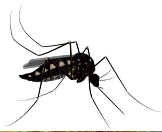
Sciences & technologies Update

# REMOTE SENSING AND SPATIAL MODELLING

## Applications to the surveillance and control of mosquito-borne diseases

Annelise Tran, Éric Daudé, Thibault Catry, coord.



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# Foreword

**Mosquitoes**. The term is generic in nature, yet it is eminently practical for encompassing a vast array of biological, ecological, health, social, economic and historical diversity. Mosquitoes, or *Culicidae* to use their scientific name, refers to the 3,700 species described here on earth, in addition to an unknown number yet to be described. If nature abhors a vacuum, then so do mosquitoes. They are ubiquitous, occurring on every continent and across all ecosystems, and have been around for far longer than humans.

This is something which our human readers often forget. You might only think about mosquitoes if they're keeping you awake at night, stopping you from enjoying an evening outdoors, or, depending on where you live, for causing an illness in the family or to one of your livestock or pets.

**Emergence**. This has become a trendy word in recent years. Humans have become aware that diseases can emerge. The French microbiologist Charles Nicolle, in his 1933 work *Destin des maladies infectieuses*, already predicted that "there will be new [infectious] diseases. It's a fatal fact". Some of these diseases, emerging from the wild as a consequence of environmental, climatic, demographic, societal, cultural, health, and economic changes, among other factors, are vectorial diseases, and sometimes mosquitoes are responsible for this transmission through the inoculation of viruses and parasites.

Mosquitoes are insects, but their study and control go well beyond entomology (from *entoma*, meaning insect in ancient Greek). A multitude of complementary disciplines are involved, ranging from taxonomy to public health. Remote sensing and spatial modelling are counted among these, and they have become indispensable tools in medical and veterinary entomology, as well as agricultural entomology.

By the 5$^{th}$ century BC, the Greek philosopher and physician Hippocrates had already established the link between environmental factors and the aetiology of disease. He described fevers with the same set of symptoms as malaria, and noted a connection between the wetlands and these fevers in his treatise *On Airs, Waters, and Places*. Of course, at the time, even though people likely complained about mosquitoes, it was not feasible to form a causal relationship with malaria. In the not-so-distant past and closer to home, in France the inhabitants of the regions now known as Vendée, Sologne, Dombes and Camargue were invaded by mosquitoes, and fevers were commonplace in these areas until the beginning of the 20$^{th}$ century. The construction site of the Palace of Versailles was the site of numerous fatalities, likely attributable to malaria, before the surface water was channelled.

It is only in our recent past, following the formulation of modern germ theory by Louis Pasteur, that causal relationships have been established between the environment, climate, mosquitoes, microbes and diseases. Over the past two decades, significant progress in our understanding of these relationships have been made, thanks in part to novel genomic techniques, but also due to the emergence of sophisticated remote sensing technologies, spatial analysis tools for biological phenomena (mosquitoes included) and advances in health risk modelling.

The biological diversity of mosquitoes is extraordinary. These 3,700 species are particularly well adapted to specific environments and biotopes. Some mosquito larvae are only found in very specific larval habitats, such as small, water-filled cavities in trees, known as phytotelmata, or the pitchers of carnivorous plants like Nepenthes. Others are less picky and are able to thrive in lakes, marshes or on riverbanks; yet others are almost exclusively found in areas where water has collected due to human activities. Certain species are endemic to a single region (*Aedes pia* on the island of Mayotte), whereas others, which have adapted to urban environments, can be found on every continent (*Aedes albopictus*). Some of these can take blood meals from many different animals, including humans (*Anopheles arabiensis*), whereas others have very strict diets (ant regurgitate for *Malaya* sp.). Some species can survive periods of drought or cold by their eggs entering diapause (*Aedes*), or their adult form resting in sheltered sites such as houses and stables. It is, however, essential that they have access to water in order to lay their eggs and for the development of larvae and pupae. Water plays a vital role in mosquito biology, exerting influence through its presence, quality, physical and chemical properties, as well as biotic factors (plants, food, predators). Any approach that seeks to ascertain, analyse and correlate water-related parameters (rainfall, development, vegetation, etc.) is capable of more accurately estimating, or even predicting, the presence or abundance of different mosquito species and populations, as well as the associated risks.

