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A monitoring system for transboundary foot and mouth disease considering livestock keepers demographic characteristics

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A MONITORING SYSTEM FOR TRANSBOUNDARY FOOT AND MOUTH DISEASE CONSIDERING LIVESTOCK KEEPERS DEMOGRAPHIC CHARACTERISTICS

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A Thesis Submitted in Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Information and Communication Science and Engineering of the Nelson Mandela African Institution of Science and Technology

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ABSTRACT

Foot and Mouth disease (FMD) is a transboundary disease caused by a virus that affects domestic and wild cloven-hooved animals such as sheep, goats, pigs, and buffalos. FMD is transmitted from one animal to another through direct or indirect contact. Apart from other animal diseases, FMD has been given great attention due to its unique behaviour, such as being potentially dangerous, rapidly spreading disease, and it has no cure. Therefore, immediate information flow among livestock stakeholders could help to mitigate FMD. Realizing the importance of animal disease surveillance, many agencies developed systems for monitoring animal health (fast disease reporting and response). The challenge is that they were developed using advanced technologies like web-based and android, requiring skills, internet connectivity, computers, and smartphones to access them. However, most livestock keepers lack these facilities, especially in developing countries. In that case, they deny access to livestock keepers positioned at the grass-root of animals' disease reporting chain since illnesses always begin with their animals. Therefore, their lack of participation in reporting or receiving animal disease information through the electronic-based animal disease surveillance system causes a delay in identifying and reporting disease cases and provides insufficient information for controlling contiguous diseases like FMD, which require more precautionary measures through timely information sharing.

This study aims to bridge the gap between livestock keepers and top-level stakeholders by developing an animal diseases surveillance system named "Monitoring System for Transboundary Foot and Mouth Disease Considering Livestock Keepers Demographic Characteristics (AMoS4T-FMD)". The system provides a standard platform for sharing FMD-related information between top-level stakeholders and livestock keepers in time using various mobile technologies based on their demographic characteristics.

Gairo district in the Morogoro region was selected as a study area. Therefore, the surveillance system was developed and tested in Gairo district settings. However, it has flexible settings to work elsewhere. In Gairo, livestock keepers' mobile phone usage and demographic data were collected to determine the appropriate mobile technologies to communicate animal disease surveillance information among themselves and top-level stakeholders through AMoS4T-FMD. After that, an algorithm (FMD communication algorithm) which enables livestock keepers to communicate with AMoS4T-FMD using Unstructured Supplementary Service Data (USSD), Short Message Service (SMS) and Robot calls (Robocalls) based on their demographic data was developed. Also, a Model for predicting and alerting FMD outbreaks in the Gairo district using an Agent-Based Simulation modelling technique was developed. Lastly, the FMD communication algorithm and the Agent-

Based Simulation model were combined into the software using the waterfall model for system development. Finally, the system was tested using verification and validation techniques.

DECLARATION

I, Ahmed Kijazi, declaring to the Senate of the Nelson Mandela African Institution of Science and Technology that this thesis is my original work and, to the best of my knowledge, has not been submitted or presented to any other institution for a similar or different award.

03/03/2023

Ahmed Kijazi | Signature | Date

The above declaration is confirmed

3-3-2023

Prof. Shubi Kaijage | Signature | Date

3-03-2023

Prof. Michael Kisangiri | Signature | Date

Prof. Gabriel Shirima | Signature | Date

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CERTIFICATION

The undersigned certify that they have read and hereby recommended for acceptance by the Nelson Mandela African Institution of Science and Technology a Thesis titled:" *A Monitoring System For Transboundary Foot and Mouth Disease (FMD) Considering Livestock Keepers Demographic Characteristics (AMoS4T-FMD)*"in Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Information and Communication Science and Engineering of the Nelson Mandela African Institution of Science and Technology.

Prof. Shubi Kaijage	Signature	17- 3 - 2023 Date
Prof. Michael Kisangiri	Signature	13/03/2023 Date
Prof. Gabriel Shirima	Signature	21st March, 2023 Date

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DEDICATION

I am dedicating this work to my lovely wife, Ms. Eva Naimani Mseke, who has greatly supported and encouraged me throughout my PhD studies. I am also dedicating this work to my children. Lastly, I am saving this work for my parents, who ensured that I had an excellent education; I am incredibly grateful.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABMS	Agent-Based Modelling and Simulation
ABSM	Agent-Based-Simulation Model
ADIS	Animal Diseases Information System
ADNS	Animals Disease Notification System
AMoS4T-FMD	A Monitoring System for Transboundary FMD
API	Application Programming Interface
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
ARIS-AU-IBAR	Animal Re-sources Information System
ASF	African Swine Fever
BrTi	Broadcast Time Interval of Each FMD Awareness
CBPP	Contagious Bovine Pleuropneumonia
CCPP	Contagious Caprine Pleuropneumonia
CHRs	Community Health Reporters
DONs	Disease Outbreak News
DVO	District Veterinary Officer
EIS	Epidemiology and Informatics Sub Committee
EMA-i	Event Mobile Application
FAO	Food and Agriculture Organization
FMD	Foot and Mouth Disease
FMDV	Foot and Mouth Disease Virus
GDP	Gross Domestic Product
HDD	Hard Disk Drive
HPAI	Highly pathogenic avian influenza in poultry
IP	Internet Protocol
KABS	Kenya Animal Biosurveillance System
LastBrT	Last FMD Awareness Broadcast Time
LIMS	Livestock Management Information System
MATLAB	Matrix Laboratory
MoLF	Ministry of Livestock and Fisheries
NM-AIST	The Nelson Mandela African Institution of Science and Technology
OIE	World Organization for Animal Health

OsT	Current Operating System Time
PDB2	Permanent Database2
PO-RALG	President's Office - Regional Administration and Local Government
PPR	Peste des Petits Ruminant
RAM	Random Access Memory
Robocalls	Robot Voice Calls
SACIDS	Southern African Centre of Excellence for Infectious Diseases
SIMAN	National Information System for the Notification of Animal Disease in Italy
SMS	Short Message Services
SQL	Structured Query Language
SUA	Sokoine University of Agriculture
TDB	Temporarily Database
USSD	Unstructured Supplementary Service Data
WAHIS	World Animal Health Information System
ZVC	Zonal Veterinary Center

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Tanzania contributes approximately 1.4 % of the world's cattle population and 11% in Africa. It also occupies the third position in Africa in terms of goat and cattle population (National Audit Office [NAOT], 2020). However, despite the pleasant grazing land, the livestock sector contributes only 7.6% of the overall Gross Domestic Product (GDP) due to several challenges that hinder its performance.

The Tanzanian government, through its NAOT in 2020, conducted an audit to examine whether the Ministry of President's Office - Regional Administration and Local Government (PO-RALG) and the Ministry of Livestock and Fisheries (MoLF) had effectively prevented and controlled livestock disease between 2013 and 2019. The audit found that despite the control and prevention measures instituted previously for some major animal diseases, such as Contagious Bovine Pleuropneumonia (CBPP), Contagious Caprine Pleuropneumonia (CCPP) and Foot and Mouth Disease (FMD), there has been an upsurge in the magnitude (NAOT, 2020).

The audit report mentioned several factors accelerating this situation, including the government's outdated animal disease surveillance and reporting mechanism (95% paper-based), which causes delays in identifying and reporting cases due to poor communication between the livestock keepers and the livestock field officers. Also, in this mechanism, government officials use physical documents to pass surveillance data between administrations instead of being electronic (NAOT, 2020; Mwabukusi *et al.*, 2014). Furthermore, the audit mentioned the lack of timely feedback on the reported cases from the Zonal Veterinary Centers (ZVC) to the District Veterinary Officer (DVO) and livestock keepers as another challenge that hindered the performance of the livestock sector.

Generally, poor communication between livestock keepers and top-level stakeholders such as veterinarians, researchers, and laboratory staff is among the difficulties in controlling contagious animal diseases (i.e., Foot and Mouth Disease (FMD), CBPP and CCPP) in Tanzania. One should realize the importance of livestock keepers in combating animal diseases since they are at the grass-root of the disease reporting chain, as illnesses always begin with their animals (NAOT, 2020). Regardless of other diseases, FMD has been given great attention due to its high mortality, especially in calves, and its ability to cause significant losses in milk production and draught animal power, which limits livestock production and affects food security (Michael, 2018; Knight-Jones & Rushton, 2013). The FMD is a transboundary disease caused by a virus from the Picornaviridae family that affects domestic and wild cloven-hooved animals such as sheep, goats, pigs, and buffaloes (Kasanga *et al.*, 2014). The FMD has already affected many countries, including Tanzania (Food and Agriculture Organization [FAO], 2019; Fig. 1 & 4). There are currently 7 known serotypes of the FMD virus and many more subtypes. For example, type A, O, SAT1, SAT2, and SAT3 serotypes are present in Tanzania (Fig. 1; FAO, 2019).

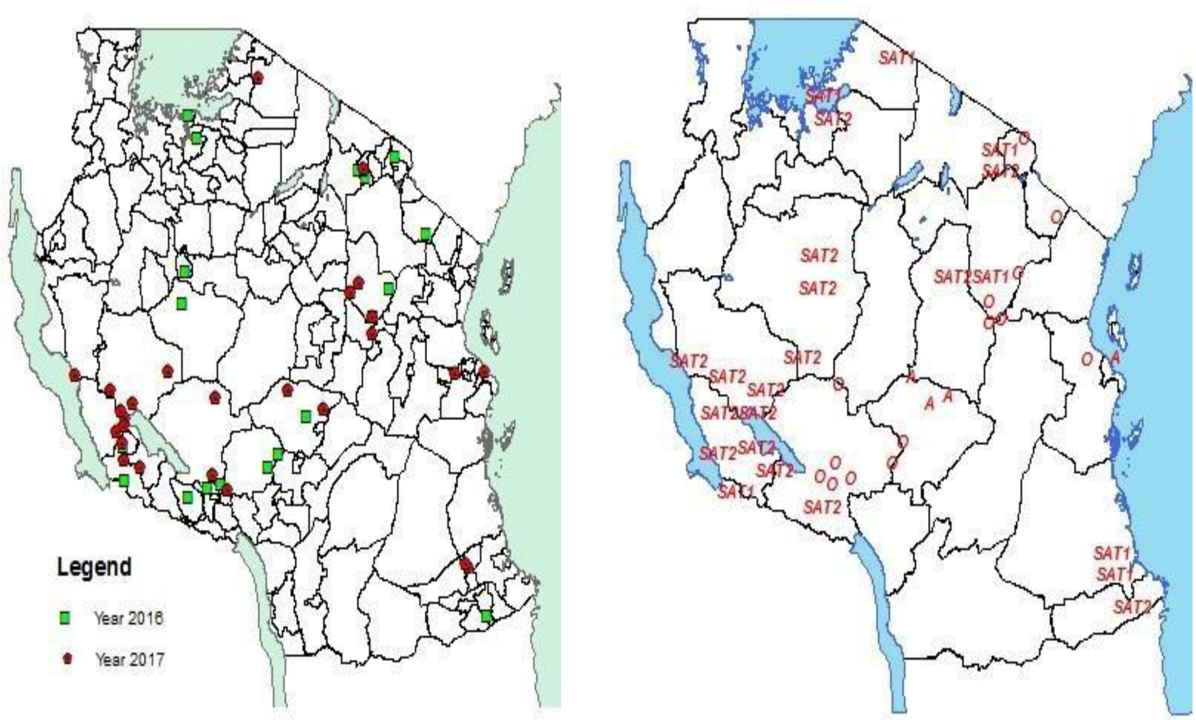


Figure 1: Foot and mouth disease outbreaks between 2016-2017 and serotypes distribution in Tanzania (Michael, 2018)

The FMD is transmitted from one animal to another through direct or indirect contact, e.g., through contaminated inanimate objects (fomites). The FMD clinical signs include high fever (up to 42^{o}) accompanied by severe depression and inappetence (William & Juan, 2002). Other clinical signs are the appearance of wounds on the feet and tangle of the animal (Plate 1; William & Juan, 2002).

Vesicles found on cattle mouth (a)

Loose-off hoofs in pig (b)

Vesicles found on cattle hoof (c)

Plate 1: Mouth (a) and hoofs (b & c) vesicles of the FMD-affected animals (Infonet biovision, 2022; Bio, 2022)

The disease has no cure; hence, vaccination is the essential control measure for FMD. However, vaccines do not protect between serotypes, and sometimes protection within a serotype is limited. Therefore, the vaccines must match the virus strain circulating in livestock for effective prevention (Jamal & Belsham, 2013). Unfortunately, FMD-free countries prohibit the importation of FMD-vaccinated animal products or only allow it after additional risk-mitigating measures, which reduce the possibilities of international trade, which in turn affect livestock keepers' economy and the countries in general (Knight-Jones & Rushton, 2013; Kijazi *et al.,* 2021b). Therefore, immediate information sharing during FMD outbreaks and predicting future attacks is mandatory for preparedness and mitigating the disease before its adverse impact on livestock-keeping communities and the country's economy (prevention is better than cure for FMD) (Kijazi *et al.,* 2021b).

Aswini *et al.* (2017) observed that Information systems play a significant role in developing different practical approaches to prevent, detect, respond to, and manage infectious disease outbreaks in plants, animals and humans. This study, therefore, aims to bridge the gap between top-level stakeholders and livestock keepers by developing an electronic-based surveillance system named "A Monitoring System for Transboundary Foot and Mouth Disease (FMD) Considering Livestock Keepers Demographic Characteristics". The AMoS4T-FMD is a given system short name which means a Monitoring System for Transboundary FMD.

The system accommodates livestock keepers among the users for sharing FMD events such as transmission pathways, clinical signs, predictions, negative impacts and outbreaks between themselves and top-level stakeholders in time, realizing their importance in the animal disease reporting chain as illness starts from their animals (Primary informer of FMD incidents/outbreaks).

Realizing the importance of information systems in monitoring animal health, many agencies developed several surveillance systems like AMoS4T-FMD (Aswini *et al.,* 2017; Mwabukusi *et al.*, 2014; ProMED-mail, 2022). However, they were developed using more advanced technologies such as web-based and android, requiring skills, internet connections, computers, and smartphones to access them. However, most livestock keepers lack these facilities, especially in developing countries.

In that case, they deny access to livestock keepers. As a result, the systems utilize top-level stakeholders as messengers to pass surveillance information between livestock keepers and the systems as they have facilities to access them (Fig. 2). During the disease outbreaks, top-level stakeholders manually/physically collect surveillance data from livestock keepers and upload them to the systems for record purposes and Disease Outbreak News (DONs) (Fig. 2). On the other hand, top-level stakeholders deliver to livestock keepers any relevant information available in surveillance systems, such as disease outbreaks and predictions in various locations, clinical signs, and precautionary measures generated by surveillance systems or uploaded by other systems top-level stakeholders (Fig. 2).

The manual process of collecting or giving information to livestock keepers has several challenges, including difficulties in delivering disease mitigation information or getting data in the hard-to-reach livestock keepers' villages, especially during rainy seasons. Similarly, it leaves many unreported cases due to unfriendly terrains that hinder access to remote livestock-keeping communities, especially during rainy seasons. Also, it requires a significant number of infield veterinarians to be effective, while the Tanzanian government reported an insufficient number of infield veterinarians (<30%) for the entire country (NAOT, 2020; Allport *et al.,* 2005). Therefore, this mechanism is not efficient enough to control contagious diseases like FMD, which requires timely information sharing for preparedness as it has no cure.

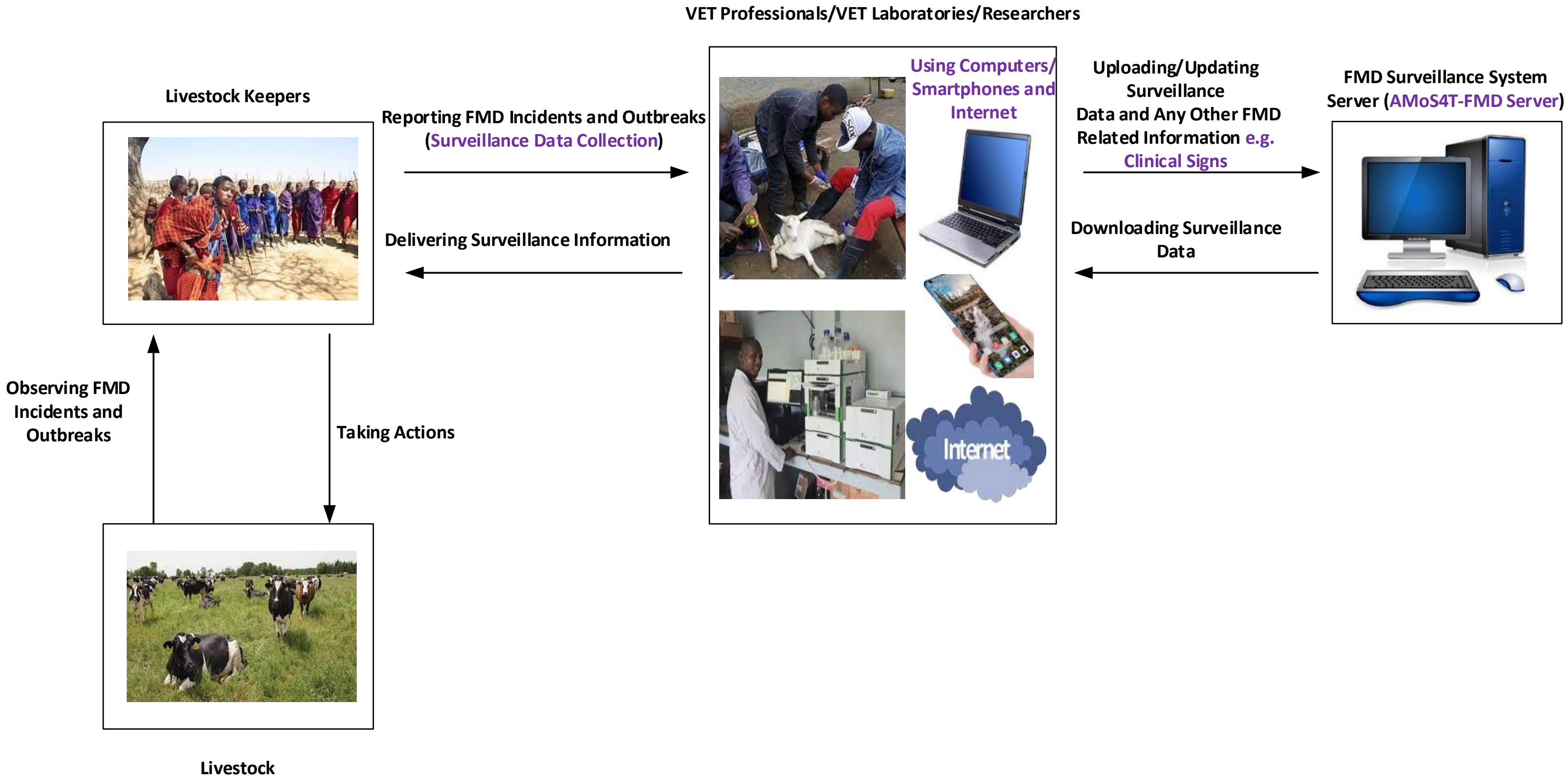


Figure 2: **Foot and mouth disease communication framework using existing surveillance systems**

Unlike other existing animal diseases surveillance systems, the AMoS4T-FMD enables livestock keepers to receive or send FMD data (information) directly to the system using mobile technologies such as Short Message Services (SMS), Unstructured Supplementary Service Data (USSD) and Automatic Voice Calls (Robocalls) (Fig. 3). Robocalls or Robot calls are automated voice calls generated by a computer system that dials more than one mobile number at once and plays the audio message for anyone who picked the call (The Conversation, 2019). The SMS and USSD enable livestock keepers to report FMD outbreaks to the system using mobile phones. The system also periodically broadcasts FMD-related information such as precaution measures, negative impacts, clinical signs, transmission pathways, outbreaks, and predictions to livestock keepers in SMS and Robocalls (Fig. 3, 17, 51) (The Conversation, 2021).

Similarly, AMoS4T-FMD provides an opportunity for livestock keepers to access similar information at any time (excluding predictions) via the USSD menu option after dialling a particular USSD code (Fig. 55) (e.g., *384*90005#) (Kijazi *et al.*, 2021a; Kijazi *et al.*, 2021b). This information enhances FMD awareness among livestock keepers and maintains communication with top-level stakeholders. In addition, the Agent-Based Simulation Model (ABSM) is a part of AMoS4T-FMD, which periodically predicts FMD outbreaks (Fig. 9, 23-27). The ABSM generates FMD prediction data while the top-level stakeholders upload the rest to the system based on their privileges. Top-level stakeholders also have the right to register livestock keepers and validate FMD outbreaks data reported by livestock keepers via SMS and USSD before being permanently saved in AMoS4T-FMD (Fig. 17, 18 & 44). On the other hand, the system provides a common platform for sharing FMD outbreak data among top-level stakeholders based on their systems' privileges. Lastly, it gives secondary data to policymakers for decision-making.

Gairo district in Tanzania was selected as a study area for this research due to its easy accessibility and high frequency of FMD outbreaks. Also, it combines three cattle farming systems: Smallholder dairy, agro-pastoral, and pastoral, which is opposite to other districts, whereby one farming system may dominate (Mgongo *et al.*, 2014). Therefore, Gairo promised to provide sufficient data for this research. Thus, the system was designed and tested for Gairo district settings; however, it has flexible settings to work elsewhere.

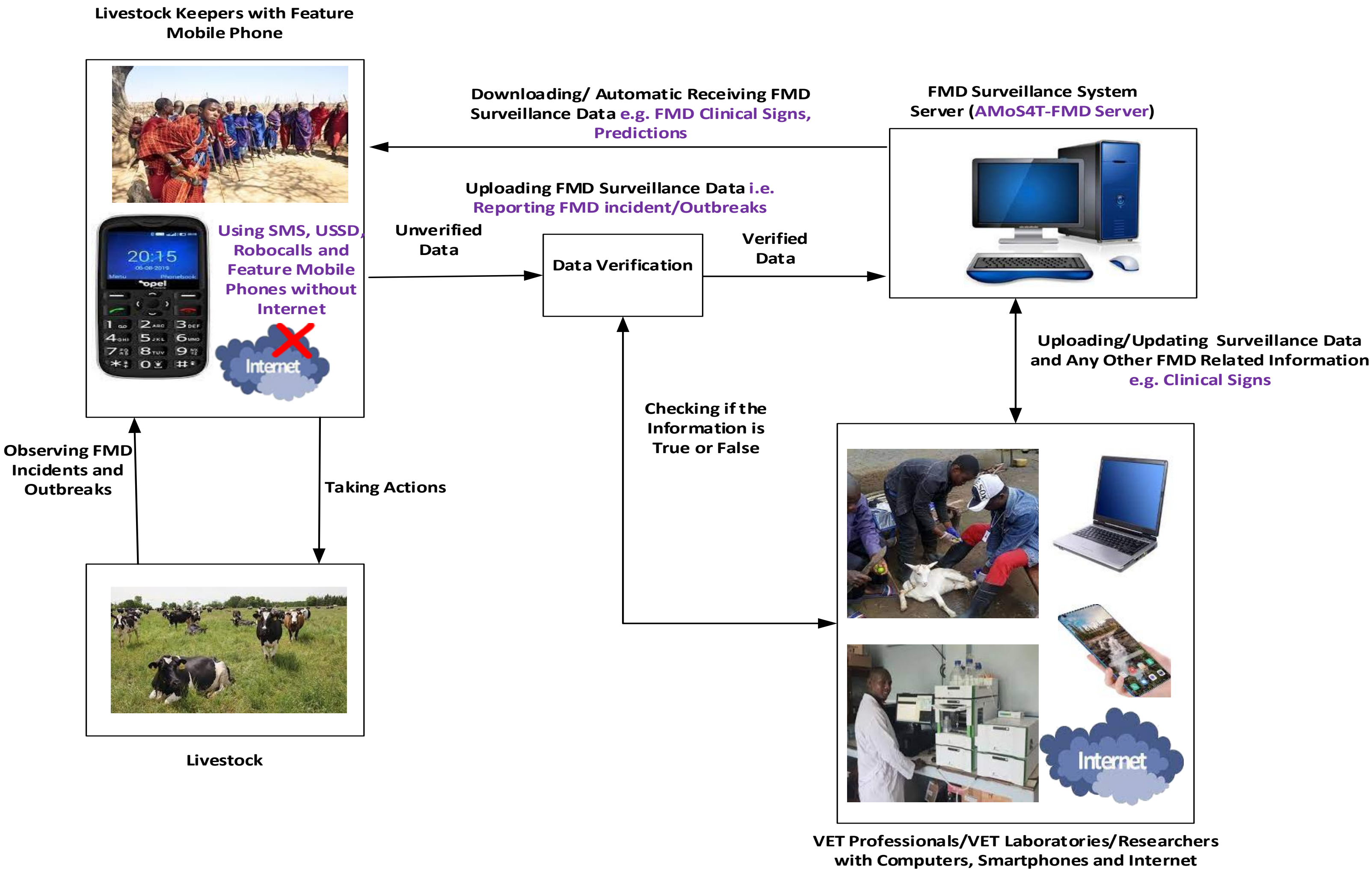


Figure 3: **Proposed FMD communication framework using AMoS4T-FMD**

1.2 Statement of the Problem

Livestock owners who are the primary informer of FMD outbreaks/incidents were not considered/included in most electronic-based animal diseases surveillance systems developed. The surveillance systems were implemented using advanced technologies such as android and web-based applications, requiring skills and special devices (smartphones or computers) to access them. In contrast, most livestock owners, especially in developing countries, lack these facilities. Similarly, the systems require an internet connection to access them, which is highly limited in rural settings. The negligence of livestock keepers in giving or receiving FMD information through the surveillance systems causes the delay of information for FMD control. Therefore, an electronic-based surveillance system that could accommodate livestock keepers among the system users for sharing FMD-related information between themselves and top-level stakeholders using friendly technologies is needed.

1.3 Rationale of the Study

Foot and mouth disease (FMD) is a severe, highly contagious transboundary viral disease of livestock that has a significant economic impact due to its ability to cause substantial loss in draught animal power (the use of animals in different economic activities such as farms cultivation, harvesting and load carrying). Similarly, the disease causes a loss in milk production and disrupts regional and international trade in animals and animal products (Knight-Jones & Rushton, 2013). This viral infection costs Africa roughly US$2.3 billion in economic damages annually (Galvmed, 2022). According to the World Organization for Animal Health (OIE), FMD is estimated to circulate in 77% of the global livestock population (Fig. 4). One hundred per cent (100%) morbidity rate is possible if adequate precautionary measures are not implemented during the FMD outbreaks (Mahmoud & Galbat, 2017).

The OIE recognizes FMD as a potentially dangerous and rapidly spreading disease (Galvmed, 2022). Therefore, since FMD has no cure, timely information sharing among livestock stakeholders during its outbreaks may enhance preparedness against the disease and reduce its impact. Livestock keepers at the grass-root of the animal diseases reporting chain are the primary informers of FMD outbreaks since diseases start from their animals (NAOT, 2020).

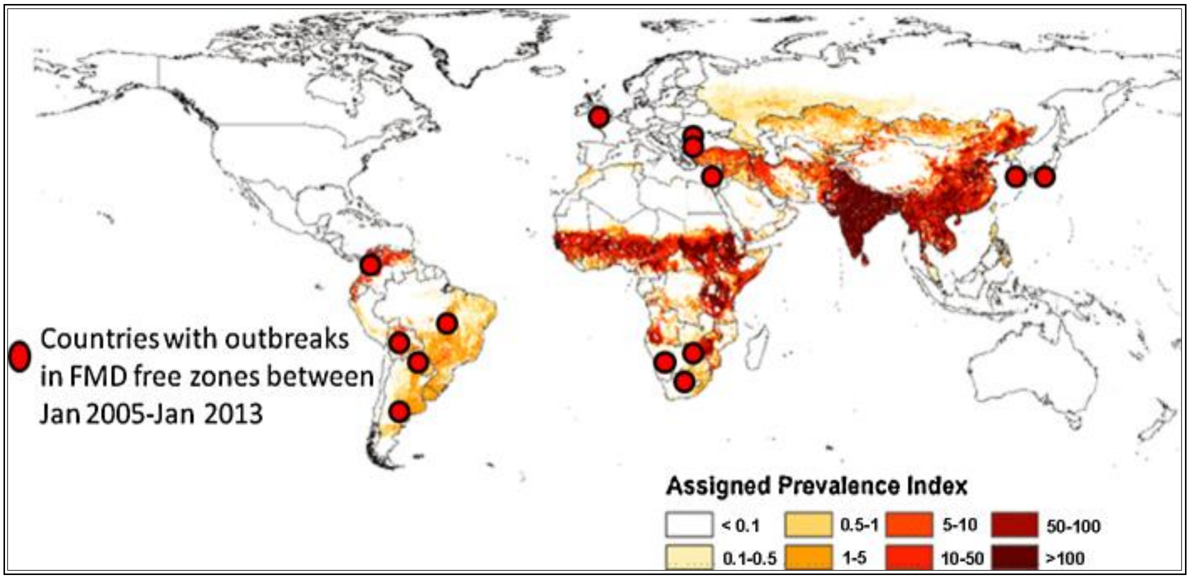


Figure 4: **Global FMD status between 2005-2013 (Knight-Jones & Rushton, 2013)**

Therefore, an electronic-based surveillance system that could accommodate livestock keepers among the system users for sharing FMD-related information between themselves and top-level stakeholders will provide a rapid response and preparedness for managing FMD.

The study named "Stakeholders' perceptions on the performance of the Livestock Disease Surveillance system in Uganda: A case of Pallisa and Kumi Districts" conducted by Namayanja *et al*. (2019) revealed that farmers contributed to the reporting of significant disease outbreaks. In the two areas, they were able to identify the clinical signs of five prevalent cattle diseases such as FMD, CBPP, African Swine Fever (ASF), Peste des petits ruminant (PPR), and Highly pathogenic avian influenza in poultry (HPAI). In this study, Farmers remarked that their role in the early detection and reporting of disease outbreaks was crucial for controlling and preventing the spread of such illnesses among animals. Therefore, the researcher believes that the full participation of livestock keepers in animal disease surveillance will improve early FMD outbreak detection and reporting and provide real-time quality data for rapid disease epidemic response and disease control. Additionally, receiving various FMD information/events via SMS or voice calls regularly raises awareness of livestock keepers.

1.4 Research Objectives

1.4.1 General Objective

To develop an electronic-based surveillance system that accommodates livestock keepers among the system users for sharing FMD data between themselves and other stakeholders using various mobile technologies based on their demographic characteristics.

1.4.2 Specific Objectives

(i) To gather user requirements in the Gairo district for developing the FMD surveillance system.

(ii) To formulate an algorithm for livestock keepers to communicate with the surveillance system by considering their demographic characteristics.

(iii) To develop an Agent-Based Simulation Model for predicting FMD outbreaks in the Gairo district.

(iv) To develop the FMD surveillance system by combining objectives no (ii) and (iii).

(v) To validate the developed FMD surveillance system.

1.5 Research Questions

(i) Can Gairo district livestock keepers' demographics provide sufficient information to develop an animal disease surveillance system?

(ii) Which mobile technologies could livestock keepers use to communicate with the surveillance system based on their demographic data?

(iii) Which modelling approach can simulate and display the interaction between more than one object to predict the occurrences of a particular phenomenon?

(iv) Which software development model is better for a project with tight timelines and clear deliverables?

(v) Can livestock keepers share FMD-related information with top-level stakeholders via the surveillance system?

1.6 Significance of the Study

The output of this research is a surveillance system named the "Monitoring System for Transboundary Foot and Mouth Disease (FMD) considering Livestock Keepers Demographic Characteristics (AMoS4T-FMD)", which has the following advantages:

(i) It will enable early identification and reporting of FMD cases since livestock keepers, who are the primary FMD informers, will be allowed to report the outbreaks/incidents directly to the system

(ii) It will maintain FMD awareness among livestock keepers by periodically broadcasting any new information available in the system to their mobile phones.

(iii) Creating a common platform for sharing FMD surveillance information would improve the long chain and reduce the time for notifying FMD outbreaks across livestock stakeholders.

(iv) The Agent-Based Simulation Model (ABSM), a part of the surveillance system for predicting FMD outbreaks, will enhance FMD preparedness before impacting livestock-keeping communities and countries in general.

(v) Decision-makers may use the secondary data available in the system for decision-making.

(vi) The FMD-affected cattle shed spatial distribution map generated by the ABSM that will help understand the disease distribution behaviour at a particular time and take the necessary action (Fig. 8, 23-25 & 27).

1.7 Delineation of the Study

This study explains the development of an animal diseases surveillance system named Monitoring System for Transboundary Foot and Mouth Disease (FMD) Considering Livestock Keepers Demographic Characteristics, abbreviated as AMoS4T-FMD. The AMoS4T-FMD is web-based like other animal diseases surveillance systems but with additional SMS, Robocalls, and USSD functionalities to extend its accessibility. Gairo district in the Morogoro region was selected as a study area. Therefore, the surveillance system was developed and tested in Gairo district settings. However, it has flexible settings to work elsewhere. The AMoS4T-FMD aims to bridge the communication gap between livestock keepers and other top-level livestock stakeholders such as veterinarians, researchers and laboratory staff, which was an unforeseen challenge in the existing surveillance systems (NAOT, 2020). The system provides the standard platform for communicating FMD-related information, including outbreaks/incidents, clinical signs, precaution measures, negative impacts and predictions among the stakeholders through the system web interface, SMS, USSD and Robocalls. However, before accessing the system, livestock keepers and top-level stakeholders should be registered in the system. The system has flexible settings to add more stakeholders or update the existing ones. The FMD prediction data will be periodically automatically generated by the Agent-Based-Simulation Model (ABSM), a part of the surveillance system. However, top-level stakeholders uploaded the rest to the system. Top-level stakeholders may access the system through its web interface based on their privileges. Similarly, livestock keepers may access the system using SMS, Robocalls and USSD based on their demographic characteristics in the following ways:

(i) The system periodically broadcasts to livestock keepers' clinical signs, precaution measures and negative impacts in SMS and Robocalls following the time interval allocated for each piece of information.

(ii) At any time, livestock keepers may access the same information using the USSD menu option after dialling a specific USSD code with their feature mobile phone.

(iii) The system displays on the map and broadcasts to livestock keepers FMD prediction information at the instant they are available (Fig. 23-25 & 27).

(iv) At any time, livestock keepers may report FMD outbreaks through the USSD menu option after dialling a specific USSD code or by sending the SMS to a particular mobile number indicating the number of suspected FMD cattle using their feature mobile phones (Fig. 53).

CHAPTER TWO

LITERATURE REVIEW

The Tanzania government's current animal disease surveillance system is 95% paper-based (Fig. 5). Government officials use physical documents to pass surveillance data between administrative structures instead of electronic systems (NAOT, 2020; Mwabukusi *et al.*, 2014). Often this surveillance mechanism has many challenges that hinder efforts to combat animal diseases disaster in the country. Among the challenges is the long chain of communicating disease outbreaks/incidents among livestock stakeholders. Usually, the Ward Veterinary Officer receives outbreaks/incidents from livestock keepers by routine visits or phone calls from immediate livestock keepers. Once the veterinarians receive the information, they report the incident to the District Veterinary Officer (DVO) by calling or visiting the DVO office (Kijazi *et al.*, 2021b). Finally, the DVO forwards the information to the Directorate of Veterinary Services at the Ministry level for decision-making. Sometimes, a communication breakdown may happen if somebody is irresponsible along the reporting chain (Fig. 5).

Similarly, whenever there is a disease outbreak threat, veterinarians visit individual livestock keepers to alert them about the disease and precaution measures that could be taken efficiently by using the information system. Sometimes, the current reporting mechanism causes delays and insufficient information for controlling the disease (Kijazi *et al.,* 2021b). Also, veterinarians leave unreported cases due to unfriendly terrains that hinder access to remote livestock-keeping communities, especially during rainy seasons. Similarly, visiting livestock keepers to collect or give information is costly and requires a higher number of veterinarians for it to be effective. Furthermore, the paper-based mechanism does not timely capture data from livestock keepers, wildlife and private sectors hence contributing to the delay of reporting and response during disease incidents and outbreaks (NAOT, 2020).

