Contribution of a hydrologic pond model to predict spatial and temporal mosquito population dynamics in Northern Senegal

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Summary

We developed a spatial and temporal model to predict the population dynamics of the two main mosquito vectors (*Aedes vexans* and *Culex poicilipes*) involved in the Rift Valley fever virus transmission. Covering an area of 11x10 km around the village of Barkedji, and located in the Ferlo Valley (Northern Senegal), the study area is characterized by a complex and dense network of ponds that are filled during the rainy season (from July to mid-October). These ponds are the main mosquito breeding sites in the area. The vector population dynamics model combines a spatial and temporal hydrological model with a mosquito population model. The hydrological model uses daily rainfall as main input to predict spatial and temporal changes in pond surfaces. Output is then fed into the mosquito population model to predict vector population dynamic. This approach will allow predicting how mosquito abundance varies in space and in time.

The Rift Valley fever in Senegal

- Rift Valley Fever *(RVF)* is an **arbovirosis** caused by a **Phlebovirus** (Bunyaviridae)
- Main RVF vectors in Senegal are ***Ae. vexans*** and ***Cx. poicilipes*** genera mosquitoes [Fontenille et al., 1998; Diallo et al., 2000]
- Main hosts : ***ruminants*** (sheep, goats and cattle)
- **Temporary ponds** are favorable areas for RVF transmission

Ae. vexans* species** *oviposit their eggs on the soil above the water level depressions.* ***Aedes eggs *required consecutive drying (7 day minimum) and immersions periods for hatching. Eggs are resistant to dessication for several weeks, months or years.*

Cx. poicilipes poicilipes lay eggs directly on water surfaces [Gjullin et al, 1950] . Eggs could not resist to dessication requiring ~ 10 days immersion for hatching.

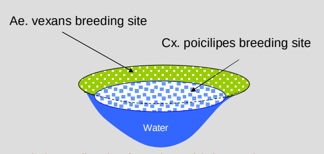


Fig 3: Breeding sites for Aedes and Culex species

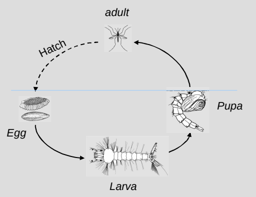


Fig.4: Mosquito life cycle

Cx. poicilipes population model

$$\frac{dM}{dt} = -\alpha M(t) + k\sigma(T)\chi(t,T)M(t-T)$$

M(t): nbr of adult females at time step t
k: sex ratio
a: mortality rate

σ (T)=vectorial production capacity

$$\sigma(T) = \beta\frac{\lambda}{L}S_m\phi(T)$$

β: Imago emergence probability/day
λ: number of eggs per female/day
Φ: Pre-imago survival probability
Sm : maximum pond surface (m²)
L: Gonotrophic cycle

x(t,T) = breeding habitat capacity

$$\chi(t,T) = \frac{S(t/t-T)S(t-T)}{S_m^2}$$

Sm: maximum pond surface (m²)
S(t-T): oviposition surface (m²)
S(t/t-T): effective emerging surface (m²)
T: developement period

Adapted from [Porphyre, 2005]

Ae. vexans population model

$$\frac{dM}{dt} = -\alpha M(t) + k.\beta.\Phi(T_1).E(t-T_1)$$

M(t): nbr of adult females mosquitoes at time step t
a: mortality rate
k: sex-ratio
b: Imago emergence probability
Φ1: Pre-imago survival probability
T1: Development period
E(t): number of hatching eggs at time step t

$$E(t) = \begin{cases} \left[(1-r)\dfrac{\Delta S_p(t-T_2) - \sum_{j=1}^{i} S_R(j,t-T_2)}{S_e(t-T_2)} + r\right].Eggs(t-T_2) & if \quad \Delta S_p(t-T_2) - \sum_{j=1}^{i} S_R(j,t-T_2) > 0 \\ 0 & otherwise \end{cases}$$

r: Leach rate
T2: Desiccation period
Sp(t): Water surface of the pond at time step t
ΔSp(t): Pond surface variations between t and t-1

