The Role of Remote Sensing and GIS for Impact Modeling and Risk Assessment of Vector Borne Diseases

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ABSTRACT - Understanding the relationships between climate change, the environment, and vector borne disease outbreaks is becoming increasingly important. An efficient means of integrating and analyzing diverse data sources in a spatially registered environment is required to develop the cause/effect relationships that will support predictive models. A GIS-based vector borne disease decision support system is presented that will significantly improve the management of vector borne disease events by providing: (1) an improved prediction capability based on climate and environmental models; (2) improved remediation measures through efficient allocation of resources; and (3) improved methods of prevention by providing a capability to perform scenario evaluation. The components of this system are described with an emphasis on the role of remote sensing for providing environmental inputs into the system models.

I. INTRODUCTION

The threats to health from vector borne disease continue to be a global problem. Climate change, coupled with anthropogenic impacts, has increased the need to understand the relationships between infectious disease and climatic and geographic regimes. Changes in vegetation, environmental impacts of new development, and other factors have created or altered habitats for vector borne disease hosts. Both spatial and temporal changes in environmental conditions may be important determinants of vector-borne disease transmission.

Understanding how these changes impact the propagation of vector borne diseases requires an analytical environment that promotes the integration of diverse data sources and provides the ability to model conditions and test hypotheses based on the latest available data. Geographic information systems (GIS) provide the architecture and analysis tools to perform spatio-temporal modeling of climate, environment, disease transmission, and other factors relevant to understanding the impacts and risk associated with vector borne disease (VBD). A GIS-based decision support system (DSS), with a remote sensing component, could significantly improve the management of vector borne disease events by providing: (1) an improved prediction capability based on climate and environmental models; (2) improved remediation measures through efficient allocation of resources; and (3) improved methods of prevention by providing a capability to perform scenario evaluation.

The increased threat of terrorist attack using biological agents has also magnified the need to better understand VBD. It is important to separate a natural vector borne disease from an anthropogenic biological warfare (BW) event. Many of the remote sensing, GIS, and DSS tools discussed in this paper are equally applicable to the BW problem.

In this paper we discuss the development of a GIS-based decision support system that integrates remote sensing, in situ, and baseline data sets with climate, environmental, and economic process models to significantly improve management of VBD events by providing both an impact prediction capability as well as an effective response tool. In Section 2 we discuss the four phases of effective information management and follow this with the description of the vector borne disease decision support system in Section 3. In Section 4, we provide an overview of remote sensing capabilities and describe the role of remote sensing in supporting the decision support system. The value of geographic information systems as the analysis environment for the system is outlined in Section 5 and a description of how the system fits within an overall event management approach is provided in Section 6.

II. INFORMATION MANAGEMENT

Effective information management is based on an end-to-end process applying data resources, analysis tools, and user support capabilities. This process can be broken down into four distinct phases: (1) data collection; (2) information extraction; (3) information synthesis (modeling); and (4) decision support. Data collection involves the acquisition and

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conditioning of data. These data sources can be imagery, in situ measurements, reports, or even phone calls from the field stating the current conditions. In the information extraction phase, the data are distilled to extract the desired information such as geophysical parameters or environmental conditions. This information, in turn can be used to support the synthesis or modeling phase where relevant event knowledge can be generated based on the current set of inputs. Once the information is gathered and the modeling phase is complete, we enter the decision support phase. In this phase, decision makers have the ability to modify the parameters to the models and perform alternative scenario testing to develop better-informed action plans. Each of these information management phases can be performed within an efficiently designed decision support system.

III. VECTOR BORNE DISEASE DECISION SUPPORT SYSTEM

Fig. 1 shows the basic components of the VBD-DSS that couples geophysical information derived from remote sensing data and in situ sensors with process models into a single platform. The core system consists of a Geographic Information System (GIS) that will: (1) accept remotely sensed data and apply the algorithms for estimating habitat conditions from the satellite data; (2) provide the ability to incorporate online sources of information such as socio-economic data, other archived data or near real-time in situ data collections; (3) contain regional baseline environmental GIS databases as appropriate; (4) use these data and derived parameters as inputs to process models to predict future conditions; and (5) integrate the results to generate map-like value-added products tailored to user requests. Key to the value of this system is a firm understanding of the ecological, epidemiological, and economic factors that will ultimately define the rules that drive the development of the decision support products and capabilities to be provided by the decision support system.

