Methodology for probabilistic risk evaluation linked to MAR activities based on fault tree analysis.

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MARSOL Workshop

Technical Solutions for MAR

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Motivation

- In MAR we deal with very complex and multidisplicinar problems
- Unless we homogenize the methodology to evaluate potential risks, we will be in trouble
- Problems involve things we do not know for lack of knowledge/information (epistemic uncertainty), and also that we just cannot know (aleatory uncertainty)
- Solutions probably involve heavy numerical modeling
- Solution: the “divide et impera” approach, reducing the megaproblem to a finite number of smaller simpler problems, and then integrate them properly (procedurial and mathematically speaking)

Risk is NOT a YES/NO thing

- Forget about the question: is there risk?
- So, we should deal with hazards (something that may happen and we do not wish it to happen). IF it eventually happens, we say that the system has FAILED
- The combination of epistemic and aleatory uncertainty leads us to treat the system in a probabilistic framework
- RISK is defined as the probability of system failure by a given hazard or a combination of hazards (by definition it goes between 0 and 1)

Risk evaluation by fault trees is just ONE of the many existing methods

- We propose to assess RISK as the probability of system failure (0 - 1) based on fault tress
- Many alternatives exist, some with a similar idea behind (Event Tree Analysis)
- Complete different approaches – Cost-Benefit

Applications of FT-PRA

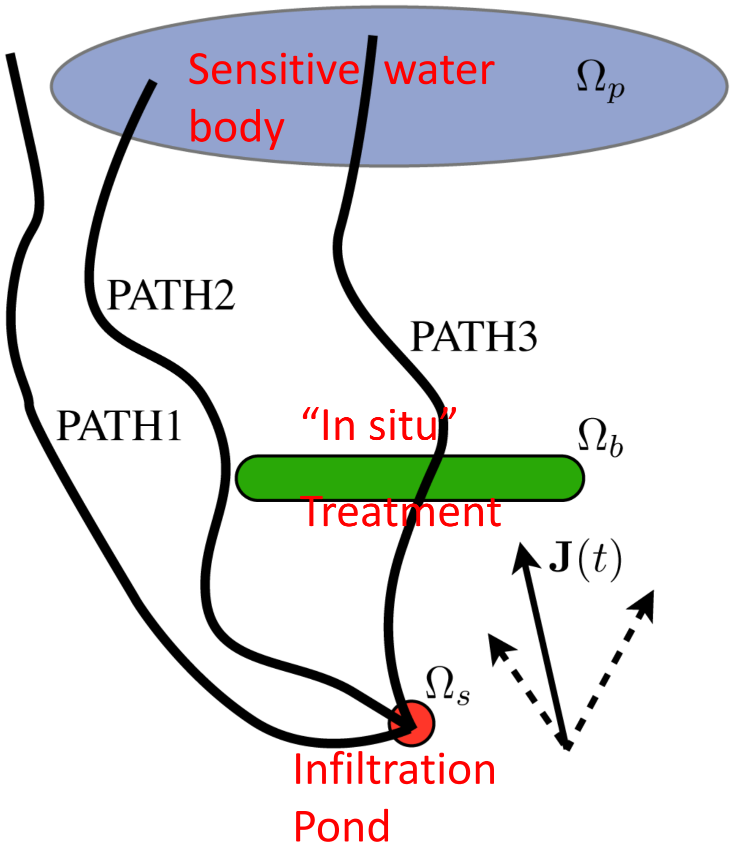
A large number of engineering problems

- Safety of nuclear power plants
- The airspace shuttle
- …

So, using it to the assessment of MAR facilities should be straightforward

Visualizing it through an example

- Water from the infiltration pond may affect a sensitive area (ecosystem, drinking well area). An “in situ” treatment is designed to be placed
- Main actors:



- Hydrogeologists/geochemist/modelers - evaluate the concentration of a potential hazardous substance at the water body, and the impact of the “in situ” treatment
- Ecologists/toxicologists – evaluate the impact upon ecosystem or human health of substances and potential metabolites
- Chemists – what metabolites are expected?
- Experts in monitoring
- …

Possible (not exclusive) approach

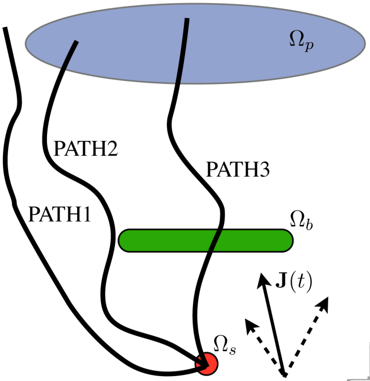
- In a Dream World (computer infinite capacity and speed): the problem can be treated from a probabilistic point of view using Monte Carlo simulations of high resolution, but that cannot be done in a real world because:
- (1) many pollutants (and its metabolites)
- (2) physical parameters heterogeneity and lack of knowledge
- (3) heterogeneity of transport parameters and scale dependence + reactive transport
- (4) uncertainty in monitoring and in the impact of remediation actions
- (5) BUDGET and time limitations (there is less than 1 life)

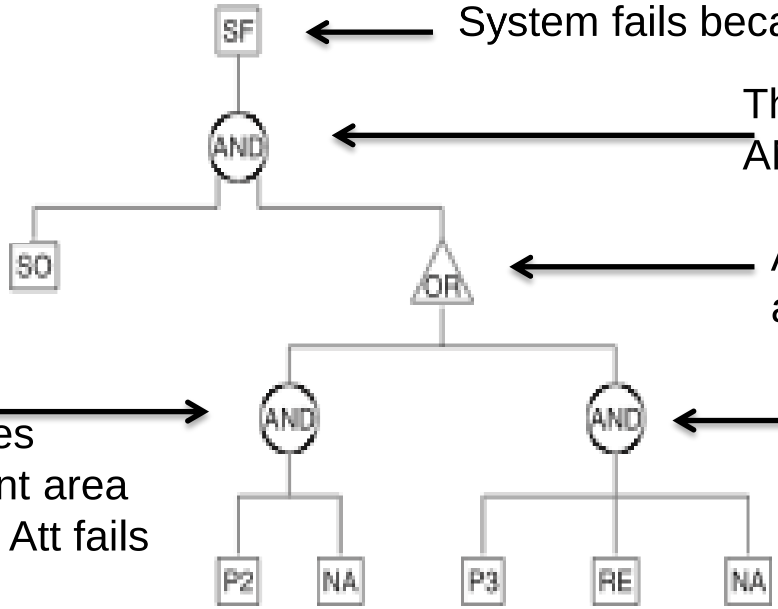
Worse, incorporating information of any kind means re-running all simulations!

