

Effect of sedimentation ponds on the mitigation of eutrophication lake: evidence from lake Aydat (France)

Auguste Caen¹

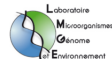
Jean-Denis Mathias¹

Delphine Latour²

¹IRSTEA, LISC

²UBP, LMGE

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The Aydat lake : an eutrophication problem

Eutrophic state



Oligotrophic state



The eutrophication :

An excess of nutrients in lake body water.

The common nutrients are :

- Phosphorus
- Nitrogen

In this study we focus on **Phosphorus** (it is the limiting nutrient in the Aydat lake).

The Aydat lake : an eutrophication problem

Eutrophic state



Oligotrophic state



The eutrophication :

Caused by :

- Agricultural spreading
- Urbanisation
- Pollution

The eutrophication causes a cyano-bacteria proliferation :

It causes :

- Lack of oxygen and biodiversity
- Toxins production

The Aydat lake : an eutrophication problem

Eutrophic state



Oligotrophic state



issues

- health
- ecology
- economy

Objective

How to mitigate eutrophication ?

The Aydat lake : an eutrophication problem

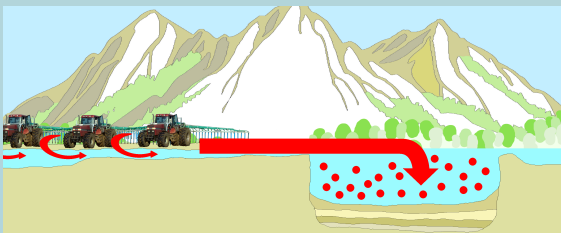
Eutrophic state



Oligotrophic state



Two main methods



The Aydat lake : an eutrophication problem

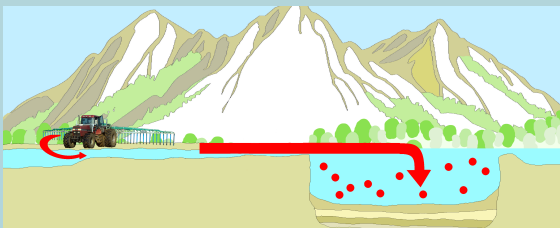
Eutrophic state



Oligotrophic state



First solution : decreasing of input phosphorus



The Aydat lake : an eutrophication problem

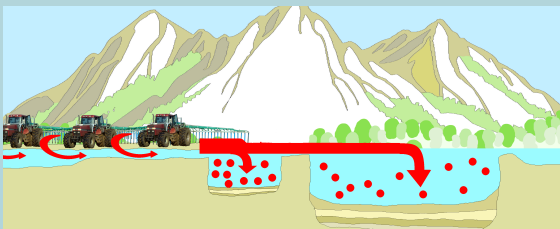
Eutrophic state



Oligotrophic state



Second solution : filtering structures



The Aydat lake : a study case of filtering structures application

In 2013 : design of the wetland

- Two sedimentation ponds.
- One semi-natural area.

Objective :
To filter input nutriments in the lake.

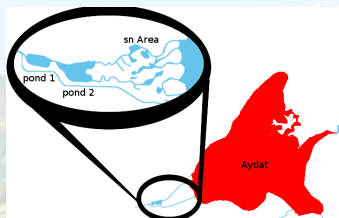


FIGURE – The Aydat lake : two sedimentation ponds and one semi-natural area.

The lake

- Very slow dynamics of phosphorus in water body.



The Aydat lake : a study case of filtering structures application

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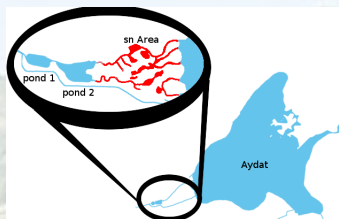


FIGURE – The Aydat lake : two sedimentation ponds and one semi-natural area.

The semi-natural area

- Moderately fast dynamics of phosphorus in water body.

The goal of the semi-natural area
filtering of Nitrogen.



The Aydat lake : a study case of filtering structures application

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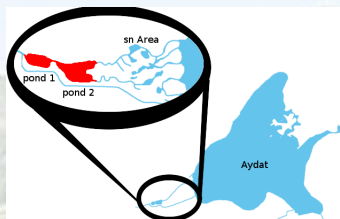


FIGURE – The Aydat lake : two sedimentation ponds and one semi-natural area.

The sedimentation ponds

- Very fast dynamics of phosphorus in water body.
- Very slow dynamics of sediment filling.



The Aydat lake : a study case of filtering structures application

Observations :

- An important quantity of phosphorus filtered.
- No significant improvement of the lake water quality.

