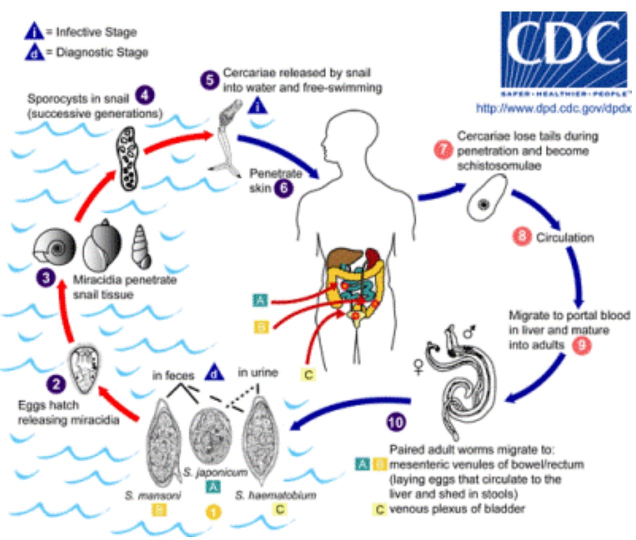
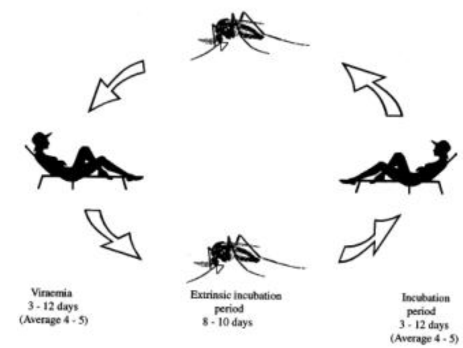
Hydrology considerations in health

Adrian Tompkins
tompkins@ictp.it

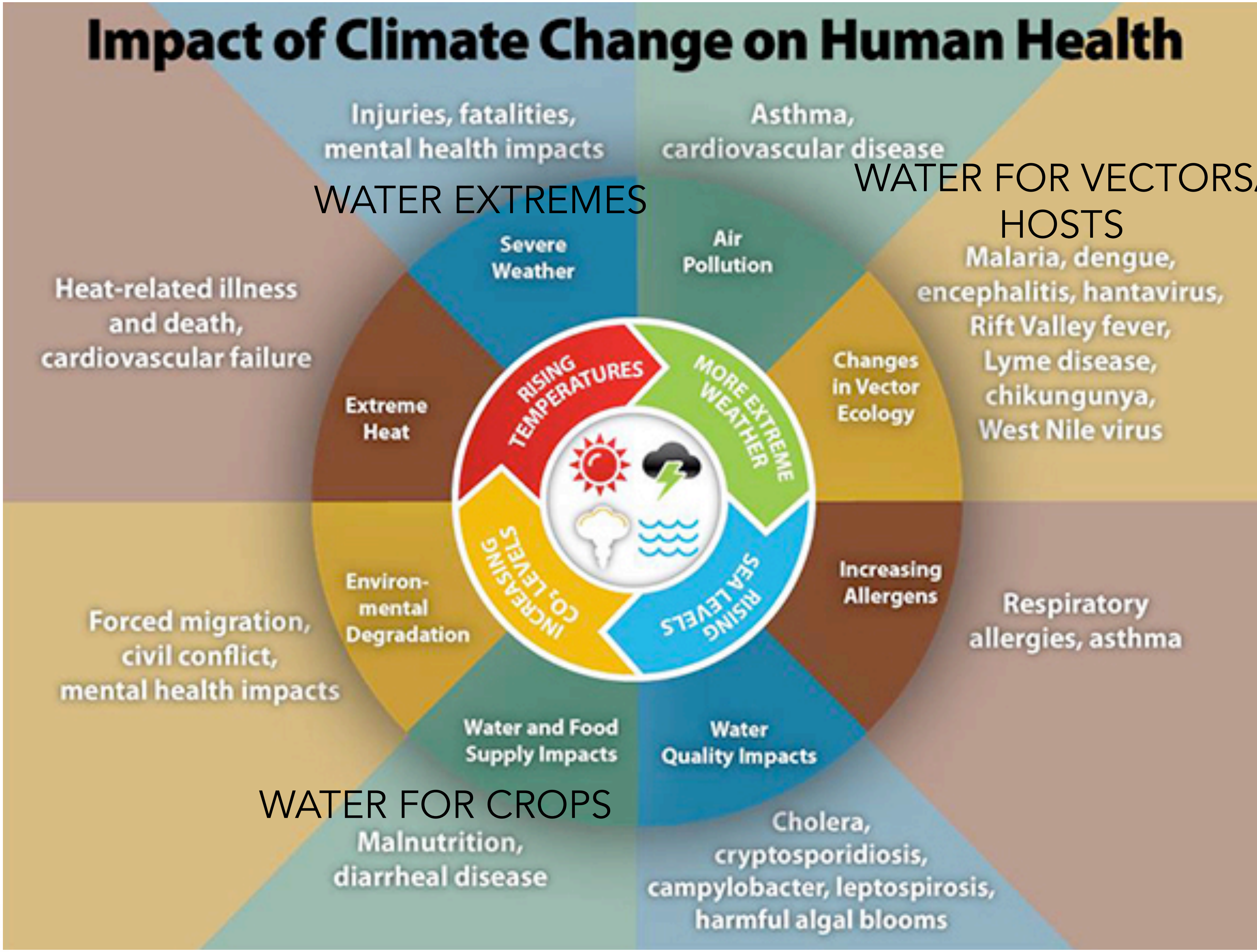
Some slide sources:

Dengue	Felipe Colón and Rachel Lowe
Schistosomiasis	Nicky McCreesh and Mark Booth
Rift Valley Fever	Cyril Caminade





Chapter 1: Where do we start?



WATER FOR PATHOGENS

Source: CDC

Chapter 2: Things are complicated!

We will see that relationships between health and water are

uncertain,

nonlinear

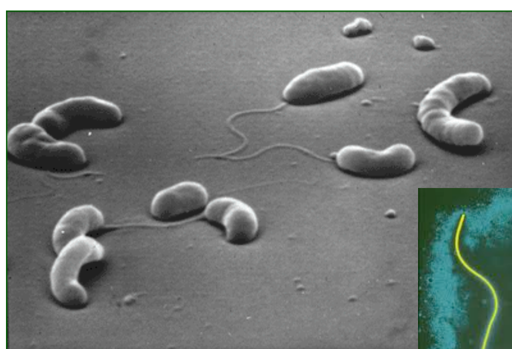
and often

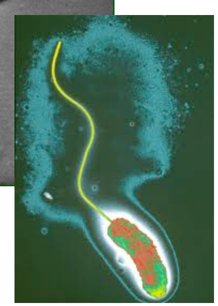
location specific

Example 1: Cholera

- Infection of the small intestine caused by the bacterium *Vibrio cholerae* (Filippo Pacini, 1854).
- The bacterium produces a toxin, which can cause profuse diarrhea and death due to dehydration.
- Transmission is oro-fecal, via the ingestion of contaminated water or food. Usually the infecting inoculum is rather high (ca. 1 million bacteria).
- 75% of infectives are asymptomatic, but produce bacteria in fecal excretions for 7-14 days

Filippo Pacini





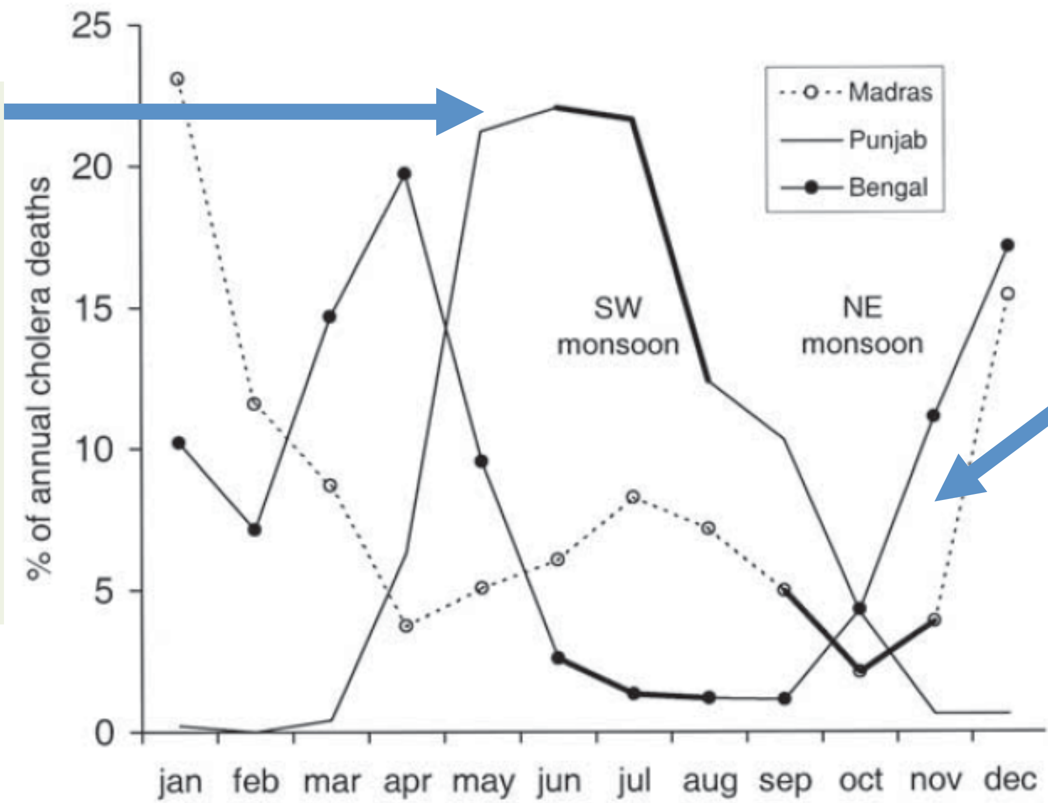
Diversity in seasonality

M. Pascual et al. / Microbes and Infection 4 (2002) 237–245

Dry Regions

Peak in monsoon season

In dry regions, water is a limiting factor for transmission



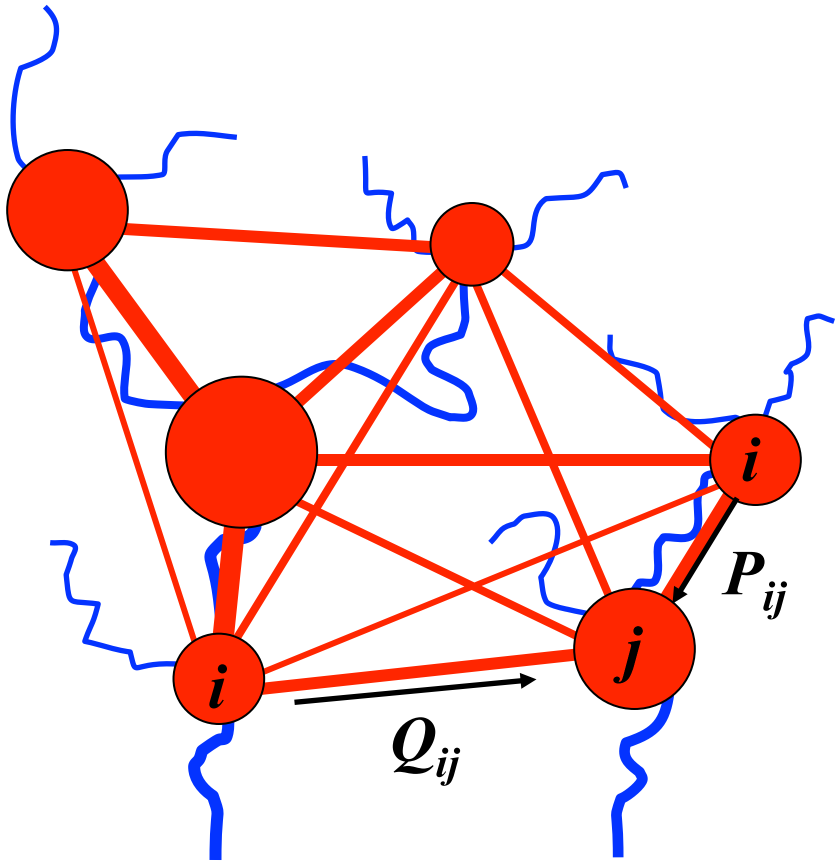
Estaurine Regions

Peak in dry season

Monsoon rains dilute pathogen

Fig. 5. Variability of seasonal cholera in the high endemic provinces Bengal and Madras (bimodal pattern) and in the epidemic Punjab province (single peak). Bold lines show the main rainfall season with the South West monsoon in Bengal and Punjab, and the North East monsoon dominating Madras. Data from [16].

Transport is by host movement and by water transport



Hydrologic Transport

random walk on oriented graph

↕

advection-diffusion equation
on a river network

Need to know: Water temperature, salinity, PH and flow characteristics

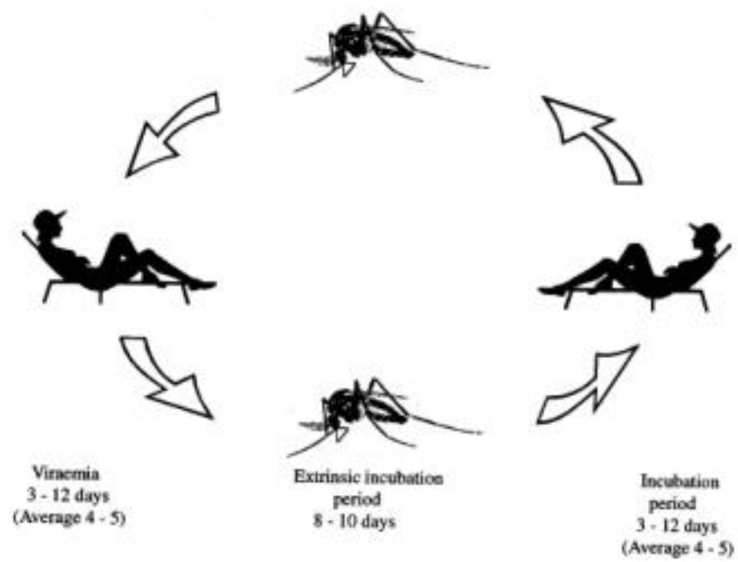
Vector Borne Disease

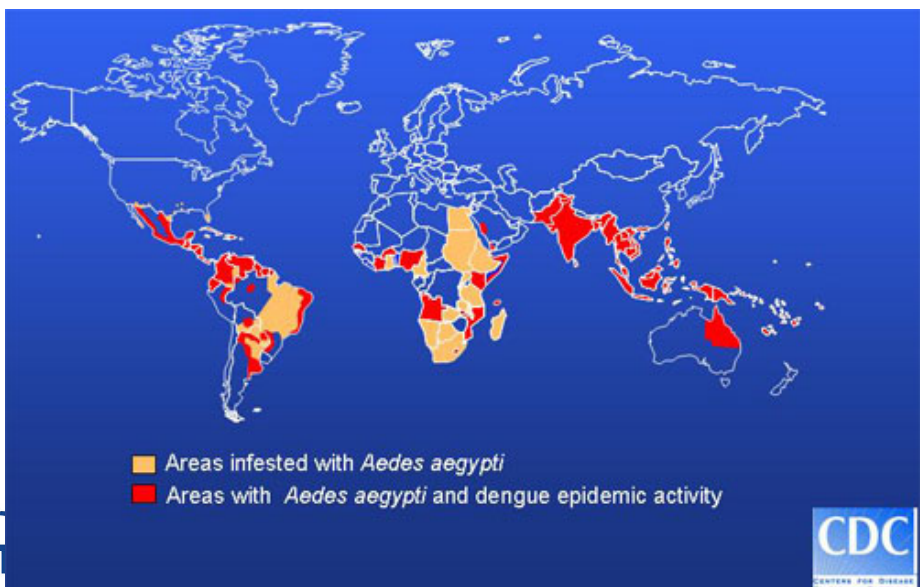
- There are many diseases (viruses, parasites, bacteria) that are transmitted by a vector or have an intermediate host.
  - Dengue
  - Malaria
  - Blue Tongue
  - Rift Valley Fever
  - Chagas
  - Yellow Fever
  - Japanese Encephalitis
- These diseases are climate sensitive – why?

