Improving Design & Usability of Interactive Vulnerability Mapping Tools for Global Health Preparedness

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Abstract

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The ability of organizations and governments to anticipate disease outbreak risks and respond to emergent threats, commonly known as global health preparedness, presents both a challenging opportunity and an urgent imperative for public health informatics interventions. An example is the need to address the public health risks of vector-borne and zoonotic disease (VBZD) outbreaks, as understanding and preparing for such multifactorial events involves the careful integration of human, animal, entomological, environmental, and infrastructure data. The integration, presentation, and understanding of this data, and associated risks, demands usable tools and technology. Visualization can be a useful way to apply systems thinking to such problems. Unfortunately, existing visualization tools frequently do not assess whether they meet the needs of their users [1] and do not incorporate best practices championed by human centered design (HCD) [2]. In my dissertation research, I propose design recommendations for

visualization tools to help decision makers in global health preparedness identify spatial areas that are vulnerable to outbreaks, meaning better awareness in areas at a relatively high risk for VBZD outbreaks and a lower capacity to contain spread.

Spatial Systems for Decision Support (SSDS) are a type of visualization tool that enable public health practitioners to make critical decisions informed by timely access to pertinent, analyzed data. In my research, I propose a new type of SSDS, *interactive vulnerability mapping tools*. This new tool can provide critical, rapid support to decision makers and practitioners in global health. Decision makers include epidemiologists, public health planners, vector control specialists, and directors, each of whom might use this information to allocate vaccine resources or plan intervention activities to high-risk regions.

In my dissertation research, I have applied principles of human-centered design (HCD) [3] and data visualization [4] to design and evaluate the usability of interactive vulnerability mapping tools for dengue vulnerability in Peru (Aim 1) and Rift Valley fever vulnerability in Kenya (Aim 2). To situate my Aims 1 and 2 in the context of existing literature, I conducted a scoping review of interactive vulnerability mapping tools for VBZD preparedness (Aim 3) that describes current literature by characterizing data, users, technology, and use cases. I then compare findings from Aims 1 and 2 to the existing literature to identify gaps and inform design recommendations for future work. This work contributes: 1) usable interactive vulnerability mapping tools designed with public health decision makers in Peru and Kenya; 2) empirical data on the design, data visualization preferences, usability, and acceptance of interactive vulnerability mapping tools for VBZD vulnerability in global health settings; and 3) design recommendations for interactive mapping tools for VBZD informed by a scoping review of the literature and findings from Aims 1 and 2. This research will advance the fields of global health and pandemic preparedness, human computer interaction, and data visualization. It provides evidence to suggest that interactive vulnerability mapping tools hold the potential to more effectively prepare for and prevent VBZD outbreaks when they are designed and evaluated with purposeful user engagement.

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CHAPTER 1: INTRODUCTION

Evidence suggests that outbreaks of vector-borne and zoonotic disease (VBZD) will continue to increase in frequency and severity [5]. The increased frequency of outbreaks is attributed to climate change-related temperature increases, making more areas suitable for vector survival and subsequent VBZD transmission [6], [7]. The increased severity is attributed to difficulty in containing spread of outbreaks due to globalization and increased international travel as well as population growth and more densely populated areas [8]. Over the last decade, the One Health approach has developed as a systems-oriented way to understand and mitigate VBZD outbreak-associated risks that considers a variety of data from animal, human, vector, environment, and infrastructure systems and sources [9].

Public health practitioners need tools to help them analyze and integrate data sources and provide a comprehensive assessment of the various factors that influence risk in order to effectively prepare for and prevent spread of future disease outbreaks. Some examples of influential factors for VBZD risk are population density, travel time to health facilities, land cover, and location of live animal markets. Further, these tools should have a user-friendly display that visualize information in a clear and acceptable way. Spatial Systems for Decision Support (SSDS) are a subset of data visualizations that allow decision makers to complete spatially related tasks more efficiently and effectively [10]. Unfortunately, SSDS frequently do not assess whether they meet the needs of their users [1] and do not incorporate best practices championed by advocates of human centered design (HCD) [11].

In my dissertation research, I introduce a new type of SSDS, *interactive vulnerability mapping tools*, which can help users in global health preparedness identify spatial areas that are at risk for disease outbreak. There are various users and use cases for interactive vulnerability mapping tools, including epidemiologists who might use this information for proactive surveillance, or public health planners who might use this information for vaccination campaigns or to inform resource distribution. Given gaps in prior research on data visualization and usability in global health preparedness, the overarching objective of this dissertation project is to develop visualization tools that can be evaluated for usability, propose design recommendations for interactive vulnerability mapping tools, and contribute evidence about the use of such tools that can advance the field of global health preparedness.

Specific Aims

In my dissertation research, I undertake the following aims:

Aim 1: Design, build, and evaluate an interactive mapping tool for dengue vulnerability in Peru. I iterated on design, investigated data visualization preferences, and performed a usability evaluation for interactive vulnerability mapping for global health preparedness through the use case of dengue vulnerability in Peru. In aim 1.1, I designed and built an interactive mapping tool utilizing a human centered design approach, engaging with end users early and often to iterate on the design through storyboards, interviews, wireframing, and prototypes. In aim 1.2, I evaluated the tool using a modified group usability methodology with representative end users during a workshop held in-country.

Aim 2: Design, build, and evaluate an interactive mapping tool for Rift Valley fever vulnerability in Kenya. To build on my first aim, I examined data visualization and usability in a different use case: interactive vulnerability mapping for Rift Valley fever vulnerability in Kenya. I held a co-design workshop with end users to identify users, use cases, and data where I shared information and answered questions about the vulnerability model and broke into topical focus groups to shape design of the interactive vulnerability mapping tool in Aim 2.1. In Aim 2.2, I evaluated the usability of the interactive mapping tool through remote interview sessions with screen and audio capture. Aim 2 furthers the work of my first Aim in both the design and evaluation approach. In the design, user involvement was more inclusive and deliberative in the co-design workshop than electronic communication with a smaller group of participants in Aim 1.1. In the evaluation, task analysis and individual-level data was better captured during the usability interviews than during the group usability testing in Aim 1.2.

Aim 3: Propose design recommendations informed by a scoping review of interactive vulnerability mapping tools of vector borne and zoonotic diseases. My scoping review objectives were two-fold: 1) describe the current landscape of interactive vulnerability mapping tools for VBZD outbreaks by characterizing data, technology, users, and use cases of previous studies (Aim 3.1); and 2) identify gaps in existing literature and compare to my studies in Peru and Kenya to inform design recommendations for interactive vulnerability mapping tools (Aim 3.2). I used a reproducible search strategy informed by PRISMA- ScR guidance and previous reviews to identify timely, relevant studies. To synthesize information across my research and the literature, I compare the findings from Aims 1 and 2 to inform design recommendations for interactive vulnerability mapping tools that may better engage users for short term acceptability, usability and, likely, long term sustainability.

Dissertation overview

In chapter two, I detail the importance of interactive vulnerability mapping tools and the potential impact on global health. To do this, I introduce the problem space by providing a summary of related work and map my research to these areas.

In chapter three, I describe methods for design, development, and evaluation of an interactive mapping tool for dengue vulnerability in Peru (Aim 1). I report on the findings from my collaborative design work with partners from public health and an academic institution in Peru (Aim 1.1). I share findings from a group usability workshop with end users held in Lima that included focus groups, task analysis, design preference selection, and a survey (Aim 1.2).

In chapter four, I build on the research from Aim 1 to inform the design, development, and evaluation of an interactive mapping tool for Rift Valley fever (RVF) vulnerability in Kenya (Aim 2). I describe the co-design approach and outcomes from the workshop held in Nairobi with a diverse set of key stakeholders involved in RVF work as participants (Aim 2.1). For usability evaluation (Aim 2.2), I share the methods and findings from remote usability interviews with medical and veterinary epidemiologists based across Kenya.

In chapter five, I return to the literature to describe related studies and highlight gaps in research on interactive vulnerability mapping tools for VBZD by performing a scoping review of the literature (Aim 3). I characterize data, technology, users, and use cases to describe the current literature (Aim 3.1) and then compare my own findings from Aims 1 and 2 to synthesize knowledge and inform design recommendations for future work (Aim 3.2).

In the final chapter (chapter six), I summarize the findings of my three aims and the contributions each makes to move forward the fields of global health, human computer interaction, and data visualization. I conclude my dissertation with a proposal for future work and a reflection upon the impact of this research on the field.

Chapter Two: Related Work

To provide a background and frame my Aims in relation to previous studies, I share a summary of pertinent work in global health preparedness, data visualization, human computer interaction. Finally, I ground my research questions by describing my interpretation of the Munzner framework. The Munzner framework is a nested model for data visualization that I have adopted for public health operational use.

Global Health Preparedness

There is critical need for health informatics tools to support global health preparedness. As global access to technology and connectivity increases, so does the potential to improve health outcomes by leveraging health information technology and informatics tools. Globally, we have the opportunity to harness 'big data' using data science techniques to provide better information to public health practitioners than ever before. This great opportunity is met with great need. Increased and emergent threats from VBZD outbreaks necessitates tools to support systems thinking for global health preparedness. The United Nations defines global health preparedness as "*the ability (knowledge, capacities, and organizational systems) of governments, professional response organizations, communities and individuals to anticipate, detect and respond effectively to, and recover from, the impact of likely, imminent or current health emergencies, hazards, events or conditions. It means putting in place mechanisms that will allow national authorities, multilateral organizations and relief organizations to be aware of risks and deploy staff and resources quickly once crisis starts*."[12] Borrowing vocabulary from this definition, my dissertation research contributes to preparedness through visualizing information to facilitate *knowledge* among public health practitioners for *anticipation* and the *likely impact* of health emergencies by allowing for the *awareness of risk, in particular* for a VBZD outbreak.

A deliberate consideration of the users, their needs, and use cases is necessary to effectively develop informatics tools [13]–[15]. Human centered design is an evolution of user centered design that involves stakeholders early and often in the design process to initially help understand user needs [16] and ultimately develop better designs. In public health, understanding the needs of users is no easy feat: there are often numerous user roles and ways to use the tool or system. Disentanglement of the different user groups, their workflows, and the associated use cases requires evidence-based methods and the deliberate analysis of needs and requirements. Several studies have demonstrated the importance of understanding context, users, and tasks in local and international locations[17]–[20]. Additionally, global public health informatics projects are complicated by several factors, including competing and changing demands, limited resources of both staff and funding, and restricted timelines. These factors may be more challenging in low and middle income countries (LMICs)[21], [22]. Unfortunately, researchers frequently do not take sociotechnical factors, such as human computer interaction, people, and organizational values, into consideration and build tools that are not able to be maintained in-country and, ultimately, prove unsustainable. In my dissertation research, I describe methods that are informed by the human centered design [3] and data visualization literature [4], [23]–[25] to design interactive vulnerability mapping tools across two countries and provide design recommendations for future work.

New vulnerability modelling algorithms provide invaluable information for global health preparedness, but it is crucial that it is presented in an acceptable and usable way. The interactive vulnerability mapping tools in this dissertation work harness published statistical methods for understanding outbreak vulnerability and will be available for public health practitioners in Peru and Kenya. I build on an outbreak vulnerability algorithm developed by Pigott and colleagues at the Institute for Health Metrics and Evaluation (IHME) to understand vulnerability to Ebola and other hemorrhagic fever virus outbreaks in western Africa.[26] I incorporated the same vulnerability model, which includes health, environment, and infrastructure datasets, into visualizations for the vector borne diseases dengue and Rift Valley fever in Peru and Kenya, respectively. The model has already been applied to Ebola. The model spatially identified areas at higher risk for an Ebola outbreak across three stages of an epidemic: 1) index case, or first case of a disease; 2) outbreak, or multiple localized cases; and 3) epidemic or widespread transmission of the virus. . The model uses a boosted regression approach with specific data considered at each stage. In stage 1, the model incorporates data for environmental suitability for vector survival as well as population density. In stage 2, indicators for health system strength are considered to understand what is the capacity of the health system to contain spread. In stage 3, travel data are modeled to understand human travel and proximity to cities using a measurement of travel time [27]. Please see Figure 1 for a depiction of the stages of the vulnerability model with corresponding datasets. Although the vulnerability information was highly valuable, it was not clear how or if the model is currently being used to prepare for or prevent future outbreaks. The project stakeholders believed this inaction was caused by poor usability of the Ebola visualization that was developed. Please see Appendix 1 for a screenshot of the Ebola visualization. By involving end users consistently and frequently throughout the design and development, and measuring usability, I sought to create interactive vulnerability mapping tools that are acceptable and usable to users and grounded in data visualization principles.

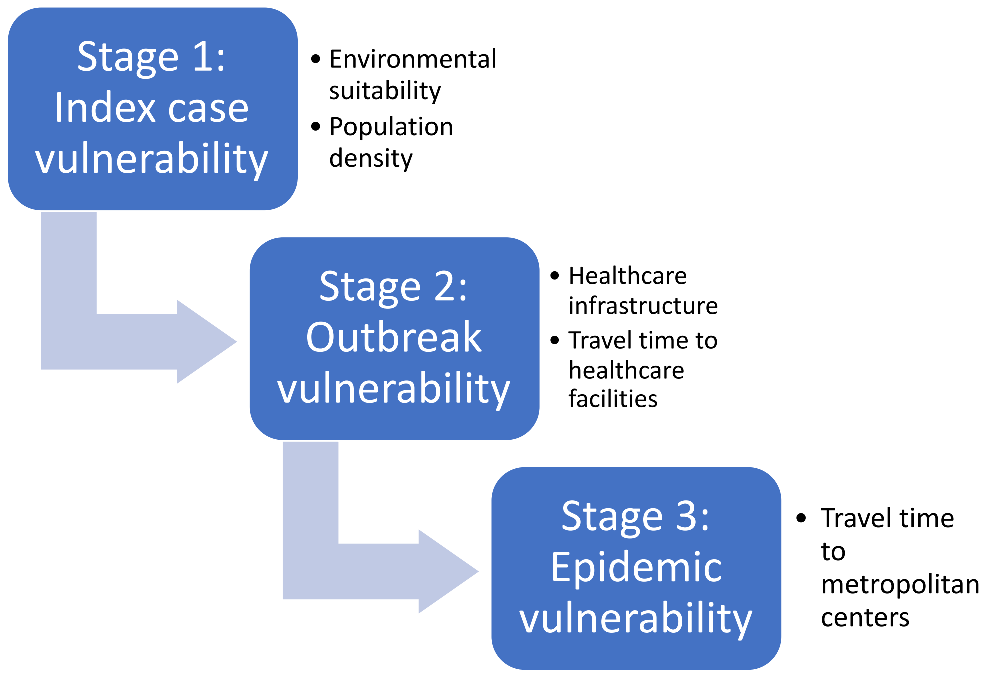

Figure 1: The Pigott model for outbreak vulnerability depicting the three stage approach and datasets used in each stage.

VBZD outbreaks are of increasingly global concern, but current tools do not meet data visualization best principles from color theory to providing contextual information. Changing environmental factors and population growth are creating a higher risk of vector borne disease outbreaks [5]. Two vector borne diseases of special interest to this research are dengue and Rift Valley fever. The World Health Organization recognizes dengue as the most important mosquito-borne disease due to the number of people at risk (2.5 billion) and the number of cases in a year (20 million)[28]. Further, incidence is increasing at an alarming rate: there has been a 50-fold increase in the number of cases in the last 20 years[28]. Latin America is particularly susceptible to a dengue epidemic as *Aedes aegypti* mosquitos are found in tropical climates throughout Latin America and may transmit the disease to humans. Dengue is endemic in some tropical regions in Latin America, meaning there is an expected number of cases on a regular basis that remain contained to a certain region. There are also periods of risk of epidemic dengue, where an outbreak may grow to affect a larger number of people and spread to more than one region.[29] The Pan-American pandemic of 2010 caused over 1.7 million cases of dengue [30]. Rift Valley fever (RVF), meanwhile, is a zoonotic disease that can be transmitted through mosquitoes or livestock to humans. There are two forms of RVF and dengue: a mild form and a severe form. The severe form of RVF can include serious symptoms such as ocular disease, meningoencephalitis, and/or hemorrhagic fever. Those cases presenting with the hemorrhagic fever form have a case fatality ratio of 50%, with death usually occurring in 3-6 days. There have been nine major outbreaks of the severe form of RVF since 2000, all on the continent of Africa.

To fully understand the risk of VBZD outbreak, many disparate data sources should be considered. The vulnerability model utilizes the One Health approach [31], highlighting the interconnectedness of different domains of health. One Health suggests that animal, environmental, and human health (and the corresponding datasets) should be taken into account holistically and systemically [32]. One Health requires incorporating many datasets across information sources to better understand the complete picture of health; visualization tools for One Health should similarly incorporate several data sources to understand vulnerability. Figure 2 suggests One Health datasets for vulnerability mapping based on previous studies [8], [26], [33], [34]. Because vulnerability requires the incorporation of so many datasets, it may be confusing or misunderstood by the end user. A One Health approach to VBZD vulnerability could provide valuable information to public health practitioners when developed and visualized in a clear, user friendly way.

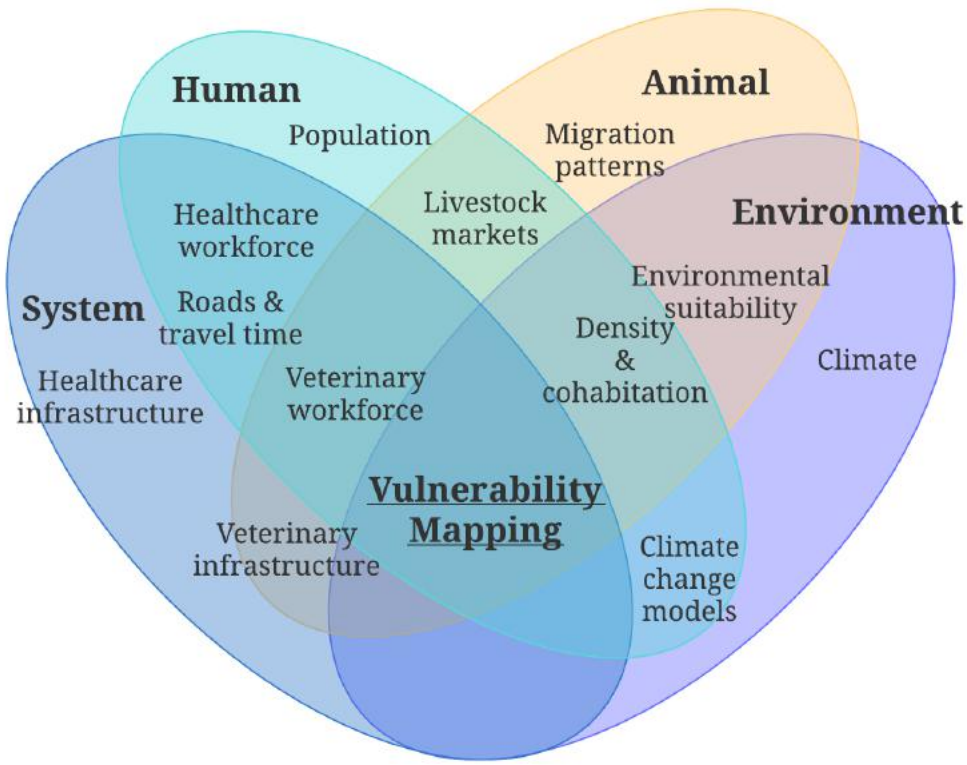

Figure 2: Understanding vulnerability entails incorporating many data sources. A proposed diagram of data that can be used to understand VBZD vulnerability is informed by the One Health approach.

Data Visualization

Given the surprising lack of research on visualization in global public health preparedness tools, I assessed design recommendations in the field of data visualization to determine if there were transferable findings. Data visualizations help end users to efficiently and effectively complete a task by displaying information and graphics for analysis, surveillance, or context[35].

Data visualization has long been used to understand and communicate vital, quantitative information. Florence Nightingale charted health and disease data to visually as early as 1854 [36]. W.E.B. Du Bois used data visualization to communicate data about institutional racism in the United States [37]. Edward Tufte suggested some design concepts for data visualization: considering the use of space or density, maximizing data ink, and minimizing chart junk.[38]. Importantly, his work suggests a thoughtful consideration of all visual design choices and how they might influence the user. Ben Schneiderman further contributed to the field by proposing that the user task (or task that the data visualization is supposed to convey) should be intentionally matched with the type of graphic displayed.[24] His adage "overview first, zoom and filter, then details-on-demand" lays the foundation for interactivity and suggests that a dashboard should meet both high level and more detailed needs of users.

There have been published recommendations for data visualizations for maps and GIS, including color scale recommendations and usability testing.[39]–[45], but these design considerations have not be adequately evaluated in global health settings.. In the literature of visual analytics for health informatics, 70% of included publications were conducted in North America with only one study from Africa and no included studies from South America.[46] The only African study was conducted in Ethiopia for mHealth application, and, though findings included usage statistics and qualitative usability feedback, the authors did not report any visualization or design-specific findings[47].

Spatially visualizing disease has been seen in history as far back at the 19th century when John Snow mapped Cholera in his community [48]. There are several important considerations for spatial data visualizations, such as shape [49], uncertainty [50], and spatial smoothing [51]. For the purposes of this research, I investigate three design considerations, color layout, and format, by providing participants choices among these considerations to select their preference. Color is of interest to the spatial visualizations in public health community. The red to green, diverging color scale is often reported in the public health literature commonplace practice [52], whereas other GIS or spatial visualization literature recommends other color scales for maps[53]. I also investigate the use of small multiples in maps to see if this data visualization principles holds true for global health settings as a design consideration for layout [25]. Finally, I investigate the narrative or story telling approach, as opposed to a minimalism, as a format design consideration [54]. The narrative or story-telling approach has gained popularity in many non-academic outlets, such as the New York Times [55], but, to my knowledge, has not be investigated in global health settings.

Effective data visualizations for timely epidemiological surveillance and outbreak preparedness are lacking; a recent literature review found that only seven of 55 visual analytic tools in public health included in the study use standard definitions or frameworks for design [56]. Though dengue and RVF comprise a significant threat to global health preparedness, and the need for effective data visualizations for both has been established in the literature[57]–[59], current visualizations do not adhere to data visualization best practices. These best practices include color theory [39], narrative or storytelling approach [54], and interactivity [60]. See Appendix 2 for a RVF and dengue spatial visualization from the literature. The first example demonstrates the lack of interactivity, poor use of space, and inappropriate color scale [58]. The second example show an inappropriate zoom level for the audience and a lack of contextual information for the user [59]. One potential solution for the lack of effective visualizations for VBZD vulnerability are Spatial Systems for Decision Support (SDSS). SDSS are a type of visualization that are meant to provide geographical data in a timely, user-friendly way to complete spatial tasks more efficiently and effectively [61]. The intent of a SDSS is to provide actionable information for decision making that is integrated into the current healthcare system. Unfortunately, SDSS are not often designed with user feedback or evaluated for usability [1]. In my dissertation research, I propose that design for SDSS would be strengthened by the incorporation of data visualization principles and use of human centered design.

Human Computer Interaction

An important evaluative component of human computer interaction (HCI) is usability. Usability applies to any interaction a user might have with usability testing of Health Information Technology (HIT) and is not routinely and effectively performed in global health settings. In their 2011 review, Yen and Bakken summarize 629 published usability research papers on HIT.[62] Their review found that most studies perform usability testing after implementation, when it is harder to make changes to the technology, rather than earlier in the development process. Similarly, a review of SDSS for zoonotic disease outbreaks in public health found that only 5 of the 12 included studies noted any type of usability assessment at any stage, and only 2 noted user input as a data source for their visualizations.[1] One of Beard and Scotch's key findings was that public health officials were only infrequently involved in these projects, but necessary to connect systems with their end users. Finally, a recent scoping review of usability methods in eHealth applications found that most studies did not report on usability findings. Those that did, the authors found, may not be using appropriate methods [63]. To ensure that my dissertation research used appropriate methods, I utilized a mixed method approach informed by Yen and Bakken's comprehensive literature review and analysis.

Applying a new method for testing usability in a group setting will provide insight into its feasibility for global public health. Many traditional usability methodologies, such as eye tracking, which is sometimes used for testing maps[64], may be too complex or expensive for global health, or, like ‘near live scenarios’ used in clinical informatics,[65] not suitable for the context. The group usability method allows researchers to observe multiple users while they collaborate on tasks and discuss their feelings about the tool in a focus group format.[66] This approach could be particularly effective for collaborative work, such as global health preparedness, and for finding high level usability issues before full development and implementation. Additional usability methods should be used to identify smaller scale issues and then refine usability in later stages of development, but the group methodology may be time- and cost-efficient for earlier stage usability testing. Given financial constraints and competing demands of public health practitioners, especially in LMICs, the group usability methodology provides an avenue to collect usability data in a lower cost and more efficient way in comparison to traditional individual usability testing. The group usability methodology has been used in virtual reality,[67] community planning,[68] and online learning research,[69] but to my knowledge has not be used in HIT. The approach consists of three parts: 1) a user background survey, 2) task-based exercises, and 3) usability discussion. Further, I propose additional components for the three suggested steps: a data visualization preference selection will provide evidence for design choices, as there is a lack in the global health literature; and a short, standardized survey to assess usability will provide an assessment that is frequently used in HIT.

I describe the application of my enhanced group usability methodology to the dengue interactive vulnerability mapping tool described in Chapter 2 as a demonstration of a new usability methodology to achieve Aim 1.