A rigorous Probabilistic Risk Assessment based on fault trees (FT-PRA)

FT-PRA should include the following steps:

- Define Systemic Failure (SF) – this to be done by managers/regulators
- Identify the key system components, which are the events that may lead to failure (better if they are independent or weakly dependent)
- Build the Fault Tree, reflecting combinations of events leading to failure
- Develop a mathematical representation of the FT using Boolean algebra
- Calculate the probability of occurrence of each event
- Use P(event) to calculate the probability of system failure as a whole
- Update with new data as it becomes available





System fails because ONE substance reaches water body

The infiltrated water is polluted (SOURCE) AND SOMETHING ELSE HAPPENS

Any of those combinations (one OR another – Boolean “OR”)

Bypasses treatment area and Nat Att fails

Goes through the treatment, but it fails, and NA fails too

Probability can be computed through Boolean algebra

$$P(SF) = P(P2 \cap NA)P(SO) + P(P3 \cap RE \cap NA)P(SO)$$

To evaluate this, we can combine marginal and conditional probability

$$\frac{P(SF)}{P(SO)} = P(NA / P2)P(P2) + P(NA / RE \cap P3)P(RE / P3)P(P3)$$

And each of these probabilities can be assessed by different methods, depending on our technical capabilities; e.g., to obtain P(P3) we could have alternatively:

- Heavy numerical methods
- Invoking macrodispersion concepts from stochastic approaches

$$P[P3] = \frac{1}{2\pi\sigma_b\sigma_p} \int_{y_{p_{min}}}^{y_{p_{max}}} \int_{y_{b_{min}}}^{y_{b_{max}}} \exp\left[-\frac{y_b^2}{2\sigma_b^2}\right] \times \exp\left[-\frac{(y_p - y_b)^2}{2\sigma_p^2}\right] \mathrm{d}y_b \mathrm{d}y_p.$$

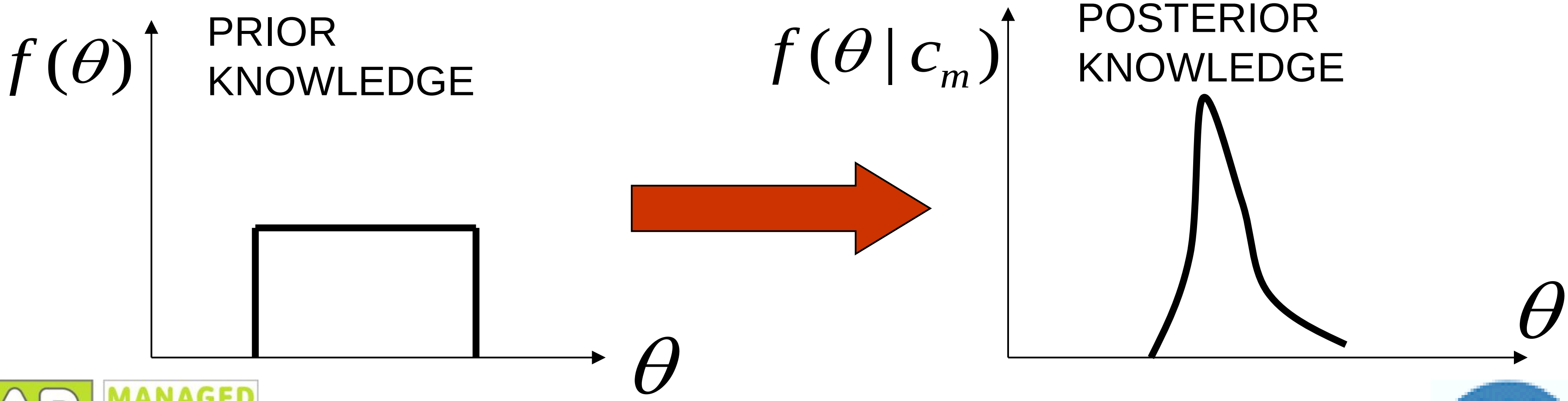
- Simple analytical solutions
- Expert opinion based on geolog

The big advantage of this method is that each box (prob value) can be evaluated by a different expert or pannel of experts; I do not need to know anything about macrodispersion, just need to work with someone that does

