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TECHNICAL REPORT

MALARIA EARLY WARNING IN ETHIOPIA

A ROADMAP FOR SCALING TO THE NATIONAL LEVEL



May 2021

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Cover Photo: Michael Wimberly, March 2009. Rural landscape in the Amhara region of Ethiopia.

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May 2021

Prepared for:

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ACRONYMS

API	Annual Parasite Incidence
COVID-19	Coronavirus Disease 2019
EPIDEMIA	Epidemic Prognosis Incorporating Disease and Environmental Monitoring for Integrated Assessment
EPHI	Ethiopian Public Health Institute
EPSA	Ethiopian Pharmaceuticals Supply Agency
FMOH	Federal Ministry of Health
GEE	Google Earth Engine
GIS	Geographic Information System
HMIS	Health Management Information System
IRB	Institutional Review Board
NMEP	National Malaria Elimination Program
NGO	Non-Governmental Organization
PHEM	Public Health Emergency Management
PMI	President's Malaria Initiative
TOT	Training of Trainer
US	United States
USAID	United States Agency for International Development
WHO	World Health Organization

EXECUTIVE SUMMARY

OVERVIEW

Although tremendous progress has been made in reducing the global burden of malaria, innovative approaches are needed to control and eliminate the disease (Feachem et al., 2019). Malaria surveillance, including outbreak detection, is one of the pillars of the World Health Organization's (WHO) Global Technical Strategy for Malaria (WHO, 2015). Timely surveillance provides critical information on emerging outbreaks that can inform appropriate interventions at the times and places most needed. Transmission is sensitive to fluctuations in temperature, humidity, and precipitation (Mordecai et al., 2013; Smith et al. 2020). These relationships can be used to develop early warning systems to predict changes in malaria incidence. Forecasts add lead time that permit proactive interventions to reduce outbreak severity.

An extensive body of scientific literature documents the influence of climate variability on malaria in Ethiopia. Annual cycles of malaria transmission are closely linked to seasonal weather patterns (Wimberly et al., 2012; Midekisa et al., 2015). Malaria outbreaks have been associated with climate anomalies, including warm temperatures in cooler highland environments and excess rainfall in dry environments (Abeku, 2003; Abeku et al., 2004a; Midekisa et al., 2015; Teklehaimanot et al., 2004a). The limit for malaria transmission is shifting to higher elevations because of climate change. As a result, 6.5 million people are estimated to be at increased risk of malaria (Lyon et al., 2017). Multiple calls to translate these findings into malaria early warning systems that can target interventions (Abeku et al., 2004b; Midekisa et al., 2012; Teklehaimanot et al., 2004b) have met with technical and logistical barriers.

This project builds on more than a decade of collaborative research on malaria-climate relationships and malaria forecasting, culminating in the Epidemic Prognosis Incorporating Disease and Environmental Monitoring for Integrated Assessment (EPIDEMIA) project. We implemented this malaria early warning pilot with regional public health partners in Amhara (Merkord et al., 2017). The project produced the EPIDEMIA system—computational tools that leverage surveillance data systems, automate complex workflows to integrate climate data, and generate formatted early warning reports with alerts for public health stakeholders. It uses relatively inexpensive computer hardware and free cloud-based services.

This report recommends a path for scaling EPIDEMIA to the national level. We reviewed the suitability of national-level malaria surveillance datasets for classifying districts based on malaria risk (malaria stratification) and for calibrating and validating climate-driven models for malaria early warning. We developed new techniques for screening anomalous data values and imputing missing data to improve the robustness of these applications. To gain a better understanding of the opportunities and challenges of national-level implementation, we met with public health sector stakeholders from Ethiopia.

KEY FINDINGS

1: Implementing a national malaria early warning system in Ethiopia is necessary and feasible.

Routine forecasting of malaria outbreaks can help target prevention, control, and elimination activities that will reduce the burden of disease and mortality. We demonstrated that climate-based malaria forecasts are more accurate than predictions based on malaria surveillance alone. The cost to implement a malaria early warning system is estimated at \$725,000 a year for three years, plus \$400,000 for a fourth year of follow-up and evaluation. This is a relatively small investment compared to the estimated \$200 million spent on malaria control and elimination each year in Ethiopia (Assebe et al., 2020). Implementation will increase the capacity of the public health sector to use data effectively for public health decision-making, yielding benefits that extend to other diseases.

2: The system must have committed owners with a large stake in achieving sustainable implementation. We recommend forming a multi-institutional *steering committee* to monitor scale-up and make key implementation decisions. It should include representatives from the National Malaria Elimination Program (NMEP), the Ethiopian Public Health Institute (EPHI), the U.S. President's Malaria Initiative (PMI), and personnel from the Federal Ministry of Health (FMOH) working with health information systems and representatives of the regional health bureaus. A *core team* should handle technical implementation, day-to-day operation, and continued development of the system. This *core team* should be part of EPHI, which has the capabilities in public health surveillance, research, and emergency response.

3: Timely and accurate data are critical requirements for malaria early warning. Suitable malaria surveillance data are available to support early warning, but several challenges must be addressed. These include gaps in completeness and accuracy of malaria data, barriers to accessing climate data, and difficulties connecting malaria and climate data. We dealt with these challenges by 1) developing new techniques for data screening and imputation of surveillance data, and 2) creating web-based tools to download and process remotely sensed climate data in low-bandwidth areas. Incorporating additional data on malaria interventions and mosquito surveillance can improve malaria outbreak predictions and enhance decision-making.

4: Modern data science techniques and tools are needed to capitalize on the growing body of available information. Automating routine data processing and modeling is essential to support malaria forecasting. Computational tools can be implemented as free and open-source software to eliminate barriers to access and permit future updates. In addition, technologies such as cloud computing can streamline implementation and data access. Tools should be designed to work with existing data management systems to provide value-added results.

5: The EPIDEMIA tool meets the need for data science tools to support malaria early warning. The EPIDEMIA tool has been used to generate malaria predictions for the Amhara and Oromia regions. Critical elements include tools for data screening and cleaning, access to climate data via Google Earth Engine (GEE), and scripts that automate key data processing, modeling, and reporting. EPIDEMIA uses free and open-source software that can be implemented on affordable laptop and desktop computers. Validation results show the accuracy of climate-driven forecasts is higher than predictions based solely on historical malaria case data.

6: Malaria forecasting must be connected to public health responses across multiple levels of the public health system. Although malaria early warning will be implemented at a national level, the forecasts must be disseminated throughout the public health system. The decisions to be made and the information required will vary. At the national level, long-term forecasts (three to six months) will support decisions about drug and supply purchases. Information on the locations of future outbreaks is less important at this level. Decisions about where to distribute supplies require predictions at zone and district (*woreda*) levels with a lead time of one to three months, where timely, effective responses are critical. Decisions about where and when to apply malaria control interventions require precise locations at the sub-district level but can be carried out relatively quickly if the necessary supplies are locally available.

7: Training and other capacity building is essential for the tools developed to be widely used.

The core team will need strong foundational knowledge of the data science techniques used in EPIDEMIA, including coding in the R language, remote sensing science, and predictive modeling of malaria outbreaks. Training must be a sustained, multi-year effort that includes scientists from public health agencies and university faculty. A larger number of individuals working across multiple levels in the health system will also need training to interpret and apply the forecasts. This can be met through a training-of-trainers (TOT) approach, using participants from national and regional public health agencies and universities with the knowledge and resources to train public health professionals.

CONCLUSIONS

We propose the malaria early warning system EPIDEMIA be scaled to the national level using a four-year roadmap. Implementation and training occur during the first three years. The Ethiopian partners will operate the system independently in the fourth year with aid from the U.S. technical support team.

To begin implementation, the critical actions are:

- 1) obtain feedback on this document from major implementing partners, including the FMOH, NMEP, and EPHI, and make improvements based on their input,
- 2) receive formal buy-in and strong support from these partners to scale up the program,
- 3) develop a detailed project budget in collaboration with the implementing partners,
- 4) secure funding from one or more donor organizations.

Once begun, major steps in the roadmap involve:

- 1) formally establishing the steering committee to oversee and govern the process,
- 2) identifying the core team responsible for system operation,
- 3) determining the key tasks and developing a manual with guidelines for implementation,
- 4) initiating capacity-building and training programs for sustainable implementation,
- 5) gradually increasing the geographic scope and the core team's responsibility for generating forecasts,
- 6) identifying opportunities to use the forecasts to support decisions for malaria elimination and public health emergency response.

BACKGROUND

Tremendous progress has been made in the past two decades to reduce the global burden of malaria and begin to eliminate the disease from many countries (Bhatt et al., 2015; Feachem et al., 2010). However, malaria remains one of the most significant public health challenges in many low- and middle-income countries, particularly in sub-Saharan Africa. Progress toward eliminating malaria has stalled as malaria cases have declined globally (WHO, 2019). The causes of this slowdown are multiple, but one important reason is the limited set of tools and approaches available for malaria control and elimination (Feachem et al., 2019).

New technologies, including innovations in malaria informatics, are needed to facilitate data-driven management of malaria programs (Feachem et al., 2019). Malaria surveillance, including outbreak detection, is one of the pillars of the WHO's Global Technical Strategy for Malaria (WHO, 2015). To make surveillance a more effective and efficient core intervention, technical innovations in malaria informatics are needed to better use available data to target and evaluate malaria interventions (Hemingway et al., 2016). A major opportunity for using malaria surveillance data more effectively involves shifting from a reactive to a *predictive* approach by using widely available malaria data to understand variation in malaria transmission over space and time. This knowledge can be used to develop models for forecasting where and when will malaria risk will increase.

One promising strategy for malaria prediction involves integrating malaria case surveillance with other information about risk factors for the disease. Data on the variability of climate factors such as temperature, humidity, and precipitation, are particularly valuable. Temperature and humidity affect the vital rates that drive mosquito population dynamics, parasite development in the mosquito, and parasite transmission (Mordecai et al., 2013). Precipitation is a critical component of the hydrological cycle that influences the aquatic habitats where anopheline mosquito larvae develop (Smith et al., 2020). The relationships between these meteorological drivers, mosquito populations, and malaria transmission cycles are mediated by physiographic features that influence local hydrology and human activities, such as agriculture and water management. These create larval habitats and affect human exposure to mosquitoes. Despite this complexity, often just one or a few main climate variables influence malaria transmission at a given site. If these climate drivers can be identified, monitoring climate variability can provide early warning of an impending epidemic.

In Ethiopia, an extensive body of research documents the influences of climate variability on malaria cases over time. Temperature and precipitation have been highlighted as important drivers of malaria epidemics, but their effects on malaria vary depending on local climate and geography (Abeku, 2003; Abeku et al., 2004a; Midekisa et al., 2015; Teklehaimanot et al., 2004a). In general, temperature is a more important driver in cooler highland regions; precipitation is more important in drier areas. These relationships have led multiple researchers

to propose applying climate-driven models for malaria early warning in Ethiopia (Abeku et al., 2004b; Midekisa et al., 2012; Teklehaimanot et al., 2004b), and for sub-Saharan Africa (Thomson & Connor, 2001). However, translating these ideas into operational systems has proved challenging. Although the potential for malaria early warning has been demonstrated through retrospective analyses of historical data, technical and logistical barriers combined with a lack of funding for implementation have prevented the use of climate-driven malaria forecasting to support public health programs.