Interpretation of Munzner's Framework

The Munzner Nested Model for Data Visualization provides a conceptual basis on which I ground the research aims of my dissertation.[70] The overall framework provides guidance on design considerations that should be analyzed across four key dimensions to best design a visualization. Please see Figure 3 for my interpretation of Munzner's model for this dissertation. The first layer focuses on the domain situation where the data visualization is needed; in this layer, the researchers should ask the question ‘why is a data visualization needed?’. In the second layer, the question ‘what data are available for the visualization’ should be assessed along with the tasks or workflows currently performed related to the visualization objective. Relatedly, Munzner notes the importance of understanding constraints, metadata, and current workflows in determining the functional requirements of a data visualization. And in the third layer, the question ‘how to construct the visualization’, or the ‘visual encoding/interaction idiom,’ should be evaluated. The visual encoding/interaction idiom refers to stylistic visualization decisions, such as use of color and markings, as well as interaction considerations such as the resulting image when a user selects a filter or parameter. To simplify the terminology, I refer to the visual encoding and interaction idiom as the ‘design’. The fourth layer focuses on the algorithm used to generate the visualization including processing time and memory usage. As I used a proprietary software with an unalterable underlying algorithm for my visualization design, I focused on the first three layers of Munzner’s framework: 1. domain, 2. task & data, and 3. design.

Munzner also suggests validation steps at each layer of the data visualization model. At the first (domain) layer, performing observations and measuring adoption can be used for

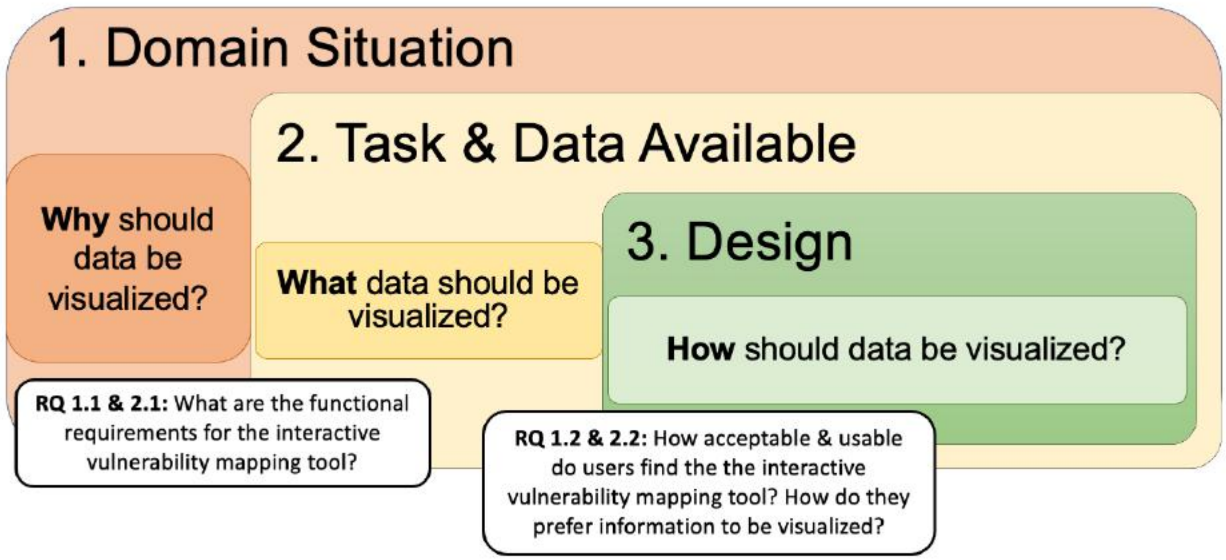

Figure 3: Adjusted Munzner nested model for visualization design with dissertation research questions [Munzner 2015]

validation. In the second (task and data) layer, a workflow analysis is recommended. In the third (design) layer, validation techniques include collecting qualitative data about the design from end users, measuring time to complete a task, and comparing design choices with alternatives. In the framework, validation techniques associated with each layer are not ordered and can be performed in any sequence. Munzner's validation techniques influenced the methodology I use to evaluate the design of the interactive vulnerability mapping tools, including qualitative methods, justifying design choices in respect to alternatives, and measuring time in lab experiment used in the third layer.

In this research, I applied the Munzner model as a guiding framework to design and evaluate the interactive vulnerability mapping tools. As depicted in Figure 1, I modified these terms for clarity and applied the model to my research aims: I referred to Munzner's 'justifying design choices with respect to alternatives" as "landscape analysis" in Aims 1.1 and 2.1. I refer to "measuring time in lab experiment" as "task analysis" in Aims 1.2 and 2.2. The first and second layers of Munzner's model were used to identify the requirements for Aims 1.1. and 2.1 by investigating the domain, task, and data. The design choices were investigated in the third layer; similarly, I established design principles and usability in Aims 1.2 and 2.2. I have adjusted the Munzner framework and situated the research question in Figure 3. As noted previously, I did not perform an in-depth investigation of the fourth (algorithm) layer, as I used a proprietary software platform that optimizes for memory, processing, and complexity. As an overall contribution to the field, I compared the findings from Aim 1 and 2 to studies gathered from a scoping review of the literature in Aim 3 to suggest design recommendations that should guide future work.

CHAPTER THREE: INTERACTIVE VULNERABILITY MAPPING TOOL FOR DENGUE IN PERU

Introduction

Changes in the environment and population growth have created a higher risk of vector borne disease epidemics in many places around the world, though this increased risk is often not met with risk mitigation measures, including public health planning and preparedness. Dengue, a vector borne disease for which half the global population is currently at risk according to the World Health Organization, is a leading cause of death for some populations in Latin America and Asia [45]. There has been steady interest in the human-computer interaction community for development and information visualization for public health [21, 22, 24] as well as increased interest due to Covid-19 [71]–[73]This chapter extends this previous work by exploring the potential for interactive information visualization tools to support public health interventions for global health preparedness, through my research on dengue vulnerability in Peru.

Understanding and planning for vector borne diseases, including dengue, can be challenging as there are many factors (such as weather and population density) that influence the risk of epidemics. Spatial Systems for Decision Support (SSDS) are a type of data visualization that allow decision makers to complete spatially related tasks more efficiently and effectively than they would without the tool. Interactive vulnerability mapping tools are a new innovation in the SSDS space that can help decision makers in global health preparedness identify spatial areas that are at a high risk for disease outbreak and make decisions such as where to spray for vector control and when to hold vaccination campaigns or increase other health services. Users of SSDS include epidemiologists, public health planners, health system administrators, entomologists, economists/finance, and administrators. Please see Appendix 5 for a detailed list of users and use cases. Prior work suggests the design of interactive vulnerability mapping tools for this diverse set of users should incorporate design concepts from geographic systems, design for development, and computer supported cooperative work [7, 9, 24]. However, there is a gap in the literature for design standards and usability methods for disease vulnerability tools on which to ground future work.

As part of an interdisciplinary team of researchers from the University of Washington and the Universidad Peruana Cayetano Heredia in Lima, I sought to address both dengue vulnerability as a threat to global health preparedness and a lack of empirical evidence in the literature on designing SDSS for global health preparedness. To accomplish this goal, I worked with public health stakeholders to design an interactive mapping tool for dengue vulnerability in Peru. Alongside stakeholders, including epidemiologists, directors of public health departments, vector control specialists, and economists, I built a simple, flexible design for a dengue interactive vulnerability mapping tool, then evaluated our design in a group usability workshop. The tool provides information that can help public health professionals plan for and prevent dengue epidemics in Peru. I purposefully and frequently included these users in our design and evaluation activities to create a usable tool with high operational value that encourages long-term use and engagement. Our study contributes empirical evidence to support design recommendations for information visualizations in the critical context of global health preparedness, a demonstration group usability format for user engagement in global health efforts, and a technological solution for mapping dengue vulnerability in global health preparedness.

Related work

A recent literature review of SDSS for vector borne diseases highlights the need for further design and usability research [3]. The authors found that, of the 12 systems included in the review, only 3 included user input and only 5 performed usability testing to any degree. Though there have been studies on visual analytics in healthcare [8, 42] and the use of technology in epidemiology [10], these findings have not been validated in global health preparedness tools at large and specifically for a new type of SDSS, interactive vulnerability mapping. It is important that I understand the application and fit of data visualization principles from other fields such as computer science [37] by conducting an evaluation of our data visualization with end users and contributing to the knowledge base. Further, I am contributing to health information technology (HIT) by addressing 2 of the 5 recommendations from a recent JAMA article on usability problems in HIT by 1) establishing basic design standards and 2) developing usability methods and measures [35].

There have been other visualizations that include data on vector borne diseases [5, 11, 19], but these projects have not focused on the design or usability of the tool. I have not found another SDSS tool with interactivity that allows more flexibility and user selection. To situate this work in an HCI framework, I applied Munzner's nested model for data visualization [29], which allowed us to conceptually understand the appropriate design questions and validation techniques for a data visualization. The first layer focuses on the domain situation where the data visualization is needed. In this layer, the researchers should ask the question 'why is a data visualization needed?' In the second layer, (the task and data layer), the question 'what data are available for the visualization' should be assessed along with the tasks or workflows currently performed related to the visualization objective. Relatedly, Munzner notes the importance of understanding constraints, metadata, and current workflows in determining the functional requirements of a data visualization. In the third layer, (design layer), the question 'how to construct the visualization', or the 'visual encoding/interaction idiom,' should be evaluated. The visual encoding/interaction idiom refers to stylistic visualization decisions, such as use of color and markings, as well as interaction considerations such as the resulting image when a user selects a filter or parameter. I explain my design processes in reference to the Munzner conceptual framework.

In the following sections, I describe the setting l and then describe the design process. The design methods and results included storyboards and interviews, wireframes, a landscape analysis, and development of the tool with alternate design prototypes. Next, I describe the usability evaluation methods and results, which included design preference selection, perceived usability survey, task analysis, and focus groups.

Study Setting

Our research partners from Universidad Peruana Cayetano Heredia (UPCH) engaged local health stakeholders in Peru for this work. Peru is located on the northwest side of the continent of South America. It is one of the most populous countries in Latin America with over 30 million people. Peru is environmentally diverse; it is one of the few countries that has distinct rain forest, desert, and mountainous regions. Peru also experiences diversity and disparities throughout the country in terms of wealth, infrastructure, and access to health services. The public health system in Peru is decentralized, with three organizations (including the national public health department) providing health care services to 90% of the population. The remaining 10% is provided by the private sector. One of the interesting components of the healthcare and pollical systems is the transition of power – there is frequently changes in political leadership and parties that might create various disruptions in healthcare provisions [74]. It is also home to the *Aedes aegypti* mosquito, which transmits dengue to humans and results in numerous cases annually. These conditions make Peru an exceptional location for a proof-of-concept research study to develop interactive maps that visualize geographic areas that are vulnerable to risk of a dengue outbreak.

Design methods

I carried out 4 key phases of work to design and build an interactive mapping tool for dengue in Peru. I situate this work in layers of Munzner's nested model for data visualization [29] and indicate the corresponding nested layer to each phase of our work in the following description.

A bilingual member of the research team translated all materials and instruments from English to Spanish and another team member verified to ensure accuracy.

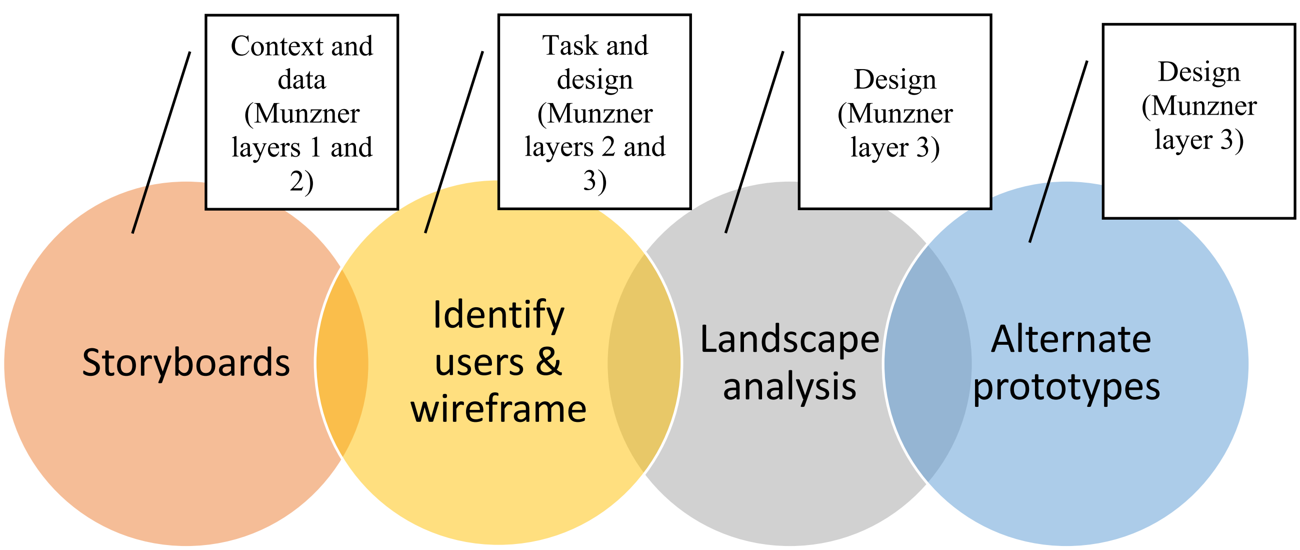

Figure 4: A graphic of the four phase design methods used to generate the interactive vulnerability mapping tool for Dengue mapped to the layers of the Munzner framework.

Phase 1: Storyboarding interviews to understand user context and needs. To begin the design process, I used storyboarding interviews to characterize the needs, characteristics, and tasks performed by end users as well as the context of their work. The Munzner framework describes these layers as the domain situation, Munzner Layer 1, and task and data, Munzner Layer 2, respectively. Storyboards are a pictorial display of a specific user interaction or sequence and are typically accompanied by a narrative [30]. I used a storyboard to explain the concept of the visualization tool and to gather feedback from end users on its appropriateness and suitability to their work using the 'storyboard that' software program [75]. The UW research team conducted interviews with eleven public health practitioners in Peru who would use the tool in the future, including subject matter experts in dengue surveillance. Interview participants were recruited by convivence sample. Interview questions included: (1) What data are needed and available for the visualization? (2) How do you currently perform dengue surveillance activities? and (3) What constraints or roadblocks do you have when assessing dengue vulnerability? During these interviews, participants were also asked to review and provide feedback on the storyboard. I summarized notes from the interview and consolidated documentation for the phases 2-4 of the design.

Phase 2: Identify user groups and create wireframes. I worked with the UPCH team members to identify and classify the main types of interaction for the visualization tool. I facilitated this interaction discussion by considering the types of users, including their job roles and organizations, their jurisdiction (local, regional, national), their expertise (epidemiology, finance, vector control, policy), and their context of use. I then created an initial set of three wireframes using the prototyping software, Sketch[76], based on information needs obtained during the interviews in Phase 1. Members of the research team from UPCH reviewed and refined the wireframes to serve as functional requirements to implement in the future as high-fidelity prototypes on a visualization platform. My Phase 2 activities correspond to Munzner's layers of task and design idiom layers 2 and 3. For analysis, I worked with UPCH team members to annotate the wireframes with notes and considerations and summarized users and use cases in tabular form. Wireframes and user group documentation was shared with UPCH team members for review and refinement through email.

Phase 3: Landscape analysis to select a visualization platform. A comparison of visualization options can help determine the best avenue for tool development [34]. This analysis of technology and design implications corresponds to Munzner's design idiom layer (layer 3). A landscape analysis typically is similar to market research techniques, [28] and analyzes best fit of current market options by ranking important considerations. Landscape analysis has been used in global health informatics to understand the state of technology development in LMICs [34]. I used dimensions are based on the taxonomy for visualization platform suggested in the literature [4] and worked with 5 local representatives to score each option from best to worst. I compared the dimensions of functionality, accessibility, and sustainability across four popular visualization platforms with research team members from UPCH: 1) D3.js using the leaflet library [77], 2) R using the shiny app [78], 3) Tableau [79], and 4) the Microsoft Power BI [80].

Phase 4: Build alternative prototypes that concretely illustrate interactive dengue maps. I iterated the interactive prototype design using Tableau Version 2019.2.0 with four key members of the

UPCH research team who work on dengue surveillance and visualization. I deployed the interactive prototype tool on a public server in preparation for our evaluation. To inform design recommendations, I also created alternative wireframes of the tool to isolate different design elements (i.e., color, layout, format) for comparative evaluation. I selected these elements to build on prior studies examining color in design of data visualizations preferences [4, 20, 23] as well as to understand layout and format considerations as part of the storytelling approach to data visualization [36]. Phase 4 also corresponds with Munzner's design idiom layer, layer 3, as she suggests providing design choices to users with respect to alternatives.

Design Results

Phase 1: Storyboarding interviews to understand user needs and context. The storyboard described an epidemiologist using the tool to understand and plan for dengue vulnerability in her jurisdiction. Please see Appendix 3 for the resulting storyboard. I learned from participants how activities and workflows for dengue preparedness and surveillance are currently performed in Peru. Participants also described an unmet need for information that integrates information from multiple sources such as vectors or climate and population or incidence data. Participants indicated they may use an interactive mapping tool for dengue vulnerability to make financial, vector spraying, and vaccine campaign decisions. I made some minor alterations to the storyboard to reflect feedback from participants that the epidemiological workflow would be slightly different.

Phase 2: Identify user groups and create wireframes. Please see Appendix 4 for an example wireframe that was developed during phase 2. I identified a wide range of users with varying information needs and analytic requirements, including job roles at various levels of government.

Some of the job titles included epidemiologist, public health planners, vector control, directors, policy analyst, laboratory technicians, and administrators. Further I identified 6 different Peruvian organizations where these users might work. They might interact with the tool to answer the following questions: Where should I focus preparedness efforts? Is this an El Nino year? Where should I spray more? Why are there more cases in this area than are expected? I validated these interaction types with the UPCH research team members and designed wireframes with flexibility in mind to meet a greater number of user cases. Please see Appendix 5 for user group descriptions.

Phase 3: Landscape analysis to select a visualization platform. Please see Appendix 6 for a graph with relative ranking of four visualization platforms. Based on that discussion, I selected Tableau for its ease of rapid prototype iteration and maintenance, current licensing and hosting ability with users in Peru, and the previous experience of the end users with this software. D3.js offers the greatest flexibility in design of mapping functionality but is the most difficult to maintain and build capacity for sustainability in our setting. R-shiny falls somewhere in the middle of our choices as there is still a server cost (high accessibility) and high technical expertise needed (low sustainability). Microsoft BI has a cost on the higher end of the spectrum, and I felt the mapping functionality was not as high, though the maintainability was reasonable. Ultimately, Tableau proved to be the best choice as it has very good interactive mapping functionality and is likely able to be maintained with less technical experience. I also learned that some organizations that were involved in this work had licenses and a server for Tableau, further reducing the cost and increasing the likelihood of maintenance.

Phase 4: Build alternative prototypes. I created seven alternative wireframes that varied these design elements and enabled us to assess users' design preferences during usability testing: three variations for color, two for format, and two for layout. Please see Appendix 7 for the alternative wireframes. For color, I included three wireframes, each with either a diverging (red to green), sequential (going from light to dark blue), and qualitative (or distinct colors) color scheme. The two wireframes isolated format and included a storytelling with contextual narrative or a minimal dashboard with less textual information. For layout, I included the option of a single map with additional information on the tooltip or a side by side map showing that information. Please see Figure 5 for a screenshot of the interactive prototype that was created based on work described in design phases 1-4 and was used during the usability workshop.

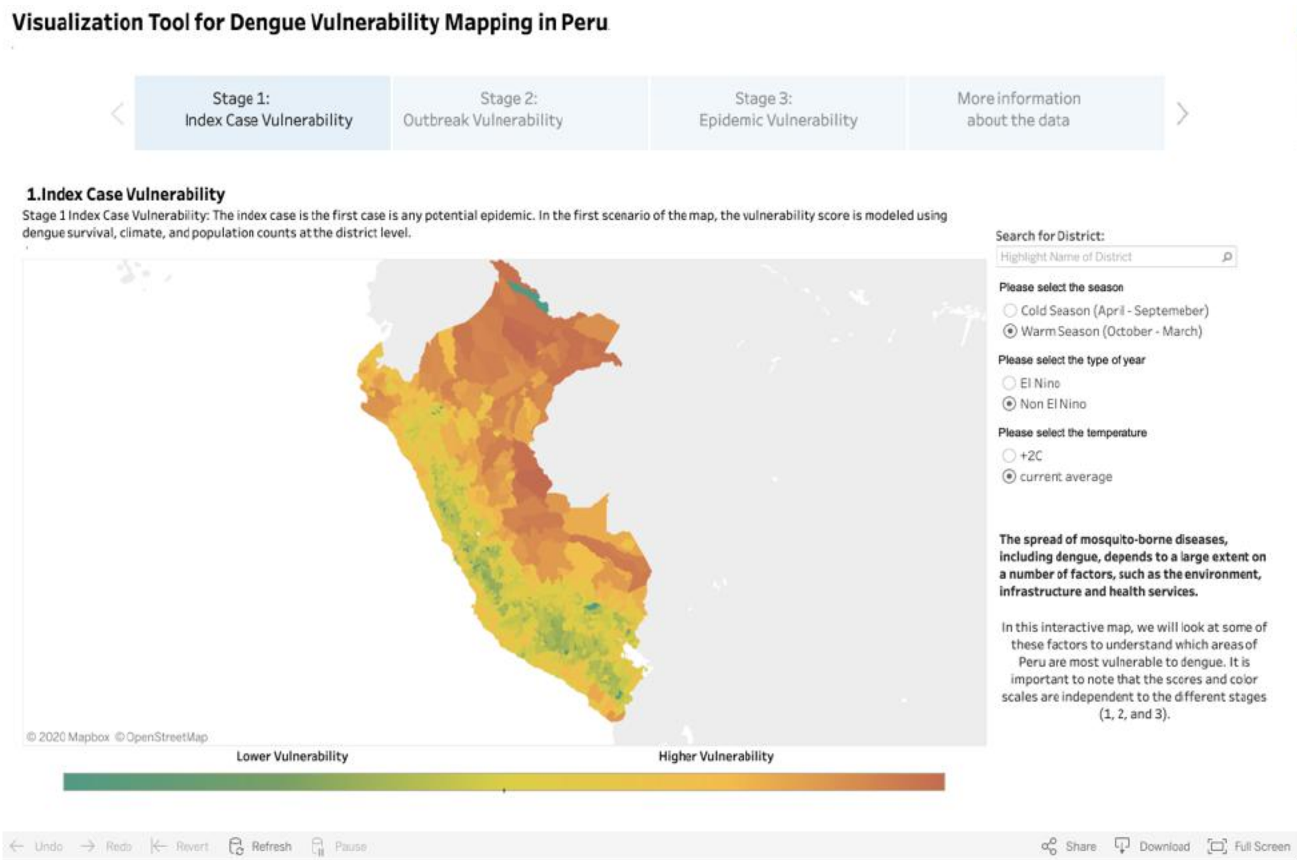

Figure 5. Screenshot of the interactive prototype for dengue vulnerability that was designed and evaluated with local users.

Usability evaluation methods

To evaluate prototype usability with local users, the research team held a half-day group usability workshop in Lima, Peru in June 2019. The workshop was held in a centrally located hotel in Lima and participants were provided a laptop with the interactive vulnerability mapping tool for dengue preloaded for use during the usability testing. The Institutional Review Boards (IRBs) of UPCH and UW approved the study procedures. I trained five bilingual graduate students in health informatics to help facilitate the workshop in Spanish. I de-identified all participant data and linked responses with a corresponding participant number.

I recruited a convenience sample of participants from public health and governmental agencies at the national level in Peru. A letter of invitation was sent from the local project champion. Participants received a certificate of participation and meals during the workshop but were not financially compensated for their participation in the study. Participants provided oral consent, as is customary for research studies in Peru.

The group usability workshop consisted of four parts: 1) introduction and background about the project; 2) online survey; 3) task analysis; and 4) focus group discussion. The workshop format adheres to the group usability method [18] but expands the individual survey to include collection of design preferences and a standardized survey on perceived usability.

1. Project introduction: At the start of the workshop, facilitators from UPCH presented an overview of the vulnerability mapping project and progress to date. This presentation was given in Spanish and paper copies of the slides were provided to participants. At this time, I asked participants for verbal consent to participate in the study and be audio recorded.

2. Survey: The individual online survey collected professional demographic data, design preferences among the seven paper prototypes, and SUS scores on the perceived usability of the interactive prototype. Professional demographic data included organization, position title, number of years at their job, and percent of job time that is dengue surveillance. I also asked participants to report their comfort level with technology and comfort level with spatial/mapping systems on a 10-point Likert scale from 1 ‘very in experienced’ to 10 'very experienced'. Participants were asked to select which visualization alternative choices they preferred for color, format, and layout and to rate the importance of each design option on a 10-point Likert scale from 1 "least important" to 10 "most important". Please see Appendix 8 for exact questions used for visualization preferences. The alternative visualizations were presented as static wireframes in the online survey, which was administered using a google form [81]. I asked participants for open-ended feedback about their reasons for each response. I collected survey data on perceived usability of the tool using the System Usability Scale (SUS) following task analysis, which is described next.