SR(i,t): Dry ring surface with eggs in desiccation phase since i days (1≤i≤T2) at time step t
Se(t): Dry surface of the pond with eggs in desiccation phase and ready to hatch, at time step t
Eggs(t): Number of eggs in desiccation phase at time step t

$$S_R(1,t) = \begin{cases} 0 & if\ \Delta S_p(t) > 0 \\ -\Delta S_p(t) & otherwise \end{cases}$$

$$S_R(i>1,t) = \begin{cases} \begin{cases} \sum_{j=1}^{i-1} S_R(j,t-1) - \Delta S_p(t) & if \quad \Delta S_p(t) - \sum_{j=1}^{i-1} S_R(j,t-1) > 0 \\ 0 & otherwise \end{cases} & if\ \Delta S_p(t) > 0 \\ S_R(i-1,t-1) & otherwise \end{cases}$$

$$S_e(t) = Sm - Sp(t) - \sum_{i=1}^{T_2} S_R(i,t)$$

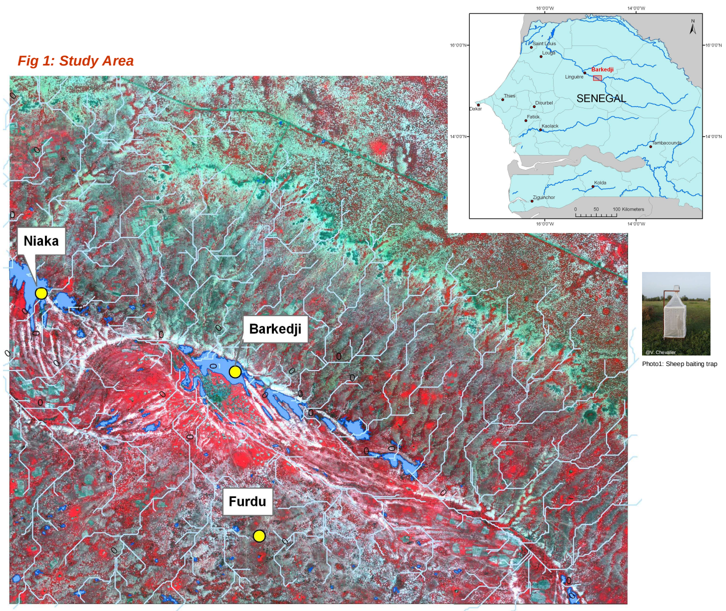
$$\frac{dEggs}{dt} = \Phi_2(T_2).Eggs(t) + \frac{\lambda}{L}M(t) - \frac{\Delta S_p(t-T_2)}{S_e(t-T_2)}.Eggs(t)$$

Sm: Maximum pond surface
Φ2: Egg survival probability during the desiccation phase
λ: Number of eggs per female/day
L: Duration of the gonotrophic cycle (days)

References

Diallo, M., Lochouarn, L., Ba, K., Sall, A. A., Mondo, M., Girault, L., Mathiot, C.- 2000: First isolation of the Rift Valley fever virus from Culex poicilipes (Diptera : Culicidae) in nature, American Journal of Tropical Medicine and Hygiene, 62, 702-704, 2000.
Gjullin C.M., Yates W.W., Stage H.H., 1950 - Studies on Aedes Vexanx and Aedes Sticticus, flood-water mosquitoes, i the lower columbia river valley – Annals entomological Society of America, Vol43, 262-276.
Chevalier V, Mondet B.,Diaitte A., Lancelot R., Fall A.G., Ponçon N, 2004 – Exposure of sheep to mosquito bites: possible consequences for the transmission risk of Rift Valley Fever in Senegal.- Medical and Veterinary Entomology (18) , 247–255
Chevalier V., Renaud L., Yaya T., Sall B., Diaité A Mondet B. , 2005 – Rift Valley Fever in Small Ruminant, Senegal 2003- Emerging Infectious Diseases • Vol. 11, No. 11.
Fontenille D, Traore-Lanmizana M., Diallo M., Thonnon J., Digoutte JP., HG Zeller HG., 1998 – New Vectors of Rift Valley Fever i West Africa- Emerging Infectious Diseases, Vol.4, n°2.
Mondet, B., Diaïté, A., Ndione, J., Fall, A., Chevalier, V., Lancelot, R., Ndiaye, M. & Ponçon, N. 2005. Rainfall patterns and population dynamics of *Aedes* (*Aedimorphus*) *vexans arabiensis*, Patton 1905 (Diptera: Culicidae), a potential vector of Rift Valley fever virus in Senegal. Journal of Vector Ecology, 30: 102-106.
Porphyre T., Bicout D.J., Sabatier P., 2005 - Modelling the abundance of mosquito vectors versus flooding dynamics – Ecological modelling, 183, 173–181.
Soti V., Puech C., Lo Seen D., A Bertran, Dessaye N., Tran A. - Remote sensing and spatial modelling for the monitoring of the dynamics of temporary ponds in arid areas- Hydrology and Earth System Sciences (submitted).