The EPIDEMIA pilot project addressed this gap, studying malaria early warning in the Amhara region of Ethiopia (Merkord et al., 2017). It led to the creation of new computational tools to automate the data processing, modeling, and report generation steps necessary for malaria forecasting. Scientists from the United States and a steering committee of stakeholders from regional public health agencies, universities, and nongovernmental organizations developed these tools. The project held multiple workshops in Ethiopia and the United States to obtain feedback from stakeholders. This informed the technical design of the system as well as the contents of reports generated for public health sector users. The result was the EPIDEMIA tool, which leverages the capabilities of existing surveillance data systems, facilitates access to and integration of climate data, and produces formatted early warning reports with outbreak alerts for public health stakeholders. It uses relatively inexpensive computer hardware and free cloud computing services.

This report expands on these efforts, proposing a roadmap for scaling up a sustainable malaria early warning system to a national level in Ethiopia. The work involves further development of technical tools to allow national-level malaria forecasting based on existing datasets and engagement with public health institutions to develop a process for implementation. We upgraded the EPIDEMIA tool to make it usable in any region of Ethiopia and to incorporate new techniques for accurate assessment of malaria forecasts. We reviewed the suitability of national-level malaria surveillance datasets to support malaria risk mapping and early warning forecasts. We also developed new tools to screen and impute missing and anomalous data values. To better understand the opportunities and challenges of national-level implementation, we engaged with stakeholders through in-person presentations and meetings, virtual webinars followed by group discussions, a web-based survey, and individual consultations with key stakeholders. These activities are described in the next section.

The intended audience is federal, regional, and district public health institutions in Ethiopia engaged in malaria elimination and research, including the FMOH, NMEP, and EPHI. These institutions have been involved throughout the report development process.

METHODS

To develop the malaria early warning roadmap, we undertook the following tasks:

1. We examined available sources of national-level malaria surveillance data to assess their suitability for supporting a national malaria early warning system. (Wimberly et al. 2020a; Wimberly et al. 2020b).
2. We made technical updates to the EPIDEMIA tool to facilitate its application across entire regions anywhere in Ethiopia. The updated EPIDEMIA tool was used to demonstrate the technical capacity for scale-up by generating and validating forecasts in Oromia, the largest region in Ethiopia.
3. We met with key stakeholder groups to gauge the level of support for malaria early warning, identify opportunities for using malaria forecasts to support decision-making, and determine barriers to scale-up.

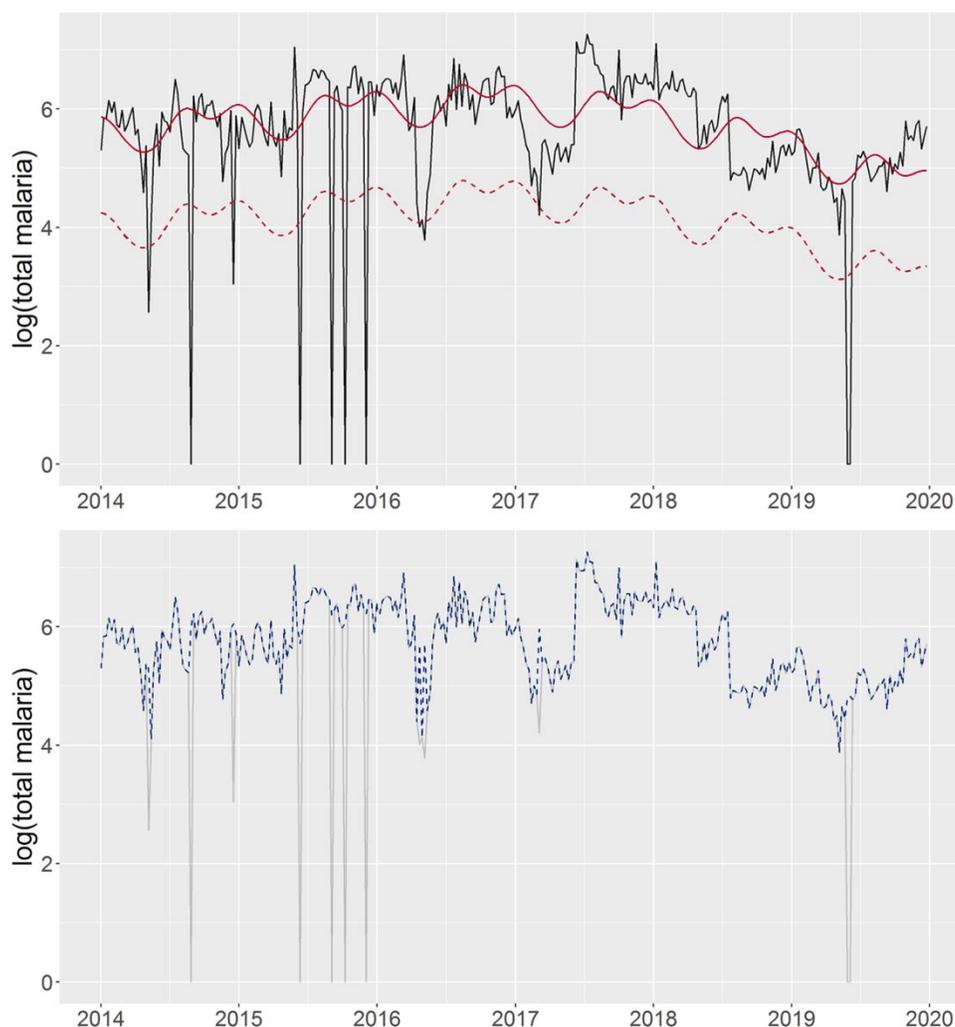
We synthesized the results of these activities into this report to develop a set of recommendations and a roadmap of actions required to scale up the EPIDEMIA tool.

DATA EVALUATION

We evaluated the suitability of three sources of malaria surveillance data for malaria stratification and early warning in Ethiopia. These are the Public Health Emergency Management (PHEM) system, the Health Management Information System (HMIS), and the U.S. President's Malaria Initiative (PMI) microplanning dataset. We also assessed two other types of data, human population, and geospatial data, which are critical for malaria applications. Human population data are essential for determining the population at risk and calculating malaria incidence from case data. Geospatial data of district and city boundaries are needed to create maps and connect climate and malaria data.

Our initial assessment found limitations of the HMIS and PMI microplanning data that made them unsuitable for malaria early warning. Therefore, we concentrated on a detailed evaluation of the PHEM dataset. We assessed reporting completeness and timeliness, and the prevalence of extreme data values suspected to be errors (Wimberly et al. 2020a). We developed and tested a novel data screening method that uses robust regression to identify suspect data values and impute suitable replacement values for missing and suspect data (Figure 1).

Figure 1 Example of screening and imputation of malaria case data for a district

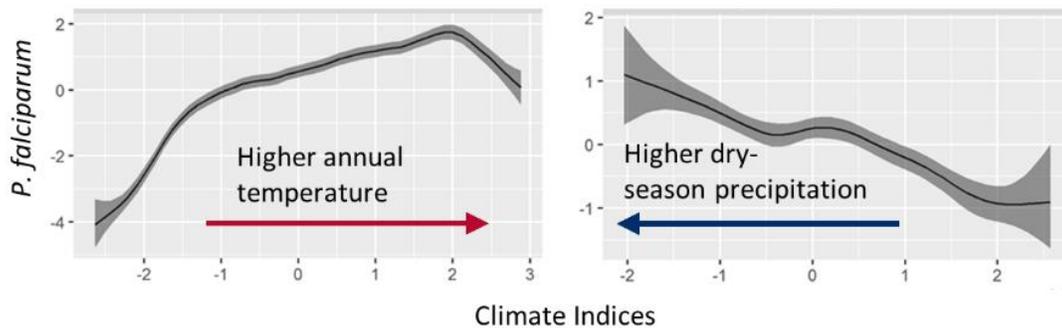


Note: The upper graph shows a fitted robust time series regression (solid red line) with a 3 standard deviation lower threshold (dashed red line). Observed values below this line are replaced with the fitted values to generate a corrected time series, shown in the lower graph. A full description of the technique is presented in Wimberly et al. (2000b).

We developed procedures for linking malaria surveillance with data on human populations and district boundaries. To accomplish this, we had to address significant challenges, including frequent splitting of districts into new districts and cities, and reconciling inconsistencies in district names and identification codes across datasets. We resolved these differences by developing a spatial crosswalk to match malaria and population data to each district boundary. The crosswalk generated a harmonized national-level dataset with consistent district-level time series of PHEM malaria surveillance and population data from 2014–2019 (Wimberly et al. 2020b). We used these data to map annual parasite incidence (API) for all of Ethiopia, model the influences of climate on geographic and interannual variations in API, and detect recent short-term trends in API (Figure 2).

Figure 2 Results from analysis of the harmonized dataset of API

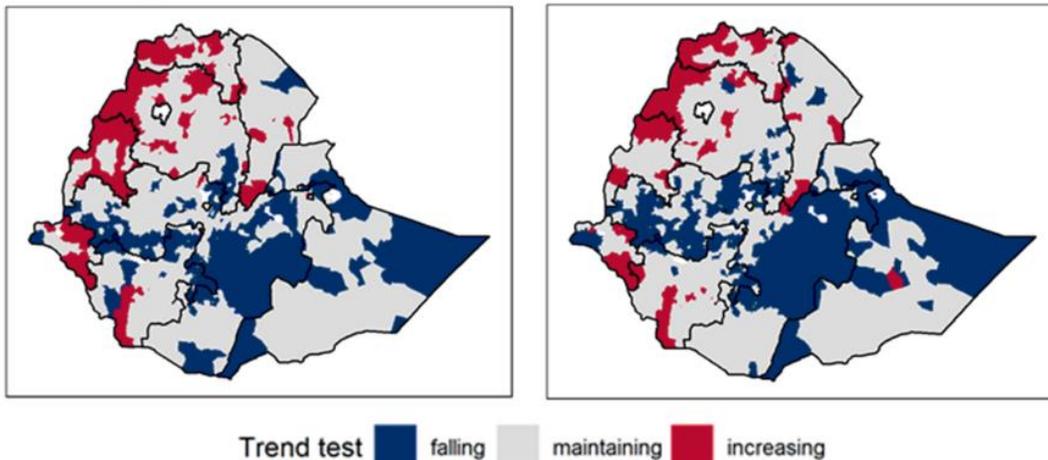
Response of annual parasite incidence (API) to climate variables.



API trends from 2014-2019 after controlling for climate.

P. falciparum cases

P. vivax cases



Note: The top row shows the influences of annual temperature and dry-season precipitation on *Plasmodium falciparum* incidence. The bottom row shows recent trends in *Plasmodium falciparum* and *Plasmodium vivax* after controlling for climate variability. Details of the analysis are in Wimberly et al. (2000a).