Questions :

- What is the effective role of the filtering structures on the lake state ?
- What is the low-cost management for the best lake state ?

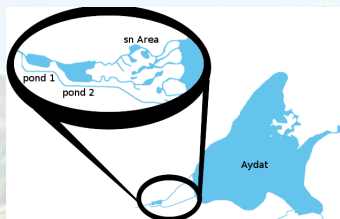


FIGURE – The Aydat lake : two sedimentation ponds and one semi-natural area.

The Aydat lake : a study case of filtering structures application

Questions :

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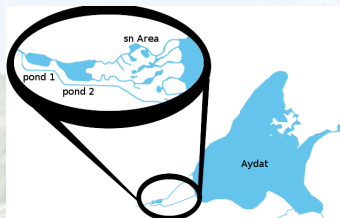


FIGURE – The Aydat lake : two sedimentation ponds and one semi-natural area.

Analysis difficulties

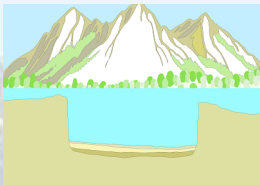
- data hard to access
- complex parameterization

A mathematical model to answer these questions

In order to predict general patterns of phosphorus evolution, and estimate the current state :

We need to model the phosphorus evolution in the Aydat system.

Carpenter et al. (1999) : a dynamical model of lake phosphorus



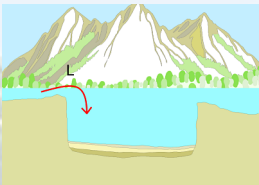
The Carpenter model :

$$\frac{dP(t)}{dt} =$$

- $\frac{dP(t)}{dt}$: Phosphorus dynamics



Carpenter et al. (1999) : a dynamical model of lake phosphorus



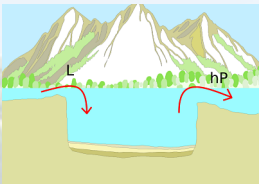
The Carpenter model :

$$\frac{dP(t)}{dt} = L(t)$$

- $\frac{dP(t)}{dt}$: Phosphorus dynamics
- $L(t)$: Phosphorus input rate



Carpenter et al. (1999) : a dynamical model of lake phosphorus



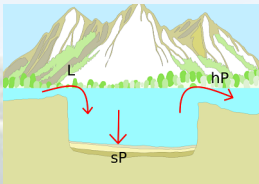
The Carpenter model :

$$\frac{dP(t)}{dt} = L(t) - hP(t)$$

- $\frac{dP(t)}{dt}$: Phosphorus dynamics
- $L(t)$: Phosphorus input rate
- $hP(t)$: Phosphorus output rate



Carpenter et al. (1999) : a dynamical model of lake phosphorus



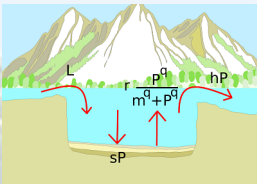
The Carpenter model :

$$\frac{dP(t)}{dt} = L(t) - hP(t) - sP(t)$$

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- $hP(t)$: Phosphorus output rate
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Carpenter et al. (1999) : a dynamical model of lake phosphorus



The Carpenter model :

$$\frac{dP(t)}{dt} = L - hP(t) - sP(t) + r \frac{P(t)^q}{m^q + P(t)^q}$$

- $\frac{dP(t)}{dt}$: Phosphorus dynamics
- $L(t)$: Phosphorus input rate
- $hP(t)$: Phosphorus output rate
- $sP(t)$: Phosphorus sedimentation rate
- $r \frac{P(t)^q}{m^q + P(t)^q}$: Phosphorus recycling rate

The states of lake (OECD standards)

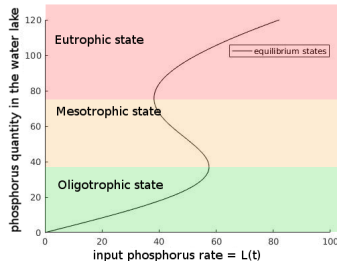
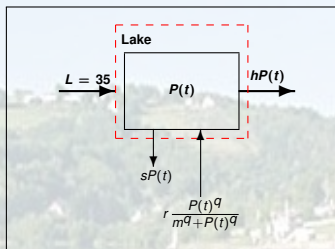


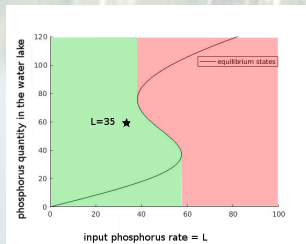
FIGURE – Carpenter model : states of lake.