Fig 1: Study Area



Study area

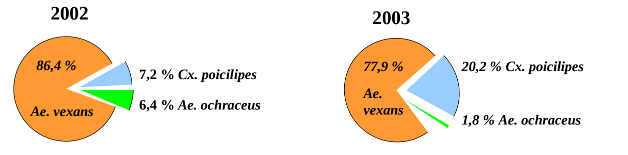
Covering an area of 11x10 km around the village of Barkedji, the study area is characterized by a complex and dense network of ponds filling during the rainy season (from July to mid-October). Located in the Ferlo region, the climate is Sahelian with 3 seasons:

- a dry, cold season from November to March,
- a dry, hot season from April to June,
- a rainy season from June to November with annual rainfall ranging from 100 to 500 mm.

DATA

During the rainy season in 2002 and 2003, mosquitoes have been collected every 20 days using sheep-baited traps (Photo1: Sheep-baited trap), in Barkedji area (Ferlo, 14.87 W, 15.28 N). Three temporary ponds, Niaka, Barkedji and Furdu, have been chosen according to ecological and structural criteria (Fig 1). A trap was laid a few meters from the pond bank. Trapping sessions were carried out between 6 pm and 6 am on three consecutive days to account for daily fluctuations in mosquitoes abundance. Figure 2 shows the total numbers of trapped mosquitoes. For this study, we have used only the trap closed to the pond to measure the capacity of each pond to produce mosquito.

Fig 2 : female mosquitoes captured

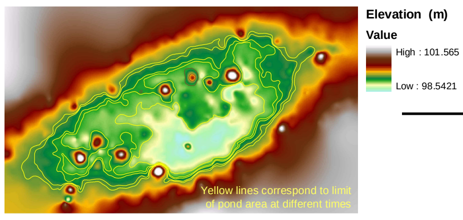


3093 female mosquitoes captured, including 2344 RVF vectors.

6290 female mosquitoes captured, including 4855 RVF vectors.

General model description

Input



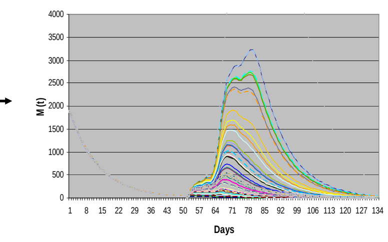
Daily water-rings variations (surface: m²) were simulated from a hydrologic pond model [soti et al, submitted paper] and calibrated and validated with field data (rainfall and water level data recorded during the rainy seasons 2002 and 2003).

Mosquito population abundance model

1) For the calibration phase, the parameters values have been chosen from the literature.

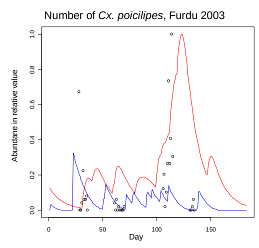
2) The results have been validated for the year 2002 and 2003 with field data.

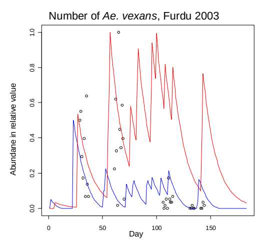
Output



Daily number of female mosquitoes (*Cx. poicilipes* & *Ae. vexans*) for each pond represented by a different color.