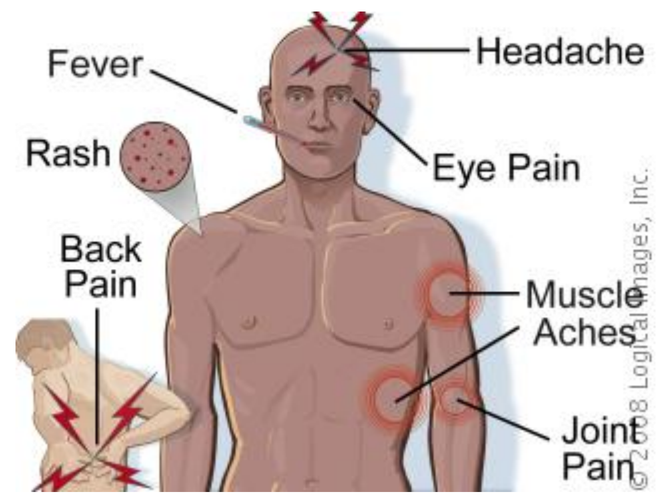
Water provides breeding site for vectors – can be complicated

Example 2: Dengue Virus

- *Aedes* Mosquito vector
- Urban environments
- 4 serotypes of virus – population migration important







Source: http://viraldiseasesd.wikispaces.com/Dengue+Fever

Dengue transmission

- **Human drivers**, e.g.
  - Population growth / urbanisation / poverty (substandard housing)
  - abundance of water-storage containers/bad drainage
- **Environmental drivers**, e.g.
  - Rainfall (filling of containers)
  - Temperature/humidity (mosquito development)

Thanks: Rachel Lowe

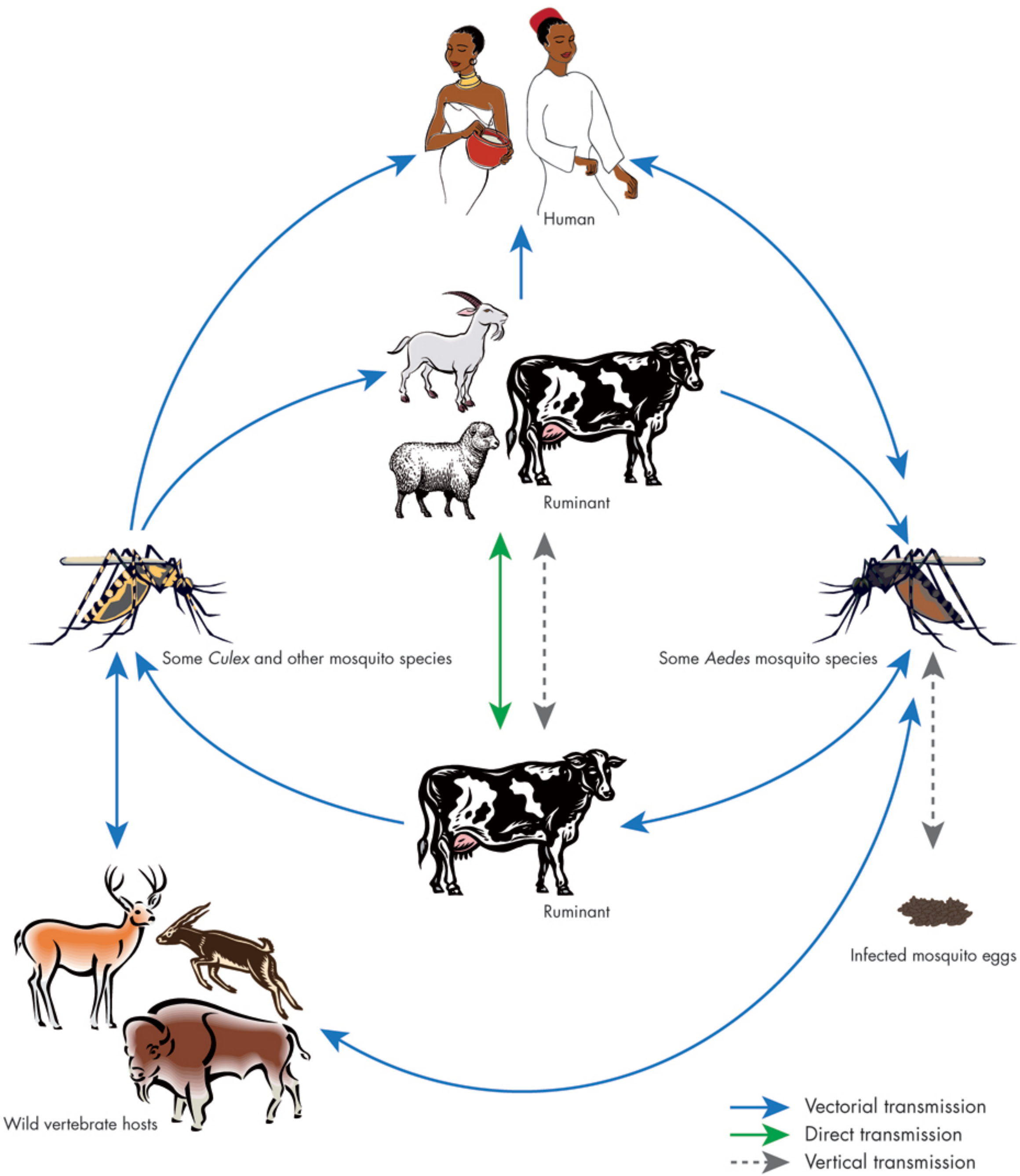
Rainfall provides breeding sites for Aedes: Singapore has banned gutting on new houses to remove common breeding grounds

Need: urban micro-scale hydrology?

But in drought situation rain harvesting can provide breeding sites if storage facilities are poor

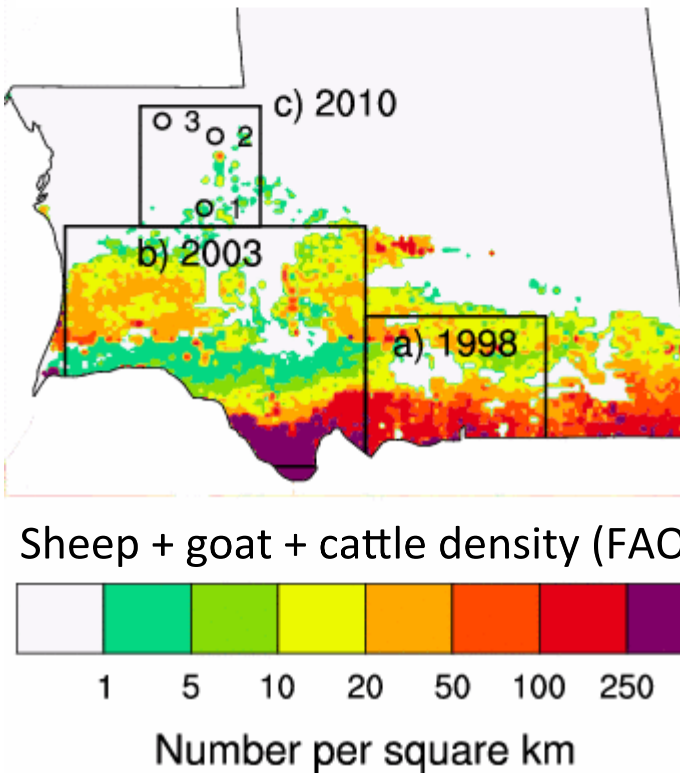
Example 3: Rift Valley Fever

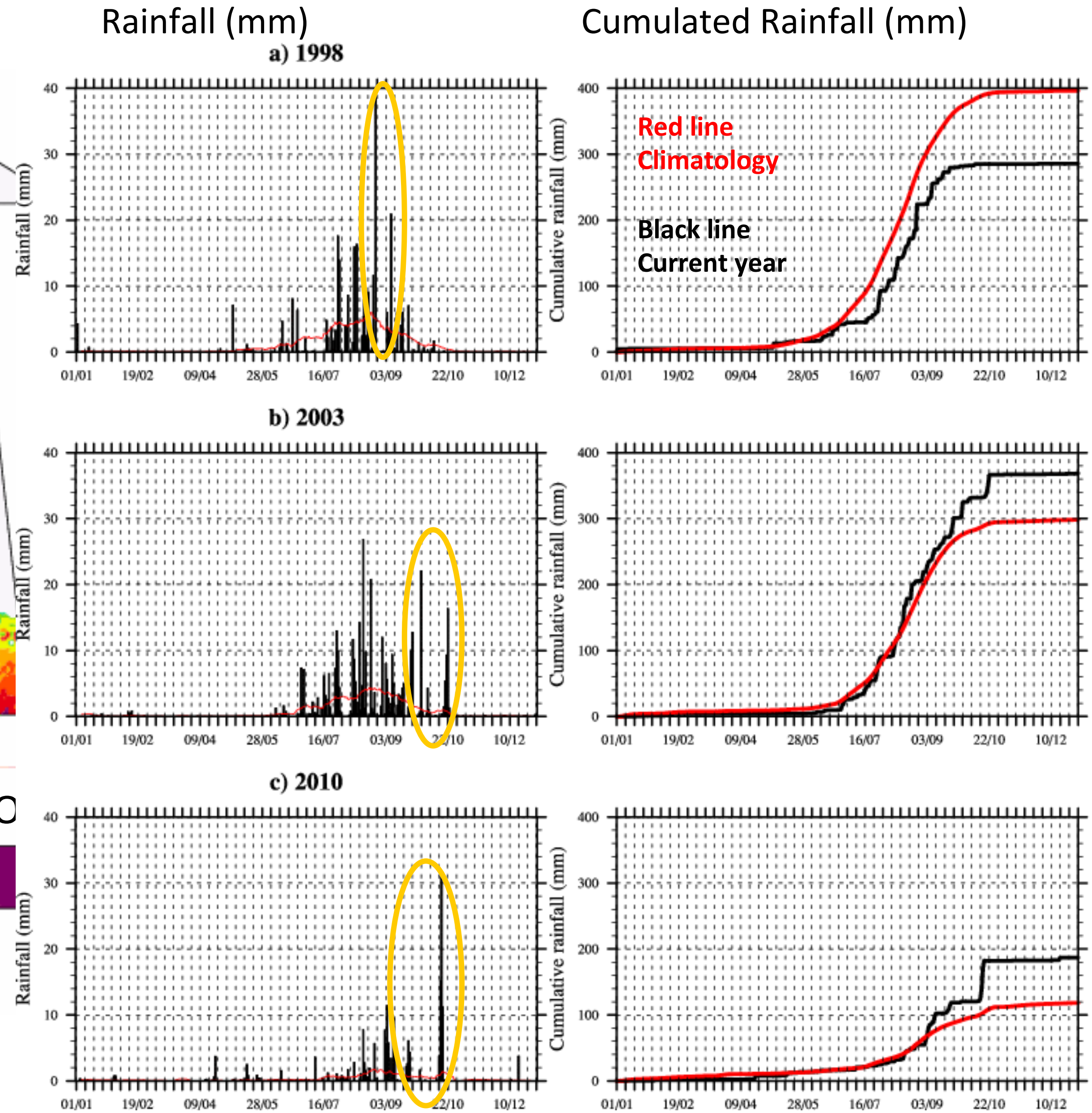
- Outbreaks occur at >10 year intervals
- Associated with immunity (lifetime of livestock)
- Vulnerability = loss of immunity
- Hazard = flood event that enable large proliferation of *Aedes* and then *Culex* vectors



Rift Valley Fever outbreaks in Mauritania

Caminade et al. suggest subseasonal variability important in West Africa, rather than season mean



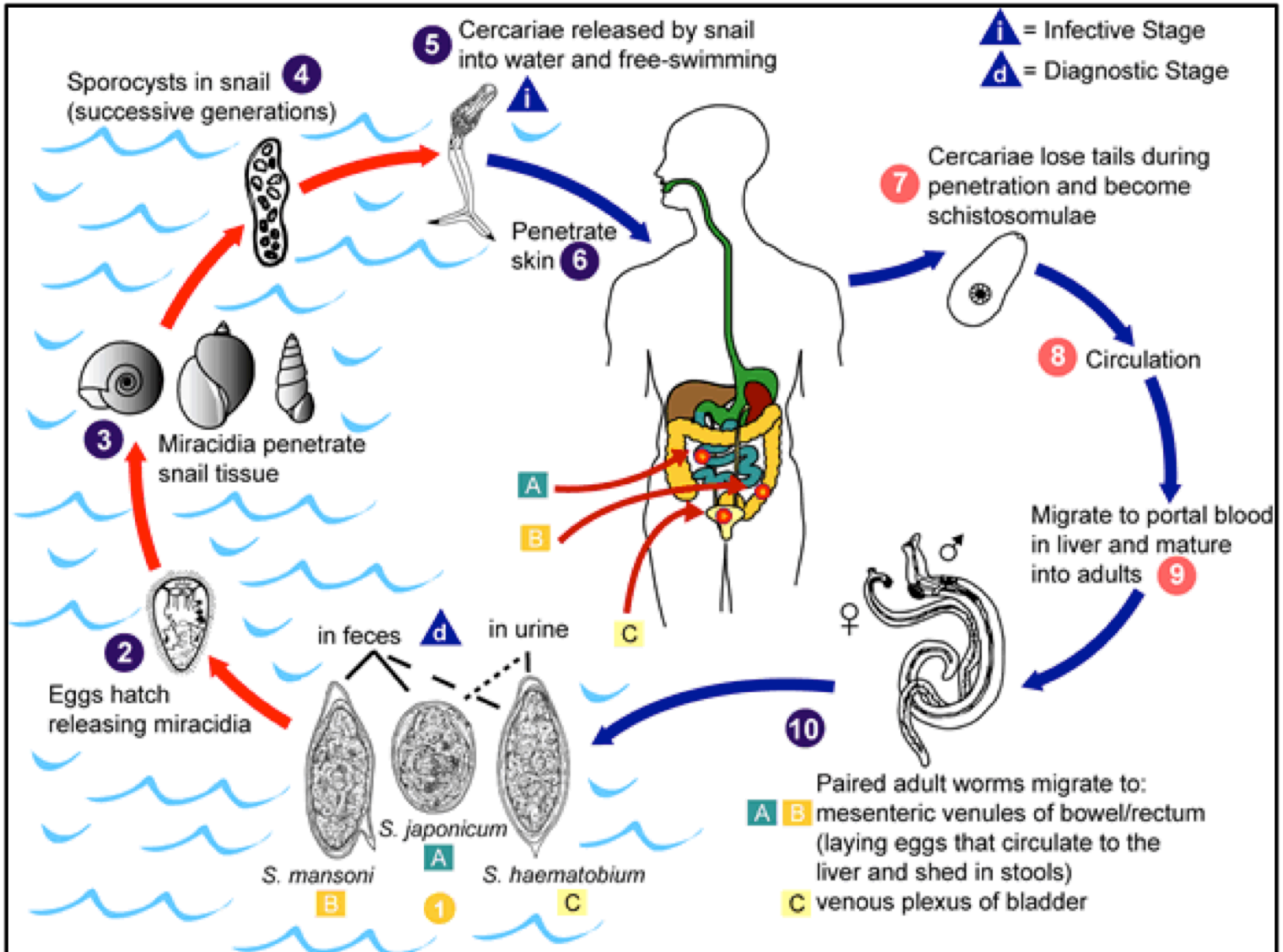


UNIVERSITY OF LIVERPOOL

Need: hydrology of village ponds

Wetting followed by dry period and then wetting again
Pond level important

Example 4: Schistosomiasis



Intermediate host snail

- Intermediate host snail species with different habitat preferences, e.g.:
  – Permanent lakes and ponds
  – The edges of permanent rivers
  – Seasonal streams and ponds
  – Irrigation systems

http://www.nhm.ac.uk

Do lake levels matter?
Does lake topography matter?

