sun et al., 2017). However, our research differentiates itself by examining the influence of timing, triggers, and scalability of control strategies on outbreak dynamics. By introducing low- and high-regret actions and implementing a dynamic scaling of control measures, our study innovates optimal control research in epidemic outbreak scenarios. However, as identified by Wang (2022), time-dependent parameters, accurate estimates, and data on the effectiveness of cholera control measures are difficult to obtain. As a consequence, our demonstration is limited and relies on assumptions to fill these gaps.

6.2.2. Societal contribution

The introduction of flexible protocols based on the DAPP method marks a significant advancement in how humanitarians can respond to the evolving dynamics of disease outbreaks. Such flexibility in control is crucial for quickly mitigating the spread of cholera, particularly in regions where the disease is a recurrent threat. This is becoming more urgent, as climate change, urbanization, and population growth are expected to increaes the risk of cholera (Global Task Force on Cholera Control, 2017). The findings of this study offer policymakers and humanitarians a novel method to develop dynamic adaptive epidemic control strategies that are grounded in an understanding of the complexities of humanitarian aid. Through its practical application, this thesis sets the groundwork for more robust and adaptive epidemic control strategies worldwide.

6.3. Recommendations for future research

This thesis has explored the DAPP method as a novel approach to enhance AA in controlling cholera outbreaks. While the findings offer promising insights into the framework's potential, they also highlight several areas where further research is necessary to deepen our understanding and improve the efficacy of epidemic control strategies. Below are recommendations for future research directions:

- *Assessment of geographic and spatial dynamics*: Future studies should address the gap in understanding how geographic and spatial factors influence epidemic control strategies. Exploring the spatial dynamics integral to the implementation and effectiveness of interventions could provide valuable insights into the complexities of controlling epidemic outbreaks and inform more effective deployment of resources and strategies.
- *Scalability of DAPP in resource-limited settings:* Research should investigate the practical application and scalability of DAPP in settings with limited resources. This includes examining how the framework can be adapted to meet the needs of organizations operating under significant constraints and exploring strategies for implementing and monitoring plans derived from the DAPP method in such contexts.
- *Extension of regret-based action prioritization:* The reliance on regret analysis for action prioritization presents challenges in environments with incomplete or inaccurate data. Future research should develop a more sophisticated method for prioritizing actions that is robust to these challenges, potentially incorporating cost-effectiveness, preparation times, and the potential for regret minimization into a comprehensive prioritization model.
- *Pathway map improvements:* The humanitarians considered the pathway maps to be rather complex. To further refine this visualization, especially in contexts with many actions, it might be beneficial to create multiple pathway maps for the epidemic phases. Such segmentation would prevent the visual from becoming overly complex and challenging to interpret. By organizing the maps according to specific phases of the epidemic, stakeholders can focus on the relevant actions and information pertinent to each stage. Integrating these separate maps into a cohesive overview presents a challenge that requires careful consideration. To effectively link these maps, a layered approach could be employed, where each map represents a distinct phase or aspect of the strategy but is designed with common reference points or indicators. These reference points could include decision nodes or timelines that are consistent across maps, enabling stakeholders to understand how different segments interconnect and influence the overall strategy. This visualization could be integrated more effectively by making it more user-friendly through interactive digital tools like a dashboard. For example, users could be able to toggle between different maps, while also maintaining an overall view to understand specific strategies in a broader plan.
- *Integration of preemptive vaccine strategies:* Investigating the logistical and strategic implications of maintaining a localized vaccine reserve for rapid deployment in endemic regions could significantly reduce response times. Future research should explore the challenges associated with vaccine shelf life, storage conditions, and immunity dynamics to enhance vaccination strategies.
- *Evaluation of anticipation actions*: Addressing the evaluation challenges associated with anticipatory actions, especially in determining the effectiveness of interventions designed to preempt outbreaks, is essential. Future studies should explore methodologies for assessing the impact of these actions, considering their contribution to building resilience and preparedness for future outbreaks.
- *Development of funding mechanisms for dynamic adaptive epidemic control:* Research into viable models for financing both immediate interventions and long-term strategies for enhancing

resilience is crucial. This research should explore funding mechanisms that support rapid control capabilities and sustainable development goals, ensuring that resources are efficiently allocated to where they are most needed.

- *Exploration of alternative DMDU methodologies*: Given the limitations observed in applying DAPP to epidemic control, particularly in resource-constrained settings, future research should explore other DMDU methodologies. These alternative approaches might offer more suitable or complementary strategies for managing complex, dynamic challenges like epidemic outbreaks. Investigating these methodologies could provide a broader toolkit for scenario planning, risk management, and adaptive policy formulation, enhancing strategic planning in public health.

