

Rift Valley fever in a zone potentially occupied by *Aedes vexans* in Senegal: dynamics and risk mapping

Cécile Vignolles¹, Jean-Pierre Lacaux², Yves M. Tourre^{3,4}, Guillaume Bigeard², Jacques-André Ndione⁵, Murielle Lafaye¹

¹CNES, Toulouse, France; ²OMP, Université Paul Sabatier (UPS), Toulouse, France; ³METEO-France, Direction de la Climatologie, Toulouse, France; ⁴LDEO of Columbia University, Palisades, NY, USA; ⁵Centre de Suivi Ecologique (CSE) and Laboratoire de Physique de l'Atmosphère et de l'Océan, Université Simon Fongang (LPAO-SF/ESP/UCAD), Dakar, Sénégal

Abstract. This paper presents an analysis of the interaction between the various variables associated with Rift Valley fever (RVF) such as the mosquito vector, available hosts and rainfall distribution. To that end, the varying zones potentially occupied by mosquitoes (ZPOM), rainfall events and pond dynamics, and the associated exposure of hosts to the RVF virus by *Aedes vexans*, were analyzed in the Barkedji area of the Ferlo, Senegal, during the 2003 rainy season. Ponds were identified by remote sensing using a high-resolution SPOT-5 satellite image. Additional data on ponds and rainfall events from the Tropical Rainfall Measuring Mission were combined with *in-situ* entomological and limnometric measurements, and the localization of vulnerable ruminant hosts (data derived from QuickBird satellite). Since “*Ae. vexans* productive events” are dependent on the timing of rainfall for their embryogenesis (six days without rain are necessary to trigger hatching), the dynamic spatio-temporal distribution of *Ae. vexans* density was based on the total rainfall amount and pond dynamics. Detailed ZPOM mapping was obtained on a daily basis and combined with aggressiveness temporal profiles. Risks zones, i.e. zones where hazards and vulnerability are combined, are expressed by the percentages of parks where animals are potentially exposed to mosquito bites. This new approach, simply relying upon rainfall distribution evaluated from space, is meant to contribute to the implementation of a new, operational early warning system for RVF based on environmental risks linked to climatic and environmental conditions.

Keywords: remote sensing, Rift Valley fever, risk mapping, pond dynamics, rainfall distribution, early warning system.

Introduction

Rift Valley fever (RVF), an arthropod-borne disease which primarily causes epizootics of abortion and high mortality rate in domestic animals, can also infect humans. It is caused by a phlebovirus of the Bunyaviridae family, which engenders public health issues with a serious socio-economic impact in affected regions. For example, in Senegal, morbidity associated with RVF epidemics is on the rise (Ndione

et al., 2003). Epidemics result from the synergy of at least three factors which can vary considerably: (i) the presence and circulation of the phlebovirus by mosquito vectors; (ii) the number of mosquito breeding sites and hatching frequency, two parameters which are both highly dependent on environmental conditions, particularly rainfall events; and (iii) the distribution of domestic animal hosts, essentially ruminants (goats, sheep and cattle), vulnerable to increased vector/host contacts at night.

It has been shown that higher than average seasonal amount of rainfall in East Africa leads to a seasonal increase of vector-borne epidemics, including RVF (Linthicum et al., 1999) and malaria (Thomson et al., 2006). The strong correlation between RVF and the climate, and the influence of

Corresponding author:
Cécile Vignolles
CNES, DSP-ARP/AV, BPi 2902
18 Avenue Edouard Belin
31401 Toulouse Cedex 9, France
Tel./Fax +33 056 1 27 33 45
E-mail: cecile.vignolles@cnes.fr

environmental variability are emphasized in the Ferlo region, Senegal. Indeed, this zoonotic arboviro-sis has been emerging, and re-emerging, over West Africa where the confounding factors seem somewhat different to those in East Africa (Ndione et al., 2003). This paper concentrates on the mechanisms linking rainfall variability with the density of aggressive vectors, i.e. mosquitoes characterized by high numbers of bites/host/day. The investigation of these environmental risks took place in the Barkedji region of the Ferlo during the 2003 rainy season (Fig. 1). The abundance of RVF vectors such as *Aedes vexans* and *Culex poicilipes* (Meegan et al., 1989; Fontenille et al., 1998; Diallo et al., 2005) is directly linked to pond dynamics (Chevalier et al., 2004; Mondet et al., 2005a,b). The association of

mosquito breeding sites with the filling-up and flushing-out of the ponds due to spatio-temporal variability of rainfall events has been pointed out by Ndione et al. (2003) and Bicout et al. (2003), among others, and depend on the mosquito species and their specific dynamics. For example, *Ae. vexans* lay their eggs along the pond edges where they mature and hatch only when more than six days of dry conditions are followed by total immersion from a rainfall event. From the entomological point of view such an event has been coined a “productive rainfall” since it favours mosquito breeding and hatching. For *Ae. vexans*, the following three conditions must be fulfilled for a “productive rainfall event”:

(i) the amount of water from a single rainfall event



Fig. 1. Geography and study site. Ponds to be studied are located within the Barkedji window (red square) (from the Cartographic Section, DPKO, United Nations, NY, NY 10017).

- must reach at least of 10 mm (lower values did not affect ponds dynamic significantly, if at all, resulting in no or very little vector production);
- (ii) a rainfall event delivering more than 10 mm, must occur after a 6-day period without rain, the latter period being a necessary condition to trigger latent hatching; and
 - (iii) a rainfall event delivering more than 40 mm, must occur after a 6-day period with less than 30 mm of rain.

Ae. vexans eggs can indeed survive in a dry environment up to a few months (Mondet et al., 2005a). Also specific to *Ae. vexans*, the virus can survive within the infected egg, i.e. until a productive rainfall

as defined above occurs, thus leading to infected vectors directly (Lupi and Tyring, 2003). *Cx. poicilipes*, on the other hand, lays its eggs on the pond surface but these do not survive the dry conditions which often occur after a flushing event. Therefore, *Cx. poicilipes* vectors usually appear during the apex of the rainy season when the ponds are well formed (Mondet et al., 2005b). The information given above is summarized and displayed in Figure 2a (Ndione et al., 2008, adapted from Bicout, 2001).

This paper refers only to the behaviour of *Ae. vexans* and it relies on earlier *in-situ* measurements made by entomologists. For example, it was learnt that the average *Ae. vexans* flying range is