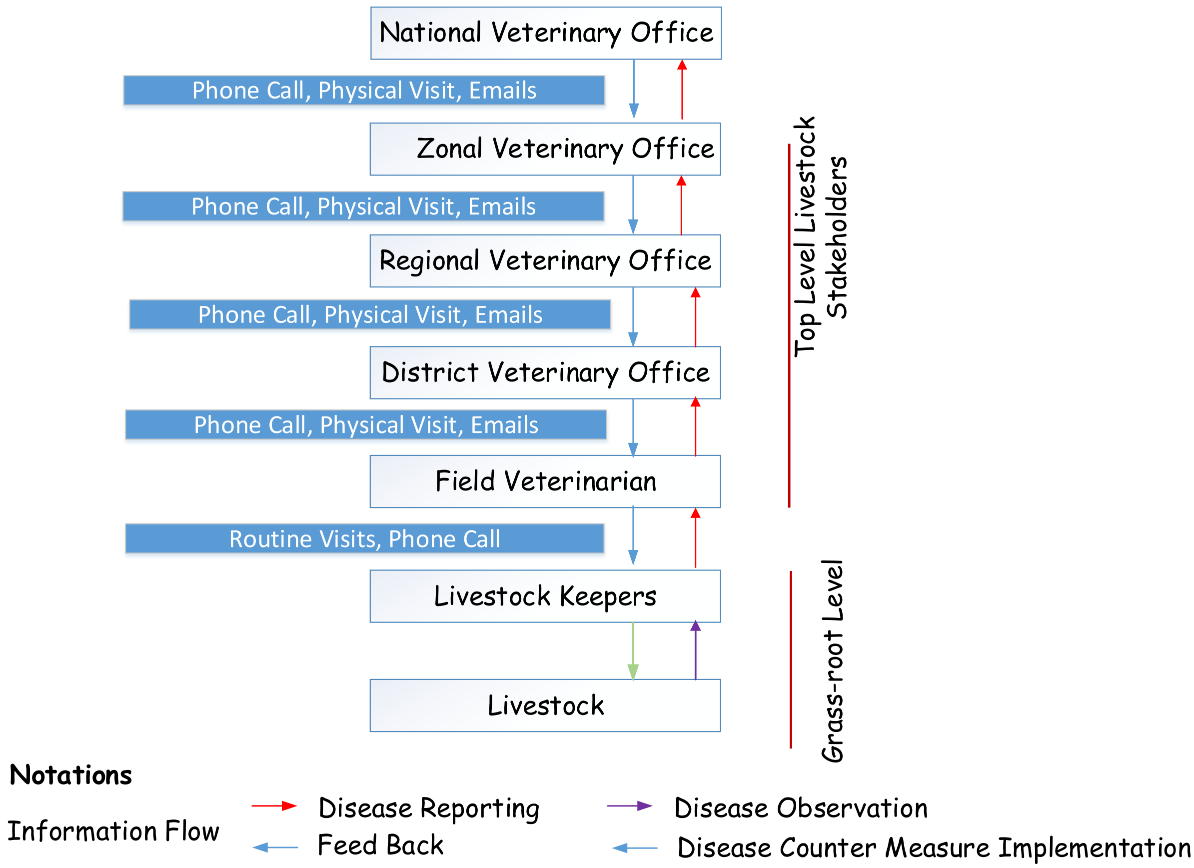


Figure 5: Information flow in the paper-based surveillance system

Realizing the importance of electronic-based animal disease surveillance systems, different livestock stakeholders developed electronic-based surveillance systems to replace the existing paper-based surveillance system in various places globally. An excellent example is an android mobile application named Afyadata, developed by the Sokoine University of Agriculture (SUA) in collaboration with the Southern African Centre of Excellence for Infectious Diseases (SACIDS) for collecting animal diseases field data for them (Karimuribo *et al.*, 2016). Similarly, the Food and Agriculture Organization (FAO) developed the mobile application named Event Mobile Application (EMA-i) for animal disease's early detection and timely reporting in developing countries, including but not limited to Tanzania, Mali and Zimbabwe (FAO, 2015; FAO, 2021).

The primary purpose of EMA-i was to upload surveillance data to the FAO public portal (EMPRES-i), which serves its member countries (FAO, 2021). Not only that but also Kenya developed the Kenya Animal Biosurveillance System (KABS) program, whereby Kenya's domestic and wild animal sectors adopted its data collection tool. The surveillance system was created using the Java platform and is free to download for Android-enabled mobile phones (Njenga *et al.*, 2021).

The Afyadata, EMA-I and KABS utilize trained community-based animal health workers and Field veterinarians to collect near-real-time surveillance data from their immediate livestock keepers. The community-based animal health workers and Field veterinarians use smartphones with android surveillance applications for collecting field data (FAO, 2015; Karimuribo *et al.*, 2016). However, although these APPs exist, delay of disease reporting cases is still a challenge because they cannot capture surveillance data directly from livestock keepers at the grass-root of the animal diseases reporting chain (Namayanja *et al.,* 2019).

Hence due to lack of access, the APPs deny livestock keepers sharing animal disease-related information such as outbreaks, precaution measures, and clinical signs. This situation contradicts other studies, emphasising that livestock keepers should be the primary source of animal disease information because sickness always originates with their animals (Namayanja *et al.,* 2019).

Another challenge is that they require a sufficient number of community-based animal health workers/field veterinarians in the area for them to work effectively; however, most developing countries reported an insufficient number of workers. For example, Tanzania reported below 30% of ward livestock field officers are available for the entire country (NAOT, 2020). Regardless of the minimum number of ward livestock field officers, getting information from livestock keeper's communities is tricky due to rugged terrains, especially during the rainy season (Karimuribo *et al.*, 2016).

Apart from Afyadata, EMA-I and KABS, there are Mobile phone-based syndromic surveillance systems for early detection and control of livestock diseases and Mobile phone-based Infectious Disease Surveillance systems available in Kenya and Sri Lanka (Wamwere-Njoroge *et al.,* 2019; Robertson *et al.,* 2010; Namayanja *et al.,* 2019). However, regardless of some valuable functionalities, the APPS still failed to accommodate livestock keepers among the users (Wamwere-Njoroge *et al.,* 2019; Robertson *et al.,* 2010). The APPs also utilize Community animal health workers to collect surveillance information on their behalf but with various names, such as Community Disease Reporter in Kenya (Wamwere-Njoroge *et al.,* 2019).

Apart from surveillance of animal health, this study also found that Mobile-based surveillance systems have applications across multiple domains and disciplines, including but not limited to surveillance of human health (Pascoe *et al.,* 2012; Search Health IT, 2021; Thirumurthy & Lester, 2012; Brinkel *et al.,* 2014).

Furthermore, this study reviewed many existing web-based surveillance systems that replaced the paper-based surveillance mechanism, which has been used in various locations globally (ProMED-mail, 2022; World Organisation for Animal Health, 2021; FAO, 2021; African Union, Inter African

Bureau for Animal Resources, 2019; European Commission, 2020; Bonnet *et al.*, 2010; Milinovich *et al.*, 2014). Excellent examples of such surveillance systems are the Animals Disease Notification System (ADNS) and Animal Diseases Information System (ADIS) for European Union member countries (European Commission, 2020 & 2022). Similarly, there are Livestock Management Information System (LIMS) under the SADC Epidemiology and Informatics Sub Committee (EIS) (Bonnet *et al.*, 2010). Also, there is an Animal Re-sources Information System (ARIS-AU-IBAR) under the African Union-International Bureau of Animal Resources (African Union, Inter African Bureau for Animal Resources, 2019).

Not only that, but also, there is a national information system for the notification of animal disease in Italy (SIMAN) which aims to communicate disease outbreaks and provide valuable tools to manage activities for emergency implementation (Colangeli *et al.*, 2011). Likewise, there is the World Animal Health Information System (WAHIS), under World Organization for Animal OIE and FAO Empress-i global animal disease etc. (World Organization for Animal Health, 2021; FAO, 2021). However, these systems still depend on input data from livestock stakeholders at the top of the disease reporting chain (veterinarians, laboratories, other healthcare providers, researchers etc.) and ignore those at the grass-root level (Livestock keepers).

General, the existing animal diseases surveillance systems were developed using more advanced technologies such as web-based and android that require skills and other resources like computers, smartphones and Internet connections to access them, while most livestock keepers, especially in developing countries, lack these requirements (Sankaranarayanan & Sallach, 2014). Therefore, it is difficult for them to report or access disease-related information whenever available in the systems (Kijazi *et al.*, 2021a; Kijazi *et al.*, 2021b).

Lack of communication between livestock keepers and other top-level stakeholders results in difficulties in early detection and response to FMD epidemics in livestock keepers' communities. Thus, it causes high livestock mortality and monetary loss due to the lack of convenient control options and negatively impacts its socio-economic development. This situation calls for a robust surveillance system that accommodates livestock keepers among the users for timely communicating FMD events with top-level stakeholders and among themselves based on their resources and demographic characteristics. Therefore, this study proposes the AMoS4T-FMD, which provides SMS, USSD and Robocalls services for livestock keepers to share FMD events with top-level stakeholders based on their education level, mobile phone categories and usage. The system will bridge the gap between livestock keepers and other top-level stakeholders by developing an all-inclusive surveillance system for sharing FMD information that was not covered by the existing monitoring system.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Objective: To Gather user Requirements in the Gairo District for Developing the Foot and mouth Disease Surveillance System

3.1.1 Description of the Study Area

Gairo district is in the Morogoro region and located between the latitude 36′450E-37′25 0E and longitude 6′400S-5′500S along the Morogoro–Dodoma highway (Fig. 6). The Gairo district was selected as a study area for this research (Appendix 1& 2). Therefore, the surveillance system was developed based on the Gairo district settings. However, the system has flexible configurations to work elsewhere. There are many districts in Tanzania with a significant number of cattle populations compared to Gairo. However, Gairo was selected as a study area because of the easy availability of three livestock farming systems: Zero-grazing, agro-pastoralism, and pastoralism, in contrast to other districts whereby one farming system may dominate, e.g., pastoralism in the Chalinze district. As a result, the researcher was convinced that the Gairo district would provide sufficient information/data for the study. Usually, zero-grazing is available in peri-urban areas; agro-pastoralism is practised in rural areas, while pastoralism is available in rangeland areas long-distanced from urban centres.

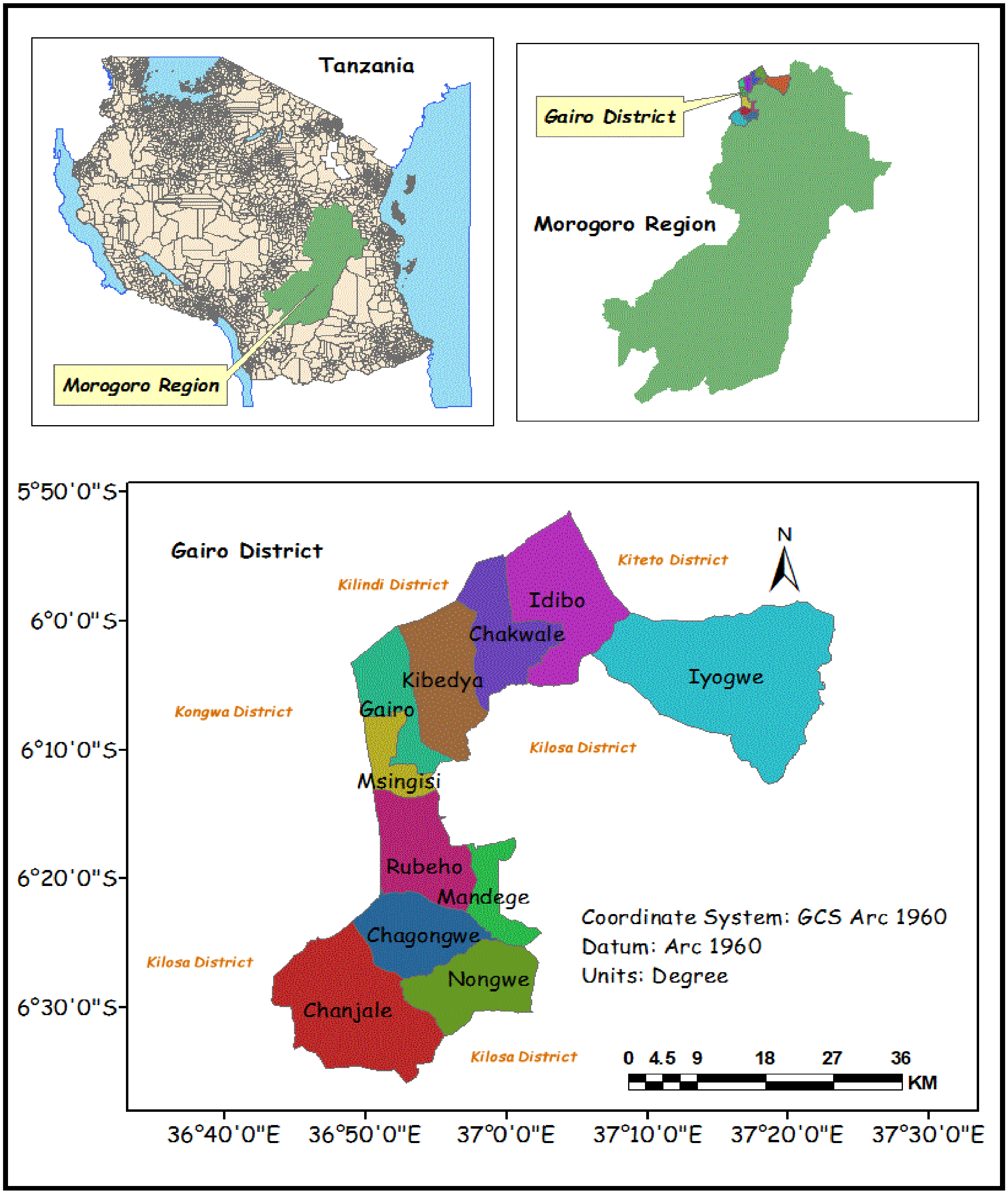


Figure 6: A map of the Gairo district

3.1.2 The Sample Size and Data Collection for System Requirements

The researcher used closed-ended interviews to collect data in the Gairo district using questionnaires with multiple and single-response questions (Appendix 3). Since some of the livestock did not know to read and write, even their native language (Swahili), the researcher decided to fill out questionnaires. The questions were formulated to gather data for different purposes (Appendix 3). Data about FMD-affected households and the relationship between the FMD outbreaks and seasons of the year were collected to determine the general FMD status in Gairo. In addition, the data about the time taken for livestock keepers to receive information about FMD outbreaks in their communities and FMD outbreaks information sources also were collected to determine the FMD communication challenge in Gairo. Also, the researcher collected data about livestock keepers' demographics to determine the appropriate technologies they could use to communicate FMD events with other stakeholders in the district.

During data collection, some livestock keepers refused to disclose information during the interview for various reasons, such as ignorance and livestock security. In such livestock-keeping communities, the researcher utilized the focus group discussion to explain the research's aim, eliminating fear and generating trust and friendship between the two sides for smooth data collection (Plate 3(a)).

The sample size of 180 livestock-keeping households from 6 villages in the Gairo district named Kilama, Chogoali, Chakwale, Kilimani, Gairo town, and Ibuti were interviewed. The interviewees were the heads of the families, regardless of their gender (Plate 2 & 3). The number of households to be interviewed was selected using the rule of thumb to determine the sample size of households, which states that a minimum sample size of 25–30 homes is appropriate for a village that ranges from 100 to 500 families (Arild, 2011). As a result, 30 households from each village were interviewed. To obtain the number of villages to be interviewed, the researcher used a stratified sampling technique to group 54 Gairo district villages into 3 groups based on livestock farming systems (Kothari, 2004). Hence, the 54 villages were divided into zero-grazing, agro-pastoralism, and pastoralism (Kothari, 2004). The three groups were then listed in the Excel sheet, and two villages were randomly selected from each group to collect data.

During the interview, the households were randomly chosen to avoid biases. The MATLAB was used for generating the frequency distributions table for the data, and Aeronautical Reconnaissance Coverage Geographic Information System (ArcGIS) was used to render maps in this study (Fig. 6 & 7).

Plate 2: **Interviewing livestock keepers in zero-grazing livestock-keeping community**

(a)

(b)

Plate 3: A focus group discussion (a) and interviewing (b) livestock keepers in pastoralism livestock keeping community

3.1.3 Data Analysis Plan

Data were collected using questionnaires with multiple and single-response questions (Appendix 3). Therefore, questionnaires were gathered from 180 livestock keepers in six communities in the Gairo district, and replies were recorded in an Excel spreadsheet. Then the spreadsheet was imported into MATLAB for analysis.

The data analyzed include the FMD-affected households and the relationship between the FMD outbreaks and seasons of the year, which were used to determine the general FMD status in (Table 2; Fig. 8). Similarly, the time taken for livestock keepers to receive information about FMD outbreaks in their communities and FMD outbreaks information sources was used to determine the FMD communication challenge in Gairo (Table 3). Also, the livestock keepers' demographics were used to determine the appropriate technologies they could use to communicate FMD events with other stakeholders in the district (Table 4).

On the other hand, the livestock keepers' cattle sheds/kraal's locations data (Latitudes and Longitudes) were recorded in an Excel spreadsheet and imported to the ArcGIS for drawing the distribution of FMD surveyed households in the district to determine the FMD status in each livestock-keeping community (Fig. 7).

3.2 Objective: To Formulate an Algorithm for Livestock Keepers to Communicate with the Surveillance System by Considering their Demographic Characteristics

3.2.1 Algorithm Formulation

An algorithm is a problem-solving strategy. During the algorithm formulation process, the following steps were followed.

(i) Obtaining a Description of the Problem

How can we facilitate communication between AMoS4T-FMD and livestock keepers so they can share FMD information among themselves and top-level stakeholders via the system? This question is the primary issue that has to be addressed. Since the functionality that enables the communication between livestock and AMoS4T-FMD is an important component of the system, which is complex because it involves information flow in both directions, the researcher decided to formulate the algorithm to handle the challenge. The algorithm was developed and tested separately before being embedded into the system

(ii) Problem Analysis

The geographical complexity of livestock-keeping communities and their perception and willingness to adopt communication technologies such as websites, smartphones and computers raised many questions about the technology they could use to communicate FMD scenarios among themselves and top-level stakeholders in the district via the AMoS4T-FMD. As a result, the researcher analyzes livestock keepers' demographic characteristics in six villages of the Gairo district to find suitable communication. Thus, the livestock keepers' communities' demographic characteristics analysis part formulates the first objective of this study and results were used as the benchmark to develop the algorithm, which is the second objective of this study. Aswini *et al.* (2017) explained that information systems play a significant role in creating different practical approaches to prevent, detect, respond to, and manage infectious disease outbreaks in plants, animals and humans. Therefore, the researcher believes that if a suitable communication mechanism is established between livestock keepers and other stakeholders, it may reduce the impact of the FMD in the district.

As a result, this study considered livestock keepers' demographic characteristics to suggest the best technology to communicate FMD events with other livestock stakeholders through AMoS4T-FMD. The data showed that the Gairo district has a reasonable number of livestock keepers owning feature phones and mostly use them for SMS and voice calls (Table 4). Therefore, the study suggests that SMS, USSD code and automatic broadcasting calls (Robocalls) will be the best way to communicate FMD incidents/Outbreaks among livestock farmers and other stakeholders in the Gairo district.

The SMS, USSD code and Robocalls will technically satisfy those with a primary school level and above who can read and write SMS (Table 3). In contrast, Robocalls will benefit those without formal education who can not read and write SMS (Table 4). However, all the mentioned technologies will satisfy most livestock keepers because most own feature mobile phones that do not require an internet connection to access the AMoS4T-FMD and are easy to use. Thus, the study suggests formulating the FMD communication algorithm, which is a part of the FMD communication module using the mentioned technologies.

(iii) Development of High-level Algorithm

The goal of the high-level algorithm is to provide general explanations of how the algorithm works. The high-level algorithm is written so that someone with no professional or specialized experience in computer programming can understand it.

01 Upload FMD-related information to the system, such as FMD awareness and outbreak alerts Messages
02 Load all cattle sheds/kraals to the map and indicate them as healthy ones with green colour
03 Livestock keepers decide to report FMD outbreaks or access FMD awareness information from the system using a feature mobile phone
04 If livestock keeper report FMD outbreaks
05 Livestock keeper may report FMD outbreaks by SMS or USSD
06 If he/she reports FMD outbreak by USSD
07 Dial a USSD code e.g., *384*90005#
08 Select Option number 1 of the USSD menu
09 Enter the number of FMD-suspected cattle
10 Submit
11 The system checks if the livestock keeper is registered
12 If the livestock keeper registered
13 Store the reported number of FMD-suspected cattle in Temporary Database (TDB)
14 Update reporter cattle shed/kraal on the map to the blue disc
15 If the livestock keeper not registered
16 Discard the reported case and inform the reporter that she is not registered
17 If he/she reports FMD outbreak by SMS
18 Open the SMS panel and enter the number of FMD-suspected cattle
19 Send an SMS to a given AMoS4T-FMD mobile number
20 The system checks if the livestock keeper registered
21 If the livestock keeper registered
22 Store the reported number of FMD-suspected cattle in Temporary Database (TDB)
23 Update reporter cattle shed/kraal on the map to the blue disc
24 If the livestock keeper not registered
25 Discard the reported case and inform the reporter that she is not registered
26 After the FMD valid case is received in the system, Top level stakeholders validate their truth
27 If the case is valid
28 Store the number of FMD-reported cases and the reporter's mobile number in Permanent Database 2(PDB2)
29 Send SMS alerts to all villagers informing them that there is an FMD outbreak in the reporter village
30 Update the reporter cattle shed on the map from blue to red
31 If the case is invalid
32 Discard the case and inform the reporter via SMS that the case is invalid
33 If the livestock keeper access FMD awareness information
34 Dial a USSD code e.g., *384*90005#
35 Select other options (2……………) than option no 1
36 Fetch a particular FMD awareness information from permanent Database 2(PDB2)
37 Broadcast a particular FMD awareness to the reporter via SMS and Robocalls

38 The system also periodically broadcasts FMDinfo in SMS/Robocalls from PDB2 to livestock keepers based on allocated time interval
39 The system checks if there is any FMDinfo to broadcast after every 30 seconds
40 If the time to broadcast has already elapsed
41 Broadcast that particular FMDinfo to livestock keepers
42 If the time to broadcast has not elapsed
43 Skip that particular FMDinfo

(iv) Development of the Detailed Algorithm

The goal of the detailed algorithm is to provide a programming overview of the algorithm. The detailed algorithm was formulated so the programmer could clearly understand the logical view of an algorithm. The detailed algorithm can be easily converted to pseudocode (Appendix 5).

```
Upload FMD-related information to the system, such as FMD awareness and outbreak alerts Messages
Load all cattle sheds/kraals to the map and indicate them as healthy ones with green colour
Livestock keeper decide to report FMD outbreaks or access FMD awareness information from the system using a feature mobile phone
    If livestock keeper report FMD outbreaks
        Livestock keeper may report FMD outbreaks by SMS or USSD
            If he/she reports FMD outbreak by USSD
                Dial a USSD code e.g., *384*90005#
                Select Option number 1 of the USSD menu
                Enter the number of FMD-suspected cattle
                Submit
                    The system checks if the livestock keeper is registered
                        If the livestock keeper registered
                            Store the reported number of FMD-suspected cattle in Temporary Database (TDB)
                            Update reporter cattle shed/kraal on the map to the blue disc
                        If the livestock keeper not registered
                            Discard the reported case and inform the reporter that she is not registered
            If he/she reports FMD outbreak by SMS
                Open the SMS panel and enter the number of FMD-suspected cattle
                Send an SMS to a given AMoS4T-FMD mobile number
                    The system checks if the livestock keeper registered
                        If the livestock keeper registered
                            Store the reported number of FMD-suspected cattle in Temporary Database (TDB)
                            Update reporter cattle shed/kraal on the map to the blue disc
                        If the livestock keeper not registered
                            Discard the reported case and inform the reporter that she is not registered
        After the FMD valid case is received in the system, Top level stakeholders validate their truth
            If the case is valid
                Store the number of FMD-reported cases and the reporter's mobile number in Permanent Database 2(PDB2)
                Send SMS alerts to all villagers informing them that there is an FMD outbreak in the reporter village
                Update the reporter cattle shed on the map from blue to red
            If the case is invalid
                Discard the case and inform the reporter via SMS that the case is invalid
    If the livestock keeper access FMD awareness information
        Dial a USSD code e.g., *384*90005#
        Select other options (2….) than option no 1
        Fetch a particular FMD awareness information from permanent Database 2(PDB2)
        Broadcast a particular FMD awareness to the reporter via SMS and Robocalls

The system also periodically broadcasts FMDinfo in SMS/Robocalls from PDB2 to livestock keepers based on allocated time interval
    The system checks if there is any FMDinfo to broadcast after every 30 seconds
        If the time to broadcast has already elapsed
            Broadcast that particular FMDinfo to livestock keepers
        If the time to broadcast has not elapsed
            Skip that particular FMDinfo
```

3.2.2 Algorithm Implementation

The researcher considered open-source software or services to minimize maintenance and development costs. Therefore, the algorithm was implemented using open-source programming languages, i.e., PHP hypertext processor, Jquery, HTML, JSON, Javascript, MySQL database and Apache webserver. Similarly, MySQL database and Apache web server were used to provide data storage engine and web services for accessing the system using computers and smartphones with a web browser. The MySQL database and Apache web server were installed through the XAMPP software package. However, there were no options for the third-party applications (software) and services that required purchasing. Therefore, SMS Deliverer was used to providing SMS and voice call (Robocall) functionalities (SMS Deliverer, 2022; Fig. 32 & 33). Similarly, the Unstructured Supplementary Service Data (USSD) service enabled communication between AMoS4T-FMD and livestock keepers via their feature mobile phones (Africa’s Talking, 2021).

On the other hand, a spot map was used to show cattle sheds/kraals' status when livestock keepers report FMD to the system via SMS or the USSD menu. The spot map is a Gairo district Google map embedded with cattle sheds/kraals (Fig. 8). The cattle sheds/kraals were created by Adobe graphics design software as disk images of different colours indicating their status (Fig.7). The Images were imported on the map as cattle sheds/kraals using JavaScript and PHP programming languages based on their latitudes and longitudes data stored in the MySQL database when registering livestock keepers ‘in the system through a specific menu (Fig. 44).

The 3G four ports SIMCOM multimedia modem pool provided SMS and automatic voice call broadcasting services (Shenzhen Antecheng Technology, 2022).

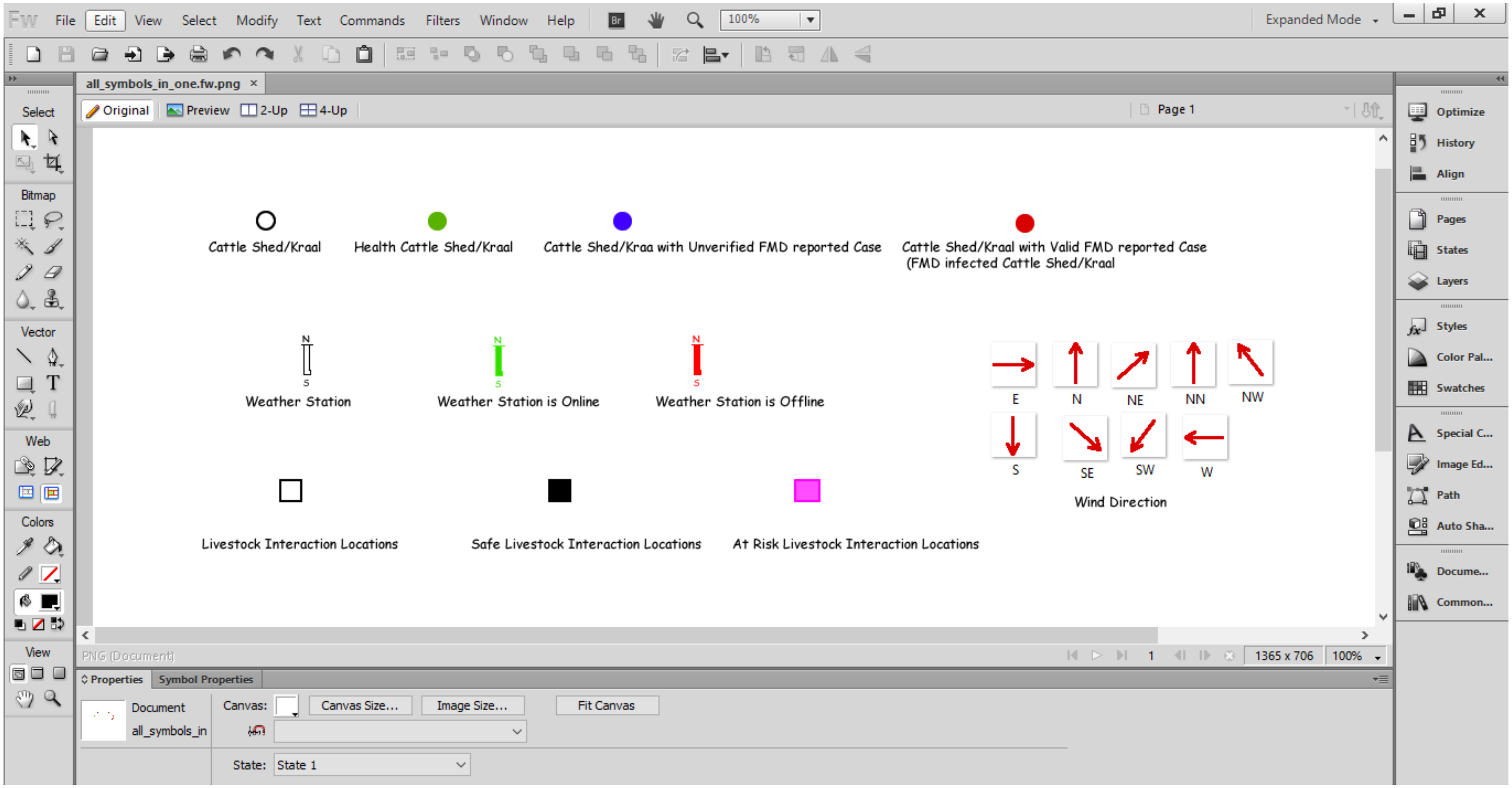


Figure 7: **Spot map images (symbols) generation process using Adobe Fireworks (Adobe, 2022)**

Figure 8: **Spot map showing FMD-reported and confirmed case**

3.3 Objective: To Develop an Agent-Based Simulation Model for Predicting Foot and Mouth Disease Outbreaks in the Gairo District

Agents are heterogeneous autonomous objects which can interact with each other through the interactive environment (space) (MacAl & North, 2010; Bonabeau, 2002). Agents also interact with other agents in the space (MacAl & North, 2010; Bonabeau, 2002). Each agent has its attributes and behaviour, which unequally differentiates it from others in the group. The behaviours of individual agents sometimes generalize the group's behaviour. The ABMS was used in this study due to its ability to model the interaction of objects with different characteristics. Therefore, ABSM would be the best approach for predicting FMD outbreaks in the Gairo district since interactions between animals (livestock) and contaminated fomite objects like human beings, drinking water points, vehicles, and wind influences the spread of FMD.

Various research explained different components of the Agent-Based Simulation Model (ABSM), including: (a) Agents, which are objects involved in the interactions (e.g., person, animals, organization). Each agent has its attributes (colour, age, name) and behaviour (changing colour, moving, increasing) (Future Learn, 2022; MacAl & North, 2010; Bonabeau, 2002), (b) Set of agent relationships and interaction methods that describe various ways the agents can interact. For example, sharing grazing land and water drinking points between animals is an interaction that may lead to the spread of FMD from infected to healthy cattle herds (Bonabeau, 2002; MacAl & North, 2010; Bonabeau, 2002), (c) Environment, which is the space agent interaction. Space can be the space or layer of a Geographical Information System (GIS) such as MapInfo or Google Map. The environment may be static or dynamic, changing with time (Bradhurst *et al.*, 2015; Future Learn, 2022), and (d) Time of interactions between agents. For example, animals share water drinking points every year from January-April due to the drought (Future Learn, 2022).

Therefore, this study set the components of an ABSM as follows:

3.3.1 Agent Environment

The agent environment is the space in which agents interact. This study used the Gairo district Google map as space (Geographical Information System) to develop the model. The Google map was embedded in the model using the google maps API concept (Google, 2022). The Google map, by default, is composed of different things, including village names connected by the road networks for driving, walking and bicycling. Regardless of having these valuable features, they are insufficient to build the model. Therefore, this study generates a spot map by embedding the Google map with cattle sheds/kraals, a weather station, wind direction and livestock interaction locations (Fig. 7, 23-25 & 27). The researcher collected the centre coordinates (Latitudes and Longitudes) of animals' interaction locations and livestock keepers' villages details to create the spot map. Therefore, the spot map provides the agent interaction environment for building the ABSM in this study.

This study considered all places whereby animals came into contact, such as livestock drinking water points, grazing areas, animal markets and livestock loading ramps as interaction points (Table 5). Creating and importing cattle sheds (discs) have been explained in this study's FMD communication module and General setting module sections in Chapter four. However, unlike cattle sheds, the livestock interaction locations were created using Adobe fireworks graphic design software as square images (.png) with different colours indicating their status at a particular time (Adobe, 2022; Fig. 7).

The interaction locations were imported on the map using JavaScript and PHP programming languages based on their latitudes, longitudes and names stored in the MySQL database. During data collection, the interaction location details were noted and inserted in the AMoS4T-FMD through the Register/Update animal's interaction locations menu in the General setting module (Fig. 28; Table 5). The process of registering and updating animals' interaction locations in the system has been explained in detail in this study's General setting module section in Chapter four. Other components added to the map include wind direction and weather station.

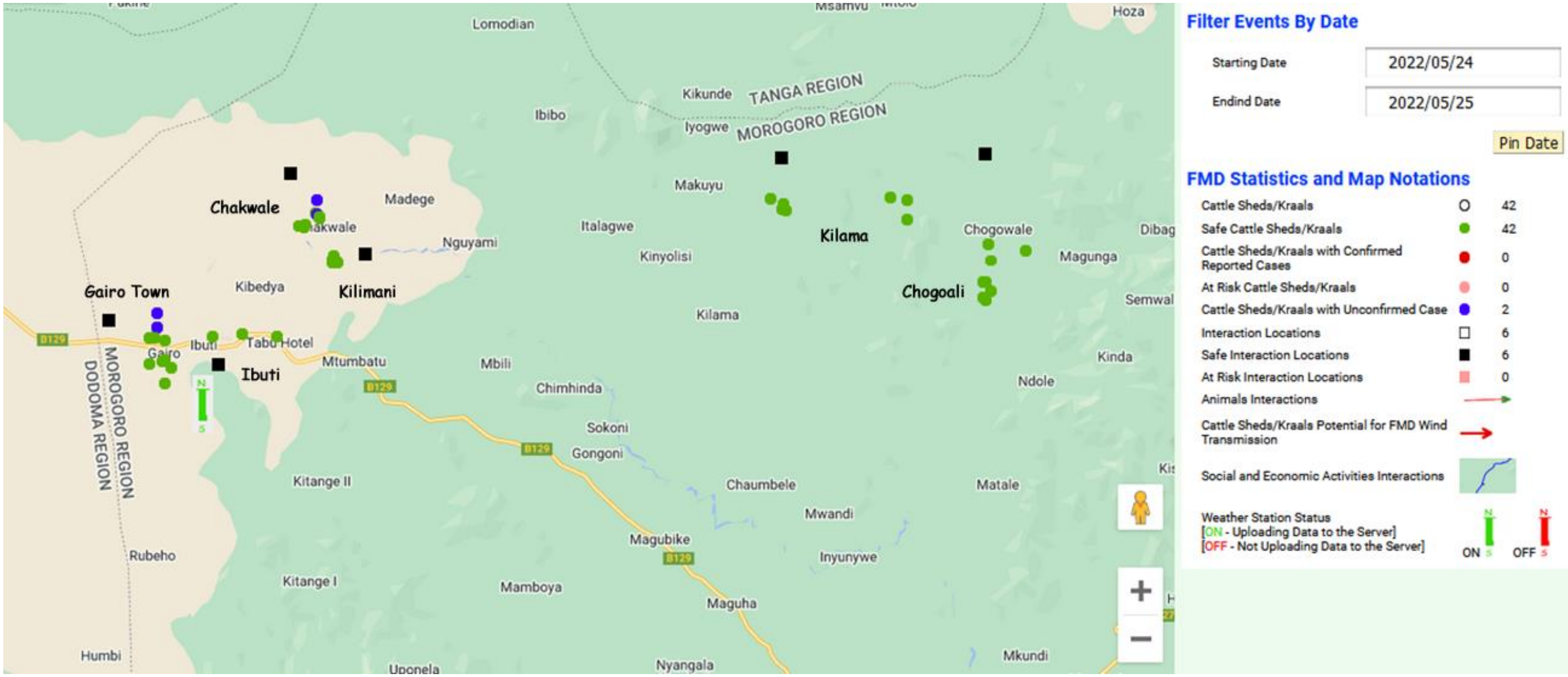


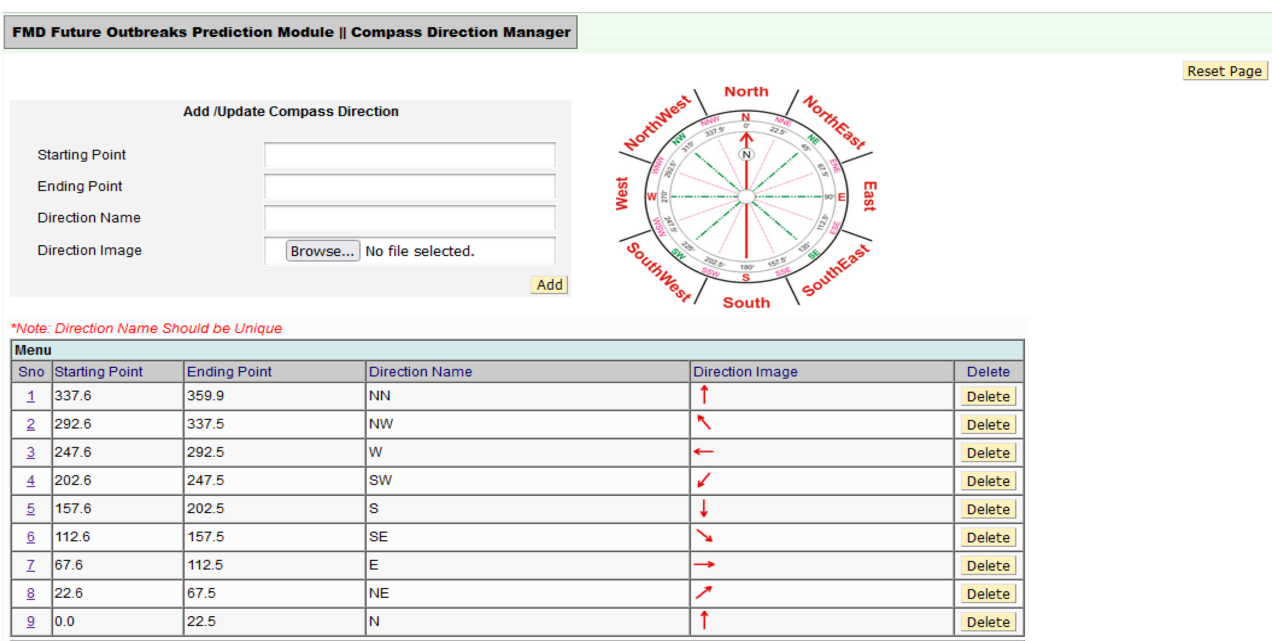
Figure 9: **Agent-Based Simulation Model (ABSM) before FMD outbreak prediction (Google, 2022)**

The weather station also was created using the Adobe fireworks graphic design software as an image stick (.png) pointing to the north and south poles (Fig. 7, 23-25 & 27).

