Multi-disciplinary Development of a Proposed Early Warning and Automated Response System (EWARS) for Epidemic Prevention

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Abstract: It is becoming increasingly clear that changes in the environment can promote growth of disease vectors like mosquitoes and rodents as well as rise in water-borne illnesses like cholera and other enteric diseases. Our paper is based on the concept that a multidisciplinary informatics scaffold can serve as an Early Warning and Automated Response System (EWARS) for a variety of communicable diseases. It will utilize multiple information resources including Remote Sensing (RS), Global Positioning Systems (GPS) and Geographic Information Systems (GIS) for exposure assessment (John et al 2004). Early warning systems are not new (Witt et al 2009). However, what is novel in the proposal is the integration of an adaptive Fuzzy Logic Decision Support System to the early warning component being developed by the investigative team. It also markedly differs from other efforts to provide decision-support in the unique degree of detail and process guidance delivered as well as in the broad multidisciplinary nature of the study group. Use of such a system will enable prophylactic public health interventions to be rapidly deployed based on a real-time, scientifically-based assessment of the threat environment. Particular attention will be paid to environmental factors amenable to corrective interventions. The informatics component of the system will be based on open source software, and the software developed during this project will also be in the open source domain. The project is multinational and multidisciplinary.

Keywords: early warning systems; human health; environmental models; fuzzy logic

1. INTRODUCTION

In 1985, NASA initiated the Biospheric Monitoring and Disease Prediction Project, to determine if remotely-sensed data could be used to identify and monitor environmental factors that influence malaria vector populations. Initial studies used high resolution images from LANDSAT to monitor the development of canopy cover in Californian rice fields. Changes in rice canopy cover over the season were successfully used to predict fields with high or low mosquito densities.

Another long-term NASA project has been the Malaria Modeling and Surveillance Project by the Armed Forces Research Institute of Medical Sciences in Thailand and the US Naval Medical Research Unit in Indonesia as reported by Kiang et al [2006].

The European Space Agency's two-year Epidemio project, launched in 2004, combined data from Earth Observation satellites, such as ESA's Envisat or the French Space Agency's Spot, with field work to combat the spread of epidemics. Specific situations in which Epidemio assisted in the analysis of and response to epidemics include studies of Ebola hemorrhagic fever in Congo and Gabon. Combining ESA Envisat satellite data on water bodies, forest cover and digital elevation models (DEMs) with field results, scientists were able identify dryness and drought as key factors connected to the Ebola epidemics. High-resolution images through Epidemio also helped in controlling an outbreak of the Marburg virus in Angola in 2005.

In China, there have been recent studies on Highly Pathogenic Avian Influenza (HPAI), identifying risk factors for transmission. A study published by Fang et al [2008] compared confirmed HPAI H5N1 outbreaks in poultry and wild birds, as well as 21 human cases in mainland China during 2004-2006. These data, together with information on wild bird migration, poultry densities, and environmental variables (water bodies, wetlands, transportation routes, main cities, precipitation and elevation), were integrated into a Geographical Information System (GIS). A case-control study was followed by multivariate logistic regression analysis which revealed that minimal distance to the nearest national highway, annual precipitation and the interaction between minimal distance to the nearest lake and wetland, were important predictive environmental variables for the risk of HPAI.

A number of international efforts are active in various parts of Africa to use RS and GIS for control of Malaria, Leishmaniasis and other vector borne disorders, particularly focusing on weather anomalies and rainfall related indices. The major thrust has been on malaria given the high levels of mortality and morbidity associated with this disease on the African continent as highlighted by Ceccato et al [2005].

There have been a number of studies in India, largely with the assistance of the Indian Space Research Organization (ISRO) that have also evaluated the use of remote sensing with and without GIS such as those by Sudhakar et al [2006] and Bhunia et al [2010], studying Japanese Encephalitis (JE) and Leishmaniasis in the North-East. Sabesan et al studied Filariasis in South India [2006] while Sharma and Srivastava [1997] investigated Malaria near Delhi. The findings from all of these studies showed promising results.