3. Task analysis: The survey linked the participant to the interactive prototype so that they could interact and answer questions for usability task analysis[82]. Data collection included answers to questions associated with the 5 usability tasks, an option for open-ended feedback with each response, and total time to complete all tasks. After completing usability tasks, participants were asked to report perceived usability on the 10 item SUS [6]. I considered several usability surveys [13, 15, 25, 31] and selected the SUS because it added little cognitive burden and time to the respondent given its concise, standardized format and use as an industry standard for benchmarking. A SUS score of 68 or greater is considered adequate usability [83]. I asked tasks that would be representative of how a user might interact with the system and utilized all the features of the tool. The task analysis questions are as follows:

Number	Task	Response type	Feature that was tested
1	According to the model shown on the maps, which areas of the country have the highest risk of index cases of dengue in winter of a non-el Nino year?	Structured, multiple choice	Overall map/visualization
2	What is the index case vulnerability score for Satipo district in summer of a non-el Nino year?	Structured, multiple choice	Search function for specific district
3	Which of the following are high vulnerability score districts for index cases (stage 1) of dengue in summer of an el Nino year? (select all that apply)	Structured, check box	Using the parameters (season and el Nino)
4	In the region of Piura, is vulnerability higher to index case (stage 1) or outbreak (stage 2)?	Structured, multiple choice	Changing between stages
5	In the Purus district, how does the vulnerability score change from stage 2 (outbreak vulnerability) to stage 3 (epidemic vulnerability) in summer of an el Nino year?	Structured, multiple choice	Finding specific vulnerability scores and changing stages

Table 1: Tasks with response type and feature notes that was conducted during the group useability workshop

4. Focus groups: Group discussion focused on interactive prototype usability. I divided participants into four groups of five participants and matched with a facilitator. I formed groups that each had a mix of job roles and representation of organizations (e.g., a health specialist from the Ministry of Health and lab technician from an environmental organization). Facilitators asked participants about their perceptions and understanding of interactive prototype along with the open-ended questions based on the Model for Information System Success to guide the discussion [16]. This model is frequently used in HIT usability studies and includes factors on system quality and information quality, among others (i.e., system use, user satisfaction, and individual and organizational impact). I asked questions regarding system quality (easy to understand, relevant, and complete) and information quality (reliable, adaptable, and verifiable). To conclude the workshop, participants were asked if they had any closing thoughts. Focus groups were audio recorded, transcribed, and translated into English. For a full list of questions mapped to Model for Information System Success factor please see Appendix 9. Our focus group questions included:

- What, if anything, did you like and/or dislike about the tool? Please be as specific as possible.
- Do you think this type of tool would be helpful in your current work for dengue preparedness?
- Is there additional information that would be helpful for you to see? If so, what information?
- Was there too little, too much, or the appropriate amount of contextual information and narrative?
- Did this tool allow you to complete the tasks more accurately or quickly than you would be able by other means? Were there other tasks that you would like to be able to complete?
- Did you trust the information that was displayed? Did you believe it to be accurate and reliable?
- Where and how would you like to access this tool?

Data Analysis

I used a data analysis plan for mixed methods data collected during the group usability workshop. For quantitative data from the survey and task analysis, I summarized data with descriptive statistics. I ranked design preferences (i.e., color, layout, and format) and perceived importance of those design choices. I reported the percentage of correct answers for accuracy of usability task responses.

For qualitative analysis of focus groups transcripts, I used an inductive qualitative approach [39]. A local researcher (Javier Silva Valencia) and I systematically read the transcripts to create a set of codes and definitions in a codebook. We began coding transcripts from two of the four group discussions and then compared codes to finalize the codebook through discussion. We then applied the codebook to the remaining two focus groups. We discussed coding discrepancies until reaching consensus. After making final coding adjustments, we discussed emergent themes. We discussed findings with the research team to ensure a group consensus on those themes.

Usability Evaluation Results

In the following sections, I share details and findings from the group usability workshop summarized by participant characteristics, survey findings, including design preferences and perceived usability, task analysis, and themes from the focus group discussions.

Participant characteristics

Twenty participants attend our group usability workshop (P1-P20). This included a diverse set of professionals including lab technician, health specialist, executive director, systems analysts, follow up specialist, among others. Of the twenty participants, eighteen provided professional demographics and experience on the survey. The average years of experience of respondents was 6.4 and 67% reported currently performing dengue surveillance in their jobs. Of those that currently perform dengue surveillance, this activity constitutes, on average, about 67% (range 10-100%) of their time. Most respondents were comfortable with technology and spatial systems, reporting an average 8.7 and 7.8 out of 10, respectively.

Design Preferences for Color, Format, and Layout

Among the seven paper prototypes illustrating variations in color, format, and layout, participants strongly preferred the diverging color scheme option, with 18/19 participants (95%) choosing this option over the sequential and qualitative color schemes. On average, participants rated color as very important (mean = 9.6 out of 10, range 8-10). Twelve participants (63%) preferred the single map layout with a narrative tooltip over side by side maps. On average, they rated the importance of layout 9.2 out of 10 (range 5-10). Thirteen participants (68%) preferred the storytelling format over the minimal dashboard format, and also rated 'approach' as important with a mean rating of 8 out of 10 (range 3-10). Please see Figure 6 for visualization preferences by reported importance. Free text responses to explain why participants chose each option were optional on our survey, and participants provided the most explanation for the color scale, likely because they also ranked color as highly important. Participants noted that they preferred the diverging or red to green scale because 1) the colors align with other reports and data visualizations that they reference, 2) the colors are intuitive, and 3) allows for easy differentiation.

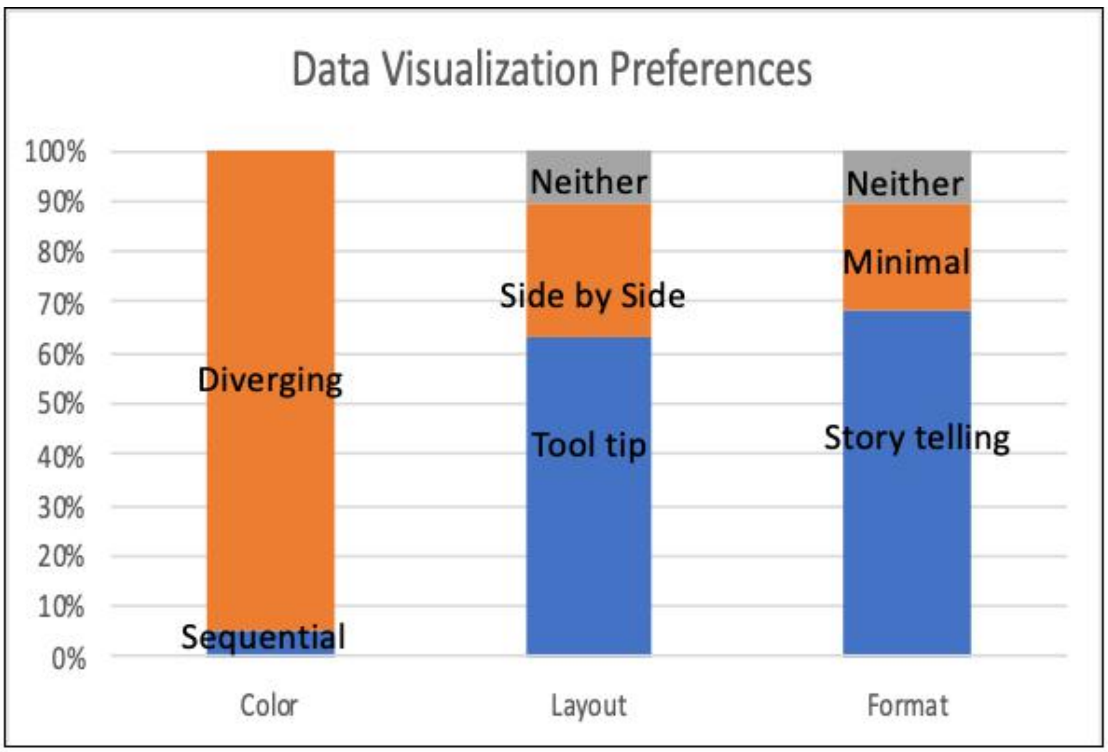

Figure 6: Participants' preferred visualization options for dengue vulnerability visualization tool. For color options, no participants preferred the qualitative scale (option 3) or responded that they did not prefer any option.

Perceived Usability

The average SUS score was 75.13, SD =19.97 and there was a wide range of individual scores from 25 to 100. Per standard use, a score of 68% or better is considered 'good usability' and would be a "B" score per industry standards. The participants rated the two statements "I felt very confident using the tool" and "I would imagine that most people would learn to use this tool very quickly" highest and rated the statement "I thought there was too much inconsistency in this tool" lowest. The learnability subscale was 78.29 and usability subscale= 74.34, indicating that learnability and usability were similar to overall SUS ranking [84].

Task Analysis

There were mixed results from task analysis. All participants completed the 5 tasks in under 50 minutes (range 23-49). Average accuracy for tasks 1, 2, and 3 was 100%, whereas accuracy was lower for task 4 (89%) and task 5 (33%). Participants expressed confusion regarding certain aspects of the tool and this likely contributed to poorer performance on task 4 and 5. The expressed confusion on vulnerability score meaning in relation to the data provided in the hover over. For instance, many participants did not reset filters when they changed from Stage 2 to Stage 3 in the final task and answered the question incorrectly. The filters automatically refresh to the default setting when you change stages, so participants sometimes did not remember to change filters between stages.

<u>Focus Group Themes</u>

I identified 6 emergent themes from focus groups discussion on prototype usability, which I describe below with representative quotes.

There is an unmet need for an interactive tool

All four groups provided positive feedback that they found the design easy to use and appreciated the interactivity. They found the information that the prototype provides could be beneficial to their work in dengue preparedness or resource allocation. Related responses were that the tool was simple, easy to use, flexible to answer different questions, and provided information they found useful. I heard that the interactivity was helpful as it allowed participants to customize the visualization to answer multiple questions they might have of the data. A participant below highlights the need for this type of information.

> "A great weakness of the country is the issue of information, and what better if this information, characterized in the location, could allow us, as my partner indicated, to make decisions and be perhaps more equitable in the allocation of budgets under some indicators or characterizations of what are the determining factors to produce the disease." (P3)

Additional data sources yield additional value

Participants expressed a strong desire to include additional data sources beyond the vulnerability model and related factors that I included in the visualization. For example, participants wanted a layer unmodeled data (such as vector density and dengue incidence rates) with our model to make the prototype more valuable and comprehensive. Participants requested adding a variety of data sets, some of which I anticipated (e.g., mosquito vector data, historical dengue incidence data, altitude data, human migration patterns), and others I did not anticipate (e.g., financial resource data, sanitation data, data on presence of a dengue campaign in the last 6 months. They noted that these additional data sources not only increase the operational value of the tool, but also increase trust and improve decision-making. A participant reflects on additional data that she would find helpful.

> “Another small thing is that I have vulnerability data, I have accessibility (access to health services) data. I would need to see a mechanism of how to integrate them to obtain a better interpretation. Someone can say: "This throws the data", but you as a decision-maker, what would you have to consider from that data." – (P14)

Confusion about data may lead to distrust

Trust might influence a users' future use of the tool, so I purposefully asked participants about trust in the tool and information provided. Participants did not explicitly express distrust in the visualized information but raised several questions about both the raw data and the algorithm to model the vulnerability score. There were questions about specific sources of data, such as what DPT vaccination rates were used to formulate the vaccination score, and how the raw data ultimately influenced the overall vulnerability score. Participants who were more familiar with dengue surveillance and data analyses were more likely to express these concerns. Participants were also concerned about specific indicators used in the model, specifically travel time to the nearest population center and travel time to the nearest health facility. Finally, there was confusion about the relative nature of the vulnerability scores and the climate change filter, which can be selected to increase the model by two degrees Celsius. The "+2C" filter feature was designed to show the impact of climate change in the future and visualize how it could impact dengue vulnerability. Though participants did not express initial distrust, I speculate that this confusion about the tool and/or underlying data would ultimately result in distrust in the long term as this confusion-distrust affinity was experienced during the H1N1 [85] and Covid-19 pandemics [86]. Whether it be related to trust or confusion, any concerns expressed by participants that may impact future use, should be carefully considered and addressed in the design.

Special attention is needed for the consideration of time and space

Participants raised concerns about the temporal and spatial aspects of the data and visualization. Participants desired having clear language about when the data were collected, timespan data represents, and when data was last updated. They noted that the presence of this temporal metadata influences their likelihood of use and acceptance of the information. Participants also noted issues concerning spatiality and geographic divisions. They expressed the desire for the model to be aggregated at several levels of geography: province, region, district, and population center. Additionally, labels for the current visualization needed to include all the geographic division names, as there are multiple districts that share the same name, making misidentification possible for users that were not familiar with the area. Spatio-temporal queries are an important component of disease tracking as public health practitioners need to understand location of and trends over time [87] and similar functionality has been incorporated into visualization tools to understand the Covid-19 pandemic [88].

Diverse users led to a wide variety of use cases

I included a larger group of participants than are typically necessary for required for usability testing [89]. With different perspectives, there was an expressed need to analyze these data in a number of different ways. Some participants wanted more precise, predictive information about how many cases of dengue were expected with various selection filters and how much resources would be needed. Others wanted precise information about how the selected vulnerability score for point in time compared to that exact historical scenario, for example week 22 in 2016 in Lima compared to the future vulnerability score for that population. The need for comparison was expressed in other ways: participants desired the ability to see a selected area at all three stages at the same time. They also wanted to be able to compare different filter selections for a selected area on the same screen. There was a need to not only align with current reporting measures, but also allow for comparisons between time periods, geographic locations, and stages. Participants also desired the ability to download data to be able to do their own analyses outside of the tool. They also expressed wanting a similar vulnerability score for other diseases and health conditions such as malaria and anemia. A participant shared the need to analyze health data through multiple lenses:

> "Dengue is not just a health problem. There is a problem of (social) determinants that correspond to the local government." – (P8)

Plans for sustainability should occur concurrently with design

Some of the participants touched on the concern for sustainability and having a plan for maintenance, ownership, and long-term use. One group brought up the need for a champion for the tool by having a high-level person in their organizations promote use and understanding. Others noted the need to include local health departments as early as possible so there would be local engagement and ownership. There was the expressed desire to have conversations early about agreement and documentation of roles and responsibilities around hosting, data refreshes, and other considerations for maintenance. Lastly, participants mentioned the importance of accessibility across the country. As technological infrastructure varies across Peru, there should be a way to download a version of the tool for use in locations with low connectivity and a mHealth app to allow use on mobile devices and tablets.

Discussion

Our design process and usability evaluation of an interactive vulnerability mapping tool for dengue in Peru provided a number of considerations for design of SDSS tools for global health preparedness, as well as key insights for improving the next version of our tool. Next, I summarize the implications of our findings for future work.

Design Recommendations for Data Visualization

As interactive mapping tools for global health preparedness is in its nascence, I sought to understand some foundational elements of design standards. Our findings that participants prefer a diverging color scale and a storytelling approach confirms literature in other domains with similar results [23, 36]. I advance previous studies by including a larger sample size and application to a new domain. A diverging color scheme differentiates better (low vulnerability) scores from worse (high vulnerability) scores and likely takes little mental effort to associate the scores with the color. Further, I heard from participants that starkly different colors make the tool very visually easy to understand. I chose a stoplight-like diverging color scheme (i.e. red, yellow, and green) that is very common in public health visualizations and is a familiar association in the local culture. This finding confirms work in understanding localization in health projects [40] and in Peru [38] and serves as an extension to public health data visualizations. Additional research to understand whether other contrasting color schemes are favorable would be interesting to further support design standards. Relatedly, future studies could isolate specific elements of the storytelling or narrative approach, such as the suggested amount of contextual information to provide different ways to use the 'stepper' visual [ref]. Finally, a very interesting finding was that participants reported that all design considerations were very important (on average above an eight or above out of ten) to them. This may indicate that public health users consider design elements to be impactful and critical to understanding and use of a data visualization.

Designing for Two User Types

Although our participants were diverse in job titles and roles, I found that our user groups could be summarized by two primary roles: data experts and data consumers. *Data experts* may be epidemiologists, economists, analysts, or technicians, and analyze different types of quantitative data frequently. They make complicated decisions about the correct analysis method and presentation of information. *Data consumers* may be directors, managers, planners, or administrators and interact with data frequently, but may be more likely to receive reports or previously analyzed information. They often receive reports from a number of different sources to make complex decisions. Previous studies have suggested that information needs are dependent on public health job role or segment [90], [91], and I suggest information visualization should also be tailored to user purpose of use. Both groups work across topic areas and have distinct purposes of use, necessitating additional layers of data and ways to interact with a visualization tool. A tool design could accommodate for these two levels of use by providing ways to receive high level summaries (for consumers), but also more detailed and access to downloadable data for their own analyses (for experts). This is reflected in the GIS literature as the roles of "map makers" and "map users" in public health [52]. Further, research in data visualization suggests "overview first, zoom and filter, then details on demand" [24], a design suggestion that would address the purposes of use of both 'data experts' and 'data consumers'. Simplifying user groups among the 'data expert' and 'data consumer' roles may provide an accessible and understandable approach to design for future developers of interactive vulnerability mapping tools.

Better Data Communication and Embedding Understanding

Prior to the workshop, the research team spent a great deal of time to consider the simplest, easy to use design of the vulnerability data possible. I sought to streamline information and reduce cognitive burden as much as possible. The vulnerability model itself is a somewhat challenging concept for users to learn, perhaps providing more information about the model and how data are used is a more beneficial approach. Next iterations of the design should include communication about what information I can infer from the model, such as where environmental, population, and infrastructure factors make vulnerability to dengue high, and which inferences cannot be made, such as exact number of cases expected and associated costs. Further, the climate change scenario seems to be particularly confusing for users. I included this a "+2 C" option, indicating a change in the underlying climate model if temperatures increase in the future. This design choice was intended to show the impact of climate change or "+2 C" to current climate models to visualize how dengue vulnerability may be impacted with increasing temperatures. Warmer temperatures mean a larger spatial area that is suitable for vector survival, which may lead to greater vulnerability to dengue. Though I continue to feel that this is an important feature to include as climate change and vulnerability to vector borne diseases are intrinsically related, better explanation of this feature and our reasoning for its inclusion in the tool is needed.

Building trust

When working with stakeholders to design a tool that is intended to become a part of their workflow, it is important to build trust in the tool, the data feeding the tool, and the project itself [ref]. I heard this from participants in a number of ways: the importance of champions, the need to engage local stakeholders, transparency in data transformation, integration, and sources, and were closely tied to their concerns about sustainability. I have proposed measures in the previous section to encourage understanding and transparency about the data and sources. I expect that national hosting and management of the tool will also increase trust [ref]. A documented agreement for a sustainability plan should also be developed working closely with stakeholders in Peru. There may also be additional trust in future iterations as I demonstrate that feedback from participants was incorporated and valued by the designers. Our findings extend work in sustainability of health information systems in Africa [28] and designing of non-health related technology in Peru [38]. These previous studies and my own contribution emphasize the importance of stakeholder trust through interaction with communities, local considerations, and capacity building.

Limitations and future work

With convivence sampling, I only included national public health and government officials in our feedback gathering. I acknowledge the importance of local public health workers, and it is a limitation of our findings that they were not included. I also did not include the vulnerability risk for pandemics in the tool, as pandemics necessitate a larger research scope and involvement of more than one country.

Another limitation is more in-depth analysis of user groups. My perspectives for user groups and associated needs are based on my own recollection and informal conversations with stakeholders in Peru. During the transcription and translation process, personal job role was not captured in the focus groups, and I was not able to correlate to their responses. I intend to revise my methodology in Aim 2 to address this issue.

As participants noted in focus groups, the design of this interactive mapping tool may be transferable to other health conditions and locations. I continued this work in Kenya to design a similar tool for Rift Valley Fever and continued to demonstrate its use in a global health setting as well as gathered more data to understand design standards for vulnerability mapping tools.

Conclusion

By engaging with end users from the onset of the project, I designed an interactive mapping tool for dengue vulnerability, thoroughly evaluated the design with local users, and provided the tool to public health practitioners in Peru. Our visualization tool incorporates a model to calculate vulnerability and other data sources, such as health system factors and geographic location. The design incorporates functional requirements gathered during interviews, storyboarding, and iterative prototyping, and was evaluated for acceptability and usability. Additionally, this work provides insight into understanding design preferences for spatial systems for decision support in public health and serves as a demonstration of the application of a group usability methodology for evaluating global HIT visualization tools. This work builds on the nascent literature for design in global health and provides a tool that allows for evidenced based decision making for dengue vulnerability.

Next steps in Aim 2

In my next chapter, I refine design recommendations with a new use case and setting, namely Rift Valley fever in Kenya by:

- Using a more structured, collaborative co-design workshop to engage more users than was performed in Aim 1
- Capturing timing data for task analysis and individual participant data in usability evaluation
- Transitioning from vulnerability score to relative quintile for vulnerability level (i.e. from a continuous to ordered data)

There was another change between Aims 1 and 2; I was not able to perform the group usability methodology in person as Covid-19 travel restrictions prevented the use of these methods. Alternatively, I utilized remote usability testing using Zoom video conferencing with screensharing. I compare these methodological approaches in the next chapter to share some strengthens and limitations of the different methods.

Chapter Four: Interactive Vulnerability Mapping Tool for Rift Valley Fever in Kenya

Introduction

In Chapter 3 (Aim 2), I built upon and improved methods and design considerations from Aim 1 to investigate interactive vulnerability mapping in a new country with a new disease. To accomplish this objective, I leveraged SDSS and principles of human-centered design to conduct a co-design workshop and usability study of an interactive mapping tool for Rift Valley Fever (RVF) vulnerability. The key stakeholders of the RVF interactive vulnerability mapping tool, including primary and secondary users, are those who are involved in public health preparedness, veterinary services, vector control, and epidemiology (primary users) or financial planners or community health workers (secondary users). These groups were engaged during our co-design workshop. Primary end users, including medical and veterinary epidemiologists, were represented in our usability testing.

As previously noted, One Health requires incorporating many datasets across information sources to better understand the complete picture of health; the RVF interactive vulnerability mapping tool similarly uses several data sources to understand vulnerability. Figure 4 suggests One Health datasets for vulnerability mapping based on previous studies [8], [26], [33], [34]. Health informatics tools that leverage big datasets and integrate disparate data types from distinct information systems could help advance the One Health initiative [92], [93]. Further, human-centered methods for co-design, prototype iteration, and usability testing can help to ensure that, as tools like SSDS are developed, they are accepted and utilized by the intended audience [11]. As RVF is a significant threat to public health in Kenya, with unique design and data considerations, this setting provides a great opportunity to investigate interactive vulnerability mapping tools.

Study setting

Kenya is located in eastern sub-Saharan Africa with a population of about 54 million people. The economy is growing very quickly – their GDP is increased more than 10-fold in the last 30 years based on data reported by the World Bank [94]. There are many competing priorities for public health in Kenya, where US based organizations like the CDC and USAID have had a longstanding presence [95]. USAID reports that healthcare in Kenya is constrained by the limited financial resources, capacity and technical expertise, and a shortage of healthcare workers [96]. New solutions and tools, such as interactive vulnerability mapping tools, that engage the healthcare workforce and builds capacity is needed for improving public health in Kenya.

METHODS

To design, develop, and evaluate our tool, I undertook a 2-stage approach, including a co-design workshop and usability testing.

Co-Design Workshop Methods

To collaboratively design the RVF interactive vulnerability mapping tool, I held a full-day workshop in Nairobi, Kenya to co-design the tool with 25 public health and veterinary stakeholders. Participants were recruited by in-country partners based on their job roles and influence in current RVF prevention activities in Kenya. Two researchers from the University of Washington, one researcher Institute of Health Metrics and Evaluation (IHME), and two researchers from International Teaching and Education Center for Health - Kenya (I-TECH - Kenya) led the discussion for the in-person meeting. Notes captured during the workshop, outputs of the group presentations, and follow-up emails with participants were utilized in the revised design of the RVF interactive vulnerability mapping tool.

The workshop consisted of two main parts: 1) group discussion about RVF vulnerability and introduction to the vulnerability model; and 2) smaller group discussions of design considerations. In part 1) local project champions moderated group discussion about current RVF preparedness and planning activities in Kenya, including accompanying data sources and obstacles to current work. David Pigott, DPhil introduced the statistical model used to assess vulnerability in the RVF interactive vulnerability mapping tool and held an open question session for inquiries into the methodology and data sources. As a large group, we brainstormed ways to display this type of information, as well as potential users and use cases using a co-design format to guide the discussion [97]. After a presentation explaining the data and mathematical approach that is used in the RVF interactive vulnerability mapping tool, we held a question and answering session with participants. In part 2) we broke out into two moderated, topical groups to separately to discuss animal and human health and how the interactive vulnerability mapping tool might be designed for each of these views. At the end of the day, these groups each presented a summary of their discussion and design considerations for the tool.

A research team member was the designated notetaker during the co-design workshop. Notes summarized activities and discussion during the workshop. Participants' questions were captured verbatim and transcribed after the workshop. Notes from the practice barriers and use case discussion were captured in shorthand notes. All research team members added to the co-design workshop notes and debriefed after the engagement to consider and summarize design results.

Usability Testing Methods

After the tool was iteratively designed, I conducted usability testing with new set of primary users, including medical and veterinary epidemiologists, to evaluate our design. My usability testing objectives were to address the following research questions (RQ):

- *Investigate acceptability*: RQ1) How do end users perceive the tool's design and utility? What are their preferences for data visualizations?
- *Investigate understandability*: RQ2) How accurately and efficiently do end users complete representative tasks and interpret information visualized in the tool?
- *Investigate actionability:* RQ3) How do end users foresee using a tool like this in their preparedness work? Will this information influence their decision-making processes in their jobs?

I define acceptability as the user's desire to use and favorable perception of the tool, understandability as the ability to complete representative tasks in a timely manner with a basic level of comprehension, and actionability as an expressed intent to use the tool for decision making or assisting in RVF public health activities.