EPIDEMIA TOOL DEVELOPMENT

We developed the EPIDEMIA tool using free, open-access software (Figure 3). EPIDEMIA integrates surveillance and climate data to generate malaria forecasts up to 12 weeks. The forecasts require historical databases of weekly malaria surveillance and daily district-level climate variables. These data are used to calibrate generalized additive models that allow flexible, non-parametric fits to the lagged climate effects as well as seasonal and long-term trends in malaria incidence. An important part of model specification and calibration is selecting clusters of districts with similar climate sensitivities so a specific model can be used for each cluster. We developed a novel clustering technique based on an evolutionary algorithm that selects an optimal set of clusters for modeling (Davis et al., 2019).

Once the initial setup is complete, EPIDEMIA is run weekly (Figure 3). It is designed to minimize the number of steps for the user and requires less than an hour to generate a weekly forecast

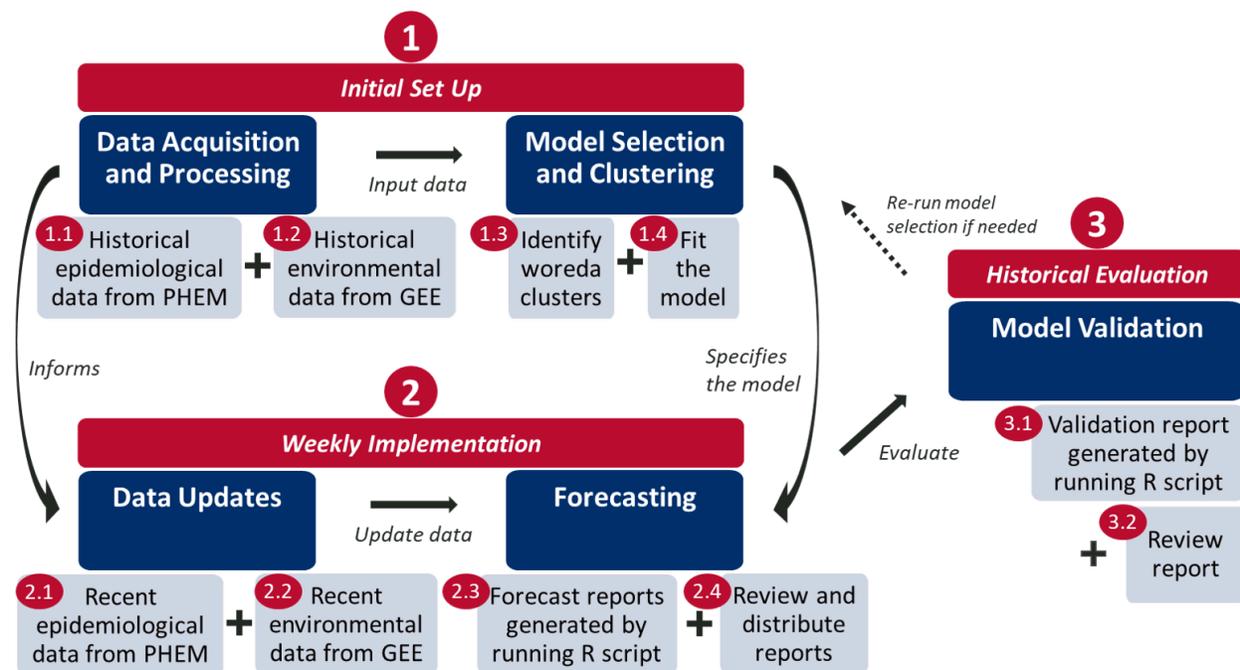
for an entire region. Each week, the user manually queries the existing data management system (PHEM) to obtain new surveillance data and downloads climate data via a simplified web interface implemented in GEE. The user copies these data files into the appropriate folders on the computer and runs a customized script using R, a free and open-source language and environment for data science. The script automatically executes all data processing and modeling steps and generates a detailed report containing maps and charts that summarize the forecasts along with recent malaria and climate observations.

Two types of alerts are generated:

- 1) *Early detection alerts*: Compares recent malaria case observations to an alert threshold based on historical patterns.
- 2) *Early warning alerts*: Compares the EPIDEMIA forecasts of malaria cases out to 12 weeks to the alert thresholds for this future period.

Alert thresholds are based on the Farrington methods for outbreak detection, which account for seasonality as well as multi-year trends in malaria cases (Nekorchuk et al., 2021).

Figure 3 Flowchart of the major stages and steps in the EPIDEMIA forecasting system



Note: Stage 1 includes processing the historical epidemiological and environmental data and fitting the model with selected spatial clusters of woredas. Stage 2 generates weekly forecasts by acquiring recent data, running the forecasting models, and generating a formatted report with early detection and early warning alerts that can be reviewed and distributed. Stage 3 evaluates the forecasting model performance for any historical period, comparing accuracy statistics from the forecast model against two naïve models built solely from epidemiological data.

At the beginning of this project, the EPIDEMIA tool had been piloted in 47 districts in the Amhara region (Merkord et al., 2017). The major components included the *epidemiarr* package, a set of core functions for data management, modeling, and visualization, and the *epidemia-*

demo project, which includes data and a sample script for using these functions to generate forecasts for the pilot districts using synthetic demonstration data. To use EPIDEMIA for malaria early warning at the national level, these forecasts need to be expanded to the entire Amhara region and other regions of Ethiopia. We therefore tested EPIDEMIA in Oromia, the largest region in Ethiopia, using the harmonized, national-level PHEM dataset.

To facilitate national use of EPIDEMIA, we made significant updates and improvements requested during initial consultations in Ethiopia. The previous version of EPIDEMIA (Version 2.0.0, released August 21, 2019) had a limited set of modeling options optimized for the Amhara region. The current version (Version 3.1.1, released November 10, 2020) has an expanded set of modeling options implemented in a new companion package, *clusterapply*. These improvements permit malaria forecasting over large geographic areas and allow us to adapt the climate-driven models to generate malaria predictions in new environments. We also added a validation module to the *epidemiAR* package that automatically assesses the accuracy of the forecasts by excluding historical observations from the model training dataset and comparing predictions to these observed values (Figure 3).

STAKEHOLDER ENGAGEMENT

At the beginning of the project in November 2019, we went to Addis Ababa to consult with key stakeholder groups on the proposed activities and gather feedback. We met with representatives of USAID/PMI Ethiopia and several implementing partners, the EPHI, the Oromia Regional Health Bureau, the National Meteorological Agency, the FMOH, the Health Development and Anti-Malaria Association, and Addis Continental Institute of Public Health. A major objective was to establish memorandums of understanding with key partners and set up data-sharing agreements to facilitate data evaluation and tool development.

Our original plan was to return to Ethiopia in spring 2020 to hold workshops and in-person stakeholder meetings. However, because of COVID-19, we conducted a series of virtual meetings during the summer and early fall of 2020.

With the support of the USAID Ethiopia mission, we identified four major groups of stakeholders:

- 1) the FMOH, responsible for administering the health system, including the NMEP,
- 2) the EPHI, the main federal research institution focused on public health and responsible for the national PHEM surveillance system,
- 3) the Oromia Regional Health Bureau, which administers the health system of Ethiopia's largest and most populous region, and
- 4) the Malaria Research Network, a consortium of malaria researchers from universities throughout Ethiopia.

The objectives were to inform stakeholders of recent updates and current capabilities of the EPIDEMIA tool for malaria early warning, to identify opportunities to use climate and weather data to enhance malaria surveillance, to get commentary from public health experts on the

prospects for scaling up malaria early warning, and to identify opportunities and roadblocks to expanding malaria early warning. The project team developed the following questions for the meetings:

- What are the gaps in our understanding of the effects of climate and other drivers of malaria outbreaks?
- What are the benefits and challenges of implementing malaria early warning at a national level in Ethiopia?
- What additional types of data could be used to improve predictions of malaria outbreaks?
- What institutions should be involved in the operation, maintenance, application, and continued development of malaria early warning systems in Ethiopia?
- What training and other capacity-building activities are required to facilitate implementation?
- What further updates should be made to EPIDEMIA to improve its suitability for implementing malaria early warning in Ethiopia?

WEBINAR AND DISCUSSION

We held four webinars in August and September 2020, one for each of the four stakeholder groups. Each webinar was scheduled for two hours. This allowed time for introductions, which took 15 minutes, and a presentation that took 45 minutes. We interspersed breaks to encourage attendees to ask questions and offer feedback.

INDIVIDUAL CONSULTATIONS

After the webinars, we invited participants to individual follow-up consultations. Six workshop participants took part in these one-hour consultations from October 21 to 31, 2020. The conversations covered the six original questions, but tended to focus on a subset, depending on the participant's interest and expertise.

ONLINE SURVEY

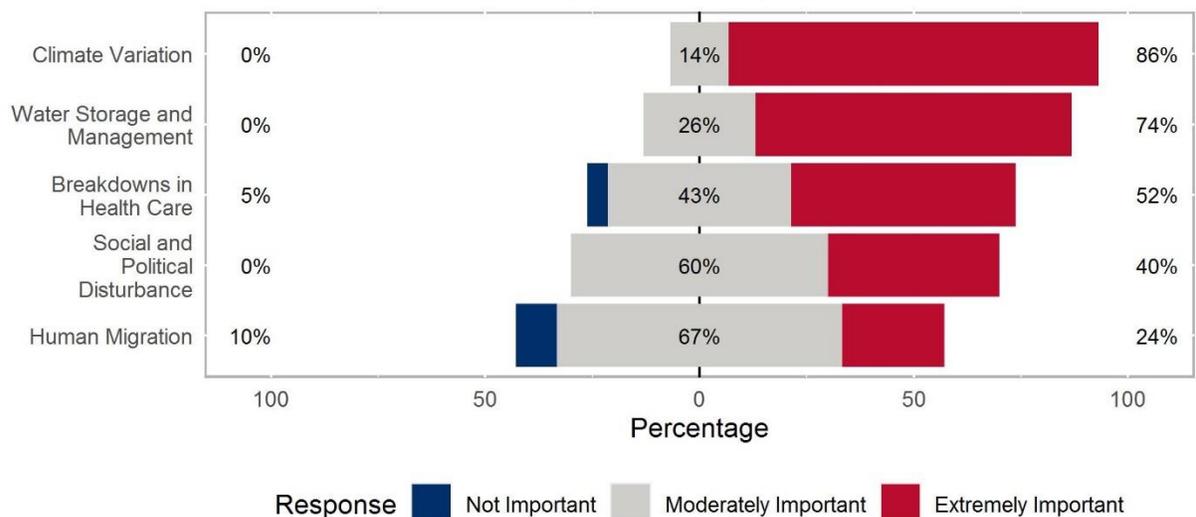
The team developed survey questions based on the six original questions and implemented the survey on the internet using the Qualtrics platform, suitable for mobile platforms as well as laptop and desktop browsers. Via email, we invited 57 people to take the survey, including all those who attended a webinar and those who were invited but did not attend. The survey was open for two weeks, October 21–November 4, 2020. An initial invitation was sent October 21, followed by reminder emails on October 27 and November 2. The University of Oklahoma's institutional review board (IRB# 12603) approved the survey and all associated protocols.