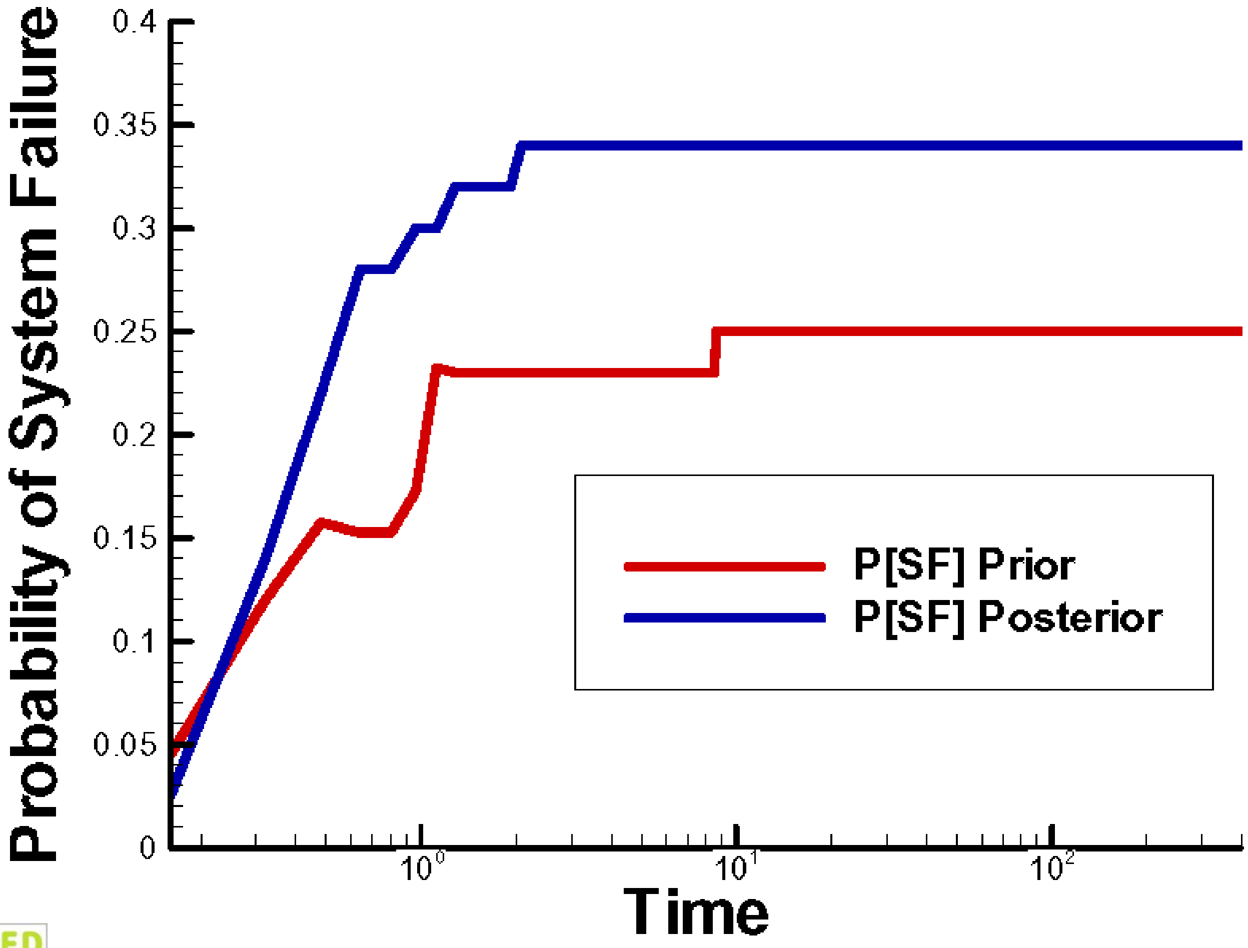
Updating PRA by formally including new data

"Simple" application of Bayes' Theorem

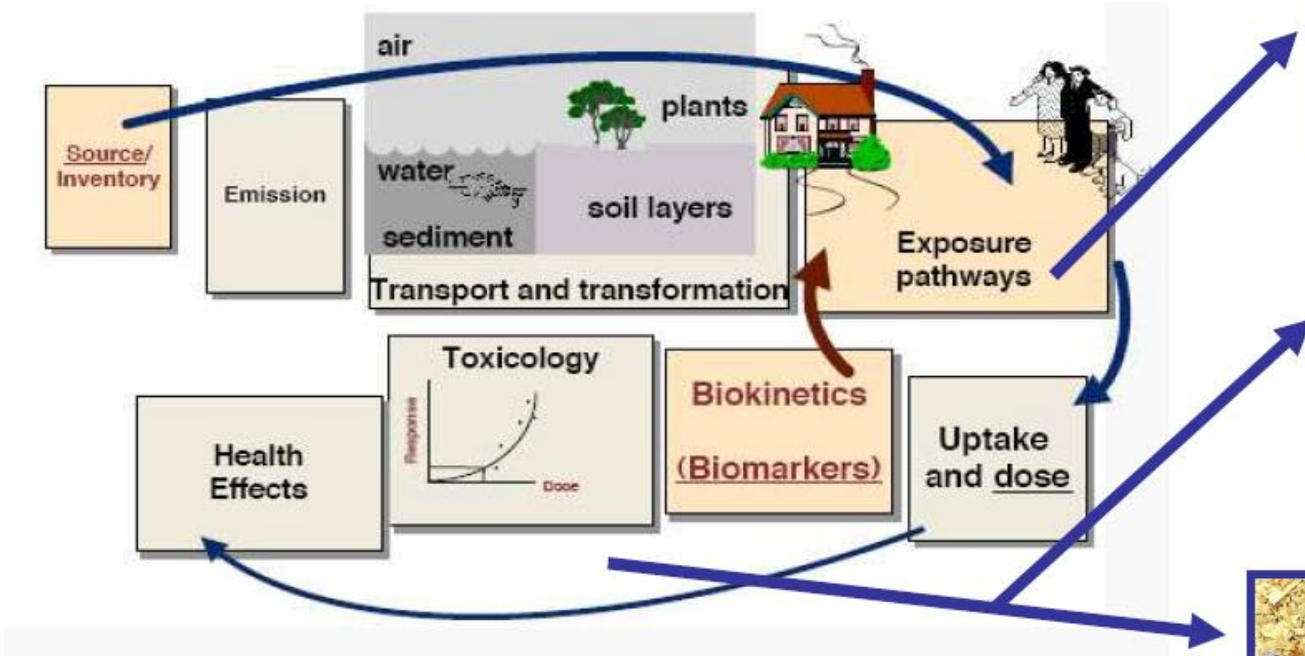
$$f(\theta \mid c_m) = \frac{f(c_m \mid \theta)\, f(\theta)}{\int f(c_m \mid \theta)\, f(\theta)\, d\theta}$$

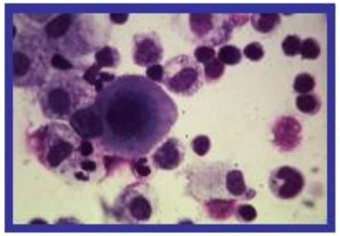


Evolution of Risk with time



But, what about formally include interdisciplinarity





Source: T. McKone's Risk Lecture, UC Berkeley

Need Probabilistic Concepts!