Recruitment of participants: We used convenience sampling to recruit participants who work in public health in the human or animal domains in Kenya. Inclusion criteria were experience or expertise in RVF, fluency in English, access to high-speed internet, and a computer with the ability to use Zoom. Our minimum sample size was nine participants, as is recommended in usability literature [89]with an understanding that recruitment may continue until saturation was achieved.

To assess usability, I used methods in alignment with health information technology and eHealth usability research [63], [98]. Due to COVID-19 travel restrictions, usability testing was conducted remotely through Zoom video conferencing rather than in person. The usability sessions consisted of four parts: 1) task-based think aloud [82], [99]; 2) System Usability Scale [100]; 3) semi-structured interview; and 4) visualization preference selection. During part 1 (the think aloud) I asked participants to complete three tasks that were representative of intended use. In part 2, I administered the System Usability Scale (SUS) to allow for comparison to industry standards. Finally, in parts 3 and 4, I asked participants to explain more about their preferences and intent to use the tool and to select the visualization options they preferred. Two researchers conducted the sessions, one based in the United States and the other in Kenya. The sessions were audio and video recorded with screen capture and transcribed for mixed method analysis.

Data collection: My data collection instrument was reviewed by the research team for cultural competence and ability to accomplish research objectives. For the task-based think aloud, I chose three representative tasks that mirror how a real-world practitioner might use the tool based on co-design feedback. The tasks ensured that participants recognized and used the various filters and functions of the tool. Please see Table 2 for the three tasks mapped to the specific actions that should be observed to complete the task.

Number	Task	Participant actions
1	How does vulnerability change from present to 2050 in September in Stage 1 or index case vulnerability for humans in Mandera West (sub county)?	Change month and climate projection model. Search for sub county.
2	Which areas are most at risk for a human case stage 2 or outbreak vulnerability in March with current vulnerability projections?	Change vulnerability stage and month. Maintain a national view of map.
3	In the livestock view, please locate Busia (county) using current vulnerability projections. How does the vulnerability change over the months of the year for Stage 3 or epidemic vulnerability	Change vulnerability stage and species. Search for county. Select all months of the year.

Table 2: Tasks that participants were asked to complete during the usability testing.

As a measure of acceptability (RQ1), the SUS was administered orally in the current 10-item format [83] with a shared screen so the participant could read the questions and response options. Interview questions were developed to investigate acceptability and actionability based on the Information Systems Success model [101]. Interview questions were the same as asked in Aim 1.2 and can be found in Appendix 9. Finally, I mocked up alternative data visualizations options for color encoding, layout, and design approach to allow participants to select their preference in each category as was completed in Aim 1. The alternative visualizations were screenshots of the tool. Please see Appendix 10 for alternative visualizations. My intent for collecting visualization preferences was to understand what design participants preferred and why they chose that option. For color, I tested monochromatic (light to dark blue), a contrasting qualitative (bold colors from across the color spectrum) and a stop light (red to green) color scale. For layout, I tested side-by-side maps for incidence as case points and chloropleth with encoded vulnerability versus an all-in-one map with incidence and vulnerability as point-and-shape layers on the same map. Finally, I tested a storytelling design approach that includes more context and narrative for the users against a minimalist or dashboard design that includes only the necessary information to complete basic tasks [54]. Questions to elicit preferences were the same as administered in Aim 1.2 and can be found in Appendix 8.

Data analysis: I used mixed methods to analyze data collected during the sessions. I reviewed the video screen capture of the participants interacting with the tool during the task analysis for accuracy and time stamps to investigate how users navigated the tool. Quantitative data from the SUS and visualization preferences were summarized with descriptive statistics. For the qualitative interview data, a local researcher (Charles Atleau) and I analyzed the transcripts using a template analysis approach [102]. An initial a priori template was developed based on the three research questions. Researchers then updated the template after an initial read of the transcripts. CA and LS coded the same set of three interviews, then discussed all notable differences and consulted another research team member for any discrepancies. The remaining interviews were coded by the researchers independently, then cross-reviewed to reach a final consensus.

RESULTS

Co-design Results

Participants: A total of 25 individuals participated, drawn from Kenya Ministry of Health and Ministry of Agriculture, Livestock and Fisheries, Food and Agriculture Organization of the United Nations-Kenya, US Centers for Disease Control and Prevention, Kenya Agricultural and Livestock Research Organization, Kenya Medical Research Institute, and two county government representatives from Directorate of Health and Veterinary Services.

Current practice barriers: During our discussion about RVF preparedness and planning activities in Kenya, including accompanying data sources and obstacles to current work, I heard that livestock maps were important to consider for RVF prevention, but hard to access at a national level. I also heard that surveillance work is often reactive to immediate needs but would be more effective if there were also proactive efforts to plan and prevent outbreaks. As we discussed what type of solution might address some of the challenges, participants emphasized the need to incorporate capacity building and training in our roll-out plans as well as considering sustainability.

Model Discussion: I share the questions from participants below (two questions were omitted as they were for clarification purposes only). Bolded questions were asked by participants and answers were provided by the facilitators/research team.

i) ***Is it possible to incorporate the economic impact and livelihoods of RVF into the Vulnerability mapping tool?(Livelihoods in this question refer to wages and income, in other words, can financial data be incorporated in the tool)***
Answer – Yes, it can be explored based on a weighting scheme applied, though this may be complicated by the variation in livestock production systems in the country.

ii) ***Are there success stories on the presented prototype mapping tool anywhere in the world?***
Answer. Yes, the tool has been applied in mapping out Ebola outbreaks in Central and western Africa e.g. in Ghana, DRC

iii) ***Can the tool capture the impact of vaccinating animals against RVF? How can this information be analyzed to back up advocacy for resources (i.e. vaccinating vs not vaccinating)?***
Answer. I do not currently have that data, but it can be incorporated in the future

iv) ***How useful and accessible are the interactive vulnerability maps in decision making/outbreak response?***
Answer. The maps can be accessed and assessed at both the national and at the sub national levels by various users.

v) ***What informed you to use the 2016 RVF data and not the latest 2018 data to come up with maps?***
Answer. This is a limitation in data availability. 2018 data was not complete at the time of developing the maps, therefore resorted to the complete 2016 data set that was available.

Brainstorm: Participants ideated primary use cases, which I used to design the key features of the tool. They noted several user roles and use cases, and the research team and I grouped into 3 main areas after the workshop: planning, preparedness, and enhancing surveillance. For planning, participants noted that they would use the tool to plan vaccination campaigns, stockpile resources, and allocate veterinary and public health staff. For preparedness, the tool could be used for identification of high-risk areas and to perform vector control. For enhancing surveillance, the tool could be used to further increase understanding of RVF epidemiological trends and identify gaps in surveillance.

Topical discussion groups: The participants expressed the need to discuss animal health and human health separately, as these use cases necessitated different views of vulnerability. In the human health and animal health groups, participants reported users, data, and questions of the tool specific to their discussion topic (animal or human health). The animal health group reported users to be the Zoonotic Disease Unit, Department of Veterinary Services, environmental groups, and Kenya Wildlife Serve as well as policy makers such as the Council of Governors, Intergovernmental Relations Technical Committee, State Department of Livestock, and the Treasury. The animal health group reported veterinary staff capacity and sentinel herd surveillance as datasets and questions concerned where to have vector control, herd surveillance, and vaccine stockpiles. The human health group reports laboratories, including reference, research, and county labs, as the primary users. These users would want to know about capacity, stockpiling of resources, risk factors, and when to have alerts. The human health group reported capacity of laboratories and hospitals as needed datasets.

Revised design: Based on the co-design workshop, I mapped the use cases to features while also considering available data sets and scope of the project. One of the most salient findings from the co-design workshop was the need to visualize human and animal vulnerability to RVF in separate views of the RVF interactive vulnerability mapping tool. This design change entailed adjusting the underlying vulnerability model; understanding animal-specific vulnerability to RVF meant the incorporation of livestock population density data and live animal market maps. Our resulting features include: 1) change ‘vulnerability stage’ and visualize vulnerability to index case (stage 1), outbreaks (stage 2), or epidemics (stage 3); 2) filter vulnerability model to change species (human or livestock), climate project model (current or future), and month for seasonal differences; 3) search for and highlight counties or sub counties on the map; 4) link to another view of the tool that shows the animal and human vulnerability maps side by side; and 5) display a ‘hover over’ for regions of the map showing additional data including the filter selections (stage, species, etc) and counts of humans and livestock. Please see Figure 7 for a screenshot of the RVF interactive vulnerability mapping tool interface. These features are also represented in the use case description in Appendix 11.

Usability Results

I conducted 13 usability sessions with participants located across Kenya. Participants in the usability study did not take part in the co-design session. The average interview length was 41 minutes (range 32-55). Participants represented 10 (out of 47) counties as well as a national perspective. Please see Appendix 12 for a map of locations where participants were located. As a

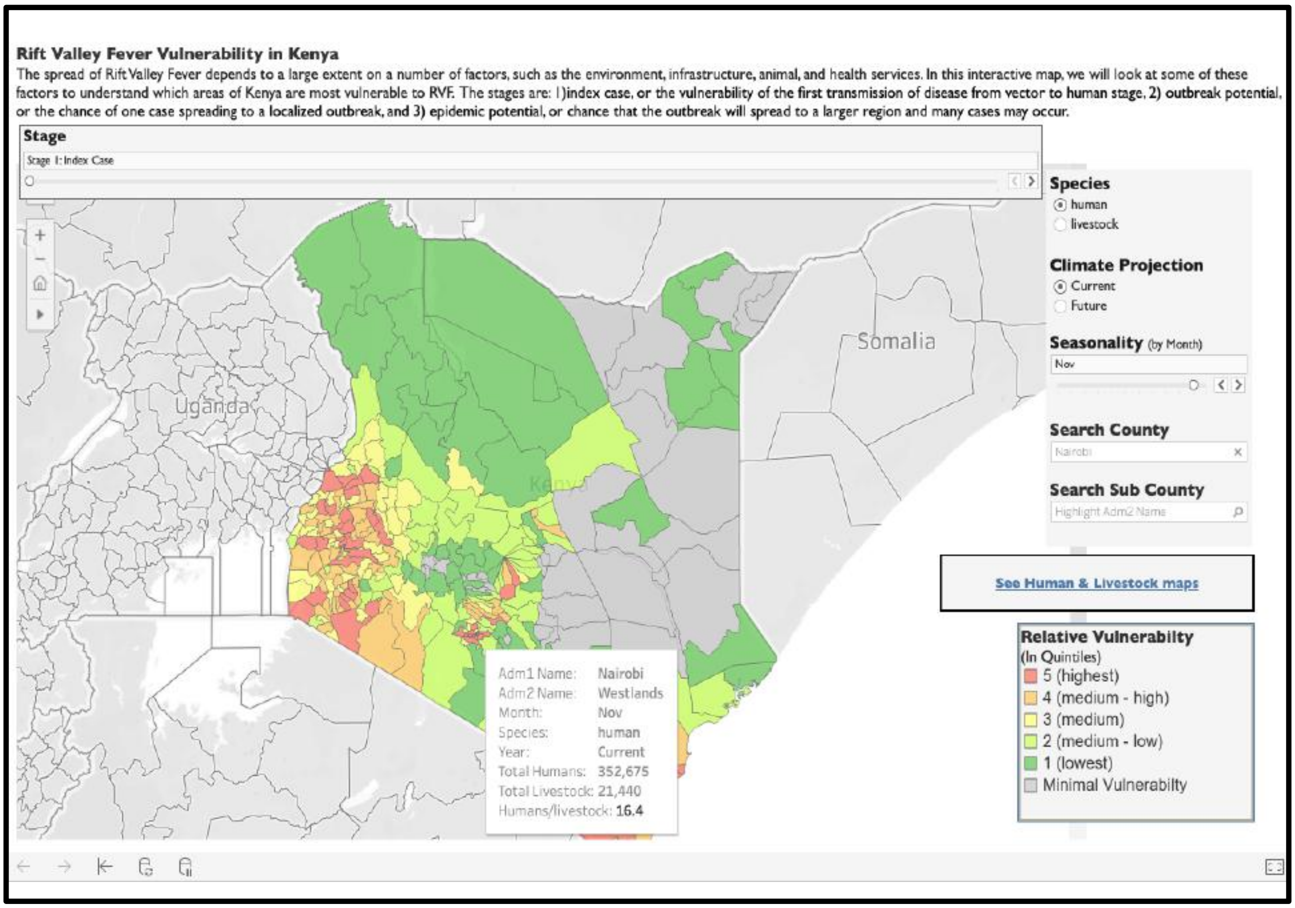

Figure 7: A screenshot of the RVF interactive vulnerability mapping tool that was used for usability testing.

key primary user and early adopter of the tool, I targeted human and animal-focused epidemiologists as participants for the usability sessions. Participants could be described as data experts, which was a finding of Aim 1. Participants' job titles included veterinary epidemiologist (n=7), medical epidemiologist (n=5), and public health officer (n=1).

Task analysis: All participants were able to accurately complete assigned tasks in the task-based think aloud, though some participants required minimal assistance from the interviewer and not all participants were asked all 3 tasks due to time limitations; the majority (n=10) participants completed all 3 questions and 3 participants completed 1 or 2 tasks. Some interviews were very delayed, and I scheduled multiple interviews per day, so I had to occasionally omit some of the task analysis to save time for the other parts of the interview. The average time to complete each task was approximately 3 minutes (range >1 to 6 minutes). In examining participants' navigational workflows during screen capture, 4 main usability issues were identified: 1) selecting the vulnerability quintile rather than changing the vulnerability model stage; 2) confusion and incorrect use of the climate model projection filter; 3) inappropriately searching county and/or sub county; and 4) selecting a specific location on the map, thereby changing the highlighting and geographic selection.

System Usability Scale: The mean SUS score was 86.73 out of 100 (range 70-100, SD = 10.62). As an industry standard, this score reflects an "A" grade. All participants strongly disagreed with the statement "I found the tool awkward to use" and 11 of the 13 strongly agreed that "I would like to use the visualization tool frequently". The learnability subscale score was 67.31 and usability subscale score was 89.58[84].

Design preferences: All participants preferred the red-to-green color scale option for the color scheme. They mentioned that the strong contrast between these colors made differences in sub counties easy to notice and they easily associated the red encoding with the highest risk. There was more variation in preferences for the other two design considerations. For the layout, 50% of respondents preferred having the incidence as a point layer on the chloropleth vulnerability map. One quarter of participants preferred incidence and vulnerability to be shown on side-by-side maps. The final quarter of participants said that their layout preference depended on the specific use of the map; independent analysis, health risk communication, and departmental planning all might necessitate different map views. Finally, all but 3 participants (77%) preferred the storytelling approach that included more context and information for the user. Two participants preferred the dashboard or minimalist design because they liked the more simple and less cluttered aesthetic. One participant responded that the design approach was also dependent on the specific use of the tool; they'd like the more information/text rich version for most uses but would prefer the simpler version for presentations when they could provide that context orally during the presentation. Please see Figure 8 for a chart of design preferences for the RVF interactive vulnerability mapping tool.

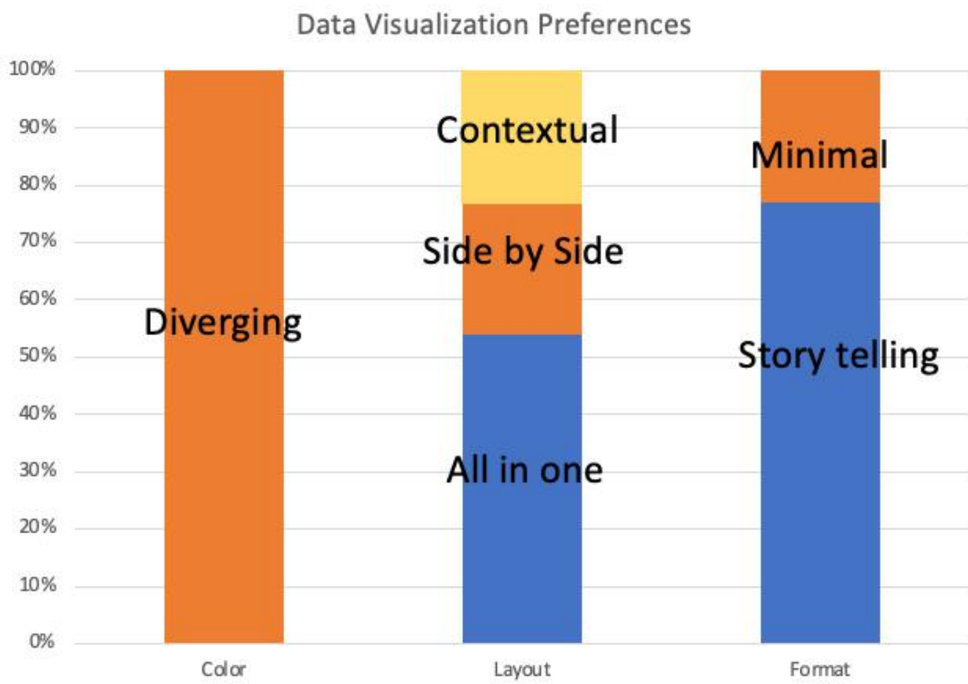

Figure 8: A chart of the design preferences reported by participants for color, layout, and format.

Interviews: Our template analysis highlighted themes that spoke to our acceptability (RQ1) and actionability (RQ 3) questions. Our initial use case of the tool was to assist primarily in preparedness and planning, as a means to proactively think about vulnerable regions and create annual plans to help prevent outbreaks. Additionally, the participants spoke at length about the potential of the tool to enhance and improve current surveillance activities. They saw great value in the use of additional data sources, interactivity to address multiple questions, and insight into gaps in surveillance. Participant 11, a medical epidemiologist, articulates his desire to utilize the RVF interactive vulnerability mapping too as a surveillance support tool:

> *"… (We) are getting Rift Valley cases in places that I did not expect. And therefore, when you go to interact with other organizations, they will rely on the government document that has the Rift Valley Fever management plan that has indicated certain counties as higher risk and not others. And therefore, this tool I think it's important in terms of it allows other factors to be put into play, so that then you are able to demonstrate the evolution. Because if you have a document, for example, a strategy plan for five years on a plan at the national level, it isn't*

reviewed until the five years are over and there is so much that would have likely to have changed over that period."

I also heard, especially from the veterinary participants, that this tool would assist in current syndromic activities. Syndromic surveillance holds great potential for zoonotic diseases [103]. As a proactive planning tool that can incorporate novel data sources, the inclusion of active and syndromic surveillance seems pertinent.

> *"I should expect for somebody who values data, I think this would really work well because you're looking at the possibility of, I mean, what could have happened in the past and you're looking at... The other thing, you want to bring in what you're seeing currently, and you want to see... I mean, you want to mark the two and see, is it something that I missed in the past? And now I've getting information which you can use to strengthen some of the activities of surveillance activities. So to me, I think it's something that definitely I would love to use it."*
> - Participant 8, a veterinary epidemiologist

Of the design considerations (i.e., color, layout, approach) I investigated, the one most consistently favored by participants was color. They responded that it was an important construct, either because of the ability to quickly discern, or familiarity and cognitive association with the preferred color scale (red-to-green). Though he still preferred the red-to-green scale, Participant 7, a veterinary epidemiologist, noted a potential consequence of using a red-to-green color scale to mis-associate the color encoding of green as no vulnerability rather than lower relative vulnerability:

> *"And one of my favorite sayings is diseases don't know boundaries. So you've had scenarios where somebody will look at the red and green and say, 'Oh, the sub county next to me is green, and I'm yellow, so, I'm zero risk.' It's just how people perceive."*

In fact, I did hear this mis-association from Participant 3, a veterinary epidemiologist:

> *"So to me [the] color red is very good when it is used in maybe when I have the highest risk vulnerability risk level, that you this vulnerability to the disease. And maybe now, also the color for no vulnerability it is calm. It tells us that there's no risk of getting the disease there. So it is calm. It is calm. It is nothing."*

After this feedback, I made some design changes to mitigate the risk of mis-association, such as clearer data labels, reflective of what participants noted in the interviews.

Discussion

These results achieve the objectives of our usability testing. For acceptability (RQ1), participants scored the SUS favorably for usability (i.e., "A" grade) and provided qualitative data to suggest acceptance (i.e., indicating excitement to use or approval of the tool). Participants largely preferred a diverging red-green color scale in agreement with similar studies [41] but responded that layout and design approach depended on the specific use of the tool and context. For understandability (RQ2), there were some navigational and conceptual issues that I saw during the task analysis and heard during the interviews. Overall, however, participants were able to complete all tasks accurately, with little assistance, and in a reasonable amount of time. Finally, for actionability (RQ3), all participants shared that they would use this information for planning, preparedness, and surveillance and that it would enhance their current decision-making processes for RVF preparedness.

Though the RVF interactive vulnerability mapping tool tested highly in usability overall, the learnability subscale was lower on the SUS. As assessing vulnerability using a One health approach is a new concept for many users, initial limited learnability is expected. Prior research suggests that there is a distinction between operational readiness of a disease prediction model and its validation and verification method maturity [104].Though the vulnerability model has a high level of technological readiness [105] ensuring the tool users and intended uses (i.e., operational readiness) are equally successfully developed is critical. I can improve operational readiness by including specific design features to improve learnability and include steps to improve learnability during implementation or roll out. For design features, I provide a comprehensive user guide accessible within the tool and link to additional metadata about the vulnerability model. During RVF interactive vulnerability mapping tool roll out, training and capacity-building will be provided by partners in-country with instructions and guidance for use, maintenance, and other strategies for greater understanding.

It is important to consider our results in the context of the COVID-19 pandemic. Our data collection took place in June of 2020, at a time when Kenya was experiencing very high incidence of COVID-19 and hospitalization [106].I was forced to delay our study timeline and switch to remote methods rather than face to face. Transitioning to Zoom video conferencing for data collection entailed positive and negative consequences. I lost some of the context, body language, and rapport building that I would have experienced had the interviews been held in person. Though this critical interpersonal component was lost, I was able to reach more participants since the data collection was virtual. I included participants that were spread across Kenya rather without having logistic and travel complications associated with in-person methods. Finally, hardware and connectivity were inclusion criteria for our study as I needed to conduct the usability interviews virtually. These criteria may have biased our sample to skew towards participants with better access to the internet and hardware or technology. Further, one of the complications of using Zoom for remote usability testing is delineating the usability of Zoom from the usability of the interactive vulnerability mapping tool. I did not ask participants about their prior experience with Zoom, and all participants required some assistance in sharing their screen and/or navigating other Zoom functionality. This guidance required additional time with participants when I was trying to minimize the overall time burden to participants.

The impact of COVID-19 extended beyond the use of remote methods. As the public health system was already stressed, I stressed that participation was optional and were diligent about keeping the interview times under one hour to minimize burden on participants. This limited our time to fully discuss the usability issues, and, in three cases, I was not able to fully complete our data collection instrument. At the same time, the conversation around outbreak preparedness was more pertinent and critical due to the international public health emergency at hand and, perhaps, allowed for more in-depth and realistic dialogue with participants about the need to plan and prepare for disease outbreak and to identify actionable steps to help mitigate risks.

Despite these limitations, our study has many strengths that lead the way for future work. These findings speak to the potential impact of using a similar tool for preparedness for other zoonotic diseases. I heard from participants that interactive vulnerability mapping tools would be helpful for neglected tropical diseases as well as anthrax. Future iterations of the tool could allow users to see multiple pathogens, allowing users to understand where areas were at risk for more than one outbreak and perhaps use this information for prioritization. Similar interactive mapping tools could harness these design and usability results to build tools that show outbreak risks and vulnerability in other settings. For example, I quickly built a similar tool for stakeholders in Kenya at the start of the pandemic to show spatial areas where the population had one or more high risk factors, such as heart conditions and advanced age, for COVID-19.

Our study provides insight into future directions for research. The SUS is a widely used and validated scale that is used frequently during health information technology usability studies. The scale can be a helpful instrument to compare similar tools in other contexts and to set a baseline to measure usability against future iterations. Though this instrument has been used in international settings, I heard from our participants that there may have been some issues with using the SUS. “Awkward is not really a word I use in Kenya,” noted Participant 7. Though empirical evidence suggests that ‘awkward’ is better understood that ‘cumbersome’ in the SUS, it still might not be the language in this setting. Further research should examine the instrument in African countries where participants are fluent in English but may have linguistic nuances that make administering the SUS less reliable than in other countries.

One of the beneficial outcomes of this research and future use of the RVF interactive vulnerability mapping tool is the opportunity to discuss climate change and its impact on global health preparedness. The vulnerability model incorporates a NASA climate model to assess environmental suitability for a vector based on current climate data or projections for the year 2050, depending on the filter that the user selects. Users of the tool can visually see how climate change might impact vulnerability to RVF as temperatures increase and more geographic areas become suitable for vector life. Related research has shown that climate change models predict outbreaks of other zoonotic diseases in unexpected geographic locations, notably Chikungunya in western Europe, sub-Saharan Africa, northern Australia, and the southern United States [107]. In Baringo County, Kenya researchers found that changing climatic factors (in this study, an increase of rainfall) resulted in higher rates of Malaria [108]. In fact, a recent study measured the perceived impact of climate change on health preparedness and found that 66% of respondents from Kenya felt that this is an important consideration [109]. Their study also found that 47.1% of respondents in Kenya felt 'not so much prepared' to respond to extreme events related to the health impacts of climate change. The RVF tool may help accelerate the conversation by visualizing the effects of climate change to public health audiences, as well as helping users to increase their level of preparedness for emergencies and extreme events. Future work could utilize interactive vulnerability mapping tools as tangible evidence to show the connection between climate change and vulnerability and

Conclusions

This research contributes to the knowledge base spanning global health informatics and human-computer interaction by providing an actionable, acceptable tool for visualizing disease vulnerability, namely the RVF interactive vulnerability mapping tool. This tool was co-designed and evaluated with public health and animal health practitioners in Kenya. I address the need to provide empirical data on the data visualization preferences, usability, and acceptance of SSDS for disease vulnerability in global health settings and provide a demonstration of a methodological approach for remote usability evaluation in global public health settings. Feedback from participants during the co-design workshop suggested that animal and human health views should be distinct for this type of visualization and that participants would welcome the tool in their RVF prevention and planning work, which is a novel design consideration that, to my knowledge, has not been previously established in the literature. The RVF interactive vulnerability mapping tool may benefit preparedness and response activities in Kenya and an approach for design and usability evaluation of interactive vulnerability mapping tools for other pathogens and locations.