The weather station was added to the map using the JavaScript programming language, referring to the weather station's location (latitude and longitude) installed in the Gairo district. The green colour stick image indicates the weather station is online and uploads data to the AMoS4T-FMD using API. Conversely, the red stick image denotes that the weather station is offline and does not upload any data to the AMoS4T-FMD (Fig. 23-25 & 27). The process of uploading weather data into the AMoS4T-FMD has been explained in Chapter four (The weather station and weather condition API).

On the map, the wind is also denoted by an arrow beside the cattle shed/kraal, pointing in the wind direction (Fig. 7 & 24). The wind direction arrows were also created as (.png images) using Adobe fireworks and uploaded into the AMoS4T-FMD through the Campus direction manager menu as part of the FMD feature outbreaks prediction module (Fig. 10). This study uploaded wind direction arrows to the system based on the 8-point compass rose. However, the system is flexible to upload more than 8-point compass rose such as 16-points, 32-points, 64-points etc. (Fig.10). The ABSM imports wind direction symbols from the database using JavaScript and PHP, like cattle sheds and animals’ interaction locations. The wind direction symbols will only be shown on the map if the condition for FMD transmission by wind is met.

Similarly, roads connecting villages through walking, driving, and bicycling provide the model interaction environment for social and economic activities between Gairo’s district village.


FMD Future Outbreaks Prediction Module || Compass Direction Manager

Reset Page

Add /Update Compass Direction

Starting Point

Ending Point

Direction Name

Direction Image Browse... No file selected.

Add

*Note: Direction Name Should be Unique

Menu

Sno	Starting Point	Ending Point	Direction Name	Direction Image	Delete
1	337.6	359.9	NN	↑	Delete
2	292.6	337.5	NW	↖	Delete
3	247.6	292.5	W	←	Delete
4	202.6	247.5	SW	↙	Delete
5	157.6	202.5	S	↓	Delete
6	112.6	157.5	SE	↘	Delete
7	67.6	112.5	E	→	Delete
8	22.6	67.5	NE	↗	Delete
9	0.0	22.5	N	↑	Delete

Figure 10: Compass direction manager menu

3.3.2 Agents

All movable objects capable of spreading FMD by carrying the FMD virus from one location to another through interacting with themselves were considered agents in this study. Therefore, this study utilized livestock (cattle), villagers and wind as agents for developing the ABSM to predict FMD outbreaks in the Gairo district. Unlike other objects, wind-borne FMD transmission (also known as aerosol transmission) occurs only under favourable weather conditions (temperature, humidity and wind speed) and at an acceptable distance from the source (FMD-infected herd). Various studies suggested the maximum possible distances from the FMD source and the favourable weather condition for FMD aerosol transmission (Björnham *et al.,* 2020; Mikkelsen *et al.,* 2003).

As a result, this study utilizes the maximum suggested weather parameters such as relative humidity > 60 RH, temperature <27°C and wind speed 2-5M/S as favourable weather conditions for FMD aerosol transmission (Hagerman *et al.,* 2018). Similarly, other studies reported that the FMD virus could be transmitted up to 60 km over the land and 250 km over the sea under favourable weather conditions (Garner & Cannon, 1995). Consequently, this study utilized 60 km as an acceptable distance from the FMD source to develop the ABSM since all Gairo district villages were on dry land. All variables influencing FMD aerosol transmission were inserted (stored) into the system through the Manage weather condition threshold values menu (Fig. 11).

The model is also indirectly considered moving objects like cars and bicycles since they provide a means of transport when villagers and animals move between villages via the road channels. This study utilizes the Spot map (Google Maps) as an animal interaction environment (space) (Fig. 23-25 & 27). Various mechanisms have been used to describe agents in space. For example, cattle were represented by their cattle sheds/kraals denoted by discs (Fig. 23-25 & 27).

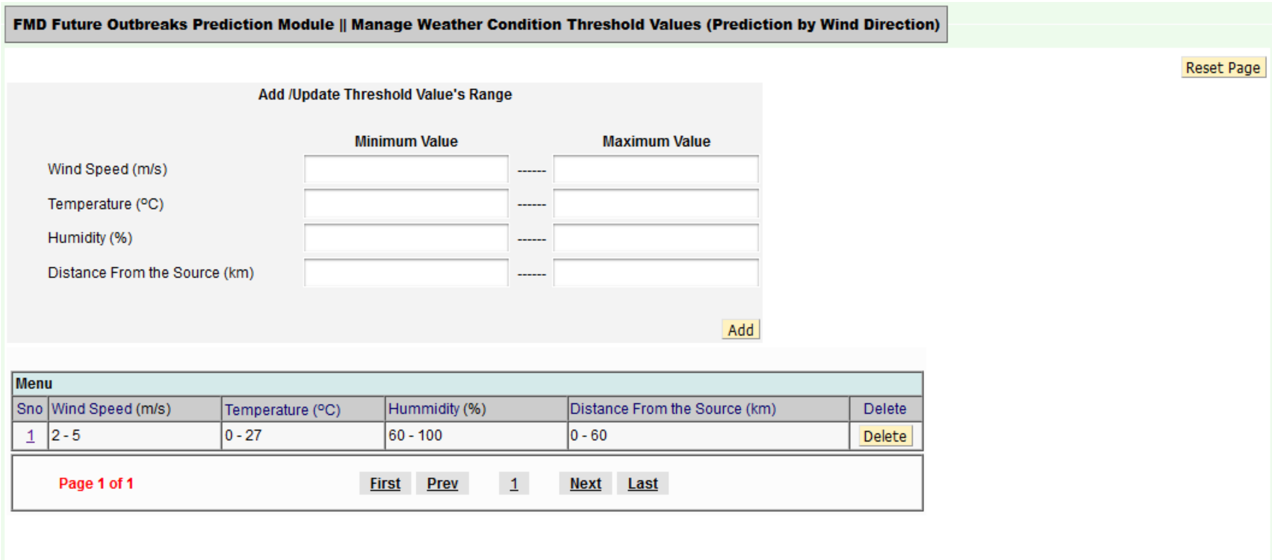


Figure 11: Weather condition threshold values manager menu

Similarly, villagers were represented on the map using their villages' location information (latitude and longitudes) inserted into the system with other details when registering villages (Fig. 46). Lastly, the map represented the wind using an arrow pointing in the wind direction beside the cattle shed/kraal (Fig. 24).

3.3.3 Agent Relationships and Methods of Interaction

This study considered agent relationships as possibilities for agents to interact or collaborate in the Gairo district. For example, villagers can move between villages for daily social and economic activities such as selling and purchasing livestock in the livestock market, moving with animals in the loading ramps, shared grazing areas and drinking water points (Table 5). Similarly, this study considered the possibility of wind blowing through the downwind cattle sheds or kraals as among the agent relationship.

On the other hand, the mechanisms by which the agents interact, such as animals, wind, and human movement, were considered a method of interaction that influences agent relationships. The agent relationships and methods interactions influence the spread of FMD when the health agent meets the FMD suspected ones in the district. Therefore, this study generates the matrix of all agents (livestock, villagers, vehicles, etc.) possible interactions for the six Gairo district villages named Kilama, Chogoali, Chakwale, Kilimani, Ibuti, and the Gairo town (Table 5). Similarly, the Agent's possible Interaction topology was generated from (Table 5) to indicate how agents were connected. The blue vertices (arrows) indicate an interaction between agents when moving between villages, while black means an interaction between agents through the animals' interaction locations, e.g., Animal markets (Fig. 12).

In Table 5, the agent's interactions can be in the form of (X_{vl}, Y_{vl}) or $((X_{vl}, Y_{il})_1, (X_{vl}, Y_{il})_2)$ coordinates. The (Xvl, Yvl) signals the interaction when agents move from one village to another. For example, (Jvl, Hvl) demonstrates that agents may move from Kilama to Chakwale village. Similarly, $((X_{vl}, Y_{il})_1, (X_{vl}, Y_{il})_2)$ indicates interaction between agents through the animals' interaction location. For example, $(G_{vl,} A_{il})$ can be interpreted as Gairo town villages using Chakwale livestock market for selling and buying animals. Also, $(I_{vl,} A_{il})$ means that Kilama villagers use the same Chakwale livestock market to sell and buy animals. Therefore, one may deduce that villagers and animals from Kilama and Gairo towns interact through the Chakwale livestock market with the relationship $((G_{vl,} A_{il}), (I_{vl,} A_{il}))$.

Table 1: Gairo district Agents' possible interaction matrix

				X					
				Villages					
				Gairo town	**Chakwale**	**Kilimani**	**Kilama**	**Ibuti**	**Chogoali**
				G_{vl}	H_{vl}	I_{vl}	J_{vl}	K_{vl}	L_{vl}
Y	Livestock interaction location	Chakwale livestock market	A_{il}	√	√	√	√	√	√
		Kilama pond, shared livestock drinking water point	B_{il}				√		√
		Magamba shared livestock grazing area	C_{il}				√		√
		Chakwale river shared livestock drinking water point	D_{il}		√	√			
		Ibuti shared livestock grazing area	E_{il}					√	
		Ukwamani (Minjenga) livestock loading ramp	F_{il}	√	√	√	√	√	√
	Gairo district villages	Gairo town	G_{vl}		√			√	
		Chakwale	H_{vl}	√		√	√	√	
		Kilimani	I_{vl}		√				
		Kilama	J_{vl}		√				√
		Ibuti	K_{vl}	√	√				√
		Chogoali	L_{vl}				√	√	

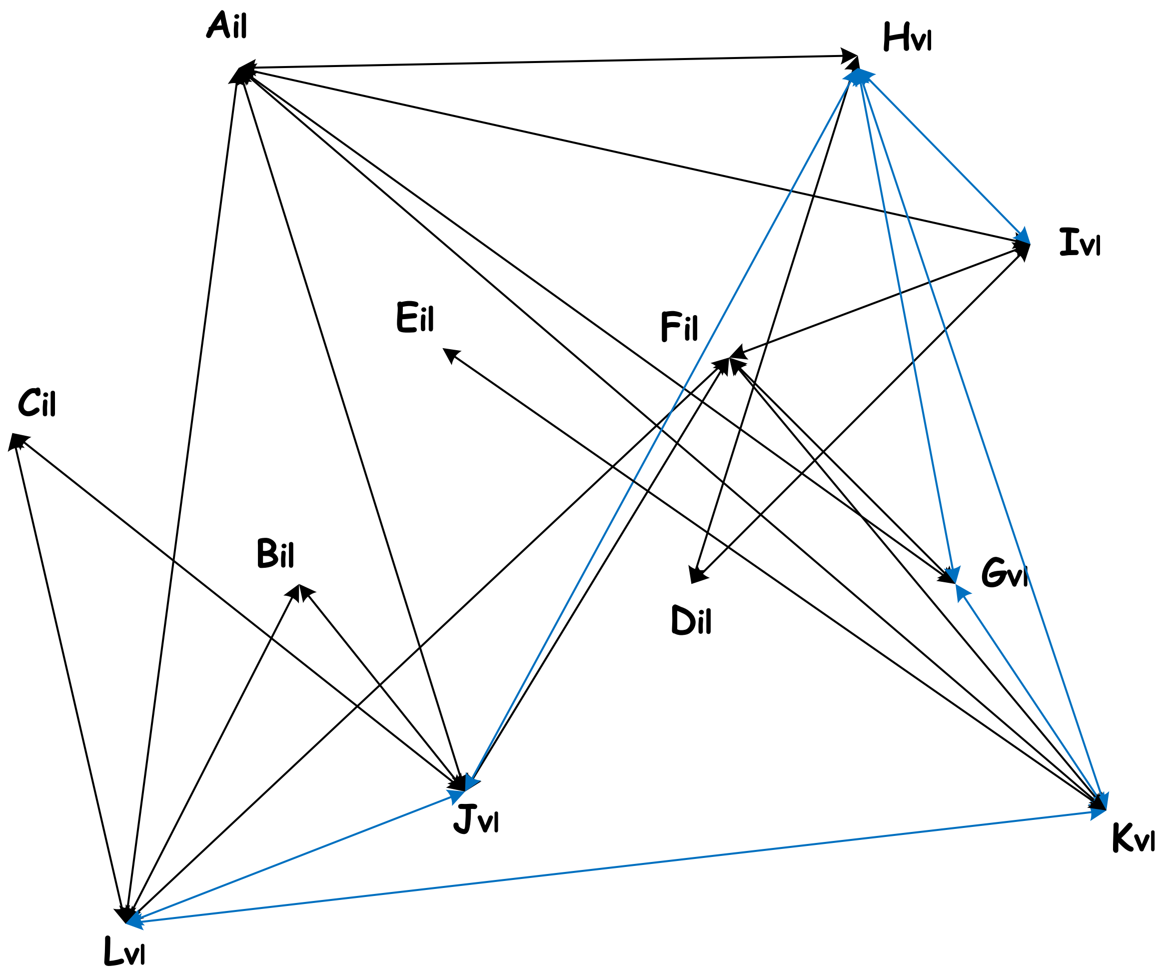


Figure 12: **Agents ‘possible interaction topology**

In the ABSM, the interactions when agents move between villages were enforced by matching the nearby villages through the Villages matching menu in the FMD future outbreaks prediction module. This menu provides flexibility to match and unmatch nearby villages in the model (Fig. 13). Similarly, the model's interactions between agents were enforced by matching villages and animals' interaction locations via the Animals interaction location matching menu in the FMD future outbreaks prediction module (Fig. 14). This menu also provides flexibility to match and unmatch villages and interaction locations in the model. Remember that villages and animals interaction sites were added to the system via the General settings module's Register/Update villages and Register/Update animals interaction locations menus (Fig. 13 & 14).

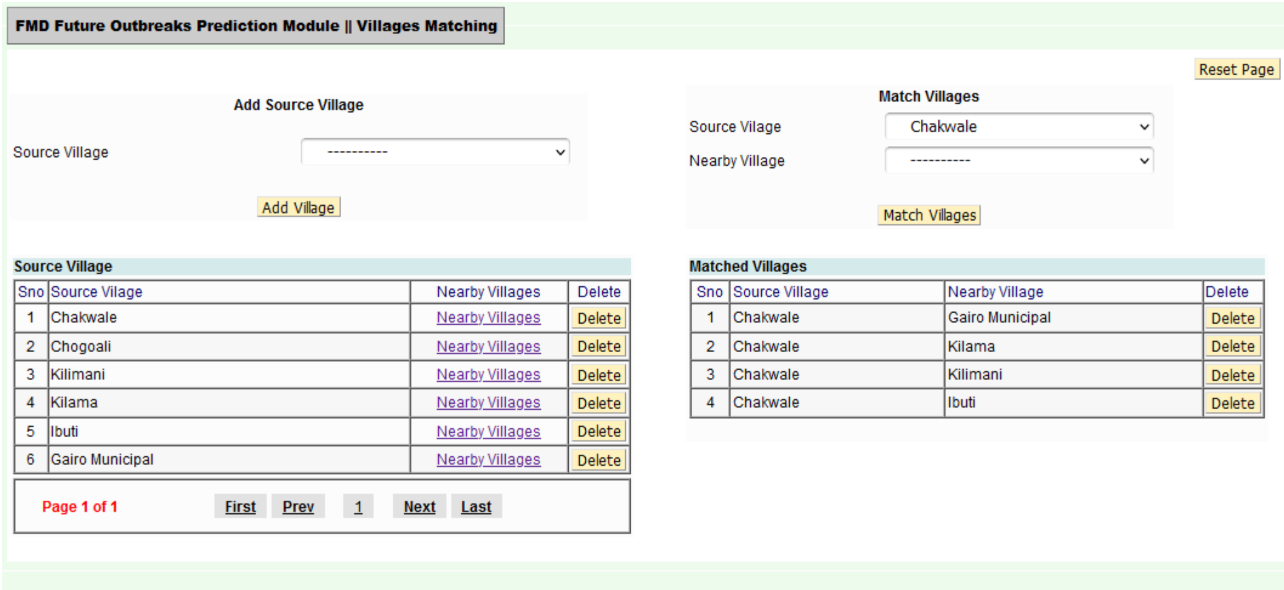


Figure 13: **Villages matching menu**

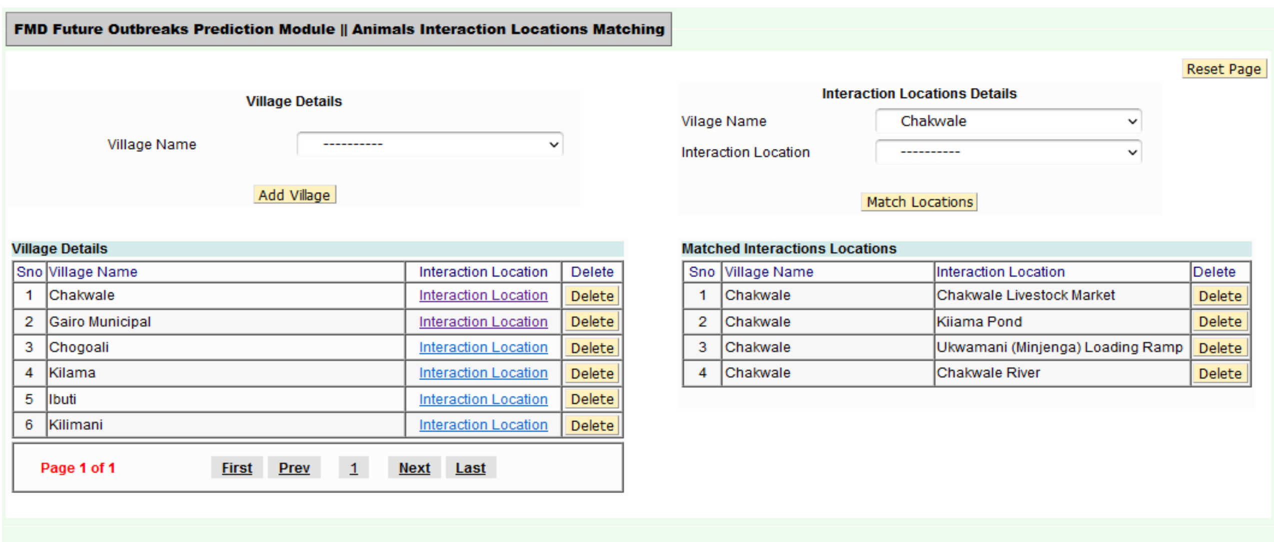


Figure 14: **Animal's interaction location matching menu**

3.3.4 Time of Interactions between Agents

The model shows agents' interactions and predicts FMD outbreaks daily based on the reported FMD valid cases. However, showing interactions and predictions for a particular period is flexible by specifying the starting and ending date (Fig. 23-25 & 28).

3.4 Objective: To Develop the Foot and Mouth Disease Surveillance System by Combining Objectives no (ii) and (iii)

3.4.1 System Development Approach

The waterfall model was used to develop AMoS4T-FMD because it is easy to use and focuses more on deliverables than customers when all user requirements are known and fixed (Tutorials point, 2022). Therefore, it saves system development time when the researcher combines the FMD communication algorithm and the Agent-Based Simulation model into a software

3.5 Objective: To Validate the Developed Foot and Mouth Disease Surveillance System

3.5.1 Foot and Mouth Disease Future Outbreaks Prediction Module Validation

The model's operation was validated using the replicative validation technique, in which the model outputs were compared to actual Gairo district FMD incidents/outbreaks data (Darvishi & Ahmadi, 2014). As a result, the model was validated using four months of FMD incident/outbreak secondary data (March 2021-June 2021) from six selected villages in the Gairo district: Kilama, Chogoali, Chakwale, Kilimani, Gairo town, and Ibuti (Appendix 8). However, the data on FMD incidents/outbreaks from Ibuti village, on the other hand, was excluded because no FMD cases were reported during the stated period. Similarly, testing did not involve the weather condition data since no weather condition parameters favour the FMD transmission by wind direction reported by the Weather station at that time (March 2021-June 2021).

3.5.2 Foot and Mouth Disease Communication Module Validation

The ability of livestock keepers to access AMoS4T-FMD using their mobile phones was tested as part of the FMD communication module validation. As a result, 36 livestock keepers from Chogoali and Kilama villages were randomly chosen to see if they could use their feature phones to access the system using the USSD menu, SMS, and Robocalls on the first trial. As a result, a closed-ended interview with a questioner was undertaken to see if they could access the USSD menu and use SMS and USSD menus to report disease outbreaks to the system (Appendix 9). They were also asked if they could get FMD awareness information from the system on the first attempt, such as precautions, negative effects, transmission pathways, and clinical indicators via SMS and automated voice calls (Robocalls) utilizing the USSD menu.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Foot and Mouth Disease Status in Gairo District

To determine the FMD status, 170 livestock keepers out of 180 responded that either they had already observed FMD infection in their cattle or not. The question was a single-response question (Appendix 3). The livestock keepers responded “yes” to the question and were informed to mention at least three FMD clinical signs to validate their answers (Appendix 3). The data found that 133 (78%) of the interviewed livestock keepers had already observed FMD infection in their cattle (Table 2; Fig. 15). A larger number was experienced in the pastoralist community, that 97% of them had already observed FMD infection in their cattle, followed by the agro-pastoral community, 93% (Table2; Fig. 15). In contrast, only 44% was observed in the zero-grazing community.

Table 2: Frequencies of livestock keepers who have already faced FMD challenges

Livestock farming system	Responses	Frequency	Per cent
Zero-grazing **(N=55)**	no	31	56%
	yes	24	44%
	Total	55	100%
Agro-pastoralist **(N=57)**	no	4	7%
	yes	53	93%
	Total	57	100%
Pastoralist **(N=58)**	no	2	3%
	yes	56	97%
	Total	58	100%

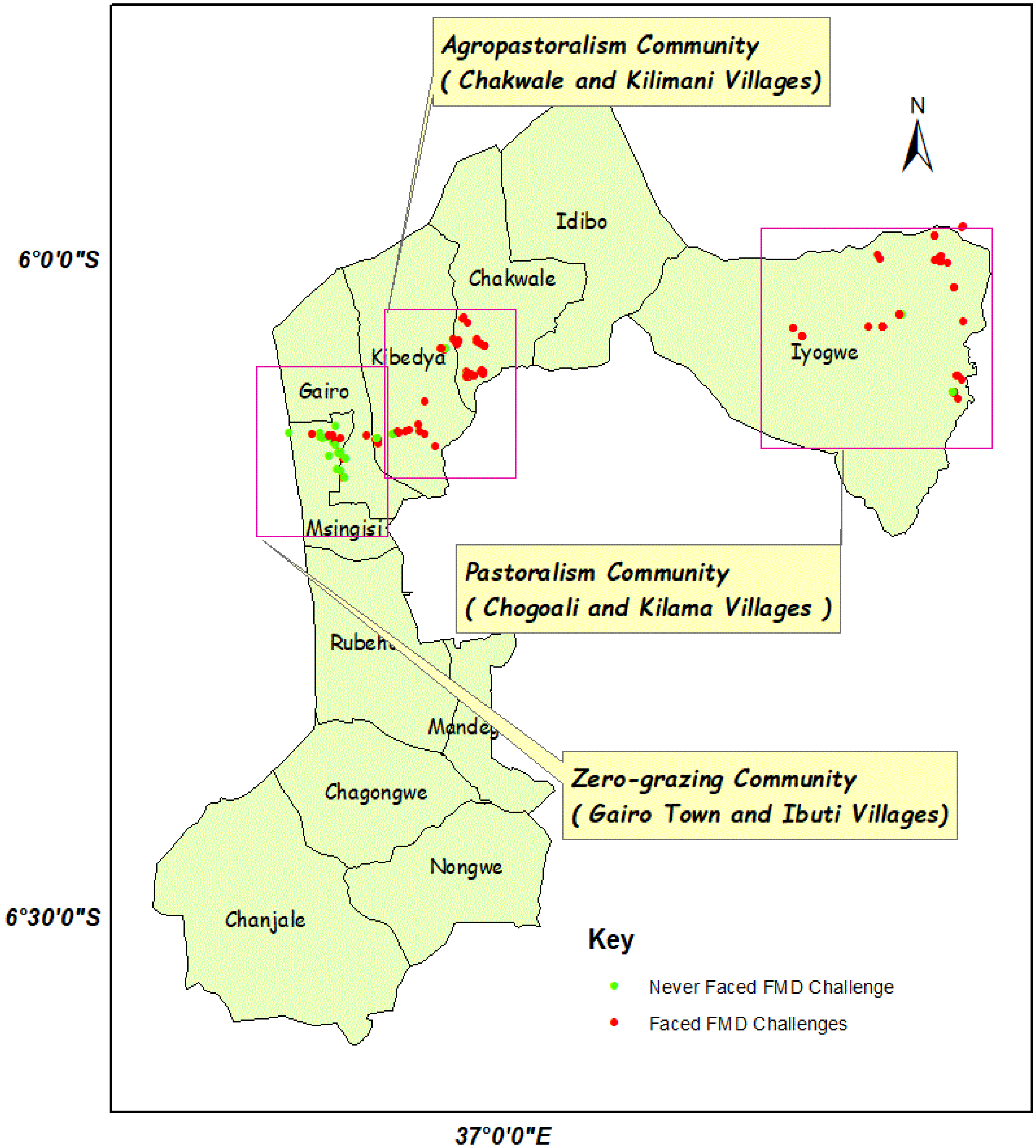


Figure 15: Spatial distribution of FMD surveyed households in the Gairo district

4.2 Relationship between the Foot and Mouth Disease Outbreaks and Seasons of the Year in the Gairo District

The five years FMD outbreaks secondary data (Jan 2015 to May 2019) were collected from Gairo district veterinary office. Data shows that most FMD outbreaks were reported in January-May, August, October and December. However, there were very few cases in July, September and November, and no FMD cases were reported in June for the past five years consecutively (Fig. 16). The reason for this variation was not identified in this study.

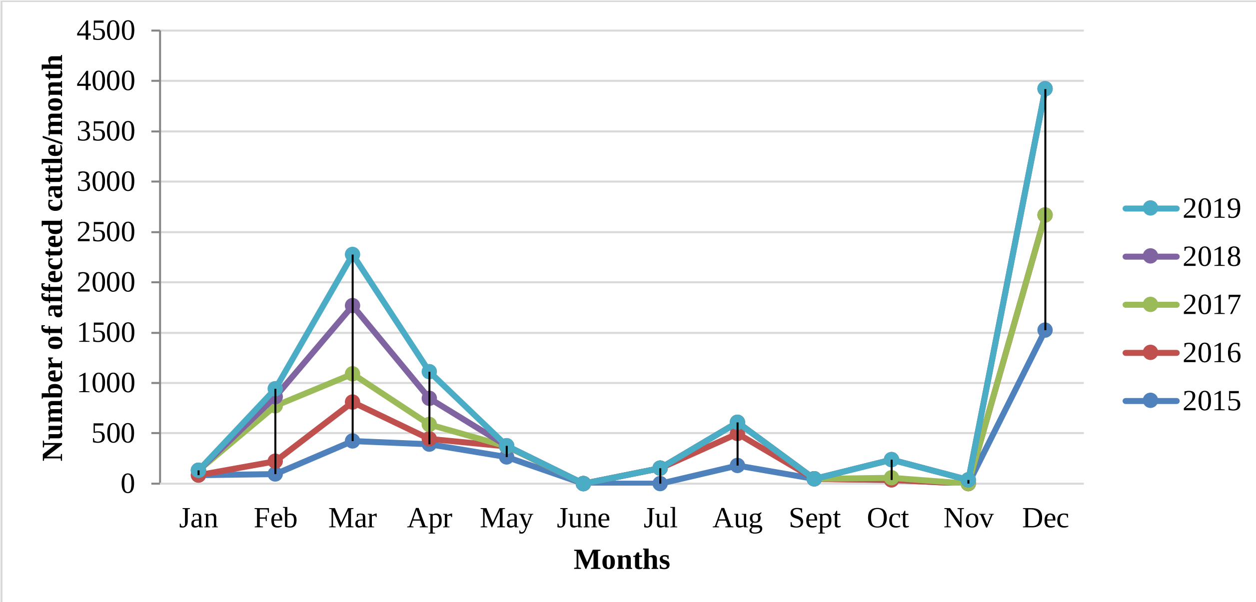


Figure 16: Foot and Mouth Disease affected cattle in the Gairo district by the year (Jan 2015 to May 2019)

4.3 The Time taken for Livestock Keepers to Receive Information about Foot and Mouth Disease Outbreaks in their Communities

The study revealed a delay in information flow in livestock-keeping communities during the FMD outbreak. The data indicated that most livestock keepers got information one day after the disease outbreaks (Table 3). Thus, 79% of pastoralists, 74% of agro-pastoralists, and 67% of zero-grazing got information more than one day after the FMD outbreaks (Table 3). Also, livestock keepers mostly communicate FMD incidents/outbreaks and control measures among themselves rather than getting official information from liable sources such as local and regional VET offices or Veterinarians (Table 3). This is because the government established no official communication channels for reporting or delivering FMD outbreak information in their communities.

Since most livestock keepers received FMD outbreak information more than one day after the outbreaks, and clinical signs can appear in animals within 2 to 14 days after FMD virus exposure, the likelihood of receiving information after animals have been affected is higher (World Organization for Animal Health, 2022). Not only that, but also the majority of livestock keepers received FMD outbreaks information from other livestock keepers and just heard rumours from their nearby villages. However, very few receive information from veterinarians. Generally, there are no official ways of communicating FMD events among livestock stockholders in the district.

Table 3: Time taken by livestock keepers to receive FMD outbreaks information from different sources and sources of FMD information

Livestock Farming system	Variables	Frequencies	Per cent
Time taken by livestock keepers' communities to receive information during FMD outbreaks			
Zero-grazing (N=39)	Within 1 hour	2	5%
	Within 6 hours	1	3%
	Within 12 hours	3	8%
	Within 1 day	4	10%
	More than 1 day	26	67%
	No Information at all	3	8%
	Total	39	100%
Agro-pastoralist (N=39)	Within 1 day	6	15%
	Within 6 hours	0	0%
	Within 12 hours	0	0%
	Within 1 day	0	0%
	More than 1 day	29	74%
	No Information at all	4	10%
	Total	39	100%
Pastoralist (N=52)	Within 1 hour	1	2%
	Within 6 hours	3	6%
	Within 12 hours	0	0%
	Within 1 day	6	12%
	More than 1 day	41	79%
	No Information at all	1	2%
	Total	52	100%
Sources of FMD information in livestock keepers' communities			
Zero-grazing (N=43)	VET professional	11	19%
	Other livestock keepers	39	67%
	Special meetings	1	2%
	Just hearing rumours	7	12%
	Other	0	0%
	Total	58	100%
Agro-pastoralist (N=49)	VET professional	5	8%
	Other livestock keepers	44	75%
	Special meetings	0	0%
	Just hearing rumours	4	7%
	Other	6	10%
	Total	59	100%
Pastoralist (N=55)	VET professional	0	0%
	Other livestock keepers	54	91%
	Special meetings	1	2%
	Just hearing rumours	0	0%
	Other	4	7%
	Total	59	100%

4.4 Livestock Keepers' Demographic Characteristics

The researcher collected information about livestock keepers' demographic characteristics to determine the user requirements. Therefore, one hundred and eighty livestock keepers (180) were interviewed to determine their demographic characteristics, including their level of education and mobile phone categories, possession and usage. The data found that 91% of livestock keepers own feature phones, and 9% own Smartphones (Table 4). The data also found that most livestock keepers used mobile phones to make and receive voice calls and send and receive SMS (Table 4). Not only that, but 60% of livestock keepers had primary school education, and 33% had no formal education (Table 4).

Table 4: Frequencies of livestock keepers' demographic characteristics

Variables	Frequencies	Per cent
Livestock keepers owning mobile phones (N=170)		
No	27	16%
Yes	143	84%
Total	170	100%
Mobile phone usage (N=143)		
Smartphone	13	9%
Feature phone	139	91%
Total	152	100%
Level of education (N=171)		
Primary School	103	60%
Secondary School	10	6%
University	1	1%
No Formal Education	57	33%
Total	171	100%
Mobile phone usage (N=144)		
Sending and receiving SMS	114	39%
Making and receiving calls (including Robocalls)	141	48%
Surfing the Internet	10	3%
Social Network	11	4%
Other use	19	6%
Total	295	100%

4.5 Animals' Interaction Locations and Livestock Keepers' Villages Details

The study found that there are 6 possible animal interaction locations in six villages of Gairo district namely; Gairo town, Chakwale, Chogoali, Kilama, Kilimani and Ibuti (Table 5).

Table 5: Animals' interaction locations and livestock keepers' villages details

Notations	Places	Center Coordinates (Lat, Lng)
Animal's interaction location (il)		
A_{il}	Chakwale livestock market	-6.06542996, 36.96424154
B_{il}	Kilama pond, shared livestock drinking water point	-6.05153231, 37.23789128
C_{il}	Magamba shared livestock grazing area	-6.02680034, 37.35967209
D_{il}	Chakwale river shared livestock drinking water point	-6.07756290, 36.96884716
E_{il}	Ibuti shared livestock grazing area	-6.14983980, 36.90310699
F_{il}	Ukwamani (Minjenga) livestock loading ramp	-6.12568657, 36.85628147
Place Type: Livestock keepers' villages (vl)		
G_{vl}	Gairo town	-6.15121500, 36.87513170
H_{vl}	Chakwale	-6.06099170, 36.96072830
I_{vl}	Kilimani	-6.08598710, 36.97170540
J_{vl}	Kilama	-6.05224000,37.231162500
K_{vl}	Ibuti	-6.13271670, 36.93784670
L_{vl}	Chogoali	-6.11075170, 37.35772000

4.6 Foot and Mouth Disease Communication Algorithm

The FMD communication algorithm, as the heart of the FMD Communication Module, accomplishes the overall FMD communication process with the help of a spot map (Appendix 5; Fig. 8 & 17). The algorithm performs the FMD communication process between livestock keepers and top-level stakeholders in stages. First, before any FMD case is reported to the system, the algorithm loads all healthy cattle sheds (green discs) onto the spot map (Fig. 8). Next, the system stores the number of FMD-suspected animals in the Temporarily database (TDB) and believed the information was unconfirmed anytime a livestock keeper submitted the number through SMS or USSD menu (Fig. 31 & 52). In addition, the algorithm updates the reporter's cattle shed/kraal on the map to a blue disc denoting an unconfirmed case (Appendix 5; Fig. 18).

The veterinarians (Top-level stakeholders) validate the incident by calling the livestock keeper who reported the outbreaks/incidents and physically visiting the area. The algorithm moves the number of FMD-suspected cattle to the Permanent database2 (PDB2) after the veterinarian clicks the "Accept Cases button" if the case is valid (Appendix 5; Fig. 17 & 18). Otherwise, the system discards the information and informs the cattle shed/kraal own the claim is invalid.Also, the algorithm updates the unverified (blue disc) cattle shed/kraal on the map to red, indicating it is a valid case (FMD-affected cattle shed)(Fig. 52).

Sometimes both unverified and valid status may happen in a particular shed/kraal when the FMD-affected cattle shed/kraal reports the new FMD suspected cases to the system after the preceding valid cases. The spot map represents them with blue and red discs simultaneously; however, the blue disc will be bouncing on the top of the stationary red disc (Fig. 52).

Similarly, the algorithm broadcasts alert messages to livestock keepers (excluding the reporter) explaining the scenario in SMS and Robocalls for preparedness (Fig. 17). The alert messages mention the reporter village and suggest the necessary precaution measures to minimize FMD impact in livestock-keeping communities. The process of broadcasting audio files as Robocalls has been explained in this study's SMS/Voice gateway and voice modem pool section of this Chapter.