Can we take the approach to the limit involving many different things?

Sure, it is enough to redefine system failure properly. This is the CRITICAL point

Example, instead of declaring failure if “the water body gets polluted”, we define failure as “People consuming this water gets sick”. Thus, we have to incorporate toxicological issues

So, we need a human risk model defining an “average individual”

$$\mathbf{r}(\mathbf{x},\mathbf{t}) = \beta C(\mathbf{x},\mathbf{t}), \qquad \beta = \frac{IR \times ED \times EF}{BW \times AT} \times SF$$

$$f_\beta(\beta) = \iint \underbrace{f(\beta|\text{person},\text{cohort})}_{\text{toxicology}}\,\underbrace{f(\text{person}|\text{cohort})}_{\text{Inter-individual variability}}\,\underbrace{f(\text{cohort})}_{\text{demography}}\,d\text{person}\,d\text{cohort}$$

MAR SOL MANAGED AQUIFER RECHARGE SOLUTIONS

UPC

Or a different type of failure: clogging prevents a reasonable amount of infiltration after too short time

Before flooding …

Infiltration pond after the flooding test - June 2009

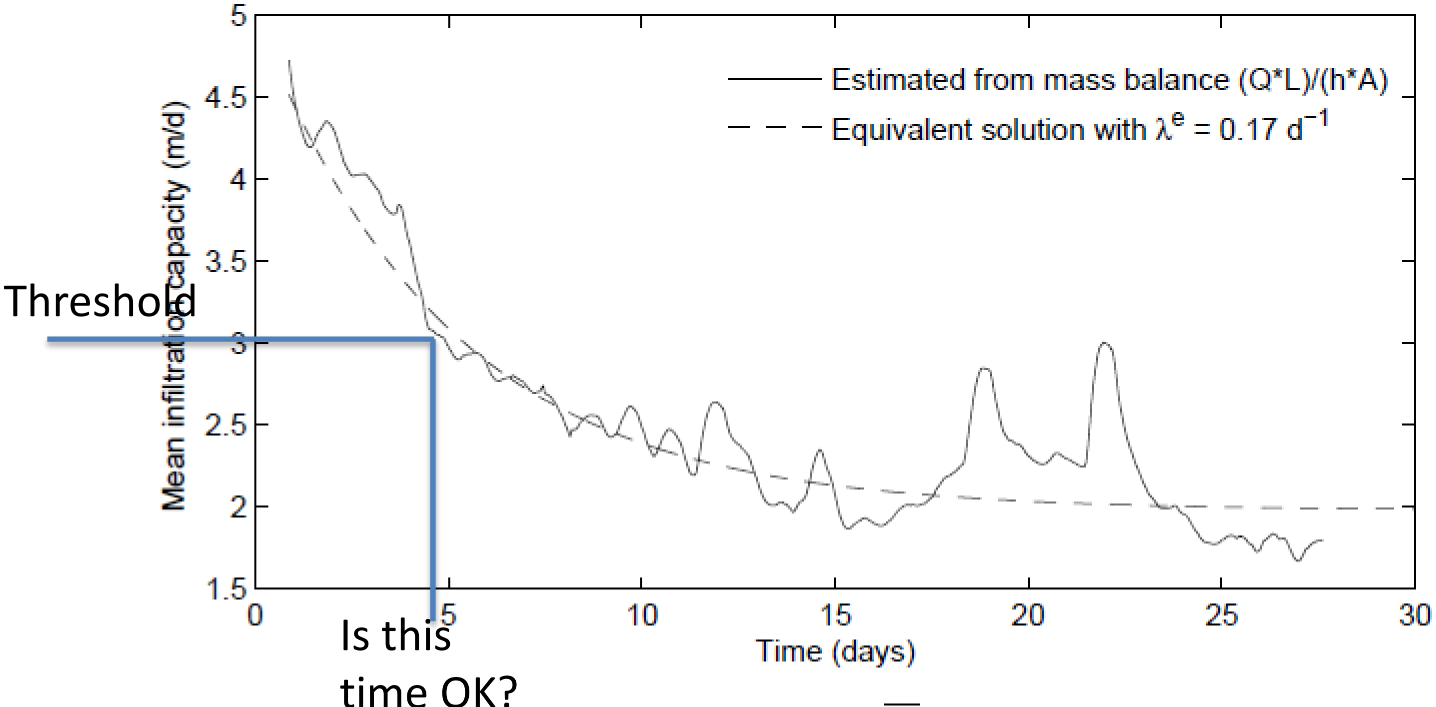
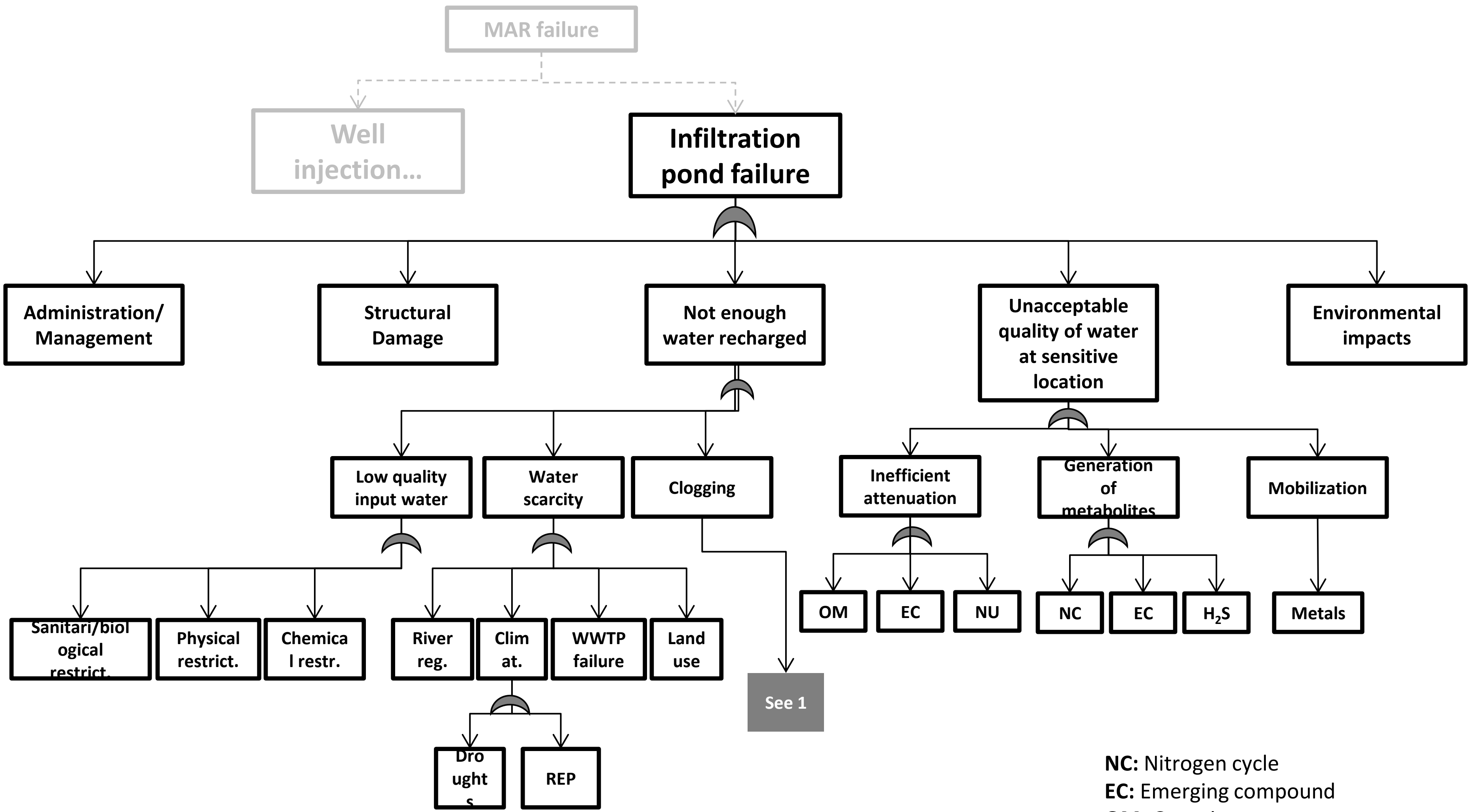