Comparison of Aims 1 and 2:

In Aim 1, I designed, built, and evaluated an interactive mapping tool for dengue with users in Peru. The design methods were conducted primarily remotely with 5 in country stakeholders and a 4 phase approach for 1) storyboarding, 2) user group identification and wireframing 3) landscape analysis to select visualization platform and 4) prototype development with visualization alternatives. Based on the design work, I developed an interactive prototype in Tableau for usability evaluation. For evaluation, I held a group usability workshop in Lima with 20 participants, using the SUS, visualization preference selection, task analysis, and focus groups. Strengths of the group usability workshop methodology include time and cost efficiency, the ability to discuss collaborative work, and the identification of high-level usability issues. Limitations of the group usability workshop methodology include challenges to collect in-depth, individual data and to timing data during task analysis.

In Aim 2, I designed, built, and evaluated an interactive mapping tool for RVF with users in Kenya. I built upon my design results in Aim 1 and held a co-design workshop with 25 participants in Nairobi. During the workshop, we discussed challenges, the vulnerability model, and implications for users and data. The workshop highlighted the need to create a separate view for animal and human vulnerability to RVF. Thus, I created an interactive prototype in Tableau with separate human and livestock/animal views. Strengths of the co-design workshop include a time-efficient way to conduct design work, having a larger group of stakeholders involved than might otherwise be engaged, and an opportunity for collaboration and buy-in early in the development process. A limitation of the co-design methodology is that participation is limited to those participants who are geographically able to attend the workshop. For usability evaluation, I conducted 13 remote usability sessions through Zoom with SUS, visualization preference selection, task analysis, and interviews. Strengths of the remote usability testing included more detailed and in-depth feedback on usability through unstructured data collection/interviewing and the inclusion of geographically dispersed participants. Limitations included a selection bias for participants who had access to a laptop, Wi-Fi, and Zoom and a smaller sample size than the group usability workshop. Please see Figure 9 for an overall and methodological comparison of Aims 1 and 2.

	Design	Usability
Peru (Aim 1)	Remote, primarily through conference calls and email N = 5	Group Usability Workshop held in Lima N = 20
Kenya (Aim 2)	Codesign session with stakeholders held in Nairobi N=25	Individual interviews conducted remotely through video conferencing N= 13
Shared	Human centered design methods administered	SUS, task analysis, preference selection, qualitative data collection

Method	Strengths	Limitations
Group usability testing	- Efficient, data collection in a few hours - Understand collaborative work - Good for high level usability issues - More breadth of feedback	- Participation is limited by proximity & availability - Hard to do timing for tasks - Individual data are to tease out
Co-design workshop	- Encourage buy-in at early stage of project - Large group of participants	- Multiple iterations hard to accomplish in one workshop
Remote usability interviews	- Participants can be geographically dispersed - More depth to feedback	- Selection bias (tech access) - Time zones make scheduling difficult

Figure 9: The top chart compares over study design of Aims 1 and 2. The bottom chart compares methods used in Aims 1 and 2.

CHAPTER FIVE: DESIGN RECOMMENDATIONS INFORMED BY A SCOPING REVIEW OF INTERACTIVE VULNERABILITY MAPPING TOOLS FOR ONE HEALTH PREPAREDNESS

Introduction:

The Covid-19 pandemic highlighted the need for a more proactive approach to protecting public health. Decision-makers and health practitioners, stymied by often-scarce and fast-changing information, must make critical decisions rapidly to prevent or contain epidemics. The systems and tools that they rely on must therefore be designed to this purpose. Despite the need to prioritize pandemic preparedness and planning, public health practitioners report a lack of visualization tools available [110].

Further, visualizations that are available may not be useful or prove misleading [111], [112]. Spatial Systems for Decision Support (SSDS) are a type of interactive visualization tool that enable public health practitioners to make critical decisions informed by timely access to pertinent analyzed data. SDSS are especially impacted by poor design as they are intended to provide real time information for decision making and should integrate into existing health systems [113]. Preliminary and informal searches of the existing literature suggest that little evidence on this topic exists to provide SDSS designers with guidance or best practices.

"An urgent need exists to develop public health surveillance systems that are user centric, based on sound principles of data visualization, incorporate intelligent interactive features, and offer public health professionals a satisfying and action-oriented view of infectious diseases in their jurisdiction" [114].This perceptive plea, written by Gesteland and colleagues in the Journal of

American Medical Informatics Association, was issued nearly ten years ago. Despite advances in technology and a growing need to address emerging outbreaks, their call has not been heeded.

Interactive vulnerability mapping tools would allow for better access and understanding of limited spatial data. Though there is a spatial rationale to map most infectious disease data, research suggest that only 4% of infectious diseases have been mapped [115]. Further, access to spatial data, along with the tools and capacity to analyze that data, is among the major challenges to public health [116]. Although SDSS could help public health practitioners by providing access, analysis, and visualization of limited disease data, the field lacks adequate design guidance.

The focus of this scoping review is vulnerability to vector-borne and zoonotic diseases (VBZD), as there is great potential to impact public health as well as unique challenges associated with these data. Population density, socio-demographic information, travel patterns, and access to medical resources datasets should all be factored into the understanding of vulnerability to infectious disease outbreaks. As VBZD are a type of infectious disease that involves animal or insect hosts or vectors [117], VBZD preparedness and surveillance inherently involves additional dimensions including veterinary and entomology data. Additionally, the environmental suitability, including additional data such climate, topography, and land coverage, are also a factor in understanding where hosts and vectors might survive and interface with human hosts.

The increased complexity of VBZD data should be met with tools that not only integrate these disparate data sources but analyze and present this risk information in a clear, actionable way.

The One Health approach [118] highlights the interconnectedness of human, animal, and environmental health to present a more comprehensive, holistic view of public health. This approach has been used to understand factors related to VBZD surveillance and preparedness in numerous recent studies [31], [119]–[121]. Though the approach for VBZD vulnerability has been well established in the literature, there is a lack of tools with user-friendly interfaces that harness One Health data.

Interactive vulnerability mapping tools, a novel type of SDSS, should be included in the VBZD outbreak prevention, preparedness, and planning toolbox. In the context of global health preparedness, vulnerability refers to a geographic area's susceptivity to a disease outbreak and ability to contain spread [122].In this chapter, I use the term "interactive vulnerability mapping tools" to describe "SDSS" as stated in the literature, or, in shorthand, "tools". SDSS have already been used in other infectious disease outbreak detection work, including tuberculosis [123], [124], HIV[125], and emergency planning [126]. Understanding the use of SDSS in VBZD work will provide a helpful knowledge base to frame future efforts. Using the current literature and my own studies from Aims 1 and 2, I will frame my design recommendations in context of Gesteland's plea, consisting of the following dimensions: 1) user-centric, 2) based on data visualization principles, 3) interactive features, and 4) satisfactory to user and action-oriented. In my recommendations, I apply a broad definition to the term design, in alignment with the human centered and user centered literature, to include the process of design, the outcome of the design work, and the evaluation of the design, which includes aspects of usability.

Research Objectives:

The objective of this scoping review is to describe current interactive mapping tools for global health preparedness, focusing specifically on vector borne and zoonotic diseases and suggest recommendations for design of future tools.

- Objective 1: Describe the current landscape of interactive vulnerability mapping tools for VBZD outbreaks by characterizing data, technology, users, and use cases of previous studies
- Objective 2: Identify gaps in existing literature, compare to my studies in Peru and Kenya to inform design recommendations for interactive vulnerability mapping tools

Methods

A scoping review, as opposed to a systematic literature review, is appropriate when the topic is relatively new or not well established in the literature [127]. For this review, I used the methodology proposed by Arksey and O'Malley in their seminal work defining scoping reviews [128]. The protocol was developed using the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) [129] and was prospectively registered on the Open Science Framework website in July 2021 [130]. Please see Appendix 13 for mapping of PRIMSA-ScR reporting elements.

To frame the review and structure my search strategy, I defined search themes that were pertinent to my research questions. The three designated search themes were: 1) planning or preparedness for disease outbreaks; 2) spatial systems for decision support; and 3) zoonotic and vector-borne diseases. To my knowledge, this is a unique search of the literature: targeting interactive and spatial tools intended to inform decision-making, and only including VBZD, entail a unique set of data, technology, users, and use cases. (These data, technology, users, and use cases are further defined in the forthcoming sections.)

Eligibility criteria

Inclusion criteria for this scoping review include published articles describing any tool or information system that visualizes spatial information to influence decision making, written in English, and published between 2011 and 2021. For a more inclusive approach, I did not limit the publication type. The exclusion criteria included non-English text and articles outside of the search time period. I also excluded publications that were theoretical or opinion only, as I was trying to gather an overview of research in this field that has actually been conducted as opposed to theoretically proposed only.

Information sources and search

Information sources included PubMed, Google Scholar, and Embase, which I searched for articles published between 01/01/2011 to 07/01/21 (see Appendix 14 for search strategy). I conducted the search on 07/04/2021. Next, I provide the rationale for these information sources and search strategy.

Though my search themes were a unique combination, I referenced a previous literature review to ground my work. A 2018 literature review on SDSS for zoonotic and infectious disease used Google Scholar to search for articles a in the previous 10 years [1].Their sole use of Google Scholar in their search strategy reflects the newness and uniqueness of SDSS, as it is difficult to utilize other traditional and indexed databases. In fact, of the 12 studies included in the 2018 review, only 10 were available in PubMed. The 10 available only shared a small percentage of indexed MeSH terms and over-elicited 70+ unique MeSH headings when analyzed through the Yale MeSH analyzer tool [131].

Though there are advantages to using Google Scholar, the disadvantage is the inability to reproduce the exact literature search results. This is due to constant web crawling and a proprietary, ever-evolving search algorithm that includes factors like the searcher's location and previous searches [132]. Fortunately, a recent scoping review published by Hasan and colleagues uses PubMed to explore a new set of search themes aimed at exploring an emerging topic for pandemics in their paper [133]. With the assistance of a University of Washington Health Science librarian, I developed a search strategy of MeSH terms and free text that covered search themes. Please see Appendix 14 for search strategy for all databases.

I supplemented my search by building from the findings in the 2018 review with a Google Scholar search. The authors used a Boolean combination of three search themes. I expanded on their search strategy to include "vulnerability" and "vector borne disease" to align more closely with my own review objectives. The search terms used in my Boolean combination were: 1) spatial decision support systems, spatial online platforms, mapping tool; 2) public health, vector borne, zoonotic disease; and 3) high risk areas, outbreak detection, cluster detection, vulnerability. Please see Appendix 14 for search strategy.

Finally, to round out the database selections, I included the Embase database. As I aimed to capture the current literature landscape, I limited the search to the previous ten years, or 2011 to 2021.

Selection of sources of evidence

After initial searches in the three databases, I removed all duplicates. Titles and abstracts were scanned, and then full text articles were reviewed for further inclusion in the scoping review based on the eligibility screening. At this stage, I excluded studies with no visual or spatial information pertaining to VBZD, had no user interface or interactive features, and were a description of the epidemiolocal model or data science method only without reporting a tool that spatially visualizes the output of the model or method. Articles that were included in the final selection for the scoping review were imported into a designated folder in Mendeley citation manager. I selected papers with a focus on the tool or information system, rather than the underlying model or method to analyze data.

Data charting

Data items were extracted into a tabular spreadsheet. The following data elements were extracted: title of article, publication type (i.e., journal or book), author, year, country, and VBZD of interest. For each article I summarized data elements that were pertinent to my research questions, including objective of the tool, data, technology, users, use cases and details pertinent to design. I based these items for extraction during data charting based on the adjusted Munzner framework for data visualization that I reference in chapter 1. Please see figure 10 for graphic of framework mapped to data charting items. As it was not directly related to my research objectives, I did not perform a critical appraisal of the literature sources, though I do summarize areas for improvements in the results. Additionally, as there is a lack of available studies in this area, I did not want to further reduce the limited number of publications to be included in the review by excluding those that did not perform well in the critical appraisal.

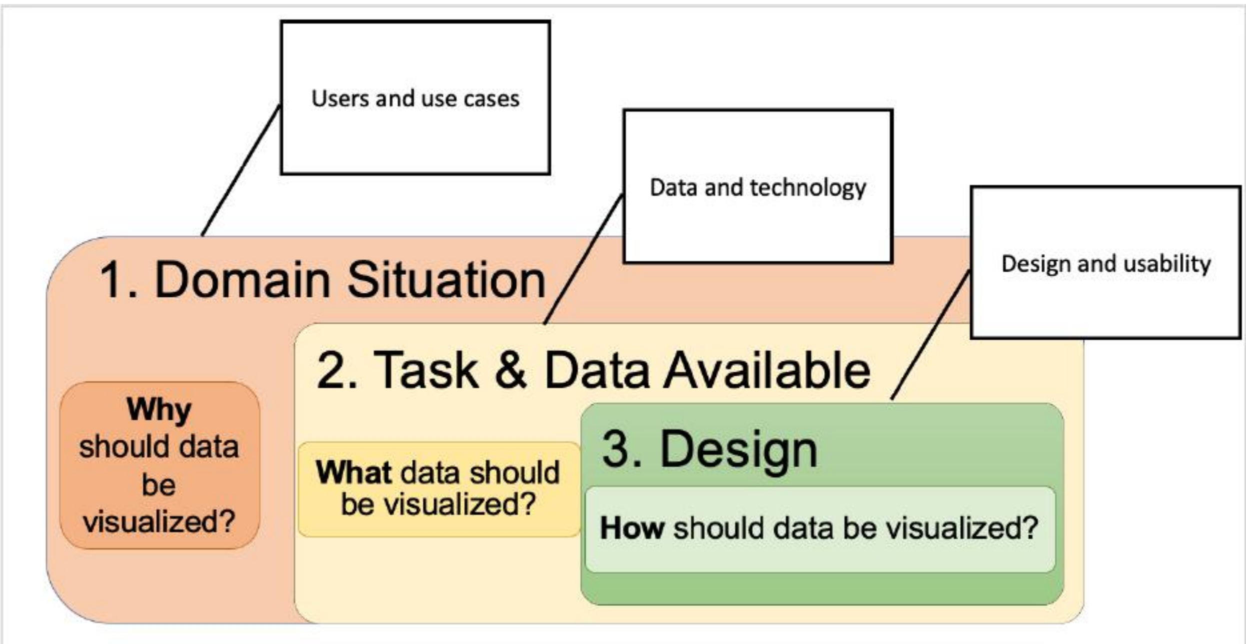

Figure 10: A interpreted Munzner's framework for data visualization with items for data charting mapped to the layers of the framework.

Synthesis of results

I charted all data items in the tabular spreadsheet and described the set of studies with a high level overview i.e. country, year, authors, and disease). I then report on the data, technology, users and uses cases in the first section of the results as described in the Munzner framework in Figure 10. In the design recommendations section, I summarize any data items reported on the design.

Results

Across the three databases (PubMed, Google Scholar, and Embase), 636 articles resulted from the initial search. After titles and abstracts were reviewed based on the eligibility criteria, 118 papers were selected for full text review. Of the 118, fourteen studies were included in the final selection for analyses in the scoping review. Please see figure 11 for a flowchart of the selection process.

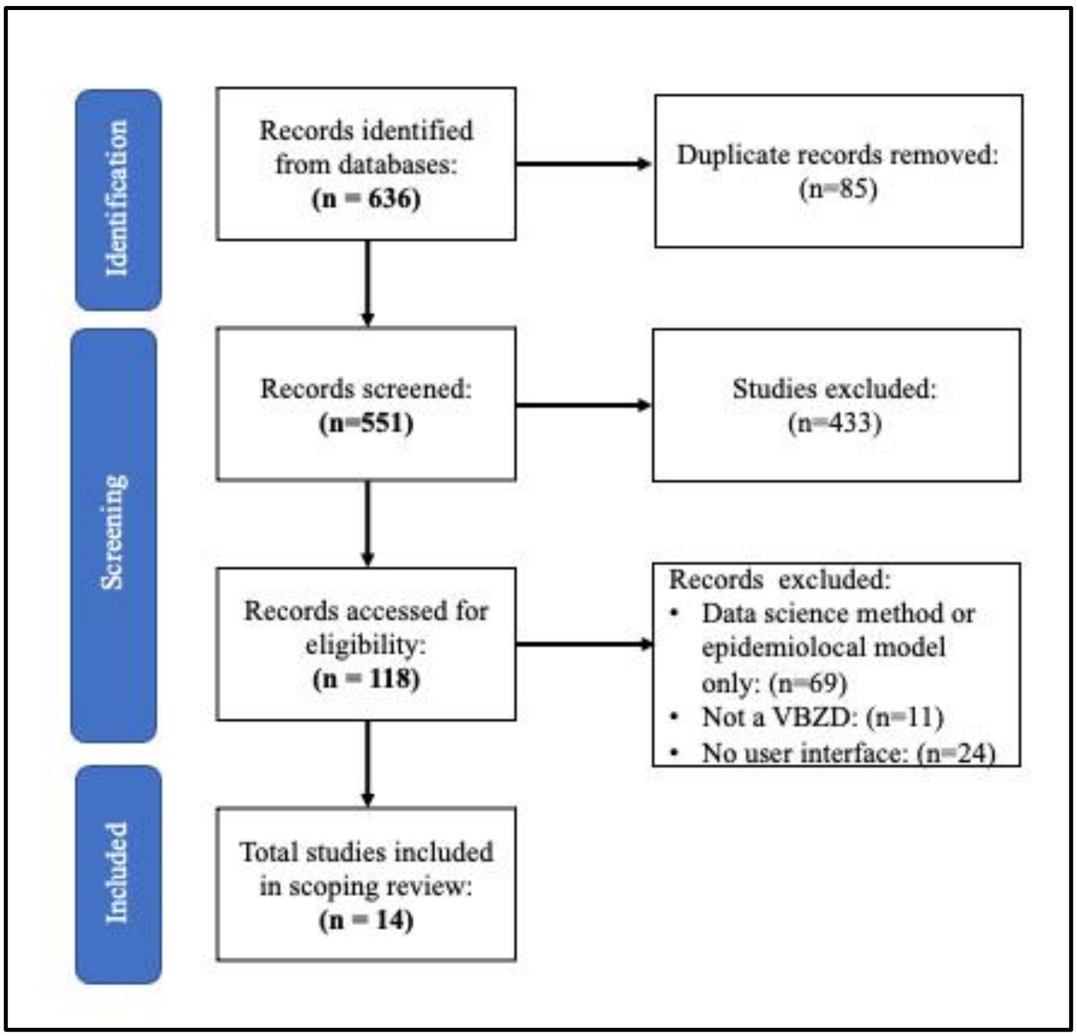

Figure 11: Flowchart showing number of studies included in each stage of the selection process

The articles selected represent a diverse set of tools and studies [29], [98-110] The literature presented an international perspective, though it was notably lacking in studies from the continent of Africa. Asia was the highest represented with 8 studies (Bhutan, two in China, Solomon Islands & Vanuatu, Pakistan, Papua New Guinea, Taiwan, and Vietnam). There were two European studies included, from Italy and France. One was United States-based, in the state of California. One was intended for use in South Africa, and the last had a global perspective. There was also a diverse representation of VBZD. Some tools included more than one disease or health outcome, but of those explicitly noted in the text, malaria was most common with inclusion in 5 out of 14 articles, or 35.7%. Dengue was next most common, in 3 out of 14 studies, or 21.4%. Brucellosis, West Nile Disease, and avian or swine influenza were each included in 2 studies, or 14.3%. Bluetongue, chikungunya, leishmaniasis, Lyme disease, rabies, and yellow fever were all included once

Ref	Tool Objective	Data	Technology	Users & use cases	Design
[134]	ID-Viewer is used for data collection/acquisition, outbreak analysis/detection, response management, and prediction modeling.	ED chief complainant data; drug sales ambulatory records, emergency calls; weather from remote sensing satellites, geographic and population density from urban unit Pakistan; historical dengue	Used a 'GIS-based distributed service-oriented architecture' hosted at an academic institution. They don't provide technical specifications at detail, but note that they use Visualization Infrastructure Management (VIM) and Pak-GIS as a reference database	Users are the government of Pakistan, and all other organizations responsible for public health as well as the public for informational purposes. It can be used for early outbreak detection, resource allocation, and response management.	The authors' lessons learned says its key to have users involved, but do not stipulate how and who were involved in the manuscript. They note that ID-Viewer is currently in use at a public health and an academic institution.
[135]	WebGIS was developed to detect clusters of malaria in Vietnam and allow user to select pattern detection tool: nearest neighbor, K-function, or spatial autocorrelation	Malaria cases from the web; geocoded to map topography	Used a PostGIS/PostgreSQL databasewith GeoServer (open source) for spatial analysis and Openlayers and Ext.js for interface. Data was collected from the web with Open Data Kit (ODK)	Health practitioners, educators, local communities, health sector authorities, and decision makers	Performed user testing with 19 people who were demoed then asked 4 questions with scale 1-10; only improvement that the authors reported from participants was the desire to get able to set administrative boundaries and indication of whether a cluster was random or significant

[136]	DYCAST system creates risk maps to push out public health reports about dead birds to identify risk areas for West Nile during a major outbreak in CA.	Dead bird reports from hotline/phone calls; public health communicable disease reports, temperature, vector data	Hosted on server using SQL and ArcIMS, available online on password protected website	Local public health departments in California could use for educational campaigns, surveillance and vector control	They surveyed 46 counties in CA to ask about use of system; use went down significantly over time which may have indicated dissatisfaction with the system or no longer needed as outbreak severity declined overtime
Ref	**Tool Objective**	**Data**	**Technology**	**Users & use cases**	**Design**
[59]	Tool allows users prospectively identify hotspots of dengue weekly at the village level	Confirmed cases of dengue from Taiwan CDC with demographics and location; obtained population counts form Ministry of Interior	Used SatScan and R for analysis and PHP, JavaScript, and HTML for interactive interface	Public health workers to plan insect spraying campaigns	Not described
[137]	Allows for collaboration for people working in vector-borne disease transmission and geography	Vector data from remote sensing; case study used sandfly data from a published literature source that they geocoded; leishmaniasis disease data was geocoded from WHO maps;	Microsoft Silverlight and ESRI's Arc GIS Server 10; SQL database; Maxent	Medical entomologists, vector disease control workers, public health officials, and health planners	Allows for data contributors, free/open access; no specific user involvement described

		ecological niche model overlays			
[138]	The visualization portal of OSCAR allows users to aggregate, analyze, model and compute disparate data in a faster way during times of emergency	Includes both static (case counts, demographics etc.) and dynamic data sources. Dynamic data includes social media and other web-based data obtained through crawlers. They use environment, social-economic, and transportation variables	Very complicated and detailed infrastructure documented the OSCAR paper. They deploy a service-oriented architecture on a distributed network. The service layer includes tools such as R and ArcGIS. The visualization component uses HTML5, JSON, SVGs, and d3.js.	Public health researchers, medical staff, and policy makers can use the tool for data collection and aggregation, cloud computing, and decision support. In their case study they use the example of closing poultry markets to control the spread of avian influenza	"User friendly" but users must have a basic understanding of spatial analysis and statistics; do not discuss user involvement
Ref	**Tool Objective**	**Data**	**Technology**	**Users & use cases**	**Design**
[139]	Analyze risk based high risk activities (typical park behavior) using spatio-temporal models	Administered paper and online surveys to visitors to capture demographics and activities performed, spatial data for forest land cover	MapServer written in Python, PHP, and JavaScript	Park visitors and the public who are planning a trip and activities in the park; they also note public health as users in tthe introduction	Noted that interface was user-friendly and simple

[140]	VBD AIR shows relative risks associated with airline travel by understanding risks of passengers and vectors infected by disease	Air travel data (online and purchased), disease distribution for 4 VBD, including environmental suitability, vector distribution datasets, climate data, travel time to nearest city,	Uses a SQL database with HTML and JSON data exchange. The base maps are Google and OpenStreetMap and GeoServer with some manipulation in ArcGIS. OpenLayers is used for visualization	Planners and decision makers at airports who oversee planning for health risks and allocating resources	Paper includes a user flow through the tool; calls the tool user friendly, and includes tool text boxes and a user guide to explain the definitions/concepts
[141]	EpiTrace is intended to help veterinarians and epidemiologists trace animal trade and locations when there in an outbreak of a zoonotic disease	Social network analysis of livestock movement data; Animals and holding (BDN database) is linked to SIMAN (national system for notification of zoonotic disease outbreaks)	Integrated into the BDN (a national database of animals and holdings) that has a search engine (using a webservice) and a visualization using a Java applet	Veterinarians and epidemiologists to address outbreaks sooner. They tested it and found that it sped up investigation activities to one day rather than several days using previous methods	The authors evaluated the use of the tool, as captured in log analysis files, to show an uptake in acceptability. They do no perform any other user testing.
Ref	**Tool Objective**	**Data**	**Technology**	**Users & use cases**	**Design**

[142]	The SDSS framework routinely captures health and spatial data, creates risk maps and tabular data, and identify areas for interventions (spraying)	Routine malaria data and entomological surveys; risks maps - personnel mapped and surveyed households to collect baseline data, where areas were sprayed	not discussed	Public health workers make decisions about where to use resources, such as nets and spraying campaigns. The tool is also developed for public health workers administering those campaigns for data collection	The authors suggest local knowledge is essential and should be included in the SDSS framework. They created technical working groups and web-based discussion boards.
[143]	Decision Support System for the Response to Infectious Disease Emergencies (DSSRIDE) can be used for data collection, timely analysis and querying, communication, and guides for handling emergencies	Didn't get into the specifics of the data, but said that baseline data included spatial distribution of diseases, demographics, environment, hosts, vectors, and medical services	Uses WebGIS service and Google maps for visualization and 3G wireless network mobile services for data collection and communication	Emergency workers, epidemiologist, hospitals, investigators, decision makers	Not described

[144]	The SDSS is part of a malaria program management dashboard to geolocate positivity rates and detect outbreaks in a timelier manner	Created a mHealth data capture tool to collect malaria testing records and patient demographics. Villages and health facility data were geocoded and incorporated in their GIS	The online platform was developed with JavaScript using a SQL server and VMware as backend using a 'proprietary GIS platform' for mapping. Data were analyzed with STATA.	eNHIS - to provide timely information on supply needs, evaluate interventions during outbreaks, and monitor transmission and outcomes.	Not described
[145]	Allows users to perform cluster detection for early outbreaks, understand speed of spread of outbreaks, model mosquitoes, and perform network analysis for livestock mobility	SIMAN (national system for notification of zoonotic diseases outbreaks) and BDN (animals and holdings) both of which are managed by Italian Ministry of Health. They also use remote sensed data and users can upload external data	Uses R and SaTScan software and 32 R-packages that the authors list in the text. There is a public website version and a private/ password protected version	Veterinary and medical epidemiologist who cannot perform theses analyses on their own, also available to the public.	Made the tool easy to understand and flexible for different types of analyses. They also made it possible for users to upload and download data. No specific user involvement during design or evaluation

[146]	Tool to help support and manage malaria activities but creating digital data capture through GPS devices	GPS collection of long lasting insecticidal nets, indoor residual spraying, and malaria cases by household	QGIS (open source GIS software) and MS excel	Health workers who were going house to house to check for spraying, nets, and cases and their managers; epidemiologists, public health decision makers	Fairly extensive training was done with users before implementation and the SDSS was evaluated for acceptability and utility after 6 months

To describe the status of the literature (objective 1), I summarize the outcome of data charting according to the items extracted or Data, technology, and users and use cases. I summarize the design data charting in the design recommendations section.