These risks are not trivial. History is replete with examples of fates being decided by mosquitoes, from the death of Alexander the Great attributed to malaria (*Anopheles*) or West Nile disease (*Culex*), and the excavation of the Panama canal being halted by malaria and yellow fever (*Aedes*), to the more recent example of the "vertical forest" buildings in China being abandoned by their inhabitants due to an invasion by Asian tiger mosquitoes. The list of infectious diseases transmitted to humans by different mosquito species is impressive. Nearly 100 human diseases can be attributed to mosquitoes. Some are still rare, such as Mayaro fever in South America. Yet others are much more common, such as malaria, which kills nearly 400,000 children every year in Africa, or dengue fever, which affects more than 300 million people each year and is present on every continent according to the World Health Organization (WHO).

The health, social and economic challenges associated with mosquitoes are therefore immense, without considering the ecological challenges. Although mosquitoes play an important role in the food chain and contribute to biodiversity, it is nevertheless essential to control species that are responsible for major human and animal diseases. This control must be rationalised, integrated, adapted, sustainable accepted and generate the least environmental impact. The era of the intensive use of insecticides is coming to an end. Other more targeted methods, including geographically targeted campaigns, are currently being developed. Approaches such as remote sensing, spatial analysis and modelling have become indispensable tools for achieving these goals, yet they remain underutilised in the decision-making process.

The examples provided in this publication—*Anopheles* and malaria risk in Camargue, French Guiana, Asia and Madagascar; *Aedes* and dengue risk in Thailand, Brazil and the Indian Ocean—show that remote sensing and spatial modelling applied to mosquitoes and mosquito-borne diseases play a crucial role in these efforts. They also show that interdisciplinary collaboration is required. Models based on inadequate documentation of biological data are not only devoid of meaning, but they can also foster false expectations among those that use them. Conversely, rigorous sampling in the field cannot be used to its full potential without good spatial modelling.

Each scientific community has its own concepts and language. Attending a specialist symposium can be a real ordeal if one is unable to decipher the code. Set an entomologist loose in a remote sensing convention, or a geomatics expert in the annual conference of the Society for Vector Ecology, and they may be unable to correctly interpret the words or acronyms being used, such as reflectance, scanning swath, exophilic, sternite, univoltine, raster mode, diapause, spectral signature, gonotrophic, Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI). Only the word vector can be understood by all, but with two very different meanings: one taken from the field of biology and the other from the field of geomatics. The idea behind this publication, authored by specialists who have worked with or even belong to both communities, is to make these concepts accessible to all with the help of well-documented and concrete examples. My sincerest thanks and best wishes go out to all the contributors. This publication will serve as an invaluable reference for those who recognise the need to adopt a global, spatial and environmental approach for the study of mosquitoes (and other vectors) and the documentation of their biology, distribution, impact and control. It will also prove beneficial to those seeking examples of the application of remote sensing and spatial modelling.

This book acts as a bridge between communities, inviting entomologists to more abstractions and macroscopic perspectives, and those working in the field of remote sensing and geomatics to discover the fascinating world of mosquitoes.

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# General introduction

*Thibault Catry, Éric Daudé, Nadine Dessay, Annelise Tran*

Remote sensing provides Earth observation data which can be particularly useful for modelling and mapping in public health. The World Health Organization (WHO) considers the identification, monitoring and control of arthropod vectors to be a priority for the surveillance of vector-borne diseases (VBDs). In this regard, over a period of more than two decades, a substantial body of research has demonstrated that satellite images and other spatially explicit data can assist in identifying the environmental and climatic variables that influence the spatio-temporal dynamics of VBDs, with a particular focus on mosquito-borne diseases. The current range of satellite sensors allows data to be acquired at high enough spatial and temporal resolutions to (i) characterise different environmental and climate variables (land cover, precipitation, temperature, humidity, etc.) associated with the presence of favourable habitats, and with vector presence and abundance, (ii) to develop predictive tools and methods to model, at different scales, the risks associated with these vectors and the pathogens they transmit, and (iii) to help monitor the evolution of this risk. These efforts are based on advanced satellite image processing techniques (pixel or object classification, use of time series, artificial intelligence algorithms, see Part 1) using multiple sensors (optical, radar, lidar, etc.) and multiple resolutions (medium, high, very high spatial resolutions), as well as a combination of these remote sensing variables with other types of spatial information in different modelling approaches (based on knowledge, data, processes or behaviours, see Part 2). These models can incorporate a large number of variables (in particular environmental and climate variables) into complex and dynamic systems, thereby enhancing our understanding of the epidemiology of mosquito-borne diseases and their transmission mechanisms, which represent a major public health concern.