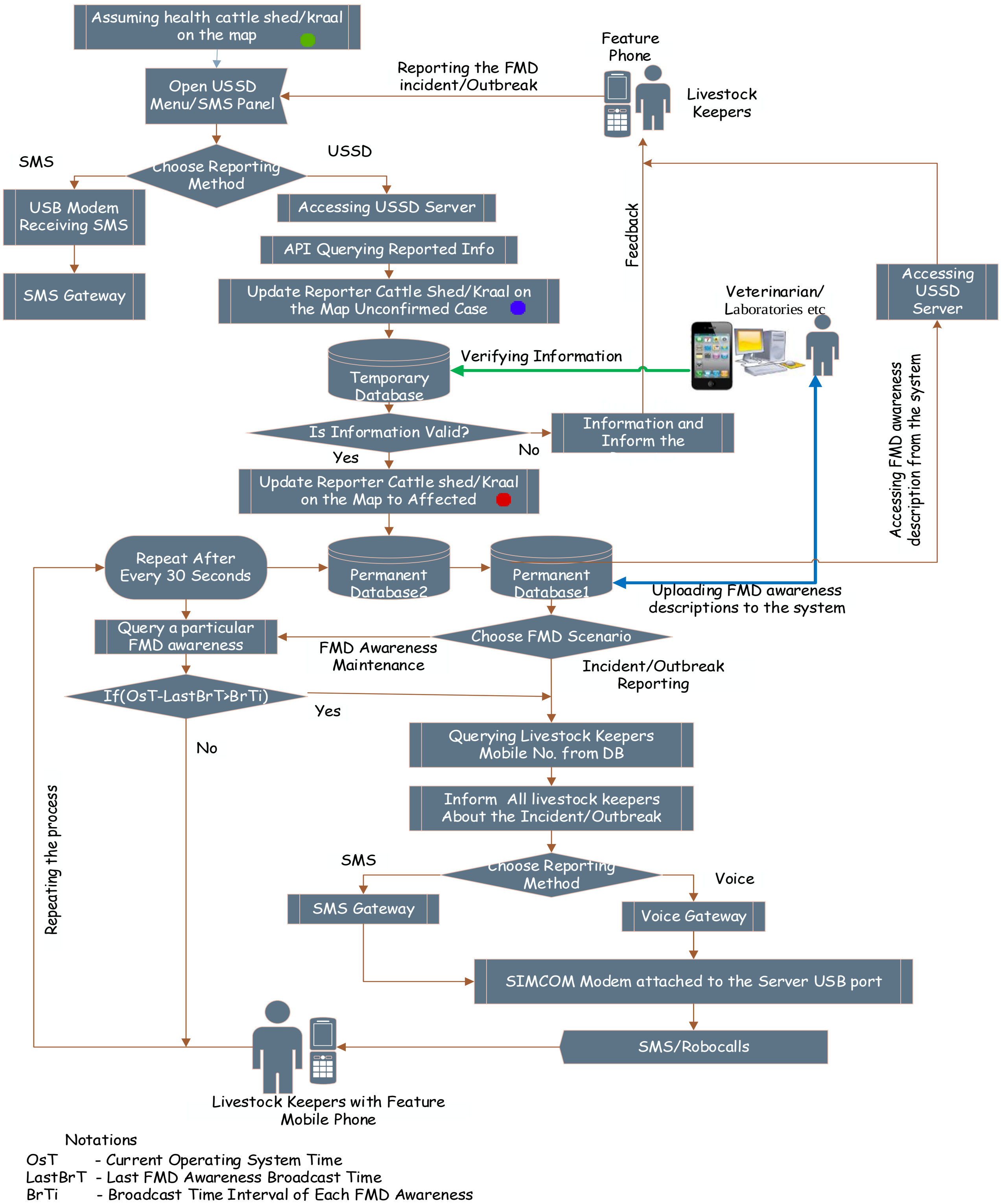


Figure 17: Data flow in the FMD Communication Module

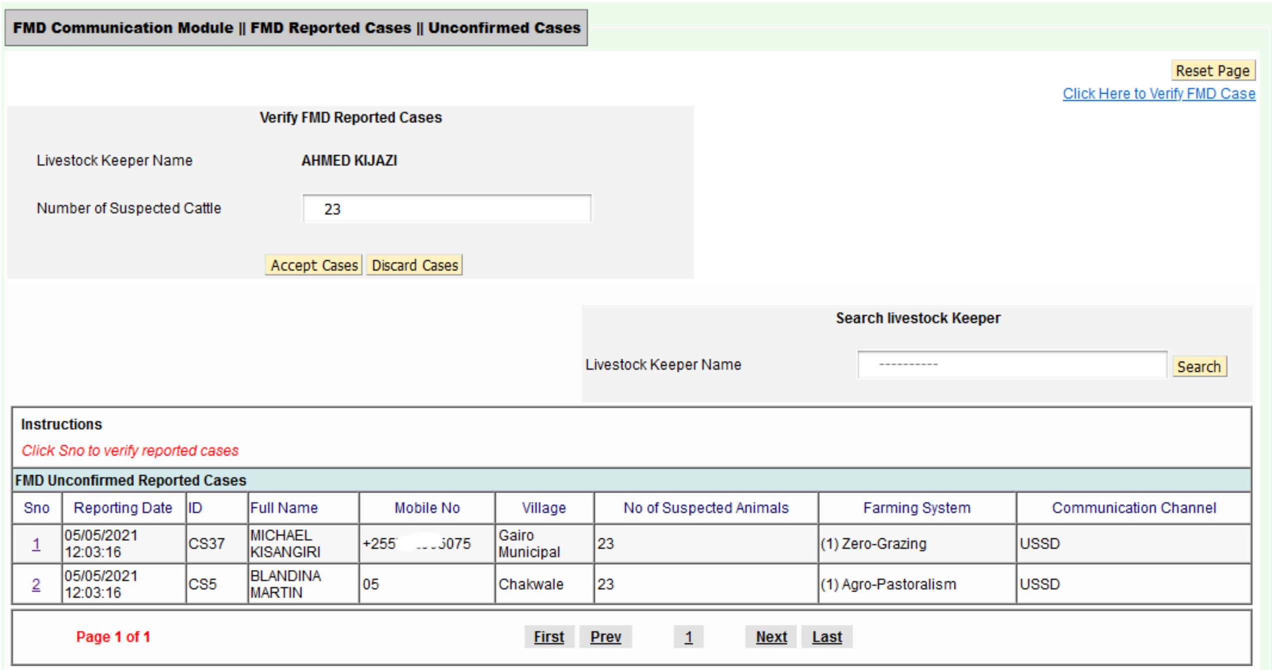


Figure 18: Foot and Mouth Disease Unconfirmed Cases menu

Apart from enabling livestock keepers to report FMD outbreaks, the algorith is also responsible for maintaining FMD awareness by periodically broadcasting FMD awareness to livestock keepers in SMS and Robocalls. The FMD communication algorithm broadcast FMD awareness information based on the time interval allocated when uploaded to the system through the FMD alerts manager menu (Appendix 5; Fig. 50). The targeted FMD awareness information includes but is not limited to FMD precaution measures, negative impacts, clinical signs and transmission pathways (Fig. 50).

The system algorithm calls or delivers SMS to multiple mobile numbers during SMS or Robocall broadcast. To archieve that, the algorith compares each recorded FMD awareness's last broadcast time (LastBrT) to the current operating system time (OsT). The algorithm only broadcasts the FMD awareness to livestock keepers via SMS and Robocalls if the difference between OsT and LastBrT is greater than the broadcast time interval (BrTi) assigned to that specific FMD awareness when it was uploaded to the system. The process repeats every 30 seconds (Fig.17). Also, livestock keepers may access the same information using options number 2-5 of the USSD menu (Fig. 55). The FMD awareness descriptions and the USSD menu were translated into English for readability in this paper. However, in the actual system, the information is in the native language (Kiswahili) system for livestock keepers to easily understand (Fig. 53-54).

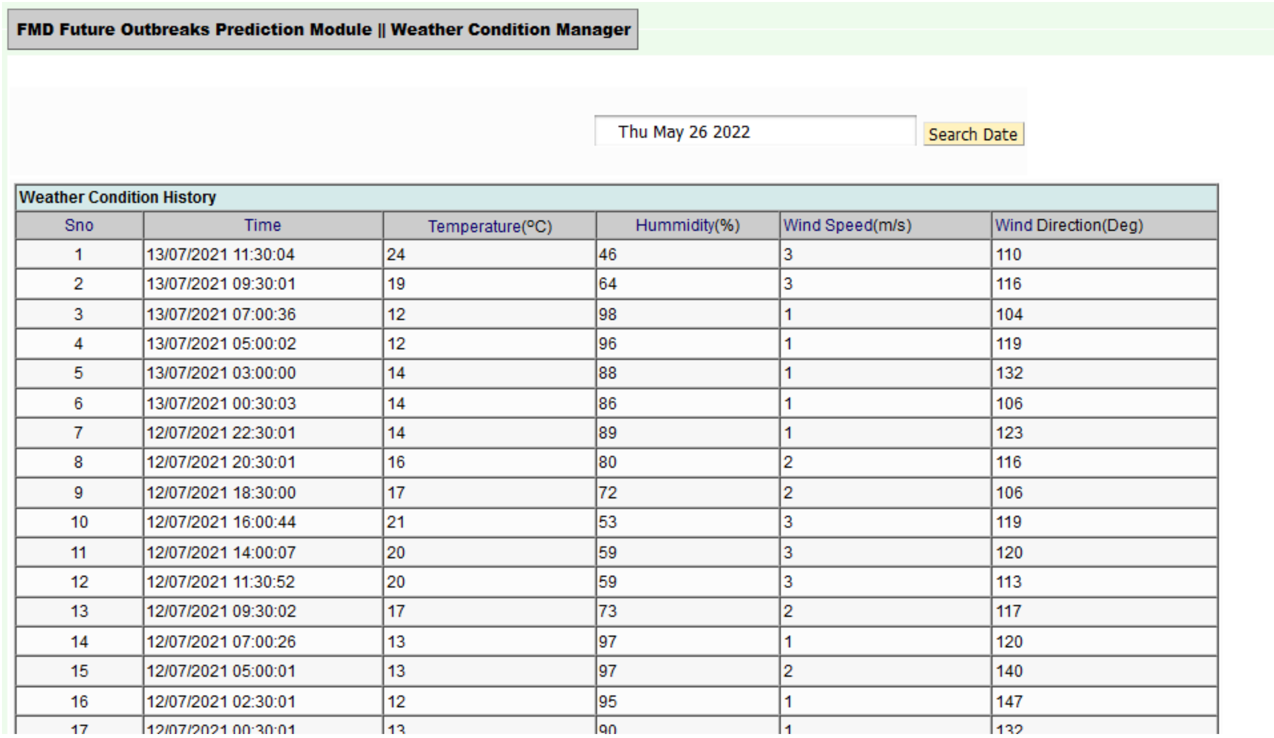
4.7 Foot and Mouth Disease Future Outbreaks Prediction Model

4.7.1 Model Working Principle

The ABSM utilize various data for the FMD prediction process. Top-level stakeholders upload some of them to the system, including FMD prediction alert messages, animals' interaction locations, cattle sheds, and village details through the menus (Fig. 44, 46, 47 & 51). Also, top-level stakeholders generate agents' possible interaction data by matching nearby villages and interaction locations against villages (Table1; Fig. 12-14). The model also utilizes weather condition variables uploaded to the system by the weather station installed in the Gairo district.

Furthermore, the system automatically generates FMD confirmed case data using the weather condition variables and unconfirmed FMD reported cases. The FMD unconfirmed cases menu in the FMD communication module can be used to view the FMD unconfirmed cases (Fig. 18). When the top-level stakeholders approve valid FMD cases, the system checks each of the 12 days' hourly recorded weather condition secondary data in thePDB1 for FMD aerosol transmission requirements (humidity > 60 RH, temperature 27^{o}C, wind speed 2-5M/S) (Fig. 18 & 19).

One may view the weather condition hourly data uploaded to the system through the Weather condition manager menu in the FMD communication module (Fig. 19). The process of uploading data to the system using a weather station installed in the Gairo district has been explained in this Chapter, Weather station and weather condition API section (Fig. 35a-c, 36-40). The secondary weather data for 12 days were considered because the FMD incubation period is 2-14 days, implying that animals may show FMD clinical signs 12 days after being exposed to the FMD virus. As a result, whenever livestock keepers report FMD cases to the system, the likelihood that their animals have already transmitted the FMD virus through wind movement in the previous 12 days is high under favourable weather conditions. Therefore, in this study, the FMD incubation period was inserted into the system through the FMD incubation period manager menu in the FMD future outbreaks prediction module (Fig. 20).



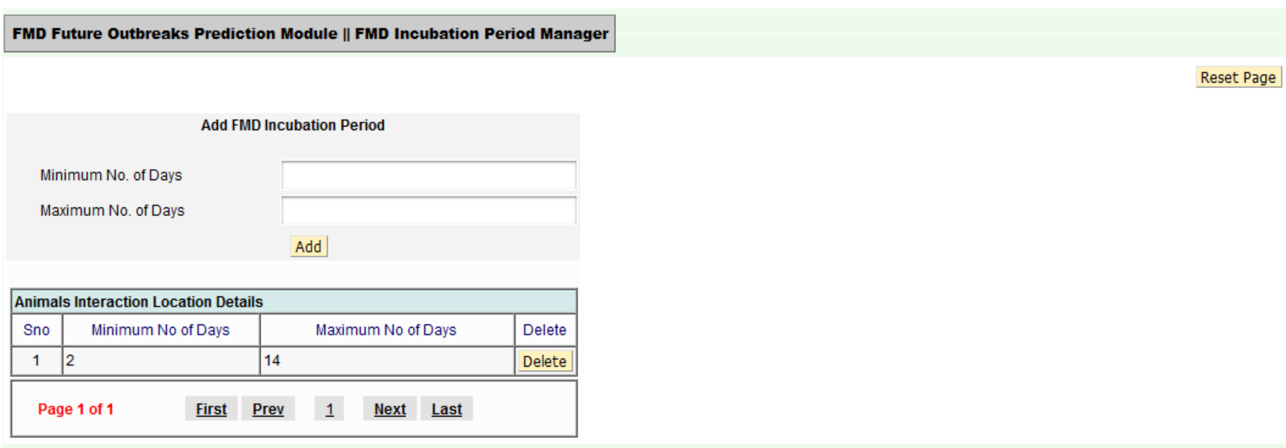
FMD Future Outbreaks Prediction Module || Weather Condition Manager

Thu May 26 2022 | Search Date

Weather Condition History

Sno	Time	Temperature(°C)	Hummidity(%)	Wind Speed(m/s)	Wind Direction(Deg)
1	13/07/2021 11:30:04	24	46	3	110
2	13/07/2021 09:30:01	19	64	3	116
3	13/07/2021 07:00:36	12	98	1	104
4	13/07/2021 05:00:02	12	96	1	119
5	13/07/2021 03:00:00	14	88	1	132
6	13/07/2021 00:30:03	14	86	1	106
7	12/07/2021 22:30:01	14	89	1	123
8	12/07/2021 20:30:01	16	80	2	116
9	12/07/2021 18:30:00	17	72	2	106
10	12/07/2021 16:00:44	21	53	3	119
11	12/07/2021 14:00:07	20	59	3	120
12	12/07/2021 11:30:52	20	59	3	113
13	12/07/2021 09:30:02	17	73	2	117
14	12/07/2021 07:00:26	13	97	1	120
15	12/07/2021 05:00:01	13	97	2	140
16	12/07/2021 02:30:01	12	95	1	147
17	12/07/2021 00:30:01	13	90	1	132

Figure 19: Weather condition manager menu



FMD Future Outbreaks Prediction Module || FMD Incubation Period Manager

Reset Page

Add FMD Incubation Period

Minimum No. of Days

Maximum No. of Days

Add

Animals Interaction Location Details

Sno	Minimum No of Days	Maximum No of Days	Delete
1	2	14	Delete

Page 1 of 1 First Prev 1 Next Last

Figure 20: Foot and Mouth Disease incubation period manager menu

Whenever livestock keeper report FMD outbreak/incident to the system, the system stores the reporter's details (including mobile number) and weather condition variables (temperature, humidity, wind speed and wind direction) in PDB2 when it finds the matching weather condition data and flags the information for FMD prediction by the wind (Fig. 17, 19 & 22). Otherwise, it stores the reporter details only in PDB2. This information is known as valid cases and can be viewed through the FMD confirmed cases menu available in the FMD communication module (Fig. 21).

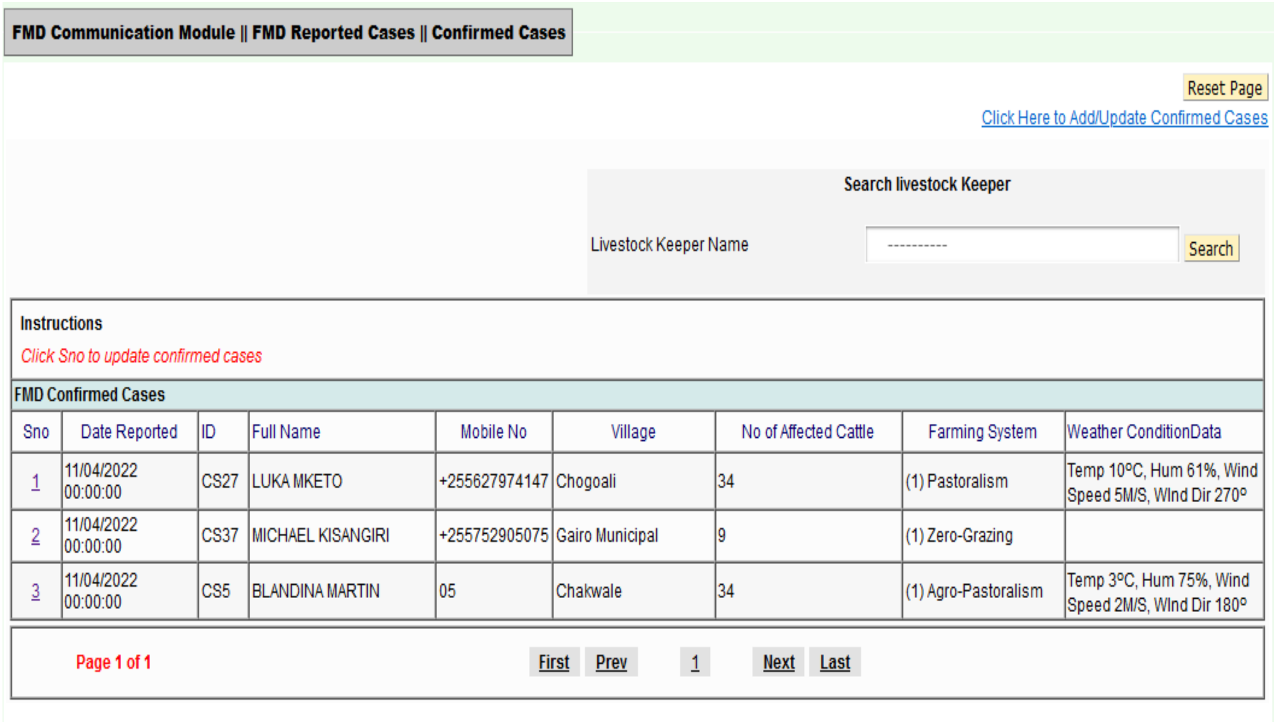


Figure 21: Foot and Mouth Disease confirmed cases menu

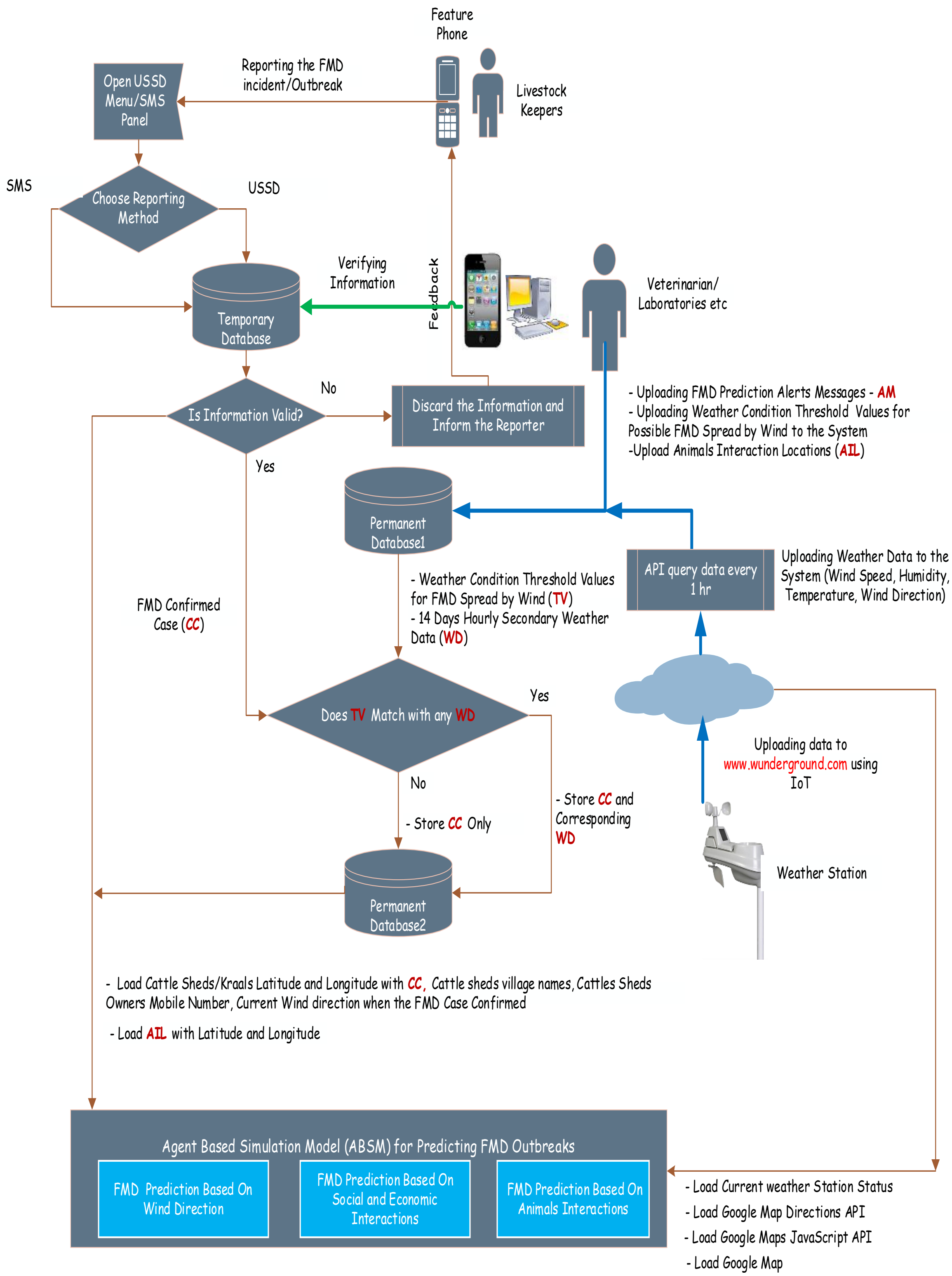


Figure 22: Agent-based-simulation model data gathering process

The ABSM predicts FMD outbreaks based on daily reported FMD valid cases; however, by specifying the starting and ending dates in the "filter events by date" search box on the model interface, it is flexible enough to forecast FMD outbreaks based on secondary FMD valid cases (Fig. 23-25 & 27). The ABSM utilizes the data stored in the PDB1 and PDB2 to predict FMD outbreaks in the Gairo district in four ways: (a) based on the socio-economic interactions, (b) based on the wind direction, and (c) based on the animals’ interactions (d) A hybrid of the three FMD prediction mechanisms.

(i) Foot and Mouth Disease Prediction based on the Socio-Economic Interaction

The model forecasts FMD outbreaks based on social and economic interactions in Kilama, Chogoali, Chakwale, Kilimani, Gairo town, and Ibuti, six villages in the Gairo district. Furthermore, the model assumed that fomite objects (that can carry and transmit FMD virus) like villagers are free to move between the villages. Therefore, during FMD outbreaks, fomite items may spread the FMD virus from FMD-infected villages to healthy villages. The ABSM predicts the FMD based on socioeconomic interactions in the following steps: First, the model loads all cattle sheds/kraals (disc images) on the spot map based on their latitude and longitude information provided in the system during the livestock keepers registration procedure (Fig. 44). Next, the model assumes that all cattle sheds/kraals are healthy and indicates them on the map with a green colour (Fig. 9 & 26).

Whenever the FMD case is confirmed, the Model updates the cattle shed/kraal on the map to a red colour, indicating that it is FMD affected and noting its village name and all nearby villages (Fig. 23 & 26). The model then uses the Google map Directions API and Maps JavaScript API to predict FMD outbreaks by socio-economic interaction by tracing (drawing) on the map all possible FMD distribution channels that could be utilized by fomite objects when moving through surrounding villages via driving, bicycling, and walking. The Google map Directions API and Maps JavaScript API have the capability (built-in functionalities) to determine and draw on the map all possible road channels connecting two points through driving, bicycling, and walking (Fig. 23 & 26). Then the model identifies all cattle sheds/kraals in the reporter and surrounding villages and changes them to pink, suggesting they are at risk. Simultaneously, the model sends SMS and Robocalls to the livestock owners notifying them of the outbreaks, naming the affected village, and outlining the essential precautions to reduce the disease's impact (Fig. 26).

In addition, the model marks all cattle sheds with unconfirmed FMD case reports with a blue disc on the spot map. However, where both unconfirmed and confirmed FMD cases concurrently appeared in the same cattle shed/kraal, the model indicates them with red and blue discs simultaneously; however, the blue disc will be bouncing on top of the fixed red disc. Finally, the model displays the FMD scenarios statistics on its right-hand side panel (Fig. 23).

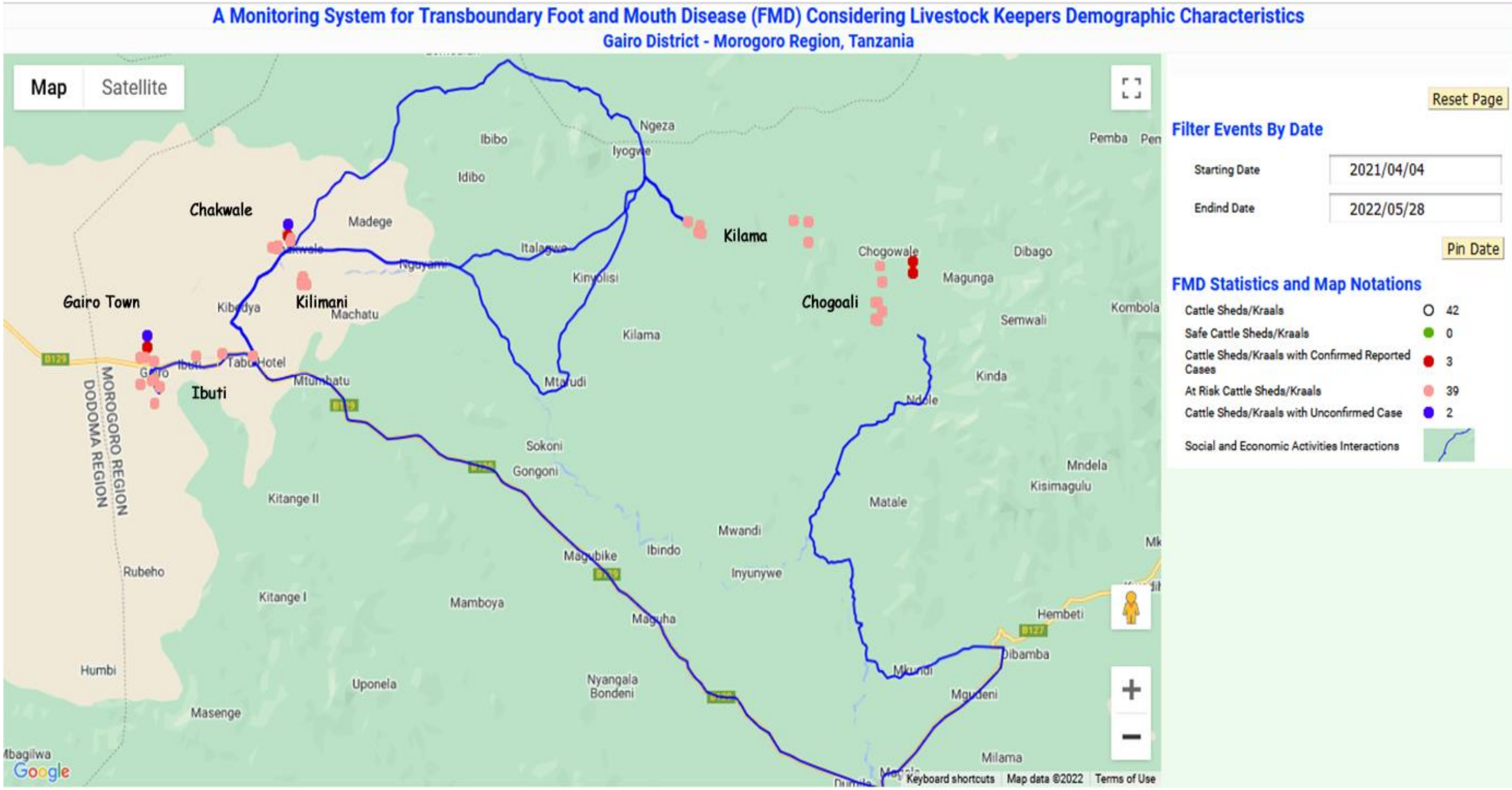


Figure 23: Foot and mouth disease prediction based on the social and economic activities interactions (Google, 2022)

(ii) Foot and Mouth Disease Prediction based on the Wind Direction

The model forecasts FMD outbreaks based on wind direction in Kilama, Chogoali, Chakwale, Kilimani, Gairo town, and Ibuti, villages in the Gairo district. The FMD prediction by wind direction considers all FMD valid cases that met the criterion for FMD aerosol transmission (the favourable meteorological conditions) when they are reported to the system. The model performs FMD prediction by wind direction in the following steps. First, the model loads all cattle sheds/kraals (disc images) on the spot map based on their latitude and longitude information provided in the system during the livestock keepers registration procedure (Fig. 44). Next, the model assumes that all cattle sheds/kraals are healthy and indicates them on the map with a green colour (Fig. 9). The model then updates the colour of all cattle sheds that fulfilled the criteria for FMD aerosol transmission to red, with a red arrow pointing in the direction of the wind (Fig. 24). If multiple FMD valid cases are submitted to the system after the wind changes direction, multiple arrows may point in various directions for a single cattle shed/kraal.

The model then detects all downwind cattle sheds by computing the bearing angle between the infected cattle shed/kraal and each downwind cattle shed/kraal (Appendix 7). For instance, when the wind blows 91 degrees from the infected cattle shed/kraal, the model deems it an East direction because it falls between $67.6^{o}$and 112.5^{o} (East) on the 8-compass rose (Fig. 10). Therefore, the model concludes that any livestock sheds/kraals positioned between 67.6^{o} and 112.5^{o} on the eight-point compass rose are downwind of the infected ones.

The model calculates the distance between the infected cattle shed/kraal and each downwind cattle shed/kraal to identify at-risk cattle sheds/kraals (Fig. 24; Appendix 7). If the downwind cattle shed / kraal is at an acceptable distance from the infected cattle shed / kraal, the model considers it at-risk and updates it on the map to pink (Fig. 24 & 26).

Finally, the model broadcasts SMS and Robocalls to all at-risk cattle sheds/kraals owners informing the outbreak and necessary precaution measures to minimize the disease impact (Fig. 26). At the same time, the model indicates all cattle sheds with FMD unverified reported cases by the blue disc on the spot map. However, where both unconfirmed and confirmed FMD cases concurrently appeared in the same cattle shed/kraal, the model indicates them with red and blue discs simultaneously; however, the blue disc will be bouncing on top of the fixed red disc. Finally, the model displays the FMD scenarios statistics on its right-hand side panel (Fig. 24).

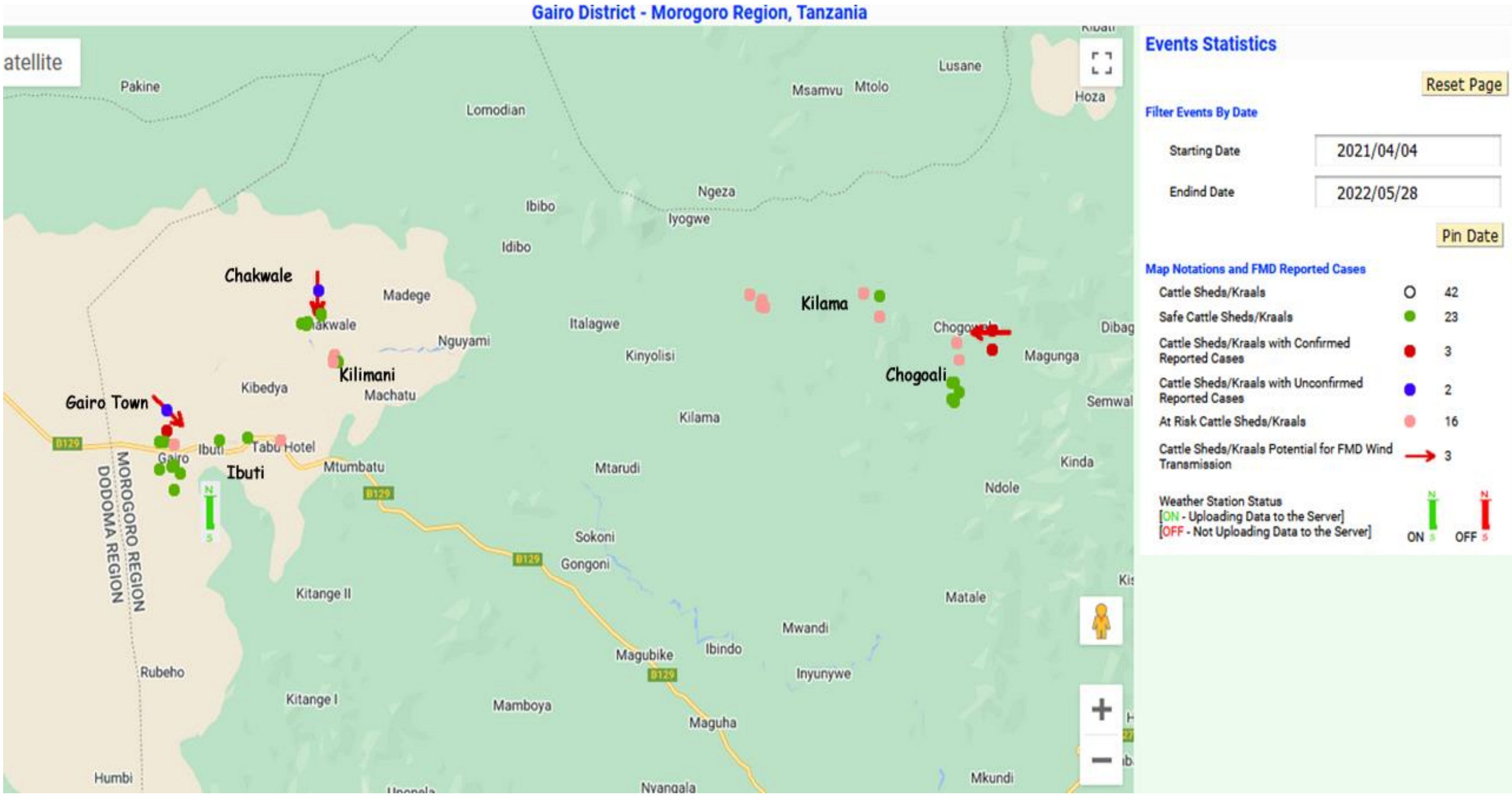


Figure 24: Foot and Mouth Disease prediction by wind direction (Google, 2022)

(iii) Foot and Mouth Disease Prediction based on the Animals' Interaction Location

The model forecasts FMD outbreaks based on animals' interactionin Kilama, Chogoali, Chakwale, Kilimani, Gairo town, and Ibuti, villages in the Gairo district. The model predicts FMD based on the animal's interaction because the Gairo district has various locations where animals come into contact for different purposes. These locations include livestock markets, shared livestock drinking water points, shared livestock grazing areas, and livestock loading ramps. At these locations, FMD-infected animals from FMD-infected villages may transmit FMD to the healthy animals when they contact or share resources like water and feeding facilities. In addition, FMD can also be transferred to the health villages when FMD-infected animals are purchased from the market. Similarly, villagers may transmit FMD to their villages if they contaminate the FMD virus at the animals' interaction points. As a result, the model can predict the disease's direction after an FMD outbreak in a specific village.

First, the model loads all cattle sheds/kraals (disc images) on the spot map based on their latitude and longitude information provided in the system during the livestock keepers registration procedure (Fig. 44). Next, the model assumes that all cattle sheds/kraals are healthy and indicates them on the map with a green colour (Fig. 9). Next, the model loads all of the animals' interaction places on the spot map using the latitudes and longitudes data recorded in the system during the registration of the animals' interaction sites (Fig. 47). In addition, the model assumes that all animal contact places are safe and marks them on the spot map with black squares (Fig. 9).

When livestock keepers report a valid FMD case to the system, the model updates his cattle shed/kraal to red colour on the spot map and notes his village name (Fig. 25). The model then updates all shared animal interaction areas used by the FMD-infected village to violet, suggesting that they are at risk (Fig. 25). Similarly, to forecast the disease direction, the model identifies all villages that share an interaction location with the FMD-infected village and changes their cattle sheds/kraals on the map to a pink colour, suggesting they are at risk. Similarly, it does to the reporter village, excluding the FMD-infected cattle sheds.

Finally, the model uses the Maps JavaScript API function to plot the polyline on the map for all potential animal interactions, demonstrating how FMD can spread throughout villages from the focal sites (Google API, 2022).

In addition, the model sends SMS and Robocalls to all at-risk cattle shed/kraal owners, informing them about the outbreak and the essential precautions to reduce the disease's impact (Fig. 26). At the same time, the model indicates all cattle sheds with FMD unverified reported cases by the blue disc on the spot map. However, where both unconfirmed and confirmed FMD cases concurrently appeared in the same cattle shed/kraal, the model indicates them with red and blue discs simultaneously; however, the blue disc will be bouncing on top of the fixed red disc. Finally, the model displays the FMD scenarios statistics on its right-hand side panel (Fig. 25).