Benefits of this system include facilitating development of cause/effect relationships between parameters as well as supporting "what if" scenario testing. In the next sections, we discuss the use of remote sensing to provide data and information to the DSS and describe the value of GIS as the analysis environment.

IV. REMOTE SENSING

For the purpose of this paper, remote sensing is limited in scope to include space-based, commercially available imaging systems. By commercially available we mean that the images are readily obtainable from sources including non-military U.S. government agencies, foreign government agencies, or businesses. Some imagery, such as AVHRR, are downloadable from the Internet, others such as RADARSAT must be purchased at a per-scene cost. There are differences in the maturity of these systems. Landsat is in its sixth functioning vehicle, whereas high-resolution sensors such as IKONOS are relatively new. The sensors work in different regions of the electromagnetic spectrum—radar, near infrared, through the optical bands. Likewise, the spatial resolutions vary widely—from kilometers (AVHRR) to meters (IKONOS). The capabilities developed using these satellite systems are usually applicable to aerial data collection systems with the same spectral characteristics as well. The benefit of aerial systems is usually higher spatial resolution (each image pixel represents a smaller piece of the ground) at the expense of less ground coverage and the often-challenging logistics associated with aerial collection.

Development of algorithms for converting remote sensing signatures to physical measurements has been ongoing since the first satellite sensors launched in the early 1970's. The techniques developed fit into four general categories: (1) direct extraction; (2) time-series analysis; (3) spectral feature analysis; and (4) data assimilation techniques. Direct extraction involves manual or automated approaches to converting imagery signatures to a geophysical value. For example, accurate land cover/land use maps can be generated from multispectral imagery using a combination of supervised classification algorithms and manual refinement. Time series analysis involves identifying change between two images collected over the same area at different times. These techniques have been shown to effectively identify areas of land use change in an automated manner and queues finer scale analysis to understand what has caused the change. Spectral feature analysis is the generation of linear combinations of spectral bands to form intuitive metrics such as "wetness" and "greenness" rather than simply a radiometric value for a specific optical band. Examples of these techniques include Tasseled Cap (Crist, 1984) and the Normalized Difference Vegetation Index

(Kimes, 1984). More recently, the concept of data assimilation has emerged to produce the next generation of algorithms. This iterative process involves combining imagery with proven process models to estimate geophysical properties. In simple terms, a simulated image is produced using estimates of the geophysical parameters of interest and these parameters are modified appropriately (based on process models) to produce a simulation that best matches the collected image.

Many disease vectors cannot be observed directly, however, the presence of the vector or the conditions under which the vector thrives can be inferred through indicators such as habitats or habitat change. For example, flooded pastures observed in multispectral or SAR imagery may indicate increased potential for mosquito breeding as demonstrated in (Pope, 1992). Remote sensing alone will not provide all the necessary information for detecting or predicting the impacts of VBDs. However, a number of studies (Fig. 2) have demonstrated the potential for correlating remotely-derived information to VBD outbreaks. For example, (Colwell, 2000) showed significant correlation between sea surface temperature and Cholera outbreak in Bangladesh. AVHRR imagery was used to produce 1 km spatial resolution temperature maps of the Bay of Bengal and these temperatures were compared with reported cholera cases. Another study (Beck, 1997) demonstrated how landscape elements could be used to predict mosquito abundance and subsequent malaria outbreaks in Mexico. In this study, Landsat imagery was used to produce land cover maps that were correlated with mosquito populations to identify the statistical landscape conditions most likely to have the highest mosquito abundance.

The characteristics of the data source (resolution, revisit time, availability) as well as the maturity of the algorithms (amount of validation), both play a key role in the value of an algorithm for vector borne disease applications. A summary of existing commercial satellite systems is provided in Fig. 3. This is not a comprehensive list of commercial satellite systems, but rather a list of those that could most likely support the algorithms of interest to the VBD research community. There is a trade-off between image swath size and spatial resolution and coarse resolution does not necessarily mean poor performance. Many features of interest are large in spatial extent and are more appropriate than high-resolution sensors for producing the desired measurement.