The examples highlighted are credible attempts to further our ability to use the unique possibilities afforded by RS towards epidemic prevention. A desirable derivative of such projects is the cross-border cooperation that arises as a natural consequence, not only between states within a nation but across nations and continents. International cooperation fostered by such activities directed to the common good can not only help to protect global health, but also set new standards for political intercourse.

Environmental variables play a key role in the propagation of vector-borne illnesses. The use of a comprehensive, data-driven early warning and response system which can lead to the optimal use of existing public health resources offers great promise. A fuzzy logic based dynamic risk mapping approach is under development by an international group, and the remainder of this paper will describe the concept, methodology and current status.

2. EWARS CONCEPT

Perhaps as a consequence of the rapid technological developments occurring across the realm of healthcare and information technology, all too often the focus of programs and “research” becomes the technology itself rather than the outcome of interest. The burden of communicable disease has been a challenge to the public health machinery in the Third World. While the specter of communicable diseases has been receding, there remains the ever present danger of the resurgence of diseases such as malaria or new problems as exemplified by the recent H1N1 outbreak. The potential for problems can be amplified by the large number of individuals from a variety of Third World countries, who may enter into countries where communicable diseases are not a significant problem as visitors or immigrants, and facilitate the transmission of a disease which the local health care system is not well equipped to detect or tackle. Clearly, a multimodal surveillance system that uses sentinel, laboratory and integrated disease surveillance will be of value in ensuring the best use of available resources to successfully mount a targeted response to potential public health threats. Our proposal is built upon the concept that a multidisciplinary informatics scaffold can serve as an Early Warning and Automated Response System (EWARS) for communicable diseases, with the potential for later extension to address non-communicable health issues of concern to the health system in question. It will utilize multiple information resources including remote sensing (RS), Global Positioning System (GPS) and Geographic Information Systems (GIS) with appropriate methodologies to store, process and visualize the products of these multilevel information sources. The structure of the system is shown in figure 4. Early warning systems for communicable diseases are not new. However, what is novel in our proposal is the integration of an adaptive Fuzzy Logic Decision Support System to an early warning component. It also markedly differs from other efforts to provide "decision-support" (such as the Malaria DSS developed by IVCC in Africa) in its unique degree of detail and process guidance (Yang et al 2007). It will generate a dynamic risk map followed by the delivery of highly specific advice to the public health authorities on exactly which threat to address as the highest priority, and the step by step process that should be followed in terms of allocating human resources, sanitation measures, chemicals or biological agents and so on, tailored to the level of the actor receiving it as well as to a comprehensive database of existing resources within the public health system. Use of such a system will enable prophylactic public health interventions to be rapidly deployed based on a real-time, scientifically-based assessment of the threat environment to minimize the risk of even small outbreaks which could presage a full-blown epidemic. The informatics component of the system will be based entirely on open source software, and the software developed during this project will also be in the open source domain, extending the generalizability of the scaffold. The collaborative group includes physicians, mathematicians, logisticians, health economists, entomologists, remote sensing experts and social scientists drawn from India, Germany, United States, South Africa, Canada, Ethiopia, Australia and Sweden. A number of group members are also members of United Nations Action Team 6 which seeks ways to Improve Public Health by using space-based technology.