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A

Anticipatory action at OCHA

The "First Steps" section of the Anticipatory Action Toolkit (United Nations Office for the Coordination of Humanitarian Affairs (OCHA), n.d.) outlines an initial approach to anticipatory action (AA), as developed by OCHA. It emphasizes the importance of acting based on increased risks rather than existing needs. Key components include defining triggers for action, pre-agreed activities, and pre-committed financing. The process involves establishing a core team, developing a framework and ensuring operational readiness for rapid and effective early actions to mitigate the impacts of potential crises.

A.1. Steps in piloting collective anticipatory action

Figure A.1 provides an overview of the process for formulating AA strategies within the OCHA framework. This approach places greater emphasis on the timelines of crises, incorporates learning mechanisms, and includes the expansion of initiatives from pilot phases. Although these elements distinguish it from the Red Cross model illustrated in Figure 2.5, the fundamental phases of the development of the AA plans remain largely consistent between the two frameworks.

Figure A.1: Steps in piloting collective AA (United Nations Office for the Coordination of Humanitarian Affairs (OCHA), n.d.).

B

Qualitative validation

This chapter presents the setup that was used for the qualitative expert-based validation with humanitarians of 510, the data and digitial initiative of the Netherlands Red Cross. Section B.1 outlines the foundational material that was shared to facilitate expert dialogue, which subsequently unfolded through the questions listed in Section B.2.

B.1. Foundational material for expert-based validation

B.1.1. Introduction to the DAPP approach

Dynamic Adaptive Policy Pathways (DAPP) is a method for making decisions when the future is uncertain. It starts with understanding the current situation, including setting goals and identifying unknown factors, such as how an outbreak might spread or if there are delays in reporting it. Then, the method involves looking closely at these uncertainties and imagining different possible futures based on them, which are known as scenarios. By combining DAPP with ideas from humanitarian anticipatory action (AA), the method then sets up triggers for when to take action for each scenario. A wide range of actions is considered and evaluated. From these, pathways are created, made up of actions that help achieve the set goals.The pathways function as a roadmap, and show when we can switch to different pathways, or adjust the scale of our current pathway. To ensure that these pathways keep us on track to our goals, backup plans and additional triggers for action are set up, which is called contingency planning. All of this comes together in a dynamic and adaptive Early Action Protocol (EAP), which, once approved, allows for preparations to begin. The final steps involve monitoring the situation and carrying out planned actions to prevent or respond to outbreaks.

B.1.2. Problem analysis

- Predicting and controlling cholera outbreaks is difficult because we can not foresee when, where, or how quickly they will happen. Static, rigid plans that set out actions too strictly do not offer enough flexibility to adjust as needed.

- At the start of a potential outbreak, when someone shows symptoms of cholera but it has not been confirmed, there is uncertainty about whether it is actually cholera. To avoid misusing resources, no steps are taken yet. However, during this waiting period, valuable time is lost. Furthermore, there remains uncertainty about the size of the outbreak, as there is under-reporting.

B.1.3. Solution requirements

- We need a flexible cholera control plan that can easily adjust to the situation. This means doing more or less depending on the outbreak's severity.

- The plan should also include actions that we can take even when we are not sure if it is a cholera outbreak yet. These early actions can be advantageous regardless of the outbreak's confirmation[1].

B.1.4. Proposed solution

We have adjusted the DAPP method to fit the context of epidemic control. By following the steps of the method, we developed a flexible plan for dealing with cholera outbreaks that looks like a map. It lists out steps we can take as the situation changes, starting with low-regret actions and moving to high-regret actions if needed. The plan includes how long each step will take to set up. Every week in the plan, shown as squares on the map, we can decide whether to do more or less, based on what is actually happening with the cholera outbreak.

Map 1: Suspected case

The plan begins with a suspected cholera case, after which volunteers are trained and we start with actions with low-regret. If the case is confirmed, we train the volunteers again and start high-regret actions. Every week, we check to see if we need to do more or less. If we see the number of cases go down, we stop the high-regret actions. And if we don't see any new cases for a week, we stop all actions.

