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Modeling the dynamics of mosquito breeding sites *vs* rainfall in Barkedji area, Senegal

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ABSTRACT

Mosquito-borne diseases like Rift Valley Fever and Malaria that cause serious health threat to human and livestock populations are known to correlate with the tremendous increase of associated mosquito vectors following periods of widespread and heavy rainfall. In the Barkedji area, Senegal, rainfall occur only during the July–October wet season, and mosquito breeding sites are provided by relatively small temporary ponds, which account for the vast majority of the water surfaces during the rainy season. Given that rain fed ponds play a key role in the epidemiology of the mosquito-borne diseases, we have developed an approach allowing to model the flooding/drying dynamics of rain fed ponds in the Barkedji area by combining the detection of ponds using optical remote sensing techniques, field data on a small set of monitored ponds and modeling of both the pond profile, shapes and the flooding/drying dynamics at the single-pond level for each pond in the entire region.

As a result, we have computed on output the daily flooding/drying dynamics for each of the 1345 rain fed ponds detected in Barkedji area as a function of the daily rainfall in input. As dry and fluctuating ponds are less productive in mosquitoes, the ponds are characterizes in terms of flooding-drying fluctuations and of resistance to dryness by computing the total number of time per year a pond dries out and the pond lifetime, respectively. And, clusters of ponds with identical behavior, i.e., clusters of temporary, semi-permanent and permanent ponds, were subsequently identified.

As a perspective, we show how this work can be used for modelling mosquito population dynamics and addressing the issues of associated impacts of climate change.

1. Introduction

Mosquito-borne diseases like Rift Valley Fever (RVF), Malaria and West Nile Fever, to cite a few, have attracted a lot of attention regarding the population dynamics of the associated mosquito vectors (Depinay et al., 2004; Ahumada et al., 2004; Shaman et al., 2002, 2006; Ndiaye et al., 2006). For instance, it has been shown that climate forecast can hint on the future anomalous malaria incidence in some areas (Thomson et al., 2006), among which relationships between malaria and rainfall patterns (Pascual et al., 2008; Krefis et al., 2011; Gao et al., 2012; MacLeod and Morse, 2014), and RVF outbreaks are commonly correlated with periods of widespread and heavy rainfall (Meegan and Bailey, 1988; Digoutte and Peters, 1989; Wilson et al., 1994; Linthicum et al., 1999; Anyamba et al., 2001, 2006). It is understood that changes in environmental factors such increasing in the availability of reproduction sites following rainfall for instance may result in a tremendous increase in the number of mosquito vectors which in turn is likely to trigger an epidemic.

This paper deals with some of the works developed within the framework of the ACCIES program (Bicout et al., 2011) for Barkedji area in the Ferlo region of Senegal. The aims of the work were to study the impacts of rainfall or weather variability on the mosquito vectors. Indeed, the area is endemic for Malaria and West Nile fever but since the first epidemic of RVF in 1987 in West Africa, Senegal is constantly experiencing episodes of emergence and re-emergence of RVF virus circulation (Zeller et al., 1997).

Malaria is transmitted to humans by several infected *Anopheles* mosquito species whereas RVF is transmitted to vertebrates by infected floodwater mosquitoes *Aedes spp.*, *Culex spp.* and other mosquito species, and from mosquito to mosquito by vertical transmission (Meegan and Bailey, 1988; Fontenille et al., 1998; Diallo

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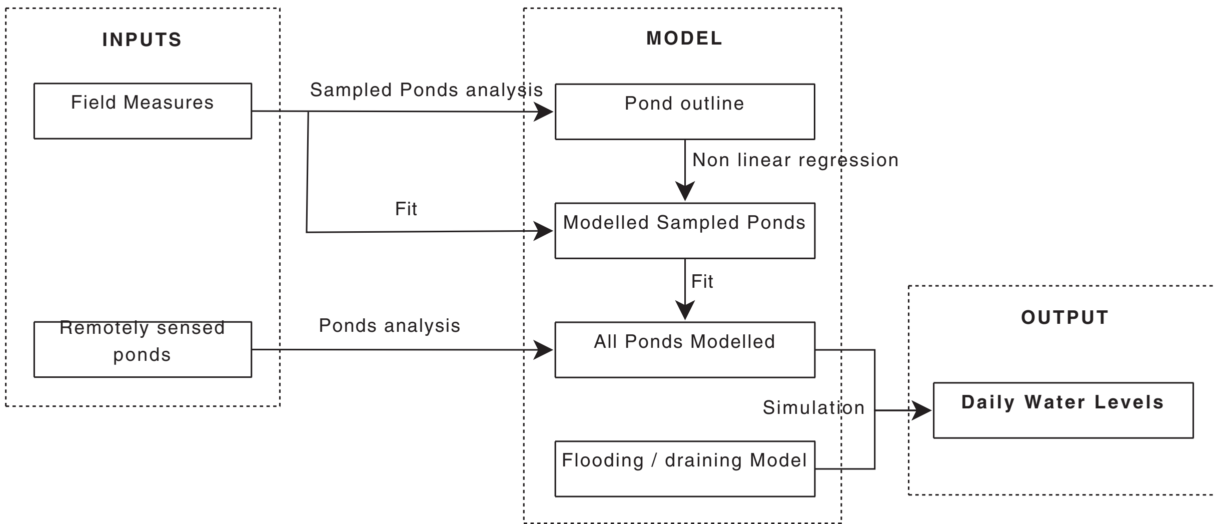