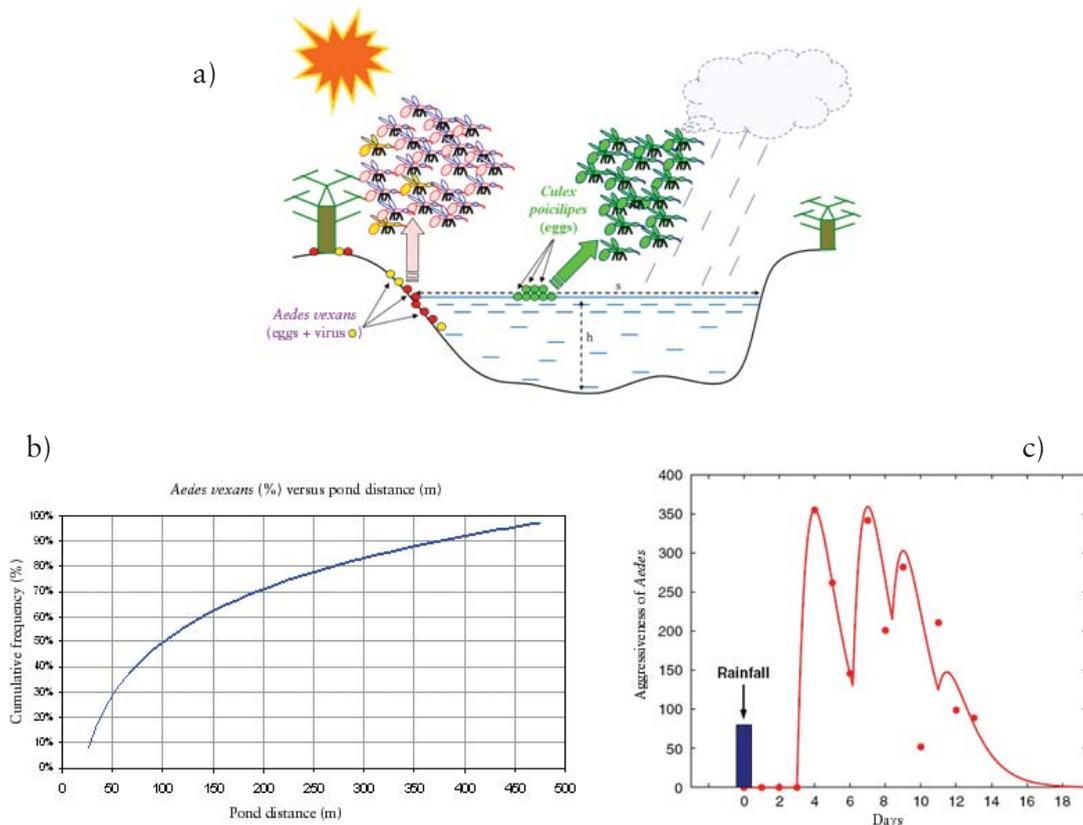


Fig. 2. Ponds and RVF vector mechanisms. a) Schematic ponds and breeding sites distribution. *Ae. vexans* eggs found around pond edges in red (in yellow when infected, i.e. vertical transmission). *Cx. poicilipes* eggs found mainly in open waters in green (these eggs are never infected by vertical transmission). The surface and depth of the ponds (which vary as a function of the rainy events) are denoted by “s” and “h”, respectively. Note that only *Ae. vexans* is considered in this paper (after Ndione et al., 2008, adapted from Bicout, 2001). b) Cumulative *Ae. vexans* distribution in % (ordinate), up to 500 m from a pond (abscissa), i.e. the zone with the highest serological incidence (after Bâ et al., 2005). c) *Ae. vexans* aggressiveness in days (abscissa) after a “productive rainfall event” (vertical blue bar) (after Ndiaye et al., 2006).

such that their total number decreases linearly up to 500 m from a given pond. In addition, in Figure 2b, the cumulative density of *Ae. vexans* is displayed according to results by Bâ et al. (2005). The aggressiveness of *Ae. vexans* hatched after significant rainfall event (delivering at least 10 mm of rain) is a function of the number of days elapsed after the rainfall. This was studied by Ndiaye et al. (2006) who were able to estimate the daily total aggressiveness of *Ae. vexans* (nulliparous + parous) using a field population dynamics model with on-site validation. The first peak of aggressiveness by a nulliparous mosquito occurs about 4 days after a rainfall event, whilst second, third and fourth peaks from a parous one occur 8, 10 and 12 days, respectively, after the rainfall event. The total aggressiveness cycle lasts about 15 days after the rain event. The mean rainfall amounts needed to produce increased *Ae. vexans* populations, triggering an increased average aggressiveness, are displayed in Figure 2c (for details, see also Ndiaye et al., 2006).

Based on the observations and entomological studies discussed above and recent results by Lacaux et al. (2007) and Tourre et al. (2008), pond dynamics has been further evaluated after productive rainfall events in the Barkedji area during the 2003 rainy season. A schematic design of the integrated methodology to determine the environmental risk levels of RVF is presented in Figure 3. The upper left box in the figure identifies key entomological factors for *Ae. vexans* (flying-range, aggressiveness and embryogenesis), environmental factors (rainfall distribution, limnometry and ponds dynamics) as well as pastoralist data such as the zones where animals are left for the night. From the upper right box, the detection of lead environmental and climatic factors (mainly rainfall) favouring the mechanisms presented in the box, are highlighted. For example, localization and optimal pond conditions for the breeding and hatching of *Ae. vexans* can be modelled. The central box refers to the zone potentially occupied by mosquitoes (ZPOM) derived from pond dynamics after a productive rainfall event including the flying ranges of *Ae. vexans*. The combination

and integration of all the elements mentioned above lead to the notion of risks: hazards and vulnerability of host exposure. This original approach (CNES, 2008) bridges the physical and biological mechanisms, linking environmental conditions to the production of RVF vectors and the accompanying potential risks (Fig. 3).

Since the vulnerability to RVF depends upon the local agro-pastoral practices, dynamic ZPOMs thus contribute to the estimation of the ranked risks for animals of being bitten by the female *Ae. vexans* mosquito. The scales considered in this study amount to 10 m spatially and measurements occurred daily for the entire 2003 rainy season. The methodology used relies on rainfall distribution based on satellite data and the aim is to contribute to the development of an early warning system (EWS) for RVF based on environmental risks. The risks constitute the climatic and environmental conditions leading to potential RVF epidemics.