The results of these studies, conducted as part of research programmes, have led to the development of operational methods based on remote sensing and modelling, which have proliferated in the field of public health in recent years. Some products (risk maps, processing chains) have thus been made available by organisations such as the land surface data and services hub, Theia[1], and in particular by its "Risks associated with Infectious Diseases" scientific expertise centre (SEC)[2]. Such initiatives

1. www.theia-land.fr/en/
2. www.theia-land.fr/en/ceslist/risks-associated-with-infectious-diseases-sec/

have allowed research communities, whether from the field of geomatics, entomology or epidemiology, as well as other stakeholders in public health, to collaborate in pursuit of common goal: the enhancement of knowledge and tools to control mosquito-borne diseases. In particular, the ANISETTE project[3] (Inter-Site Analysis: Evaluation of Remote Sensing as a predictive tool for the surveillance and control of diseases caused by mosquito), funded by the French national space agency, the Centre National d'Etudes Spatiales (CNES), between 2018 and 2022, aimed to assess the interoperability of methods combining remote sensing and spatial modelling to predict the dynamics of vector mosquitoes and their associated diseases. This project is based on the results of various other research projects, both concluded or ongoing, led by teams from different joint research units (ASTRE, Espace-Dev, IDEES and TETIS) who are engaged in entomological modelling in close collaboration with other organisations, such as institutes of the Pasteur Network, and in particular the Institut Pasteur de Madagascar (IPM, Pasteur Institute of Madagascar). The interoperability of the methods developed in the framework of these projects was tested across several sites in South America (Brazil, Antilles, French Guiana), in Europe (France), in the Indian Ocean (Madagascar, Mauritius, Réunion), in South and Southeast Asia (India, Thailand, Cambodia) and in Oceania (New Caledonia).

This publication is the culmination of efforts and reflections undertaken as part of the ANISETTE project. It presents a summary of the theoretical concepts, methodological approaches, tools and main results achieved by the project team, which is primarily composed of geographers, geomatic scientists and modellers. The aim is to introduce the concepts of remote sensing and spatial modelling and apply them to the study of mosquito-borne diseases. It is intended for laypersons who want a better grasp of these notions and their applications to public health[4]. This work is split into two separate parts: Part one covers remote sensing methods for the identification and characterisation of environmental and climate determinants of vector mosquito populations. Part two focuses on the integration of these variables into different modelling approaches in order to implement operational monitoring tools for VBDs caused by certain mosquito species. In order to facilitate comprehension, a glossary is provided at the end of the text, defining several technical terms related to the different fields under discussion, namely entomology, epidemiology, remote sensing, geomatics and mathematics. A list of acronyms and their respective definitions is also provided at the end of this publication.

## ⏩ Remote sensing concepts

Remote sensing is defined as the set of techniques used to collect information on objects at a distance. In particular, Earth observation uses an instrument (a sensor) on board a platform (satellite, aircraft, drone, etc.) to characterise the Earth's surface (land surface, oceans or atmosphere). Typical examples of remote sensing include the use of satellite imagery or aerial photography.

3. https://anisette.cirad.fr/
4. For more detailed information on vector mosquito biology and ecology, readers can refer to the publication *Le moustique, ennemi public nº 1 ?*, coordinated by S. Lecollinet, D. Fontenille, N. Pagès and A.-B. Failloux, published by Éditions Quæ (2022).

## Main characteristics of remote sensors

Different types of remote sensors exist. Passive sensors measure the natural radiation emitted or reflected by the surface being observed, as in the case of optical sensors which rely on an external energy source (sunlight). As for active sensors, these measure the reflected radiation which they themselves emit. This is the case for radar, which emits its own energy source and measures surface roughness and humidity.

The signals measured by remote sensors are referred to as "electromagnetic radiation" and possess properties which can be quantified and described. These properties include the wavelength (which represents the spatial period of a wave, i.e., the distance between two successive maxima), the amplitude (or intensity, which corresponds to the maximum value of the oscillation) and polarisation (relationship between the amplitude and the direction of travel of the wave). Sensors measure the quantity of energy carried by the electromagnetic radiation emitted or reflected by the surfaces. In particular, this includes the albedo or directional-hemispherical reflectance, which is defined as the ratio between the energy emitted and the energy received. Panchromatic images, in black and white, are obtained from recording this radiation in a single band of wavelength. "Multispectral" imaging refers to when these measurements are taken across different wavelengths. Remote sensors can measure signals in the visible spectrum (optical remote sensing), infrared spectrum or microwave spectrum (radar remote sensing), thereby providing supplementary data. Sensors can be ground-based, on board aircraft or drones (airborne remote sensing), or on satellites. Most Earth observation sensors capture information in the form of digital images characterised by pixel size and the width of the snapshot (swath width).