Data

The underlying data are an important consideration of any health informatics tool. I have grouped data sources across four broad categories: human, infrastructure, animal, and environment. It should be noted that not all studies reported metadata or specific details about what data were included in their studies. Data related to human health included the chief complaint from emergency departments, pediatric hospitals, public health case reports, ambulatory records, emergency call lines, social media posts, household surveys, and demographics including age, race, sex, ethnicity, and socio-economic variables. For infrastructure, I included transportation, health facilities, and intervention data as indicators. Data related to interventions were locations of indoor residual spraying, and long-lasting insecticidal nets. Locations of health facilities and resources were noted in the studies. Some studies also included transportation and human movement data, such as travel time to cities, movements within parks, and airline flight patterns. There were numerous animal data incorporated in the tools, such as host counts, vector counts, animal movement patterns, disease outbreak information among animals, lifecycle span, dead animal reports, and live animal market information. Finally, environment data sources included climate measurements, land cover, environmental suitability, and topography. The One Health approach suggests that optimal surveillance and preparedness should include data across these categories for a comprehensive understanding of health [9]. Though they include a varied spectrum of data sources, only two of the fourteen studies included data from all 4 categories – human, infrastructure, animal, and environment.

Technology

Technology is another important consideration to health informatics tools. Though the minute details of infrastructure and technical specifications are not an objective of this review, it is important to note the software applications and high-level details of the technical components of the tools. The studies included in the review present a wide range of approaches from open-source development to proprietary software use, and from complex cloud computing to simple GPS solutions using cell phones. The most common licensed software solutions used were ArcGIS[147], SQL servers [148], Microsoft Excel[149], and STATA [150]. Several tools utilized freely available software such as QGIS [151], R [152], SaTScan [153], and Maxent [154]. The authors use a number of different languages, standards, libraries, frameworks, such as HTML [155], d3.js [156], Python [157], SVGs[158], and JavaScript [159]. Authors includes several interesting proposals for data collection, including GPS-enabled mHealth technologies and web crawlers for scraping websites. There is variety in how these tools are deployed and hosted, including remote server hosting. distributed networks, smart phone applications, password-protected websites, and publicly available websites. Notably, of the studies that listed a publicly available URL for access to the tool, none were currently available online.

Users and Use Cases

Identification of users – along with their role, context, and needs – is another a key consideration of interactive vulnerability mapping tools. Most studies note public health practitioners as their primary end user or audience for the tool. Among the job titles in this user group were epidemiologists, planners, managers, and directors. A variety of user groups in the health domain were also noted in the studies, including clinicians, veterinarians, entomologists, and community health workers. In some studies, the general public was considered users, especially those that were visiting forested parks and planning airline travel. Though the user groups primarily focused on public health and the public, there are numerous use cases that could be very different.

The identification of users can further be explored through mapping users to their interaction with the tool or use cases. One of the most salient advantages of using the SDSS throughout the studies was the ability to do their current work more quickly or efficiently. In the case of outbreak detection, many tools incorporate epidemiological models that predict where outbreaks may occur or allow users to detect outbreak clusters sooner to contain spread. These predictive and emergent applications allow for prevention and preparedness measures to be deployed, such as vaccination campaigns, closure of animal markets, insecticidal spraying, bed nets, and educational campaigns. As the number of SDSS used for VBZD surveillance and prevention increases, the number and variety of use cases will likely grow accordingly. Possible future applications might include predictive analytics and/or genetic information considered for a 'precision medicine' approach.

Design Recommendations

There was a striking lack of design reporting in the literature, which prompted the formation of recommendations for future work. I summarize gaps in research that inform my design recommendations (objective 2) by describing the lack of research along dimensions of 1) user-centric approaches, 2) data visualization principles, 3) interactive features, and 4) displaying acceptable and actionable information. My specific design recommendations are in bold below.

Ref	User-centric	Data visualization principles	Interaction design	Acceptable & Actionable
1				
2				X
3				X
4				
5				
6				
7				
8	X			
9				X
10	X			
11				
12				
13				
14				X
Aim 1	X	X	X	X
Aim 2	X	X	X	X

Table 3: The above table shows a comparison of studies included in the review with Aims 1 and 2 across the design recommendations

User centric approaches

A key missing element of interactive vulnerability mapping tools for VBZD was the lack of methods or findings with the objective of developing a tool that was 'user-centric'. Though there was some mention of design, no studies mentioned comprehensive and continued involvement of users throughout the design process, as stipulated in human centered design (HCD). HCD is the evolution of user-centered design that extends to include important stakeholders who are not end users of the design [16]. The ISO standard 9241-210:2019 defines HCD as "an approach to interactive systems development that aims to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors/ergonomics, and usability knowledge and techniques" [160]. Two of the studies note creating user flows or technical working groups as part of the design of their tool, which are elements of HCD, but represent an incomplete piece of the overall approach.

In my Aim 1 and 2, I emphasize user-centric involvement by utilizing methods instructed by HCD. These methods include storyboards (Aim 1.1), iterative wireframes (Aim 1.1 and 2.1), co-design (Aim 2.1), creation of use cases (Aim 1.1 and 2.1), focus groups (Aim 1.2), interviews (Aim 2.2), surveys (Aim 1.2 and 2.2) and task analysis (Aim 1.2 and 2.2). My approach aligns with another study in health informatics, where the authors organize HCD methodology into three phases: 1) determine needs and context, 2) expert review, and 3) usability testing [161]. Further, one of the qualitative findings from Aim 1 and 2 was the importance of trust building in interactive vulnerability mapping, which can be strengthened by the use of HCD methods in health projects [161].

Future interactive mapping tools for VBZD preparedness should look to the human centered design literature, routinely incorporate user-centric methods in studies, and report of the use and application of these methods in publications.

Data visualization principles

The lack of discussion in design also extended to the purposeful adherence to data visualization principles. In Aims 1 and 2, I share findings from the application of three data visualization principles to interactive mapping tools. In this 2020 perspective, Midway shares some principles for effective visualizations, including the three of interest in my Aims: color, layout, and format. Midway refers to the three principles as color, simple graphics with detailed captions, and small multiples or panels [25]. Further, these principles are grounded in other research studies. Color can be a powerful way to encode meaning. Layout should include descriptive text that conveys a storytelling approach. In data visualization literature, it is frequently suggested to have small multiples or side-by-side graphics, but I report mixed preferences regarding format and this principle should requires additional research in the interactive vulnerability mapping literature.

Similar to principles, data visualization taxonomies may suggest some best practices for researchers in interactive vulnerability mapping tools. In my Aim 1.1, I perform a landscape analysis of visualization platforms to select the best technology to build the dengue interactive vulnerability mapping tools (and subsequently build on those findings in Aim 2.1 for Rift Valley fever). My 'landscape analysis' can be equated to the visualization taxonomy for visualization software as described in the second edition of *"Data Visualization: Principles and Practice"* [4]. Key metrics should be identified to compare technologies. I used "ease of use", "availability", and "sustainability", but these metrics should be customized to the specific project and context. None of the fourteen studies note performing a landscape analysis or explicitly note metrics for comparing technology.

Future work should take an intentional focus on data visualization principles by consulting the computer science literature, evaluating the design with visualization subject matter experts, analyzing technology options with a visualization taxonomy, and comparing visualization options with end users.

Interaction design

One strength of the interactive vulnerability mapping tools literature is the inclusion of interactive features in the design. Interactivity is an important component of the larger field of SDSS as tools should be flexible for multiple types of decision making [162]. In the literature, studies include interactive features such as pan and zooming on maps, selection of time periods, search, and parameters for VBZD or populations. Interaction design is another design approach that shares methods with HCD, including user-involvement, prototyping, usability evaluation, and iterative design [163]. Additionally, interaction design suggest methods that are unique to understanding how a user interacts with an interface or tool. I utilize interaction design specific methods such as parallel design and empirical testing during the usability evaluations in Aims 1.2 and 2.2 by testing with potential users and collecting data on visualization preferences with alternative prototypes.

Future work should take an inclusive approach to design both in terms of users and methods. Researchers should look to the interaction design literature to develop and assess interactive features in an evidenced-based way.

Acceptability and actionability

Acceptability and actionability are frequently objectives of usability evaluations. The majority of the studies (8 out of 14, or 57%) explicitly noted their tool as 'user friendly', yet only 4 of the studies (3 of those with the 'user friendly' self-designation) conducted any sort of usability testing to ensure the tool is acceptable and actionable. Unfortunately, even the user testing that was performed was minimal. Two studies accessed use of the system as an indication of acceptability, one with log analysis and another with a survey collecting information on use. The other two studies involving user testing included qualitative data collection through interviews only or interviews with a custom 4-question survey (rather than using a validated survey instrument).

There is a missed opportunity in the lack of methods used for usability evaluation, such as task analysis [99], validated survey instruments [100], [164], [165], heuristic evaluation [166], focus groups, and think alouds [99], which have been utilized extensively in health information technology [98] and eHealth [63]. Finally, when user testing is performed, it should be reported in a clear, meaningful way. Though additional usability methodologies may have been performed, the studies that did report user testing provided little detail about their specific methodological approach. Work by Peute and colleagues suggests a specific set of elements to include in health usability reporting which provide helpful guidance for future work in this field [167].

Future work should incorporate usability methodologies and tools to assess acceptability and actionability *and* purposefully report on those methods and findings in a complete, and ideally standardized, manner.

Discussion

The literature for SDSS over the past decade reflects a broad set of use cases for VBZD vulnerability. I summarized the data, technology, users, and use cases (objective 1). Studies included in this scoping review integrated various categories of data, including animal, human, infrastructure, and environment data as well as some novel sources such as web crawled data. Developers in this field build upon proprietary and open-source software and technologies, such as QGIS, R, and d3.js. Users across the spectrum of human and animal health use SDSS to make preparedness and planning campaigns, such as animal market closures and vaccination campaigns. The public might also access this information to inform their own risk decisions such as travel. Additionally, I highlighted gaps in the literature to inform design recommendations (objective 2) There is great opportunity for improvement in engaging with users both in design and evaluation following a user-centered approach. Finally, future studies should take a purposeful approach to analysis and understanding of design.

The Covid-19 pandemic has likely forever changed the way that public health and society think about pandemic vulnerability and preparedness. Though Covid-19 is not considered a VBZD, understanding any transferrable findings from this review to other infectious disease outbreaks is both timely and important. Lessons learned from this review include 1) taking an inclusive approach to disparate data integration; 2) building tools that are intended to provide actionable, timely information; and 3) considering the role of the user from idea inception to implementation. These lessons have been applied to Covid-19 tools in varying degrees. The COVID-19 Watcher incorporates data from 4 distinct sources and aggregates this information at various degrees, including counties, cities, and states, but does not display their data spatially on maps [168]. The CoronaViz tool takes an interactive approach to mapping and understanding spatio-temporal data, but the authors do not report involving users in any part of the design [88]. Additionally, since there has been a high quantity of visualization tools developed during the Covid-19 pandemic, there is the opportunity to advance the science of visualizations related to pandemics and public health. New research suggests evidence-based metrics to evaluate and measure efficacy of visualizations tools [71], which should be harnessed to future interactive vulnerability mapping tools.

In the near future, interactive vulnerability mapping tools have the opportunity to advance by harnessing new technologies and resources. Only one of the studies included in this review noted using cloud technology as a resource for hosting or computation. As healthcare generally moves to a remote data and server infrastructure, it is important that public health keep up [169]. As cost and capacity are always a concern for resource-limited or publicly-funded public health projects, cloud technology might allow for shared costs and increased collaboration [170]. Starting to view some of the previous technological constraints as a shared resource opens the door for growth in SDSS. New resources, such as the Planetary Computer for climate and land cover data, allow researchers to freely access very large datasets, which was previously limited by storage capacity [171]. The studies included in this review did not make full use of shared data resources. Data such as the Global Burden of Disease research [172] and NIH's All of Us project [173] should be better applied for VBZD surveillance and preparedness. Finally, the science of machine learning and artificial intelligence is rapidly advancing and may be especially helpful in forecasting disease outbreaks with a One Health approach [34], [174].

Finally, future work should look toward the grey and nontraditional literature to understand non-research approaches and best practices that could be applied to interactive vulnerability mapping tools. Resources such as the New York Times, which create interactive, narrative visualizations for broad audiences, and health specific sources, such as the Institute for Health Metrics and Evaluation and the World Health Organization, might provide useful insight outside of traditional research reporting. Though the objective of this research aim was to conduct a reproducible scoping review to inform recommendations, the next iteration of these recommendations would benefit from additional fields and sources to provide an interdisciplinary perspective.

Limitations

Though this scoping review provides a rigorous overview of the existing literature over the past decade, there were some limitations of note. The objective of this review was not to evaluate specific epidemiological model or data science methodologies nor to perform a critical appraisal of the existing evidence. My intention was to summarize current literature and highlight specific elements across the different studies and identify opportunities for improvement. As this topic continues to mature and additional studies are published, future reviews might take an evaluative approach in assessing the accuracy of the model and the fitness of the methodology used to develop the interactive mapping tool.

Conclusions

Interactive mapping tools provide an avenue for users to access and understand VBZD data that are vital to prepare and plan for future outbreaks and contain emerging disease threats before they spread. The current literature is diverse in its application of these tools but lacking in breadth (or quantity tools available) and depth (or quality of HCI rigor). Studies included in this scoping review describe data and technology spread across sources both traditional (incidence case counts and demographics datasets) and novel (such as cloud computing, social media posts, and open source software). Users included workers in a range of positions, such as vector control specialists, epidemiologists, and managers who determine personnel resource allocation. Use cases involve decision making for public health interventions, such as educational campaigns and distributing bed nets, and personal decisions such as what activities to engage in at parks or what flight to take. A strength of the literature includes interactivity; gaps concern the lack of HCD (during design and usability) and data visualization principles. Future researchers should consider user-centric approaches, following data visualization principles, incorporating interactive features, and assessing acceptability and actionability. My research in Aims 1 and 2 offer some examples of how these recommendations might be applied with HCD methods and adopt a sociotechnical understanding of interactive vulnerability mapping tools, as gaps in these areas exist in the current literature. If a human-centered approach to interactive vulnerability mapping tool research can utilize new technological advancements, the field will only continue to grow and provide ever-greater societal benefit.

CHAPTER 6: CONCLUSION

In my final chapter, I demonstrate how I have accomplished the specific aims proposed at the onset of this research. I also share how my dissertation contributes to the fields of global health informatics, human computer interaction, and data visualization. Finally, I note some limitations of this research and opportunities for future work.

Fulfillment of Specific Aims

In my dissertation research, I fulfilled the following aims:

Aim 1: Design, build, and evaluate an interactive mapping tool for dengue vulnerability in Peru. For design, I created multiple artifacts including: a story board illustrating the intended use of the tool; wireframes annotated with learning objectives for the user; and seven visualization alternatives each with varying color, layout, or approach. These artifacts were improved with feedback from users from a major research university in Peru and from the national health department. (Aim 1.1) For build, I conducted a landscape analysis of open source and proprietary visualization platforms, including R shiny, Power BI, Tableau, and d3.js. Based on the outcome of the landscape analysis, I built an interactive vulnerability mapping tool that incorporated data from a vulnerability model from IHME [26] using Tableau software. For evaluation, I held a group usability workshop in-country with 20 representative end users with focus groups, visualization preference selection, an SUS, and a task analysis exercise. In the workshop, most participants completed four (out of five) tasks accurately and scored the tool with a 75% on the SUS, which is considered above average usability. Participants reported higher preferences for contrasting color scheme, a single map layout, and a storytelling format. During the focus groups, participants shared feedback that was reflective of acceptability and utility. They also shared the desire to have more in-depth details about the data used in the vulnerability model and that providing these details would create trust in the information that is displayed. (Aim 1.2) My findings provide empirical evidence for data visualization preferences and a demonstration of group usability in a new setting, namely public health in Peru.

Aim 2: Design, build, and evaluate an interactive mapping tool for Rift Valley fever vulnerability in Kenya. I strengthened my approach from Aim 1 to design and evaluate the usability of an interactive mapping tool for Rift Valley fever (RVF) vulnerability in Kenya. For design, I engaged a larger set of users in a more collaborative format than the remote design methods used in Peru. I held a co-design workshop in Nairobi with 25 participants who worked in public health, veterinary, and international organizations. During the workshop, participants learned additional detail about the vulnerability model and provided feedback on the users, data, and use cases involved in a RVF interactive vulnerability mapping tool. Participants noted that users, data, and use cases could be grouped into 2 categories: human health and animal health. (Aim 2.1) For build, I incorporated the co-design feedback to develop an interactive vulnerability mapping tool with separately visualized human and animal vulnerability models. I used Tableau software because of existing licenses and capacity with users in Kenya. For evaluation, I conducted 13 remote usability interviews with end users, where I captured audio and screen recordings. My original intention was to demonstrate the group usability method (as conducted in Aim 1.2), but Covid-19 restrictions prevented group meetings and international travel. I found some improved usability results from Aim 2 compared to Aim 1; participants completed all tasks with 100% accuracy and scored the tool with an average score of 86% on the SUS. Most participants preferred the contrasting color scale and storytelling format but were divided on layout (with the options of one map with multiple layers or side-by-side maps). The differences in preferences for layout in Peru (Aim 1.2) and Kenya suggests the need to assess design considerations when developing interactive vulnerability mapping tools in new settings. Qualitative data collected during the usability interviews suggested high acceptability and actionability, and I heard similar themes regarding the need to have insight into the data sources and emphasizing trust. (Aim 2.2)

Aim 3: Perform a scoping review of interactive vulnerability mapping tools for vector borne and zoonotic disease global health preparedness to provide recommendations for design. I built upon previous scoping reviews including a review on SDSS for zoonotic disease [1], visualizations for infectious diseases, and visual analytics for healthcare to create a new search with the themes of global health preparedness, VBZD, and interactive spatial visualizations. I used a reproducible search strategy informed by the PRISMA- ScR guideline to search PubMed, Google Scholar, and Embase covering the years of 2011 to 2021. My initial search yielded 636 results across the three databases. After review, 14 articles were ultimately included based on topical relevance and inclusion criteria. I describe the current available literature and characterize data, technology, users, and use cases. Data and technology platforms were varied and did not typically integrate a comprehensive set of One Health data sources (animal, human, entomological, environment, and infrastructure). Users were either public health-related or public audiences. Use cases were around preparedness, such as vector nets, spraying insecticide, or closing animal markets, or personal choices, such as travel and activity planning. There were major gaps in design and usability reported in these studies compared with my approach in Aims 1 and 2. I propose design recommendations for user engagement (such as co-design and mixed methods usability studies from my studies and user centered and community-based participatory design from the literature) to better engage users for short term acceptability and usability and, likely, long term sustainability.

Contributions

This work contributes to a nascent and important knowledge base in vulnerability mapping tools for global health preparedness, and provides real world, validated tools for visualizing disease vulnerability. Overall, my contributions include: 1) usable interactive vulnerability mapping tools designed for public health decision makers in Peru and Kenya; 2) empirical data on the design, data visualization preferences, usability, and acceptance of interactive vulnerability mapping tools in global health settings; 3) demonstration of a methodological approach for group usability in a public health setting; and 4) a scoping review of the interactive vulnerability mapping tools for VBZD that characterizes current literature, highlights the need for additional human-centered methods, and suggests design recommendations from the literature and my studies. Further, my research contributes to the fields of global health informatics, human-computer interaction, and data visualization.

Contribution to Global Health Informatics

1. *Developed two evaluated, functional tools for real-world global health preparedness work.* Both tools are currently hosted online on UW public servers and available for public health practitioners to use and have been iterated during the design stage and

evaluated for usability. These tools can be accessed at: https://tinyurl.com/DenguePeru and https://tinyurl.com/rvftool

2. *Characterized key elements of a nascent literature base.* My scoping review (Aim 3) helped define and describe a new application of tools to global health preparedness. Previous scoping reviews were either incomplete or not inclusive of the necessary search themes – global health preparedness, VBZD, and interactive spatial tools. Understanding and mapping the field in this way will help future researchers build on prior work and address gaps in literature.

Human Computer Interaction

1. *Applied an enhanced group usability method to a new domain.* I applied the group usability testing methodology with the addition of data visualization preference selection and a standardized usability survey instrument. In addition to enhancing the method, I applied the group usability method to a new domain: public health. Prior studies have applied the group usability method to virtual reality [67], community planning, [68], and online learning research [69], but to my knowledge it has not been applied in public health.
2. *Identified the need for a cultural assessment of the System Usability Scale (SUS).* The SUS is a frequently used and well validated instrument for a quick assessment of acceptability. Though some aspects have been studied in the literature, including the accessibility of appropriate questions [175] and the use of specific words [83], to my knowledge there has not been an analysis of the cultural dimensions of the tool. Language and administration of the SUS may be impacted by differences in culture

norms and vernacular, as was noted by a participant in Aim 2. This requires future research.

3. *Utilized 4 approaches for a mixed method usability testing.* In Aims 1.2 and 2.2, I included four mixed method approaches for usability testing: 1) qualitative data collection with a semi-structured instrument; 2) a standardized usability survey; 3) task analysis with questions that are representative of use cases; and 4) data visualization preference selection. Each approach adds unique pieces to the complete picture of usability, yet multiple, mixed-methods are not frequently utilized in global health informatics usability studies [63].

Data Visualization

1. *Operationalized the Munzner framework for/by xxx.* Though taxonomies and recommendations exist [4], [24], [25], [39], there are very few frameworks for data visualization. Further, it can be difficult to translate a theoretical framework into research. I applied the conceptual layers proposed my Munzner to orient my research questions and ground my dissertation aims. Future studies may learn from this application and utilize the Munzner framework in a similar way.
2. *Proposed design and usability recommendations for interactive vulnerability mapping tools.* During usability testing in Aims 1.2 and 2.2, I collected visualization preferences (color, layout, format) for multi-site empirical data for foundational design recommendations. Further, my approach provides reusable methods that motivate my recommendations: to engage users in the design during co-design and iterative wireframing, and then purposefully assess their design preferences during evaluation.

These recommendations serve an unmet gap in the interactive vulnerability mapping literature.

Limitations

The two primary limitations of my research involve the underlying vulnerability model and the language barrier in international settings. The vulnerability model has been proven effective in another setting [26] and is currently undergoing analysis to determine its fit for dengue in Peru and RVF in Kenya. Though subject matter experts approved and agreed with the use of this model, there is an assumption that the vulnerability model has high accuracy that could be proven incorrect. I do not have access to the underlying script or data sources, so I am not able to do my own analyses; in any case, the results and contributions in this dissertation still stand on their own. Another risk or vulnerability model could replace the one that I have used, but the design and evaluation methods and results would still be appropriate.

Language was a limitation of Aim 1 specifically as Peru is a Spanish-speaking country and I am not fluent in the language. I took several steps to address the language barrier, including involving bilingual research team members in Peru from the start of the project, training bilingual facilitators for the focus group discussion, and involving a native Peruvian researcher as the secondary coder for qualitative data analysis. The focus groups were conducted in Spanish and names were not captured to be able to correlate their perspectives with their job role, which inhibited user group analysis. In Aim 2, all participants spoke English fluently, so this was not a limitation. Future work should be careful to allow for user group analysis during the translation and transcription process.