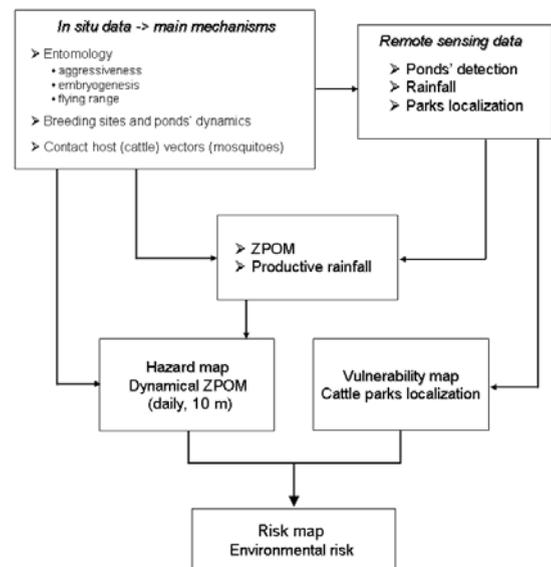


Fig. 3. Integrated methodology. The basic components for this study are presented in the top three boxes: *in-situ* data (upper left), remotely-sensed data (upper right), and ZPOM and productive rainfall (centre). The bottom three boxes distinguish between hazards (bottom left), vulnerability (bottom right), both leading to the environmental risks (very bottom).

Materials and methods

Entomological data

All information about *Ae. vexans* pertain to the 2003 rainy season in the Barkedji area in the Ferlo region of Senegal. They include flying range data (courtesy of Bâ et al., 2005), daily aggressiveness data from Mondet et al. (2005a,b) and aggressiveness as modelled by Ndiaye et al. (2006).

Seven individual ponds with different environmental characteristics and eco-zones, namely Barkedji, Niakha, Ngao, Furdu, Kangedji, Loumbel Lana and Yalope, were studied in detail previously by Lacaux et al. (2007). Limnometry, bathymetry and surface characteristics were followed during several rainy seasons (from 2002 to 2007). Relevant information about the depth (h), surface (s) and general features (with/without vegetation; turbid or not) of the ponds allowed us to establish linkages between rainfall events and pond dynamics (rates of filling-up and flushing-out). Furthermore, their surface variability and coverage (individually and clustered) led to remotely-sensed ZPOM mapping with uncertainties of $\pm 10\%$ (maximum and minimum) according to Tourre et al. (2008).

Hazard evaluation

The degree of hazard was estimated following to Bicout et al. (2003), Bâ et al. (2005), and Ndiaye et al. (2006) and defined as the number of vectors per pixel for a given period of time. The scale was obtained from the relative maximum density of *Ae. vexans* mosquitoes, which is arbitrarily divided into seven equally distant aggressiveness classes stretching from absence of vectors (no hazard) to very high degrees of hazard. The latter is a function of ponds size and rainfall amount. Finally, starting with the lowest class of hazard (zero) and by adding classes two and three (i.e. very unlikely and very low hazard) together and classes four and five (i.e. low and moderate hazards) as well as joining classes six

and seven (i.e. high and very high hazards), a final set of four hazard classes is obtained: zero, very unlikely, moderate and high. For example, between the two very unlikely and high classes, the highest hazards are 300% larger than those for the very unlikely class.

Judging from the observed vector aggressiveness (Fig. 2c), several time periods after each productive rainfall event can be considered as constituting high hazard: (i) the first 3-day period when nulliparous vectors can be infected (vertical transmission); and (ii) the following periods with much higher hazard (completed gonotrophic cycles) since the number of potentially infected bites increases considerably. Indeed, a single gonotrophic cycle is characterized by another blood meal during which the vector increases the risk of contamination.

Remotely-sensed data

SPOT-5 imagery allowed ponds detection in the Ferlo region of the Sahel using high-resolution (~ 10 m pixels) images. Four spectral bands/channels were used, i.e. the green channel (0.50 to 0.59 μm), the red channel (0.61 to 0.68 μm), the near-infrared channel (NIR, 0.78 to 0.89 μm) and the medium-infrared channel (MIR, 1.58 to 1.75 μm). Radiometric and geographic corrections, needed due to small changes in satellite altitude, inclination, position relative to the sun, curvature of earth, state of the troposphere, sensor calibration, were implemented by SPOT-Image. Digital counts (DCs) from radiometric values within each pixel, and "DC thresholds" from photo-interpretation were used for class ranking (for details, see Lacaux et al., 2007). The classification for each pixel was obtained by using a decision-tree classifier distinguishing between water and other soil elements. As such, new indices were developed, i.e. the normalized difference pond index (NDPI) and the normalized difference turbidity index (NDTI). Lacaux et al. (2007) provide details on how NDPI and NDTI were computed.