Fig. 2 Experimental observations (solid line) of $\overline{I_c}$ with time from the flooding test. The dotted curve is the best-fit approximation with $\overline{I}(t = \infty) = 1.98$ m,/d and λ^e=0.17 d^{-1}

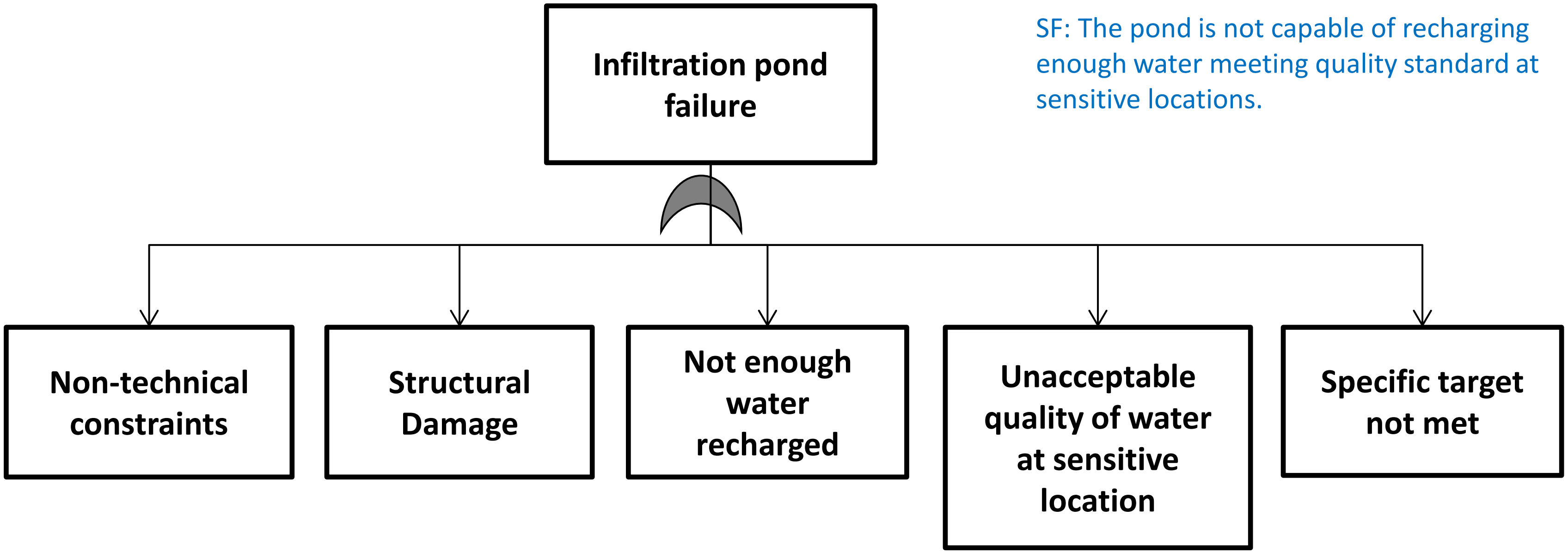
The full approach