Future work

In Chapters 3-5, I describe opportunities for future work. As applying human centered design and data visualization principles to global health preparedness is not well established in the literature, there are numerous directions and opportunities for growth and development. Two opportunities for future work are the most pertinent: namely, new VBZD applications, and applying an international layer of disease vulnerability. As there are transferable recommendations for design and usability for any VBZD, it would be easy to build similar interactive vulnerability mapping tools for other diseases, such as malaria or rabies. Additional research is needed, but a similar tool could be developed for multiple VBZD pathogens that would help public health practitioners better prioritize vulnerability in the context of other disease outbreaks. Finally, as one participant astutely noted in Aim 2, diseases know no borders. It is important for future work to take an inclusive approach and engage users from neighboring countries, as epidemic vulnerability inherently influences pandemic vulnerability. The international layer could be visualized as 'stage 4' in the vulnerability model.

My own near-term future work is two-fold, where I plan to further investigate and emphasize climate change in interactive vulnerability mapping tools. I also plan to enhance my design recommendations by investigating the grey literature. In finalizing my write up of Aims 1 and 2 for publication, I plan to further develop what impact interactive vulnerability mapping tools might have on the discussion of climate change and public health. There is the opportunity to advance the research that has already begun in the public health literature about climate change as well as make this research more accessible to non-academic audiences through the tangible application of interactive vulnerability mapping tools. Advancing current research and creating a more accessible message is also the rationale for the inclusion of data visualization grey literature, which will make a stronger set of recommendations in the publication of my Aim 3.

Conclusion

In this dissertation, I introduced a new kind of spatial system for decision support: interactive vulnerability mapping tools. Interactive vulnerability mapping tools could help mitigate spread of outbreaks and facilitate early detection of new cases that could otherwise result in an epidemic. They have the potential to help public health practitioners understand where to stockpile vaccine resources, conduct education campaigns, and prioritize preparedness activities like bed nets and spraying. Further, interactive vulnerability mapping tools could help epidemiologists distinguish areas where a few cases are likely to be contained from areas that are likely to spread rapidly to an epidemic stage if an outbreak occurs.

As any decision maker or practitioner in a crisis would no doubt report, the aforementioned tasks require timely, actionable information that can be easily accessed and understood. It is therefore critical that the interactive vulnerability mapping tools be designed in a way that is acceptable and usable to end users *and* be evaluated across these objectives. My dissertation describes the design approach for tools in Peru (Aim 1.1) and Kenya (Aim 2.1) and shares the usability evaluation results from a group methodology (Aim 1.2) and remote methods (Aim 2.2) in each location, respectively. Finally, I situate my findings in the literature by performing a scoping review and comparing my approach with similar studies (Aim 3). The comparison of methods and empirical data from Aim 1 and Aim 2 motivate a set of design recommendations that can be applied for future interactive vulnerability mapping tools. Overall, this research advances the fields of global health preparedness, human computer interaction and data visualization by demonstrating evidence-based design and usability methods and speaks to the need to continue to develop the intersection of these fields. Ultimately, global health preparedness could be strengthened by applying lessons learned from my dissertation to help build sustainable, user-driven tools to prevent the spread of VBZD outbreaks, therefore protecting public health.

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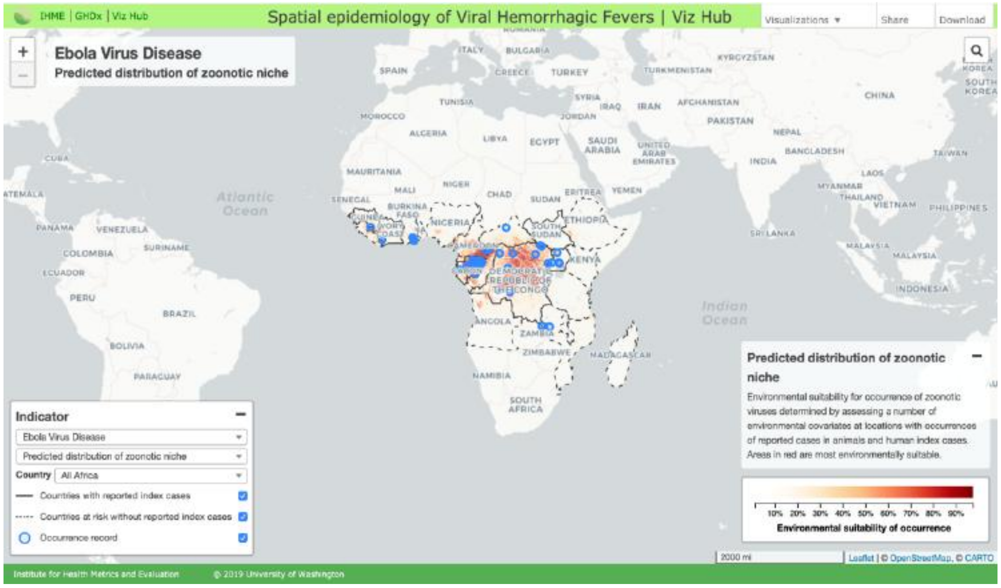
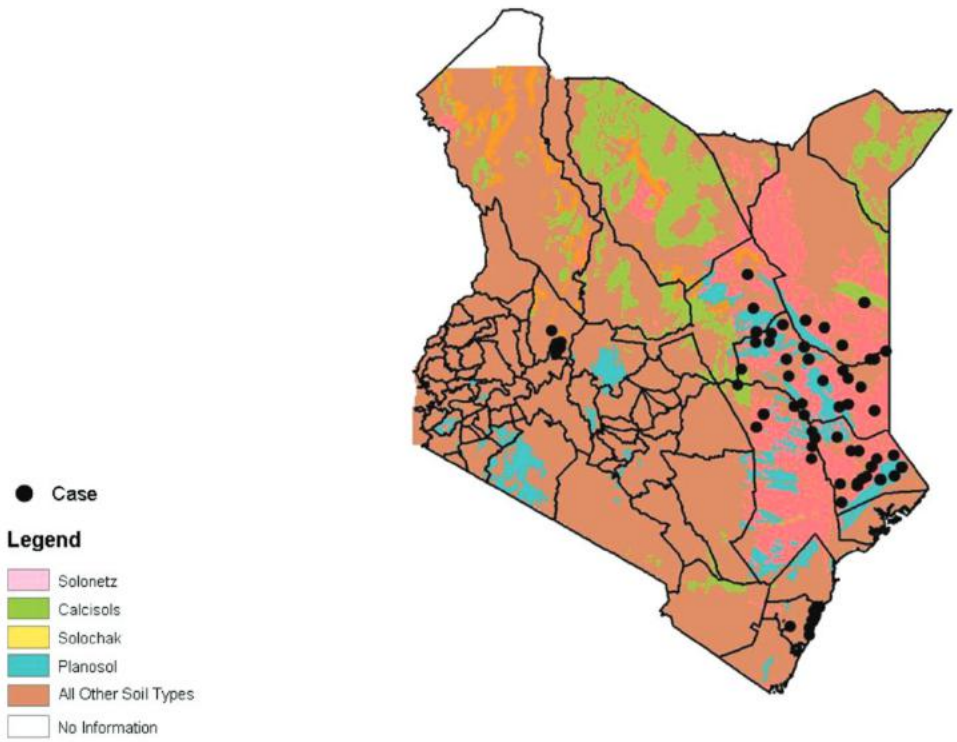
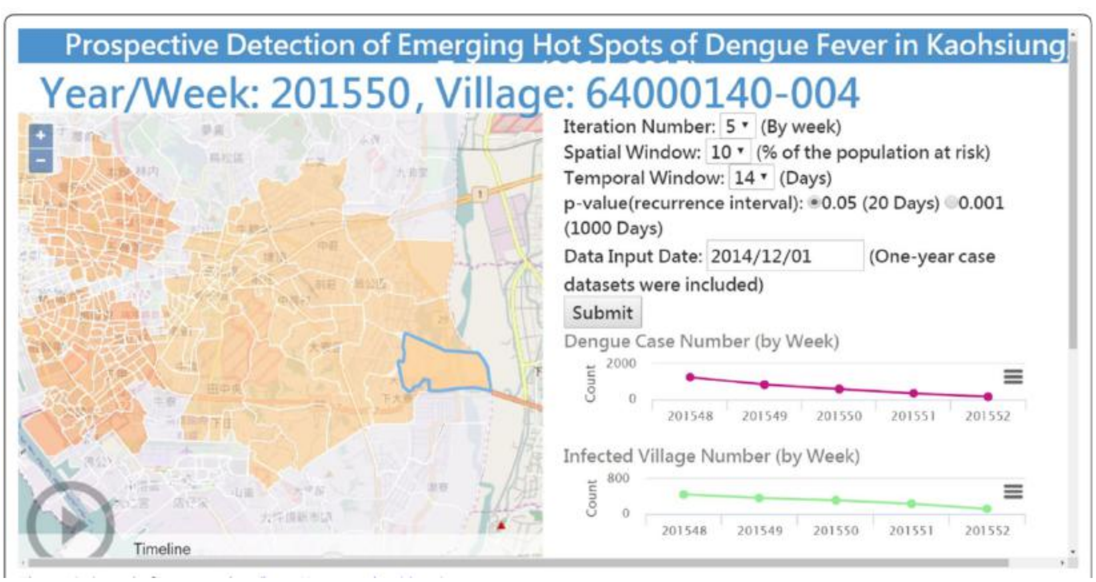
Appendix 1: Ebola/Hemorrhagic Fever Interactive Mapping Tool by IHME [176]



Visualization tool for Ebola from IHME using the vulnerability model used in Aims 1 and 2.

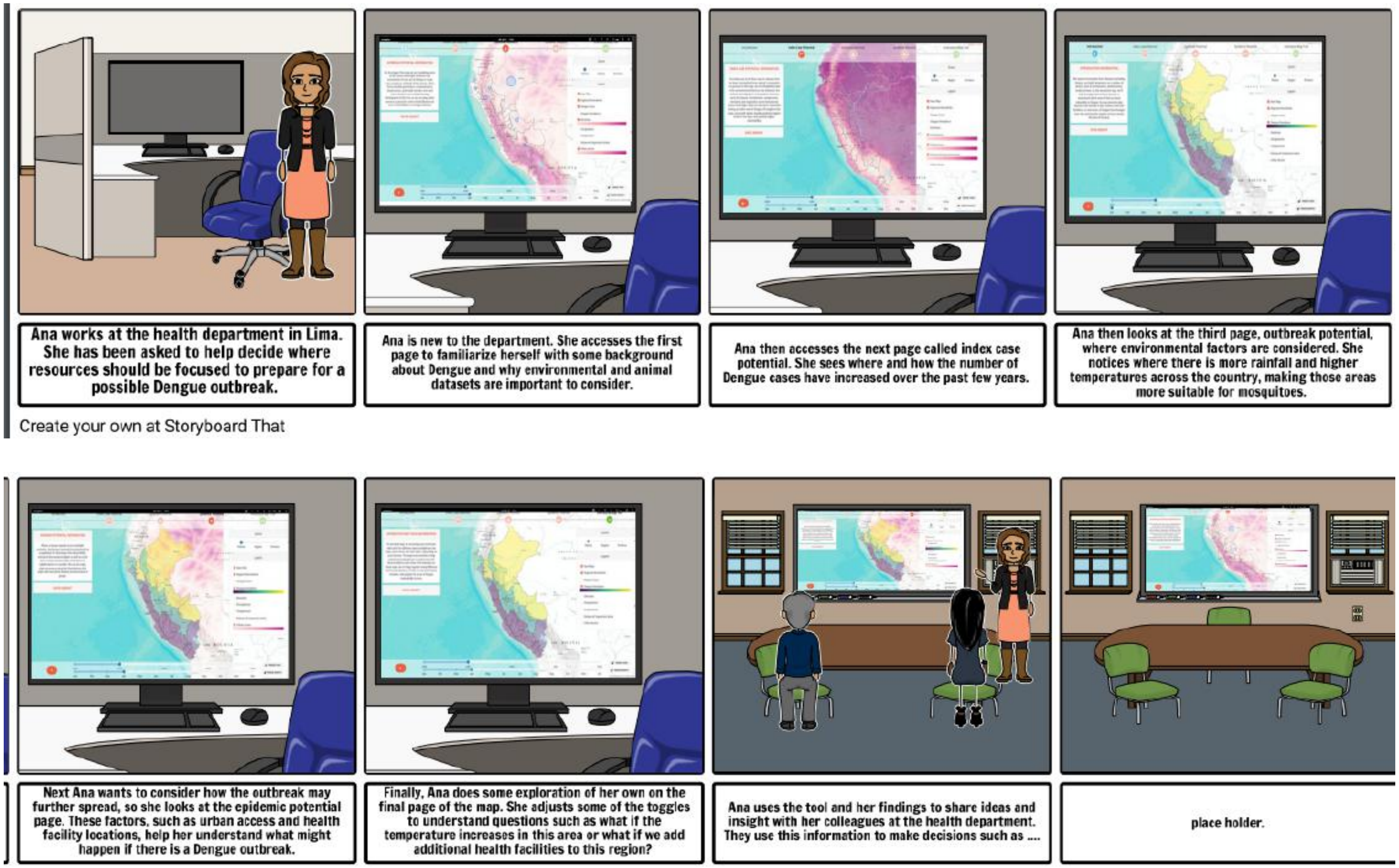
Appendix 2: Visualizations examples for RVF and dengue from the literature





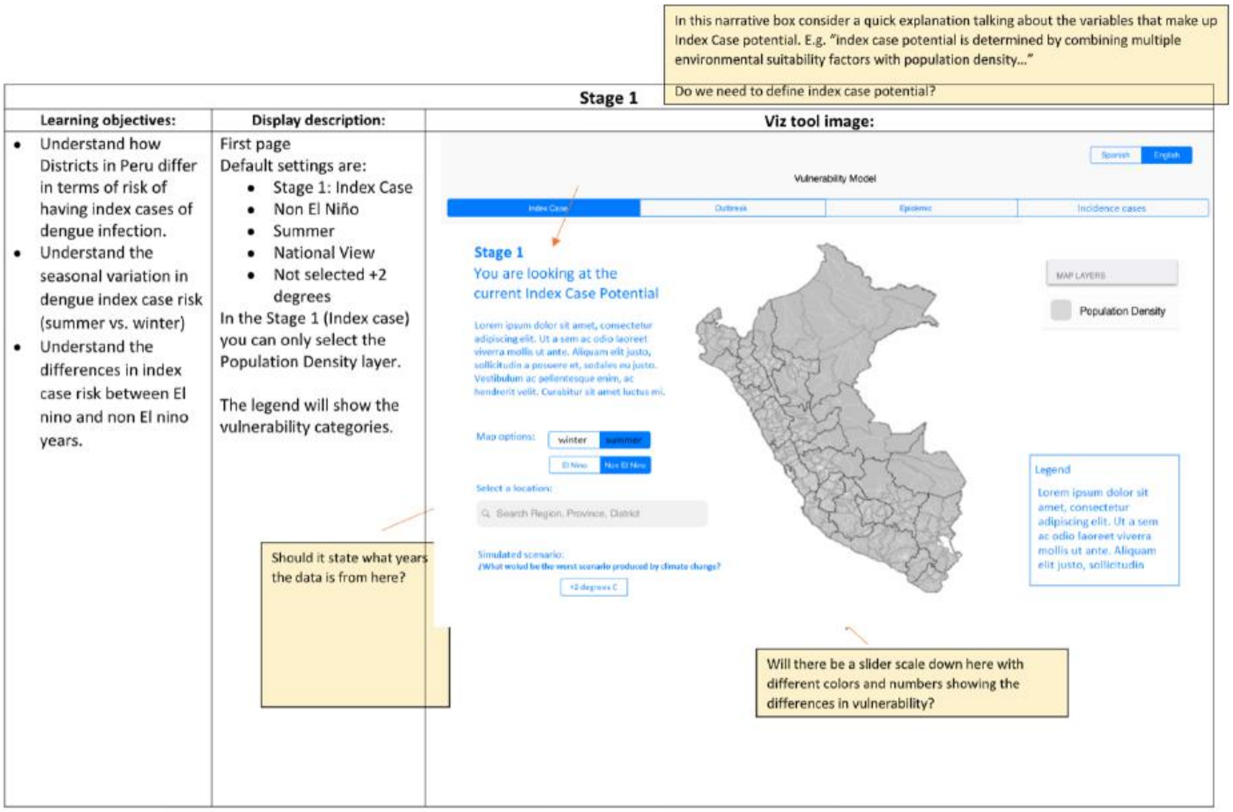
The RVF visualization (top) example demonstrates the lack of interactivity, poor use of space, and inappropriate color scale [58]. The dengue visualization (bottom) example show an inappropriate zoom level for the audience and a lack of contextual information for the user [59].

Appendix 3: Storyboard used in design of interactive mapping tool for dengue



The images above show screenshots of storyboards used in Aim 1.1 where Ana from the health department is using the interactive vulnerability mapping tool

Appendix 4: Interactive vulnerability mapping tool for dengue wireframe



The above image shows an initial wireframe used in Aim 1.1 where learning objectives were annotated on the design

Appendix 5: User group description for the interactive vulnerability mapping tool for dengue

User Group Identification – Dengue Interactive Vulnerability Mapping Tool		
Organization	**Job title**	**Primary use(s)**
MINSA/MOH	epidemiologist	What are the interesting trends/ factors in Dengue cases? Where are there more cases?
MINSA/MOH	public health planners	Where should we focus preparedness efforts? Is this an El Nino year?
MINSA/MOH	environmental scientists/ vector control	Where should we spray more? Is this an El Nino year?
MINSA/MOH	directors/policy decision makers	How should we direct resources? Are their policy implications?
MINSA/OTGI	public health planners	Where should we focus preparedness efforts? Is this an El Nino year?
MINSA/OTGI	directors/policy decision makers	How should we direct resources? Are their policy implications?
INS	Laboratory technicians	Which are effective/appropriate diagnostic tests?
Local Public Health	administrators	How do I direct local funding? Is this a bad year for us? Why are we more vulnerable?
CDC Peru	epidemiologists	What are the interesting trends/ factors in Dengue cases? How does this compare to other countries
Medixinics	environmental scientists/ vector control	Where should we spray more? Is this an El Nino year?

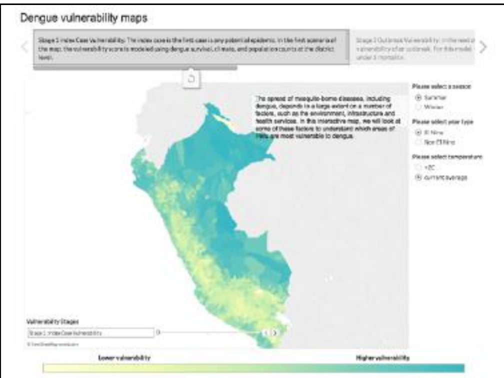
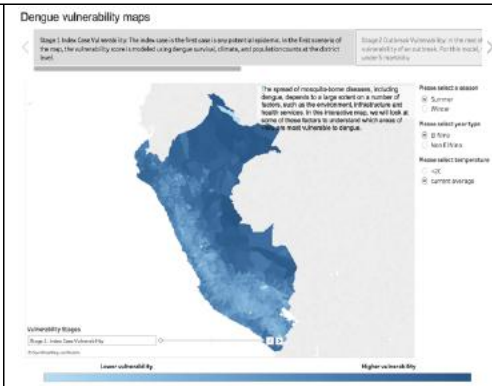
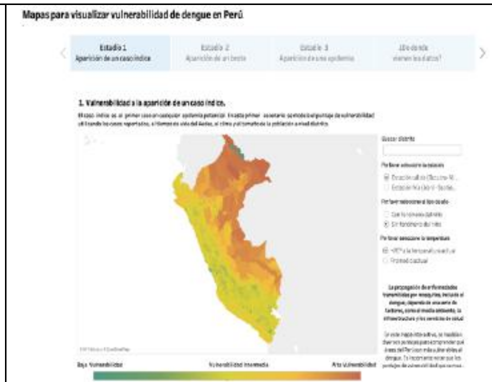
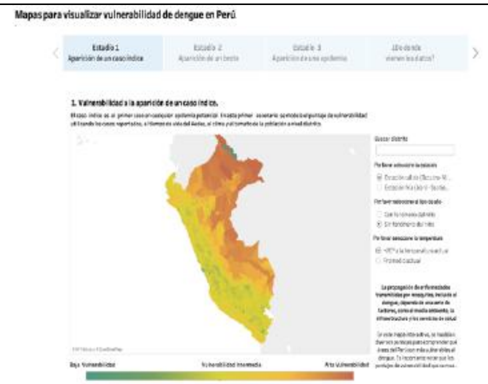
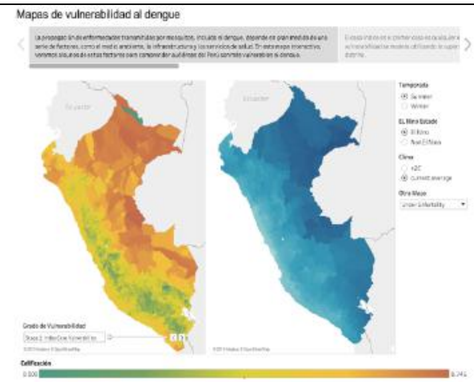
The table above describes the affiliated organizations, example job titles, and high level use cases for user groups of the interactive vulnerability mapping tool for dengue tool in Aim 1.1

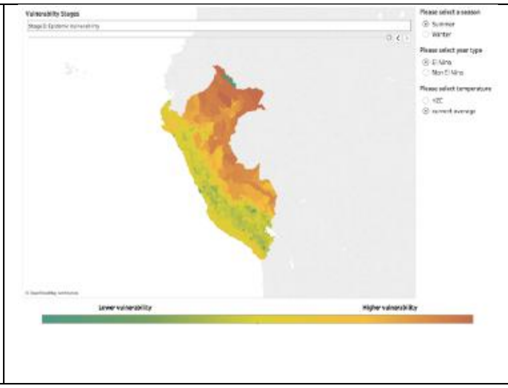
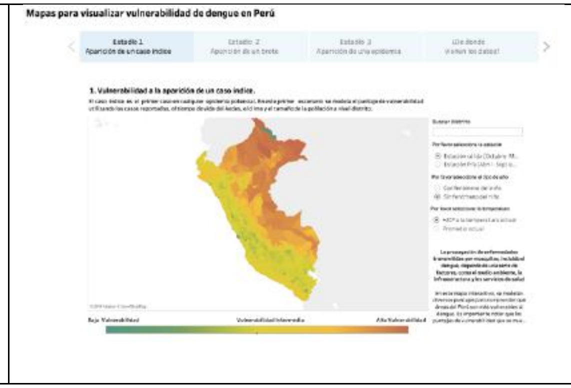
Appendix 6: Landscape analysis of visualization platforms

Option	Functionality	Accessibility	Sustainability
R - Shiny	2	2	4
Microsoft BI	4	4	2
Tableau	2	2	1
D3.js	1	1	4

The above table shows options and metrics for the landscape analysis of visualization platforms in Aim 1. Green and 1 ranking denotes favorable or relative advantage in that metric, red or 4 denotes least favorable/disadvantage

Appendix 7: Alternative prototypes for interactive vulnerability mapping tool for Peru

Color Scale			
Layout			

Format	Lower vulnerability Higher vulnerability	Mapas para visualizar vulnerabilidad de dengue en Perú	

Appendix 8: Data visualization preferences questions

Another objective of our visit is to understand how you'd prefer to see this information displayed. I'm going to show you a few options and I'd like to hear which you prefer.

Comparison 1: Color preferences (option 1. Sequential; option 2. Diverging; option 3. Qualitative)

____I prefer option __

____I like the options equally or have no preference

____ I do not like any option

> On a scale of 1-10 (with 10 being very important and 1 being not important at all), this consideration is _____
>
> Please share your thoughts on why you choose this option or any additional information:

Comparison 2: Map layout (option 1. side by side; option 2. separate screens)

____I prefer option __

____I like the options equally or have no preference

____ I do not like any option

> On a scale of 1-10 (with 10 being very important and 1 being not important at all), this consideration is _____
>
> Please share your thoughts on why you choose this option or any additional information:

Comparison 3: Narrative approach (option 1. Contextual multiscreen layout; option 2. Single screen, less text layout)

____I prefer option __

____I like the options equally or have no preference

____ I do not like any option

> On a scale of 1-10 (with 10 being very important and 1 being not important at all), this consideration is _____
>
> Please share your thoughts on why you choose this option or any additional information:

<u>Appendix 9: Usability focus group/ interview questions (mapped to ISS model factors)</u>

*(**System quality factors – easy to understand, relevant, complete**)*

1. What, if anything, did you like about the tool? Please be as specific as possible

2. What, if anything, did you dislike about the tool? Please be as specific as possible
    a. Was anything unclear or hard to understand?
3. Do you think this type of tool would be helpful in your current work for RVF preparedness?
    a. What additional information would be helpful for you to see?
    b. Was there too little, too much, or an appropriate amount of contextual information and narrative?

*(**Information quality factors – availability, adaptability, reliability**)*

4. Did this tool allow you to complete the tasks more accurately or quickly than you would be able by other means?
    a. Were there other tasks that you would like to be able to complete?
5. Did you trust the information that was displayed? Why?
    a. Do you believe that this information is accurate and reliable? Why?
6. Where would you like to access this information, such as a website or other location?