Data could be acquired at least every 26 days

(orbital cycles of polar- and helio-synchronous satellites), with a revisit time of 3 days, assuming minimum cloud coverage, allowing detailed spatio-temporal evolution and dynamics of the ponds. The programmed five SPOT-5 images (60 x 60 km each) were centred near the Barkedji village in the Ferlo (Fig. 1), covering the 2003 rainy season in its entirety. This area is particularly suitable for the study since detailed entomological data, collected and analyzed previously (see above), contribute much to the understanding of the dynamics of the ponds considered as “vector producers”. In addition, specific information on pond characteristics is available in Lacaux et al. (2007) and Tourre et al. (2008).

Among other parameters, the Tropical Rainfall Measuring Mission (TRMM) identifies rainfall events and estimates their amounts of water. TRMM, which has been in operation since January 1998, is a joint space mission between NASA and the Japan Aerospace Exploration Agency (JAXA) designed to specifically monitor tropical rainfalls. The resulting data were downloaded from the <http://disc2.nascom.nasa.gov/Giovanni/tovas/> website and averaged over the Barkedji area. As a working hypothesis, when few consecutive rainy days occurred, they were assimilated into one rainfall event (with the corresponding total rainfall amount). As discussed above, the presence and density of *Ae. vexans* mosquitoes are known to be governed by the frequency and intensity of rainfall as these events modify both the extent and the distribution of the ponds. The combined approach of ground checking and satellite monitoring takes into account not only the total amount of rainfall, but also the true accumulation of water within ponds and their extensions, all key parameters for mosquito production and ZPOM mapping.

Data from the QuickBird satellite, a high-resolution commercial earth-observation satellite launched in 2001, was used for geo-referencing only. Its panchromatic imagery is collected with a 0.6 m resolution and multi-spectral imagery at 2.4 m resolution. Details of structures such as areas fenced-in for animal keeping are thus easily visible

with precise coordinates. The latter, embedded into the August 26, 2003 SPOT-5 image, allowed a precise mapping of the study area at that date. As a result, ZPOM mapping with pond dynamics includes all fenced-in areas where vulnerable animals were kept at night in the Barkedji area.

Results

Possible hazards in the vicinity of fenced-in hosts are displayed in Figure 4, where the Barkedji area is shown with the mapped ZPOMs. Thus, parks and villages can easily be identified. Out of 18 rainfall events obtained from TRMM for the 2003 rainy season, seven were considered as productive with regard to *Ae. vexans* production (based on entomological studies). Rainfall events (on July 20, 2003 and after September 5, 2003, respectively) did not qualify as productive, following the second criteria. The third criteria is well illustrated by the August 22, 2003 event which produced 64 mm rain in total,

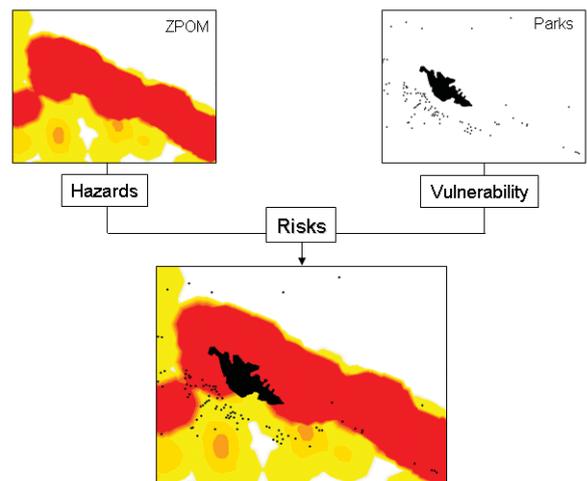


Fig. 4. Risks = hazards + vulnerability. ZPOMs with ranked risk. ZPOM in the Barkedji area judged from the pond distribution after a single rainfall event (top left). Localization of the Barkedji village and ruminants' fenced-in areas in black for the same area and time (top right). Possible risks are shown by super-imposing the two pictures (bottom).

but was not counted as productive since the total amount of rainfall in the preceding 6-day period exceeded 30 mm (third criteria). The precise percentages for the 242 parks identified as being at risk during that same period are presented in Figure 5. Overall it can be said that from the seven productive rainfall events (vertical blue bars) 15% of the fenced-in ruminants were never at risk, whilst 60% to 30% of the fenced-in areas exposed the animals to moderate or high risk. One day out of three exposes 20% of fenced-in ruminants (and one day out of five exposes 30%) to a very high risk.