Fig. 1. Diagram of the modeling approach.

et al., 2005); both *Aedes* and *Culex spp.* are also found implicated in the transmission of West Nile virus (Diallo et al., 2005, 2011). It is admitted that occurrences of RVF outbreak are correlated with tremendous increase of associated mosquito vectors which follow periods of widespread and heavy rainfall. Such rainfall floods mosquito breeding habitats of *Aedes spp.* that serve in turn as excellent habitats for development of other mosquitoes like *Culex spp* (Laughlin et al., 1979; Meegan et al., 1980; McIntosh et al., 1980; Linthicum et al., 1990; Pratt and Moore, 1993; Crans and McNelley, 1998; Fontenille et al., 1998; Bicout, 2001; Bicout and Sabatier, 2004). In the Barkedji area, the abundances of *Anopheles*, *Aedes* and *Culex* mosquito vectors, and therefore the malaria activity and the enzootic circulation of RVF virus, are linked with rainy wet season found in Barkedji in 1993 (Zeller et al., 1997; Lemasson et al., 1997). The rainfall occur only during the July–October wet season, and breeding sites are provided by relatively small temporary ponds, which account for a vast majority of the water surfaces during the rainy season (Lacaux et al., 2007; Porphyre et al., 2005; Ba et al., 2005; Mondet et al., 2005; Chevalier et al., 2005, 2004).

As rain fed ponds play a key role in the epidemiology of the above mentioned mosquito-borne diseases by providing breeding sites for reproduction and proliferation of mosquito vectors, we developed an approach allowing to model the dynamics of a large number of rain fed ponds detected in an area by using the spatial remote sensing of environment. There are several works that had been dealt with the remote sensing to address similar problems. For instance, Jacob et al. managed to identify parameters associated with mosquito aquatic habitat, using optical remote sensing, as well as geostatistics and Digital Elevation Model (Jacob et al., 2008). Lacaux et al. used satellite images to assess key environmental factors for RFV vectors reproduction in Senegal: temporary ponds with characteristics such as vegetation cover and water turbidity (Lacaux et al., 2007), allowing then to map zones potentially occupied by mosquitoes (Tourre et al., 2008; Vignolles et al., 2009). Similar work to our in the same area was done by Soti et al. (2010).

Regarding the key role of rain fed ponds, it has been demonstrated how the dynamics of mosquito abundances are related to that of rain fed ponds (Bicout et al., 2003; Porphyre et al., 2005; Soti et al., 2010) and, therefore, to the epidemic outbreak thresholds (Bicout and Sabatier, 2004). In this paper, we extend these previous works in primarily focusing on the dynamics of an ensemble of rain fed ponds. We describe in detail an approach allowing modeling the flooding/drying dynamics of an ensemble of rain fed ponds by combining data on the detection of ponds from remote sensing techniques, field data on a set of monitored and detected ponds and modeling of the single-pond flooding dynamics. The approach is implemented for the Barkedji area in Senegal.

2. Materials and methods

2.1. Modeling structure

The structure of the modelling approach as schematically depicted in Fig. 1 can be summarized in three steps as follows: (i) use of field data on a set of p ponds to allow both the derivation and calibration of a model for the flooding/draining dynamics of ponds, (ii) use the satellite imaging to detect n ($n \gg p$) ponds in the study area (as done in (Lacaux et al., 2007)) and extract the pond characteristics allowing to run the flooding/draining dynamics over all ponds, and (iii) use rainfall as input in the flooding/draining dynamics model to simulate daily water levels for each detected pond in the study area over a year period.

2.2. Study area and data

The study area (see Fig. 2) is a 46 km × 43 km region around the village of Barkedji (15°16′46″ N, 14°52′05″ W) located in the northern Senegal in the Sahelian Ferlo region. Rainfall in this region averages 250–350 mm annually, and occurs in a short rainy season (July to October) which fills the temporary ground pools. These latter remain the only source of water until to January during the 6th-month dry season (December through May). After the first rains, the number of mosquitoes, including vectors of diseases like Rift Valley Fever, dramatically increases. Both a satellite image of the region and flooding data of a very limited number of ponds were available for the same study period.

2.2.1. Satellite imaging

Multi-spectral high-spatial resolution images (10-meters) from SPOT 5 satellite, provided through the ACCIES Consortium, were used for ponds locations (Lacaux et al., 2007). The unprocessed image resolution allowed detection of ponds as small as about 10 m × 10 m. Each satellite image, covering a rectangular area of 46 km × 43 km, was centered on the Barkedji village. The image was shot on August 26th, 2003, following a heavy rain period, thus allowing to assume that almost all the ponds were filled up.

Using the satellite image, a map of ponds in the Barkedji area was processed following the methods set up and described in