RECOMMENDATIONS

KEY FINDING 1: IMPLEMENTING A NATIONAL MALARIA EARLY WARNING SYSTEM IN ETHIOPIA IS NECESSARY AND FEASIBLE

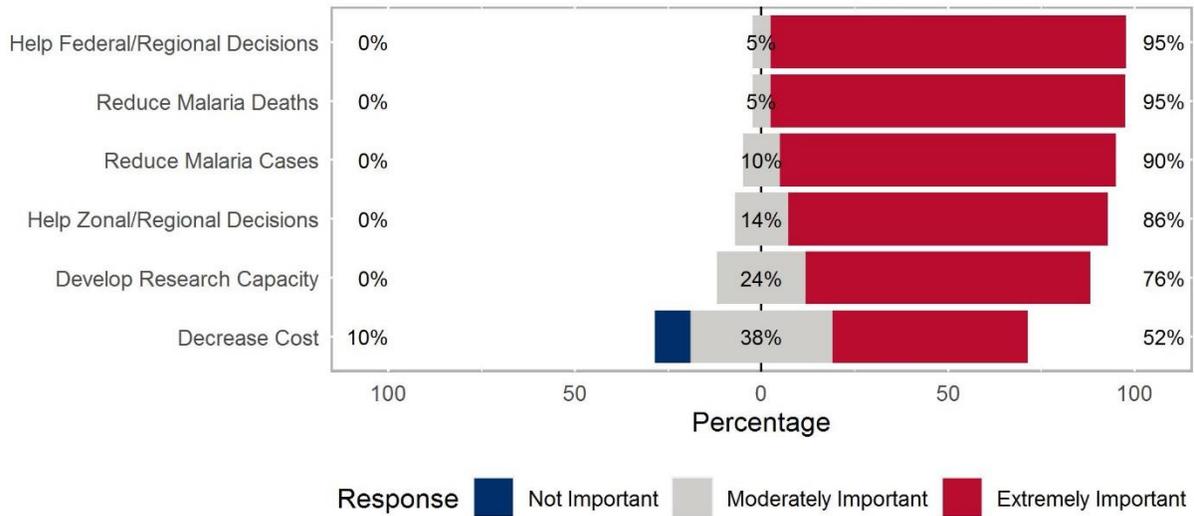
Throughout the engagement process, stakeholders voiced strong and consistent support for implementing malaria early warning at a national level. Climate variability is universally recognized as an important driver of malaria outbreaks in Ethiopia, with 86 percent of survey participants characterizing climate variability as “very important” and no respondents characterizing it as “not important” (Figure 4). There was also strong consensus that scaling up malaria early warning will improve decision-making at multiple levels in the public health system and reduce malaria cases and deaths, with more than 85 percent of respondents characterizing these opportunities as “very important” and no participants characterizing them as “not important” (Figure 5). Stakeholders identified actions that could be undertaken in response to early warning of malaria outbreaks, including distribution of anti-malaria drugs, indoor residual spraying, distribution of insecticide-treated bednets, source control of vector populations, increased malaria surveillance activities, and communication of prevention messages to affected communities.

Figure 4 Participants Characterized Climate Variability as an Extremely Important Driver of Malaria Outbreaks



Note: Responses to: “What do you see as the main drivers of malaria outbreaks in Ethiopia? Rank the importance of each driver.”

Figure 5 Developing research capacity is an extremely important opportunity in malaria early warning scale-up



Responses to: “What do you see as the biggest opportunities that would emerge from scaling up malaria early warning in Ethiopia? Rank the importance of each opportunity.”

Most survey participants also said developing research capacity is an extremely important opportunity in malaria early warning scale-up (Figure 5). Many highlighted the possibility of incorporating additional data sources for malaria surveillance and early warning, including data on historical interventions and mosquito surveillance. They also expressed considerable interest in extending the approach for malaria early warning to other diseases, including vector-borne diseases such as leishmaniasis and dengue, as well as other climate-sensitive diseases like meningitis. These efforts will require additional research, which can provide opportunities for government and university scientists in Ethiopia to apply their scientific knowledge and develop new technical skills. Implementing malaria early warning requires improvements in processing, managing, and using health surveillance data. The data science techniques required for these activities and the experience in using data for public health decision-making can be extended to other diseases.

There was less consensus that malaria early warning can help reduce the cost of malaria programs. More than 50 percent of respondents characterized cost reduction as a “very important” opportunity; only 10 percent characterized it as “not important.” During workshops and discussions, several stakeholders said malaria early warning would be a very cost-effective intervention. They noted that the overall costs for personnel and supplies for malaria early warning would be relatively low compared to the broader anti-malaria efforts now under way and would yield additional benefits for managing other diseases. The estimated cost of \$725,000 per year over three years for implementing the roadmap, and the estimated \$200 million spent on malaria each year in Ethiopia (Assebe et al., 2020) means the malaria early warning implementation would come to 0.36 percent of total expenditures. Overall, malaria early warning was viewed as an economical intervention that has the potential to strengthen malaria programs and provide substantial co-benefits for a relatively modest cost.

KEY FINDING 2: THE SYSTEM MUST HAVE COMMITTED OWNERS WITH A LARGE STAKE IN ACHIEVING SUSTAINABLE IMPLEMENTATION

For malaria early warning to be successful, committed organizations must own the system and provide an enabling environment for sustainable implementation. From our stakeholder engagements, we determined two elements are needed to ensure proper governance of the national early warning system:

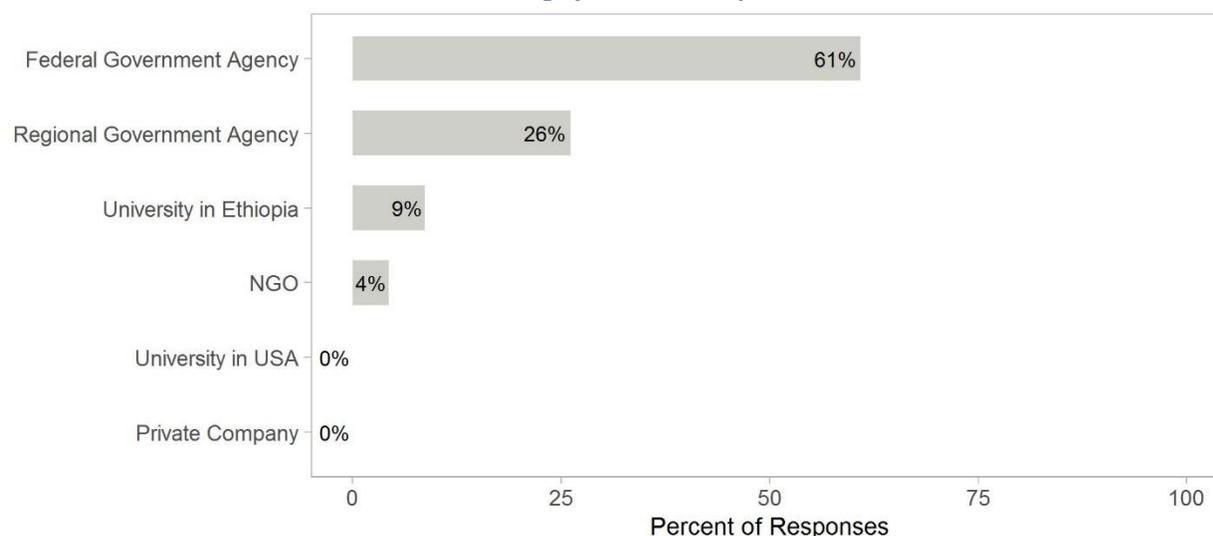
- 1) A *steering committee* responsible for monitoring implementation and making key decisions about system implementation.
- 2) A *core team* responsible for technical implementation, day-to-day operation, and continued development of the early warning system.

Most survey participants (61 percent) thought federal government agencies would be best suited to manage and operate a malaria early warning system in Ethiopia (Figure 6). Some supported regional government agency management and operation (26 percent), with <10 percent supporting management and operation by a university or non-governmental organization.

The *steering committee* should have representatives from NMEP, the EPHI, PMI, and personnel from FMOH working with health information systems. The NMEP is the main decision-making body that implements malaria programs in Ethiopia and will be the main user of malaria forecasts to support national-level decisions. However, cooperation with the other institutions is necessary for implementation and coordination with the regions so that malaria forecasts can be used for regional and local decision-making. Therefore, the steering committee should include representatives from the regional health bureaus throughout Ethiopia. Representatives from other institutions, including academia and the WHO, could also participate in advisory roles.

The *core team* should be established in EPHI, which can be the primary technical implementer and operator of the malaria early warning system. This is a close fit with EPHI's three primary foci: 1) national public health research, 2) disease surveillance, and 3) public health emergency response. EPHI can provide the technical and scientific expertise needed to implement malaria early warning in Ethiopia and will also benefit substantially from the additional knowledge and capacity gained through implementation.

Figure 6 Most survey respondents indicate the Federal Government is best suited to operate a malaria early warning system in Ethiopia.



Note: Responses to: “What type of institution do you think would be best suited to manage and operate a malaria early warning system in Ethiopia? Select one best answer.”

Regional health bureaus must buy in, as they provide the PHEM data and will have a critical role in assessing forecasts and translating them into public health responses at zonal and district levels. The main reason we recommend implementing malaria early warning at the national rather than regional level is the difficulty of replicating the technical component of malaria forecasting across multiple regions in Ethiopia. A key responsibility of the *steering committee* and the *core team* will be to engage and communicate effectively with the regions, which is why we recommend including regional representatives on the steering committee. The regions will need training and support to use the forecasts for successful implementation.

KEY FINDING 3: TIMELY AND ACCURATE DATA ARE CRITICAL REQUIREMENTS FOR MALARIA EARLY WARNING

Malaria transmission cycles are complex and highly sensitive to multiple climate drivers that affect the malaria parasite along with its mosquito vectors and human hosts. Several stakeholders emphasized that geographic variability of malaria in Ethiopia is an important challenge for control and elimination. A key implication for malaria forecasting is that it is extraordinarily challenging to develop a single model that will be accurate in these diverse settings. It is therefore essential to have localized malaria data to calibrate models and validate predictions.

Timely and accurate surveillance of malaria cases provides the foundation for detecting and predicting malaria outbreaks. We assessed the potential for three existing sources of surveillance data to support malaria stratification and early warning in Ethiopia: The PHEM system, the HMIS, and the PMI microplanning datasets. Detailed results of this assessment are in a previous project report (Wimberly et al., 2020b). The PHEM dataset was judged to be most

suitable for malaria early warning and stratification because it combines a high temporal resolution (weekly summaries) with a high spatial resolution (woreda-level) and national-level data availability from 2014 to the present.

Another important aspect of the PHEM system is the timeliness of data collection and reporting to the regional and national levels. Every Monday, health posts are expected to prepare and send weekly surveillance reports for the preceding WHO epidemiological week (Monday-Sunday) to cluster health centers via phone. Health centers are expected to aggregate and relay the data to the district health office on the same day. The district health office is expected to relay the data to the zonal health office on Tuesday, the zonal health offices report to the regional public health offices on Wednesday, and the regions report to EPHI on Thursday. Thus, the data collected during one epidemiological week should be available at the national level before the end of the next epidemiological week.