Remote sensors are mainly categorised by three resolutions:
– spatial resolution is the smallest size of observable objects, directly related to the elementary size of the image pixel. We refer to low resolution when images have a spatial resolution greater than 1 km, medium resolution when this is between 100 m and 1 km, high resolution between 10 and 100 m, and very high resolution for values ranging from a few dozen centimetres to several metres;
– temporal resolution, which corresponds to time taken by a satellite to revisit a given location, i.e., the time between taking two identical shots;
– spectral resolution which characterises the ability of the sensor to distinguish between signals of different wavelengths.

## Spectral signature concept

Each surface type is characterised by its spectral signature, defined as the variation in reflectance as a function of wavelength (Figure I.1). Spectral signature depends on the nature of the surface, its physical properties and the interaction it has with the incoming electromagnetic waves.

## Extracting information from satellite images

There are different ways to make use of the spectral information contained in satellite images. The simplest method consists of a visual interpretation of the image, or photointerpretation. More complex analysis methods are used to classify the spectral content of images based on the information contained in pixels (pixel-oriented approach), or in objects whereby images are segmented into homogeneous regions

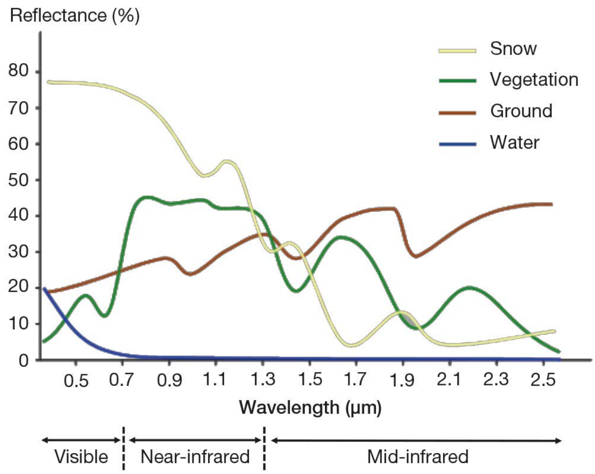


**Figure I.1.** Spectral signatures of natural surfaces across different wavelength bands. Adapted from https://e-cours.univ-paris1.fr/.

of pixels (object-oriented approach). These classification approaches can be unsupervised (without *a priori* knowledge of the image to be classified) or supervised (when prior knowledge is available) [Figure I.2]. Classification algorithms (K-means, Random Forest, Support-Vector Machine, etc.) group the information contained in each pixel or object into a cluster which describes the image in question.

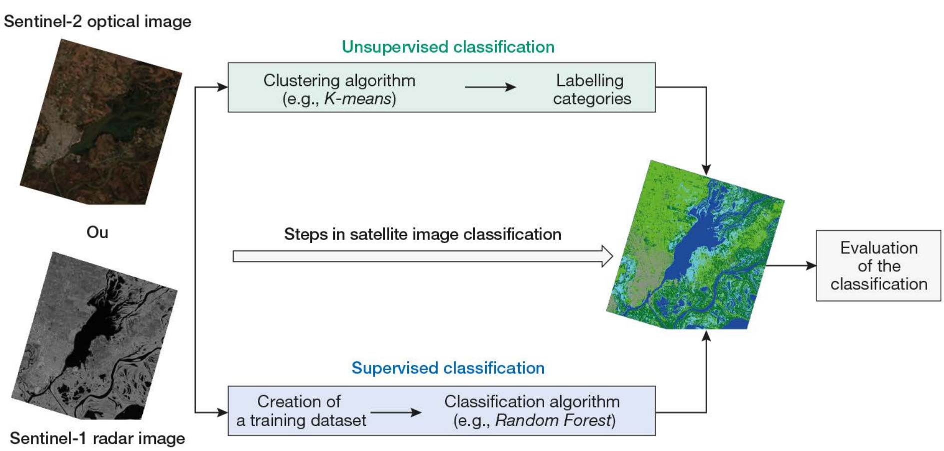


**Figure I.2.** General principles of supervised and unsupervised approaches to optical and radar satellite image classification.