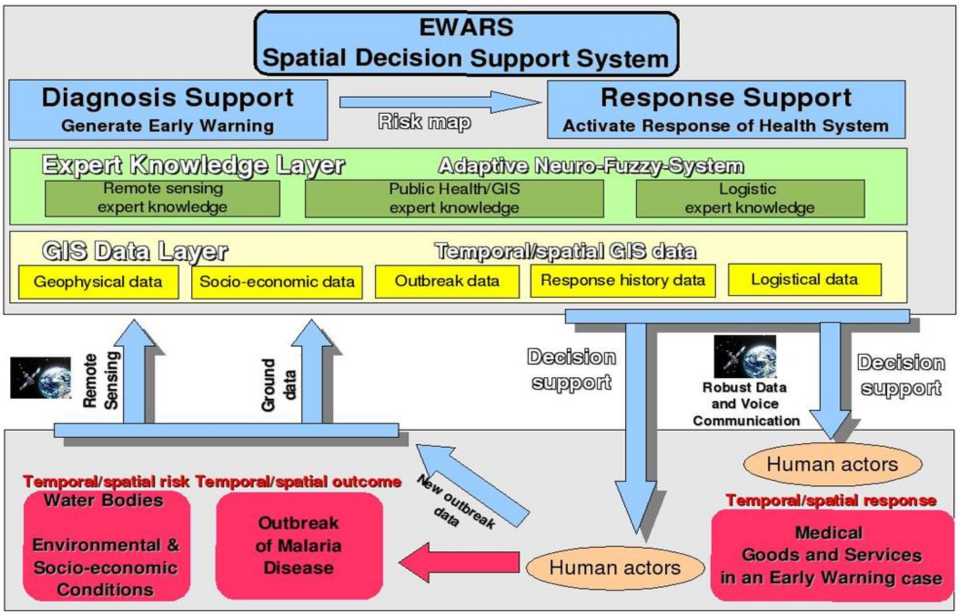

Figure 1: Schematic showing an EWARS system for Malaria

3. SOFTWARE COMPONENTS

The core software component is the GIS in which temporal spatial data are stored. This will utilize the visualization capabilities of GIS for spatial data to be used for disease prevention as advocated by Yang et al [2007] which would be the first step in providing decision support. When analyzing the Document Type Definition (DTD) in XML (eXtensible Markup Language), then all of records related to temporal spatial modeling will have attributes/tags that store time, longitude, latitude and height. Excellent OpenSource software is available for parsing XML data. The use of OpenSource software in general is preferred for all components of this project because it allows the sharing of implementations without the licensing costs associated with proprietary software, thus reducing the Total Cost of Ownership (TCO) can be reduced. The technical parameters of the developed applications will be well documented, so that technical support is facilitated and others can build on the existing application for further customization or enhancement to meet their specific needs. Software and Software Support dependencies will be minimized.

GRASS (Geographic Resource Analysis Support System, see http://grass.itc.it) is used because early warning of a possible epidemic should lead to a logistically optimized response utilizing available resources. Spatial analysis can be done with the statistical software R (http://www.r-project.org) for which GRASS provides an interface (http://grass.osgeo.org/statsgrass/). A computer algebra system MAXIMA (maxima.sourceforge.net) will be employed. In the final version of EWARS risk maps and resource supply maps according to risk will be delivered via web map server (http://mapserver.org).

4. MODELING METHODOLOGY

Modeling will focus on Spatial Fuzzy Logic as discussed by Petri et al. [2005] based on the concepts articulated by Sade [1965, 1973, and 1979]. Fuzzy Logic has been used previously in spatial decision support systems (as expert systems) for urban water management as described by Makropoulos et.al [2003]. In contrast to previous approaches the fuzzy membership functions are operating directly on a spatial domain. Furthermore we consider environmental factors that have an impact on the life cycle and propagation of a vector (*e.g.* mosquito). As a starting point we have temporal spatial data of an environmental factor (*e.g.* Temperature) available $(x, y, h, t, e_{1,} \dots e_n)$where $(x, y) \in \mathbb{R}^2$is the spatial location (*i.e.* longitude and latitude) *h* is the height above sea level, *t* is the time when the data are collected and $(e_{1,\dots,} e_n)$ are the environmental variables collected at (x, y, h, t). A single environmental factor is stored in one layer of the GIS. Applying the Spatial Fuzzy Logic concept on a GIS environment, it is necessary to process the environmental data into fuzzy membership functions. The term "linguistic values" is used in fuzzy language for knowledge representation in natural languages. For example, terms like "dangerous, big, old, optimal..." can be used to describe the attribute of the object under consideration. The validity of linguistic values cannot be expressed by values of classical logic (true =1 or false=0). The difference between probability theory and Fuzzy Logic can be described by the following example.