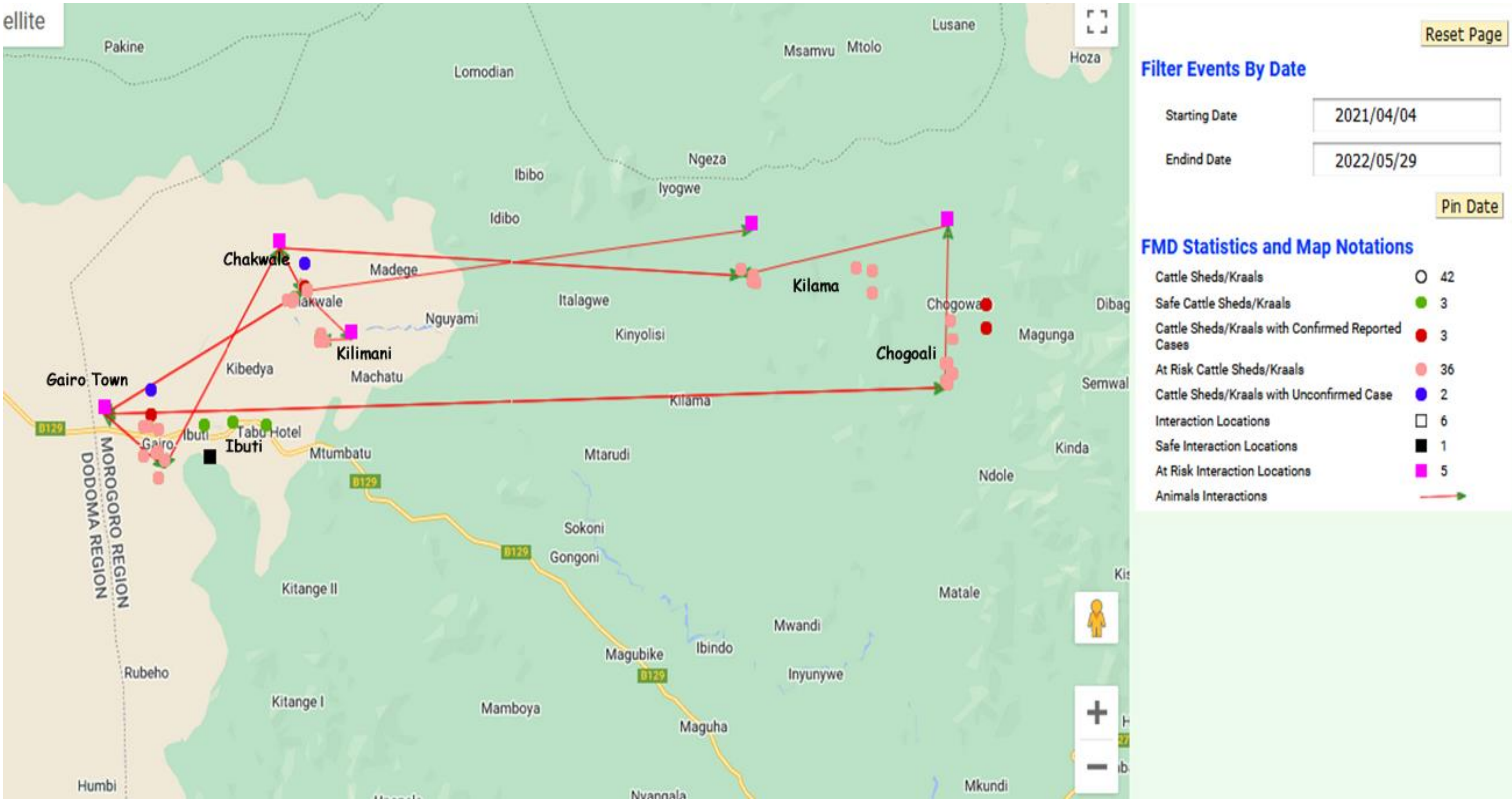


Figure 25: **Foot and Mouth Disease prediction based on the animals' interaction location (Google, 2022)**

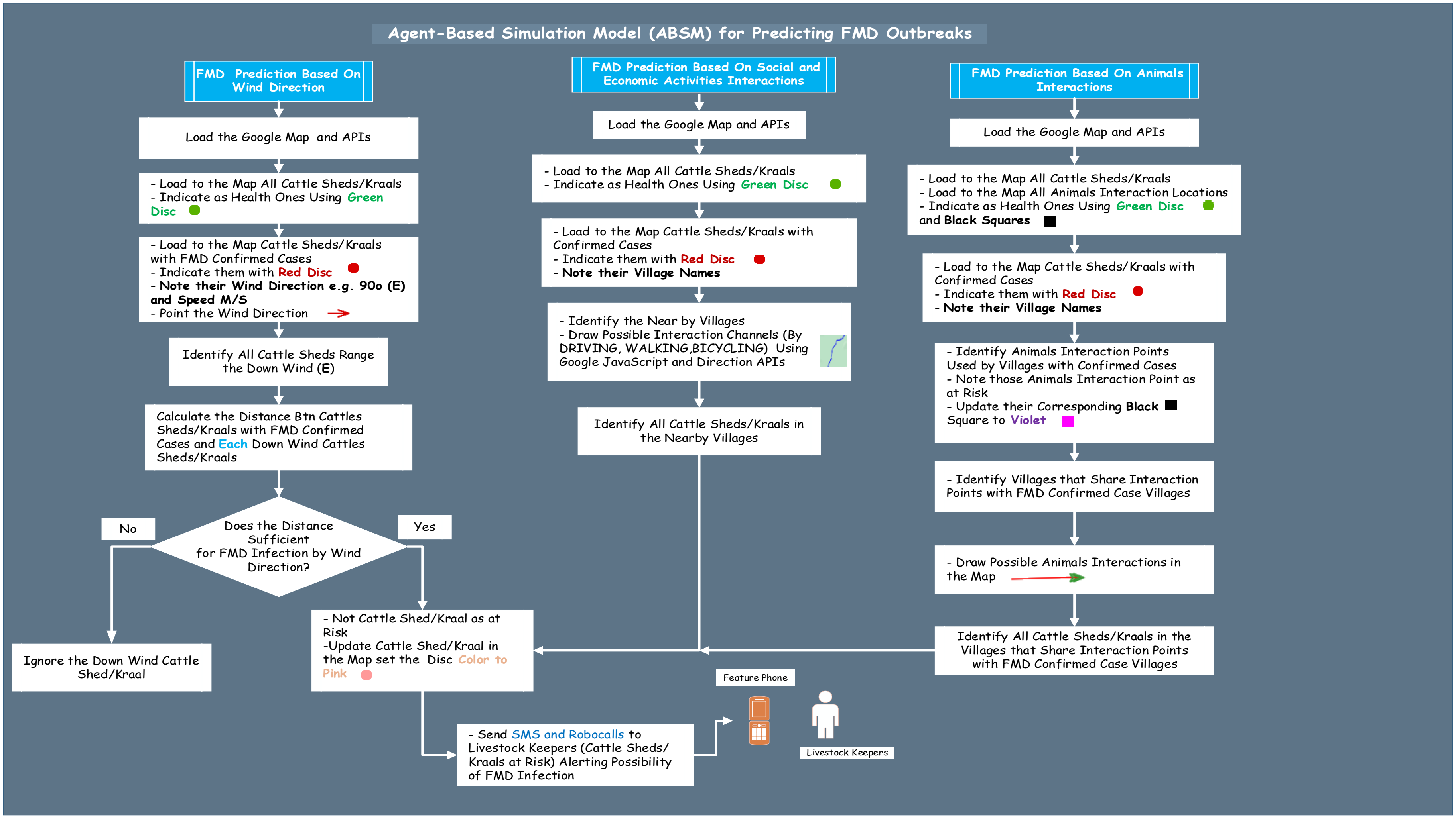


Figure 26: Agent-Based-Simulation Model Foot and Mouth Disease prediction process

(iv) A Hybrid of the three Foot and Mouth Disease Prediction Mechanisms

The ABSM allows users to observe all three FMD prediction mechanisms simultaneously, such as prediction based on socio-economic interactions, wind direction, and animal interactions (Fig. 27).

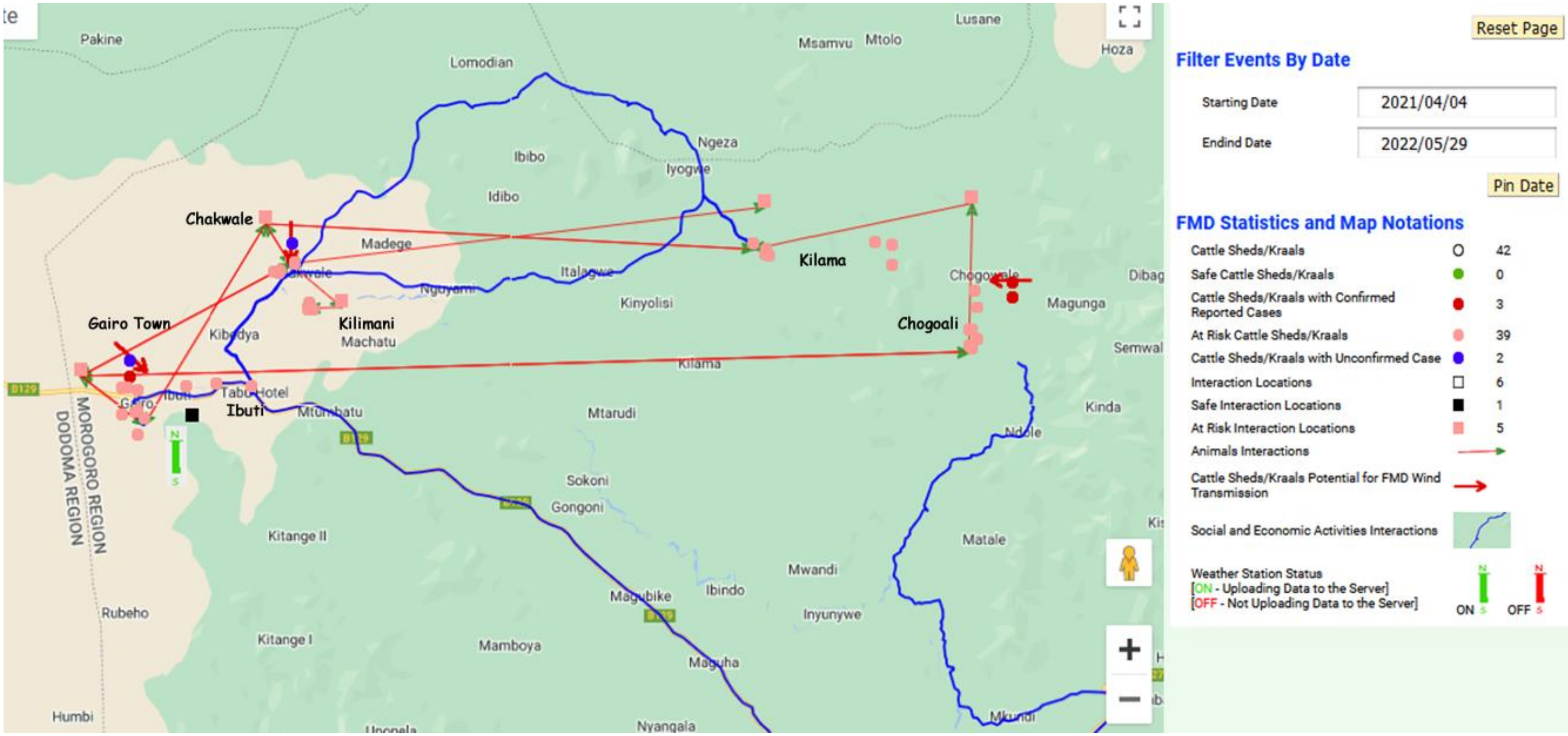


Figure 27: **A hybrid of the three FMD prediction mechanisms (Google, 2022)**

4.8 System Architecture

Generally, the system was developed using PHP hypertext processor, Jquery, HTML, MySQL database, Apache web server, JSON, and Javascript. The MySQL databases and Apache webserver were available by installing the XAMPP software package. The SMS/voice gateway software was installed to provide SMS and voice broadcast services (Fig. 28, 33 & 74). The SMS/voice Modem is attached to the server hardware via a USB port and connected to the SMS/voice gateway software through its settings menu (Fig. 28). The weather and USSD API enable communication between AMoS4T-FMD and third-party applications such as weather conditionsweb servers and cloud USSD servers (Fig. 28, 35-37, 39 & 40). Therefore the APIs provide weather data from the Gairo district and USSD services to the AMoS4T-FMD. Apart from the third-party hardware and software, the AMoS4T-FMD generally comprises four modules named: (a) General Settings Module, (b) FMD communication Module, (c) FMD Outbreaks Prediction Module and (d) Security Module (Fig. 28-31). One may use the scrollable left-hand side panel to navigate the modules after logging into the system home page (Fig. 31 & 32). The user may navigate the modules by clicking their menus (Fig. 32). The user logged in to the system by providing the username and password on the system login page (Fig. 29). All users should first be registered to the system based on their privileges assigned by the system administrator (Fig. 56-58).The system administrator also gives the user a username and temporary password, which could be changed after logging in to the system (Fig. 58). In the next section, the system components description section, all system components have been explained in detail.

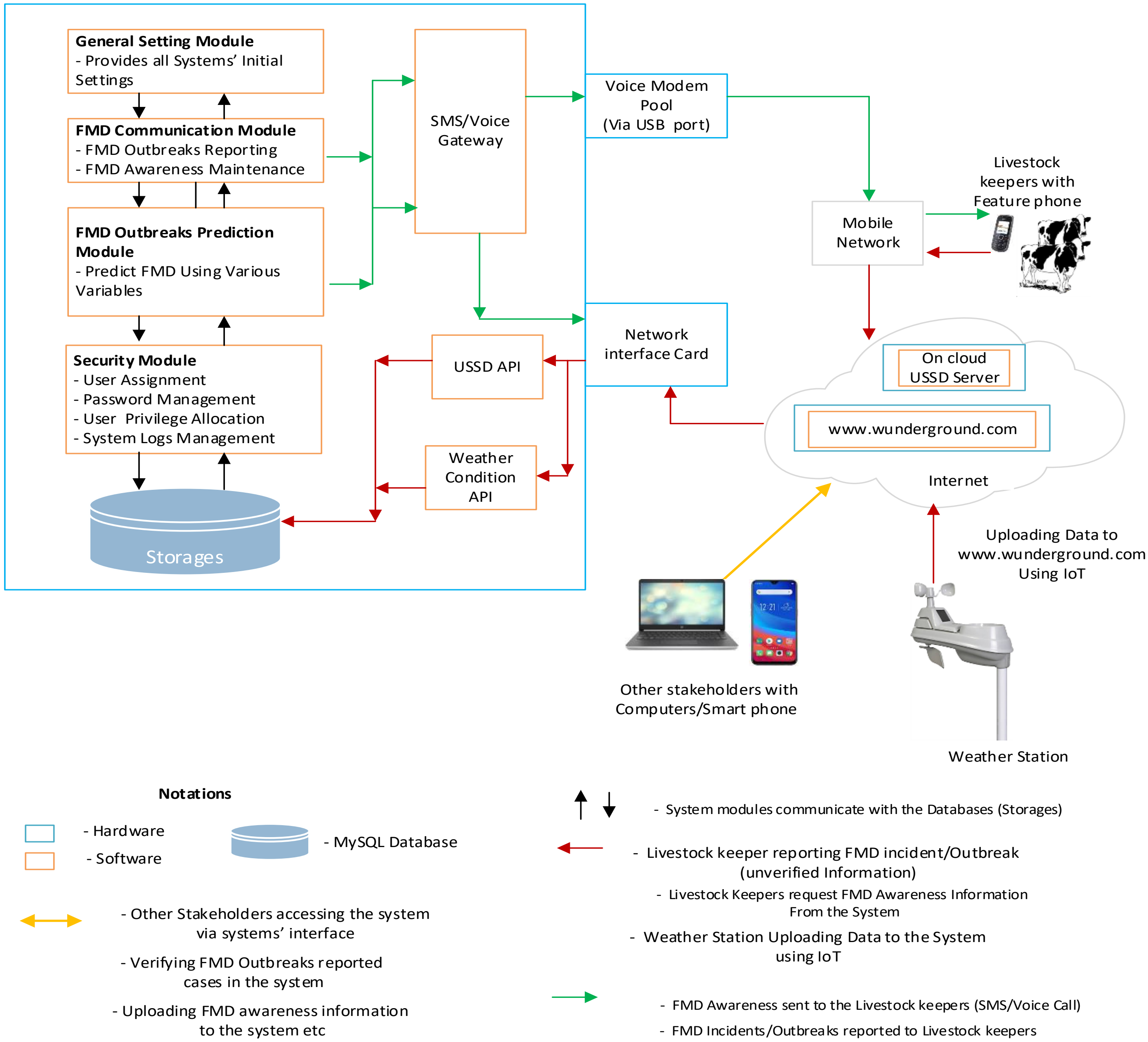


Figure 28: **System architecture**

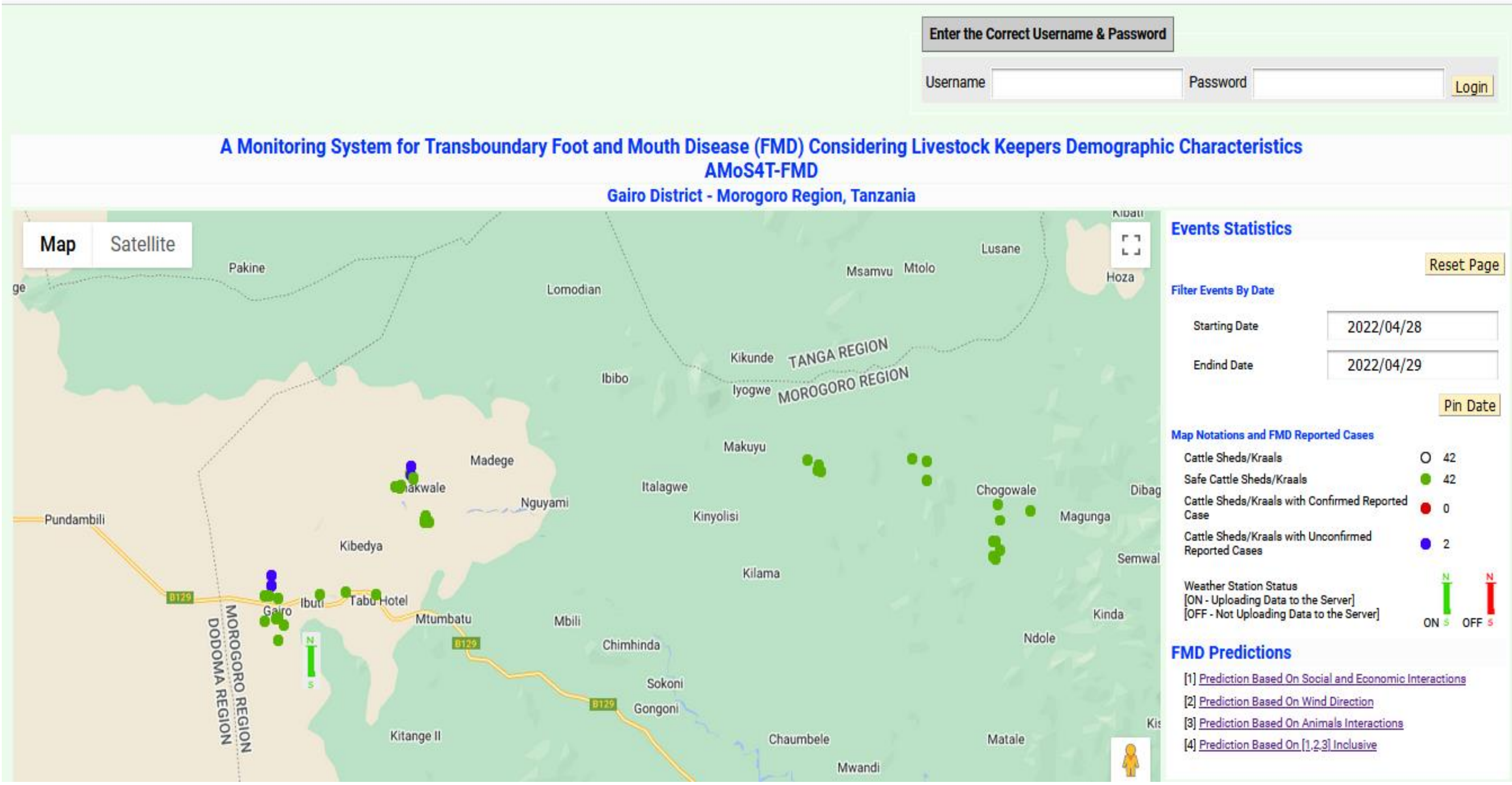


Figure 29: **System login page**

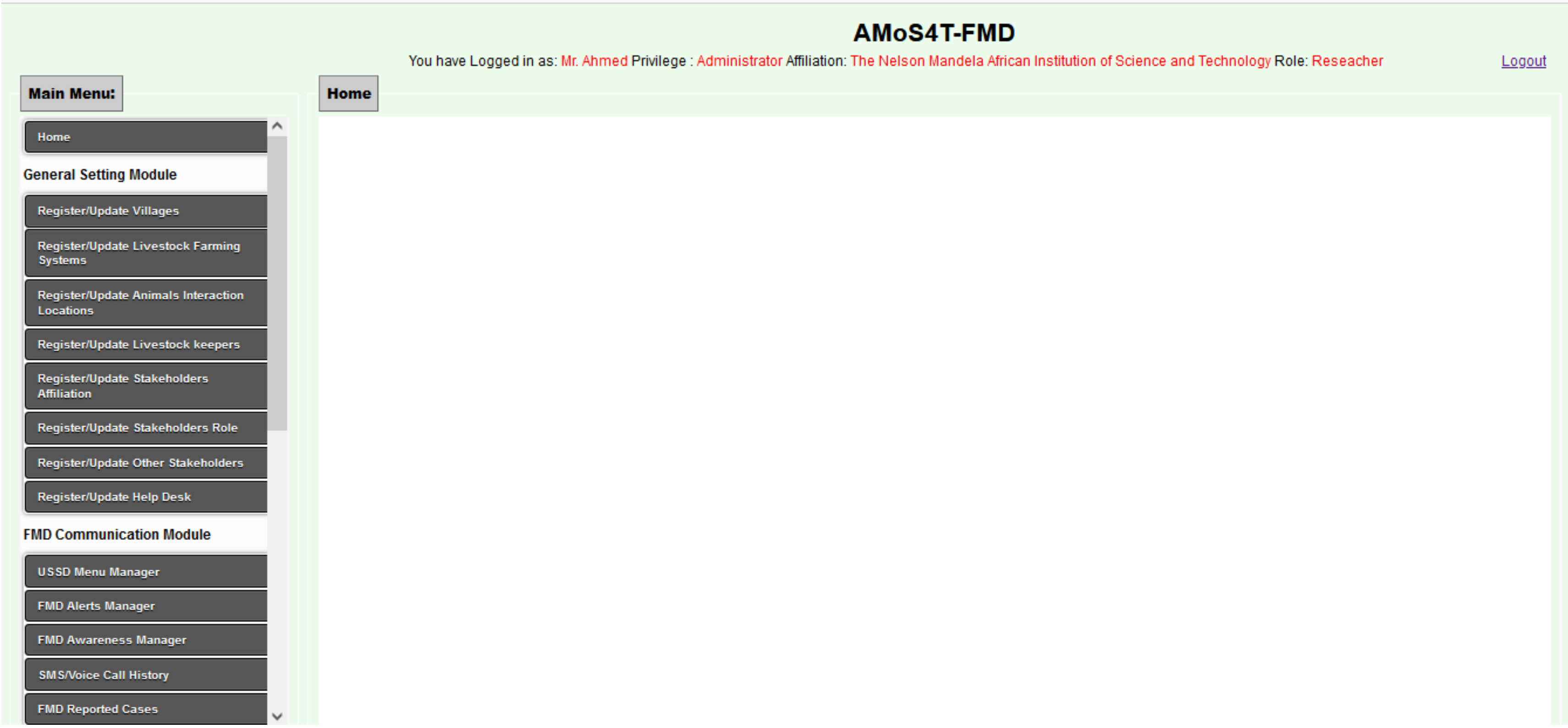


Figure 30: System home page with modules and menus lists

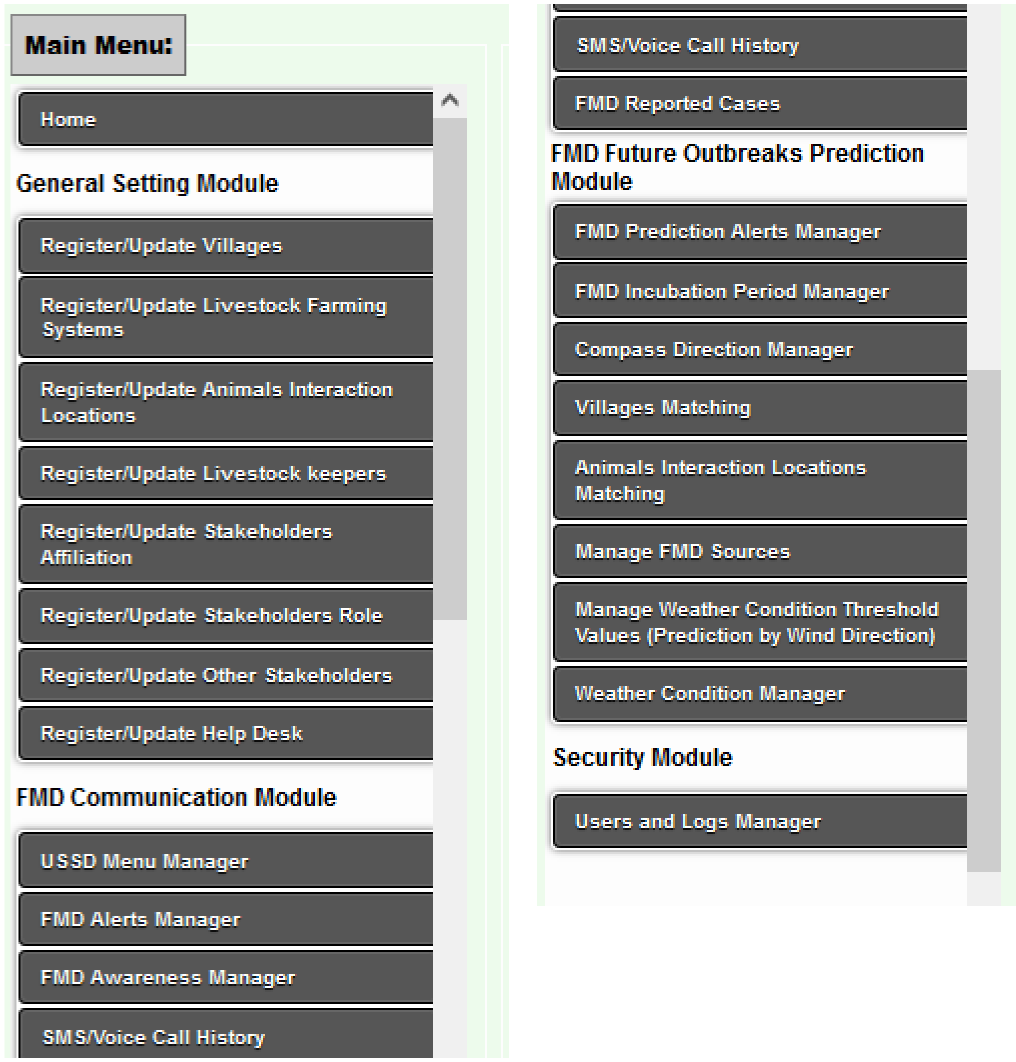


Figure 31: **System modules and menus list**

4.8.1 System Components Descriptions

(i) SMS/Voice Gateway and Voice Modem Pool

The 3G SIMCOM modem pool with 4 ports was used to broadcasts SMS and voice calls (Robocalls) to livestock keepers using the SMS/Voice gateway software (Shenzhen Antecheng Technology Co., Ltd. 2022). The SIMCOM modems, unlike other modems, have permanent memory storage for storing audio files in (.wav) format and are capable of executing “AT” commands. The SIMCOM modem can broadcast SMS and voice due to this unique feature, unlike other modems that only broadcast SMS. However, any modem with the features of the SIMCOM modem can be used for a similar task. The SIMCOM modem was attached to the server via the USB portto broadcast SMS and Robocalls (Shenzhen Antecheng Technology Co., Ltd. 2022).

The SMS/voice gateway software known as SMSDeliverer was used broadcast the intended messages with the help of SIMCOM modem (SMS Deliverer, 2022). Through the gateway Add/Edit Connection menu, the SMSDeliverer bridge the 3G SIMCOM and permanent database 1([PDB1] MySQL database), which is a part of AMoS4T-FMD (Fig. 28 & 32). As a result, it connects the SIMCOM modem and AMoS4T-FMD.

The FMD awareness (precaution measures, negative impacts, clinical symptoms, transmission pathways, outbreaks, and predictions) and FMD outbreaks alert pre-recorded audio files were uploaded to the modem using SMS/voice gateway to broadcast Robocalls (Fig. 33). However, their file names were uploaded to the system (PDB1) using the FMD alerts manager and FMD awareness manager menus in the FMD Communication module (Fig. 50 & 51). After that, the SMS/Voice gateway broadcasts the audio files to livestock keepers as Robocalls by referring to their names in the PDB1(Fig. 17). The system automatically broadcasts information as Robocalls alerts whenever FMD outbreaks are reported to the system by livestock keepers (Fig. 50 & 51). Similarly, the system periodically broadcast information as Robocall FMD awareness based on the time interval indicated when registering the file name to the system (Fig. 50 & 51).

On the other hand, the system broadcasts FMD awareness and alerts in SMS by referring to their corresponding description in the PDB1(Fig. 17, 50 & 51). Similarly, the “FMD alerts manager" and "FMD awareness manager" menus were also used to upload text descriptions to the system, like the audio files. The SMSDeliverer provides the option to upload the new audio file or update the existing ones in the SIMCOM modem through the “voice setting menu” (Fig. 32 & 33).

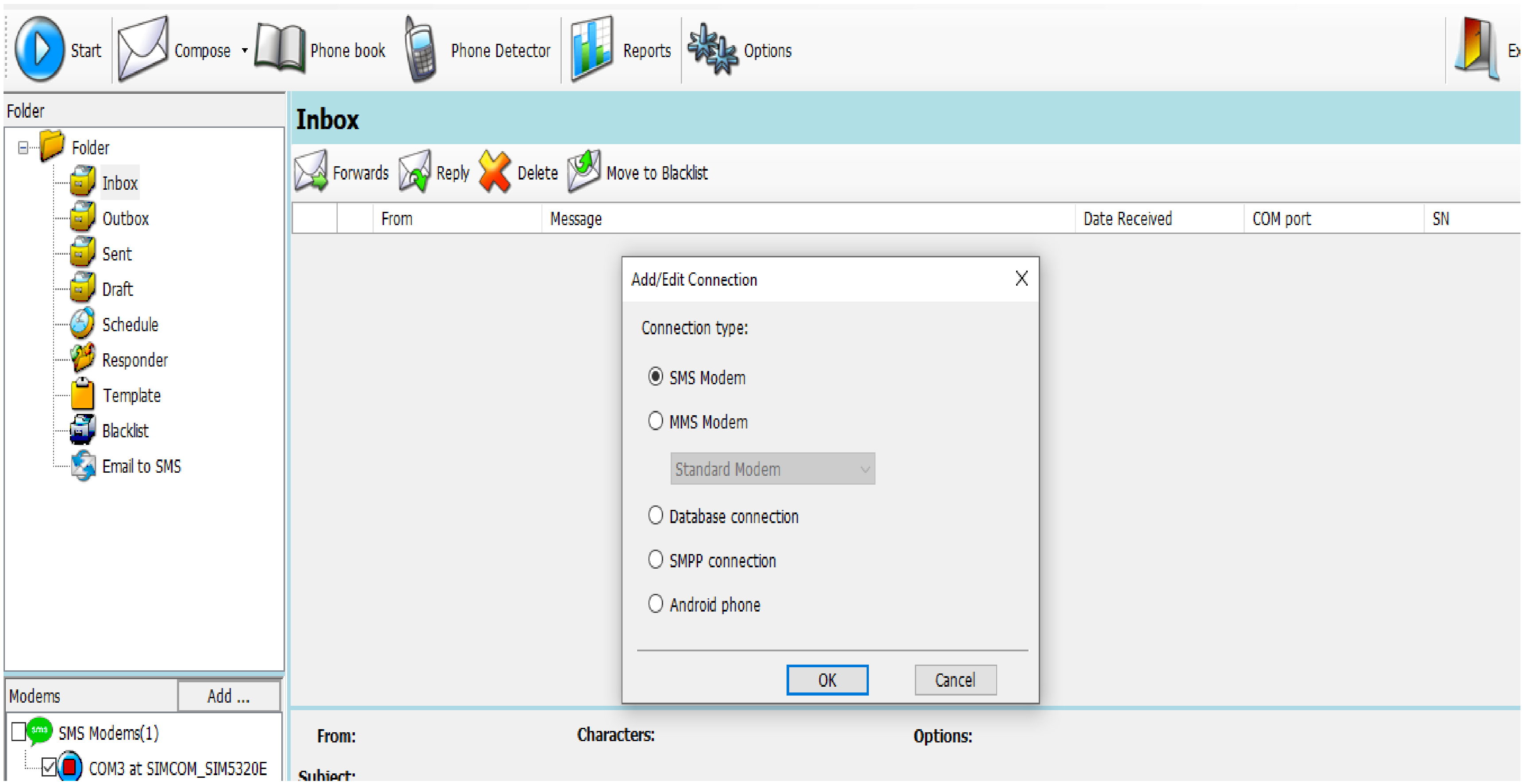


Figure 32: Connecting SMS/Voice gateway with MySQL database and voice modem (SMS Deliverer, 2022)

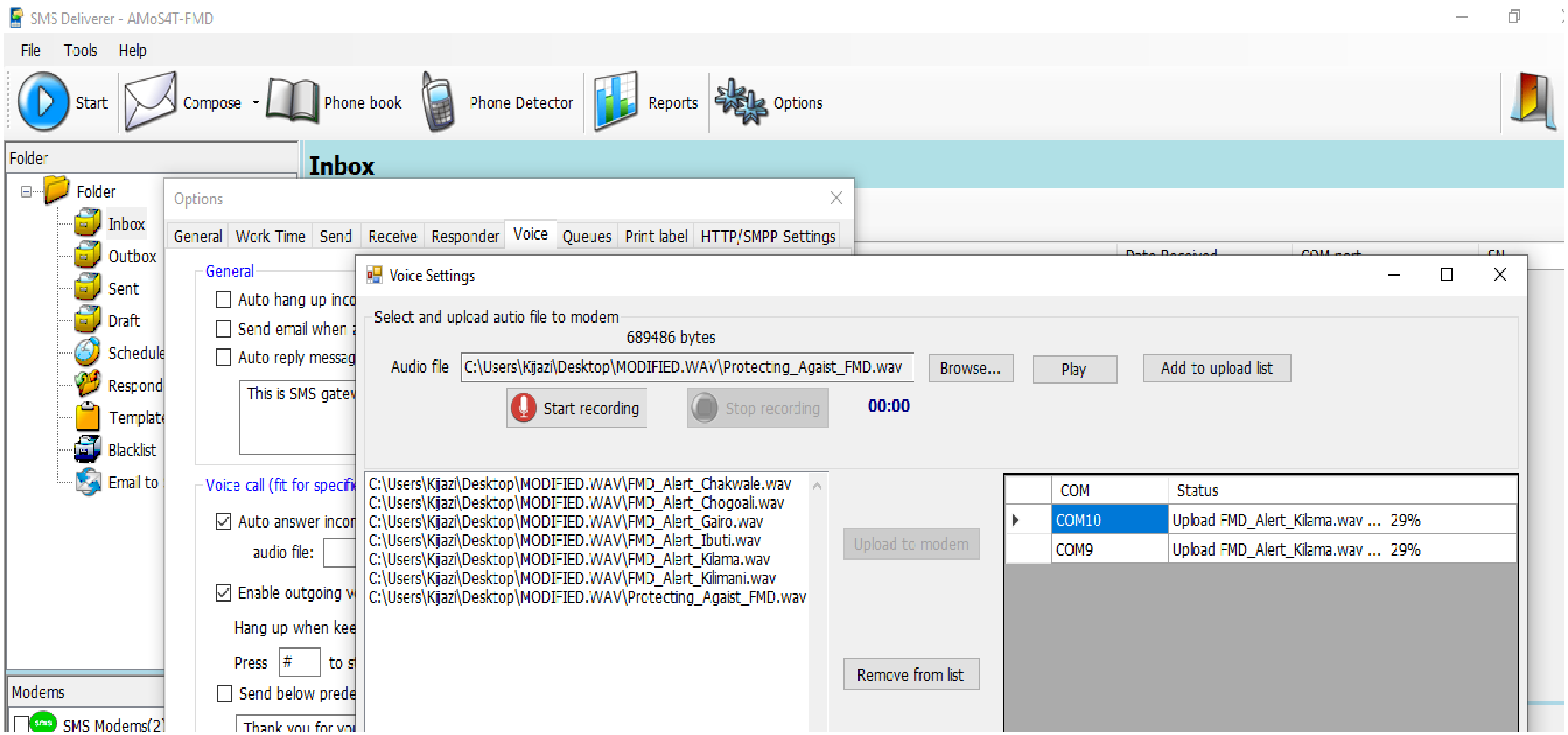


Figure 33: Storing/uploading an audio file to the voice modem using voice gateway software (SMS Deliverer, 2022)

(ii) Feature Mobile Phones

The feature mobile phones enable communication between livestock keepers and AMoS4T-FMD. The system periodically broadcasts FMD-related information in SMS and Robocalls to livestock keepers feature mobile phones. Livestock keepers also may report FMD outbreaks to the system by sending the number of FMD suspected cattle to a particular mobile number of Simcard of a SIMCOM modem or using the USSD menu (Fig. 31 & 32).

(iii) Unstructured Supplementary Service Data Application Program Interface

The USSD code for providing USSD services in AMoS4T-FMD was obtained from the vendor (Africa's Talking, 2021).The provider offers access to an online control panel called sandbox for setting the USSD code service when you subscribe to the USSD code service)(Africa's Talking, 2021; Fig. 34). Users must configure the service code (USSD code) and callback URL, the HTTP route pointing to the AMoS4T-FMD API file, in the sandbox (Fig. 34; Appendix 4). A callback URL connect the vendor's online USSD server and AMoS4T-FMD through the API. For example, Fig. 34 indicates the sandbox control panel configured with the USSD code (*384*90005#), and the callback function point to the API file (USSD.php) hosted in the AMoS4T-FMD server configured with the public Internet Protocol(IP) address 41.59.85.218. The livestock keepers may access the USSD menu by dialling a specific USSD code, e.g. *384*90005#. The USSD menu enables livestock keepers to report FMD outbreaks to the system using option number 1 by sending the number of FMD suspected cattle to the AMoS4T-FMD (Fig. 53).

The USSD menu also allows livestock keepers to request FMD awareness information from AMoS4T-FMD by selecting options 2-5 (Fig. 55) of the USSD menu. Upon the sending, the number of FMD suspected cattle or accessing a particular FMD awareness, the option numbers and the number of suspected cattle initially are stored on the on-cloud vendor USSD server (Fig. 34). Then the USSD API downloads the option number, and the number of FMD suspected cattle from the vendor USSD server and stores them in the AMoS4T-FMD MySQL database (Fig.18 & 34). The meaning of each option number prior has already been translated and registered in the AMoS4T-FMD through the USSD menu manager available in the FMD communication module (Fig. 54). Therefore the system will understand them upon imported into the database (Fig. 18**)**.