- We can then combine everything together and extend it as far as we can

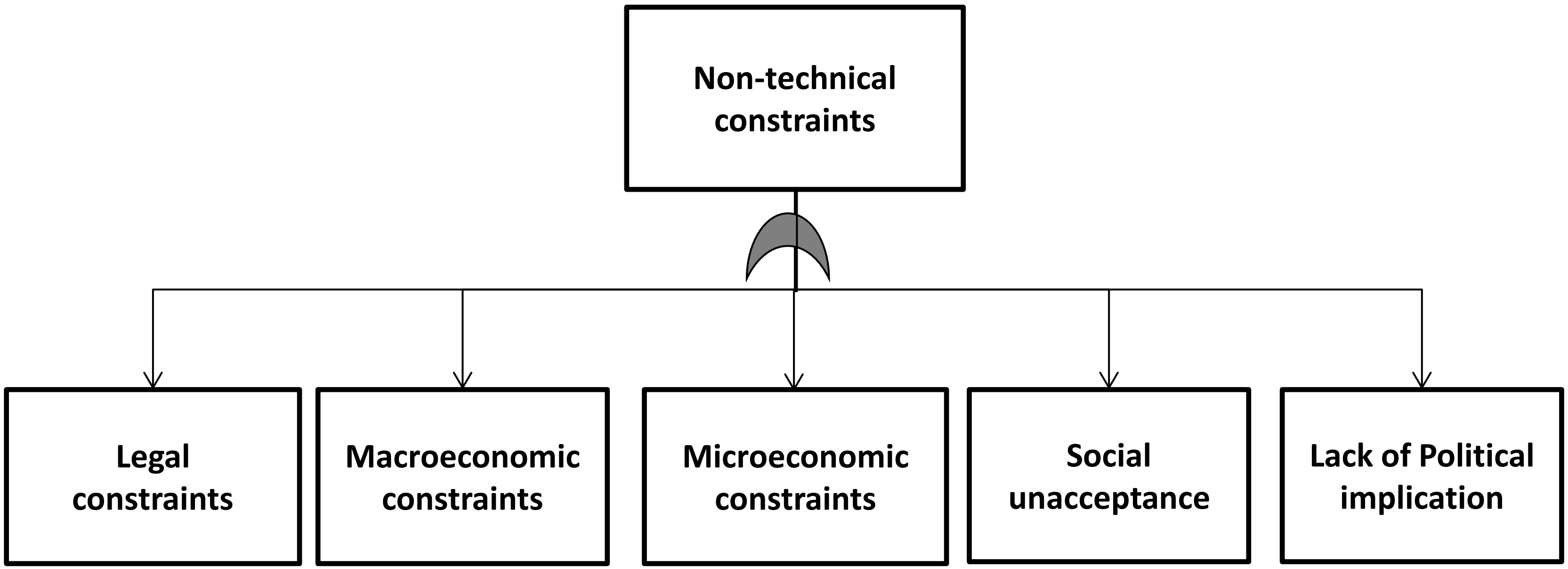


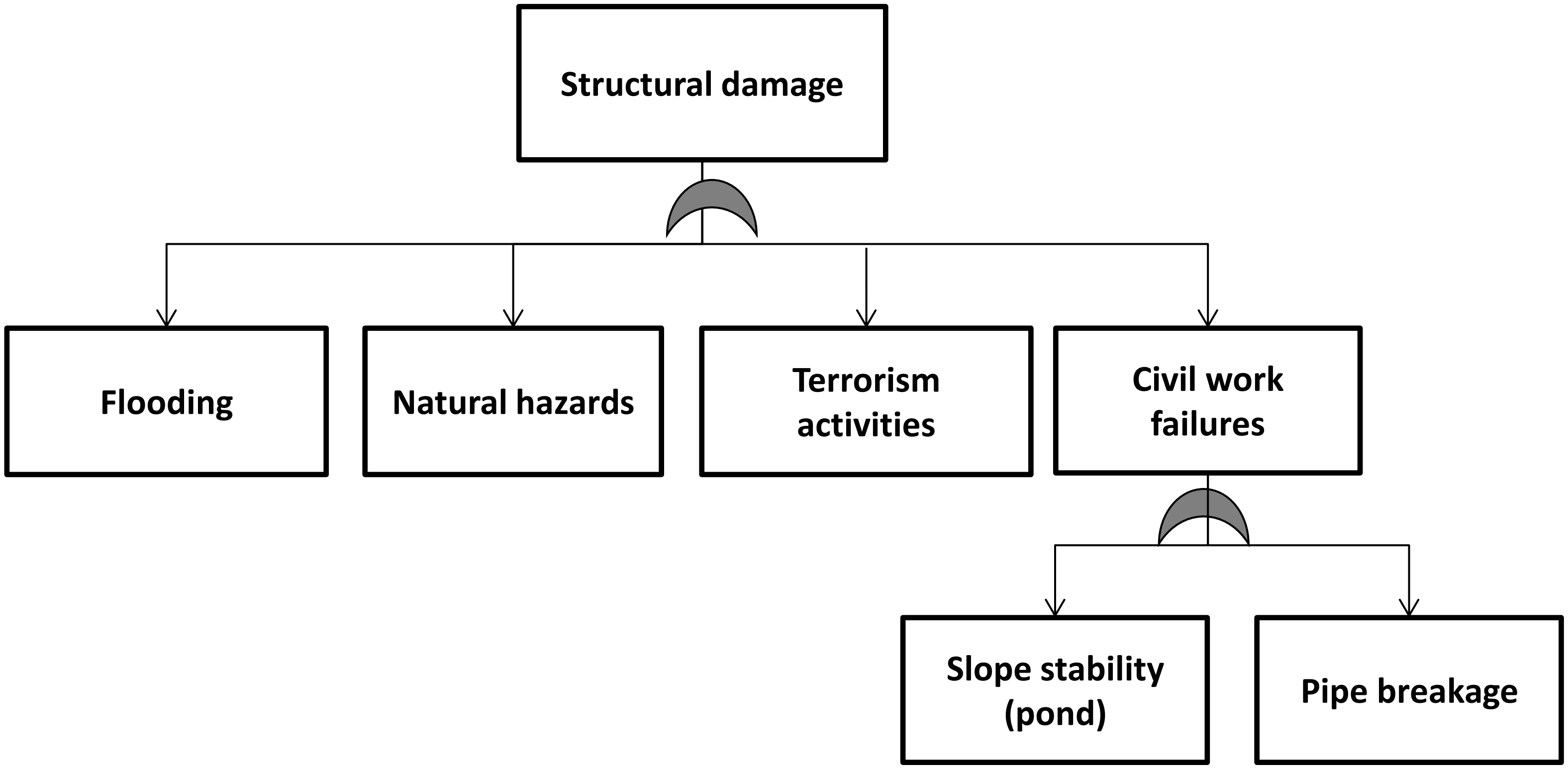
NC: Nitrogen cycle
EC: Emerging compound
OM: Organic matter
REP: Rainfall event periodicity
NU: Nutrients