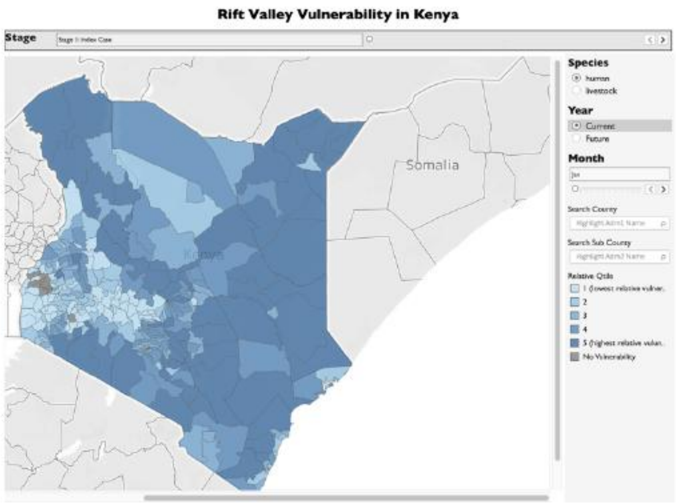
*(**Actionability**)*

7. Would you feel comfortable making decisions based on a tool such as this?
    a. If so, what type of decisions would you make?
    b. How much influence would this type of tool impact your decision making?
8. In what ways, if any, would a tool such as this impact your current or future RVF work?
9. Stepping back from the specific visualization you saw today, help me understand how you feel about the RVF vulnerability model in your preparedness work. Would this or a similar tool be helpful to you? Are there other ways that you'd like to see or use this type of information?
10. Thinking towards the future, what similar or new tools might be helpful? In the future what additional uses, data sources, or ways to think about RVF vulnerability might you suggest?

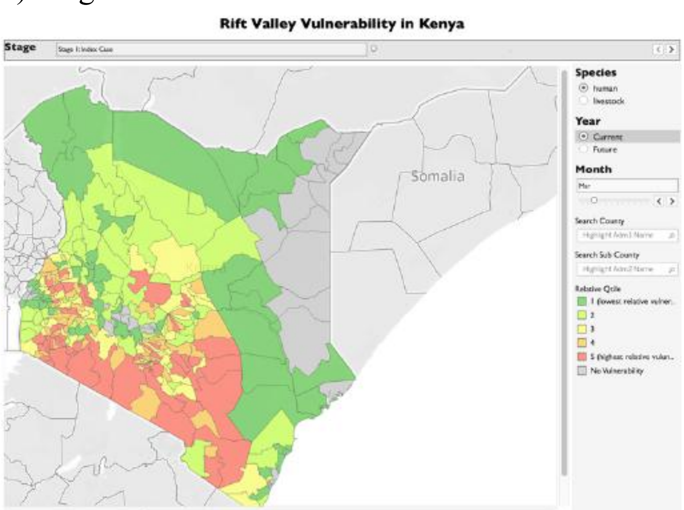
11. Do you have any final thoughts or ideas that you would like to share?

Appendix 10: Visualization alternatives for interactive vulnerability mapping tool for RVF

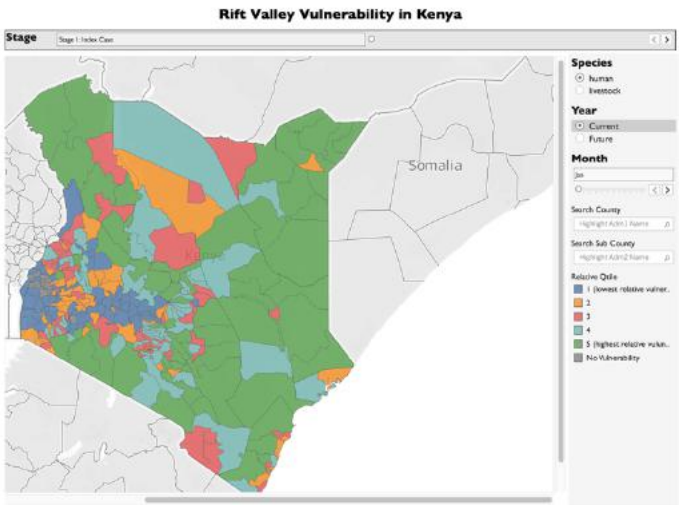
Options for color:
1) monochromatic



2)red-green

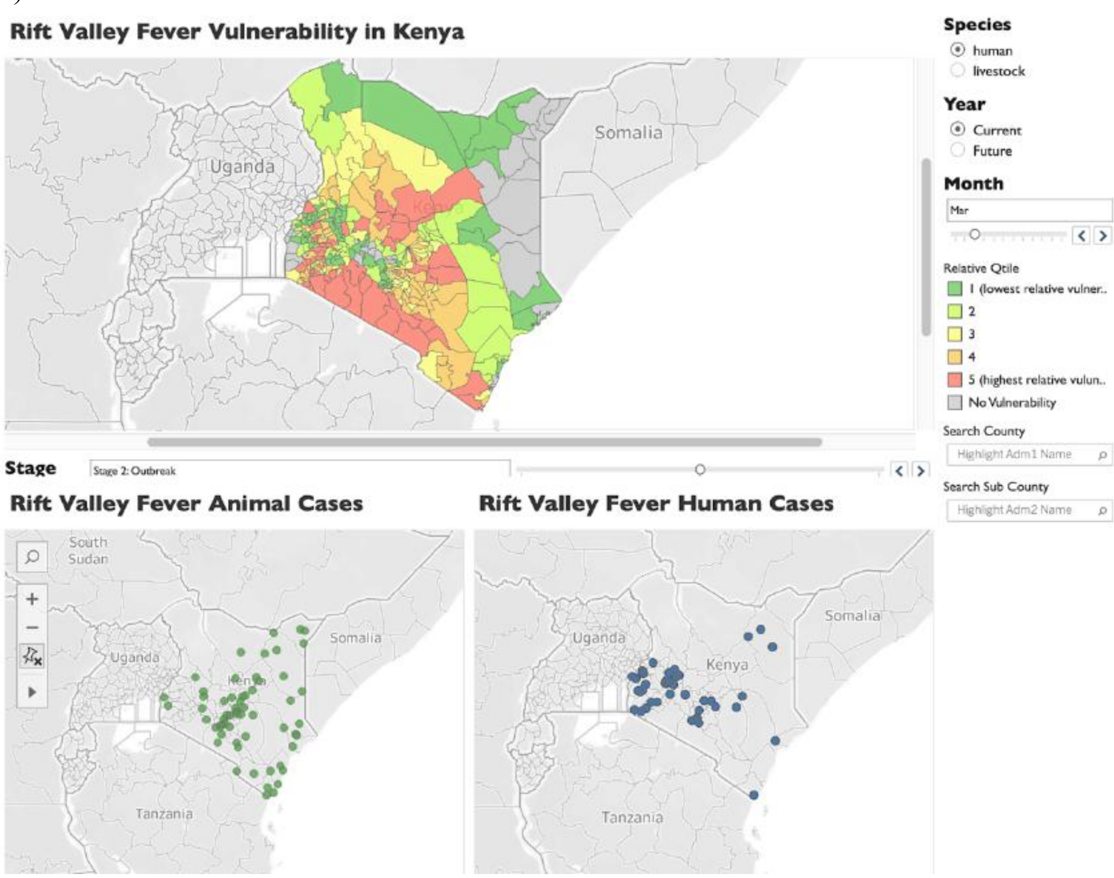


3)qualitative

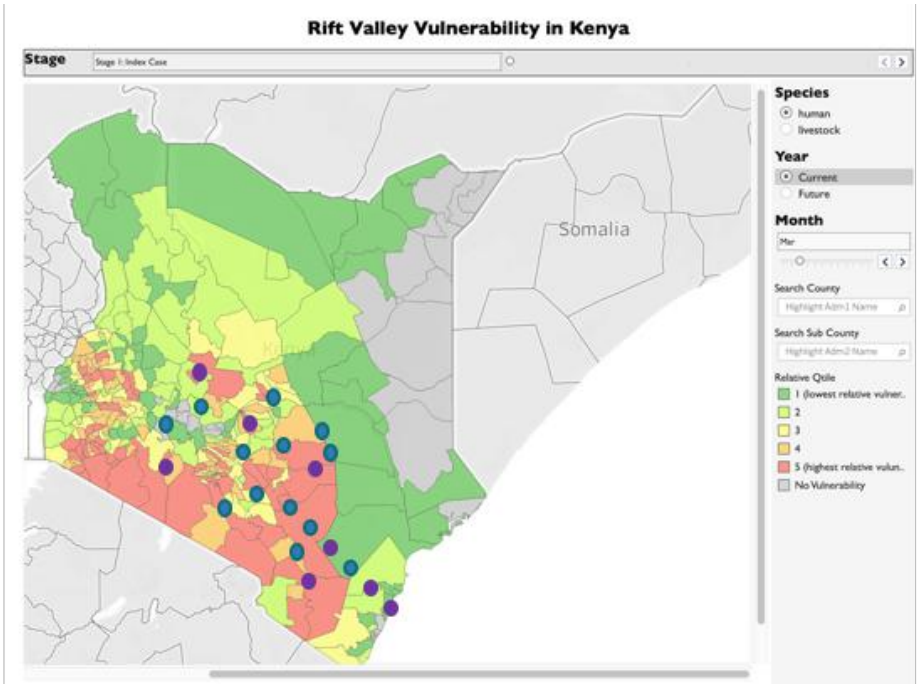


Options for layout:

1)

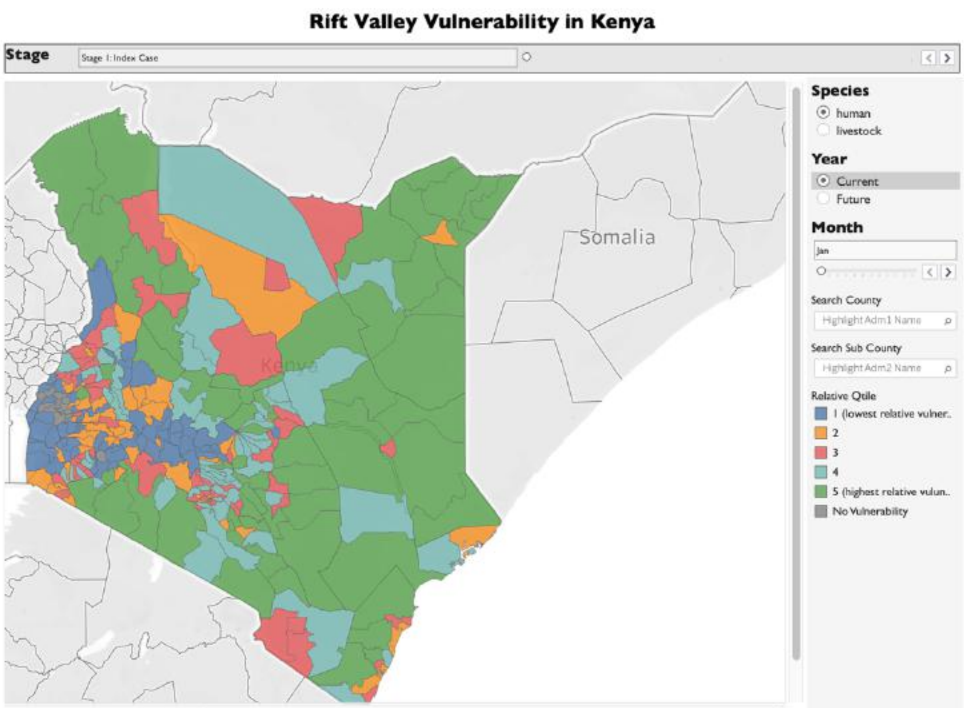


2)



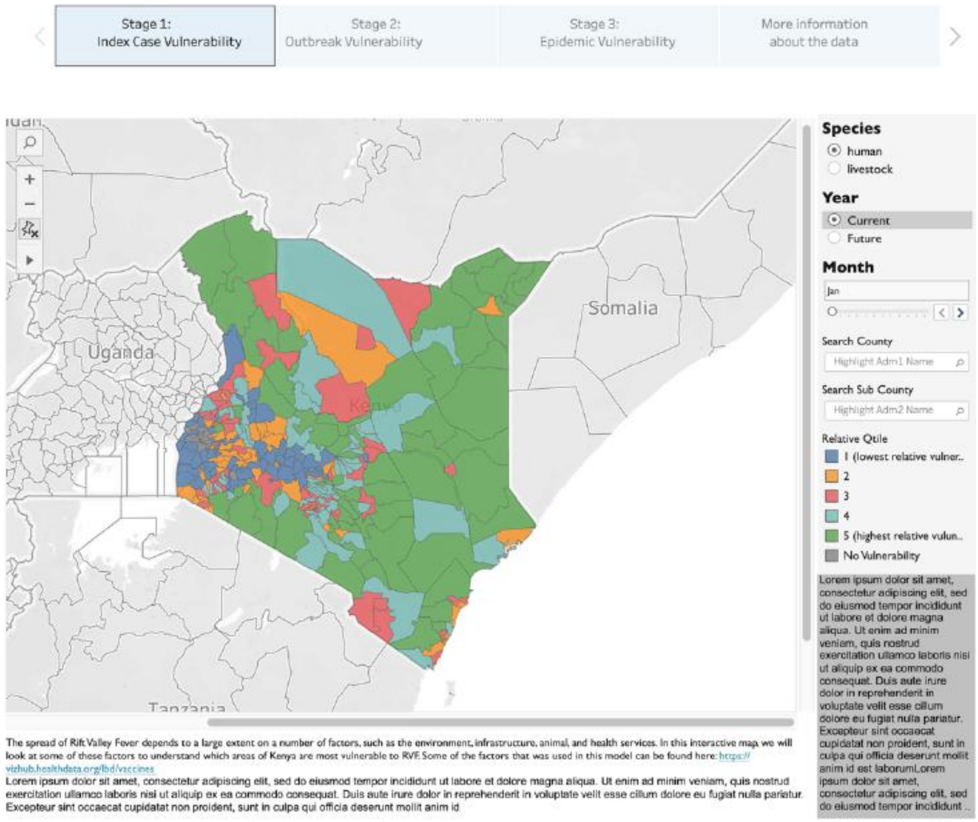
Options for narrative approach:

1)



2)

Rift Valley Fever Vulnerability in Kenya

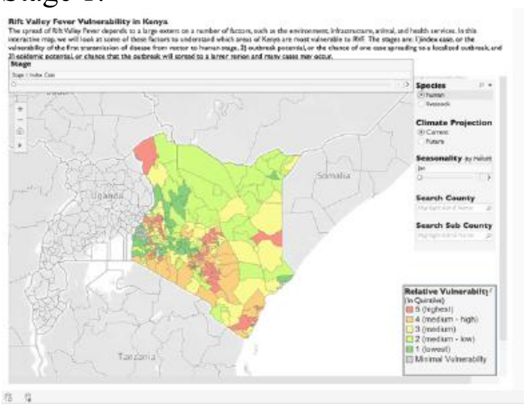


Appendix 11: Use Case Example

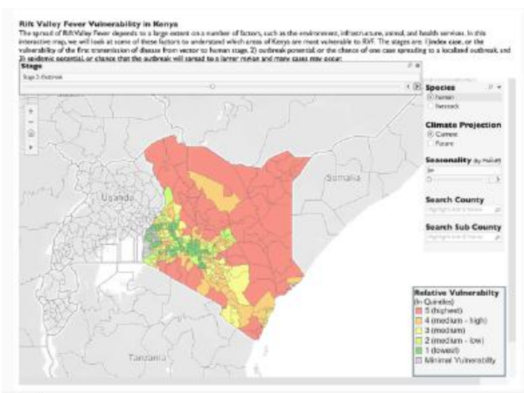
An epidemiologist at a county health department wants to create a report for her colleagues and the director of the department so they can create a 5-year plan to prevent vulnerable areas from RVF outbreaks. She uses the RVF-interactive vulnerability mapping tool to create maps visualizing vulnerability to inform these reports.

She first examines vulnerability to RVF among the 3 stages at a national level:

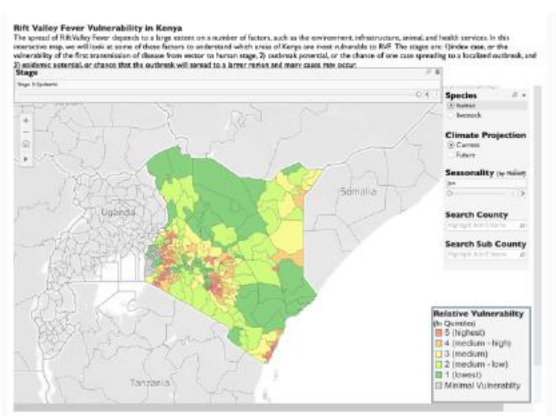
Stage 1:



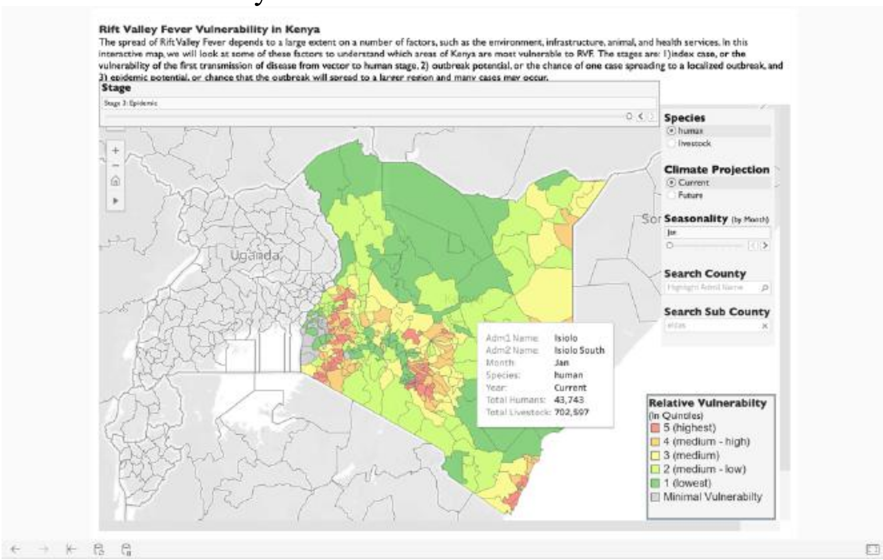
Stage 2:



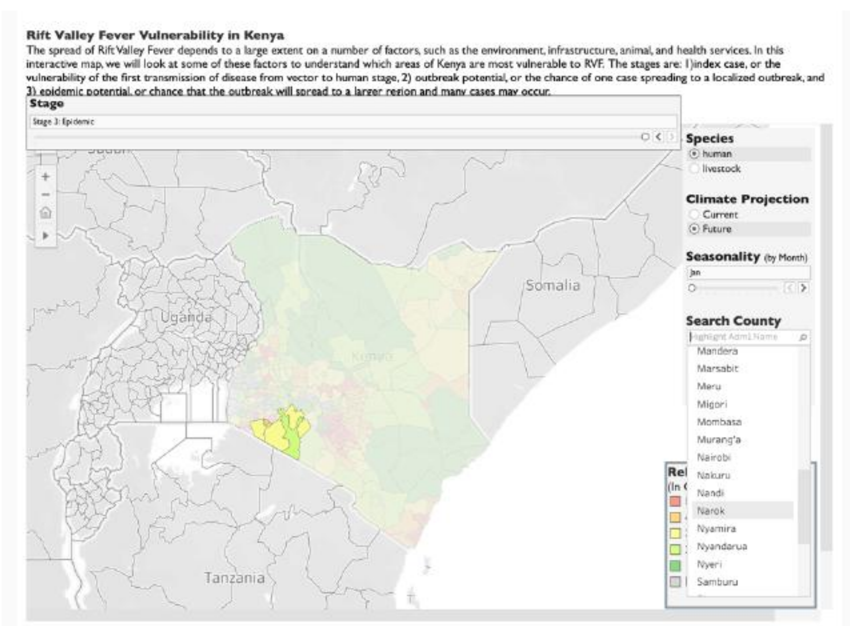
Stage 3:



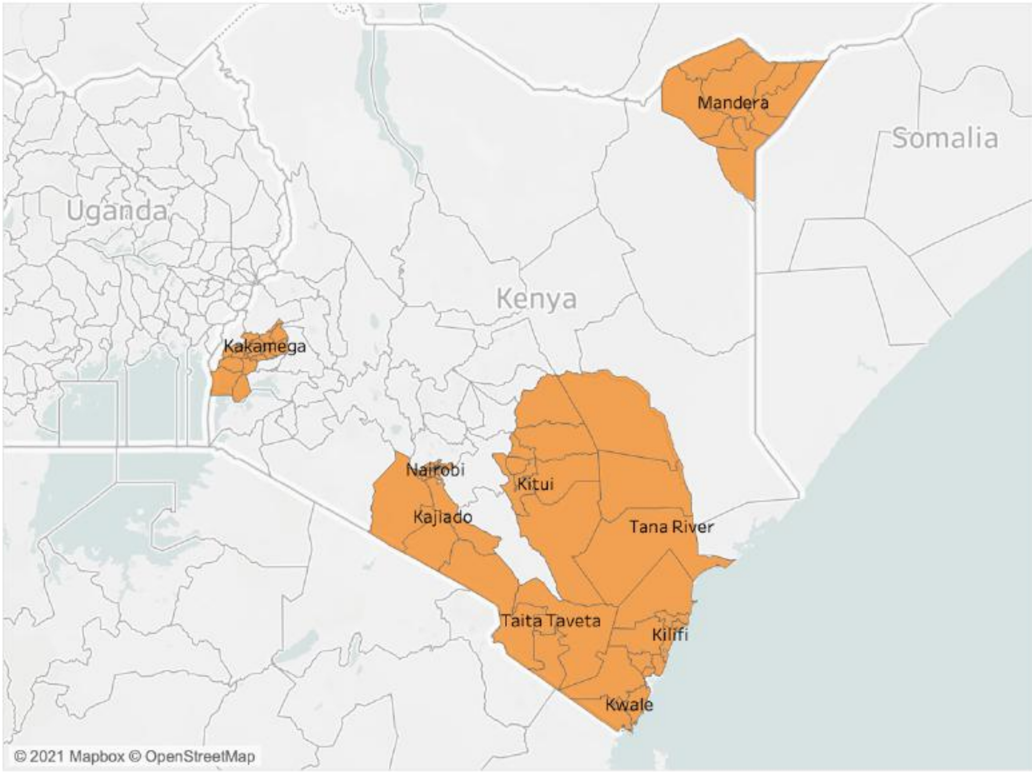
She also hovers over counties on the map to look at specific data points and some data that went into the vulnerability calculation:



Finally, she searches for her county and reviews the stages and other parameters that are pertinent to her report:



Appendix 12: Spatial representation of participants from the usability testing of interactive vulnerability mapping tool for RVF



Please see geographic location of participants in usability testing. Participants were drawn from 10 counties using convenience sampling.

Appendix 13: Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	80
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	Not applicable
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	80-82
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	83
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	83
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	84
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	84
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	86, Appendix 14
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	86

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	86
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	87
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	Not applicable
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	87
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	88
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	89
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	Not applicable
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	97-99
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	96
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	100-106
Limitations	20	Discuss the limitations of the scoping review process.	107

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	108
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	Not applicable

From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA E Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.

Appendix 14: Search strategy for scoping review by database

<u>PubMed</u>

((Pandemics[MeSH])OR ("Pandemic*"[all]) OR (Epidemic[MeSH]) OR ("Epidemic*"[all]) OR (Disease Outbreaks[MeSH]) OR ("disease outbreak*"[all]) OR ("disease*"[tw]) OR ("outbreak*"[tw]) OR (Preparedness, Emergency[Mesh]) OR (Emergency Preparedness[Mesh]) OR ("Emergency Preparedness"[all]) OR (Planning, Disaster[Mesh]) OR (Public Health Surveillance[Mesh]) OR ("Public Health Surveillance"[all]) OR ("Surveillance"[all]) OR ("Pandemic preparedness"[tw]) OR ("pandemic planning "[tw]) OR ("preparedness"[tw]) OR ("planning*"[tw]) OR ("prevention"[tw]) OR ("vulnerability"[tw]) OR ("high risk area*" [tw]) OR ("cluster detect*"[tw]))

AND (("Spatial system "[tw]) OR ("Mapping tool"[tw]) OR ("Mapping tools"[tw])OR ("Map"[tw]) OR ("GIS" [tw]) OR ("geographic information system*" [all]) OR (geographic information systems[MeSH Terms]) OR ("geographic information system*"[all])

OR (((interface, user computer[MeSH]) OR ("user interface*" [all]) OR ("data visualization*" [tw]) OR ("information visualization*" [tw]) OR ("interact*"[tw]) OR ("dashboard*" [tw]) OR ("graphical user interface*"[tw]) OR ("website*"[tw]) OR ("portal*" [tw]) OR ("online*" [tw])) AND (("Spatial system "[tw]) OR ("Mapping tool"[tw]) OR ("Mapping tools"[tw]) OR ("Map"[tw]) OR ("GIS" [tw]) OR ("geographic information system*" [all]) OR (geographic information systems[MeSH Terms]) OR ("geographic information system*"[all]))))

AND ((zoonoses[MeSH]) OR ("zoono*" [tw]) OR ("vector born disease*"[tw]) OR ("vector borne disease*"[tw]) OR ("one health"[MeSH]) OR ("one health"[all]))

<u>Google Scholar:</u>

("spatial decision support systems" OR "spatial online platforms" OR " mapping tool") AND ("public health" OR "vector borne disease" OR "zoonotic disease") AND ("high risk areas" OR "outbreak detection" OR "cluster detection" OR "vulnerability”)

<u>Embase</u>:

('spatial decision support systems' OR 'spatial online platforms' OR 'mapping tool') AND ('public health'/exp OR 'public health' OR 'vector borne disease'/exp OR 'vector borne disease' OR 'zoonotic disease'/exp OR 'zoonotic disease') AND ('high risk areas' OR 'outbreak detection' OR 'cluster detection' OR 'vulnerability'/exp OR 'vulnerability')