The detailed dynamical evolution of ZPOMs during the full 2003 rainy season with associated risks is presented in the animated (see the on-line version) Figure 6 (an area of 17 x 20 km). Key dates, almost equally distributed during the season, are given starting on July 1, 2003. A total of 468 ponds were identified, which represent 1% of the study area (the size of 80% of the individual ponds were less than 0.5 ha, whilst 2.3% were larger than 5 ha).

Discussion and conclusion

Environmental risks are constituted of mechanisms linking rainfall variability, density of vectors and their aggressiveness, with hosts vulnerability. The dynamical evolution of ZPOMs, with ranked risks (colour coded) from the ponds in the Barkedji area, has identified risk as a function of discrete and productive rainfall events which dramatically displays the socio-economic problems to which populations of the region are exposed.

From Lacaux et al. (2007) and Tourre et al. (2008), and the results of this paper, rainfall events indeed appear to be the confounding factor for *Ae. vexans* proliferation, since the water directly modifies the size and clustering of the ponds. Resulting ZPOMs and spatial dynamic variability are found to be directly linked to these rainfall events (mainly squall-lines). Based upon ponds distributed within the Barkedji zone (including a fossil river site), a new, integrated methodological

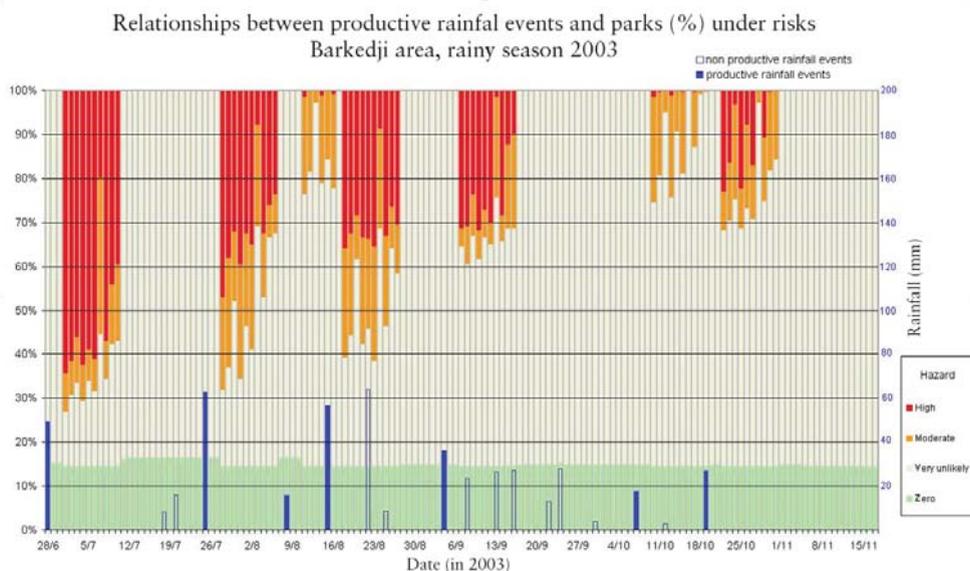


Fig. 5. Rainfall events and RVF environmental risks. From TRMM data rainfall events and amounts (in mm, right ordinates) over the Barkedji area (17 km x 20 km) during the 2003 rainy season. Timing (in date, on the abscissa) of rainfall events shown as blue bars when the event was productive with regard to *Ae. vexans* (seven of the 18 events for the full period) and as white bars when non-productive. From the 242 ruminants' fenced-in areas geo-referenced using QuickBird, percentages of areas (left ordinates) with possible RVF hazards computed using dynamic ZPOM. The hazard scale shown as a spectrum from high risk (red) to none (green).