> *Probability*: a sheep *S* is black with a probability of p(S) =0.05 means that approximately 5 of 100 sheep will be black if you select them randomly.
>
> *Fuzzy Theory*: a sheep *S* is black with a grade of validity of 0.05 means that the considered animal *S* has a colour which is not pure white but slightly grey.

So in general the validity could have "different shades of gray" expressing the full range of mathematical values between 0 and 1. Furthermore, validity is context-dependent (*e.g.* the use of the linguistic value "old" by a young child might maps the numerical age of the object he is referring to a different validity compared to the use of the same term by a 50 year old adult). Now we consider a simplified Fuzzy Logic membership function for the linguistic value:

"Water temperature is optimal for the larvae of mosquitoes"

In mathematical terms, probability refers to the relative frequency of the occurrence of an event in many independent repetitions of an experiment. On the other hand, fuzzy logic describes the degree of truth of a *single* event. Membership functions map a degree of truth (grade of validity) to the objects in the domain of the function. The following example uses water temperature as the domain of the function and the outcome the degree of optimality. If water temperature would be optimal at 21°C for larvae of mosquitoes we define the membership function as follows:

$$f : \mathbb{R} \to [0,1] x \to \frac{1}{(1+(x-b)^2)^a} \quad (1)$$

The graph of the function with *b=21* is dependent on *a>0*. The following two graphs show the differences for *a=0.6* and *a=5.0:*

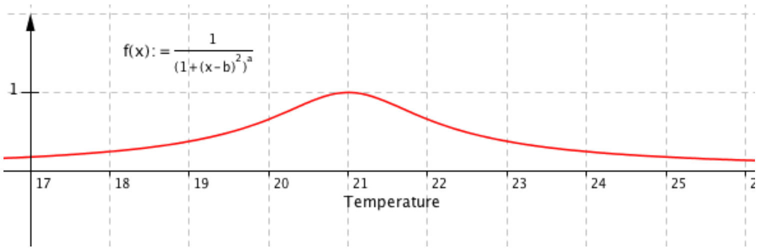

Figure 2: Graph of *f with* a=0.6

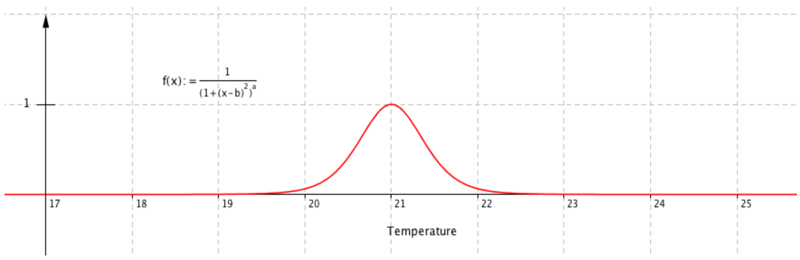

Figure 3: Graph of *f with a=5.0*

The parameter *a* defines, how tolerant the species is to the deviations of temperature from the optimal value 21°C. Let e_1 be the temperature variable. The membership function is applied on all records collected at location $(x, y, h) \in \mathbb{R}^3$ at time t. Doing this we get a spatial visualisation of the grade of optimality of water temperature in different portions of the area under study which is optimal for the larvae of mosquitoes. This creates a membership f_t showing optimal areas at time t. We limit the domain of f_t to the subset of $\mathbb{R}^2$ with longitude and latitude $(x, y) \in \mathbb{R}^2$, so that the graph of f_t is a subset of $\mathbb{R}^3$. The height is dependent on the location $(x, y) \in \mathbb{R}^2$. The following figure is showing a membership function of f_t and the z-axis is the grade of validity of linguistic value *"temperature of water is optimal for the larvae of mosquitoes"*. At the coordinates *(4,7)* of the sample datum $f_t(4,7) \approx 1$ which is indicating that the temperature conditions for the larvae of mosquitoes are most optimal in the area with that peak. Let e_1 be the temperature at $(x, y) \in \mathbb{R}^2$, then we set:

$$f_t(x, y) := f(e_1) = \frac{1}{(1 + (e_1 - b)^2)^a} \quad (2)$$

This can be done for all $(x, y) \in \mathbb{R}^2$ for which the temperature is available.