Lake behaviour according to the Carpenter model

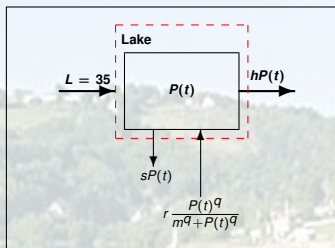


With a fixed input value :

If the initial state of the lake is in the **green zone**, the final state will be **oligotrophic**.

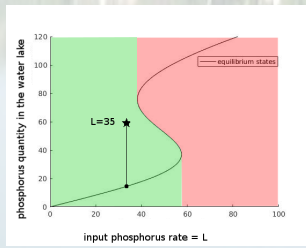


Lake behaviour according to the Carpenter model

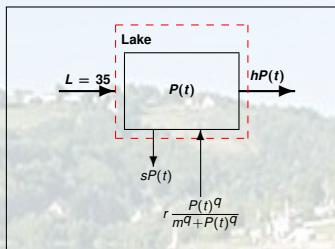


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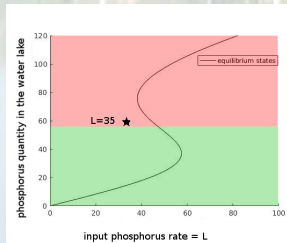


Lake behaviour according to the Carpenter model

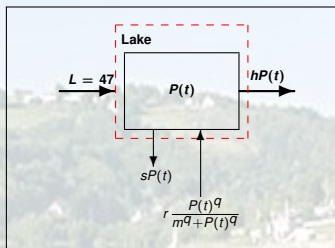


With a immediate change in the input rate towards a fixed value (here $L = 47$) :

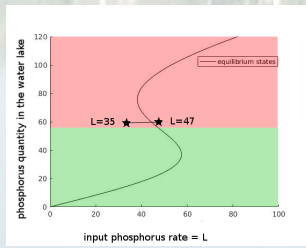
From any initial state in the red zone ...



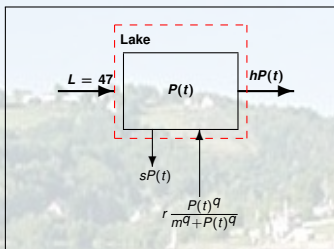
Lake behaviour according to the Carpenter model



For a immediate change in the input rate towards a fixed value (here $L = 47$) :
 ... first there is an immediate change in the input rate towards $L = 47$...

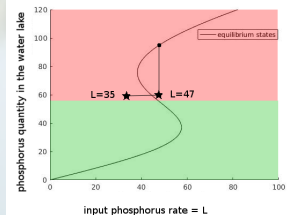


Lake behaviour according to the Carpenter model



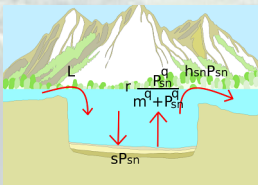
For a immediate change in the input rate towards a fixed value (here $L = 47$) :

... after the lake converges. The final state is **eutrophic**.



A dynamical model of semi-natural area

Adaptation of the Carpenter model



Qualitative behaviour

- No filter effect on the input phosphorus
- Stable depth
- Slow dynamics
- A negligible recycling rate

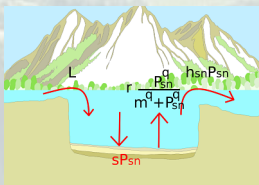
The semi-natural area model :

$$\frac{dP_{sn}(t)}{dt} = L - h_{sn}P_{sn}(t) - sP_{sn}(t) + r \frac{P_{sn}(t)^q}{m^q + P_{sn}(t)^q}$$



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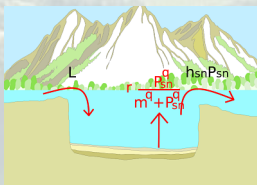
The semi-natural area model :

$$\frac{dP_{sn}(t)}{dt} = L - h_{sn}P_{sn}(t) - SP_{sn}(t) + r \frac{P_{sn}(t)^q}{m^q + P_{sn}(t)^q}$$



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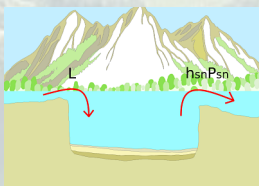
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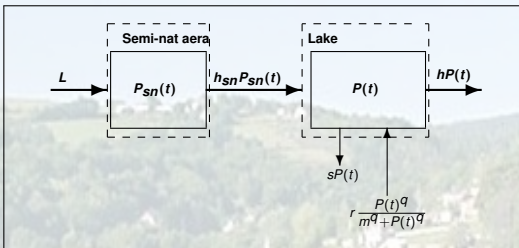
⇒ ***a priori* no impact on lake's state.**

The semi-natural area model :

$$\frac{dP_{sn}(t)}{dt} = L - h_{sn}P_{sn}(t)$$



Lake behaviour with semi-natural area upstream.



quelques modeles calibrés : \Rightarrow bonne voie pour hypotheses de modeles.