We are currently experiencing a boom in the development of commercial satellite imaging systems. These new sensors generally provide better resolution and/or more spectral bands of information.

For example, RADARSAT 2 will provide SAR imagery at a nominal resolution of 3m versus 10m for RADARSAT and will be very useful for identifying areas of standing water. Upcoming commercial hyperspectral sensors such as OrbView 4 may provide improved performance of existing multispectral algorithms and will support completely new approaches to solving key information requirements related to geology, hydrology, agriculture, and air quality.

V. GEOGRAPHIC INFORMATION SYSTEMS (GIS)

GIS provides the ability to analyze information in a geographic context by spatially registering data and information within a single processing environment. Historically, GIS has been used as a "map-maker", however, in recent years, the power of GIS as an analysis tool has grown tremendously. Capabilities include interactive visualization and analysis of spatial data as well as the potential to develop custom modeling applications (such as environmental or socio-economic) including web-accessible systems. The value of GIS for VBD applications is its ability to seamlessly integrate disparate types of data and information such as environmental conditions, substance characteristics, fate and transport models, and spatio-temporal disease transmission characteristics. GIS supports multidisciplinary analysis using a systems approach and provides the ability to perform predictions of disease outbreaks based on available information.

A number of issues must be considered when developing such a system including: (1) data quality; (2) personal confidentiality; and (3) methodological pitfalls (Albert, 2000). The currency and completeness of data incorporated into the system must be maintained. The scales of data used must be appropriate for the model or application they support. For example, 1 km imagery will not be appropriate for mapping wetlands and likewise, a 1:5000 land cover GIS is not necessary for performing climate modeling. Care should be taken to acquire the right data at the right scales. Methods must be developed that will ensure that no individual will be identified through hospital records or through isolated cases which allow personal identification with a little detective work. Finally, care must be taken in methodologies that are used during the modeling and knowledge generation phases. Methods that propagate data errors or don't account for dependencies in the data must be avoided.

VI. PUTTING IT ALL TOGETHER

The decision support system discussed in this paper can be considered a component of a larger event management system as shown in Fig. 4 that is comprised of 4 stages: (1) planning; (2) mitigation; (3) response; and (4) recovery/ preparedness. In the **planning** stage, the DSS provides the ability to monitor environmental conditions and habitats and perform environmental forecasts. If conditions are deemed likely to facilitate a VBD, the **mitigation** stage is entered where the DSS will perform a series of modeling activities based on the planning inputs and assist decision makers in developing mitigation plans for the pending outbreak. Note that these plans include not only environmental and health forecasts, but also economic and resource forecasts as well. Based on these forecasts, a **response** can be formulated which reduces the impacts of the VBD. In this stage, the ill are tended to, destruction of the vector is performed, and the public is alerted to the presence of an outbreak. In the last stage of **recovery/preparedness**, environmental restoration is performed, potentially harmful material is removed (such as tires in the case of Rift Valley Fever), and hospital inventories are stocked with appropriate supplies. Through this four-stage process, lessons are learned, needed improvements to existing models can be identified, and ultimately improved management of VBD events will result.

VII. SUMMARY

Effective VBD management requires simultaneous consideration of environmental, socioeconomic, and anthropogenic factors. GIS provides the necessary infrastructure for an end-to-end VBD decision support system for monitoring and responding to the critical phases of vector borne disease. Remote sensing can play an important role in this system by providing environmental information and supporting larger scale models. The VBD DSS could significantly enhance the ability of local communities and government organizations to conduct contingency planning for future outbreaks. A VBD decision support system would not only benefit the stakeholder community, but would also provide valuable analysis capabilities to other related domains such as biosurveillance, health care forecasting, and national issues such as country stability.