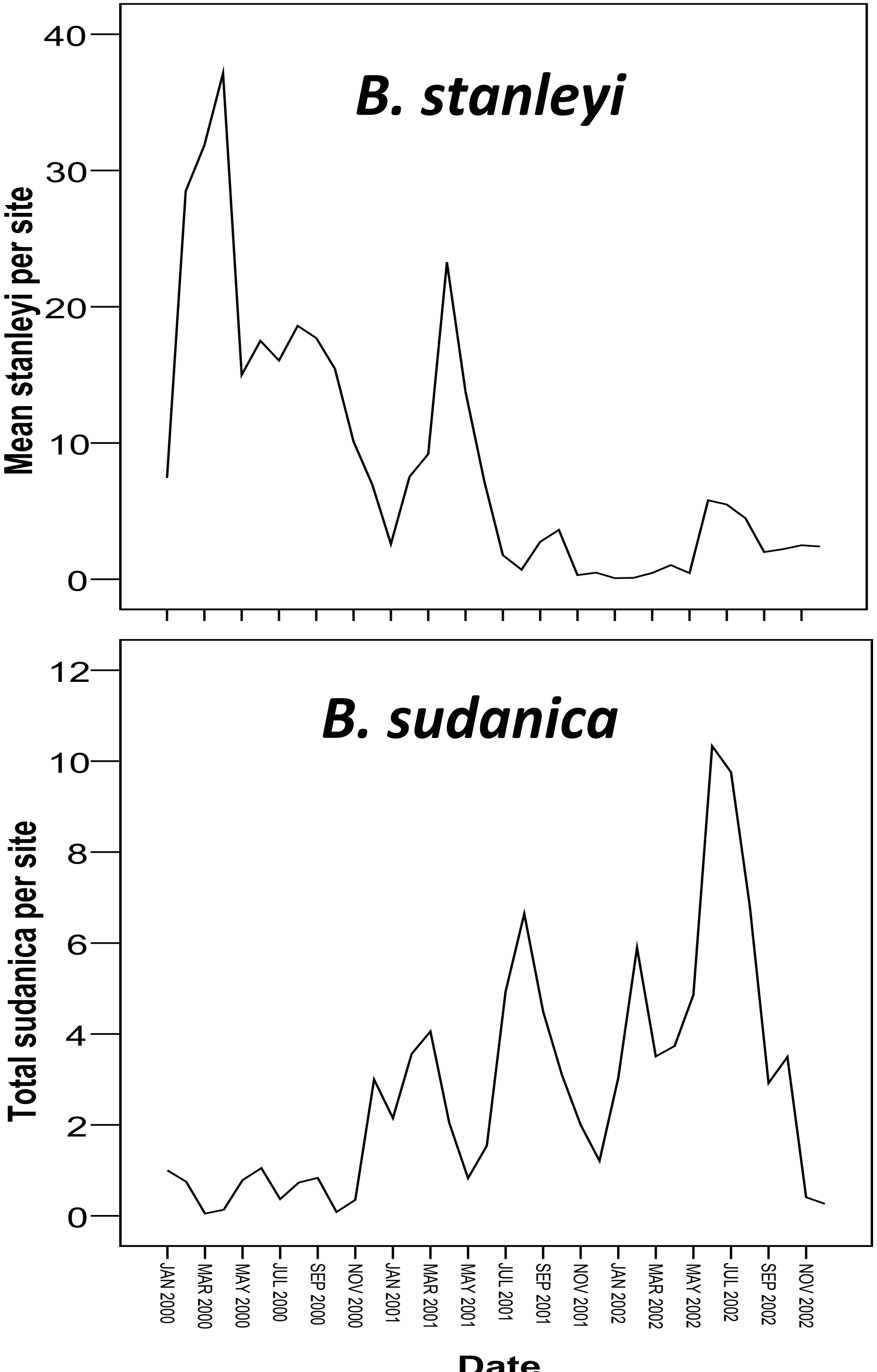
Two main species of intermediate snail host with different preferences for water depth.

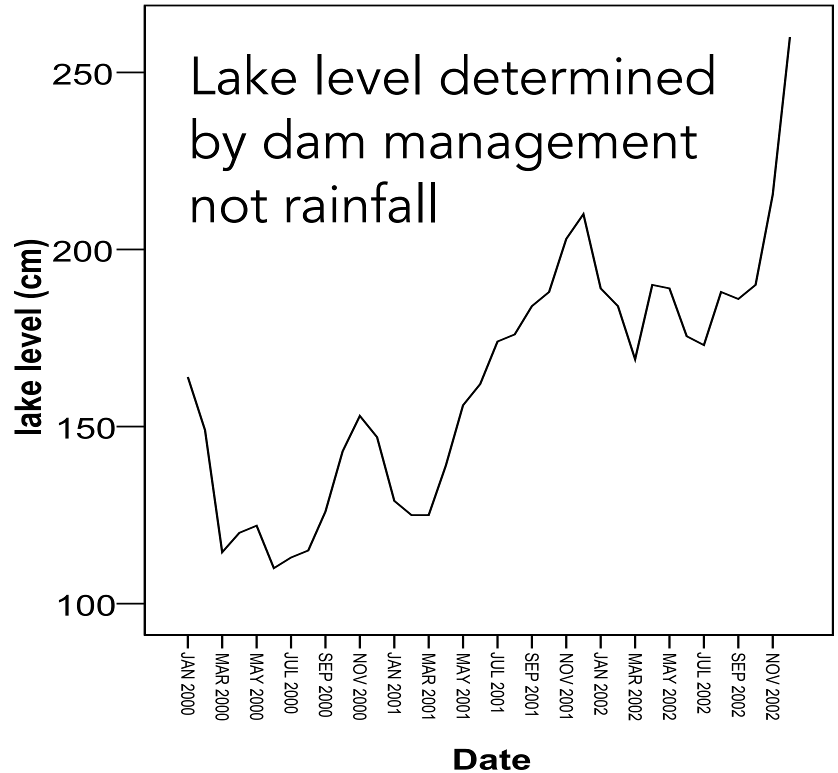
Slope also determines lake contact points

Map of Booma village

- Spatial distribution of tribes and snail species vary across Booma village

Variation in *Biomphalaria* spp abundance Jan '00 – Dec '02 in Lake Albert, Uganda





Low water flows

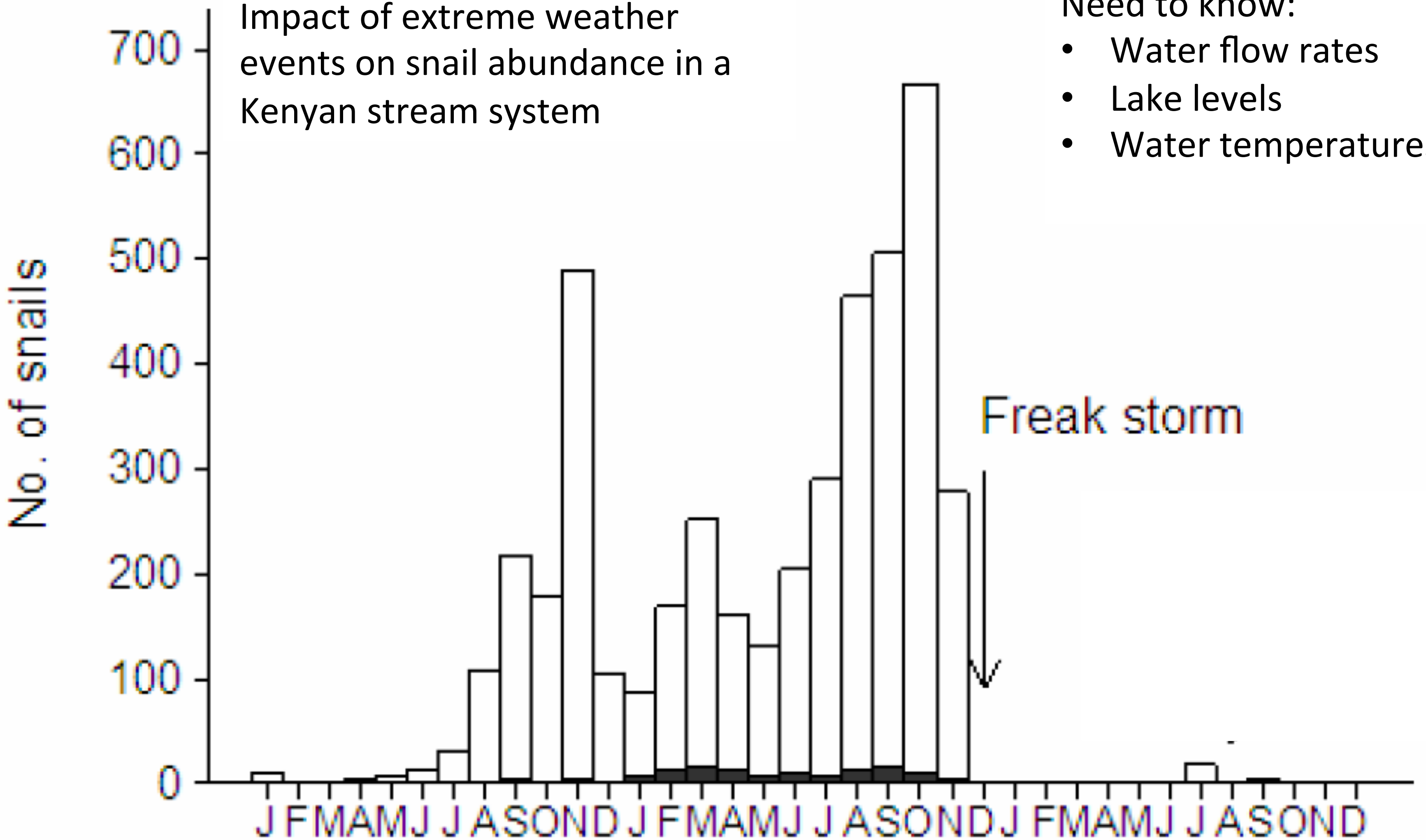
- Some species can survive the temporary drying out of their habitats by aestivation.
- Mortality is high during aestivation
  - snail populations will not survive long desiccation periods
  - require time to recover population between dry seasons.
- Factors affecting survival are poorly understood
  - speed at which habitats dry up?
  - soil moisture?

Appleton CC. Review of literature on abiotic factors influencing the distribution and life cycle of bilharzia intermediate host snails. *Malacological Review* 1978;**11**:1-25.

Brown D. *Freshwater Snails Of Africa And Their Medical Importance*. 2nd ed. London, UK: Taylor & Francis, 1994.

High water flows

Impact of extreme weather events on snail abundance in a Kenyan stream system



Need to know:

- Water flow rates
- Lake levels
- Water temperatures

Kariuki et al Parasites & Vectors 2013

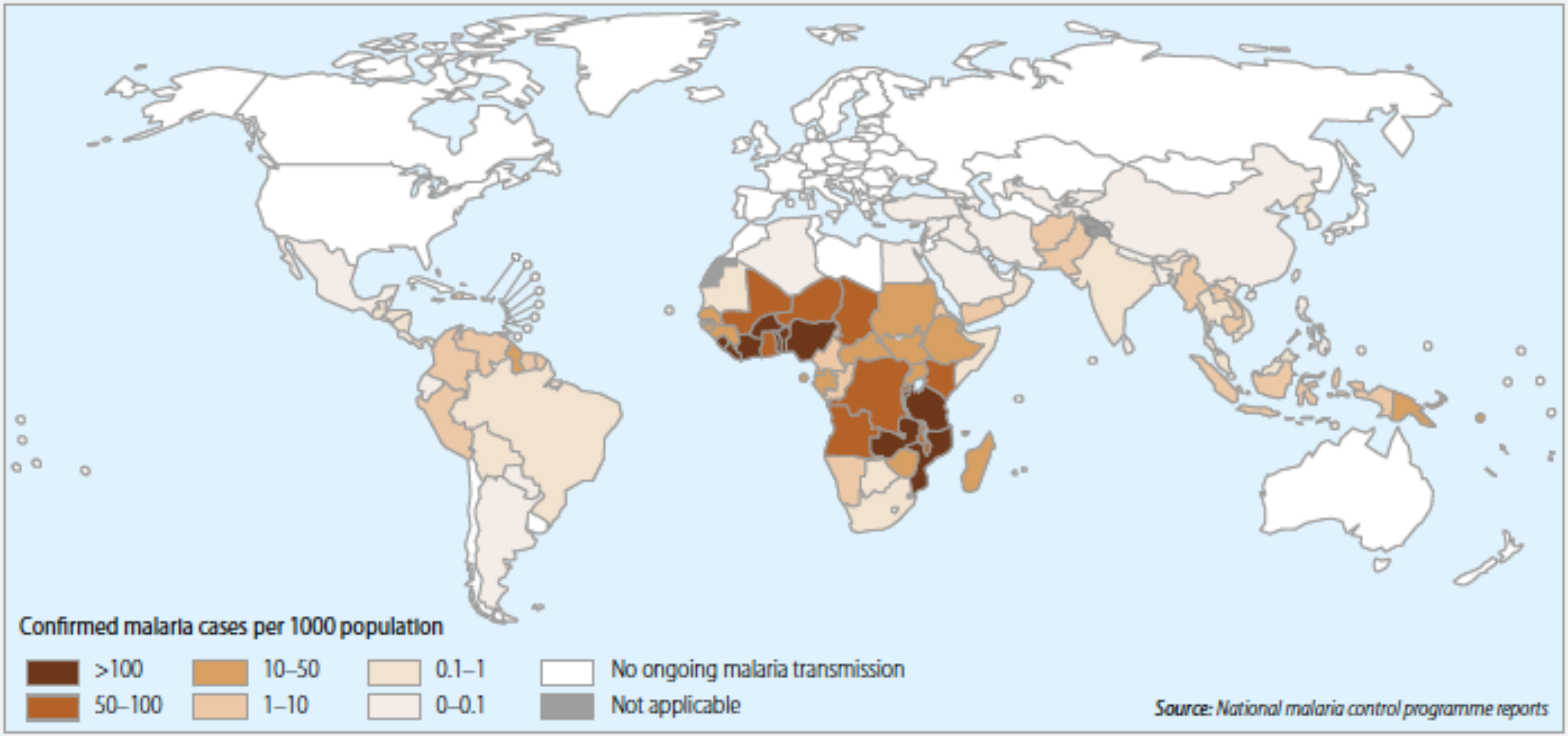
Chapter 3: Things are Simple!

How much information do we need to know?

In this chapter we will see that complex systems of many degrees of freedom can be approximated with simple parametrization schemes.