The speed of semi-natural area convergence depends on the h_{sn} value :

For the dynamical model :

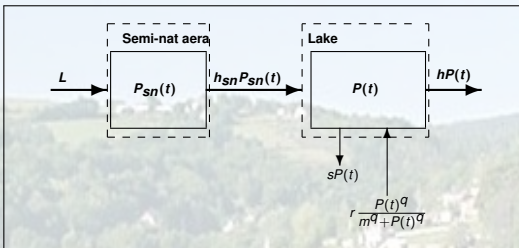
$$\frac{dP_{sn}(t)}{dt} = L - h_{sn}P_{sn}(t)$$

the solution is :

$$P_{sn}(t) = \frac{L}{h_{sn}}(1 - e^{-th_{sn}}) + P_{sn}(0)e^{-th_{sn}}$$



Lake behaviour with semi-natural area upstream.



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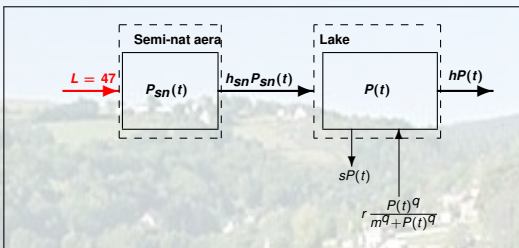
the solution is :

$$P_{sn}(t) = \frac{L}{h_{sn}}(1 - e^{-th_{sn}}) + P_{sn}(0)e^{-th_{sn}}$$

Therefore :

The convergence speed of the semi-natural area depends only on the h_{sn} value. **The greater the h_{sn} value is, the faster the semi-natural area convergence is.**

Lake behaviour with semi-natural area upstream.



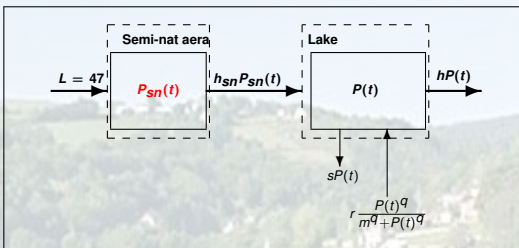
quelques modeles calibrés : \Rightarrow bonne voie pour hypotheses de modeles.

Behaviours of the lake according to the h_{sn} value :

With a fixed value of the **input phosphorus in the system** "semi-natural area + lake" (here $L = 47$),...



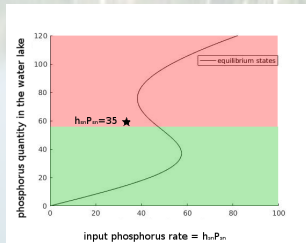
Lake behaviour with semi-natural area upstream.



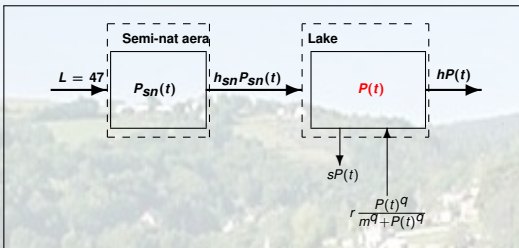
quelques modeles calibrés : \Rightarrow bonne voie pour hypotheses de modeles.

Behaviours of the lake according to the h_{Sn} value :

... , with a fixed initial value of the "output phosphorus" from the semi-natural area, which depends on the **phosphorus quantity in the semi-natural area**...



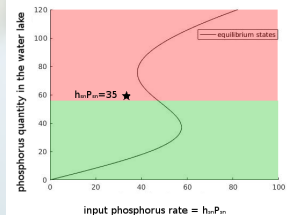
Lake behaviour with semi-natural area upstream.



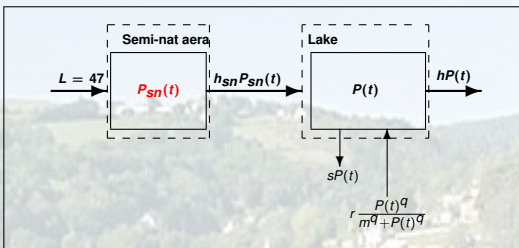
quelques modeles calibrés : \Rightarrow bonne voie pour hypotheses de modeles.