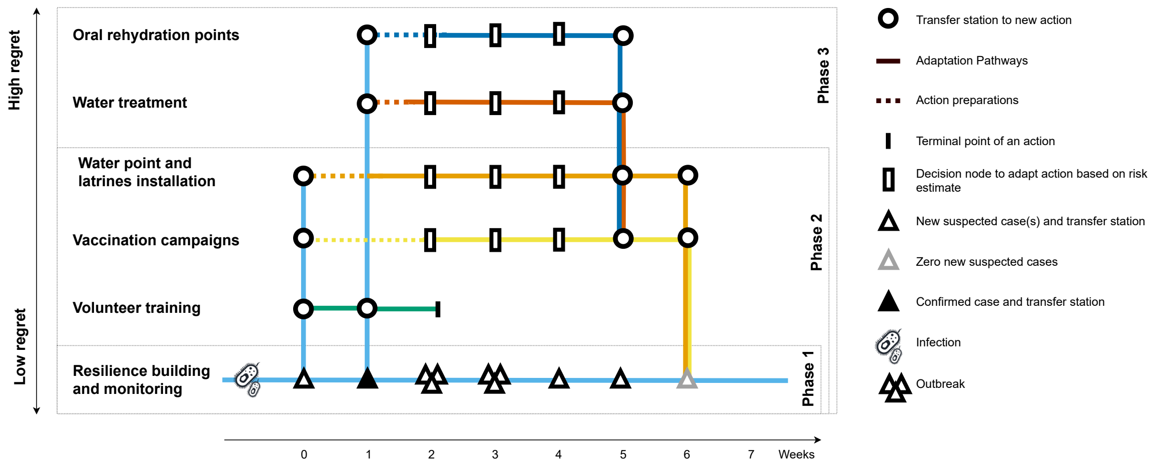

Figure B.1: Adaptation pathways map corresponding to Scenario 1.i., which begins with the identification of a suspected cholera case and is followed by the laboratory confirmation of the case. Actions are sorted according to their level of regret and organized into three distinct phases of epidemic control: Phase 1 encompasses resilience building and monitoring; Phase 2 involves anticipatory outbreak prevention; and Phase 3 is dedicated to emergency response measures. Color-coded lines delineate the progression of actions within each phase. Dotted lines indicate the preparatory stages of actions, while solid lines denote the active implementation of measures. Transfer stations, marked by circles, triangles and rectangles, allow for adjustments in control strategies, either escalating or de-escalating actions across phases, contingent on risk estimates and evolving data such as new suspected or confirmed cases.

Map 2: Flood warning

The plan begins with a flood warning, and that is when the volunteers are already trained. If a flood occurs and there is a suspected cholera case, we start to vaccinate people and set up clean water and toilets. We train volunteers again if we need to high-regret actions. Every week, we decide if we need to do more or scale down. If fewer people are getting sick, we cut back on the high-regret actions. If there are no new cases for a week, we stop the control efforts.

[1]We call these actions 'low-regret', because they are helpful even if there's no outbreak. This means that we will not regret doing them. For example, vaccinations is a low-regret action since they can protect people for up to three years.

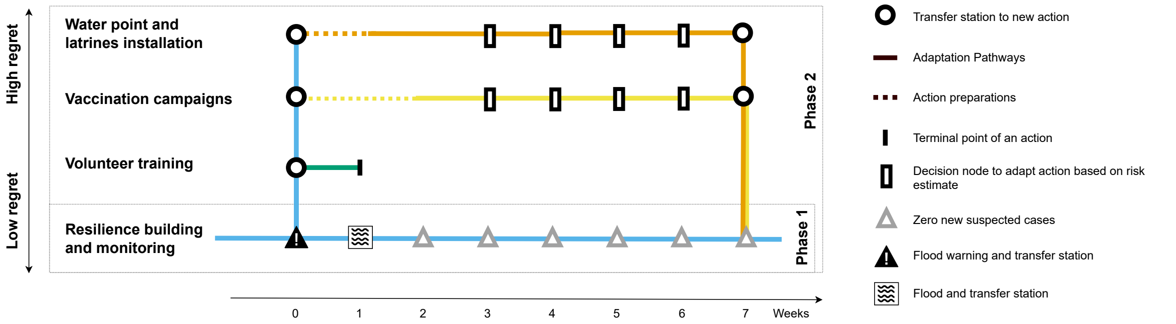

Figure B.2: Adaptation pathways map outlining the sequential events and action pathways for Scenario 2.i, initiated by a flood warning. It details the subsequent stages including the occurrence of the flood, detection of a cholera infection, and the confirmation of the case. The map visually represents the structured control timeline, indicating the critical interventions and decision points following each event in the scenario.

B.2. Questions to guide expert dialogue

1. Do you believe the problem analysis accurately captures the complexities of cholera outbreaks? Are there any aspects that you think should be added or clarified?
2. Does the solution's objectives align with what you consider necessary for an effective cholera control strategy?
3. In your opinion, does the proposed plan address the identified needs?
4. Reflecting on the DAPP approach, were there any steps, uncertainties, or actions that you think were overlooked in the scenario mapping?
5. How do you assess the clarity and utility of the action map? Do you find it straightforward, beneficial, or perhaps too complex?
6. Could the pathway map help decisionmaking in AA for cholera control in Cameroon? Why or why not?
7. Do you believe that the adaptive pathways approach is feasible to implement in Cameroon's context?
8. How effective do you think the DAPP method would be in developing EAPs for epidemics at 510?
9. Is the DAPP method practical for operational use at 510?
10. What impact do you anticipate the DAPP method will have on the effectiveness of epidemic control?