Example 5 : malaria

Figure 1.1 Countries with ongoing transmission of malaria, 2013



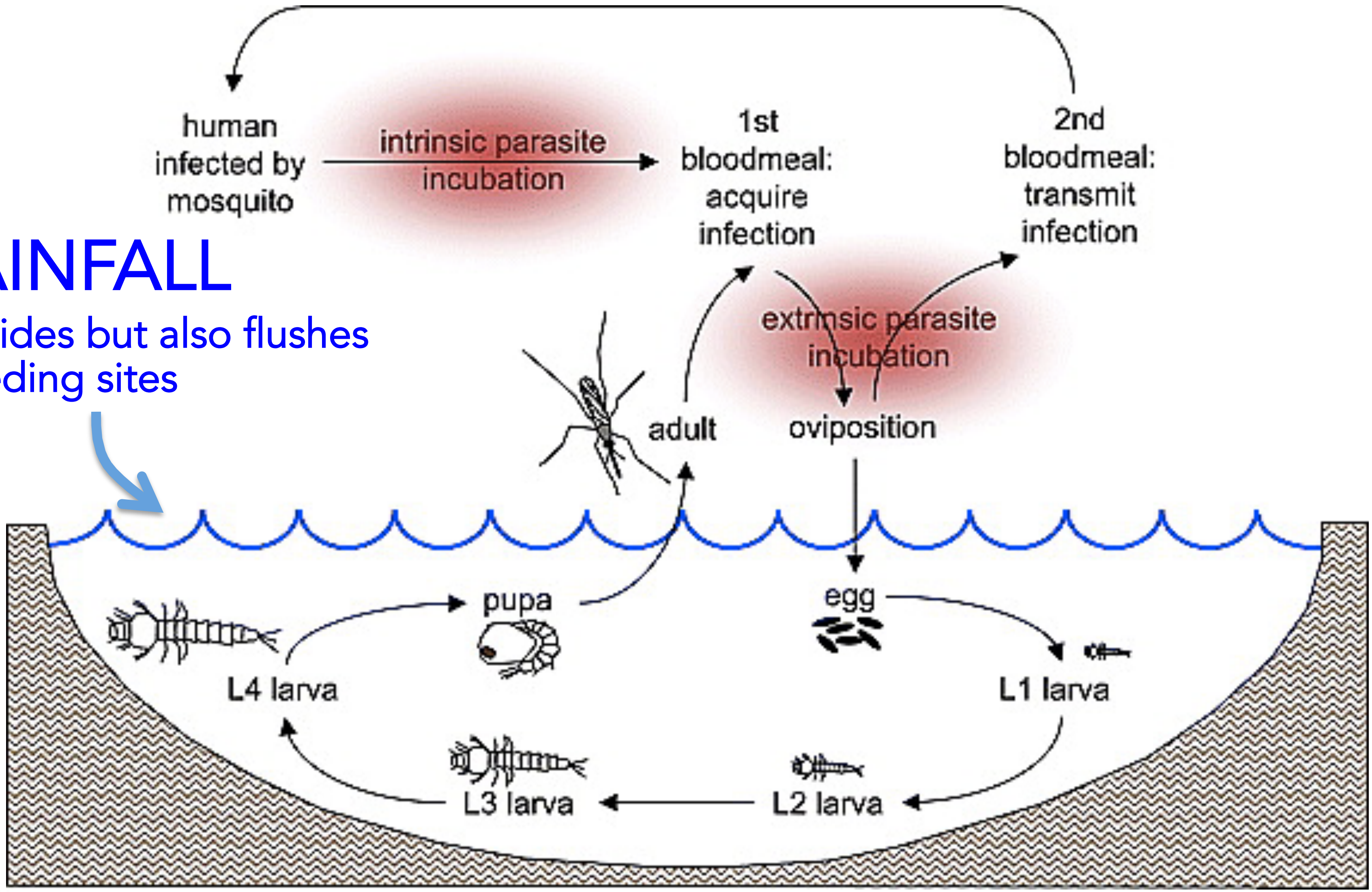
- Caused by plasmodium parasite
- Transmitted by Anopheles mosquito

TEMPERATURE

Warmer temperatures speed up parasite, larvae and egg development
High temperature impact mortality of vector (adult and larvae)

RAINFALL

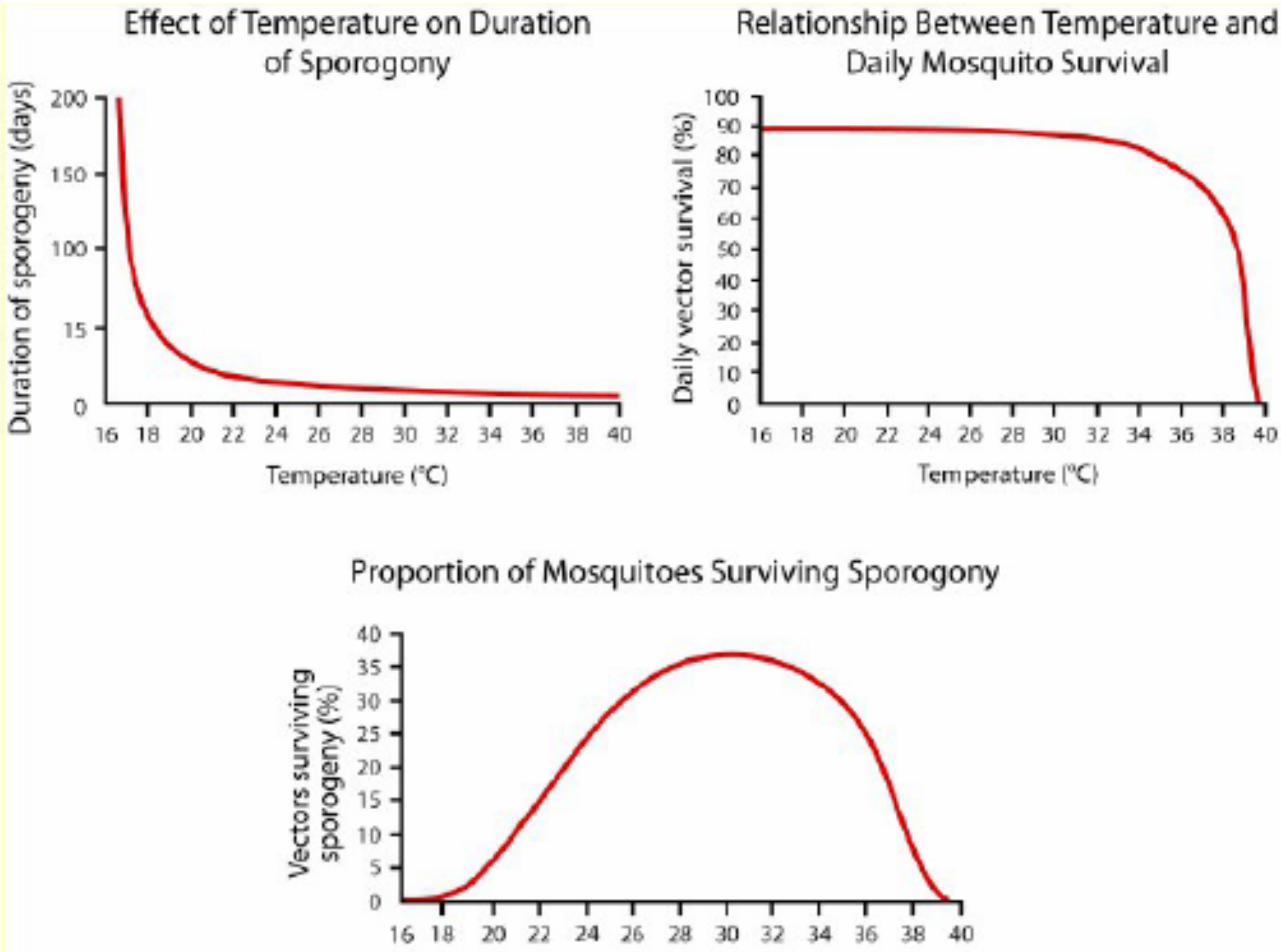
Provides but also flushes breeding sites



Bomblies et al. 2009

ICTP

Sporogonic cycle

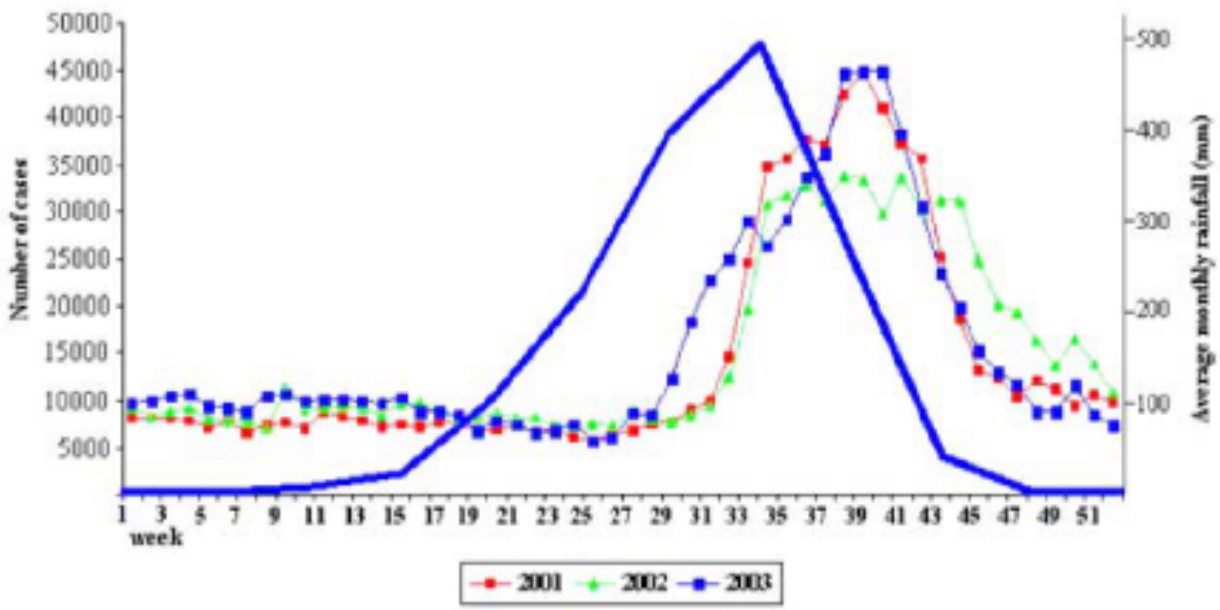


Craig et al 1999

Rainfall

- Water required for breeding.
- Anopheles Gambiae prefers natural sunlit puddles.
- highly nonlinear relationship

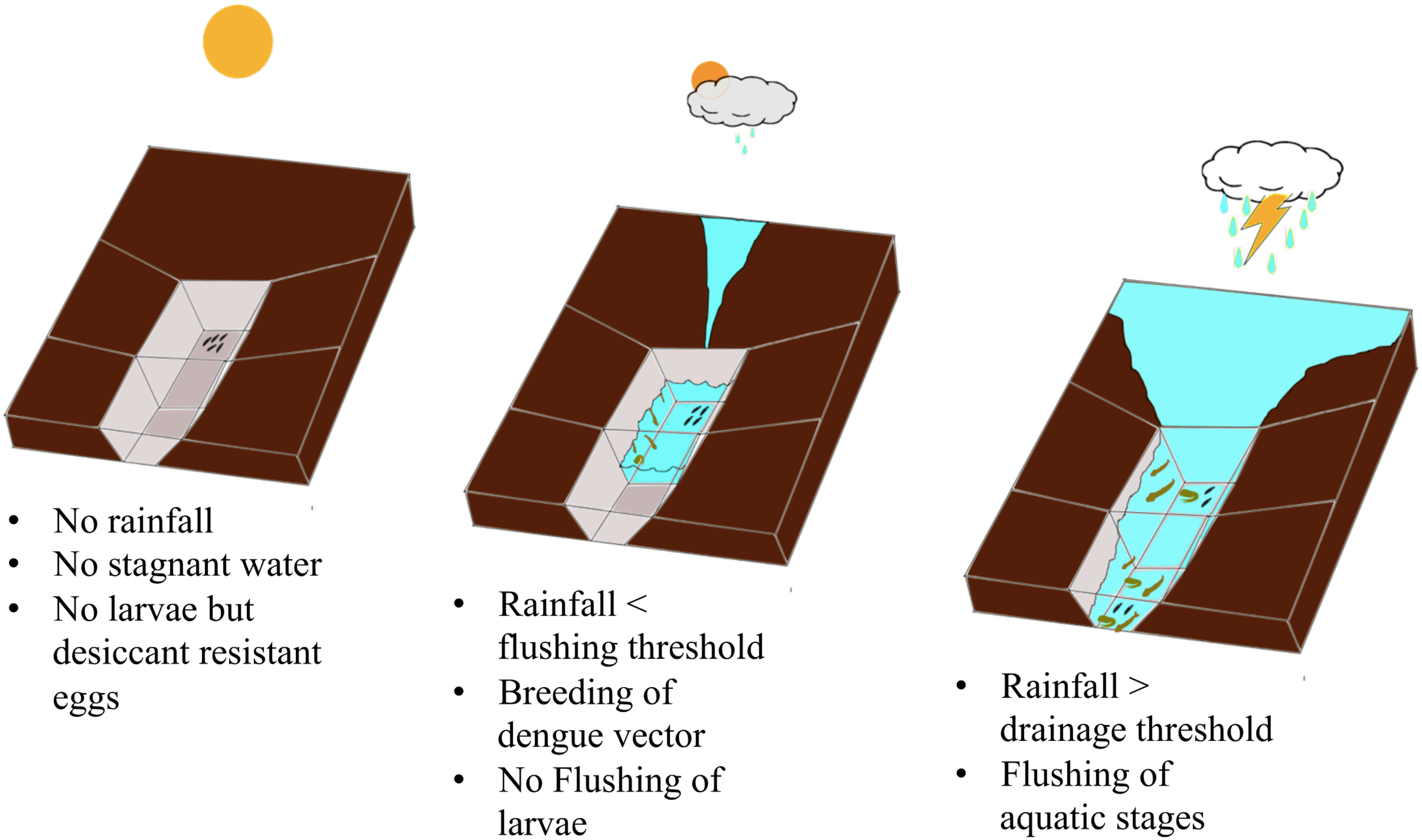
Example from village in SW Niger from Bomblies et al. (2008)