Behaviours of the lake according to the h_{SN} value :

... and with a fixed initial value of the **phosphorus in the lake water body**, we study the possible trajectory of the phosphorus in the lake water body.



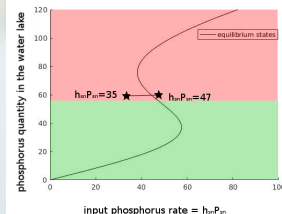
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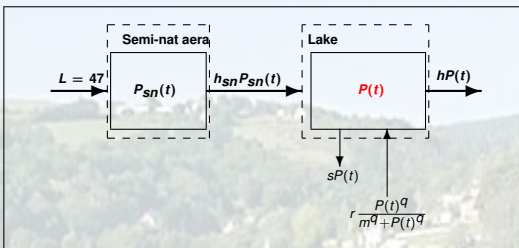
quelques modeles calibrés : \Rightarrow bonne voie pour hypotheses de modeles.

When h_{SN} very great :

The convergence of the semi-natural area is immediate...



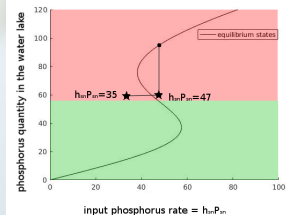
Lake behaviour with semi-natural area upstream.



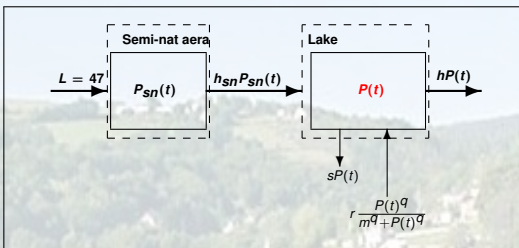
quelques modeles calibrés : \Rightarrow bonne voie pour hypotheses de modeles.

When h_{SN} very great :

...after, the lake converges.



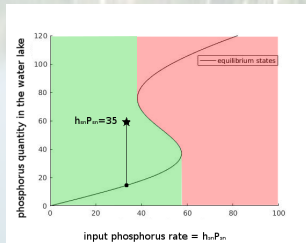
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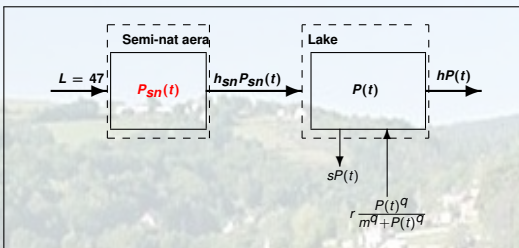
quelques modeles calibrés : \Rightarrow bonne voie pour hypotheses de modeles.

When h_{SN} very small :

First the **lake** converges...

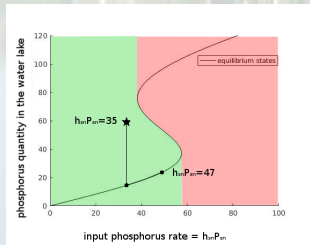


Lake behaviour with semi-natural area upstream.

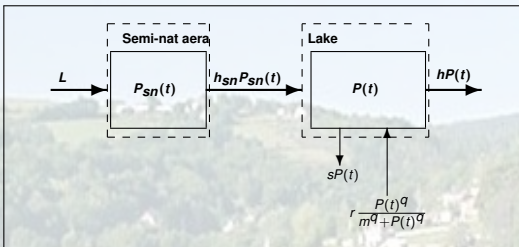


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When h_{sn} very small :
 ...after, the **semi-natural area** converges.



Lake behaviour with semi-natural area upstream.

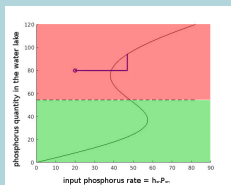
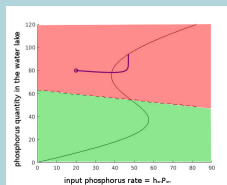
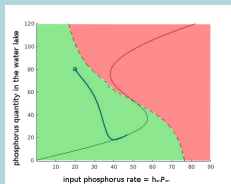
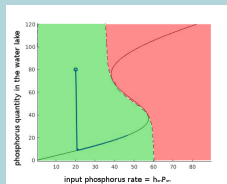


quelques modeles calibrés : \Rightarrow bonne voie pour hypotheses de modeles.

The semi-natural effect :

With the same initial values, according to the h_{sn} value, the final state can be **eutrophic** or **oligotrophic**.



