Landscape evolution models and stream piracies phenomena

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Motivations and results:

On earth, landscape morphology is mainly controlled by rivers evolutions and their interactions with hillslopes. But hydrographic network may be re-organized by stream capture and modify deeply the relief. This transition may be induced by several mechanisms (diversion, headward erosion, avulsion, or subterranean filling up). It has interested numerous scientists since a long time (Davis 1895, Blache 1943, Lesson-Quinif 2001 & Le Roux-Harmand 1997-2009…). Here we focus on stream piracies by headward erosion, when an actively eroding low level stream (called the captor) encroaches on the drainage of a nearby stream flowing at a higher level (called the diverter) and diverts part of the water of the higher stream.

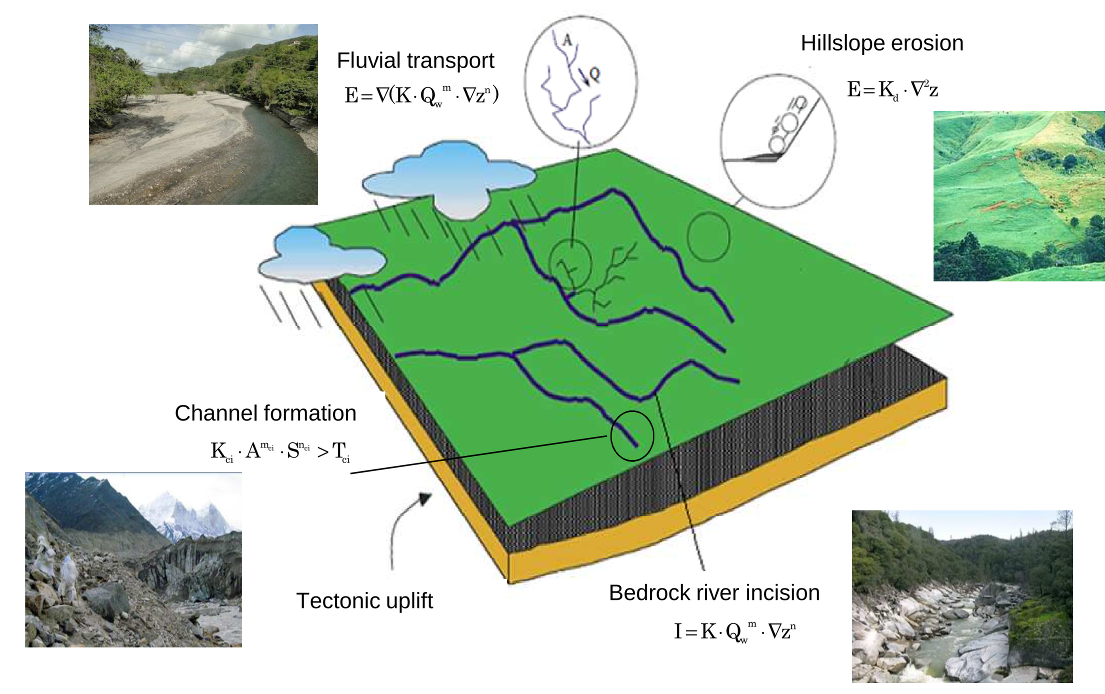
During the last decades, several landscapes evolution models (LEM) have been developed to quantify the topography evolution with diffusion and advection equations. These models play an important role in sharpening our thinking to better understand the interaction between landscape evolution processes. LEM were developed basically to simulate erosion, tectonic and climate at different scales of time and space. But, these models were not designed to describe specific mechanisms as the stream capture. It's one of the aims of this work to evaluate LEM for this purpose.