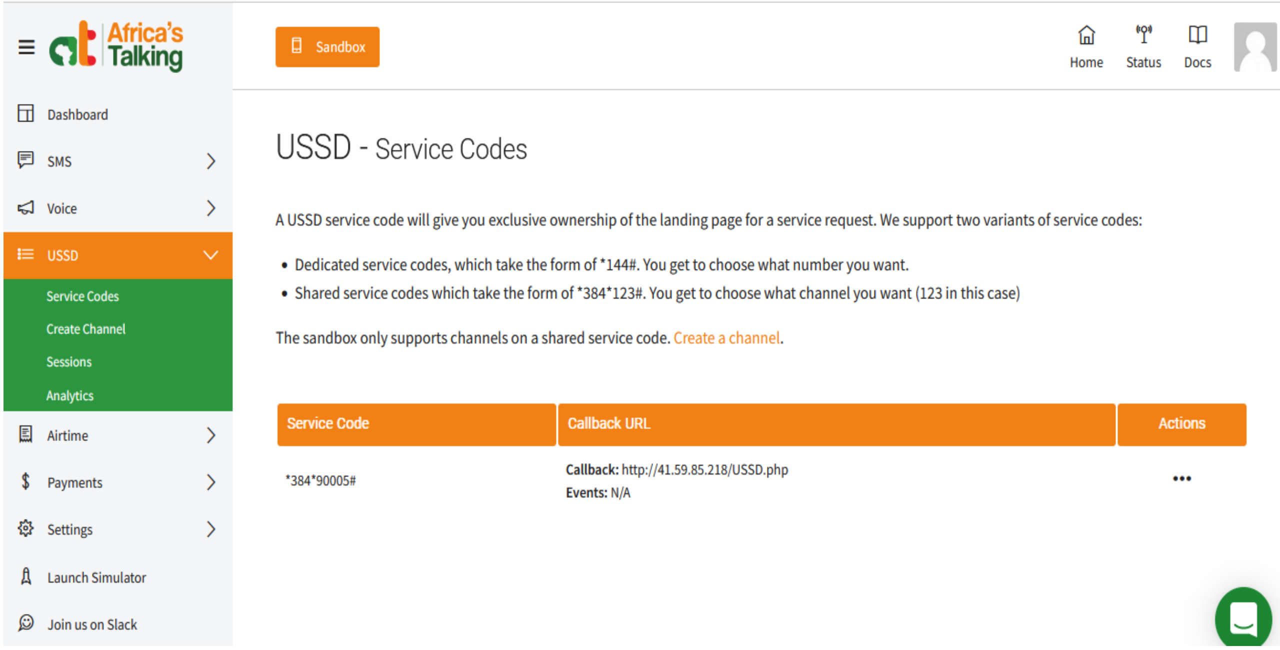


Figure 34: Vendor's USSD service configuration panel (Africa's Talking, 2021)

(iv) Weather Station and Weather Condition Application Program Interface

Since the wind movement can also transmit FMDunder favourable weather conditions, the Misol professional WCDMA/GSM weather station was installed at the Gairo district head office for capturing and uploading weather data to the AMoS4T-FMD via the Internet of Things (IoT)(Misol, 2022). The weather data was used to develop the FMD outbreaks prediction by wind partition in the FMD outbreaks prediction module. The Solar panel, outdoor sensor array, inside sensor, and receiver control unit are the four different components (devices) that make up the weather station (Fig. 35a). The outdoor sensor array is a device including multiple sensors, such as a thermo-hygro sensor, wind speed sensor, ultraviolet sensor, light sensor, and a rain collector (Fig. 35c). Rechargeable batteries power the receiver control unit and outdoor sensor array, whilst the indoor sensor is powered by non-rechargeable batteries.

The weather station components (a)

Solar panel installation (b)

Outdoor sensor array installation (c)

Receiver and indor sensor installtion (d)

Figure 35: Weather station installation at the Gairo district headquarter

The solar panel is used to recharge the receiver through the power cable connecting the solar panel and the receiver (Fig. 35b, 35d & 36). However, the outdoor sensor array's integrated solar panel allows for its recharging (Fig. 35a).

The weather station was installed at the Gairo district council office to protect it from theft for safety reasons. The indoor sensor is mounted on the wall inside the office to protect it from rainwater.The outdoor sensor array was mounted on the iron post outside the Gairo district council office.

Similarly, the solar panel unit was cramped and mounted on the rooftop of the office building to absorb the maximum solar radiation (Fig. 35a-c).

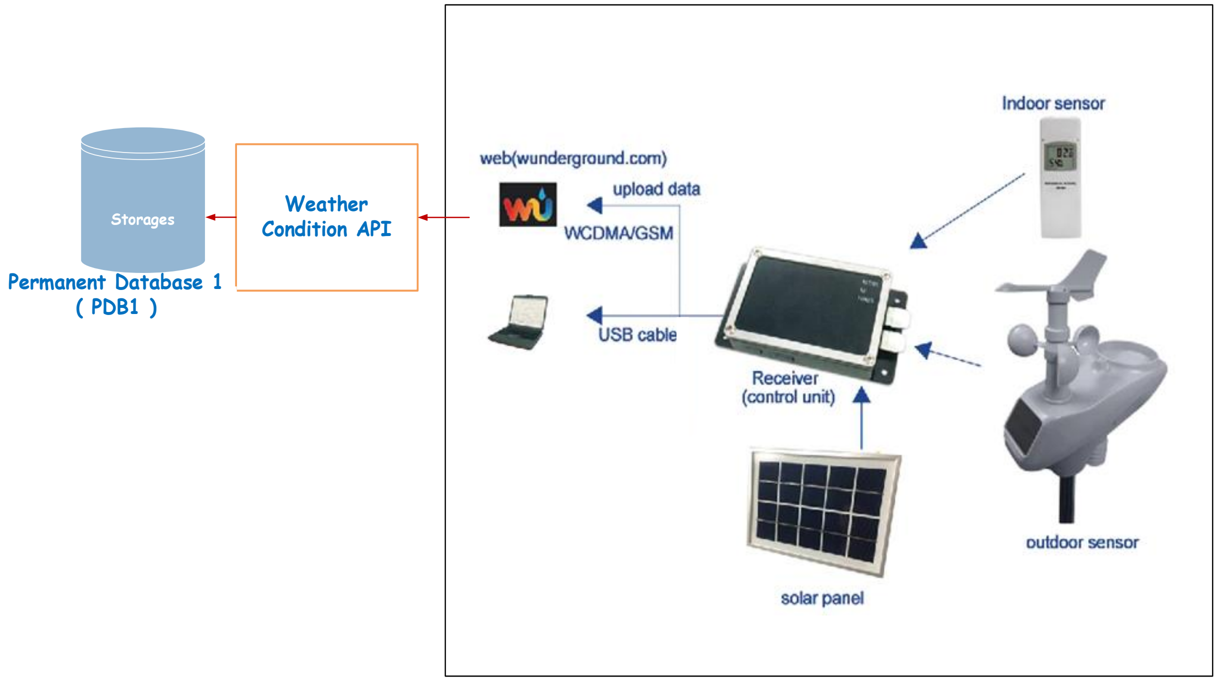


Figure 36: The weather condition data uploading process in AMoS4T-FMD (Misol, 2022)

Before uploading to the AMoS4-FMD, the weather station uploads data to an internet web server named weather underground (Weather underground, 2022; Fig. 28, 36-40). Then the weather condition API in AMoS4T-FMD periodically queries/downloads the weather data from an online web server and stores it in the PDB1(Fig. 19, 28 & 36; Appendix 6). The weather station software named weather logger used with the weather station provides the option for configuring the device for uploading data to an online web server (Fig. 37). A weather logger is installed on the computer with the receiver unit connected to the USB port to configure the Weather station.

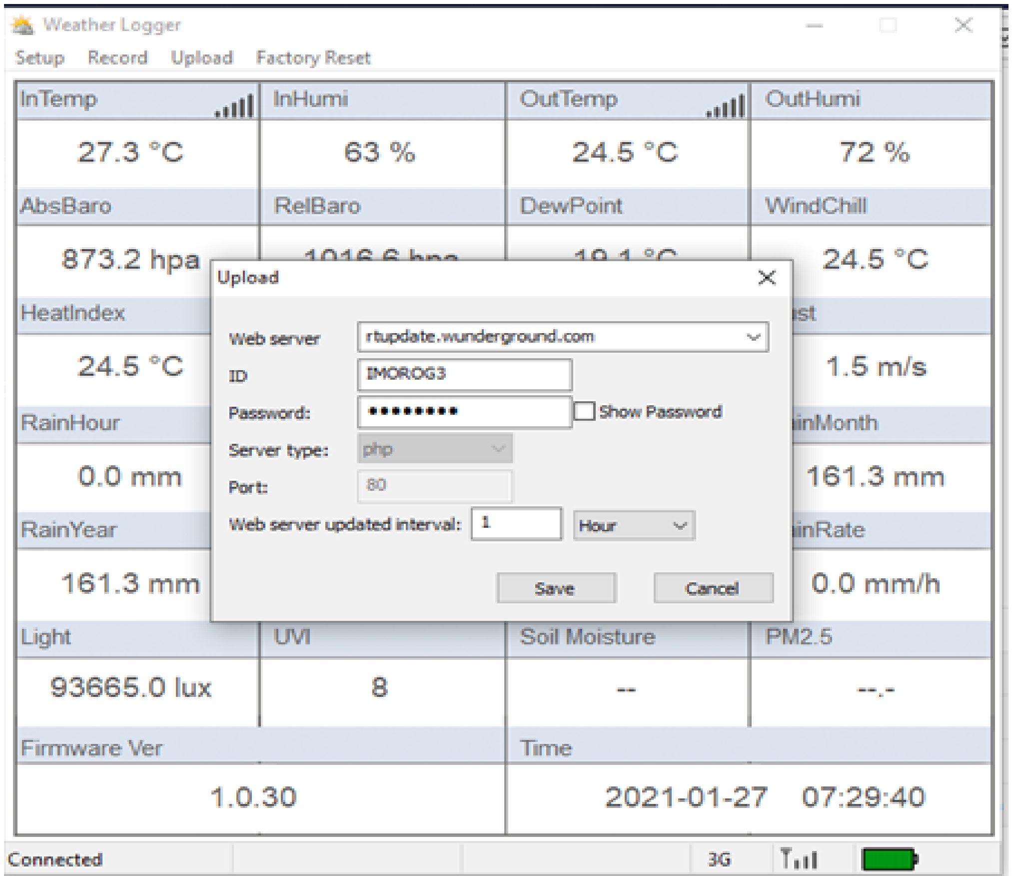


Figure 37: Connecting weather station to the web server using weather logger software (Misol, 2022)

The weather logger provides the option to enter settings such as web server domain name, weather station ID, web server login password and time interval for uploading data to the webserver. For example, Fig. 18 is a weather logger setting panel configured with the webserver name (rtupdate.wunderground.com), weather station ID (IMOROG3) and the password(indicated as asterisks). To obtain the weather station ID and login password, one should first register and login into an online webserver vendor website (Weather underground, 2022; Fig. 38 & 39). The user generates the weather station ID after login into the website (Fig. 38 & 39).

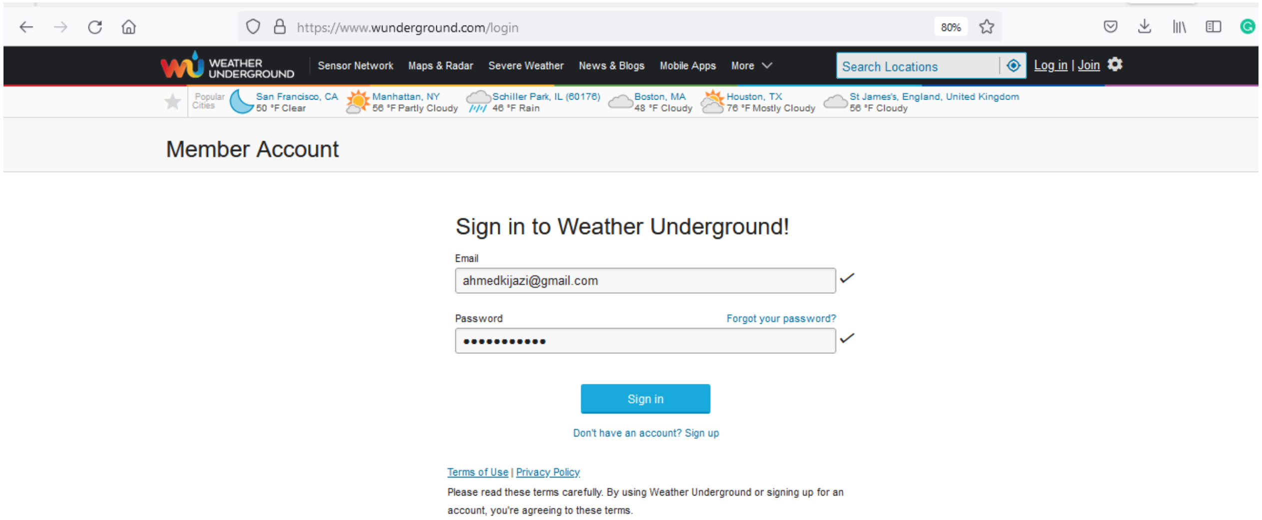


Figure 38: Web server vendor website login page (Weather underground, 2022)

Usually, the webserver owners either provide the webserver domain name on their websites or the user manual explaining the overall process of connecting weather stations and their web servers. However, this study utilized the wunderground.com website to connect weather stations regardless of many online websites (Weather underground, 2022; Fig. 36, 38-40).

The receiver unit is wirelessly connected to the indoor sensor and outdoor sensor array. The sensors capture weather condition parameters such as temperature, humidity, rain wind speed and wind direction and transfer data to the receiver control unit. The receiver periodically (based on the settings) uploads data to the wunderground.com server (Fig. 36 & 40). For example, Fig. 40 shows the Gairo district weather condition data hourly uploaded to the wunderground.com server on 6 November, 2020 by the receiver control unit. The receiver control unit is equipped with a prepaid SIM card connecting to the internet through the mobile network for uploading data.

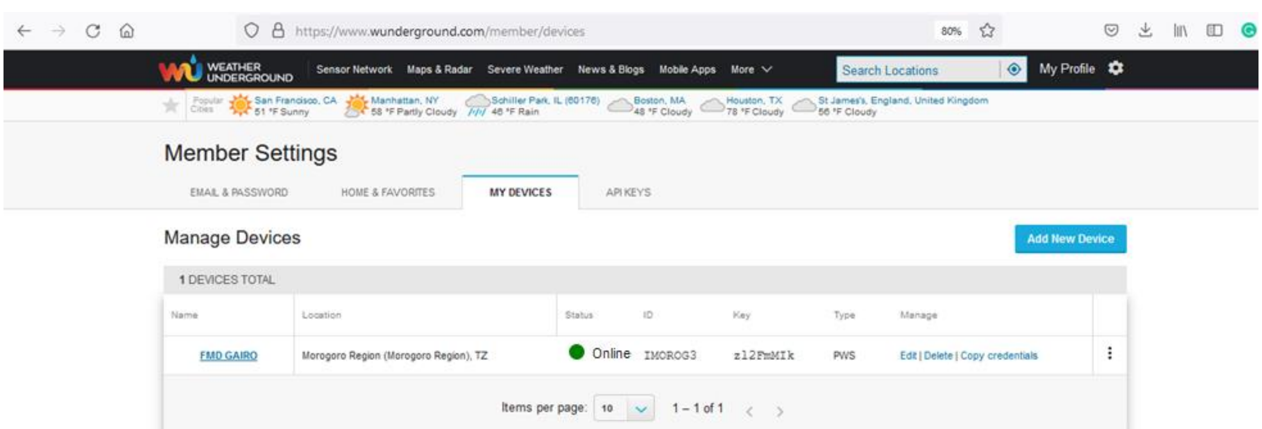
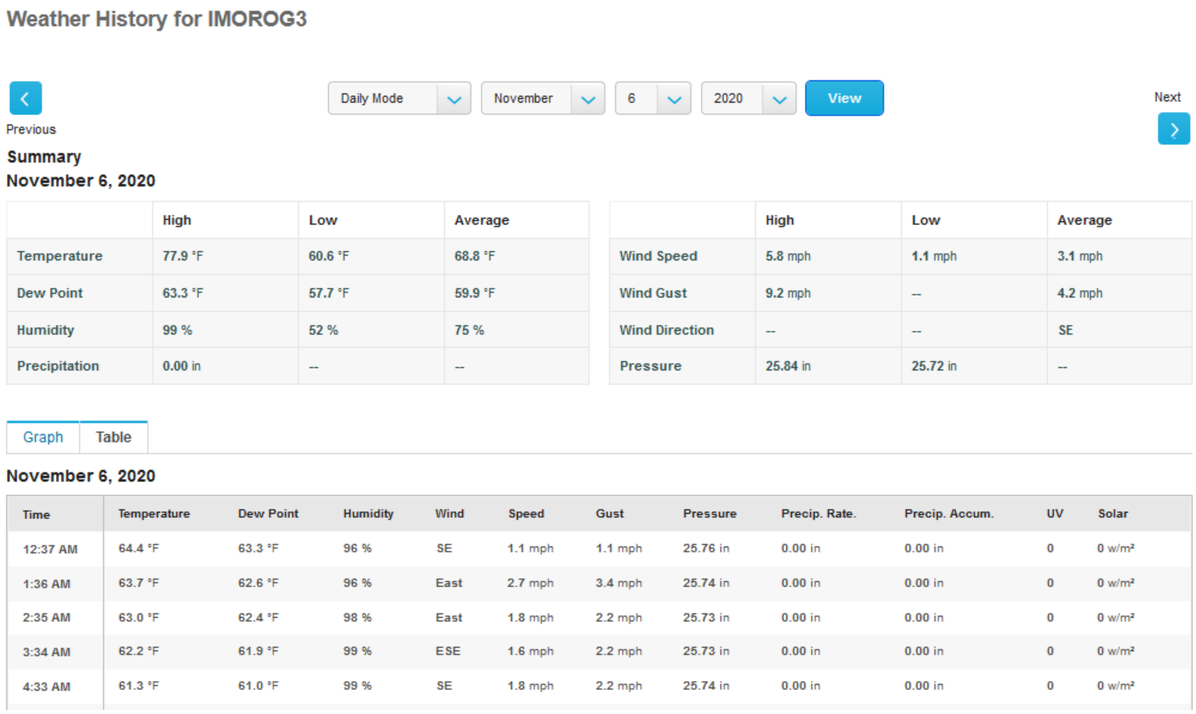


Figure 39: Web server vendor website control panel configured with weather station parameters (Weather underground, 2022)


Weather History for IMOROG3

Previous | Daily Mode | November | 6 | 2020 | View | Next

Summary
November 6, 2020

	High	Low	Average
Temperature	77.9 °F	60.6 °F	68.8 °F
Dew Point	63.3 °F	57.7 °F	59.9 °F
Humidity	99 %	52 %	75 %
Precipitation	0.00 in	--	--

	High	Low	Average
Wind Speed	5.8 mph	1.1 mph	3.1 mph
Wind Gust	9.2 mph	--	4.2 mph
Wind Direction	--	--	SE
Pressure	25.84 in	25.72 in	--

Graph | Table

November 6, 2020

Time	Temperature	Dew Point	Humidity	Wind	Speed	Gust	Pressure	Precip. Rate.	Precip. Accum.	UV	Solar
12:37 AM	64.4 °F	63.3 °F	96 %	SE	1.1 mph	1.1 mph	25.76 in	0.00 in	0.00 in	0	0 w/m²
1:36 AM	63.7 °F	62.6 °F	96 %	East	2.7 mph	3.4 mph	25.74 in	0.00 in	0.00 in	0	0 w/m²
2:35 AM	63.0 °F	62.4 °F	98 %	East	1.8 mph	2.2 mph	25.73 in	0.00 in	0.00 in	0	0 w/m²
3:34 AM	62.2 °F	61.9 °F	99 %	ESE	1.6 mph	2.2 mph	25.73 in	0.00 in	0.00 in	0	0 w/m²
4:33 AM	61.3 °F	61.0 °F	99 %	SE	1.8 mph	2.2 mph	25.74 in	0.00 in	0.00 in	0	0 w/m²

Figure 40: Weather condition data hourly uploaded to wunderground.com server by the receiver unit (Weather underground, 2022)

(v) Smartphones and Computers

Smartphones and computers enable veterinarians to verify the reported FMD outbreak information. Also, other stakeholders may use smartphones and computers to access the system because it is web-based.

(vi) General Settings Module

The General setting module provides the system's initial settings. Then, all data required for system operation was introduced into the system through the general setting module. The General setting module offers various menus such as the Register/Update livestock keepers, Register/Update villages, Register/Update animals interaction location, Register/Update other stakeholders and Register/Update stakeholders affiliation (Fig. 31). Not only that but also Register/Update stakeholders' roles and Register/Update the help desk (Fig. 31). Each menu provides data input for a particular system operation. However, some system operations depend on data from each other.

First, the General setting module's Register/Update other stakeholder’s menu allows the system administrator to register and update system users (top-level livestock stakeholders) such as Field, District, Regional, Zonal, and National Veterinarian officers, researchers, and VET laboratory personnel (Fig. 41). The system administrator adds users to the system by entering their information, such as their name, phone number, role, and affiliation. However, the stakeholder's role and affiliation lists are available after being registered from separate menus named Register/Update stakeholders role and Register/Update stakeholders affiliation (Fig. 42 & 43). Each user will be granted access to the system based on the privileges the system administrator has assigned.

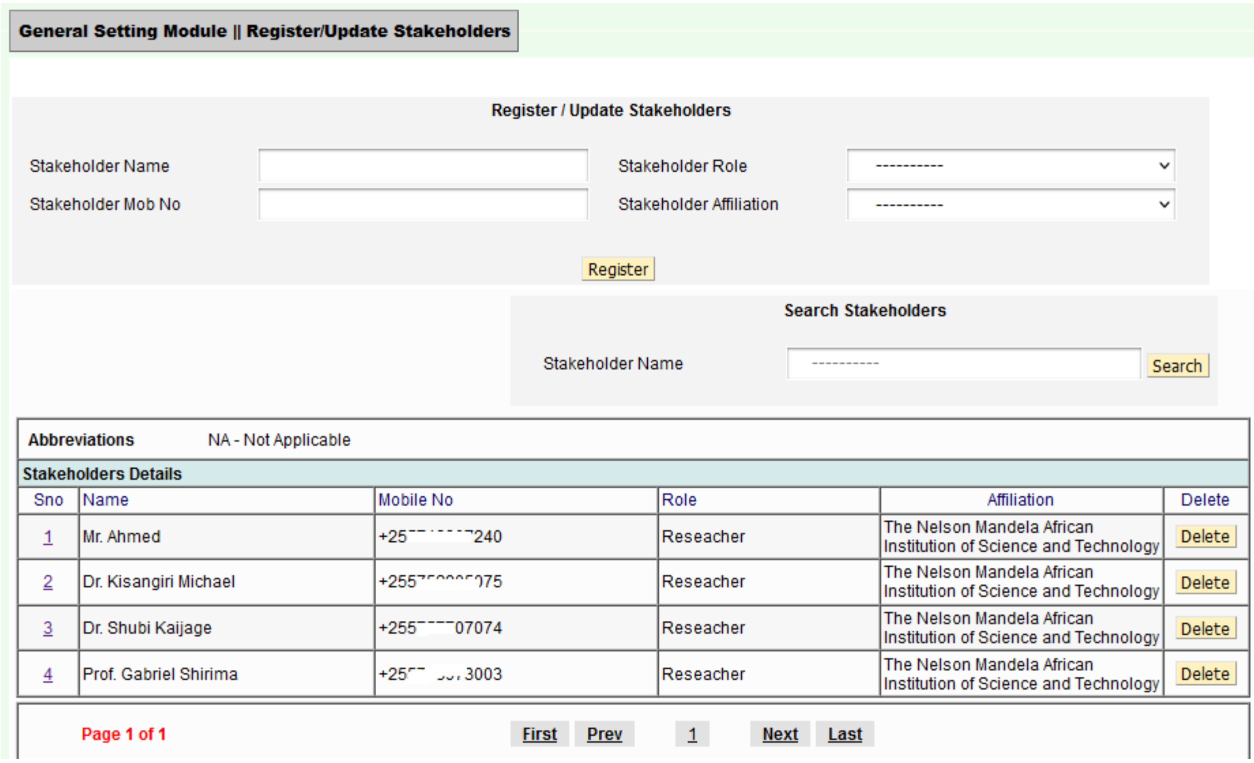


Figure 41: Register/Update other stakeholders' menu

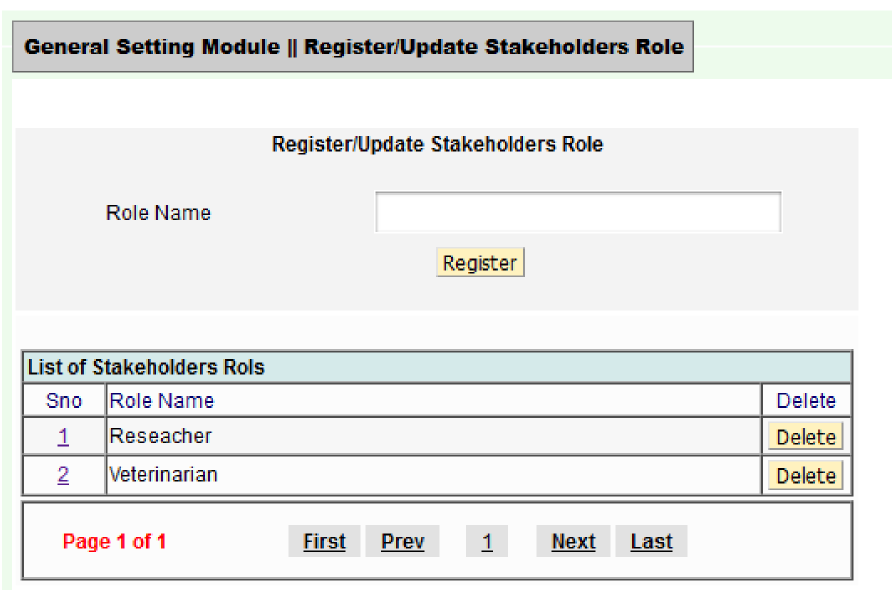


Figure 42: Register/Update stakeholders role menu

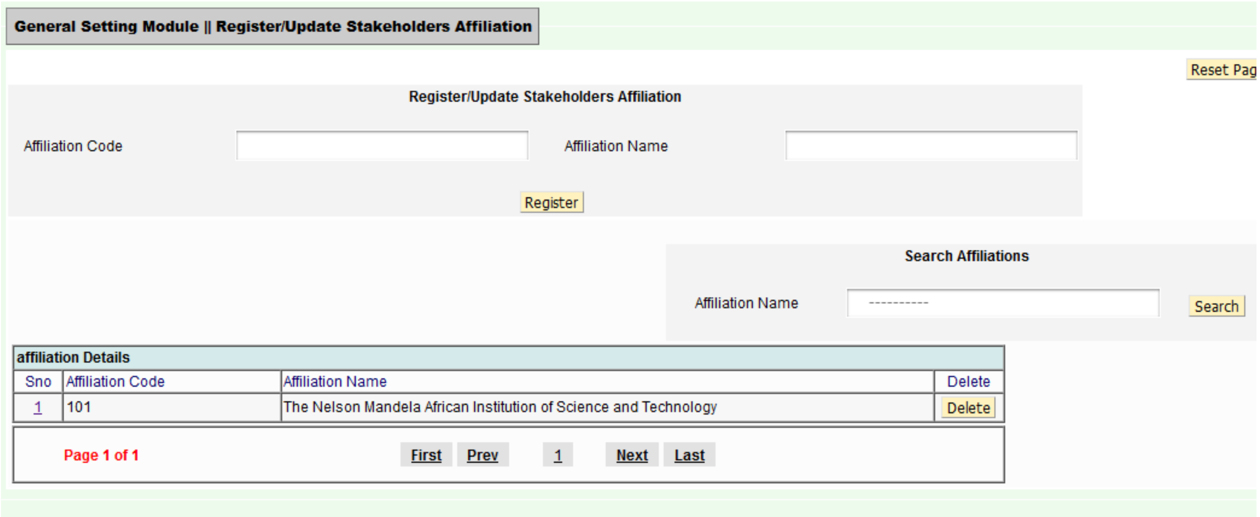


Figure 43: **Register/Update stakeholders affiliation menu**

The Register/Update livestock keepers menu allows users (top-level stakeholders) to register livestock keepers' geographical data in the system. This menu was used to register livestock keepers' details such as complete name, gender, age, village name, number of cattle possessed, status (active or seized), and cattle shed locations (latitudes and longitudes) (Fig. 44; Appendix 1 & 2). Other livestock particulars include farming systems, such as agropastoralism, pastoralism, zero-grazing, and their mobile number.This data was gathered during interviews with livestock keepers (Appendix 1 & 2; Plate 2 & 3). Only registered active livestock keepers could communicate with the system to report FMD outbreaks using SMS or USSD or receive FMD-related information in SMS and Robocalls.

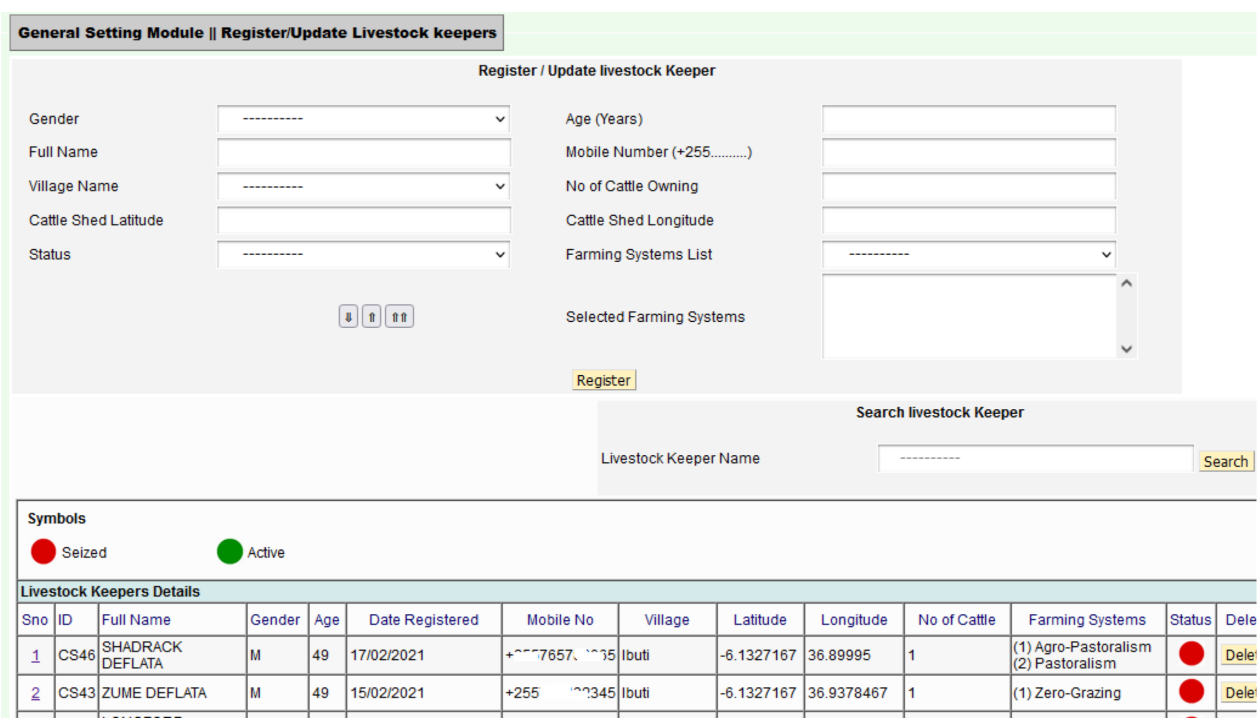


Figure 44: **Register/Update livestock keepers' menu**

The Register/Update livestock keepers menu is not self-contained; it relies on data from other menus. For example, the animal farming system list appeared in the menu only after it was added to the system via the Register/Update livestock farming system menu, which is also part of the General settings module (Fig. 45). In addition, users can register or remove livestock keepers farming systems from the system using the Register/Update livestock farming system menu. During the interview with livestock keepers, the three livestock farming systems practised in the Gairo district (pastoralism, zero-grazing, and agropastoralism) were collected and registered to the system using the Register/Update livestock farming system menu in Fig. 45, and Appendix 3.

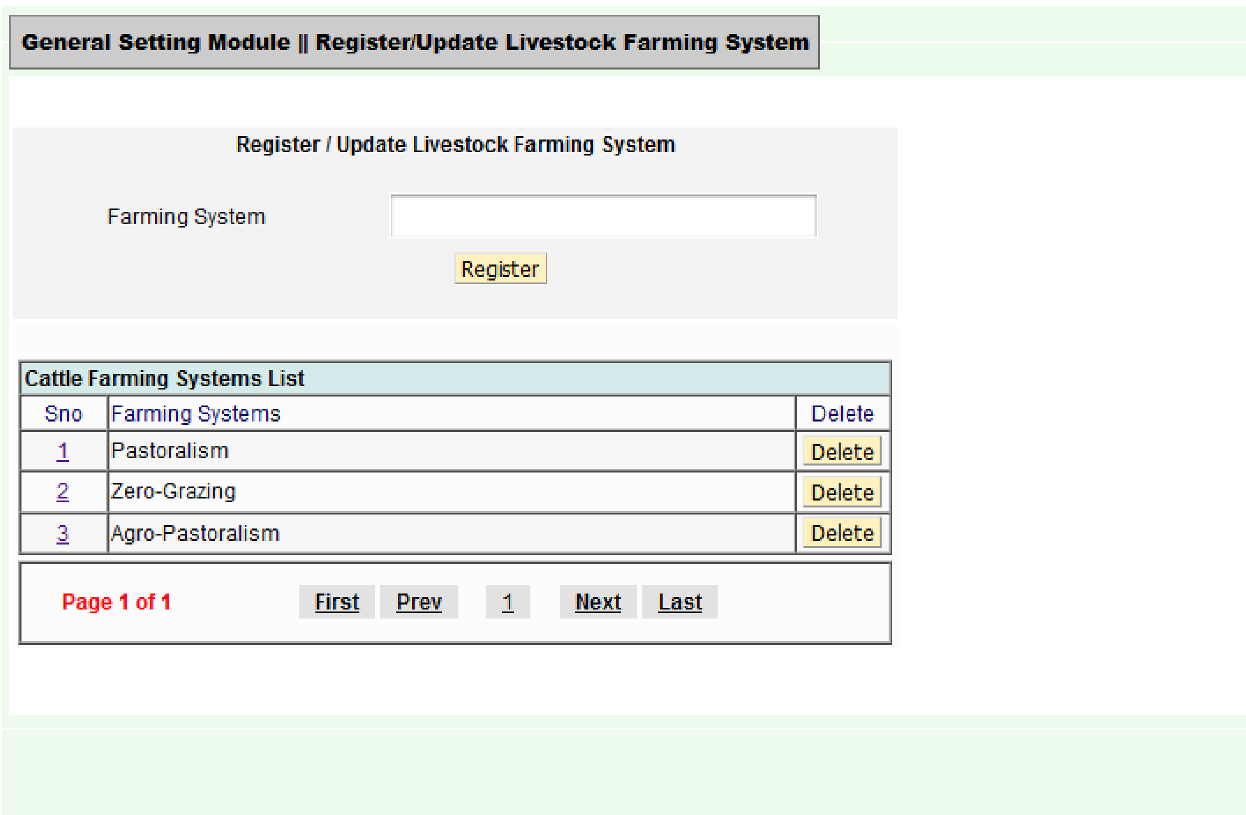
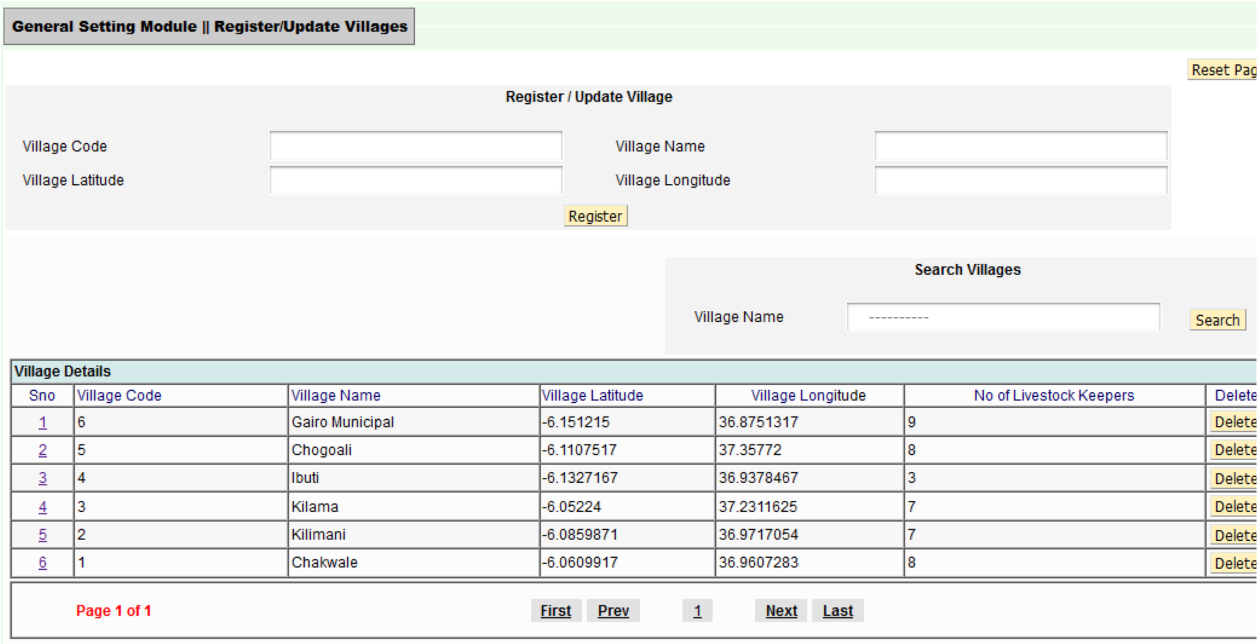


Figure 45: Register/Update livestock farming system menu

Similarly, the village names list is available in Register/Update livestock keepers menuafter registering village details like codes, names and centre latitudes and longitudes through the Register/Update villages menu (Fig. 46). The village's details were also captured during the data collection process (Table 5). The menu also enables users to update or delete village details when necessary.