The advantages of converting temperature from degrees Celsius to a grade of validity become evident if different membership functions are combined logically in the geographic space.

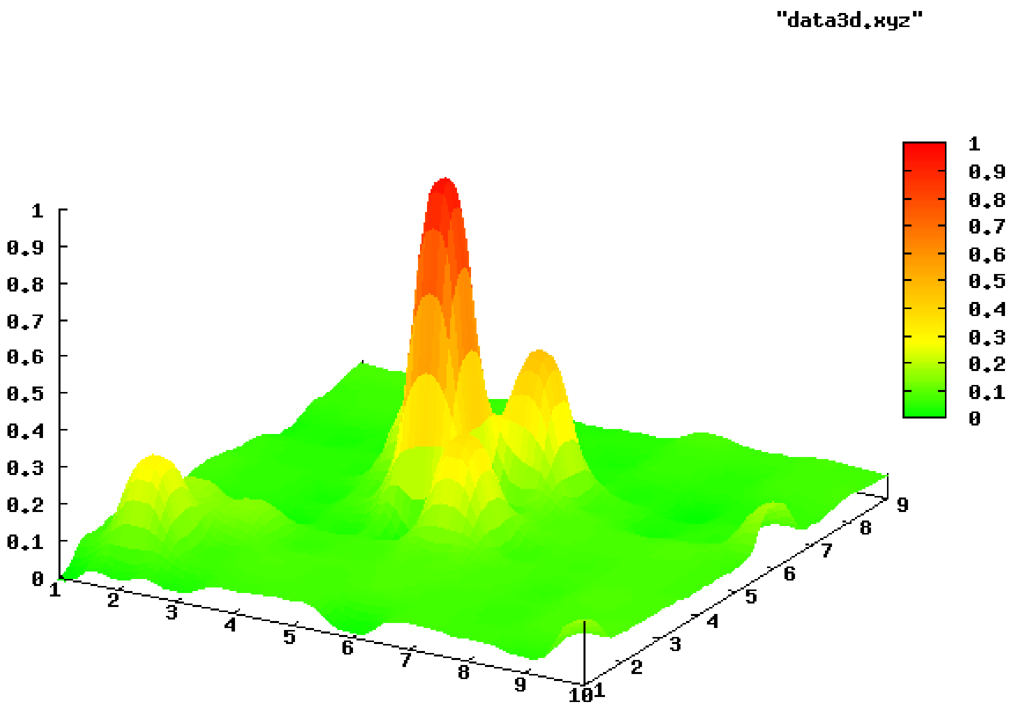

Figure 4: Spatial visualization of the optimality of temperature by membership function f_t on a rectangular space

According to visualization provided by the decision support system which is shown in Fig 4, we have only a small area where the membership function has a value close to 1 (red parts of the surface). For realistic decision support, the validity of a linguistic value is normally dependent on more than one variable. Let q_t be another membership function that is indicating the quality of the water, so that the larvae can survive. Both properties have to be true (*i.e.* membership function close to 1 at $(x, y) \in \mathbb{R}^2$), so that even at ideal temperature only a few larvae will survive if there is poor water quality (*e.g.* presence of larvicides). Applying a fuzzy-AND) on the two membership functions q_t and f_t (*i.e.* combining the two membership functions) provides a new spatial membership function indicating areas that fulfil both properties of temperature and quality of water. A fuzzy AND can be defined by the minimum:

$$\text{AND}(f_t,q_t): \mathbb{R}^2 \rightarrow [0,1] \quad (x,y) \rightarrow min\{f_t(x,y), q_t(x,y)\} \tag{3}$$