Although the PHEM data were highly suitable for malaria early warning, we also identified some limitations that must be overcome for their successful application. The data are not always collected and reported consistently, resulting in data gaps. We found missing rows in the dataset when a district does not report for a particular week, missing values when a report is made but data are not available for certain variables, and errors such as zero values that are incorrectly coded when data are missing (Wimberly et al., 2020b). Stakeholders confirmed that the Ethiopian public health community recognizes that missing and inaccurate surveillance data are an important challenge. As described in the Activities section, we addressed this by developing algorithms to screen for incorrectly coded zeroes and other data errors and impute reasonable values for missing data based on the patterns of malaria cases in the time series.

Another challenge that multiple stakeholders raised was the difficulty of acquiring timely and accurate weather and climate data. A network of meteorological stations collects relevant data throughout Ethiopia, but public health sector stakeholders reported that limited access to these data prevented their use for malaria early warning. An alternative source of climate monitoring data is satellite remote sensing. Earth-observing satellites provide daily measurements of precipitation, land surface temperature, and vegetation greenness and moisture indices across the globe (Wimberly et al., 2021). These data have been shown to be effective for modeling climate-driven malaria outbreaks in Ethiopia (Davis et al., 2019; Midekisa et al., 2015; Midekisa et al., 2012). However, public health practitioners in Ethiopia have not routinely used remote sensing data because of the high bandwidth required to download large datasets, the computer resources necessary for data processing and storage, and the specialized software and disciplinary knowledge required.

Integrating malaria surveillance and climate data for early warning requires harmonizing them to generate time series of climate indices that correspond with time series of malaria cases in every district. They must then be linked to other sources of district-level data, such as estimates of the human population at risk for malaria. Connecting these data sources is extremely challenging because of differences in the spatial and temporal resolutions of the datasets, inconsistencies in geographic names, and continual changes in district and city boundaries. We

were able to resolve most inconsistencies and develop a national district-level malaria database linked to a geographic information system database of administrative boundaries and an annual population dataset (Wimberly et al., 2020a). However, this was a time-consuming process that required manual cross-referencing of the datasets. Looking forward, developing protocols for maintaining consistency across key datasets would greatly enhance their potential for malaria early warning and other public health applications.

KEY FINDING 4: MODERN DATA SCIENCE TECHNIQUES AND TOOLS ARE NEEDED TO CAPITALIZE ON THE GROWING BODY OF AVAILABLE INFORMATION

The long-term record of malaria surveillance data in Ethiopia combined with the wealth of climate data from Earth-observing satellites presents both an opportunity and a challenge. There is potential for understanding the climatic triggers of malaria outbreaks and using this knowledge to predict emerging epidemics. However, using this information effectively requires a “big data” approach that addresses the “three Vs”: high volumes of data from a variety of sources that are continually updated at high velocity (Chi et al., 2016). Fortunately, it is now feasible to use modern data science tools combined with inexpensive computer power available locally on the desktop and virtually, in the cloud.

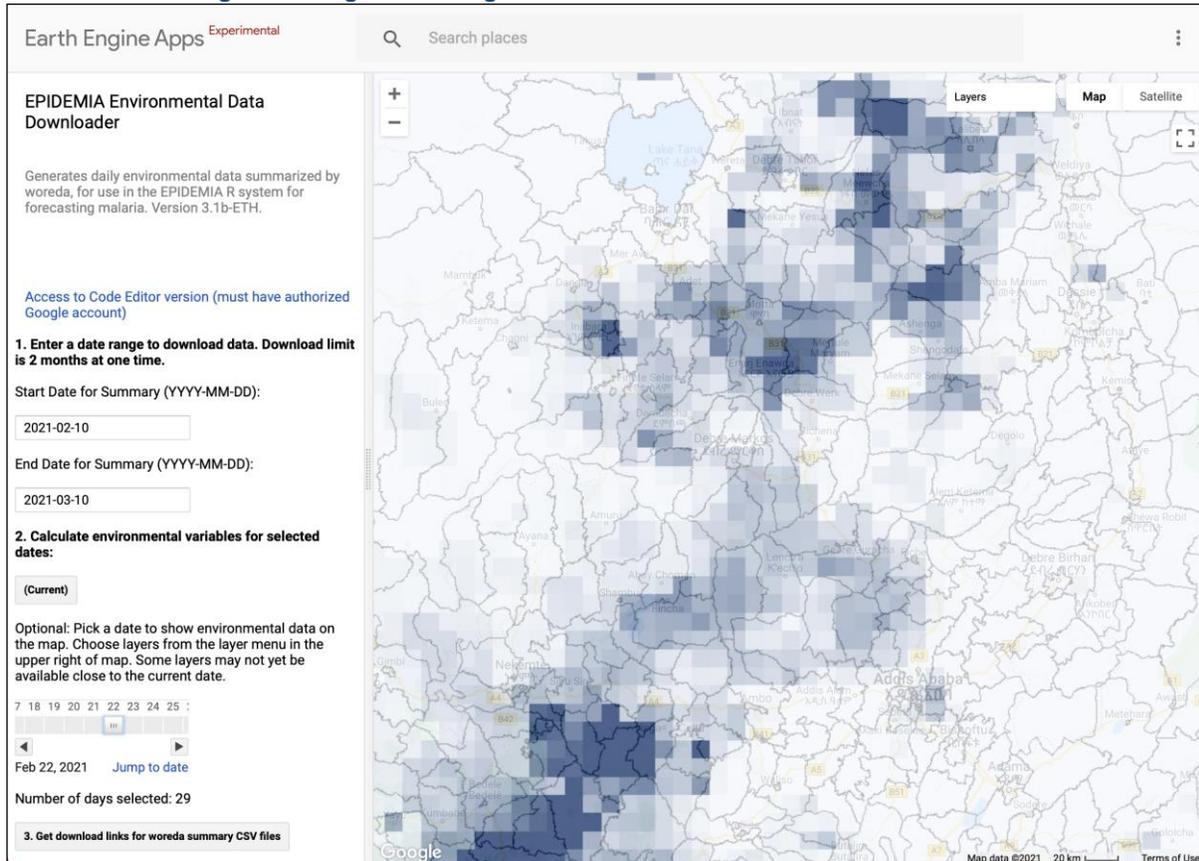
Technical implementation of a malaria early warning system requires developing a *scientific workflow*, which comprises multiple steps for data acquisition, processing, harmonization, modeling, and visualization. As with other scientific workflows, most tasks necessary for malaria early warning involve basic data preparation steps such as data cleaning, reformatting, and harmonization (Garijo et al., 2014). Performed manually, these tasks are time consuming and error prone. Because malaria early warning requires acquiring and preparing new data and updating predictions regularly, it is essential to automate all critical steps (Merkord et al., 2017).

Acquiring and processing remote sensing data from Earth-observing satellites is a particularly challenging and computationally demanding part of the malaria early warning workflow. Large daily image files must be downloaded and processed to compute climate indices and summarize them within the district boundaries where malaria data are collected (Liu et al., 2015). Even if the necessary computers, data storage, and software are available locally, low internet bandwidth or unstable connectivity can make it impossible to download the necessary datasets.

Within the past few years, cloud computing has emerged as a new platform for accessing and processing satellite remote sensing data. Cloud computing encompasses the delivery of remote computing services, including processors, storage, and software, as virtualized resources over the internet. Google Earth Engine (GEE) is the most well-known and widely used cloud computing environment for satellite remote sensing, providing free access to hundreds of petabytes of data along with an application programming interface that facilitates data access and analysis through a web browser (Gorelick et al., 2017). With GEE, the most computationally

intensive data processing tasks are performed in the cloud, allowing the user to download small data summaries for malaria early warning. The EPIDEMIA tool uses GEE as the main application for obtaining climate data for malaria forecasts (Figure 7). Our successful pilot implementation of EPIDEMIA in the Amhara region showed this approach is technically feasible.

Figure 7 Google Earth Engine Interface Provides District-Level Climate Data



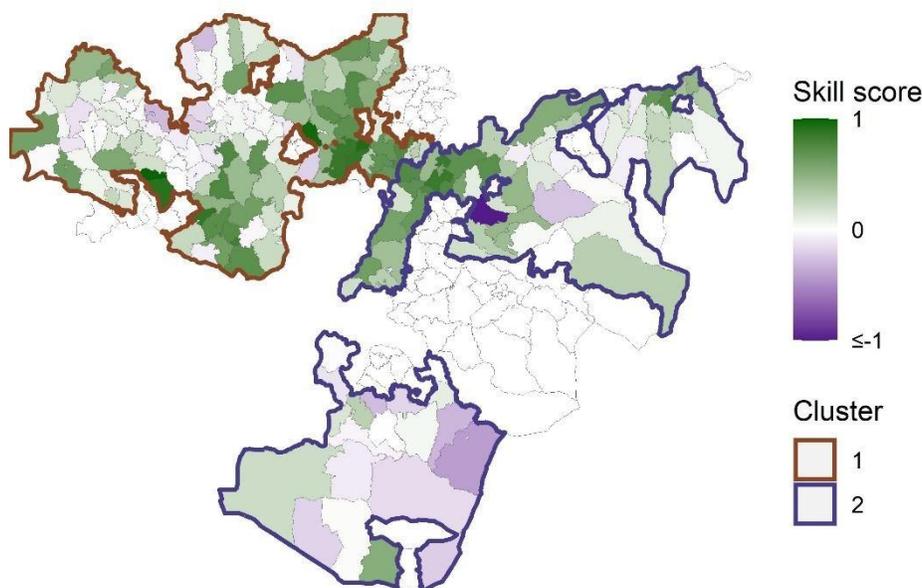
Note: Interface of the GEE application for visualizing and downloading district-level summaries of remotely sensed climate data for use with the EPIDEMIA tool. Daily precipitation for February 22, 2021 is displayed.

Because complex workflows are necessary for malaria early warning, reducing complexity by implementing as many steps as possible using the same software platform is helpful. We determined that the R language and environment for scientific computing is the best option for implementing malaria early warning systems. Because R is free and open-source software, there are no financial barriers to its use anywhere in the world. R includes a flexible programming language combined with external packages that provide functions for working with all types of data. These packages provide the capabilities for data processing, time series modeling, and report generation to automate malaria forecasts. Modern computer workstations and laptops with multi-core processors have enough power to carry out the necessary computational steps, allowing malaria early warning to be implemented in almost any institutional environment.

KEY FINDING 5: THE EPIDEMIA TOOL MEETS THE NEED FOR DATA SCIENCE TOOLS TO SUPPORT MALARIA EARLY WARNING

We completed the major upgrades to the EPIDEMIA system outlined in the Activities section and successfully generated and validated forecasts for the Oromia region using PHEM data that we harmonized and screened for data anomalies (Wimberly et al., 2020b). We only modeled districts where the annual case number was above a threshold (> 500 malaria cases during 2014–2019 in Oromia) because it was not possible to reliably fit the forecasting models in districts with extremely low case counts. Using the optimization techniques developed by Davis et al. (2019), Oromia was split into two clusters for modeling: a western cluster where temperature has the strongest influence on malaria cases, and an eastern cluster where precipitation has a stronger influence (Figure 8).

Figure 8 Map of skill of the Oromia region, 2018–2019, for a 12-week forecast against the average week of a naïve model



Note: The skill based on the root mean square error statistic is shown. Green indicates positive skill; purple negative skill in those woredas. Two clusters with different climate sensitivities are marked by brown or purple borders.