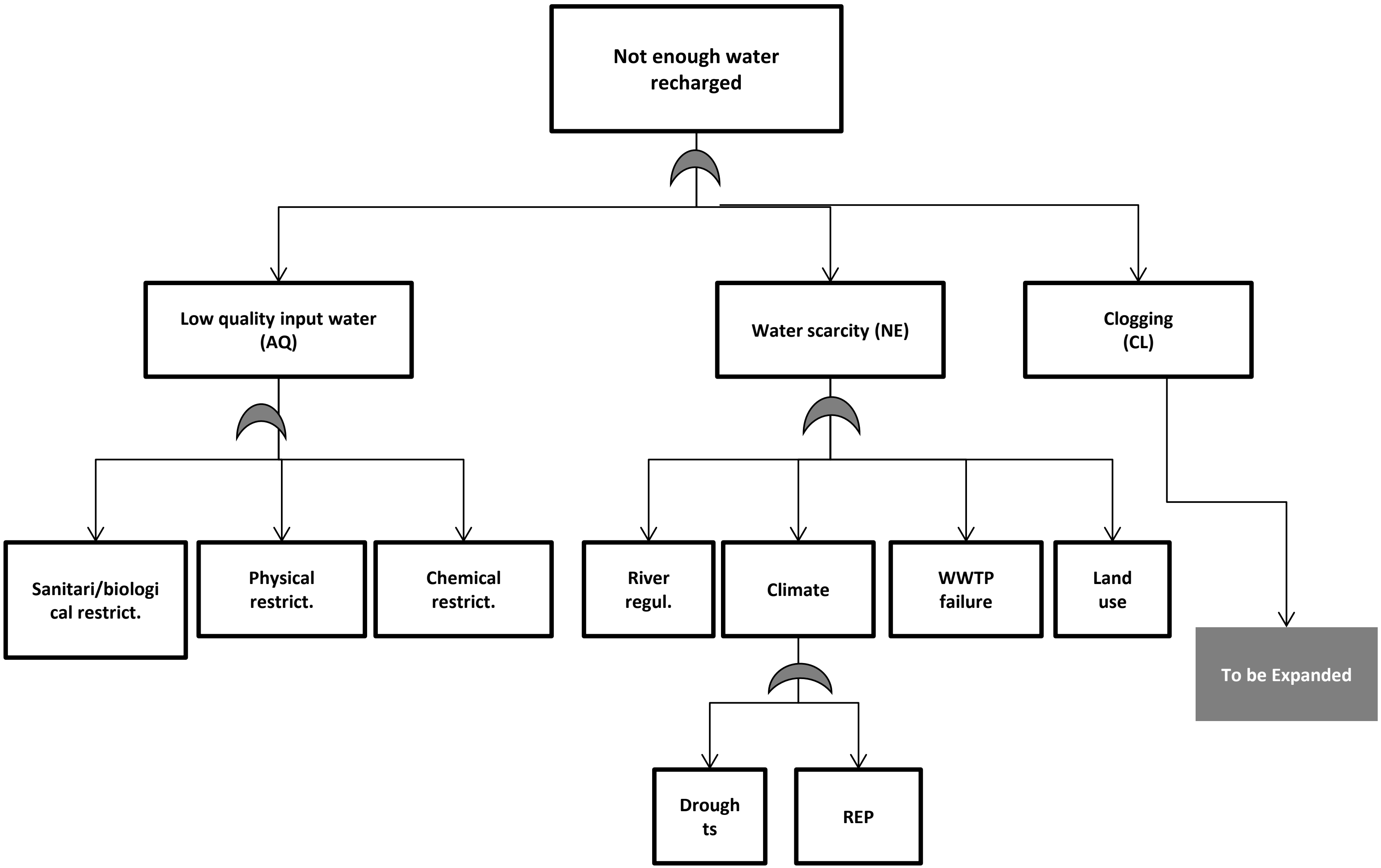
OR

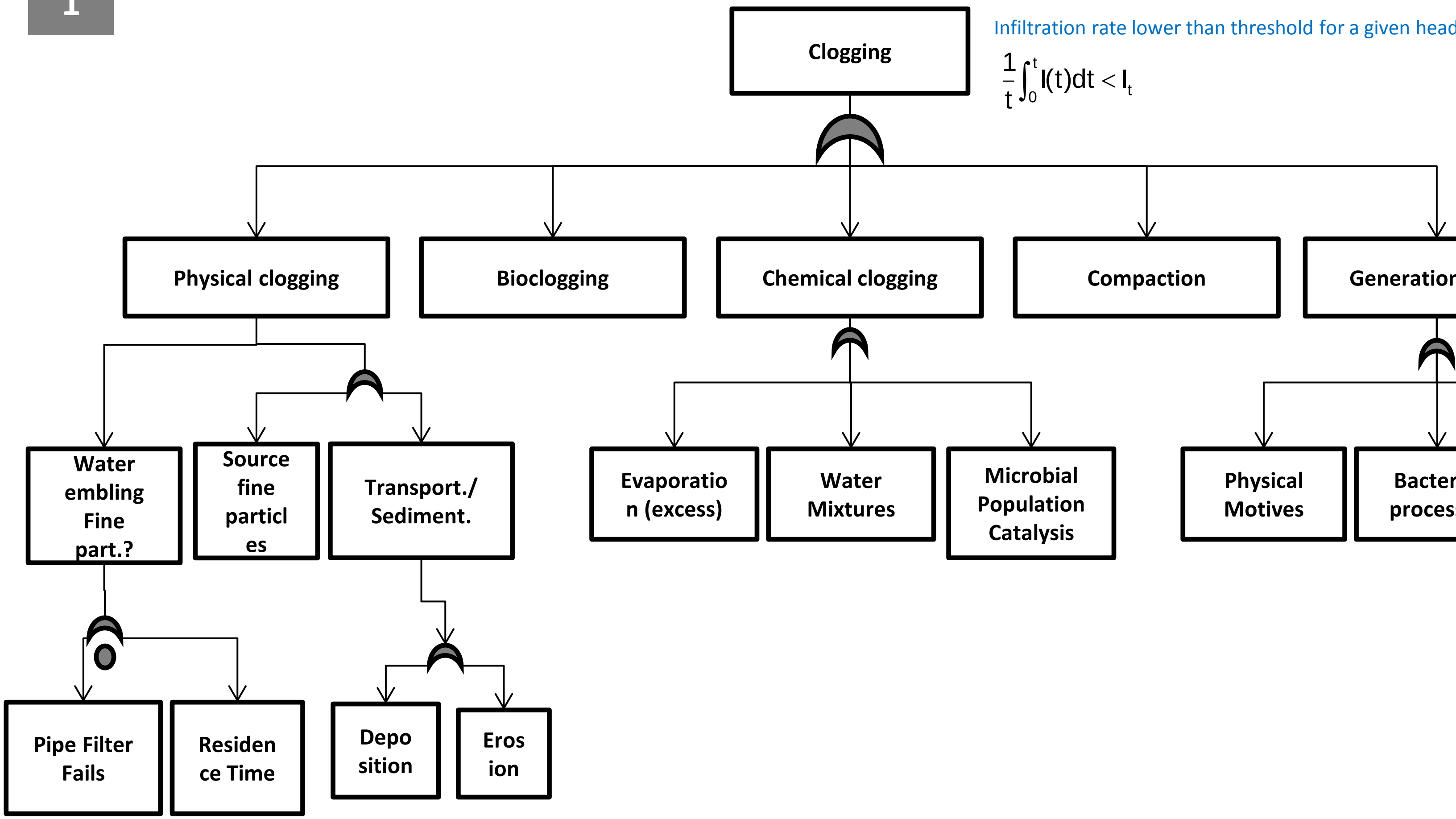


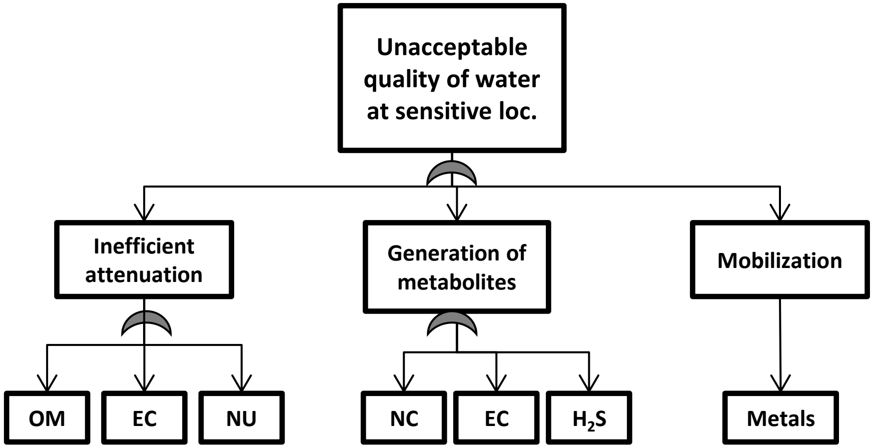
SF: The pond is not capable of recharging enough water meeting quality standard at sensitive locations.


Non-technical constraints
Legal constraints
Macroeconomic constraints
Microeconomic constraints
Social unacceptance
Lack of Political implication


Structural damage
Flooding
Natural hazards
Terrorism activities
Civil work failures
Slope stability (pond)
Pipe breakage


Not enough water recharged
Low quality input water (AQ)
Water scarcity (NE)
Clogging (CL)
Sanitari/biological restrict.
Physical restrict.
Chemical restrict.
River regul.
Climate
WWTP failure
Land use
To be Expanded
Droughts
REP


Clogging
Infiltration rate lower than threshold for a given head
$\frac{1}{t}\int_0^t I(t)dt < I_t$
Physical clogging
Bioclogging
Chemical clogging
Compaction
Generation of gas
Water embling Fine part.?
Source fine particl es
Transport./ Sediment.
Evaporatio n (excess)