Blue - Rainfall
Dots - Malaria cases in 3 seasons

FLUSHING

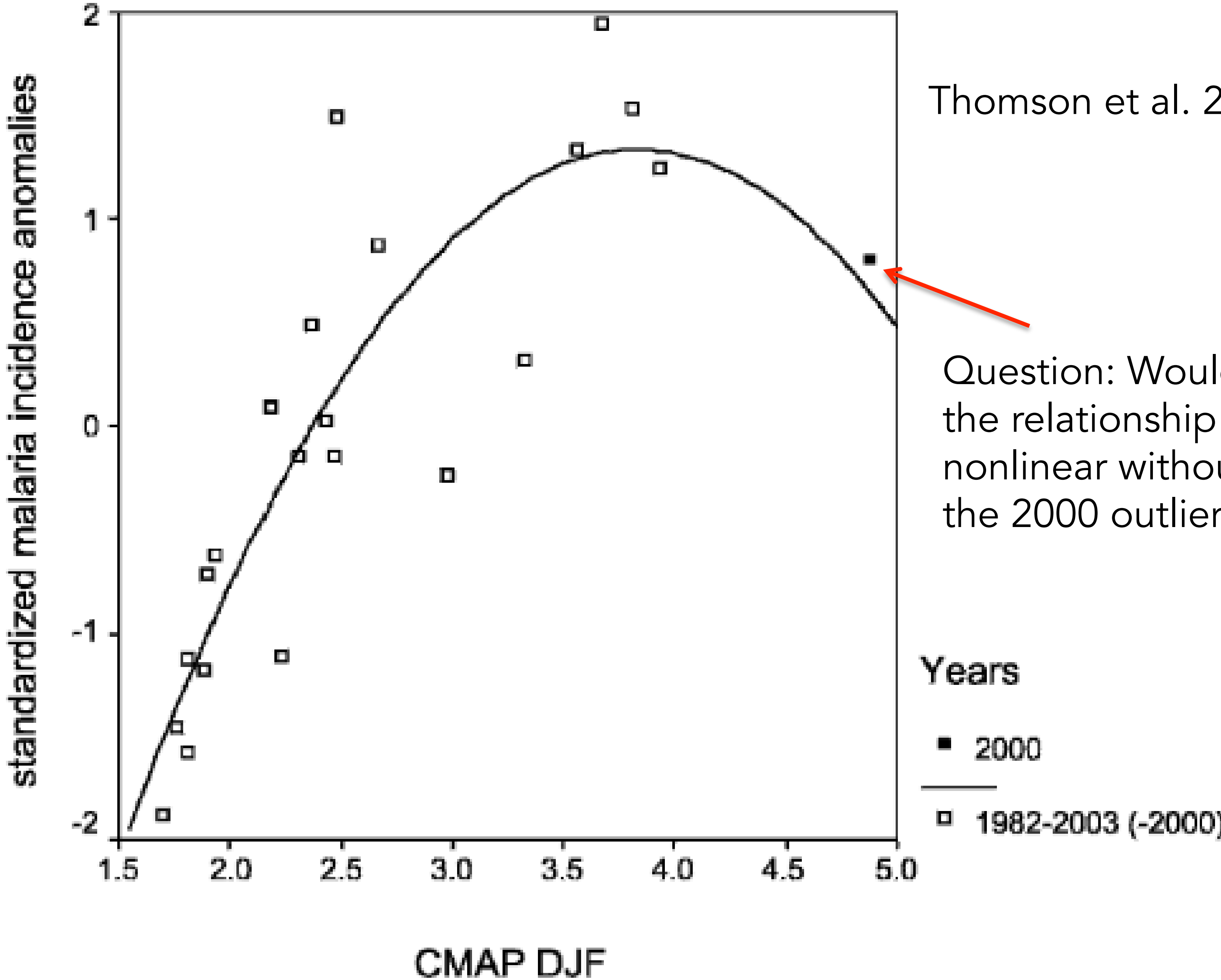
- Stage 1 larvae can be flushed by intense rainfall (Paaijmans et al. 2007)
- Implies that transmission related to sub-seasonal rainfall variability (implications for seasonal forecasting potential)



Seidahmed and Eltahir (2016)

Rainfall flushing of the dengue vector *Aedes aegypti*

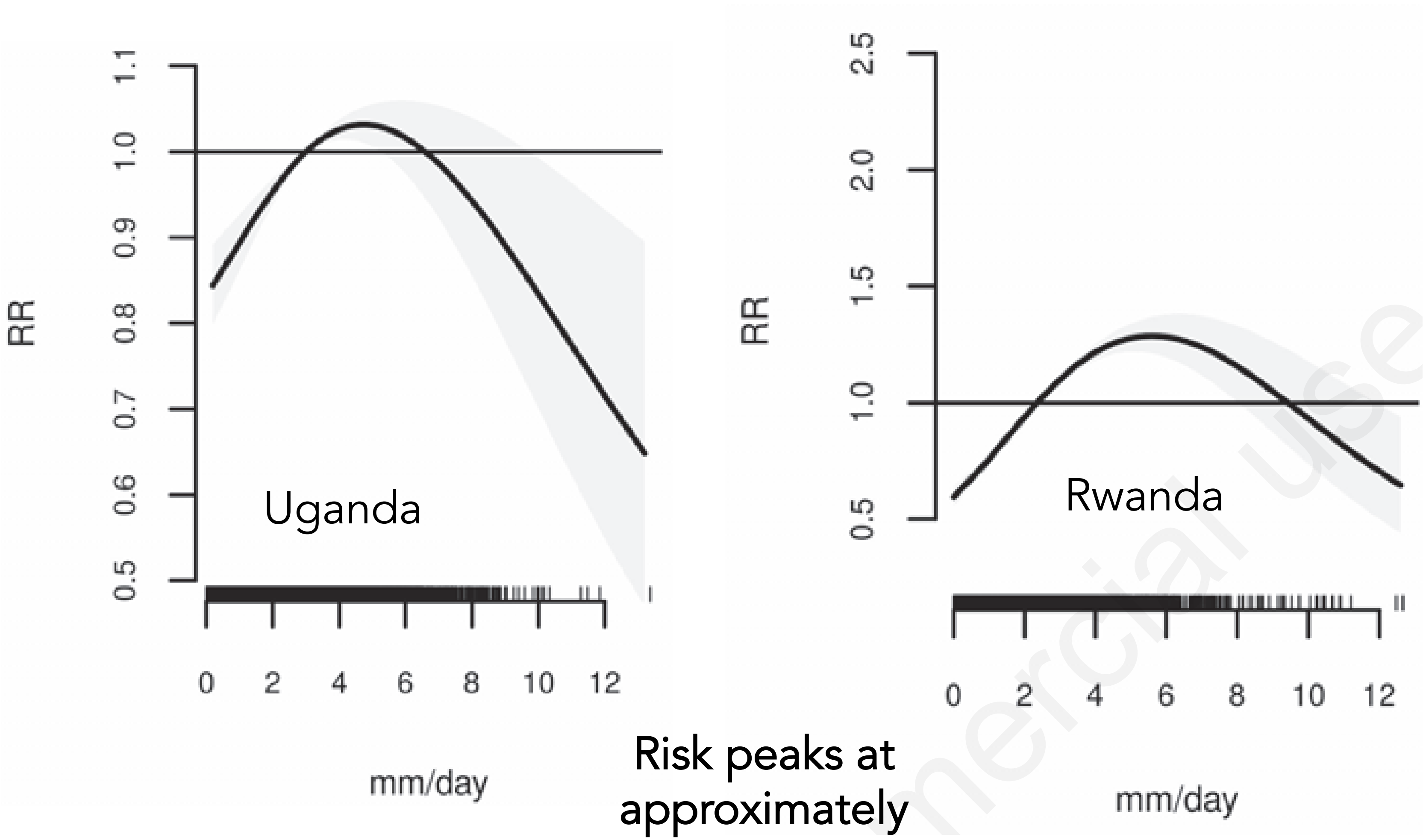
Nonlinear relationship between lagged rainfall and malaria



Thomson et al. 2005

Question: Would the relationship be nonlinear without the 2000 outlier?

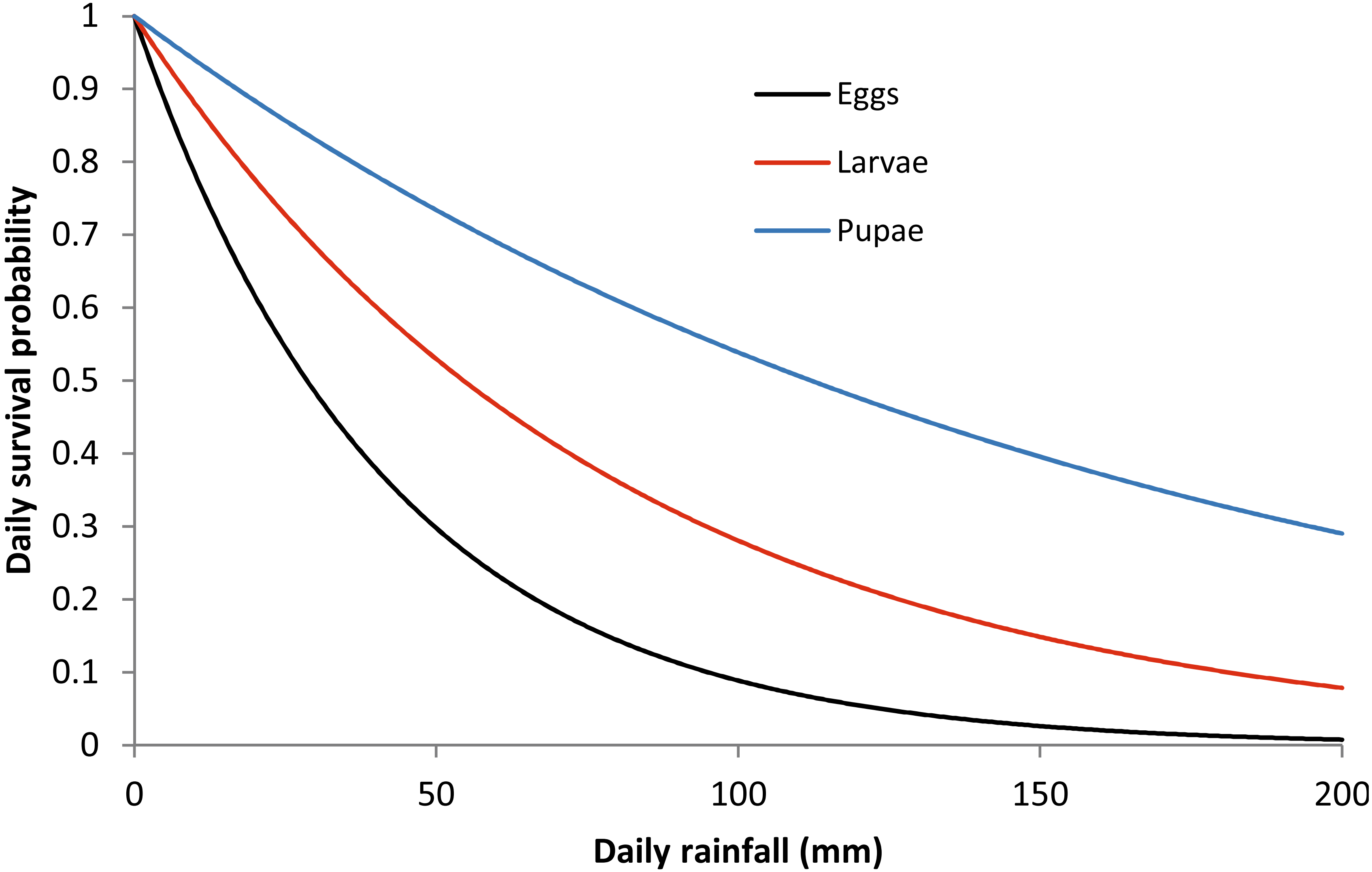
Multivariate model – Relationship between lagged (0-2) rainfall and malaria relative risk



Risk peaks at approximately 5 mm/day

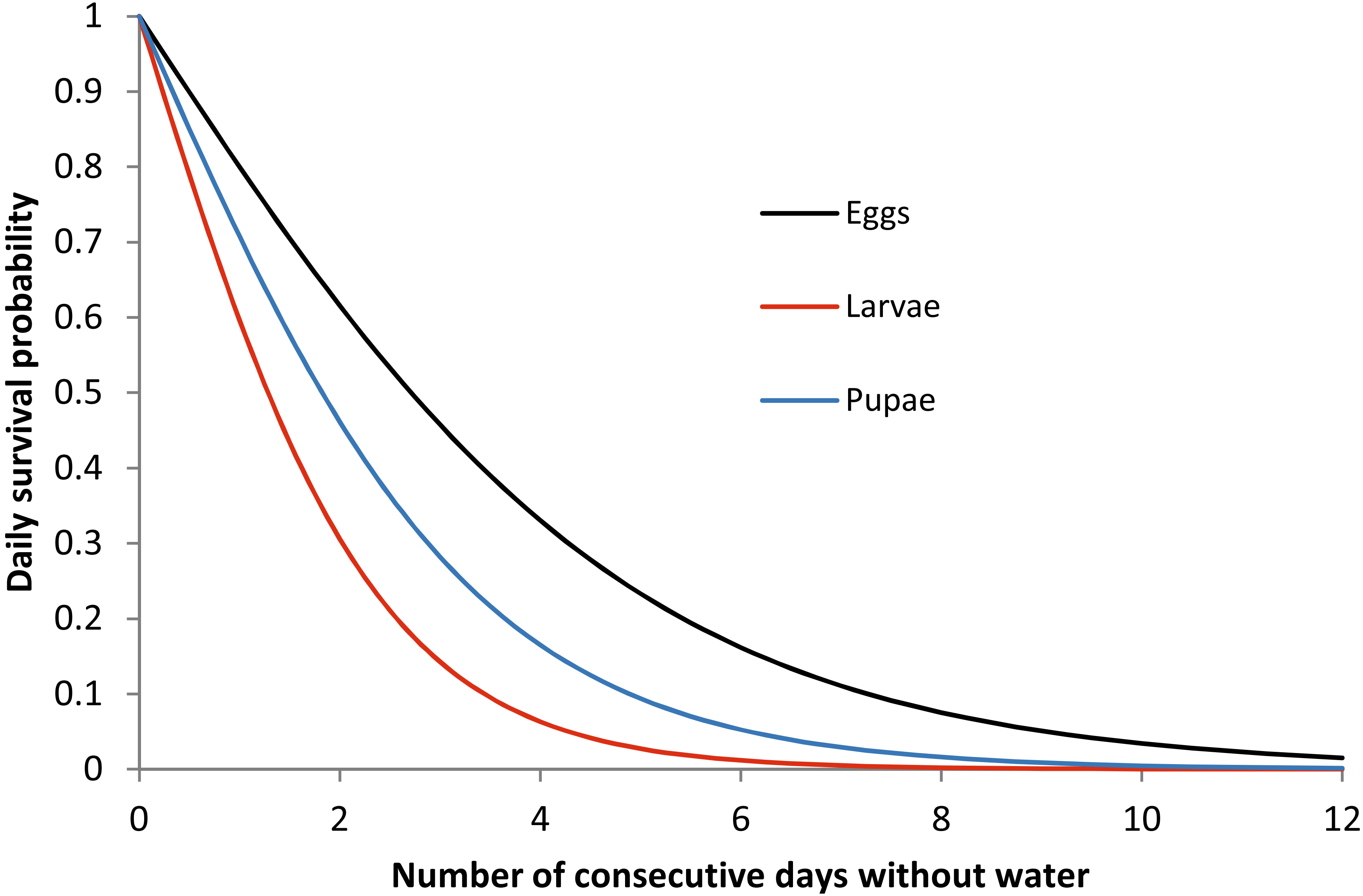
Colon-Gonzalez et al. Geospat. Health 2016