The EPIDEMIA tool generates malaria early detection and early warning alerts by comparing historical observations and future predictions of malaria incidence with an alert threshold. These alert thresholds are generated using the improved Farrington method, which uses information on historical malaria trends to estimate the amount of malaria expected during a given week in a “normal” transmission year (Nekorchuk et al., 2021). Recent observations of malaria above this threshold are interpreted as early detection of a malaria outbreak that has already started. Predictions of future malaria above this threshold are interpreted as early warning of a malaria epidemic that may occur based on observed climatic risk factors. The alerts are displayed in a

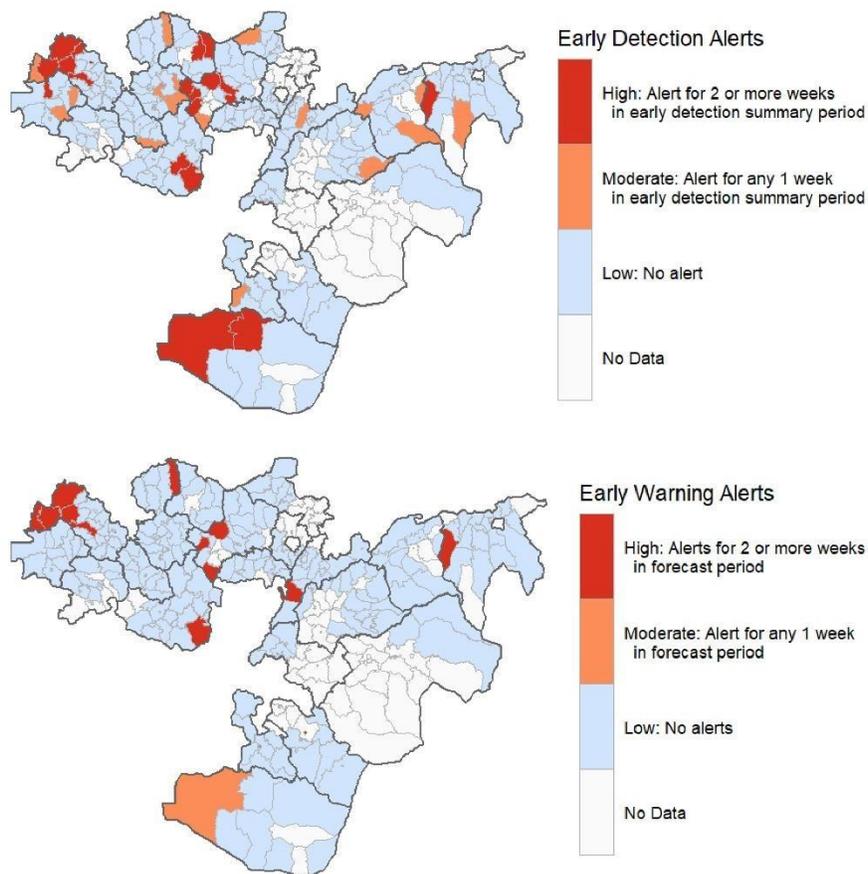
summarized map and table for the region and are marked per week on the individual woreda report pages.

The EPIDEMIA forecast reports include a suite of maps, charts, and tables to communicate the predictions and alerts and provide information on the climate drivers. They are designed to inform public health decision-makers and help target interventions at the times and locations where outbreaks are most likely to occur. The reports are in four sections: summary alert maps and tables (for each malaria species), time series charts for each woreda, maps of recent malaria incidence, and maps of recent climate anomalies. The alert maps are intended to provide high-level visuals to quickly identify areas of concern. These maps color code districts based on early detection alerts and early warning alerts (Note:).

Figure 9 EPIDEMIA forecast report of the Oromia region

1 Alert Summaries

1.1 Alert Map: *P. falciparum* and mixed

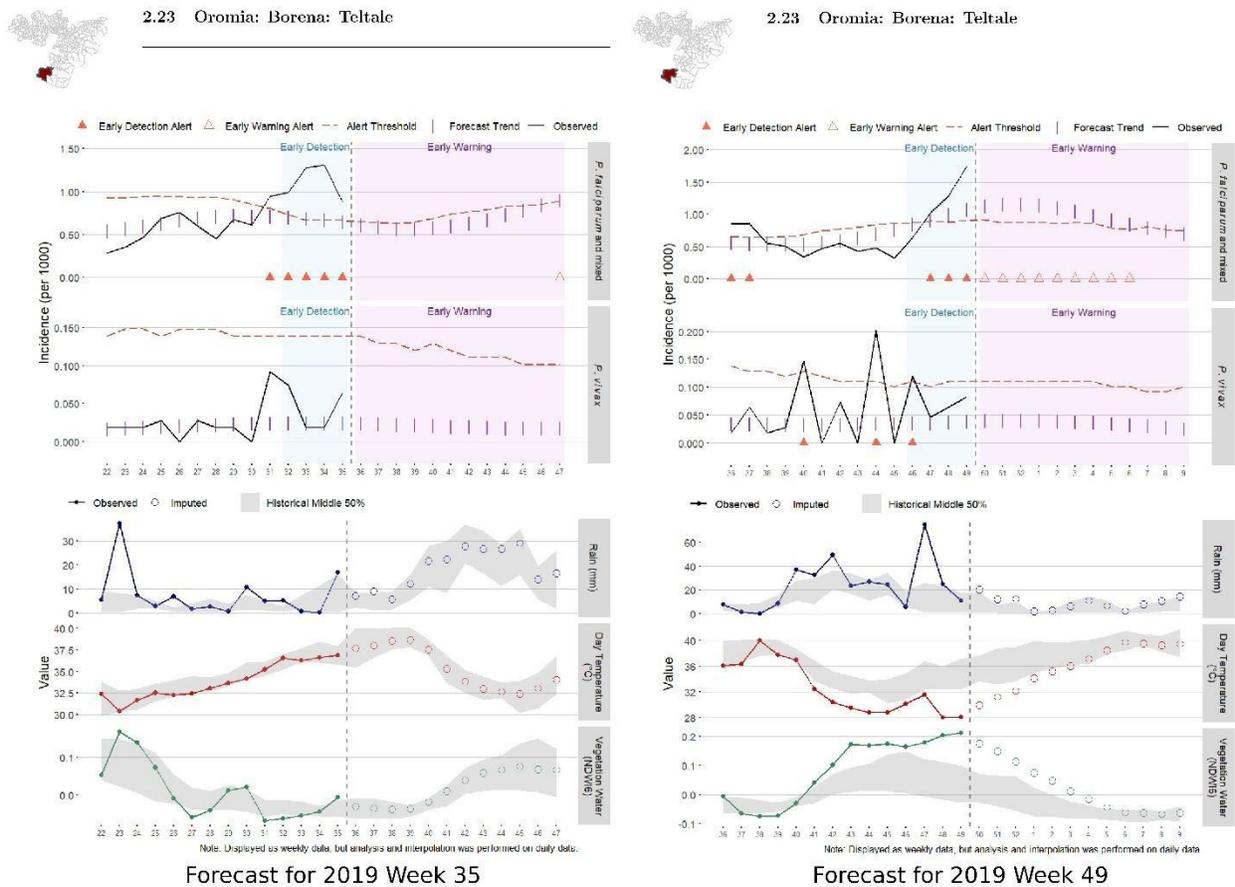


Note: Forecast report of the Oromia region for epidemiological week 35 of 2019. The early detection period is the four most recent weeks of observed epidemiological data. Woredas are colored orange if there was any one week with an alert during this time, or red if there were two or more alerts. The early warning period is the 12-week forecast, and the color coding is the same. Tables of the same information are also included to easily identify woreda names.

In addition to overview maps, a detailed set of time series charts is provided for each district (Figure 10). The top charts are control charts for both malaria species showing the observed

and forecast incidence, alert thresholds, and any triggered alerts over the report period, which encompasses 14 weeks of historical data and 12 weeks of predictions for 26 weeks total in the example given. The charts on the lower half of the page are a time series of the climate variables used in the modeling. In Figure 10, the left side report is from week 35 of 2019. Twelve weeks in the future, week 47, an early warning alert is triggered. The right-side report is the forecast from week 49. The observations from Weeks 47–49 exceed the alert threshold, indicating that the early warning of an outbreak in week 35 was accurate.

Figure 10 Comparison of two forecast reports for the woreda Teltale

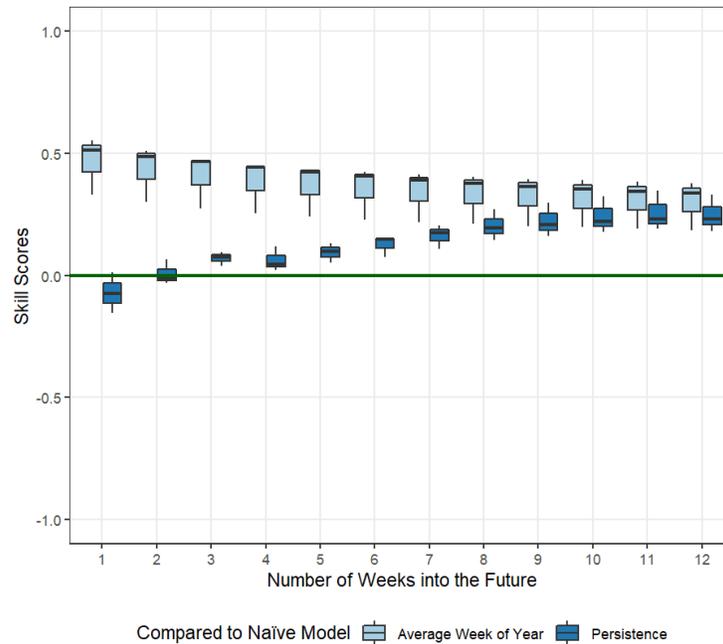


Note: The report on the left is for epidemiological week 35. It includes a malaria early warning alert 12 weeks ahead in week 47. The report on the right is the week 49 report, which shows a malaria outbreak occurred in weeks 47–49. The charts on the lower half of the reports are climate data for rainfall, daytime temperature, and a vegetation index that were used in the modelling.

To provide more comprehensive validation of malaria early warning forecasts, we built methods into the EPIDEMIA tool for on-demand accuracy assessment for any historical period. Evaluation can be made for one- through 12-week predictions and includes comparisons against two naïve models that only include epidemiological information: persistence of last known value, and weekly case averages from the historical dataset. Skill scores represent the relative increase (positive values) or decrease (negative values) in accuracy compared to these baseline models.

Validation reports summarize map forecasting skill over a range of lead times from one to 12 weeks. In Oromia, we were able to forecast with positive skill out to 12 weeks (Figure 11). We obtained similar results with even higher skills scores for forecasts across the entire Amhara region. Skill results can be calculated for individual woredas and mapped to explore geographic variation in forecasting accuracy (Figure 8). These maps can be used to identify areas where climate-driven malaria forecasts are most effective. Spatial variability in forecast skill can arise from a variety of factors, including spatial variability in sensitivity of temperature and precipitation as well as other environmental factors not included in the forecasting models.

Figure 11 Overall skill graph from a validation report for the Oromia region, 2018–2019



Note: Light blue bars indicate skill against the average week-of-year model; dark blue bars against the persistence model. This forecast for Oromia demonstrates positive skill out to 12 weeks against both naïve models.