The fuzzy OR and NOT can be defined as follows:

$$\text{OR}(f_t,q_t): \mathbb{R}^2 \rightarrow [0,1] \quad (x,y) \rightarrow max\{f_t(x,y), q_t(x,y)\} \tag{4}$$

$$\text{NOT}(f_t): \mathbb{R}^2 \rightarrow [0,1] \quad (x,y) \rightarrow 1 - f_t(x,y) \tag{5}$$

For the proper application of fuzzy logic to spatial decision support, the appropriate rules (IF-THEN statements) must be carefully identified and evaluated. For example:

IF <*environmental conditions*> THEN <*disease vector has optimal conditions*>
IF <*vector has optimal conditions*> THEN <*application of resource R necessary*>

In contrast to fuzzy logic where statements can have the grade of validity (value of truth) in the full range between 0 and 1, classical ("crisp") logic allow only two logical values – one for true (=1) and another for false (=0). An IF-THEN-statement "→" in the classical logic is a logical operator (combiner) of two statements p and q using operators like "AND" or "OR". The IF-THEN-statement is false (=0) if and only if the condition p is true and the conclusion q is false. This is illustrated in the second line of the following truth table for the implication (*i.e.* IF-THEN statement):

Table 1: Logical equivalence for IF-THEN statements

p	q	$p \rightarrow q$	$\neg p \vee q$
1	1	1	1
1	0	0	0
0	1	1	1
0	0	1	1

The equivalence of $p \rightarrow q$ to $\neg p \vee q$ can be transferred to fuzzy-implication applied to the membership functions f_t and g_t.

The IF-THEN-statement is a membership function itself as mapping from the domain $\mathbb{R}^2$ to the interval [0,1] by evaluating the given membership functions f_t and g_t:

$$\begin{aligned} &IF - THEN(f_t, g_t): \mathbb{R}^2 \rightarrow [0,1] \\ &(x,y) \rightarrow max\{1 - f_t(x,y), g_t(x,y)\} \end{aligned} \tag{6}$$

The function maps the location $(x,y) \in \mathbb{R}^2$ to the grade of validity (grade of truth) of the IF-THEN-statement at location $(x,y) \in \mathbb{R}^2$. max is used for the Fuzzy-OR that replaces the classical OR and $1 - f_t$ for Fuzzy-NOT of f_t which replaces the NOT in the classical logic.

Using the spatial information of the validity of an IF-THEN-statement, the decision maker can see the gradations of how the rule can be applied in a spatial representation of a GIS. For example, in Fig. 4, the red section of the graph represents the area with the greatest validity of the rule. Thus, $IF - THEN(f_t, g_t)(x,y)$ provides the truth (grade of validity) of the fuzzy-rule at location $(x,y) \in \mathbb{R}^2$.

It is evident that our information about the membership function that are the basis for the Fuzzy-Rule may be incomplete bringing up issues of suboptimal quality for reasons pointed out by Lovejoy [1991]. The system is called adaptive, because ongoing data collection changes the membership functions and in turn the fuzzy rules that operate on the membership functions f_t and g_t..

5. PROJECT PLAN AND IMPLEMENTATION

A pilot study will be carried out in the state of Kerala, India this year in a semi-rural region with an area of 60 sq. km. and a population of roughly 200,000 individuals. GIS information on a variety of variables including residences, public buildings, roadways and water bodies are already available from prior work performed in the same locality by collaborating members from the Achutha Menon Centre for Health Science Studies located in Thiruvananthapuram, Kerala.

- Remote sensing and GIS data will be obtained from existing databases with the governments/science councils and academic research groups. This will be supplemented by field data (both existing and specifically collected for the project). Standardized data formats will be adopted wherever feasible to ensure the usability of data in the open source system and in existing commercial IT infrastructure, and wherever feasible open-source GRASS will be used for geo-spatial data and R for statistical software.