Semi-natural area : the effect on the lake according to the h_{SN} valueEvolution of the "green" and "red" zones according to the h_{SN} value, with $L = 47$. $h_{SN} = 500$  $h_{SN} = 5$  $h_{SN} = 0.3$  $h_{SN} = 0.01$ 

Semi-natural area : the effect on the lake

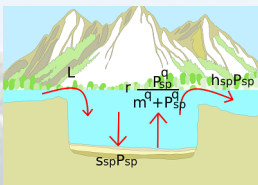
The semi-natural area :

The semi-natural area increases the "lake inertia" according to the h_{SN} value. With the semi-natural area, the **resilience** is increased, for better or for worse.



A dynamical model of sedimentation pond

Adaptation of the Carpenter model



The sedimentation pond model :

$$\frac{dP_{sp}(t)}{dt} = L - h_{sp}(t)P_{sp}(t) - s_{sp}(t)P_{sp}(t) + r \frac{P_{sp}(t)^q}{m^q + P_{sp}(t)^q}$$

with

$$\text{for } t = 0 : h_{sp}(0) = h_0 \text{ and } s_{sp}(0) = s_0$$

$$\text{for } t = \infty : h_{sp}(\infty) = h_{max} > h_0 \text{ and } s_{sp}(\infty) = 0$$

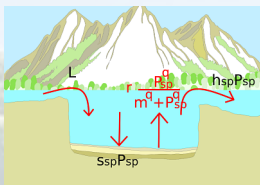
Qualitative behaviour

- A filter effect
- A decreasing pond depth
- Fast dynamics
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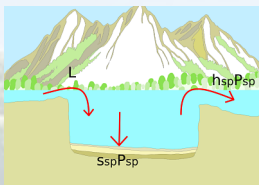
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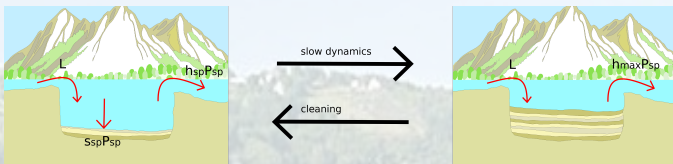
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- A decreasing pond depth
- Fast dynamics
- A negligible recycling rate

A dynamical model of sedimentation pond

Adaptation of the Carpenter model



The semi-natural area model :

$$\frac{dP_{sp}(t)}{dt} = L - h_{sp}(t)P_{sp}(t) - s_{sp}(t)P_{sp}(t)$$

with

$$\text{for } t = 0 : h_{sp}(0) = h_0 \text{ and } s_{sp}(0) = s_0$$

$$\text{for } t = \infty : h_{sp}(0) = h_{max} > h_0 \text{ and } s_{sp}(\infty) = 0$$

Cleaning of the pond

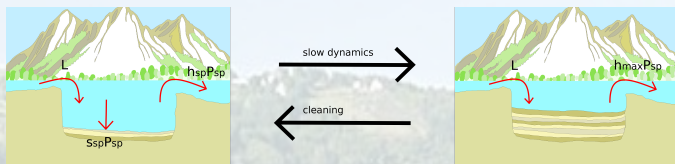
After each cleaning, the parameters are reset :

$$h_{sp}(t) = h_0$$

$$s_{sp}(t) = s_0$$

A dynamical model of sedimentation pond

Adaptation of the Carpenter model



The semi-natural area model :

$$\frac{dP_{sp}(t)}{dt} = L - h_{sp}(t)P_{sp}(t) - s_{sp}(t)P_{sp}(t)$$

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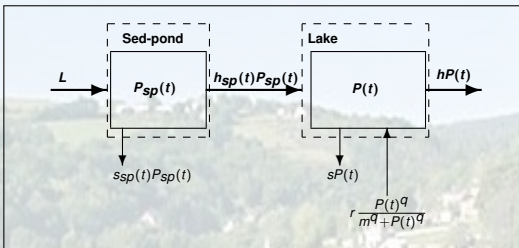
$$\text{for } t = \infty : h_{sp}(\infty) = h_{max} > h_0 \text{ and } s_{sp}(\infty) = 0$$

Evolution of the h_{sp} and s_{sp}

According to the available data from the Aydat lake, the evolution of h_{sp} and s_{sp} is linear.



Lake behaviour with sedimentation pond upstream.

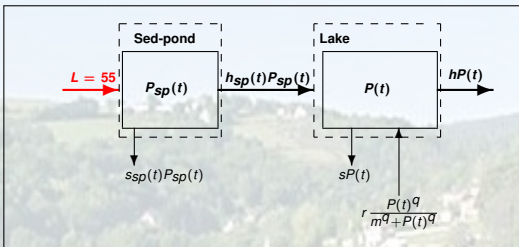


The speed of sedimentation pond convergence :

For all t value, the scale of $h_{sp}(t)$ is between 100 and 1000. So the convergence of the sedimentation pond is very fast.