KEY FINDING 6: MALARIA FORECASTING MUST BE CONNECTED WITH PUBLIC HEALTH RESPONSES ACROSS MULTIPLE LEVELS OF THE PUBLIC HEALTH SYSTEM

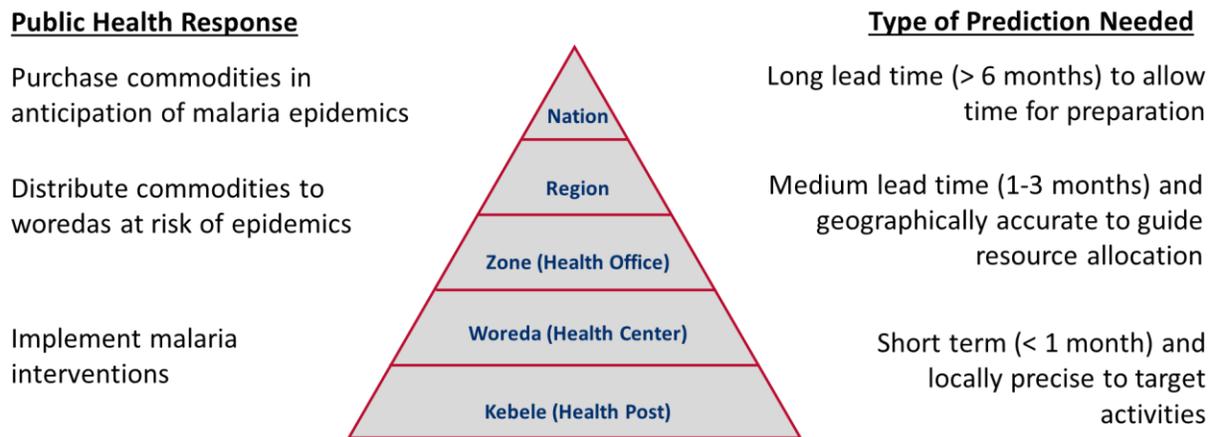
The purpose of malaria early warning is to predict locations at high risk of future malaria outbreaks so early actions can be undertaken to reduce public health effects. Two critical questions are:

- 1) How far in advance can malaria outbreaks be predicted?
- 2) How much lead time is required for a response?

As shown in the previous section, the malaria early warning models implemented with the EPIDEMIA tool have predictive skill (higher accuracy than naïve models) out to 12 weeks. In our discussions with stakeholders, we found that required lead times depend on the level in the

public health hierarchy where responses are undertaken. Requirements for the spatial resolution of forecasts also varied with the types of responses and their associated level in the public health system (Figure 12).

Figure 12 Public Health Responses to Malaria Warning and Required Types of Predictions



Note: Levels at the top of the pyramid are largest in geographic area and population size but fewer in number. At lower levels, more entities encompass smaller areas and fewer people.

At the national level, forecasts of the malaria burden can support decisions about drug and supply purchases. Because of time required to make the purchases and acquire the drugs and supplies, a substantial lead time (three to six months) is required. However, information about specific locations at risk are less important. The FMOH works with the EPSA to procure the necessary public health commodities and distribute them to zones and woredas. If sufficient supplies are available, decisions about where in the country to distribute them require a shorter lead time: one–three months. Predictions that support decisions about distribution must identify the zones and districts where malaria outbreak risk is highest. Decisions about when and where to use locally available supplies for specific malaria control interventions can be undertaken rapidly with a month or less of lead time but require specific information about district and subdistrict locations to target.

The current version of the EPIDEMIA tool was developed to provide accurate district-level forecasts out to 12 weeks based on the requirements of public health partners in the Amhara region. Thus, the forecasts are well-suited for supporting decisions about pre-positioning drugs and supplies to zones and districts with high outbreak risk in upcoming months and implementing interventions in districts where epidemics are likely to emerge in upcoming weeks. EPIDEMIA does not currently provide forecasts at a sub-district level. However, several stakeholders emphasized that local public health experts already know the locations of mosquito breeding sites and villages at highest risk of malaria in their districts and can use this knowledge to respond to district-level alerts.

There are no built-in limitations to the lead time for which EPIDEMIA can be used to make forecasts. Predictions out to six months or even a year are technically feasible, although predictive skill is likely to decrease with increasing lead time. National or regional forecasts

could be made for longer lead times by combining the results of current district-level forecasts, or by fitting new models to spatially aggregated time series of historical data. Additional sources of data, such as information about El Niño and other climate phenomena and seasonal forecasts of weather patterns could be incorporated to improve long-term predictions.

For example, our analyses of recent malaria trends in Ethiopia have found malaria generally declining nationwide. However, this decrease slowed or reversed slightly in the El Niño years of 2015–2016. Malaria also increased in many locations in 2019, another El Niño year. In many instances, the spikes in malaria cases in 2019 were large enough to result in an overall increasing trend from 2014–2019 (Wimberly et al., 2020a). The short length of the nationally available PHEM data (seven years, including 2020) limits our statistical power to detect responses of malaria to large-scale climate variations. The development of longer-term historical malaria datasets at coarser regional and national scales would facilitate development and validation of malaria forecasting models with lead times longer than three months.

KEY FINDING 7: THERE IS A STRONG NEED FOR TRAINING AND OTHER CAPACITY BUILDING

It is not possible to sustainably implement malaria early warning using a “push button” approach with a software solution that users are simply trained to operate. The core team will need strong foundational knowledge of the data science techniques used in EPIDEMIA, including coding in the R language, remote sensing science, and predictive modeling of malaria outbreaks. The immediate goal should be to work with the core team at EPHI to enable them to be co-developers of EPIDEMIA. The long-term goal is to facilitate sustainable implementation of malaria early warning in an unknown future in which the physical and social environments of malaria transmission will change continually. To be successful, the EPHI core team must assume a lead role in continually updating and adapting the system.

To achieve this, technical training must be a sustained, multi-year effort that targets partners from the core team at EPHI and includes scientists from public health agencies as well as university faculty. Participants must have experience with the statistical analysis of surveillance data and have graduate training in epidemiology, public health, statistics, or another relevant discipline. Training should cover computer programming, data management, and advanced statistical and machine learning methods suitable for predictive modeling of disease occurrence. It is essential that these trainings include follow-up activities and opportunities to apply what was learned to real-world problems. For example, one- or two-week in-person training sessions can be interspersed with virtual follow-up exercises. Trainers and trainees can collaborate to identify data analysis needs that teams of trainees can address in these exercises.

A larger number of system users working in the health system at regional and zonal levels will need training to interpret and apply the forecasts. These training sessions will need to focus on the conceptual foundations of malaria early warning and high-level understanding of malaria surveillance and early warning rather than the technical details of system design and

implementation. These goals can best be addressed through a training-of-trainers (TOT) approach that uses trainees from national and regional public health agencies and universities to train public health professionals at lower administrative levels.

ROADMAP

The major elements of the roadmap for malaria early warning scale-up in Ethiopia are identifying, training, and supporting key personnel who will carry out the work, specifying a timeline to implement the work in a series of logical steps, and producing an updated set of EPIDEMIA tools and accompanying technical manuals. The two major groups involved in the roadmap process will be:

- 1) *program implementers* working in Ethiopia, and
- 2) *technical advisors* working at a U.S. institution.

Program implementers will include a steering committee of representatives from the NMEP with other key partners, and a core team based in the EPHI. Technical advisors from the United States will transfer the necessary tools, engage in co-development with the core team, and lead training and capacity building.

Work will include in-person workshops and meetings every six months, with each group working on tasks and participating in bi-weekly virtual meetings during intervening periods. Program implementers will gradually take over forecasting for larger portions of Ethiopia, with a goal of forecasting for the entire country by scale-up project end. Technical advisors will help validate forecasting results and continue to make updates and improvements to the forecasting tools based on feedback from program implementers. Technical advisors will also run workshops to build the technical capacity of program implementers for sustainable forecasting and training of forecast end users in Ethiopia. The main portion of the roadmap covers three years. We recommend an additional year for transition, funded at lower levels, when technical advisors can continue to support system implementers and evaluate the effectiveness of the implementation.

KEY PERSONNEL

ETHIOPIA PROJECT IMPLEMENTERS

Program coordinator: A full-time program leader responsible for overseeing implementation of the scale up project, including supervising personnel, running meetings and workshops, and coordinating the steering committee. This individual will be on the steering committee and the core team.

Quantitative epidemiologists: Two full-time program staff members will anchor the core team at EPHI and share responsibility for technical implementation of the EPIDEMIA tool and

communicating outputs to the Ethiopian public health system. Two epidemiologists will build redundancy in case of staff turnover and allow each to focus on different tasks.

U.S. TECHNICAL ADVISORS

Project leader: Responsible for overseeing technical support from the U.S. team, including technical development and support work on the malaria early warning system and development and implementation of training and technology transfer.

Postdoctoral associates: One postdoctoral associate will focus on system development, testing, and documentation. The second will focus on developing training programs and materials.

PROGRAM CONTRIBUTORS

STEERING COMMITTEE MEMBERS

The steering committee will have representatives from NMEP, EPHI, and the U.S. (PMI), along with personnel from the FMOH working with health information systems and representatives from the regional health bureaus. Representatives from other institutions, including academia and the WHO, could also participate in advisory roles. Additional participants will be engaged as needed to interpret and apply forecasting results, including representatives from EPSA and others involved in managing the public health commodities supply chain in Ethiopia. The program coordinator will work with leaders from NMEP and EPHI to select members of the steering committee.

CORE TEAM MEMBERS

In addition to the two full-time epidemiologists at EPHI, the program coordinator, in consultation with leaders from NMEP, EPHI, and PMI, will select members of the core team from regional and federal public health agencies and universities. Individuals will need to apply to the core team and have appropriate expertise in computer science, statistics, epidemiology, or other relevant disciplines. We expect 10 to 20 members in the larger core team will have opportunities to participate in technical training and capacity building.

TIMELINE

We believe these goals can be achieved in four years (Figure 13). Implementation and training occur during the first three years. The Ethiopian partners will operate the system independently in the fourth year with aid from the U.S. technical support team.