- Risk mapping related to mosquito-borne disorders such as dengue will be carried out using known variables as well as additional factors that may have significance from a public health perspective. The group is currently considering a large number of potentially relevant variables, which will be reduced and refined as work continues.

- Retrospective analysis of RS and GIS data from selected areas will initially be used for validating the risk mapping followed by prospective data collection.

- An automated risk score will then be developed such that the geographic area where the greatest public health threat is deemed present will be given the highest rating. The “threat” ranking will be generated taking into account not only variables compatible with high prevalence of the vector, but also proximity to human habitations, high traffic public areas and so on.

- Resources to deal with the identified problems will be automatically recommended for allocation based on the database of existing resources that will be compiled as part of the system with an adaptive “fuzzy-logic” methodology as detailed earlier. The importance of spatial modeling and application of spatial rules in Geographic Information Systems are increasingly well established.

- The areas under surveillance will be reviewed using GIS and field data on a defined schedule to determine if the identified problems have been resolved or reduced in severity by intervention of the public health system. RS data will also be used where feasible to allow objective and timely verification of the situation on the ground.

- Risk scoring will change automatically and dynamically based on updated system inputs and resources will be automatically recommended for allocation in real-time based on the latest list of highest threats.

- The proposed system is a comprehensive Decision Support System. It supports health service administration in risk evaluation and allocation of resources based on risk scores. Feasibility and acceptance of EWARS at the level of administration, users and general populace will be systematically studied using both quantitative and qualitative methods incorporating elements of action research methodology, community-led development theory and constructivsm theory with elements suggested by Baum et al [2006] along with more traditional approaches such as models and case studies. Consistent with fuzzy-logic implementation of the EWARS, variables can be represented in GIS layers with spatial qualitative representation of the collected data. This will make it feasible to logically analyze actions in space and time. Community-led development theory will be incorporated by the fuzzy-logic approach because individual membership functions that were only valid for certain communities can be easily replaced as GIS layers in EWARS, especially when the data are collected via traditional approaches such case studies bearing in mind the individual needs and structures of a given communities.

6. FUTURE DIRECTIONS

The primary objectives over the next year will be to refine the project plan, implement the pilot project and pursue funding avenues as well as further strengthening collaborative connections with academic, governmental and public health authorities. The team is also exploring the possibility of extending the EWARS concept to dealing with public health problems outside the realm of communicable diseases – for example, motor vehicle accidents. Specific milestones anticipated include further meetings of the project group in July and September of 2010 with commencement of the pilot project in December 2010. The pilot will take 3 years for both retrospective and prospective data acquisition and analysis.

Periodic updates on the project have been presented to Action Team 6 of the United Nations, and at meetings of the UN SPIDER forum for disaster management. The group looks forward to continuing and expanding on the work commenced under this international project.

7. CONCLUSIONS

The EWARS concept represents a dynamic multidisciplinary approach towards tackling the specter of communicable diseases, utilizing modern techniques such as remote sensing, GIS and fuzzy logic modeling. The planned pilot project should shed light on the success of the model, and its scope for adoption by public health authorities.

Potential challenges include possible resistance from public health and governmental officials or skepticism from the community, general public and local academicians. However, Kerala has a long record of progressive thinking in public health, and it's approach to improving quality as well as the favorable outcomes accomplished by the public health system has been internationally recognized and acclaimed as exemplified by a recent editorial in the British Medical Journal by Bhutta et al [2004]. The strengths of the current approach include the participatory model wherein the community, government, public health workers and academicians are all included as stakeholders. The Kerala government has been aggressively promoting IT as a way of improving governance and there are impressive networks already in place for connectivity between various governmental entities both within the state and with the central government. Efforts by the central government to develop a national health information network for India (iHIND project) may also provide a means of scaling up the deployment of an EWARS should the pilot study be successful, particularly since the first author is a member of the iHIND workgroup. Ultimately, the committed participation of an international group of researchers, academicians and public health experts under the umbrella of the United Nations offers hope that the benefits which may accrue from the adoption of EWARS may extend far beyond regional or national boundaries.

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