Model implementation of the flushing effect



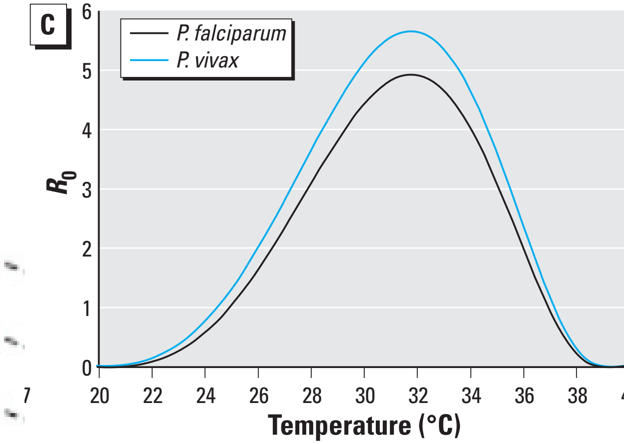
Parham and Micheals 2012

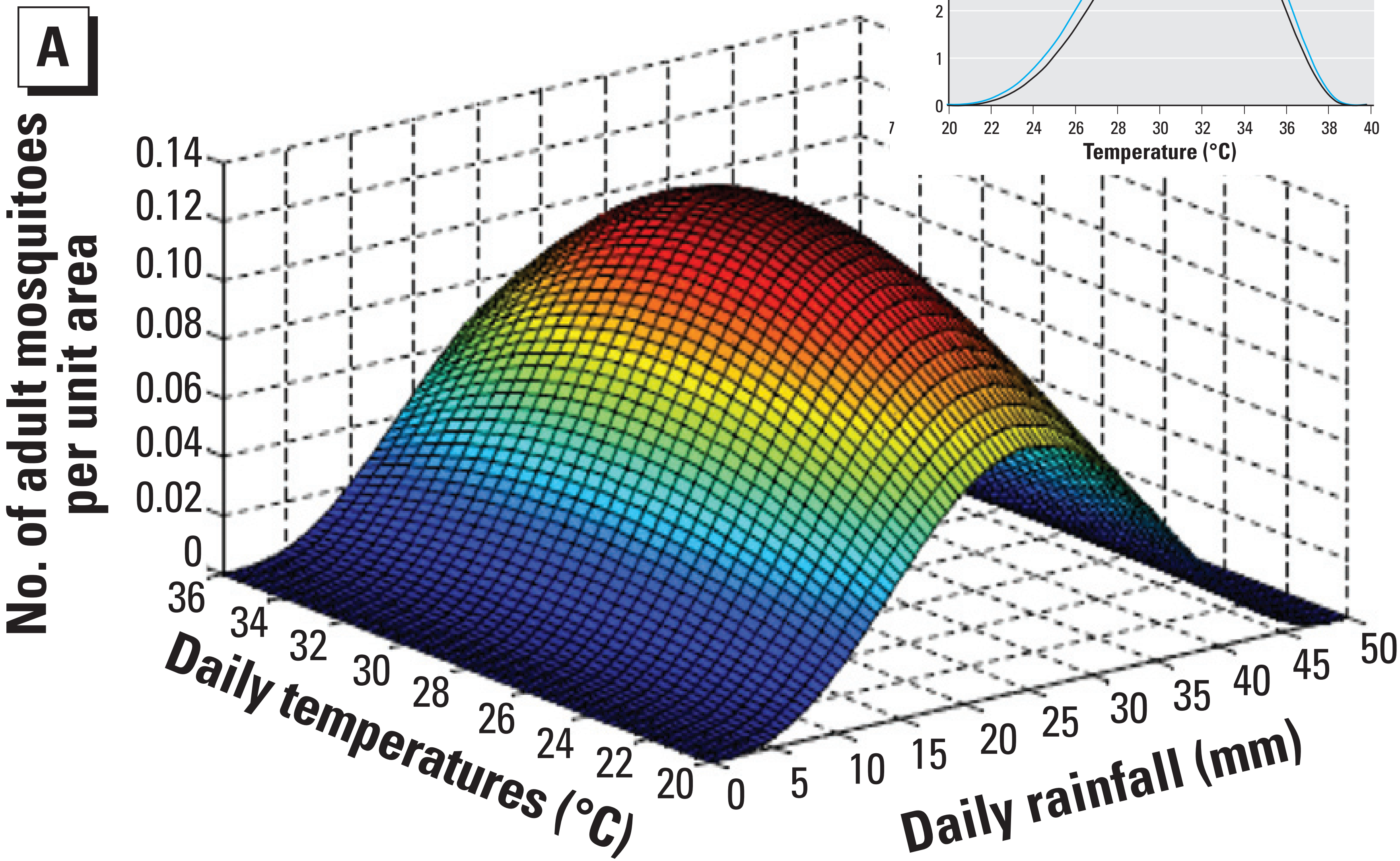
Desiccation effect on mortality relationships



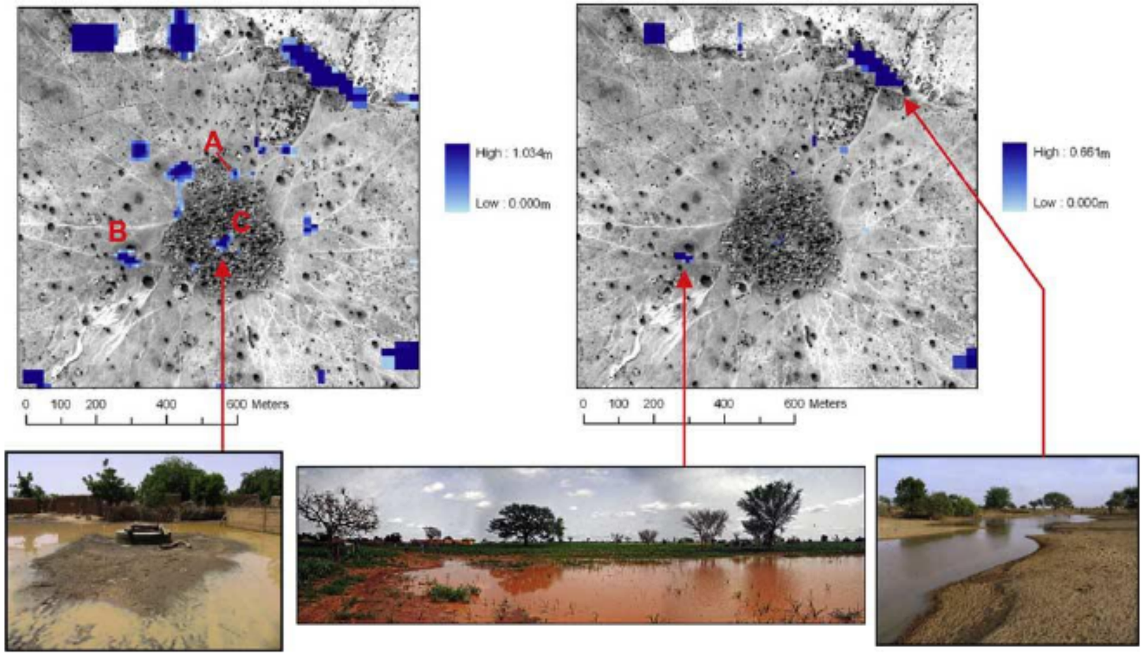
Parham and Micheals 2012

Parham and Micheals 2012



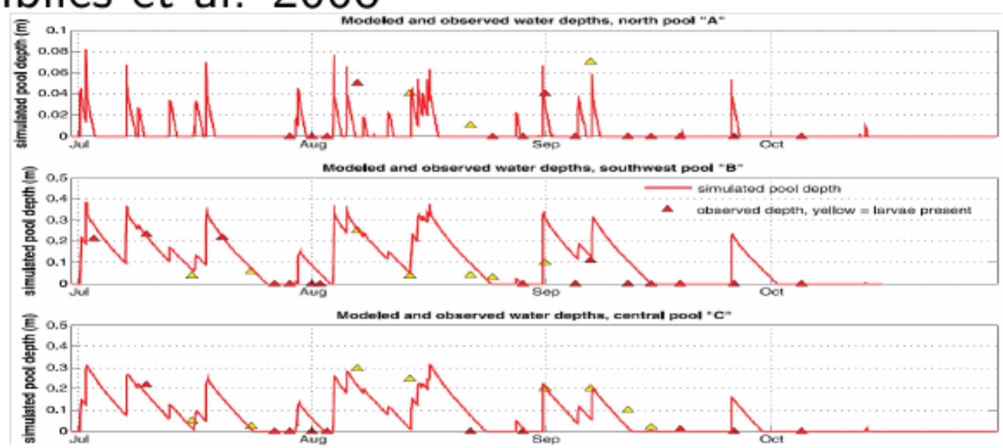


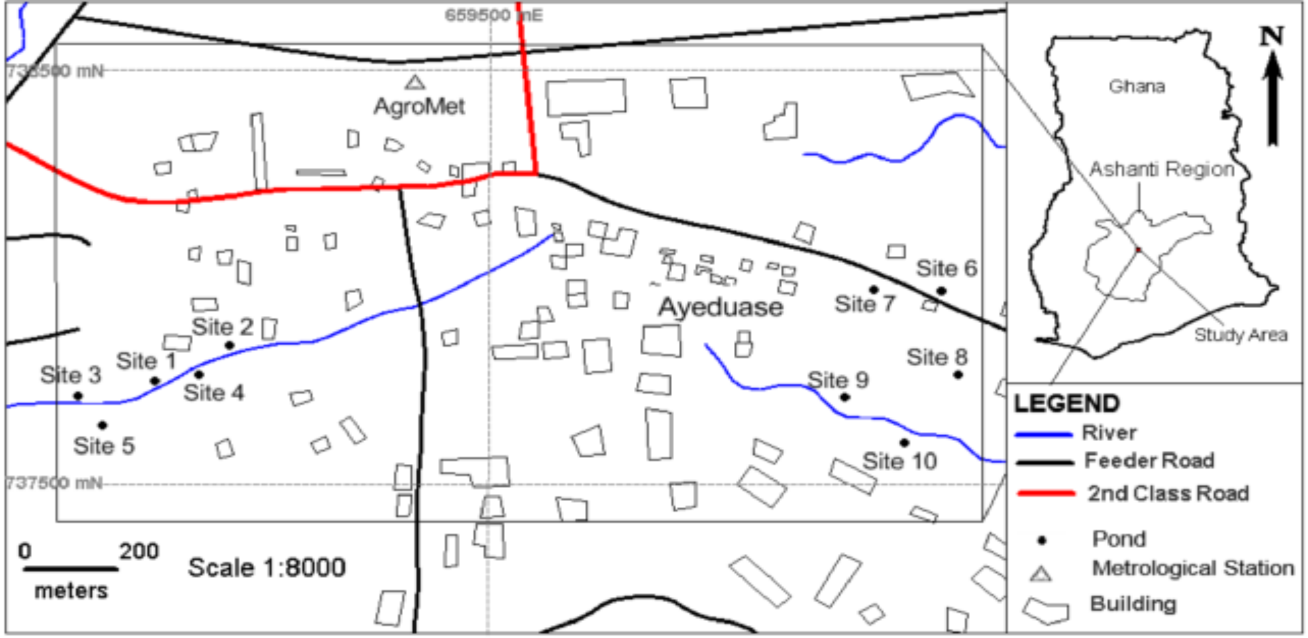
But depends on daily precipitation extremes.



Modelled pond behaviour - However the aggregated effect of these small water bodies could be represented by a pond parametrization in a coarser scale model

Bomblies et al. 2008





Study area showing the ten monitored temporary breeding sites

Surface Hydrology – breeding sites studied in Kumasi Ghana

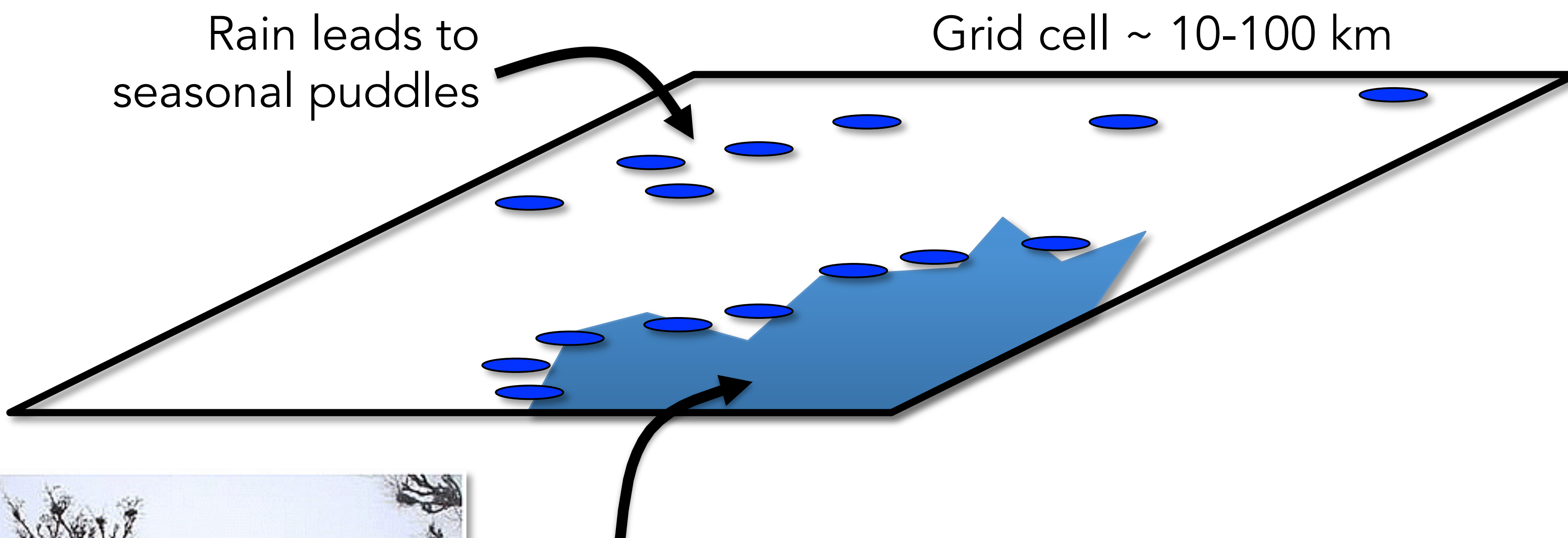
(a) Average area = 5.0 m^2
Average depth = 13.3 cm

(b) Average area = 1.4 m^2
Average depth = 8.3 cm

Two examples of the monitored habitats showing average water area and depth

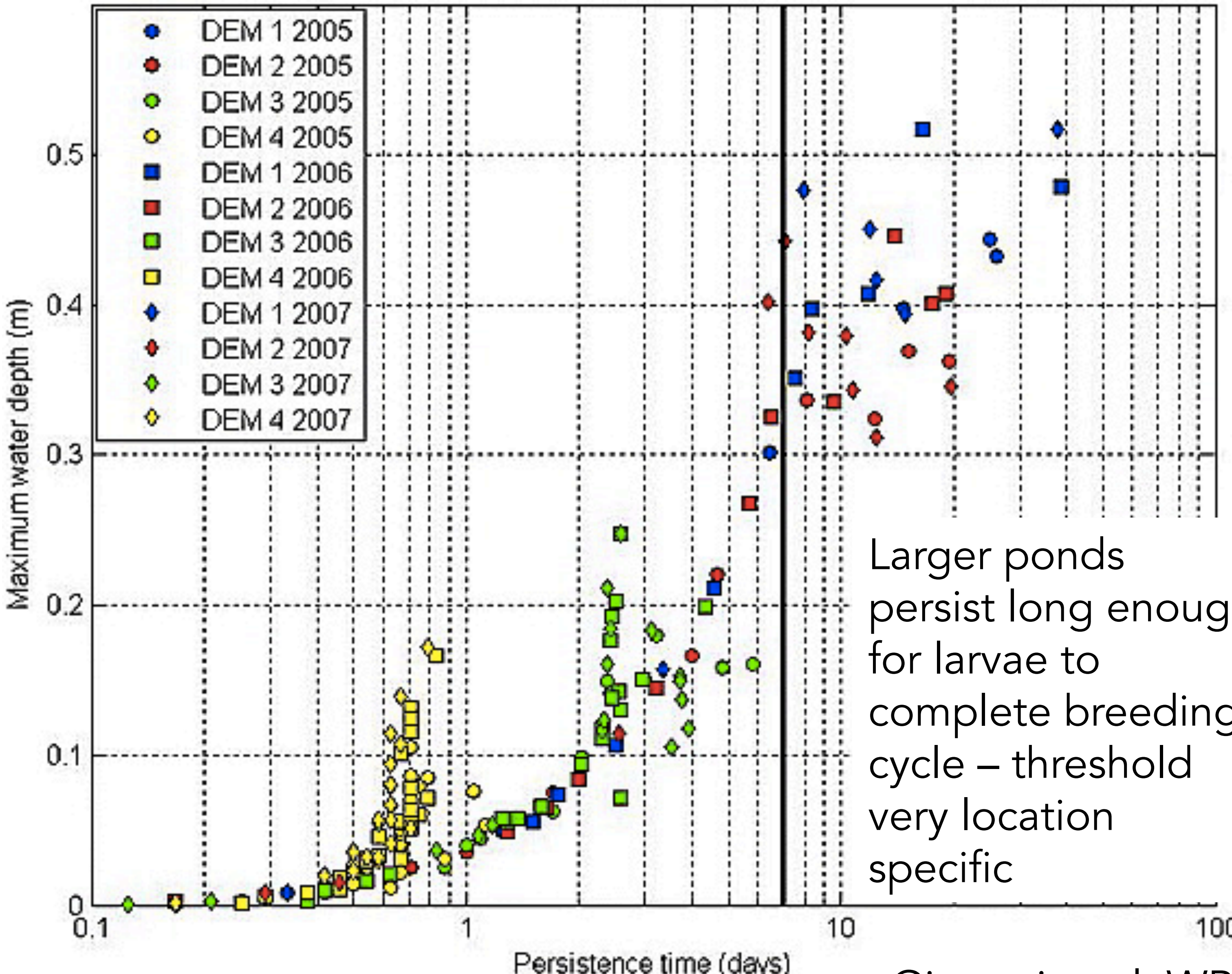
Asare et al. 2016

Schematic of approach: Breeding site sum of permanent and temporary ponds



Permanent water body
- Many puddles at edges
- Body itself not a preferred habitat due to ripples and predators