Lake behaviour with sedimentation pond upstream.

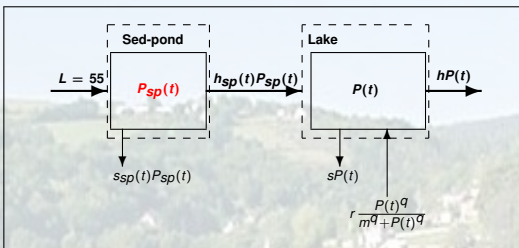


behaviours of the sedimentation pond
without cleaning :

With a fixed value of the **input phosphorus in the system** "sedimentation pond + lake" (here $L = 55$),...



Lake behaviour with sedimentation pond upstream.

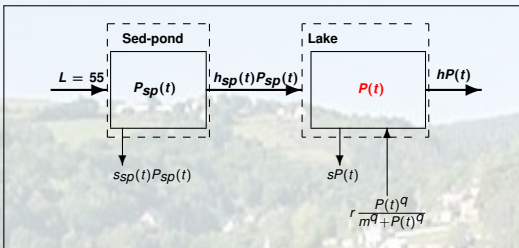


behaviours of the sedimentation pond
without cleaning :

... , with an fixed initial value of the
phosphorus quantity of the sedimentation
pond, with a initial s_{sp} value not null,...

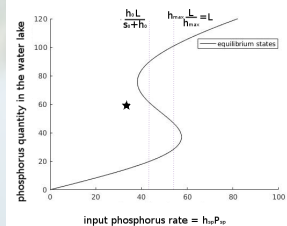


Lake behaviour with sedimentation pond upstream.

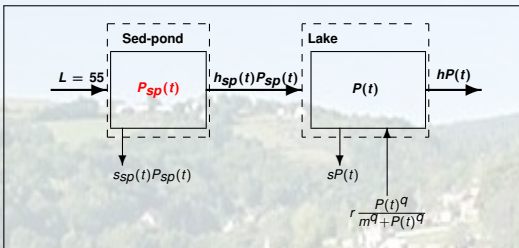


behaviours of the sedimentation pond
without cleaning :

... and with a fixed initial values of the
phosphorus in the lake water body, we
study the possible trajectory of the
phosphorus in the lake water body.

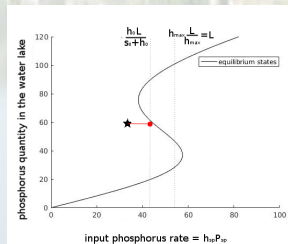


Lake behaviour with sedimentation pond upstream.

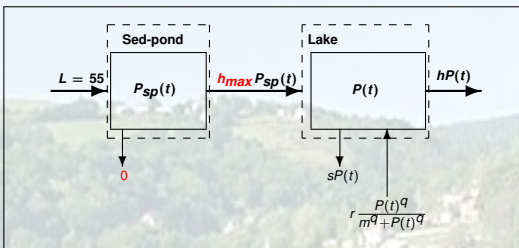


behaviours of the sedimentation pond
without cleaning :

The convergence of the **sedimentation pond** is immediate to the $\frac{L}{s_{sp} + h_{sp}}$ value. We have a filter effect.

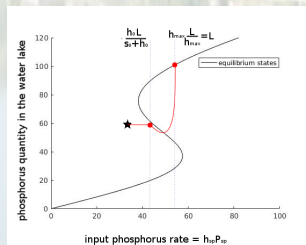


Lake behaviour with sedimentation pond upstream.

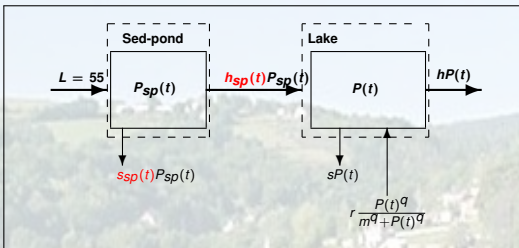


behaviours of the sedimentation pond without cleaning :

After an enough time, the parameters s_{sp} and h_{sp} converge to 0 and h_{max} . Therefore the filter effect is null, the final state is **eutrophic**.

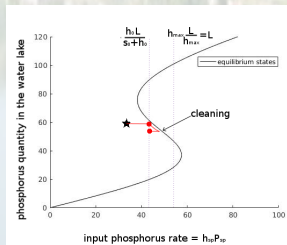


Lake behaviour with sedimentation pond upstream.