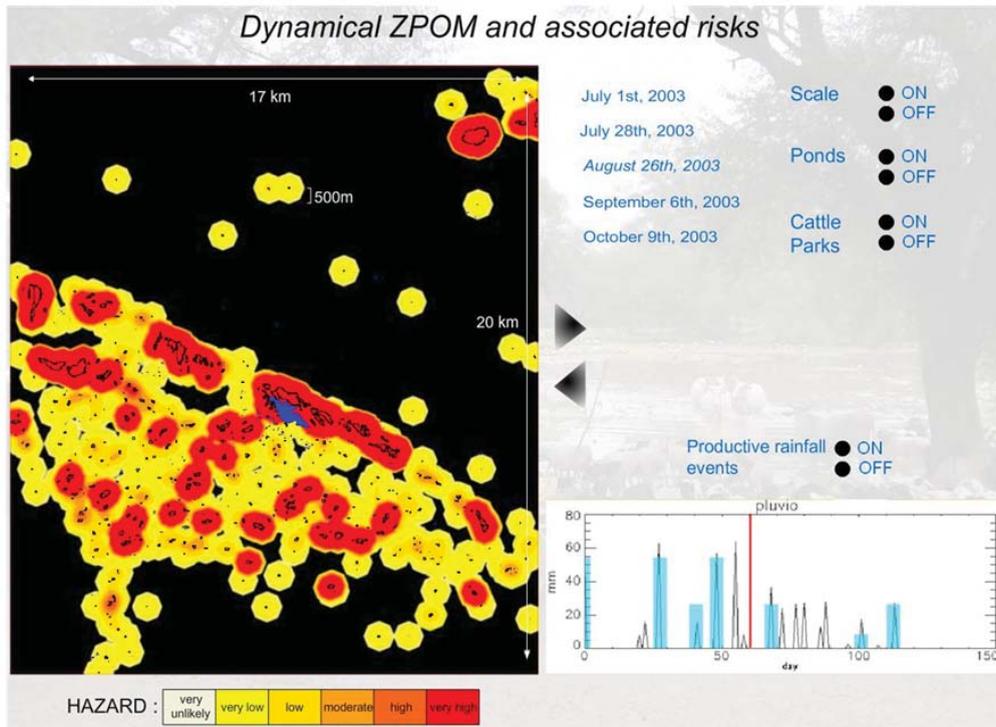


Fig. 6. Dynamic ZPOMs and risks. Dynamic ZPOMs with ranked risk (from very unlikely and very low in yellow, to very high in red, bottom scale) and ponds distribution (in blue) during the 2003 rainy season. From the hyperlinked Figure in the on-line paper, by clicking on the two fat black arrows, animated ZPOMs from productive rainfall (highlighted in blue, at the bottom right) are displayed (upper arrow is for forward motion, lower arrow for backward motion) along with the relative parks locations. The starting date is June 28, 2003. ZPOMs for specific date can also be displayed. The vertical red marker is for accurate time positioning on a daily basis. The results indicative of domestic animals vulnerability can be used as a tool for prediction of RVF environmental risks.

approach has been developed. It is to be implemented into an operational model, the main components of which can be listed as follows:

- (i) identification of ponds by remote sensing (including the distribution, size and localization) using SPOT-5 products, TRMM-based timing and amount of rainfalls in association with on-site measurements (pond area, mean depth, etc.);
- (ii) linkages with observed and modelled entomological data consisting of distribution and aggressiveness of the *Ae. vexans* vector;
- (iii) estimation of risks (hazards and vulnerability) of animal hosts kept at night in the vicinity of ponds; and

- (iv) evaluation of the dynamic ZPOM and RVF environmental risks.

The above four steps can be used in an operational mode when the location of the pond(s) has been determined within the given eco-zones and when the presence and aggressiveness of the vectors have been evaluated. The socio-economic risks can thus be anticipated based on statistical evaluation of the seasonal rainfalls which can be done already a few months prior to the rainy season (seasonal forecasts). Then, strategic displacement of the fenced-in areas during a rainy season can be managed so that the local risks decrease. To see if this reasoning holds also for the longer term, we intend to analyze the inter-annual variability of exposure to vector

bites for the 2003-2008 period using the methodology presented in this paper.

Climatic and environmental risks are necessary conditions for the RVF virus to circulate and be transmitted. This new, methodological approach which can be used in *quasi* real-time, is to be linked with biological modelling of virus transmission and circulation as well as with classical epidemiological models. Ultimately, the fully integrated approach should help understanding the mechanisms leading to potential RVF epidemics and improve related EWS. The physical and biological mechanisms are meant to be applied to other diseases in other places with different environments.

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