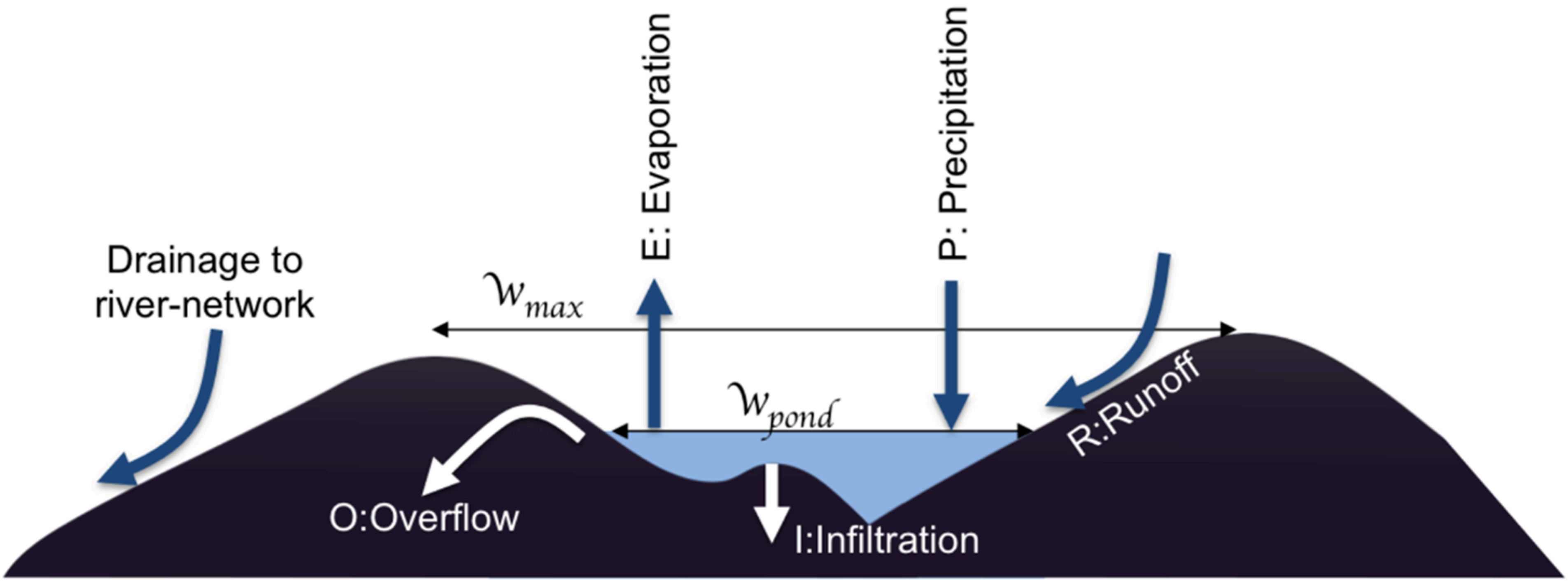
Pond Persistence times as function of depth



Larger ponds persist long enough for larvae to complete breeding cycle – threshold very location specific

Gianotti et al, WRR, 2009

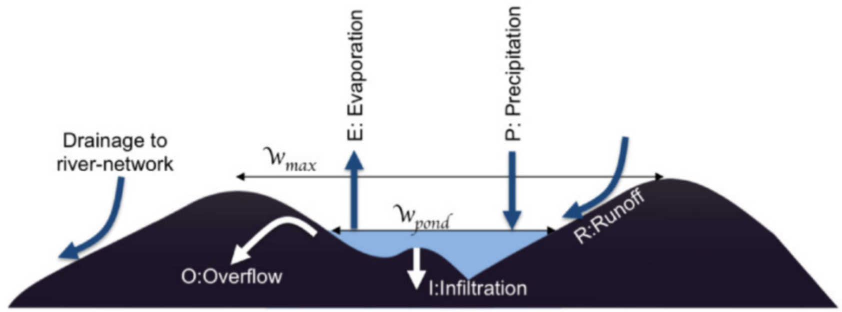
Schematic of approach
Temporary ponds



Note:

- Hayashi and Van der Kamp: pond geometry
- Soil Conservation service Curve number for run off

Surface Hydrology – model equation



Schematic of the hydrology scheme

Breeding site is given by

$$w = w_o + w_{pond}$$

w_o is the permanent pond fraction
w_{pond} is the temporary pond fraction
w_{max} is the maximum water coverage
K_w relates to the pond geometry

The default scheme

The daily fractional water coverage within each grid cell is given by

$$\frac{dw_{pond}}{dt} = K_w\Big(P(w_{max} - w_{pond}) - w_{pond}(E + I)\Big)$$

The modified scheme

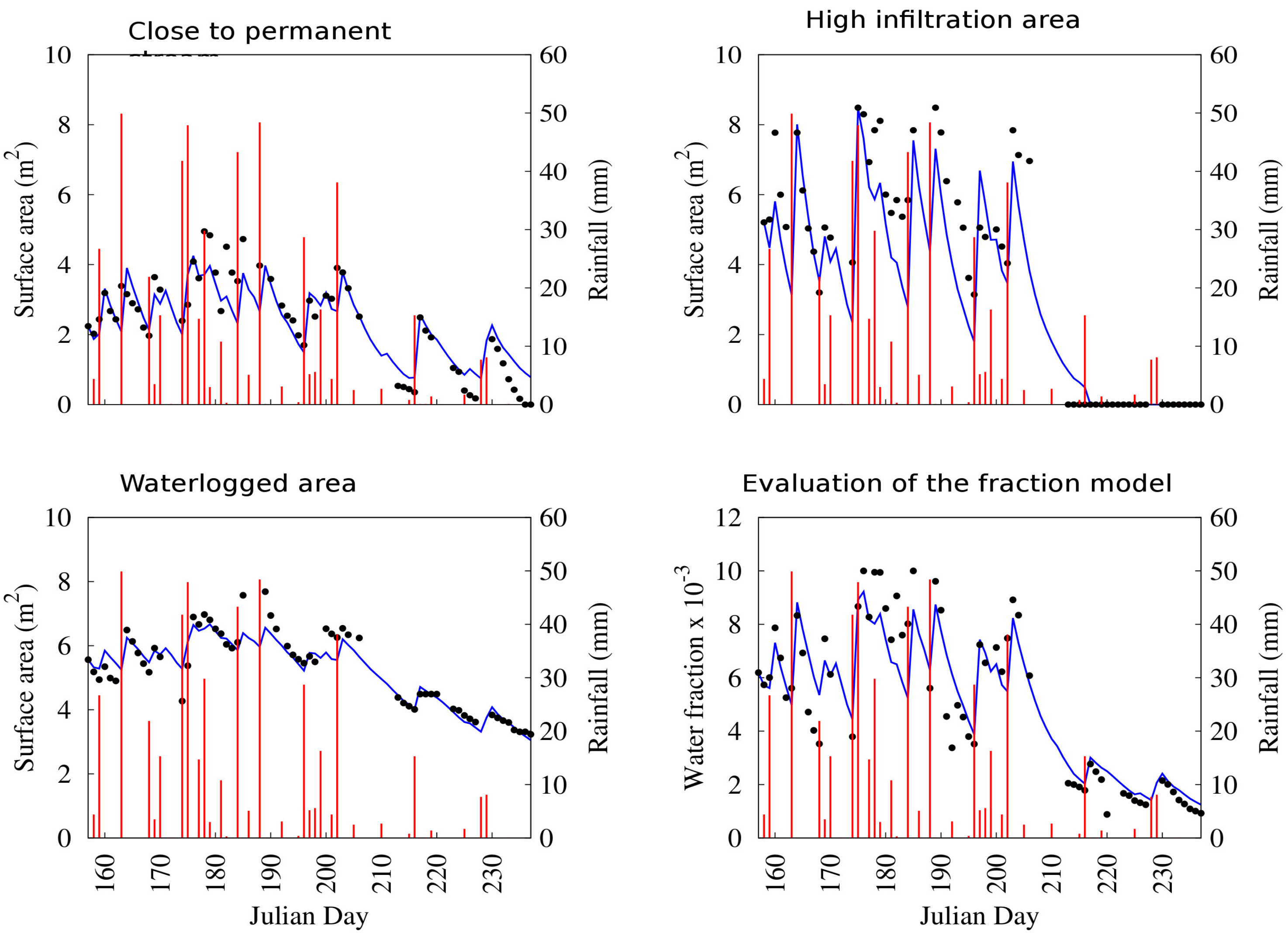
The modified scheme incorporates **pond geometry** and nonlinearities of the **surface runoff** and **infiltration** processes

nonlinear infiltration

$$\frac{dw_{pond}}{dt} = \frac{2}{ph_{ref}}\left(\frac{w_{ref}}{w_{pond}}\right)^{p/2}\Big((R(w_{max} - w_{pond}) + Pw_{pond})(1 - f) - w_{pond}(E + fI_{max})\Big)$$

where w_{ref} and h_{ref} are the reference pond surface area and depth respectively, p is the pond shape factor, R is the runoff and $f = \frac{w_{pond}}{w_{max}}$.

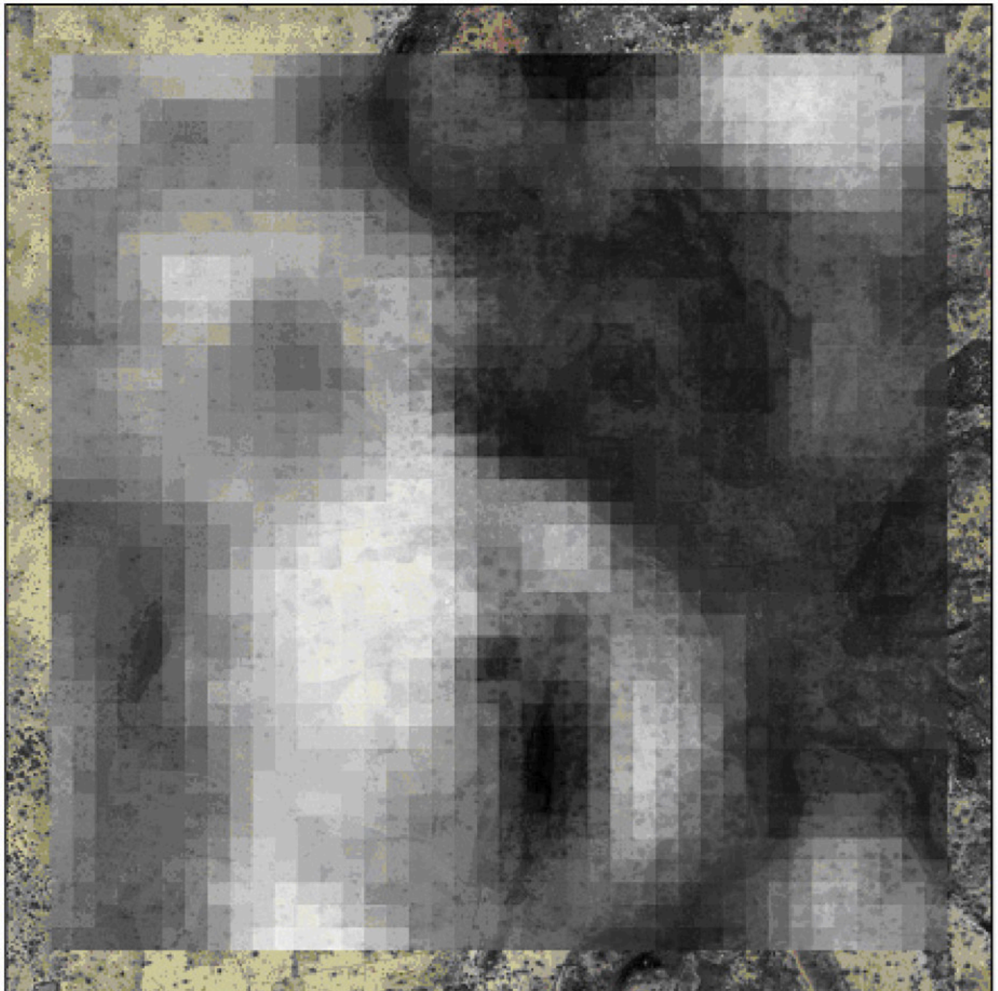
Evaluation with in situ pond observations



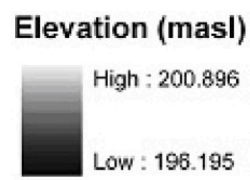
Asare ,EO, Tompkins AM, Amekudzi LK and Ermert V, 2016: A breeding site model for regional, dynamical malaria simulations evaluated using in situ temporary ponds observations. Geospatial health, 11,1S