General Setting Module || Register/Update Villages

Reset Pag

Register / Update Village

Village Code | Village Name
Village Latitude | Village Longitude

Register

Search Villages

Village Name ---------- Search

Village Details

Sno	Village Code	Village Name	Village Latitude	Village Longitude	No of Livestock Keepers	Delete
1	6	Gairo Municipal	-6.151215	36.8751317	9	Delete
2	5	Chogoali	-6.1107517	37.35772	8	Delete
3	4	Ibuti	-6.1327167	36.9378467	3	Delete
4	3	Kilama	-6.05224	37.2311625	7	Delete
5	2	Kilimani	-6.0859871	36.9717054	7	Delete
6	1	Chakwale	-6.0609917	36.9607283	8	Delete

Page 1 of 1 First Prev 1 Next Last

Figure 46: Register/Update villages menu

The General setting module also contains the Register/Update animals' interaction locations menu responsible for registering animals' interaction locations in the system. This study refers to animals' interaction locations as different places in the Gairo district whereby cattle herds come into contact (meet), such as livestock markets, drinking water points, and livestock loading ramps and grazing areas. Users register livestock interaction details such as names and location (latitude and longitude) through this menu system. Similarly, the menu allows users to register interaction location categories such as shared drinking water points, shared animal grazing areas, and animals' markets. The animals' interaction location details were also collected during data collection (Table 5). The latitude and longitude data were collected using a handheld GPS device. The animal's interaction locations were used in developing the FMD outbreaks prediction module (ABSM), which is explained in the coming FMD prediction module section.

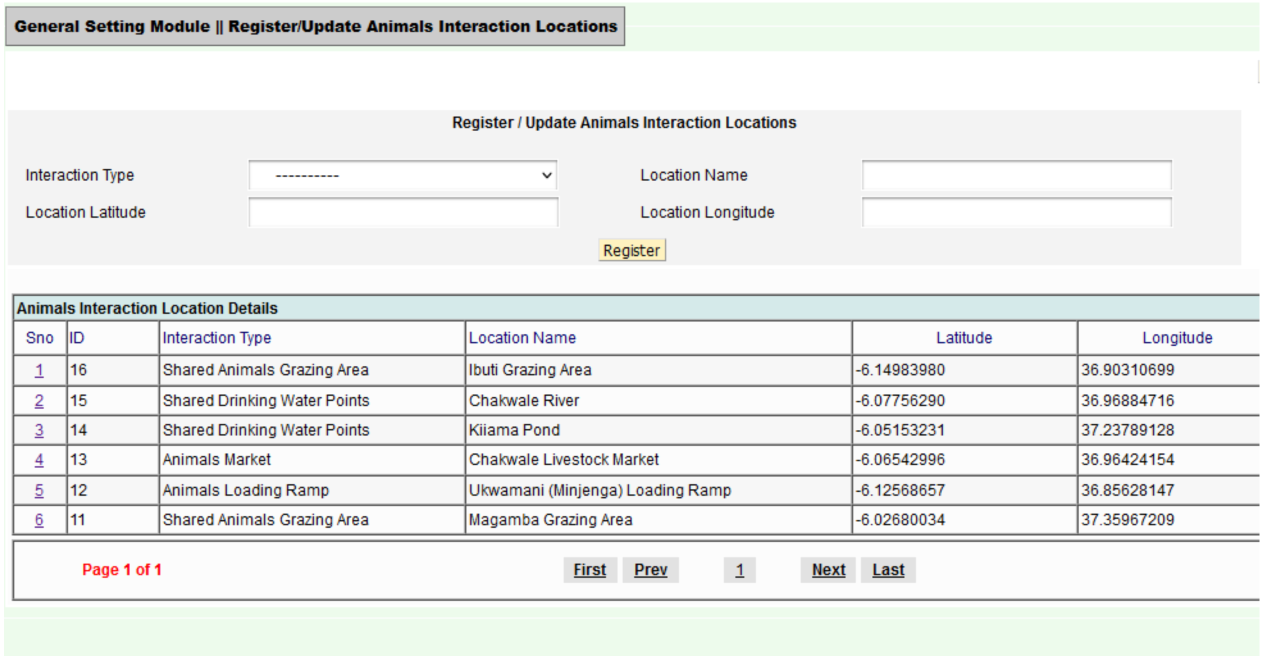


Figure 47: Register/Update animal's interaction locations menu

(vii) Foot and Mouth Disease Communication Module

The FMD communication module enables communication between livestock keepers and top-level stakeholders through the AMoS4T-FMD. The FMD communication algorithm and a spot map handles the overall FMD communication process in the module (Appendix 5; Fig. 8, 17 & 52). The FMD Communication algorithm section of this chapter has previously provided an explanation of how the algorithms works. Similar to this, the methodology section's section on algorithm implementation has already explained how to create a spot map.

The module enables FMD communication between livestock keepers and the system through SMS, Voice calls and USSD. The module handles FMD communication process through two different roots. SMS and voice calls communications are made possible through the SMS/voice gateway, voice modem pool, mobile networks, and feature mobile phones (Fig. 28). On the hand the USSD communication are made possible through the USSD API, Network interface card, on cloud USSD server (Internet) and feature mobile phones (Fig. 28).

Livestock keepers (geospatial data) and top-level stakeholders should first be registered to the system to communicate through the system. Likewise, the FMD awareness and FMD outbreaks alert information should also be uploaded to the system through the FMD alerts manager and FMD awareness manager menus which are parts of the FMD communication module (Fig. 50 & 51). These menus enable top-level stakeholders to add or update FMD alerts and awareness information in the system. Note that one should recall a particular USSD menu option number while adding corresponding information in the system through the menus (Fig. 54). Also, one should specify the broadcasting time interval of each FMD awareness information when uploading it to the system (Fig. 50).

Access to AMoS4T-FMD is restricted to active, registered stakeholders only. The top-level stakeholders use the system via the online web interface, while livestock keepers use USSD, SMS, and Robocalls with their basic mobile phones (feature mobile phones) (Fig. 29, 53 & 55). The livestock keepers may report FMD outbreaks by sending an SMS indicating the number of FMD suspected cattle to the system (Fig. 49). Alternatively, they may report FMD outbreaks through the USSD menu's option 1 after dialling a particular USSD code (e.g., *384*90005#) (Fig. 18, 48 & 53).

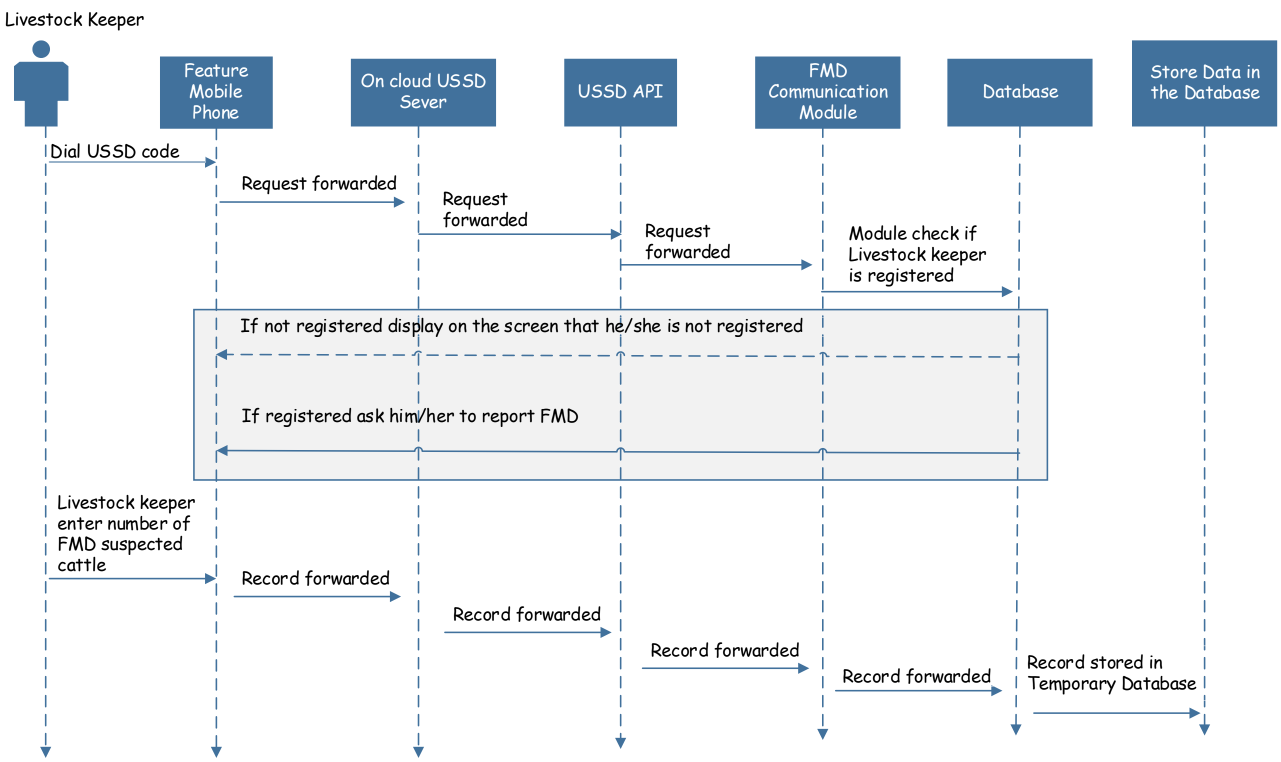


Figure 48: System and user interactions when livestock keeper report FMD by USSD menu

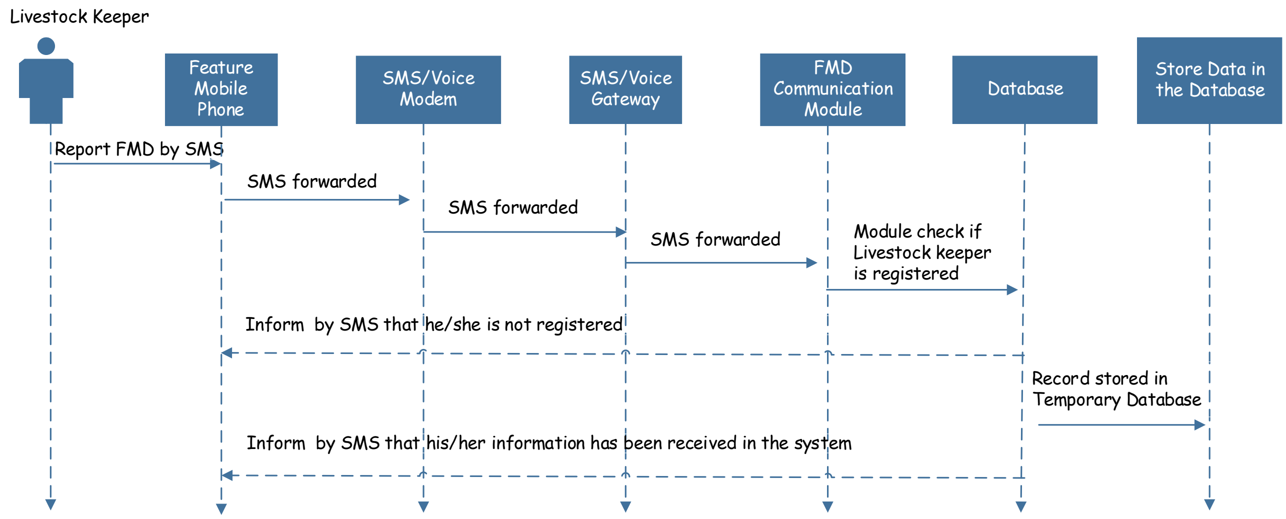


Figure 49: System and user interactions when livestock keeper report FMD by SMS

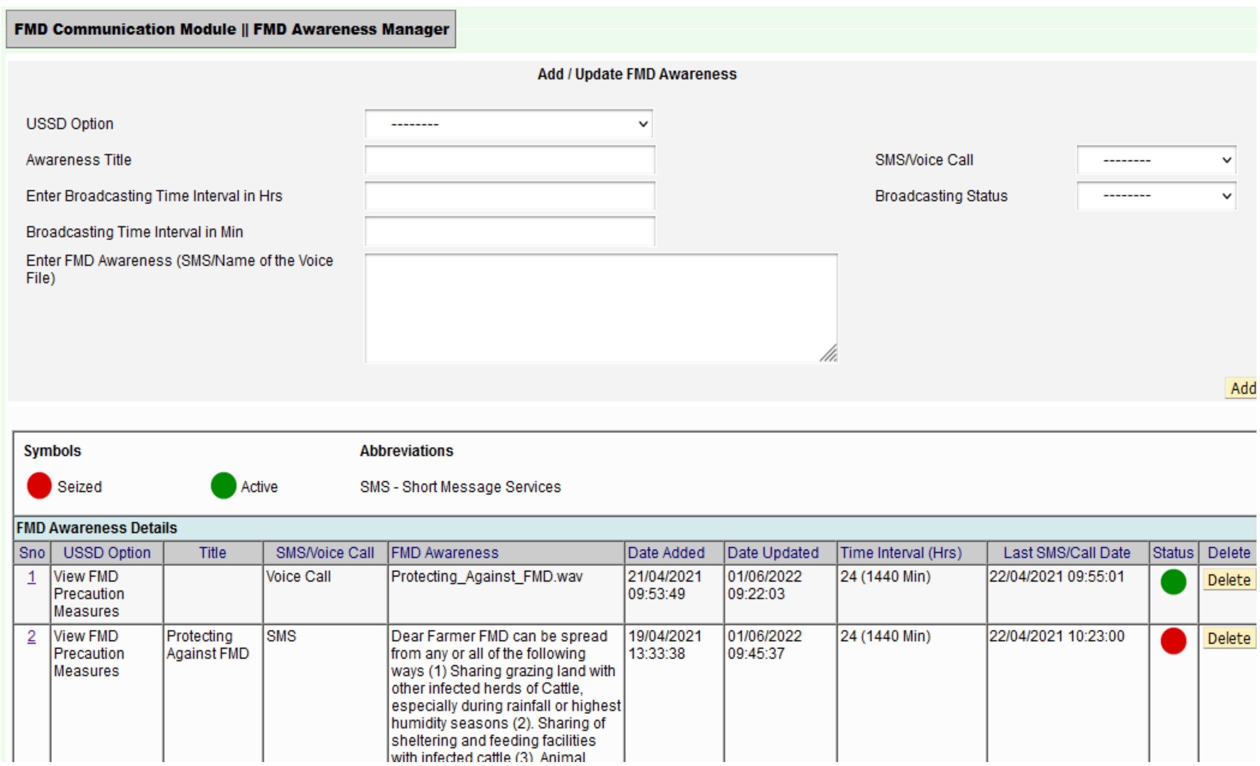


Figure 50: Foot and Mouth Disease awareness manager

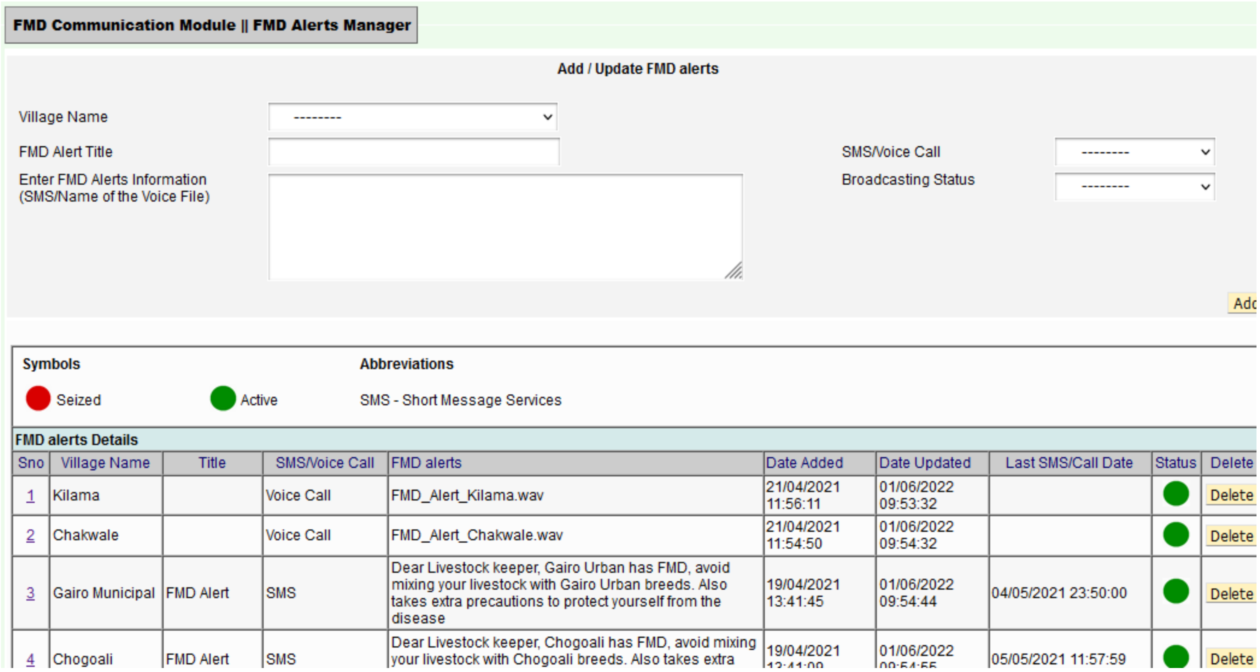


Figure 51: Foot and Mouth Disease Alerts Manager

The USSD menu option number 1 is hard-corded when developing the USSD menu part of AMoS4T-FMD (default menu that cannot be modified). However, the system is flexible to change (add or remove) other options (2- onwards) through the USSD menu manager and their contents in the FMD awareness manager menus (Fig. 50 & 54).

Figure 52: Spot map showing FMD reported and confirmed cases

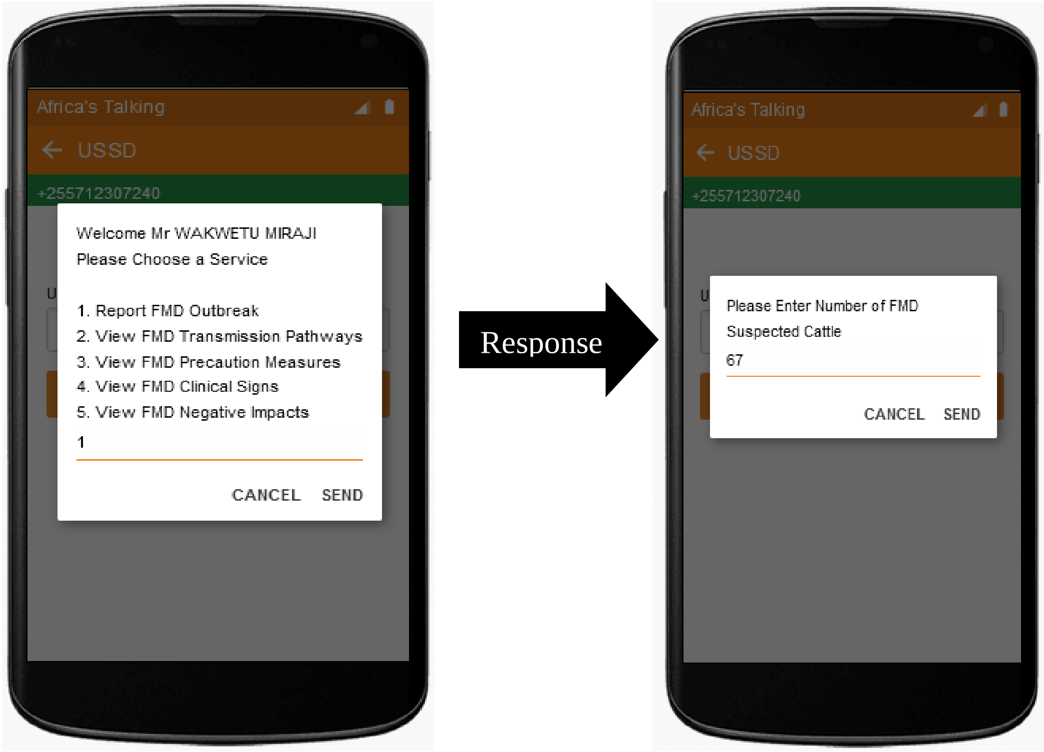


Figure 53: Livestock keeper reporting FMD outbreak to the system using USSD menu (Africa's Talking, 2021)

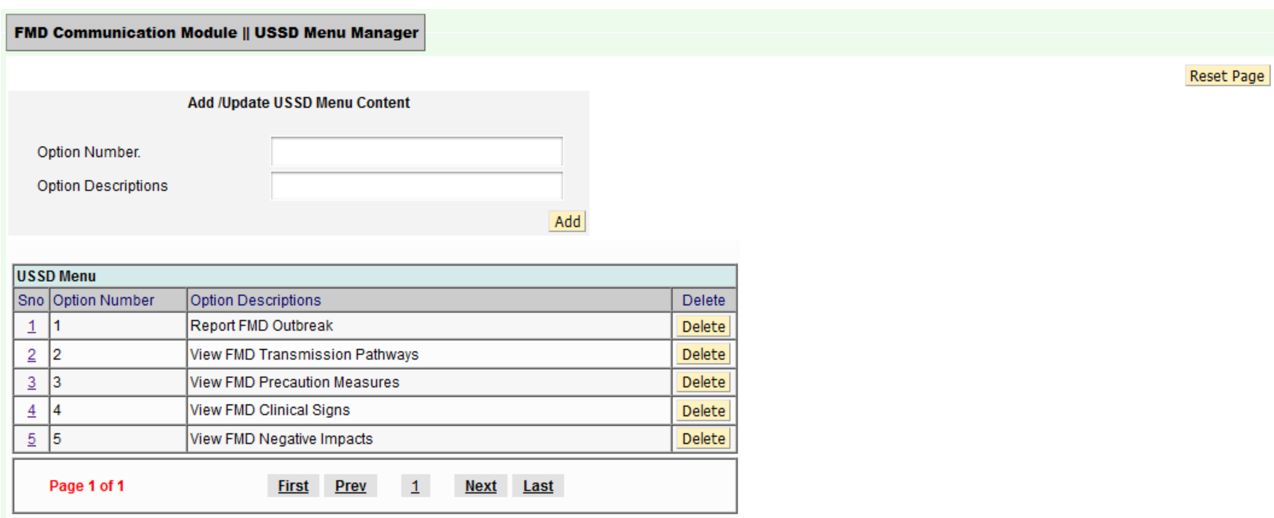


Figure 54: Unstructured Supplementary Service Data Menu Manager menu

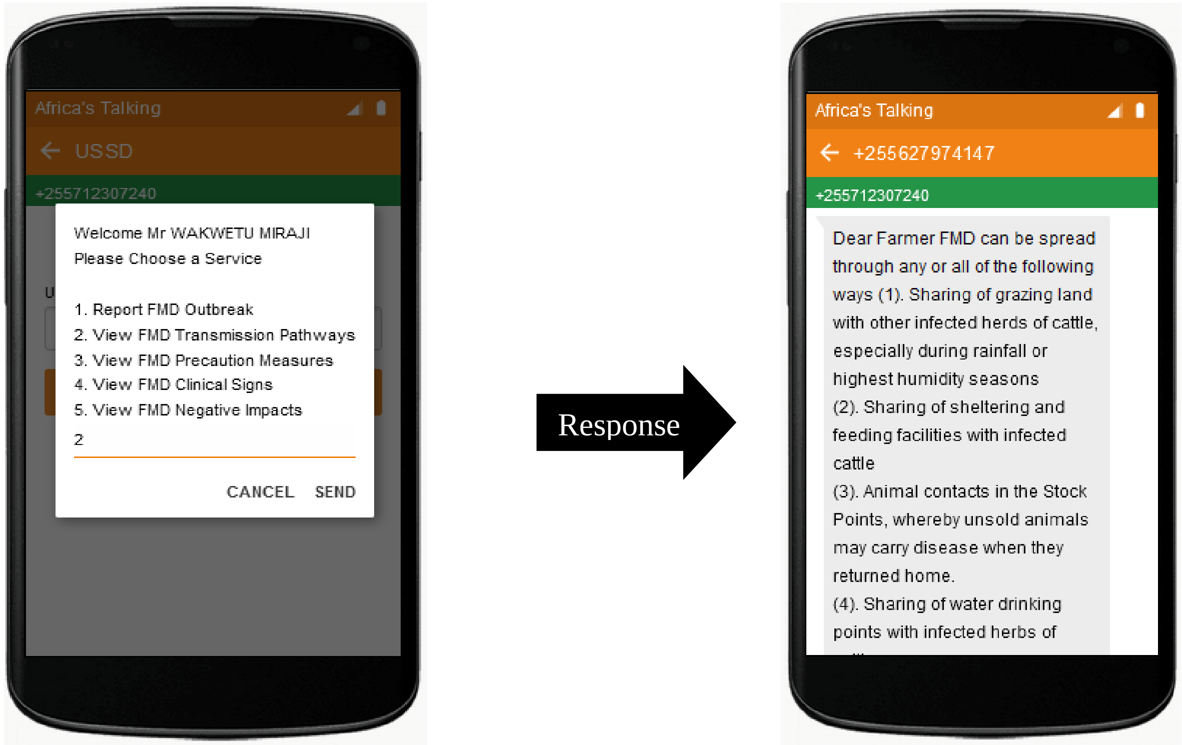


Figure 55: **Livestock keeper requesting FMD awareness information from the system using the USSD menu (Africa's Talking, 2021)**

(viii) Security Module

The security module enables the system administrator to manage users and system logs. The module provides the Manage user groups menu to create and delete user groups in the system and assign user group privileges (Fig. 56).

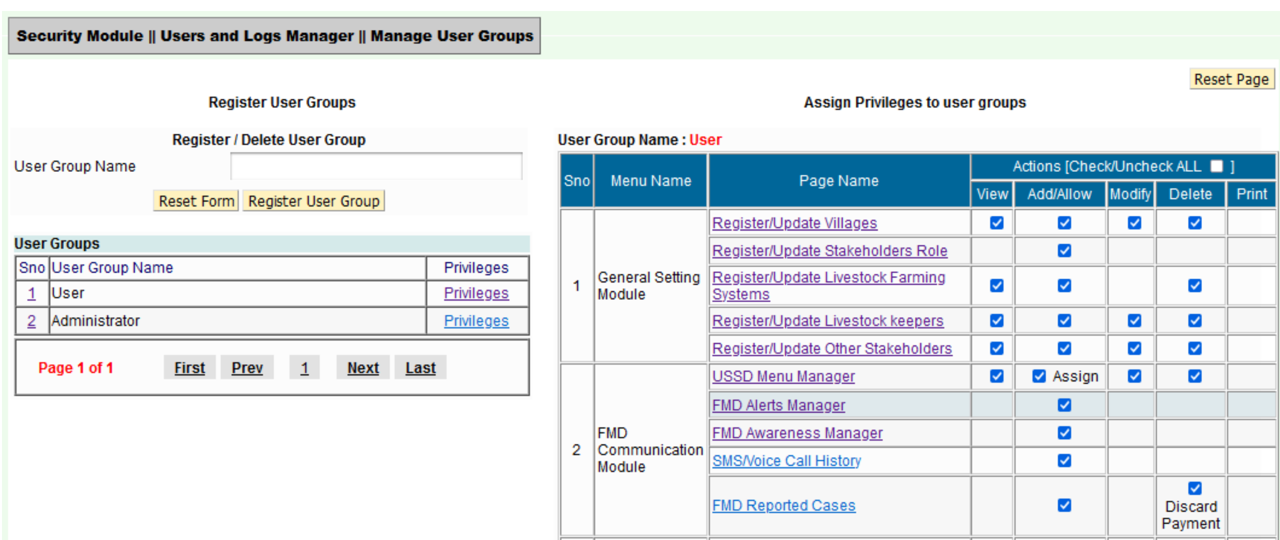


Figure 56: **Manager User groups menu**

The Manage users menu in the security module allows the system administrator to create users and grant privileges to them based on user groups (Fig. 57). This menu also allows the system administrator to delete users from the system. Similarly, system administrators can utilize this menu to activate or suspend users. Only registered active users will have access to the system.

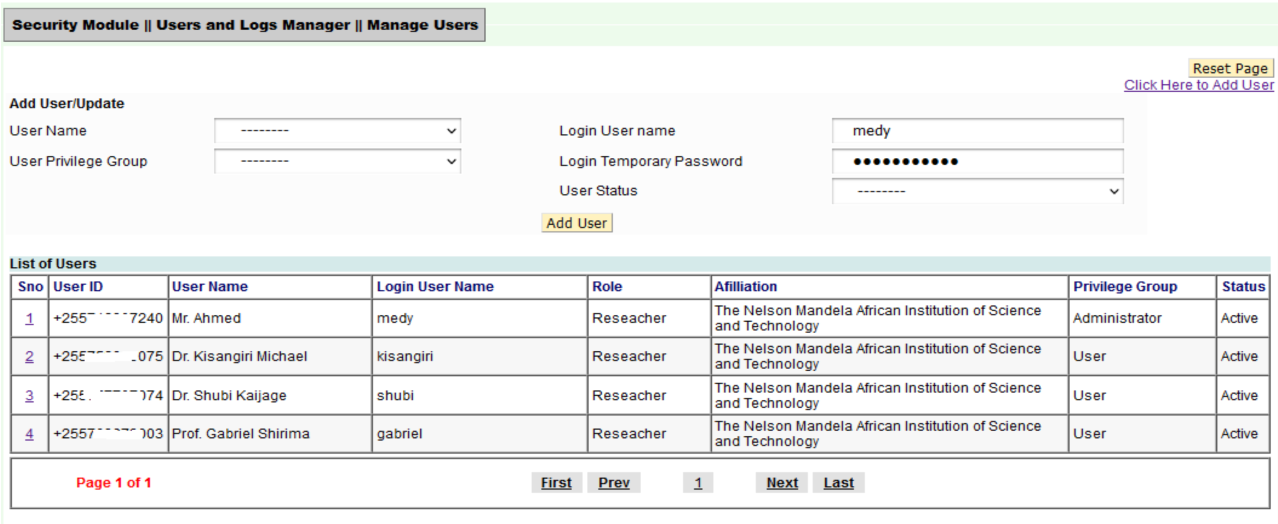


Figure 57: Manage users' menu

The module also provides the Change password menu, enabling system users to change their password at any time (Fig. 58).

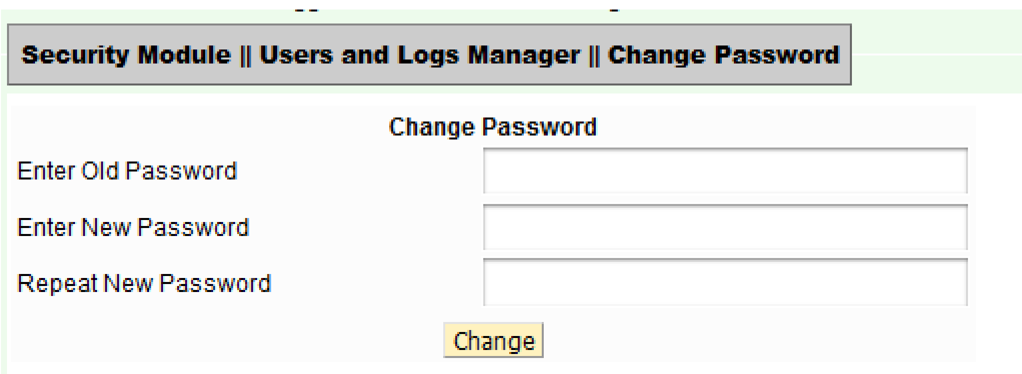


Figure 58: Change password menu

Lastly, the security module enables the system administrator to view system logs (Fig. 59).

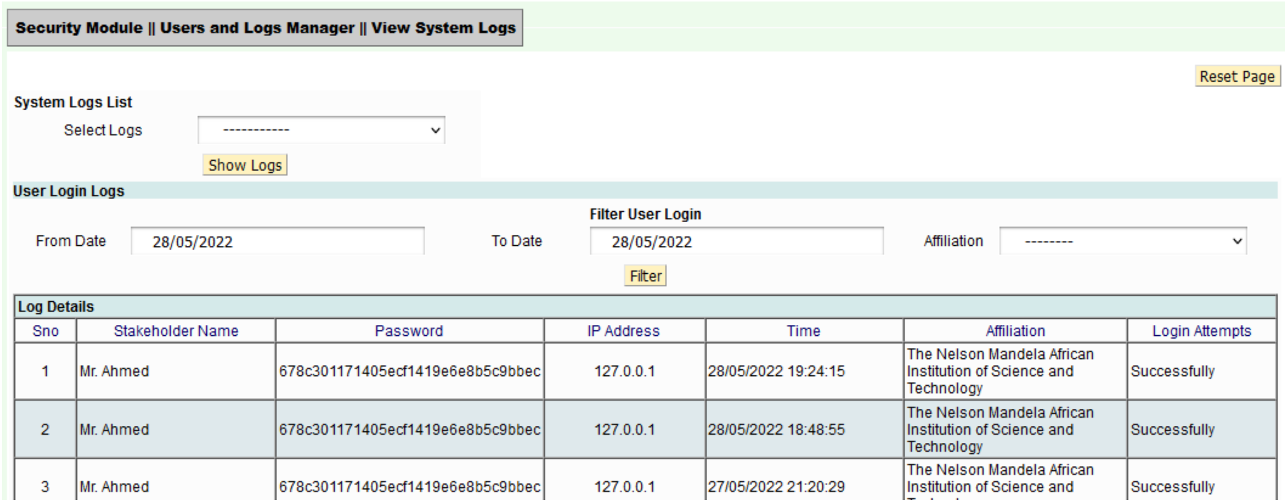


Figure 59: View system logs menu

4.9 System Testing

The researcher (system developer) utilized verification and validation techniques to test the system operations.

4.9.1 System Verification

The system developer utilized the white box and black box techniques to test the system operation. The white box testing technique was used to save system development time in the implementation phase. Different system functional blocks were tested, including looping and decision-making statements. The system's ability to retrieve and save accurate data to the database using Structured Query Language (SQL) was also tested.

On the other hand, the black box technique was used to test the system operation through the user interface. Therefore, the ability of the system to perform CRUD (creating, reading, updating and deleting data) operations through the user interface were tested. Similarly, the validation of inputs for data entry forms was tested.

4.9.2 System validation

The system developer performed validation testing for the FMD communication and FMD future outbreaks prediction (ABSM) modules which are crucial parts of AMoS4T-FMD.

(i) Foot and Mouth Disease Future Outbreaks Prediction Module Validation

The model's operation was validated using the replicative validation technique, in which the model outputs were compared to actual Gairo district FMD incidents/outbreaks data (Darvishi & Ahmadi, 2014). As a result, the model was validated using four months of FMD incident/outbreak secondary data (March 2021-June 2021) from six selected villages in the Gairo district: Kilama, Chogoali, Chakwale, Kilimani, Gairo town, and Ibuti (Appendix 8). However, the data on FMD incidents/outbreaks from Ibuti village, on the other hand, was excluded because no FMD cases were reported during the stated period. Similarly, testing did not involve the weather condition data since no weather condition parameters favour the FMD transmission by wind direction reported by the Weather station at that time (March 2021-June 2021).

Only FMD cases reported on the initial date in the five villages of the Gairo district (excluding Ibuti village) were sorted in order of occurrence and compared to the system output during the validation procedure (Table 6). As a result, the comparisons were made using a matrix that displays the expected upcoming FMD incidents/outbreaks (Table 7).

The matrix indicates that all five villages (Chakwale, Kilimani, Kilama,Ibuti, Chogoali and Gairo town) were at-risk when Chakwale village was affected by FMD (Fig. 12; Table 5). Therefore, the FMD incident/outbreak in Chakwale village, which was reported on March 3, 2021, maybe the source of FMD in Kilimani, Kilama, Chogoali, and Gairo town, according to the model output (Table 7). The same scenario applies to the rest of the villages (Table 7). Hence the researcher's opinion is that if five out of six villages comply with the model output means, the model can be used to predict FMD outbreaks in the Gairo district.

Table 6: Initial FMD incidents/outbreaks secondary data (March 2021-June 2021) from five villages in the Gairo district

Village name	FMD reporting date	Number of FMD reported cases
Chakwale	3 March, 2021	2
Kilama	3 March, 2021	1
Kilimani	3 March, 2021	3
Chogoali	3 March, 2021	6
Gairo town	21 March 2021	7

Table 7: The compliance matrix for the likely upcoming FMD incidents/outbreaks

Date reported	FMD origin village	Villages at risk of FMD per the model prediction	Complied villages based on the trend of FMD outbreaks/incidents secondary data (Table 6)
3 March, 2021	Chakwale	Kilimani	√3 March, 2021
		Kilama	√3 March, 2021
		Ibuti	
		Chogoali	√3 March, 2021
		Gairo town	√21 March, 2021
3 March, 2021	Kilimani	Chakwale	√ 3 March, 2021
		Kilama	√ 3 March, 2021
		Ibuti	
		Chogoali	√ 3 March, 2021
		Gairo town	√ 3 March, 2021
3 March, 2021	Kilama	Chakwale	√ 3 March, 2021
		Kilimani	√ 3 March, 2021
		Ibuti	
		Chogoali	√ 3 March, 2021
		Gairo town	√ 21 March, 2021
3 March, 2021	Chogoali	Chakwale	√ 3 March, 2021
		Kilimani	√ 3 March, 2021
		Kilama	√ 3 March, 2021
		Ibuti	
		Gairo town	√ 21 March, 2021

(ii) Foot and Mouth Disease Communication Module Validation

The ability of livestock keepers to access AMoS4T-FMD using their mobile phones was tested as part of the FMD communication module validation. As a result, 36 livestock keepers from Chogoali and Kilama villages were randomly chosen to see if they could use their feature phones to access the system using the USSD menu, SMS, and Robocalls on the first trial. As a result, a closed-ended interview with a questioner was undertaken to see if they could access the USSD menu and use SMS and USSD menus to report disease outbreaks to the system (Appendix 9). They were also asked if they could get FMD awareness information from the system on the first attempt, such as precautions, negative effects, transmission pathways, and clinical indicators via SMS and automated voice calls (Robocalls) utilizing the USSD menu.