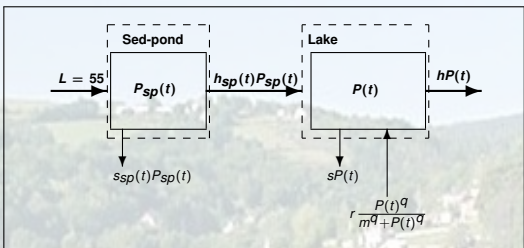


With a appropriate cleaning of the sedimentation pond :

The cleaning reset the h_{sp} and s_{sp} parameters.

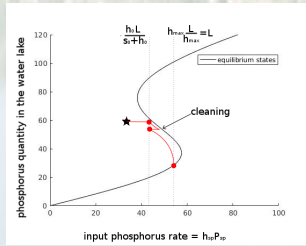


Lake behaviour with sedimentation pond upstream.

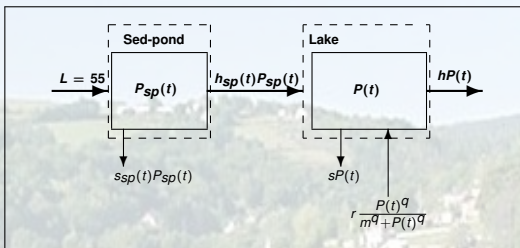


With a appropriate cleaning of the sedimentation pond :

The final state is **oligotrophic**.



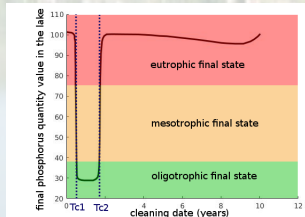
Lake behaviour with sedimentation pond upstream.



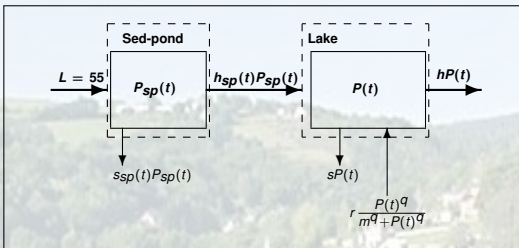
Critical times :

There is a time T_{c1} , after which the cleaning is inefficient.

There is a time T_{c2} , before which the cleaning is inefficient.



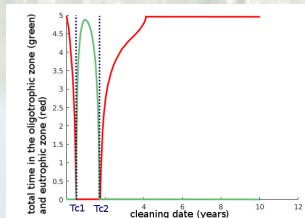
Lake behaviour with sedimentation pond upstream.



Critical times :

There is a time T_{c1} , after which the cleaning is inefficient.

There is a time T_{c2} , before which the cleaning is inefficient.



Sedimentation pond : the effect on the lake

The sedimentation pond

With the appropriate management, the filter effect allows us to maintain the lake in the acceptable state.



Take home message

Initial tools :

Carpenter model

A dynamical model of phosphorus in lake water body.

Qualitative behaviours

derived from the little available data.



Dynamical models :

Semi-natural area model

A dynamical model of semi-natural areas without sedimentation rate.

Sedimentation pond model

A dynamical model of sedimentation ponds with filling and cleaning of sediment.



Effects on lake :

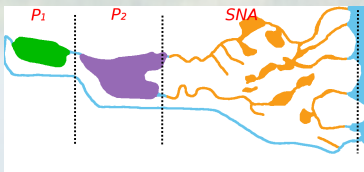
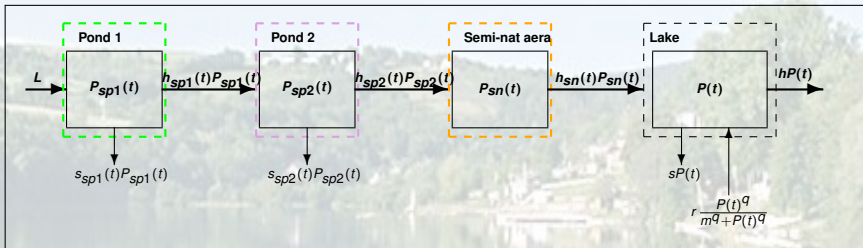
Buffer effect

According to the semi-natural parametrization, it increases the lake inertia.

Fillter effect

According to the cleaning management, the final lake state can be **eutrophic** or **oligotrophic**.

Aydat : the adapted model



To be continued

Mathematical issues

An acceptable final lake state

From any state, we want to know – if it exists – the management of the Aydat system, for which the lake remains or becomes oligotrophic.



Viability Theory

Low cost management

Any management has a cost. We want to know the management with the lowest cost.



Optimal Control

Stable management

We want management with a strong resistance to shocks (increasing of input phosphorus).



Stochastic Modelling



thanks for your attention