## Satellite image broadcasting

Today, a plethora of platforms exist to provide optical and radar satellite images. Such is the case for the Sentinel-1 and 2 sensors of the European Space Agency in the framework of the Copernicus programme[5].

5. www.copernicus.eu/en/about-copernicus/infrastructure-overview/discover-our-satellites

A wide range of free software, tools and satellite image processing algorithms are also available which help contribute to the popularisation of this technology. The information extracted from remote sensing images can then be combined and analysed with other spatially explicit data using a Geographic Information System (GIS).

## ⏩ Introduction to GIS

GIS are computational tools for the acquisition, storage, updating, integration, analysis, visualisation and recovery of georeferenced digital data (i.e., data which can be associated with a specific location through its geographic coordinates). They allow different types and sources of spatially explicit data to be handled and processed.

Georeferenced (or spatially referenced) data is organised in a GIS based on the following principle: each type of object (vegetation, water bodies, towns or mosquito trapping results) is represented by a different data layer (Figure I.3). Overlaying layers according to their spatial references enable each data layer to be visualised and analysed separately (horizontal query within the same layer, e.g., which mosquito species were observed and in what abundance?). Additionally, the relationships between different data layers can also be investigated (vertical query between different layers, e.g., what type of land cover do we observe in places with the highest abundance of mosquitoes?).

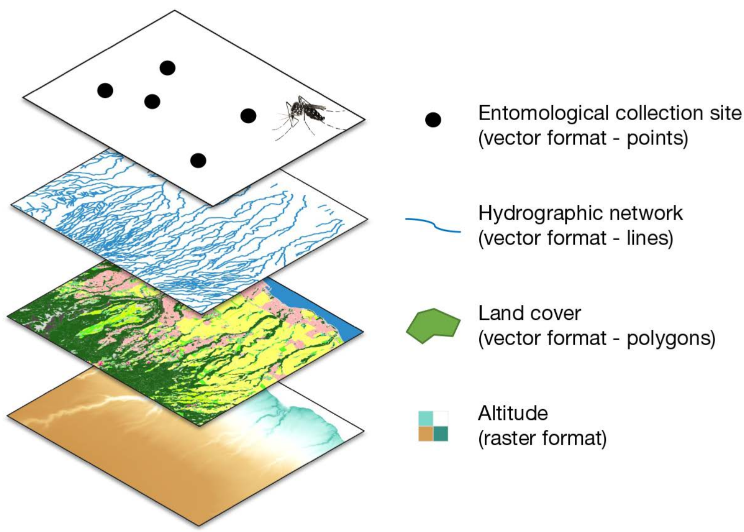


**Figure I.3. Principles** of data organisation in a GIS—thematic layers and modes of representation.

Within a single spatial data layer, objects are of the same kind and represented in two different modes:
– the vector mode or “vector”: in this mode, each object is represented in the form of polygons (e.g., a plot of vegetation), lines (e.g., a road or river) or points (e.g., location of a trapping site) [Figure I.3]. The most commonly used vector file format is “.shp” (shapefile);

– the matrix mode or "raster": in this mode, spatial data is represented in the form of an image (or grid) composed of cells of the same size, called pixels (such as in a satellite image). The most commonly used raster file format is ".tif".

In both cases, geographical data is combined with thematic data, providing information on the properties of the object. In vector mode, this thematic data is stored in an associated attribute table (e.g., for results of entomological traps, represented in form of points, the associated table will list: sample data, captured species, abundance, etc.). In raster mode, the pixel value contains the information represented (for a multispectral satellite image, the value of the pixels will be the reflectance value measured by the sensor).

# Part 1

# Spatial data for vector mosquito surveillance and associated diseases

The first part of this publication addresses the identification of different environmental, climate and demographic variables that exert an influence on the presence and dynamics of mosquito populations, with a particular focus on satellite images and their contribution to the study of vector-borne diseases.

The first chapter describes these different variables, in addition to the satellite remote sensing data and methodologies that facilitate access to this information. The following chapters present different approaches based on satellite imagery for the extraction of these variables: the use of spectral indices for water and vegetation (Chapter 2), the study of air temperatures (Chapter 3), the characterisation of human populations (Chapter 4) and finally the use of image texture analysis to characterise urban environments (Chapter 5).