Simulated — Observed • Rainfall —

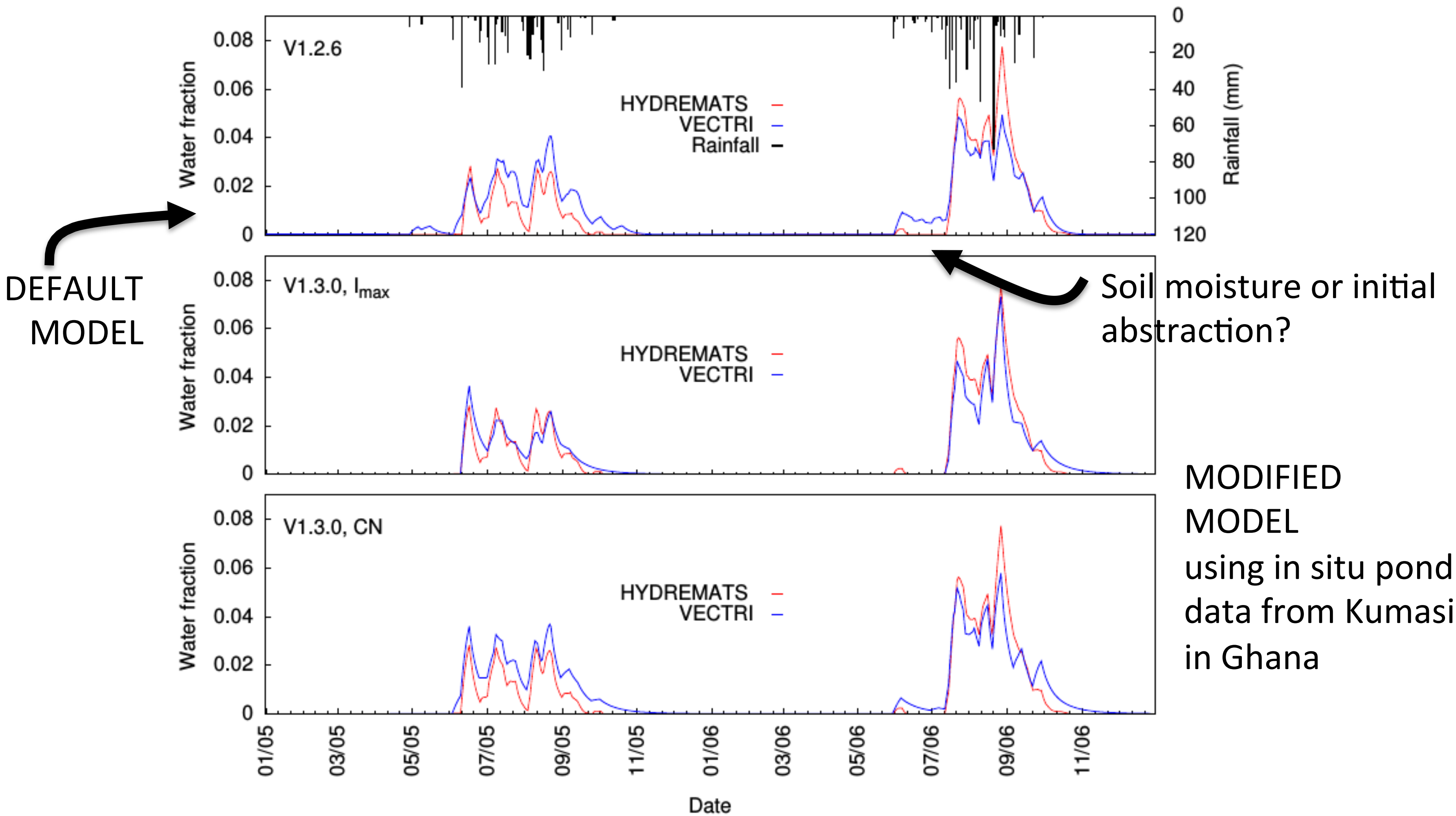
Mapping of villages at 10m scale



Bomblies et al. 2008, 2009a,b
Model set up for village with 10m resolution, modelling overland flow, soil texture



Evaluation with 10m (not km!) resolution model at the village scale in Niger.



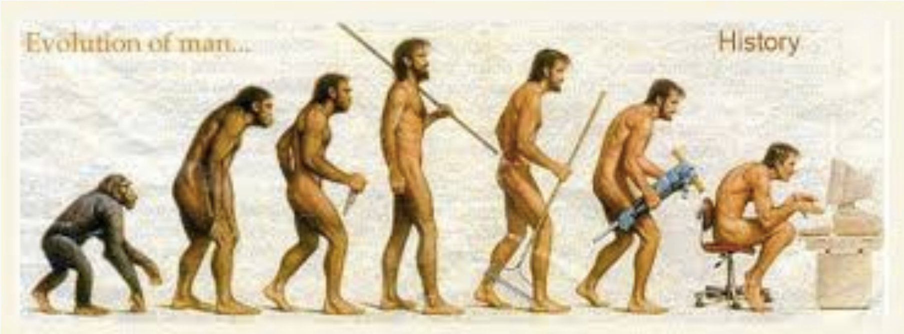
Ernest O Asare, Adrian M Tompkins and Arne Bomblies, 2016: Evaluation of a breeding site availability model for malaria vectors using explicit pond-resolving surface hydrology simulations PLOS ONE

Two further papers Asare et al. 2016 Geospatial Health

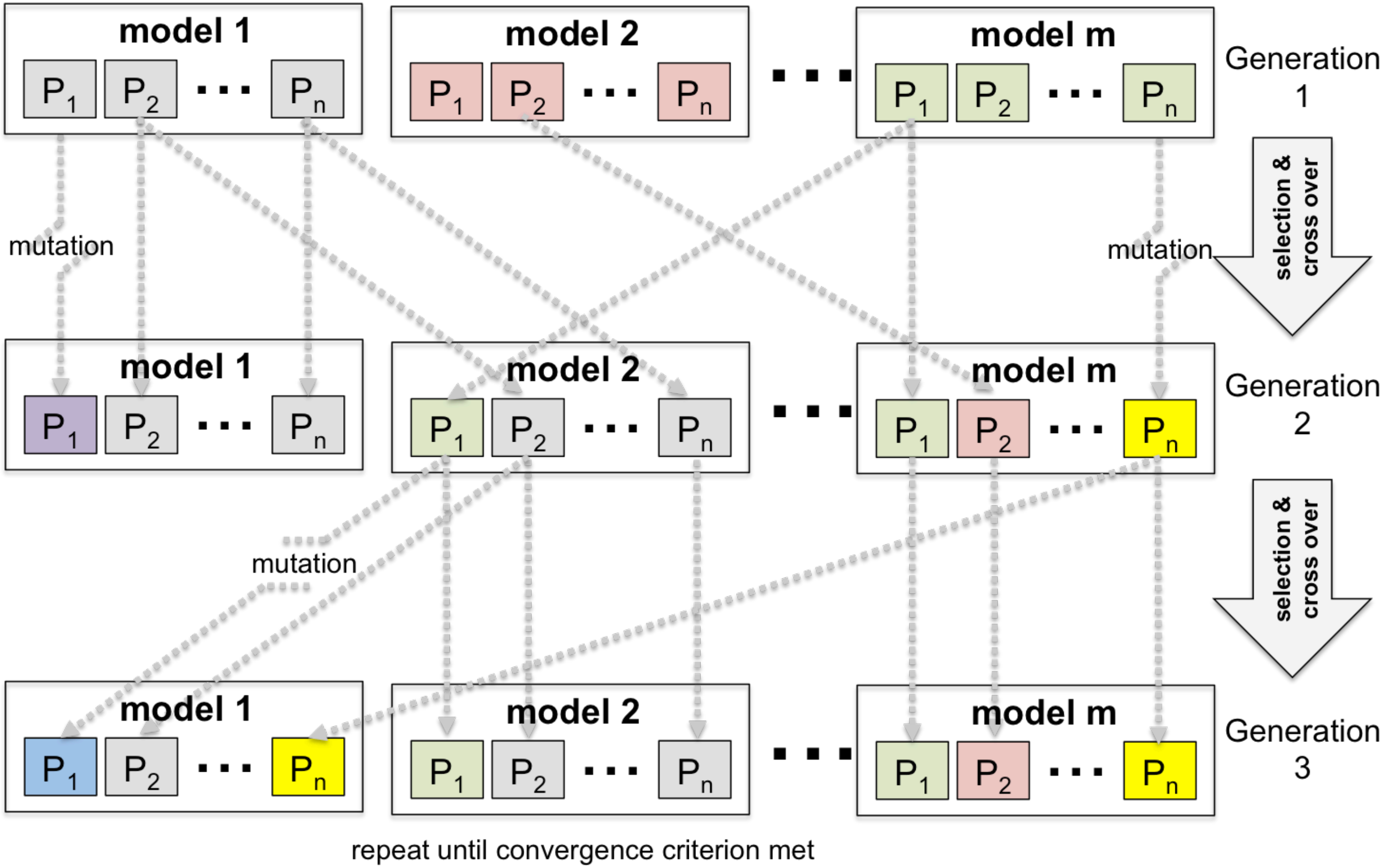
So how much detail is required?

- Do we need to add a treatment of
  - Slope?
  - Soil moisture?
  - Evapotranspiration?
- Or should we try to retain a low order model and calibrate?
  - Calibration can be end-of-line, e.g. malaria cases, or at the hydrological level
  - Which data to use for calibration for small scale water bodies?
- Other factors will always conspire to complicate the water-health relationships. e.g. irrigation and dams example.

(Soft) Constraint Genetic Algorithm for Ensemble Prediction Model Parameter Setting



- Genetic algorithms used for a large variety of problems
- Can be used for model parameter calibration - “tuning”
- Advantages:
  - Simple, no adjoint required
  - Framework suited to existing ensemble approaches
  - Can handle highly nonlinear, discontinuous problems



- Method based on evolution:
  - Ensemble of models with different parameter settings
  - Metric for their fitness determines their ability to pass parameters to child generation
  - mutation of parameters to search parameter space

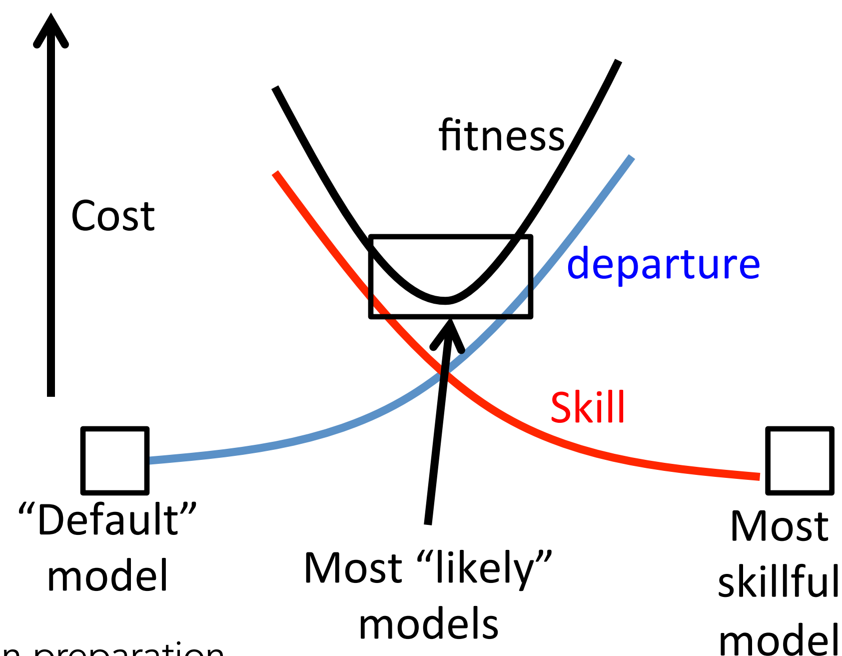
A soft constraint

- GA has been applied to a wide range of problems
- However, the dimensionality of the problem is often very high
- Introduce concept of soft constraint, penalty for departures of parameters around their default values
- Advantages:
  - Reduction of dimensionality (search essential in a N-sphere)
  - Allow the prior uncertainty of each parameter to be accounted for, preventing unreasonable parameter settings
- Not the optimum system in terms of skill but best compromise solution within the realm of assessed uncertainty (flat cost minimum).

$$\mathcal{L} = \eta \underbrace{P(C_s)}_{skill} \underbrace{\prod_{i=1}^{n} P(K_i)}_{constraint}$$

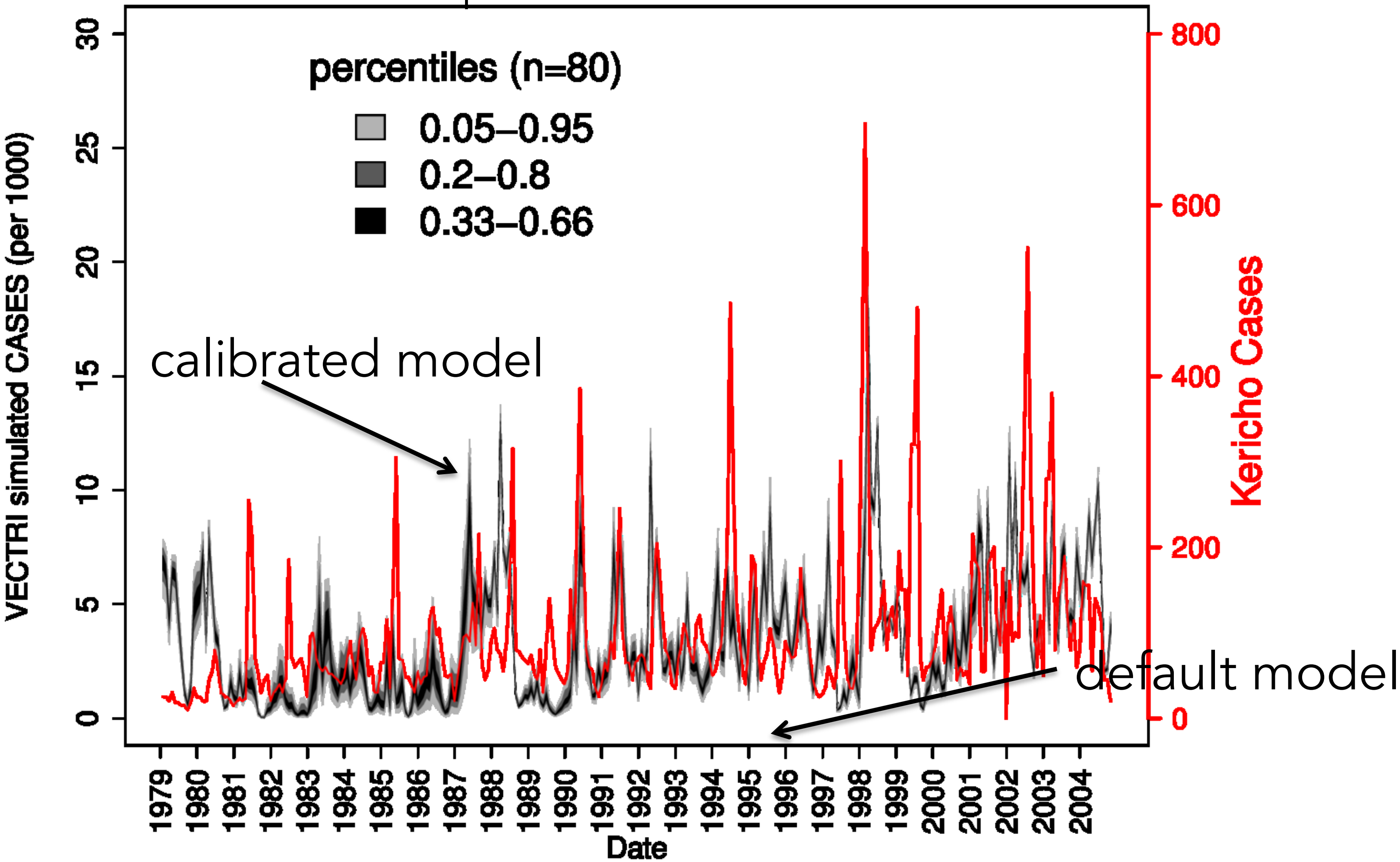
Assume parameter uncertainty is Gaussian

$$K_i \sim \mathcal{N}(K_{i0}, K_{i,\sigma}^2)$$



Tompkins QJRMS in preparation

Malaria in the Kenyan highlands
Tompkins and Thomson 2017



Where next?

- Health impacted by small and large scales hydrology
  - Dams
  - Irrigation
  - Village ponds
  - Puddles
  - Water storage/harvesting

- Many factors are required:
  - water temperatures
  - water level
  - water quality
  - water flow
- Observations of small scale hydrological processes are lacking, ideas welcome!
- The system does not have to be modeled at full complexity