Water Mixtures
Microbial Population Catalysis
Physical Motives
Bacterial processes
Inappropia te design
Pipe Filter Fails
Residen ce Time
Depo sition
Eros ion



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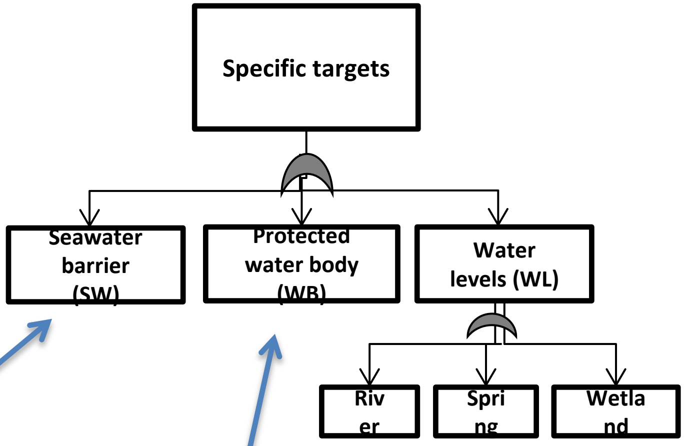

Our friends of Malta

The one we studied before

NC: Nitrogen cycle
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Conclusiones

-Cuanto más complejo el problema, mayor el beneficio
-Risk problems are complex and often controversial. Intending to provide simple results (with just one number) is suicidal, and so a probabilistic approach is a must

- Recognizing the complexity, we use a common tactic in systems engineering, which is breaking the problem into smaller "boxes" that are treated quasi-independently and then combined using Boolean algebra

- This methodology allows us studying very complex and multi-disciplinary problems, by involving experts from various fields

-The more complex the problem, the greater the benefit