Results



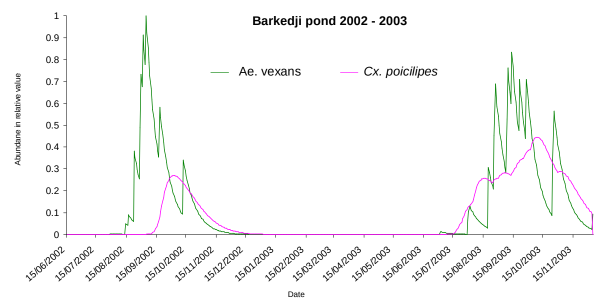


Model validation for 2002 and 2003

We have validated the model with the field data (*Cx. poicilipes* and *Ae. vexans*) collected during the rainy season in 2002 and 2003:

- peaks of mosquito density were well simulated for both *Cx. poicilipes* and *Ae. vexans*.
- for *Aedes spp.* , the peak following the first rainfall was also well simulated.
- for *Cx. poicilipes*, an important peak of simulated density was observed at the end of the rainy season, as described in the literature.

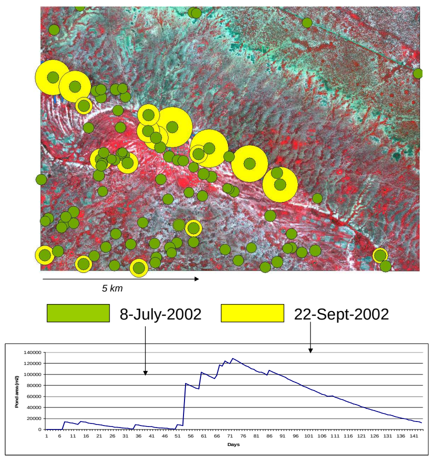
In red, number of mosquito
In blue, pond area
In black, number of mosquito captured on the field (relative value)



Simulation results showed two different population dynamics patterns:

- For the rainy season 2002, *Ae. vexans* were more abundant at the beginning of the rainy season, and *Cx. poicilipes* were dominant at the end of the rainy season [Mondet et al 2005].

- The rainy season 2003 (moderate and regular rainfall), showed a relatively stable population growth rate throughout the rainy season, with a *Cx. poicilipes* density peak at the end of the rainy season.



Barkedji surface pond area during the rainy season 2002

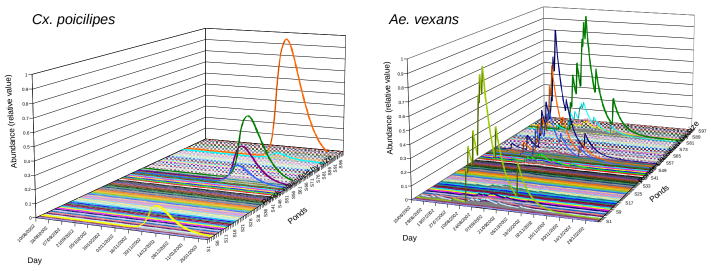
Number of *Cx. poicilipes* (log.) in space and in time

Simulated mosquito density was heterogeneous in time and in space.

At the beginning of the rainy seasons, mosquito populations were small and well distributed in space.

At the end of the rainy season, the highest density of *Cx. poicilipes* was located in the main stream of the Ferlo Valley where ponds are largest. Here, we could observe a highest *Cx. poicilipes* density at the end of the rainy season 2002. [Mondet et al 2005].

Number of mosquito in time (2002)



Each pond is represented by a different color

Here, we could observe a highest *Cx. poicilipes* density at the end of the rainy season 2002. [Chevalier et al 2005].

The graphic shows a population dynamics which starts early with the first effective rains. This dynamic is observed throughout the rainy season with a peak of density in the middle season followed by a quick decline [Fontenille et al, 1998, Chevalier et al, 2004] .

Conclusion and Perspectives

Simulation results were similar to *Cx. poicilipes* and *Ae. vexans* observations in time and space. Models were able to simulate the importance of rainfall patterns on mosquito populations. Long pauses in rainfall were favourable for *Ae. vexans* and conversely, frequent rainfall are more appropriate for the development of a high *Cx. poicilipes* population.
In subsequent steps, these models will be coupled with a mosquito diffusion model to test the importance of different parameters (vegetation density, host compound location, wind) for mosquito spread in space and in time around their breeding sites.
Results of this work will be useful to help designing better prevention and control programmes for vector-borne diseases.

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