Table 1 Four-year timeline for scale-up of malaria early warning in Ethiopia. Blue filled boxes indicate months when the activity takes place. For workshops, the black outline indicates the month of the workshop with preparation occurring in the preceding months

Activity	Month																																																																						
	Year 1												Year 2												Year 3												Year 4																																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48																							
1. Recruitment and Engagement	[Blue filled]												[Blue filled]																																																										
1.1 Initial staff recruitment	[Blue filled]																																																																						
1.2 Planning workshops and engagements	[Blue filled]																																																																						
1.3 Developing implementation manual	[Blue filled]																																																																						
1.4 Meeting with supply chain experts												[Blue filled]												[Blue filled]																																															
2. EPIDEMIA Updates	[Blue filled]												[Blue filled]												[Blue filled]												[Blue filled]																																		
2.1 Initial software updates	[Blue filled]																																																																						
2.2 Technical advisors upgrade system							[Blue filled]						[Blue filled]						[Blue filled]						[Blue filled]																																														
2.3 Identify final system modifications												[Blue filled]												[Blue filled]																																															
3. Workshops and Training	[Blue filled]												[Blue filled]												[Blue filled]												[Blue filled]																																		
3.1 Workshop for initial transfer						[Black outline]																																																																	
3.2 Workshop on advanced data techniques							[Black outline]																																																																
3.3 Workshop on predictive analysis												[Black outline]																																																											
3.4 Workshop on software design and development																		[Black outline]																																																					
3.5 Training of Trainer (TOT) workshop																									[Black outline]																																														
3.6 Implementers train across public health system																															[Blue filled]																																								
3.7 Wrap-up workshop																																				[Black outline]																																			
4. Technical Advisors and Implementers							[Blue filled]						[Blue filled]						[Blue filled]						[Blue filled]						[Blue filled]																																								
4.1 Forecasts generated in parallel and planning							[Blue filled]						[Blue filled]						[Blue filled]						[Blue filled]						[Blue filled]																																								
4.2 Plan for further implementation												[Blue filled]																																																											
4.3 Review interpretation and decision support												[Blue filled]																																																											
4.4 Develop training materials for health community																									[Blue filled]																																														
4.5 Workshop on sustainable implementation																																				[Blue filled]																																			
5. EPIDEMIA Implementation							[Blue filled]						[Blue filled]						[Blue filled]						[Blue filled]						[Blue filled]																																								
5.1 Implementation in single region							[Blue filled]						[Blue filled]						[Blue filled]						[Blue filled]						[Blue filled]																																								
5.2 Implementation in multiple regions													[Blue filled]												[Blue filled]												[Blue filled]																																		
5.3 Implementers generating weekly reports																			[Blue filled]												[Blue filled]												[Blue filled]																												
5.4 Implementation in all regions																															[Blue filled]																																								
5.5 Monthly steering committee meetings	[Blue filled]																																																																						
6. Follow Up and Evaluation																																					[Blue filled]												[Blue filled]																						
6.1 Continued technical support																																					[Blue filled]												[Blue filled]																						
6.2 Assessment of implementation success																																																[Blue filled]																							

ACTIVITIES BY YEAR

YEAR 1

Months 1 – 6

- Recruit project staff (1.1).
- Develop a detailed plan for workshops and engagements (1.2).
- Identify key tasks and development a manual for implementation (1.3)
- Operationalize new tools, including algorithms for data screening and imputation (2.1).
- Plan and develop training materials for kickoff workshop (3.1).
- Monthly steering committee meetings (5.5).

Month 6

- Week-long kickoff workshop on initial transfer of the malaria early warning system (3.1).
- Technical advisors and the steering committee meet for two days to discuss high-level topics on system implementation (5.5).
- Technical advisors and core team meet for three days for basic training on the R language and computational environment along with tutorials on running the EPIDEMIA tool in R (3.1).

Months 7 – 12

- Technical advisors upgrade system in response to feedback from project implementers (2.2).
- Plan and develop training materials for data science workshop (3.2).
- Technical advisors and core team generate forecasts in parallel and plan for the next workshop (4.1).
- EPIDEMIA is implemented for one region in Ethiopia (5.1).
- Monthly steering committee meetings (5.5).

Month 12

- Meet with supply chain experts to begin planning how malaria forecasts can be used to support decisions about purchasing and allocation of public health commodities (1.4).
- Technical advisors and steering committee review results over the past six months and extend the forecasts to one or more additional regions (5.5).
- Week-long workshop to train the core team on data science with R, focused on advanced methods for processing, analysis, and mapping of PHEM surveillance data (3.2).

YEAR 2

Months 13 – 18

- Technical advisors upgrade system in response to feedback from project implementers (2.2).
- Plan and develop training materials for predictive analytics workshop (3.3)

- Technical advisors and core team generate forecasts in parallel and plan for the next workshop (4.1).
- EPIDEMIA is implemented for multiple regions in Ethiopia (5.2).
- Monthly steering committee meetings (5.5).

Month 18

- Further meetings with supply chain experts (1.4).
- Week-long workshop to train the core team on data science with R focused on predictive analytics for disease outbreak detection and forecasting (3.3).
- Project implementers and technical advisors meet to review early warning results, make plans for implementers to take over forecasting responsibilities (4.2).

Months 19 – 24

- Technical advisors upgrade system in response to feedback from project implementers (2.2).
- Plan and develop training materials for predictive analytics workshop (3.4).
- Review and develop strategies to use forecasts to inform malaria program decisions (4.3).
- EPIDEMIA is implemented for multiple regions in Ethiopia (5.2).
- Weekly forecasting reports are generated by the core team (5.3).
- Monthly steering committee meetings (5.5).

Month 24

- Week-long workshop on workflow development and software design (3.4).
- Technical advisors and steering committee meet to review interpretation and decision support (4.3).

YEAR 3

Months 25 – 30

- Plan and develop training materials for the Training of Trainers (TOT) workshop (3.5).
- Develop materials for training of the broader health community in Ethiopia (4.4).
- EPIDEMIA is implemented for multiple regions in Ethiopia (5.2).
- Weekly forecasting reports are generated by the core team (5.3).
- Monthly steering committee meetings (5.5).

Month 30

- The steering committee and technical advisors review forecasting results over the past two years and determine any final modifications to the system before transfer (2.3).
- Week-long training of trainers workshop (3.5).

Months 31 – 36

- Technical advisors make final system upgrades (2.2).
- Plan and develop training materials for wrap-up workshop (3.6).
- Weekly forecasting reports are generated by project implementers (5.3)

- EPIDEMIA is implemented for all of Ethiopia (5.4)
- Monthly steering committee meetings (5.5)

Month 36

Week-long wrap-up workshop to review and synthesize experiences with implementation of malaria early warning (3.7).

Steering committee, core team, and technical advisors meet to plan for sustainable implementation (4.5).

YEAR 4

Months 37 – 48

- The program implementors operate the system independently to generate national malaria forecasts (6.1).
- Technical advisors provide support to the project implementors to ensure they can use the EPIDEMIA tool effectively (6.1).

Month 48

- Three-day workshop to assess the success of national-level malaria early warning from roadmap activities. Data will be collected through a survey of the steering committee and in-person focus group discussions to explore major challenges and successes of the scale-up effort (6.2).

CONCLUSION

Further development and implementation of a national-level malaria forecasting system for Ethiopia is necessary to support malaria control and elimination, however implementing malaria early warning by building on the extensive body of climate-malaria research conducted in Ethiopia and other parts of sub-Saharan Africa is feasible. Timely and accurate data are critical for malaria programs in general and for malaria early warning. Although the quality and completeness of the available surveillance data is a challenge, model data science tools and techniques address these problems, and it can be used more effectively than ever before.

We developed the EPIDEMIA tool to harness these techniques for malaria early warning and vetted it in a pilot study of a subset of districts in the Amhara region of Ethiopia. Implementing this tool at a national level will require committed institutions to own and implement the system. A steering committee with representatives from NMEP and other cooperating government agencies will need to lead implementation. A core team of experts housed in EPHI will be essential to manage the technical aspects of implementation. The early warning and early detection alerts that EPIDEMIA generates can be used throughout the public health system, but the information requirements and public health responses will be different at national, regional, and district levels. Capacity building must include technical training to enable the core team to operate the EPIDEMIA tool sustainably. Broader training on using the malaria forecasts to support decisions can be implemented in TOTs.

This roadmap is a staged, three-year implementation plan followed by a year for Ethiopian partners to operate the malaria early warning system and receive continued technical support. All recommendations in the roadmap have been informed by our extensive engagement with stakeholders from federal public health institutions, regional health bureaus, and universities. The schedule will permit relatively rapid execution while ensuring enough time for comprehensive testing and validation of the EPIDEMIA tool and sufficient training to support Ethiopian ownership and operation of the malaria early warning process. The critical first steps are:

- 1) obtaining feedback on this roadmap document from major implementing partners, including the FMOH, NMEP, and EPHI, and making necessary adjustments to the roadmap based on their inputs,
- 2) receiving formal buy-in and strong support from these partners to implement the malaria early warning scale-up,
- 3) developing a detailed project budget in collaboration with the implementing partners, and
- 4) securing funding from one or more donor organizations to support the project and initial the roadmap activities.

Once these steps are complete, we are confident the roadmap can be implemented successfully. The result will be a sustainable, national-level malaria early warning system. This will facilitate more effective, data-driven decisions that will reduce the burden of malaria in Ethiopia and support progress toward its elimination.

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ANNEX A: ESTIMATED COSTS

Estimated costs for program implementers and technical advisors are in Table 2. These initial estimates will be revised based on more detailed budget information from each group.

Table 2. Estimated costs (USD) for major categories in each year of the scale up project.

Group	Item	Year 1	Year 2	Year 3	Year 4
Program Implementers	Personnel (salary and fringe)	179,000	186,000	193,000	101,000
	Participant Support (workshops)	24,000	24,000	34,000	12,000
	Travel	14,000	14,000	14,000	14,000
	Computer Supplies	11,000	0	0	0
	Subtotal	228,000	224,000	241,000	127,000
	Indirect Costs	125,000	123,000	133,000	69,000
	Total	353,000	347,000	374,000	196,000
Technical Advisors	Personnel (salary and fringe)	192,000	200,000	208,000	108,000
	Travel	38,000	38,000	38,000	24,000
	Computer supplies	10,000	0	0	0
	Subtotal	240,000	238,000	246,000	132,000
	Indirect Costs	132,000	131,000	135,000	72,000
	Total	372,000	369,000	381,000	204,000
Total	725,000	716,000	755,000	400,000	

For *program implementers*, salary costs include a full-time program coordinator who is responsible for overseeing the entire effort and serving as a liaison NMEP and groups within the Ethiopian Public Health System as well as the technical support team. The program coordinator will have a lead role in developing and executing the strategy for malaria early warning implementation. Two full-time quantitative epidemiologists located at EPHI will be key members of the core team and will have primary technical responsibility for data management, analysis, and implementation of the EPIDEMIA tools. Having two individuals in this role will help to provide continuity in the event of staff turnover. Participant support costs include per diem for workshop attendees along with other expenses, with two workshops planned for years 1-3 and one workshop planned for year 4. Travel costs, including airfare, hotel, per diem, and registration, are for the program coordinator and epidemiologists to attend the annual American Society of Tropical Medicine and Hygiene (ASTMH) conference to present on the project and

meet with the technical support team. Computer supplies include workstation and laptop computers capable of running the EPIDEMIA system.

For *technical advisors*, salary costs include two months annual salary for a project leader who will oversee all technical aspects of the implementation. Project staff includes two postdoctoral research associates. One research associate will focus on the development and implementation of training activities, and the other will focus on technical support for the EPIDEMIA tool, including troubleshooting and updating the tool. Travel costs cover two week-long trips to Ethiopia for the project workshops, and include airfare, hotel, and per diem for the project leader and two research associates. Costs for computer supplies include two desktop workstations for the research associates as well as laptop workstations to use while travelling.

The goal of the scale-up project is to achieve national malaria early warning implementation by the end of the third project year. The focus on in year 4 will be on follow-up and evaluation. Technical advisors will be available to help address challenges with implementation, and implementation success will be evaluated. Because of the lower level of project activities, salary, and travel costs in year 4 are reduced accordingly.

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