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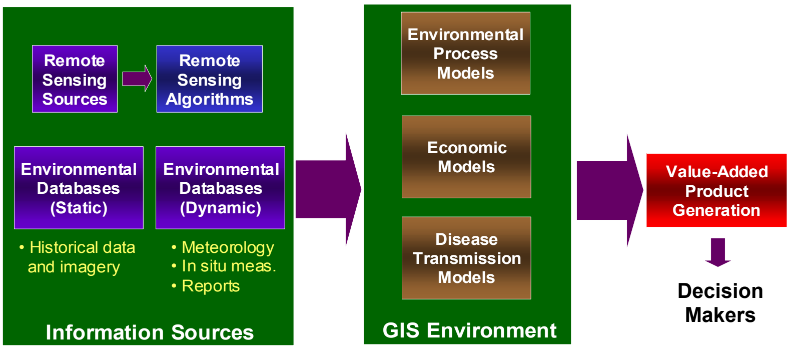

Fig. 1. Vector borne disease decision support system components.

RESEARCH USING REMOTE SENSING DATA TO MAP DISEASE VECTORS

Disease	Vector	Location	Sensor
Cholera	Water/food supply	USA, Latin America	Ocean Color Scanner (now SeaWiFS)
	Water/food supply	Bay of Bengal	AVHRR
Dracunculiasis	Cyclops spp.	Benin, Nigeria	TM
Eastern equine encephalomyelitis	Culiseta melanura	Florida, USA	TM
Filariasis	Culex pipiens	Egypt	TM, AVHRR
Leishmaniasis	Phlebotomus papatasi	SW Asia	AVHRR
Lyme Disease	Ixodes scapularis	New York, USA	TM
	I. scapularis	Wisconsin, USA	TM
Malaria	Anopheles albimanus	Mexico	TM
	An. albimanus	Belize	SPOT
	An. spp.	Gambia	AVHRR, Meteosat
Rift Valley Fever	Aedes & Cx. spp.	Kenya	AVHRR
	Cx. spp.	Kenya	TM, SAR
	Cx. spp.	Senegal	SPOT, AVHRR
Schistosomiasis	Biomphalaria spp.	Egypt	AVHRR
Trypanosomiasis	Glossina spp.	Africa	AVHRR
	Glossina spp.	Kenya	TM

Fig. 2. Previous VBD-related remote sensing studies.

Sensor	First Launch	Bands	Number of Spectral Bands	Nominal Spatial Resolution	Swath Size (km)
Landsat MSS/TM	1972/1987	MS	7	80m/30m	185
Landsat ETM+	1999	Pan/MS	7*	13 m Pan / 25 m MS	185
SPOT	1986	MS	4*	10 m Pan / 20 m MS	60
IRS	1988	MS	4-6*	6 m Pan / 23 m MS	148
IKONOS	1999	MS	4*	1 m Pan / 4 m MS	11
RADARSAT	1995	C-band SAR	1	10-100 m	45-500
ERS1/2	1991	C-band SAR	1	12.5-100 m	100
SeaWiFS	1997	MS	8	1000 m	2800
AVHRR		MS	4	1100 m	2399
Terra	2000	MS	14	15/30/90m VNIR/SWIR/TIR	60
MODIS	2000	MS	36	250-1000 m	2330

* In addition to Pan band

Fig. 3. Commercial Satellite Imagery Sources.

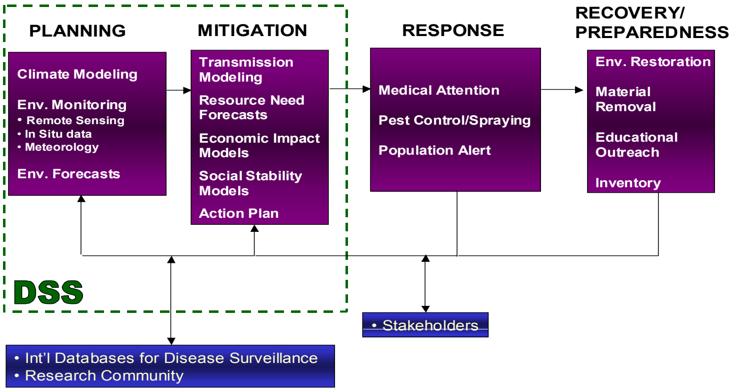

Fig. 4. The DSS is part of an overall event management system.