The testing found that (94%) of livestock keepers were able to access and report FMD incidents/outbreaks using the USSD menu (Table 8). Similarly, the test found that (83%) of livestock keepers were able to report FMD incidents/outbreaks to the system using SMS, while (17%) failed because they lacked SMS bundles (Table 8). Not only that but also (89%) of livestock keepers were able to access FMD awareness information from the system using the USSD menu in the first attempt (Table 8). However, they succeed in the proceeding attempts.

Table 8: Foot and Mouth Disease communication module validation response

Variables	Frequencies	Per cent
Able to access the USSD menu with their feature mobile phones?		
yes	34	94%
no	2	6%
Total	36	100%
Reporting FMD incidents/outbreaks using the USSD menu		
yes	34	94%
no	2	6%
Total	36	100%
Reporting FMD incidents/outbreaks using SMS		
yes	30	83%
no	6	17%
Total	36	100%
Accessing FMD awareness information using the USSD menu		
yes	32	89%
no	4	11%
Total	36	100%

4.10 System Deployment

The AMoS4T-FMD system is a web-based application. For testing purposes, the system was installed on server computer hardware with 4 GB RAM and 500 GB HDD storage at NM-AIST computer lab (Plate 4). The PC server was installed with the Windows 10 operating system set with a public Internet Protocol (IP) address. The Windows operating system was chosen since the SMS gateway software is only compatible with Windows. Similarly, the public IP address allows AMoS4T-FMD to communicate with third-party services like USSD and Google Maps APIs via the Internet. It also enables top-level stakeholders to access the system through a web browser on Smartphones and computers with Internet connectivity. The SIMCOM modem equipped with pre-paid SIM cards was also attached to the server via a USB port to broadcast SMS and Robocalls (Plate 4).

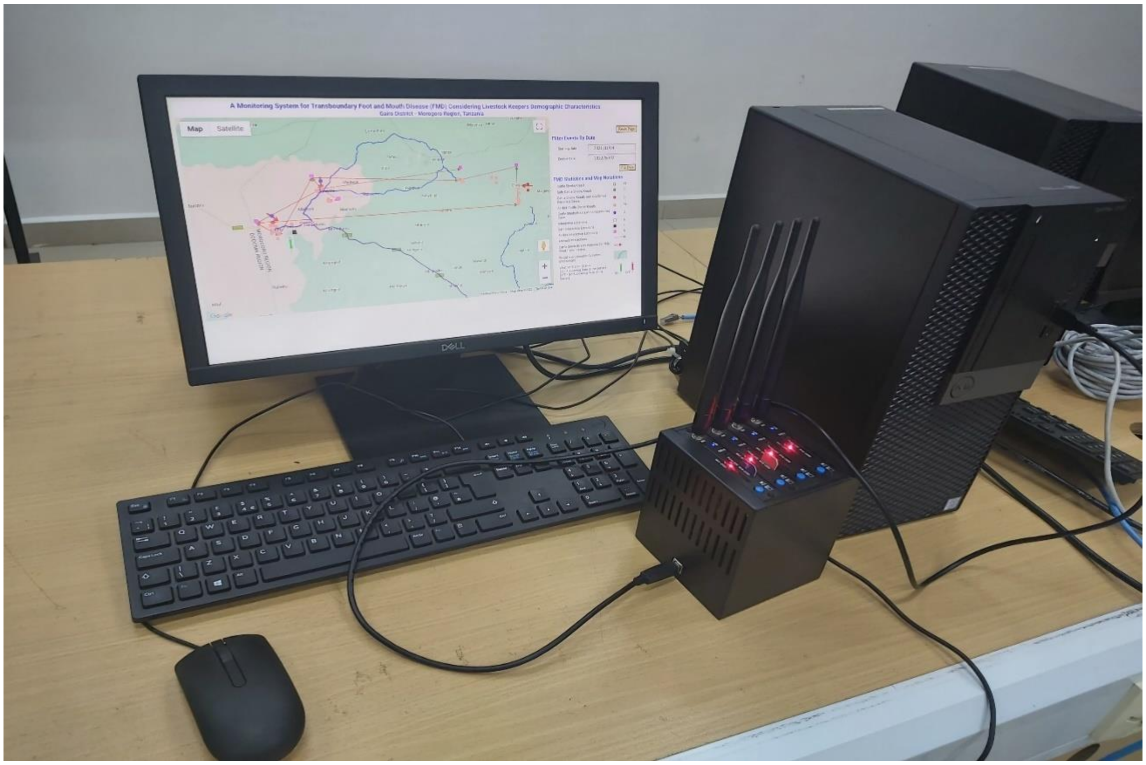


Plate 4: Deployment of AMoS4T-FMD

4.11 Discussion

Apart from Monitoring System for Transboundary FMD, there are other existing web-based, mobile-based, and integrated (mobile and web-based) systems developed for similar purposes (HealthMap, 2020; Karimuribo *et al.,* 2016; Mwabukusi *et al.,* 2014; Milinovich *et al.,* 2014; Thumbi *et al.,* 2019). Although exists; they offer limited access to the local communities, who are the main stakeholders in animal disease reporting since disease always starts from their cattle (Karimuribo *et al.,* 2017). In the case of existing web-based surveillance systems, only the top-level stakeholders such as laboratories, researchers, and other international agencies can upload or access disease information from the system because they have skills and devices for browsing the internet (HealthMap, 2022; ProMED-mail, 2022). Unfortunately, most livestock keepers, especially in developing countries, do not use these systems due to a lack of skills and tools for accessing them (Table 4). Thus, denying communities from accessing such information. There are also existing mobile-based animal and human health surveillance systems, such as EMA-I and AfyaData, developed by FAO and SACIDS, which tried to collect nearly real-time surveillance data in the local communities' context (FAO, 2015; FAO, 2021; Karimuribo *et al.*, 2016). Still, these systems deny livestock keepers to communicate the surveillance data to the respective authorities directly. Instead, the organizations utilize veterinarians and community health reporters (CHRs) in the livestock-keeping communities to collect the data on behalf of livestock keepers using smartphones. The challenge of this mechanism of collecting data sometimes leaves many unreported cases, especially in far away, hard-to-reach livestock-keeping communities (Karimuribo *et al.*, 2017). Also, it requires more veterinarians and community health reporters (CHRs) in the field to be effective and well-facilitated.

Therefore, the developed Monitoring System for Transboundary FMD (AMoS4T-FMD) is designed to cover the existing surveillance systems' deficiencies through its FMD communication module. The extra integrated USSD and automatic voice call (Robo-calls) features in the Monitoring System for Transboundary FMD provide two-way communication to the server without internet for the local communities (Livestock keepers). As a result, livestock keepers can access and receive information directly from the server using any mobile phone (Feature or Smartphone). These features differentiate this system from the rest. The system continuously maintains awareness among livestock keepers by reminding them about disease precaution measures, clinical signs, negative impacts, and transmission pathways in SMS and Robo-calls. Also, livestock keepers can access this information and any other uploaded to the server using a USSD menu instead of web browsers. Different stakeholders may also access similar information using web browsers, Smartphones, or Computers with the internet like in other surveillance systems (ProMED-mail, 2022; World Organisation for Animal Health, 2021; FAO, 2021; African Union, Inter African Bureau for Animal Resources, 2019; European Commission, 2020; Bonnet *et al.*, 2010; Milinovich *et al.*, 2014). Similarly, the system enables livestock keepers to report disease outbreaks through the USSD menu.

On the other hand, the AMoS4T-FMD ABSM, like other FMD prediction models, anticipates the risk of FMD outbreaks in neighboring villages whenever an FMD case or outbreak is reported in one village (Kim *et al.*, 2016; Dion *et al.*, 2011; Bradhurst *et al.*, 2015). However, unlike previous FMD prediction models, which only predict FMD occurrences, the AMoS4T-FMD ABSM promptly sends out alarm messages through SMS and Robocalls to at-risk cattle shed/kraal owners, advising them of the FMD situation. The alert message mentions the FMD-infected village and the required precautions that livestock keepers might take to reduce the disease's impact on their livestock.

This study also found that (91%) of livestock keepers in the Gairo district own feature phones compared to smartphones (9%). This is comparable to Karimuribo *et al.* (2016), who found that 96.4 % of livestock keepers in the Gairo and Kilosa districts own feature phones. This study also found that most livestock keepers use mobile phones to call (48%) and send SMS (39%). The sufficient number of livestock keepers owning feature mobile phones and their calling and sending SMS preferences motivated the use of USSD and Robo-calls services in the Monitoring System for Transboundary Foot and Mouth Disease.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The researcher believes that livestock keepers' total involvement in animal disease surveillance will enhance early disease outbreaks detection and reporting and provide real-time quality data for fast response to disease epidemics and disease control. Also, periodically receiving various FMD information/ events in SMS or voice calls increases awareness among livestock keepers. Policymakers may also use the FMD secondary data for decision-making, like in other surveillance systems.

The AMoS4T-FMD does not only provide FMD communication services at the local/community level (Livestock keepers). Additionally, it generates the spatial distribution map of FMD-suspected and affected cattle sheds or kraals on the homepage to determine the disease distribution behaviour for a specific period. Unlike previous monitoring systems that generate spatial distribution at the regional, national and global levels. Also, the spot map on the AMoS4T-FMD home page and ABSM enables top-level stakeholders to know the precise location of cattle sheds for prompt intervention whenever a livestock keeper reports an FMD case to the system, which enhances the FMD control process.

The ABSM, responsible for predicting the possibility of FMD occurrence and alerting livestock keepers via SMS and Robocalls, enhances preparedness against the disease before it negatively impacts livestock keepers' communities.

The AMoS4T-FMD was designed and tested in the Gairo district; however, its settings are flexible enough to work in other areas if the necessary parameters, such as villages, animal interaction locations, and livestock keepers' particulars, are uploaded. Similarly, the FMD communication module in AMoS4T-FMD might be used to report diseases other than FMD.

5.2 Recommendations

Many private and government institutions worldwide performed research and introduced several ways of combating FMD. Furthermore, the research findings were published in various places, including but not limited to research journals, magazines and surveillance systems. However, this study found that some livestock keepers in the Gairo district still lack knowledge of FMD control regardless of the literature's existence. The reason is the lack of knowledge and devices for accessing the materials.

For this reason, the researcher is in the position to advise non-FMD-free declared countries to analyze their livestock-keeping communities to find various alternatives for sharing materials and animal disease information with livestock-keeping communities through their resources. For example, this study used feature phones to share FMD events in the Gairo district after analyzing livestock keepers' demographic characteristics.

This study also recommends that the functionality enabling Veterinarians to receive an SMS alert when a new FMD case is reported in the system should be in place to improve the efficiency of the AMoS4T-FMD. The feature will enable veterinarians to attend/verify FMD cases as faster as possible once they are available in the system.

Lastly, since the Tanzania government reported the availability of below 30% of field veterinarians for the entire country, this study is in a position to advise the government to employ more of them to improve the animal disease surveillance process.

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Appendix 1: A request letter for the Gairo district to be a study area

The title was updated from "Detection and Monitoring System for Transboundary Foot and Mouth Disease Outbreak in Cattle Using Predictive and Analytic Algorithms" to "A Monitoring System for Transboundary Foot and Mouth Disease Considering Livestock Keepers Demographic Characteristics (AMoS4T-FMD)" as part of the research improvement.

THE NELSON MANDELA
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P.O. Box 447
Arusha, TANZANIA
Website: www.nm- aist.ac.tz

OUR Ref.No. NM-AIST/P.267/T.17/12

Date: 14th March, 2019

District Executive Director (DED),
Gairo District Council,
P.O.Box 40,
Gairo-Morogoro.

GAIRO DISTRICT COUNCIL
RECEIVED
SIGNATURE
DATE 12-4-2019

Dear Sir/Madam,

RE: INTRODUCTION TO MR. AHMED KIJAZI

Kindly refer to the above heading.

I wish to introduce Mr. Ahmed Kijazi with Registration No. NM-AIST/P.267/T.17, a PhD student at Nelson Mandela African Institution of Science and Technology in the School of Computational and Communication Science and Engineering.

As part of the requirement for PhD degree, Mr. Ahmed is undertaking a research with title "***Detection and Monitoring System for Transboundary Foot and Mouth Disease outbreak in Cattle using Predictive and Analytic Algorithms***".

In order to accomplish his research objectives, he would like to collect some information from your organization/district. The information to be collected will be used for research purposes only and will help student to develop a Computer based system which can early detect, predict and communicate FDM epidemics as it states in the research objectives.

It is my sincere hope you will assist the student in accomplishing his study.

Looking forward for your cooperation.

Sincerely,

Shubi Kaijage,*PhD*
Ag. Dean

Appendix 2: Acceptance letter for Gairo district to be a study area

The title was updated from "Detection and Monitoring System for Transboundary Foot and Mouth Disease Outbreak in Cattle Using Predictive and Analytic Algorithms" to "A Monitoring System for Transboundary Foot and Mouth Disease Considering Livestock Keepers Demographic Characteristics (AMoS4T-FMD)" as part of the research improvement.

GAIRO DISTRICT COUNCIL

[All correspondences to be addressed to the District Executive Director]

Tel. No: 255 - 23 -
Fax No: 255 - 23 -
Email: info@gairo.go.tz
Website: www.gairo.go.tz

DISTRICT EXECUTIVE OFFICE,
P.O. Box 40,
GAIRO.

In reply please quote:
Ref. No. GDC/T.20/2 VOL III/183

Date: 15 April, 2019.

The Nelson Mandela,
Africa Institution of Science and Technology(NM-AIST),
P. O. Box 447,
TENGERU – ARUSHA.

RE: REQUEST FOR MR. AHMED KIJAZI TO CONDUCT RESEARCH

Reference is made to the heading above,

Response is made to the letter introducing Mr. Ahmed Kijazi with registration number REF:No.NM-AIST/P.267/T.17/12 dated 14th March, 2019 to our organization with intention of carrying out data collection to justify claims of the research titled " **Detection and Monitoring system for Transboundary Foot and Mounth Disease outbreak in Cattle using Predictive and Analytic Algorithms."**

I would like to respond that your request has been accepted and you are welcome to collect data.
We hope that you will adhere to research ethics during the whole period of data collection.

Sincerely,

Halima Sendoro
FOR DISTRICT EXECUTIVE DIRECTOR
GAIRO DISTRICT COUNCIL

For. DISTRICT EXECUTIVE DIRECTOR
GAIRO

Copy: Ahmed Kijazi – Student,
GAIRO.

Appendix 3: Questionnaire for livestock keepers

"Monitoring System for Transboundary Foot and Mouth Disease (FMD) Considering Livestock Keepers Demographic Characteristics in Gairo District"

Livestock Owners Informed Consent

You are being invited to participate in a research study that will lead to developing a Monitoring System for Transboundary Foot and Mouth Disease (FMD) Considering Livestock Keepers Demographic Characteristics in Gairo District. This study aims to bridge the gap between livestock keepers and top-level stakeholders in Gairo district by developing an animal diseases surveillance system which enables to communicate FMD scenarios. We hope that the results from this research will increase the productive lifespan of animals to reduce the costs of restocking and buying animals. Also, it will provide early warning indicators of disease outbreaks, planning and monitoring of disease control programmes, provision of sound animal health services, and certification of export livestock and livestock products which are international proof to be free from diseases. In addition, the research will improve awareness and knowledge of the distribution and behaviour of disease outbreaks and infections. This research is being conducted by experts from the Nelson Mandela Institution of Science and Technology (NM-AIST) in Tanzania under African Development Bank (AFDB) Project Fund. Please read the information in this sheet which explains what is involved and any benefits or challenges. We encourage you to ask the study representative to explain parts of the study that are not clear or you have further questions. Take as much time as you need to decide whether you would like to be involved or not.

STATEMENT OF CONSENT

I confirm that I have read the information in this document or that it has been read to me thoroughly. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason and without my legal rights being affected.

__________________________ __________________ __________________

Name of the Subject Date Signature

__________________________ __________________ __________________

Name of a Person taking consent Date Signature

QUESTIONNAIRE FOR LIVESTOCK OWNERS

1. BIODATA
   - 1.1 Study no……………
   - 1.2 Date of interview (dd/mm/yy)………..
   - 1.3 Interviewees names………………….
   - 1.4 Sex………
   - 1.5 Age ……………
   - 1.6 Marital Status …………….
   - 1.7 Village……………
   - 1.8 District……………..
2. What is your level of education?
   - A. [ ] Primary School
   - B. [ ] Secondary School
   - C. [ ] University
   - D. [ ]No formal education
   - E. [ ]Other, Indicates
3. Do you own a mobile phone(s)?
   - A. [ ] Yes
   - B. [ ] No
4. Which kind of a mobile phone(s) do you own (*if Q2 the answer is yes*)(*Tick all applies*)
   - A. [ ] Smart phone
   - B. [ ] Cell phone

5. How do you use your mobile phone (*Tick all applies*)?
   A. [ ] For SMS (Receiving and Sending)
   B. [ ] Calling
   C. [ ] Surfing through the internet
   D. [ ] Social Networks e.g. Whatsapp, Facebook, twitter
   E. [ ] Other. Mention 1)_________ 2)_________
6. Have you heard about foot and mouth disease (FMD) in cattle?
   A. [ ] Yes
   B. [ ] No
7. (1) What are the clinical signs of FMD in cattle? Mention at least four
   i. …………………… ii…………………iii……………………iv…………………

   (2) Do you know different ways in which Foot and Mouth disease can spread from one animal to another?
   A. [ ] Yes. If Yes, Can you mention only two of them (1) _______ (2) ________?
   B. [ ] No
8. Have you ever faced an FMD challenge from your cattle?
   A. [ ] Yes
   B. [ ] No
9. How did you handle the incident (if *Q8, the answer is yes*)?
   A. [ ] I treated my animals myself
   B. [ ] I reported the incidence to the VET professionals via Mobile phone, who then cured my animals
   C. [ ]I reported the incidence to the VET professionals physically, who then cured my animals
   D. [ ] I just kept quiet because I had no option
   E. [ ] Other (Mention)
10. Have you ever thought about precaution measures against FMD?
   C. [ ] Yes
   D. [ ] No
11. What are those measures (*if Q9 the answer is yes*)
   1. ………………..
   2. ………………..
   3. …………………
12. Have you ever heard FMD outbreak within or outside your village?
   A. [ ] Yes

B. [ ] No

13. Was this information officially communicated to you (are they coming from respective authorities)? (*If Q11 the answer is yes*)

C. [ ] Yes

D. [ ] No

14. How long does it take for you to receive information about FMD incidences/Outbreaks that happened either within or nearby villages?

    A. [ ] Within 1 hour
    B. [ ] Within 6 hours
    C. [ ] Within 12 hours
    D. [ ] Within 1 day
    E. [ ] More than 1 day
    F. [ ] No information at all

15. If either A-G in question no 8. Who gives you the information?

    A. [ ] Vet professional
    B. [ ] Other livestock owners
    C. [ ] Special meetings
    D. [ ] Just hearing rumours
    E. [ ] Other indicates

16. Would you like to receive alerts for current and future likely FMD incidents via SMS?

    A. [ ] Yes
    B. [ ] No

17. Why do you think to receiving information via SMS?

Appendix 4: USSD API

```
                $mobilenumber=$phoneNumber;
                $message="Dear Livestock keeper you are denied to use this service, please call the following numbers for help: - ";
                while($sqlstakdetailsrows=mysqli_fetch_array($sqlstakdetails))
                {
                  $message.=$sqlstakdetailsrows['stakeholder_mobno'].",";
                }
                Broadcast_sms_and_Voice($subject,$message,$link,$messagename,$mobilenumber);
              }
              else
              {
                $subject="";
                $messagename=199913;
                $mobilenumber=$phoneNumber;
                $message="Dear customer your account was closed, please try again later";
                Broadcast_sms_and_Voice($subject,$message,$link,$messagename,$mobilenumber);
              }


          }
        }

    }
    else
    {

          $response="END You are not registered to use this service, you will receive SMS for help";
          $sqlstakdetails=mysqli_query($link,"select help_desk.*,stakeholders_details.*,affiliation_details.* from help_desk,
          stakeholders_details,affiliation_details where help_desk.stakeholder_mobno=stakeholders_details.stakeholder_mobno and
          stakeholders_details.affiliation_code=affiliation_details.affiliation_code and stakeholders_details.stakeholder_mobno!='1212134'");
          if(mysqli_num_rows($sqlstakdetails)>0)
          {
             $subject="";
             $messagename=199913;
             $mobilenumber=$phoneNumber;
             $message=" Dear livestock keeper you are not registered to use this service, please call the following numbers for help :- ";
             while($sqlstakdetailsrows=mysqli_fetch_array($sqlstakdetails))
             {
                $message.=$sqlstakdetailsrows['stakeholder_mobno'].",";
             }
             Broadcast_sms_and_Voice($subject,$message,$link,$messagename,$mobilenumber);
          }
          else
          {
              $subject="";
              $messagename=199913;
              $mobilenumber=$phoneNumber;
              $message="Dear livestock keeper you are not registered to use this service, please try again later";
              Broadcast_sms_and_Voice($subject,$message,$link,$messagename,$mobilenumber);
          }
    }
```

```php
}
else if($explodedtextvalue[0]=="1")
{
    if($explodedtextvalue[0]=="1" && isset($explodedtextvalue[1]))
    {
        if(is_numeric(trim($explodedtextvalue[1])) && filter_var(trim($explodedtextvalue[1]), FILTER_VALIDATE_INT))
        {
         //insert number of affected cattle to the database
          $uniquid=uniqid();
          $sqlinsrt=mysqli_query($link,"insert into smsdlv_inbox(ID,FromNo,Message,RecTime,channel) values('".$uniquid."',
          '".$phoneNumber."','".$explodedtextvalue[1]."','".date("Y-m-d H:i:s")."','USSD')");
          $response="END Thank you for information";
        }
        else
        {
          $response="END Please select the correct option number";
        }
    }
    else
    {
        $response="CON Please Choose a Service\n";
        $response.="1. Please Enter Number of FMD Suspected Cattle";
    }
}
else
{
    //Tuma ujumbe wa sms and audio
    $sqlselussdoption=mysqli_query($link,"select * from ussd_menu where option_no='".$explodedtextvalue[0]."'");
    if(mysqli_num_rows($sqlselussdoption)>0)
    {
        while($sqlselussdoptionrows=mysqli_fetch_array($sqlselussdoption))
        {
            $sqlselectAwareness=mysqli_query($link,"select * from fmd_awareness where broadcast_status='Active' and
            option_no='".$explodedtextvalue[0]."'");
            if(mysqli_num_rows($sqlselectAwareness)>0)
            {
                $response="END Please wait, you will receive the Message";
                while($sqlselectAwarenessrows=mysqli_fetch_array($sqlselectAwareness))
                {
                    if($sqlselectAwarenessrows['sms_voice_call']=='SMS')
                    {
                        Broadcast_sms_and_Voice($sqlselectAwarenessrows['fmd_awareness_title'],$sqlselectAwarenessrows['fmd_awareness'],
                        $link,$sqlselectAwarenessrows['option_no'],$phoneNumber);
                    }

                    if($sqlselectAwarenessrows['sms_voice_call']=='Voice Call')
                    {
                        $voicefilename="<".$sqlselectAwarenessrows['fmd_awareness'].">";
                        Broadcast_sms_and_Voice($sqlselectAwarenessrows['fmd_awareness_title'],$voicefilename,$link,$sqlselectAwarenessrows[
'option_no'],
                        $phoneNumber);
```

```
                    }
                }

            }
            else
            {
                $response="END The information you have requested was not yet uploaded, please try again later";
            }

        }
    }
    else
    {
      $text="";
      $response="END Please choose the correct service and try Again";
    }


}

header("Content-Type:text/plain");
mysqli_close($link);
echo $response;

//Broadcast sms OR Voice
function Broadcast_sms_and_Voice($subject,$message,$link,$messagename,$mobilenumber)
{
    //Broadcast Events
    $uniquid=uniqid();
    $sqlsendsms=mysqli_query($link,"insert into smsdlv_outbox(ID,ToNo,Subject,Message,CreateTime,message_name)
    values('".$uniquid."','".$mobilenumber."','".$subject."','".$message."','".date("Y-m-d H:i:s")."','".$messagename."')");
}
?>
```

Appendix 5: FMD communication algorithm

```
- Start
- Upload the FMD related information (FMD awareness and outbreaks alerts)(FMDInfo) to the
  Permanent Datbase 2(PDB2) ;continue; //Top-level stakeholders
- Load all cattle sheds/Kraals on the map(on the AMoS4T-FMD index page) as health cattle sheds
  (indicate them with green disc);continue; // AMoS4T-FMD
- Livestock keeper Decision to Report FMD Outbreak(ReportFMD)/Access FMD Awareness
  Information (FMDAwarenessInfo) with Feature Mobile Phone(LivestockKeeperMobileNumber);continue; // Livestock Keeper
  if(ReportFMD)
  {
   - Select Reporting Mechanism (by USSD/SMS);continue; // AMoS4T-FMD
    if(USSD)
    {
     - dial a USSD code (e.g. *384*90005#);continue;  // AMoS4T-FMD
     - Select the Option number 1 (Report FMD Outbreaks) ;continue; // AMoS4T-FMD
     - Enter number of FMD suspected cattle and submit;continue;  // AMoS4T-FMD
      if(LivestockKeeperMobileNumber registered=='Yes')
      {
          - Store the reported number of suspected cattle in the Temporary Database (TDB);continue; // AMoS4T-FMD
          - Update the reporter cattle shed/kraals on the map from green to blue disc (indicating unverified case); continue;// AMoS4T-FMD
      }
      else
      {
          - Discard Reported Case and send SMS to the reporter(Feedback) informing that she was not registered
           to use this service; end;// AMoS4T-FMD
      }
    }
    else
    {
     - Open SMS Menu and send the number of FMD suspected cattle to a Given AMoS4T-FMD Mobile Number; continue; // AMoS4T-FMD
      if(LivestockKeeperMobileNumber registered=='Yes')
      {
          - Store the reported number of suspected cattle in the Temporary Database (TDB); continue;// AMoS4T-FMD
      }
      else
      {
          - Discard Reported Case and send SMS to the reporter(Feedback) informing that she was not registered
           to use this service; end; // AMoS4T-FMD
      }
    }

    - Validate FMDReportedCase in Temporary Database (TDB)// Top-level stakeholders
     if(FMDReportedCase valid=='Yes')
     {
          - Store the number of FMD reported case and the reporter mobile number in Permanent Database 2 (PDB2); continue;// AMoS4T-FMD
          - Send SMS and Robocalls alerts to all livestock keepers informing the FMD outbreak in the respectively village; continue;//AMoS4T-FMD
          - Update the reporter cattle shed/kraals on the map from green to red disc (indicating confirmed case); continue;// AMoS4T-FMD
     }
     else
     {
          - Discard the reported case and inform the reporter that the case is invalid; end; // AMoS4T-FMD
```

```
    }
}

if(FMDAwarenessInfo)
{
    - dial a USSD code (e.g. *384*90005#) ;continue;
    - Select other Option (2.....) than Option Number 1 ;continue;
    - Fetch the particular FMDInfo from PDB2 ;continue; // AMoS4T-FMD
    - Broadcast that particular FMDInfo to the reporter in SMS and Robocall ;continue; // AMoS4T-FMD
}

- The system also periodically broadcast FMDInfo from PDB2 to livestock keepers based on allocated time interval // AMoS4T-FMD
for (every 30 seconds) // AMoS4T-FMD
{
 - Fetch FMDInfo from PDB2 and record its broadcast time interval (BrT), record time since last broadcast(LatsBrTi) and
     Operating system time (OsT)
  if (OsT-LatsBrTi< BrT)
  {
    - Broadcast that particular FMDInfo ;continue;
    - update LatsBrTi set LatsBrTi=OsT ;continue;
  }
  else
  {
    -Skip a particular FMDInfo; end
  }
  ;continue
}
```

Appendix 6: Weather Condition API

```php
<?php
$url="https://api.weather.com/v2/pws/observations/current?stationId=IMOROG3&format=json&units=e&apiKey=ee8e4b939ea7498a8e4b939ea7a98ace";
$urloutput=@file_get_contents($url,true);
if($urloutput===false)
{
}
else
{
 $data=json_decode($urloutput);
}
//Checking if weather station is online
$weatherstation_latitude="";
$weatherstation_longitude="";
if(isset($data))
{
    foreach($data->observations as $item)
    {
         $weatherstation_latitude=$item->lat;
         $weatherstation_longitude=$item->lon;
    }
}
?>
```

Appendix 7: Function to Calculate the bearing angle and distance between two latitudes and longitudes

```
Function calculate_angle_distance ($source_ latitude, $source_ longitude, $distination_ latitude,
$distination_ longitude)
{

    //Calculate bearing angle

    $x=cos($distination_latitude)*sin($distination_longitude-$source_longitude);

    $y=cos($source_latitude)*sin($distination_latitude)-
    sin($source_latitude)*cos($distination_latitude)

    *cos($distination_longitude-$source_longitude);

    $b=atan2($x,$y);

    $angle=rad2deg($b);

    if($angle<0)

    $angle=180+$angle+180;

    else

    $angle=$angle;

   //Calculate the distance between affected cattle shed and health cattle sheds

    $theta = $source_longitude - $distination_longitude;

    $dist = sin(deg2rad($source_latitude)) * sin(deg2rad($distination_latitude)) +
    cos(deg2rad($source_latitude))

    * cos(deg2rad($distination_latitude)) * cos(deg2rad($theta));

    $dist = acos($dist);

    $dist = rad2deg($dist);
```

```
        $miles = $dist * 60 * 1.1515;

        $distance = round(($miles * 1.609344),1);

        $a=array($angle,$distance);

        return $a;
}
```

Appendix 8: The four months (March 2021-June 2021) FMD outbreaks secondary data

DATE	GAIRO TOWN
21/03/2021	7
24/03/2021	25
25/03/2021	9
29/03/2021	12
01/04/2021	11
03/04/2021	15
08/04/2021	3
14/04/2021	25
20/04/2021	75
21/04/2021	32
26/04/2021	20
30/04/2021	11
03/05/2021	28
09/05/2021	11
15/05/2021	25
21/05/2021	8
22/05/2021	7
28/05/2021	4
29/05/2021	27
31/05/2021	9
09/06/2021	12

DATE	KILAMA	CHOGOALI
03/03/2021	1	6
05/3/2021	1	0
08/03/2021	1	1
09/03/2021	2	2
10/03/2021	3	1
11/03/2021	1	2
13/03/2021	4	0
14/03/2021	4	1
16/03/2021	3	5
19/03/2021	1	2
20/03/2021	5	1
22/03/2021	3	4
25/03/2021	6	0
27/03/2021	1	3
28/03/2021	2	4
02/04/2021	2	5
03/04/2021	2	5
07/04/2021	1	6
12/04/2021	2	4
13/04/2021	7	5
15/04/2021	6	11
16/04/2021	11	9
18/04/2021	7	7
21/04/2021	6	7
26/04/2021	10	4
29/04/2021	6	5
03/05/2021	4	6
07/05/2021	4	2
08/05/2021	3	2
10/05/2021	3	1
11/05/2021	1	0
14/05/2021	0	1
17/05/2021	1	0
21/05/2021	1	0
22/05/2021	0	0
27/05/2021	0	0
31/05/2021	1	0

DATE	CHAKWALE	KILIMANI
03/03/2021	2	1
04/3/2021	0	1
06/03/2021	3	4
09/03/2021	2	3
10/03/2021	2	4
11/03/2021	4	5
12/03/2021	7	4
14/03/2021	8	5
16/03/2021	9	6
19/03/2021	5	10
20/03/2021	8	5
22/03/2021	9	6
25/03/2021	14	12
27/03/2021	15	8
28/03/2021	6	13
02/04/2021	6	8
03/04/2021	7	12
05/04/2021	9	7
11/04/2021	11	16
13/04/2021	11	20
15/04/2021	12	17
16/04/2021	17	10
18/04/2021	9	14
20/04/2021	10	11
23/04/2021	11	7
24/04/2021	13	6
03/05/2021	12	5
07/05/2021	8	6
08/05/2021	6	5
09/05/2021	4	4
11/05/2021	3	1
12/05/2021	2	1
17/05/2021	1	1
20/05/2021	1	2
22/05/2021	2	1
27/05/2021	0	1
31/05/2021	0	1

Appendix 9: Questionnaire for validating the FMD communication module

"Monitoring System for Transboundary Foot and Mouth Disease (FMD) Considering Livestock Keepers Demographic Characteristics in Gairo District"

Livestock Owners Informed Consent

You are being invited to test the animal's disease surveillance system known as a Monitoring System for Transboundary Foot and Mouth Disease (FMD) Considering Livestock Keepers Demographic Characteristics in Gairo District. The test is aimed to assess your ability to access the system using your feature mobile phone and get the desired response from the system based on the given directives. We hope the testing results will help on improving the system before deployment. This research is being conducted by experts from the Nelson Mandela Institution of Science and Technology (NM-AIST) in Tanzania under African Development Bank (AFDB) Project Fund. Please read the information in this sheet which explains what is involved and any benefits or challenges. We encourage you to ask the study representative to explain parts of the testing procedure that are not clear or if you have further questions. Take as much time as you need to decide whether you would like to be involved or not.

STATEMENT OF CONSENT

I confirm that I have read the information in this document or that it has been read to me thoroughly. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason and without my legal rights being affected.

______________________	______________	______________
Name of the Subject	Date	Signature
______________________	______________	______________
Name of a Person taking consent	Date	Signature

QUESTIONNAIRE FOR LIVESTOCK OWNERS

1. Can you access the USSD menu?

   A. [ ] Yes

   B. [ ] No

2. Are you able to report FMD incident/outbreak to the system using the USSD menu?

   A. [ ] Yes

   B. [ ] No

3. Are you able to report FMD incident/outbreak to the system using the SMS?

   A. [ ] Yes

   B. [ ] No

4. Are you able to access FMD awareness information using USSD menu?

   A. [ ] Yes

   B. [ ] No

RESEARCH OUTPUTS

(i) Publications

Kijazi, A., Kisangiri, M., Kaijage, S., & Shirima, G. (2021a). A Monitoring System for Transboundary Foot and Mouth Disease considering the Demographic Characteristics in Gairo, Tanzania. *Engineering, Technology & Applied Science Research*, 11(4), 7302–7310. https://doi.org/10.48084/etasr.4140

Kijazi, A, Kisangiri, M., Kaijage, S., & Shirima, G. (2021b). A Proposed Information System for Communicating Foot-and-Mouth Disease Events among Livestock Stakeholders in Gairo District, Morogoro Region, Tanzania. *Advances in Human-Computer Interaction*, 2021, 1-9. https://doi.org/10.1155/2021/8857338

Kijazi, A., Kisangiri, M., Kaijage, S., & Shirima, G. (2022). Towards an Integrated Mobile Technology on Animal Disease Surveillance Framework in Tanzania: A Systematic Review. *Journal of Information Systems Engineering and Management,* 7(2), 1-13. https://doi.org/10.55267/iadt.07.12044

(ii) Poster Presentation

A Monitoring System for Transboundary Foot and Mouth Disease Considering Livestock Keepers Demographic Characteristics

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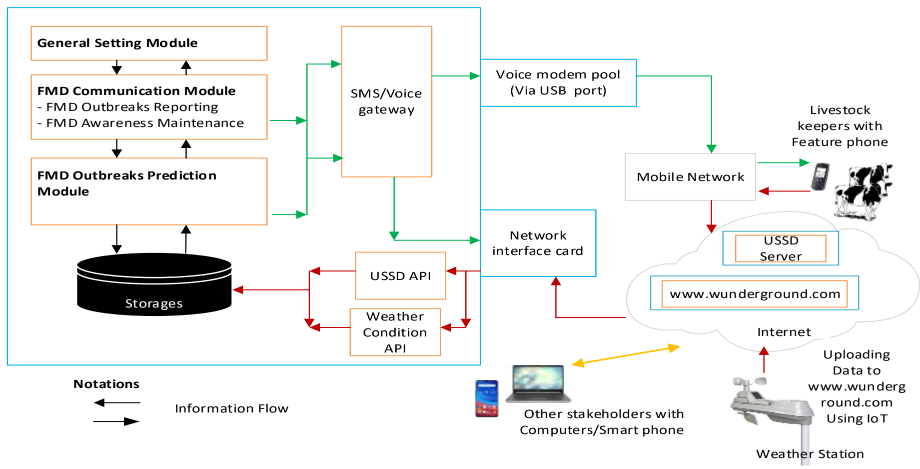
The Nelson Mandela African Institution of Science and Technology

Background

Foot and Mouth disease (FMD) is a transboundary disease caused by a virus that affects domestic and wild cloven-hooved animals such as sheep, goats, pigs, and buffalos. Apart from other animal diseases, FMD has been given great attention due to its unique behaviour, such as being potentially dangerous, rapidly spreading disease, and it has no cure. Therefore, immediate information flow among livestock stakeholders could help to mitigate FMD

FMD Communication Process



Problem Statement

Livestock owners who are the primary informer of FMD outbreaks/incidents were not considered/included in most electronic-based animal diseases surveillance systems developed. The surveillance systems were implemented using advanced technologies such as android and web-based applications, requiring skills and special devices (smartphones or computers) to access them. In contrast, most livestock owners, especially in developing countries, lack these facilities. Similarly, the systems require an internet connection to access them, which is highly limited in rural settings. The negligence of livestock keepers in giving or receiving FMD information through the surveillance systems causes the delay of information for FMD control. Therefore, an electronic-based surveillance system that could accommodate livestock keepers among the system users for sharing FMD-related information between themselves and top-level stakeholders using friendly technologies is needed

Objectives

General Objective:

To develop an electronic-based surveillance system that accommodates livestock keepers among the system users for sharing FMD data between themselves and other stakeholders using various mobile technologies based on their demographic characteristics.

Specific Objectives

(i) To gather user requirements in the Gairo district for developing the FMD surveillance system

(ii) To formulate an algorithm for livestock keepers to communicate with the surveillance system by considering their demographic characteristics

(iii) To develop an Agent-Based Simulation Model for predicting FMD outbreaks in the Gairo district

(iv) To develop the FMD surveillance system by combining objectives no (ii) and (iii)

(v) To validate the developed FMD surveillance system