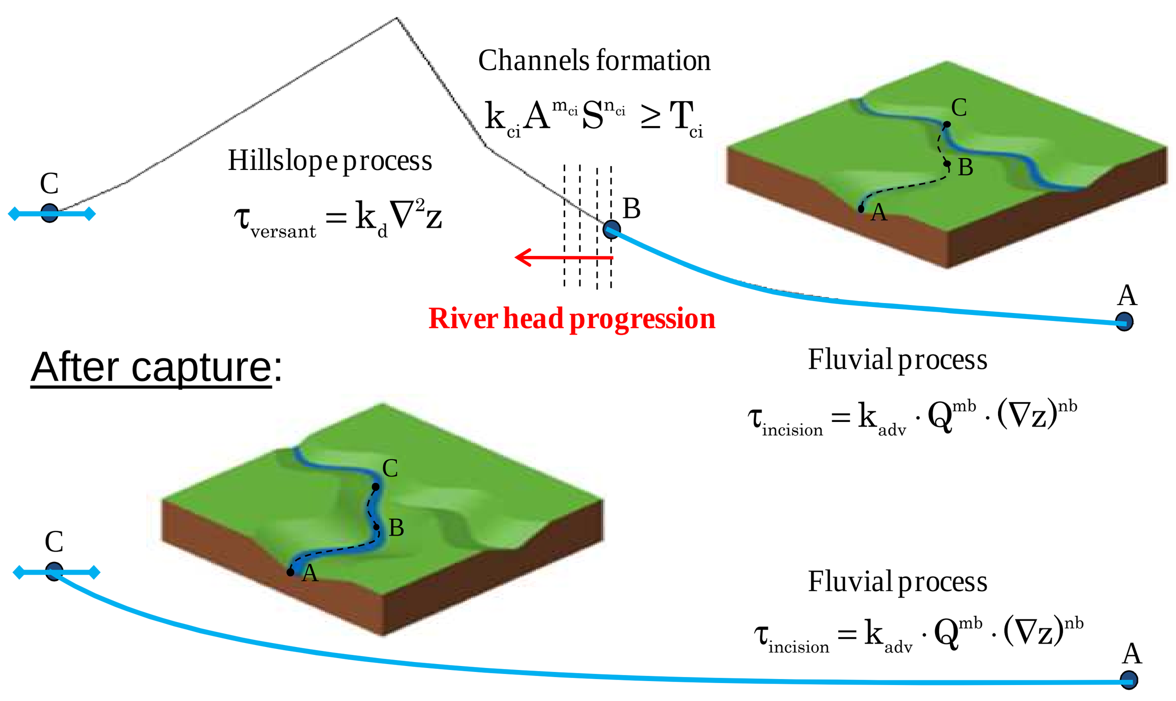
In this presentation, we develop a 1D model based on LEM equations to investigate the stream piracy by headward erosion responses to climatic or tectonic changes. This model incorporates the most common equations used in quantitative geomorphology; diffusion in hillslope, advection in river (detachment-limited mode) and an inequality based on slope and drainage area for the limit between these two domains (Montgomery and Dietrich, 1988).

First, a predictive study with an improved version of GOLEM (software developed by Tucker & Slingerland in 1994) on the Meuse basin shows that several piracies may probably occur in the future. A comparison with the 1D model gives similar results. Then, complex simulations are realized in the Meuse basin taking into account: Meuse deposition tendency and simple representation of Karst process etc.

Finally, we present a new approach for parameters calibration based on recorded terraces. The results gives a remarkable differences between this approach and the classical methods (Slope-Area relationship, etc.).

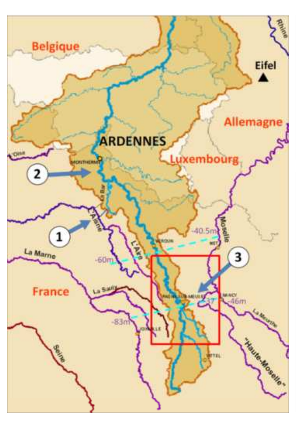
Stream piracies and landscape evolution models:





Experimentation on the Meuse basin :

Geomorphologic setting and background:

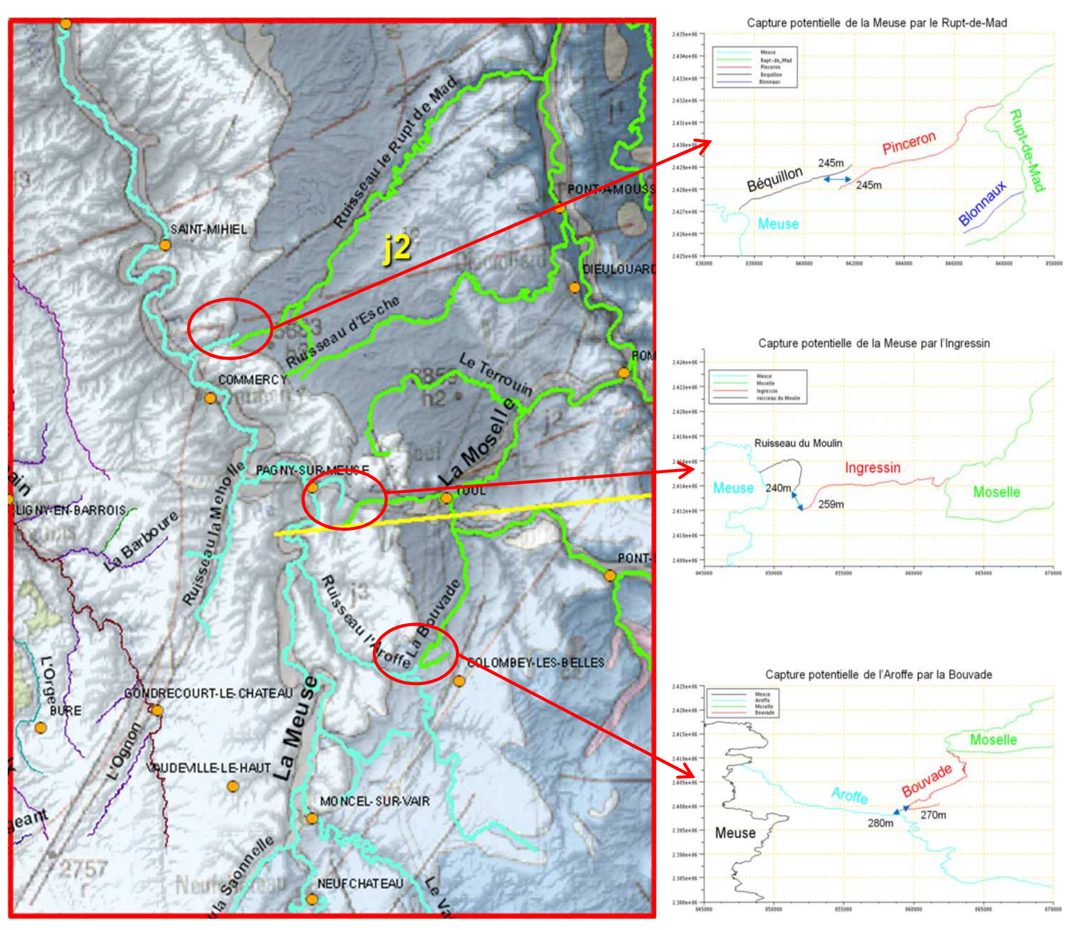


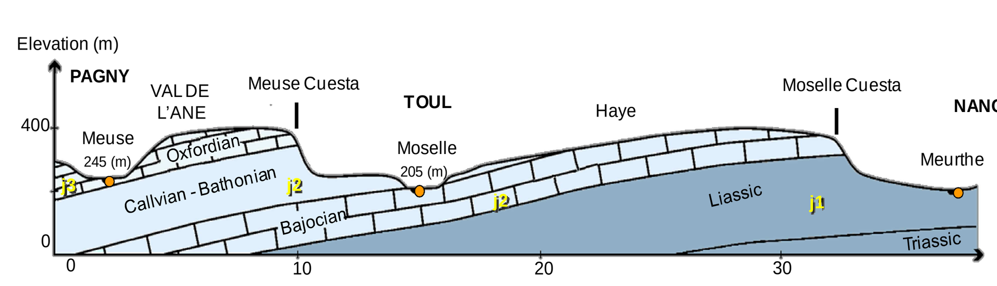
The MEUSE river
20km narrow basin (cuestas)
valley ~+50m relative elevation
10 to 25m deposit

The last My
erosion stopped at Monthermé
4 recorded captures:
Aisne, Aire ~ -0.9,-0.4Ma
Gespunsart ~ -0.9Ma
Haute-Moselle ~ -0.3Ma

Captures processes ?
Piracy (Terrouin) Avulsion, Karst
morphology & lithology control : cuesta/depression
limestone/clay

Next Capture ?
Where & when ? What Impact on the local topography?
topography analysis gives limited results1





Simplified cross section through the Meuse and Moselle cuestas

Reminder of previous results and limitations (EGU 2012):

A sensitivity analysis with GOLEM on the Meuse basin is realized to quantify the impact of the parameters (Kb, mb, nb, Kd, Kci, mci, nci and Tci) variation on the potential future piracies on this region. The variation range of each parameters is based on the published papers in this domain. For this, more than **5000 simulations** were executed.

All simulations show that piracies occurs **always between the same rivers** in 4 different locations:

1. Rupt-de-Mad/Meuse
2. Ingressin/Meuse
3. Bouvade/Aroffe
4. Meholle/Ornain

Careful analysis of results shows that the piracies can be regrouped according to 3 scenarios depending on model parameters variations:

Scenario 1: capture of 1, 2, 3 and 4
Scenario 2: capture of 1 and 4
Scenario 3: capture of 1, 3 and 4

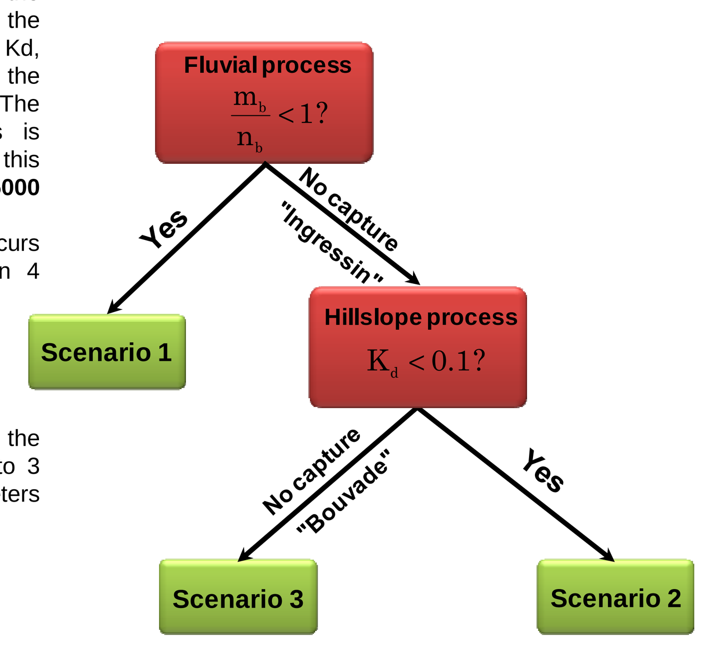
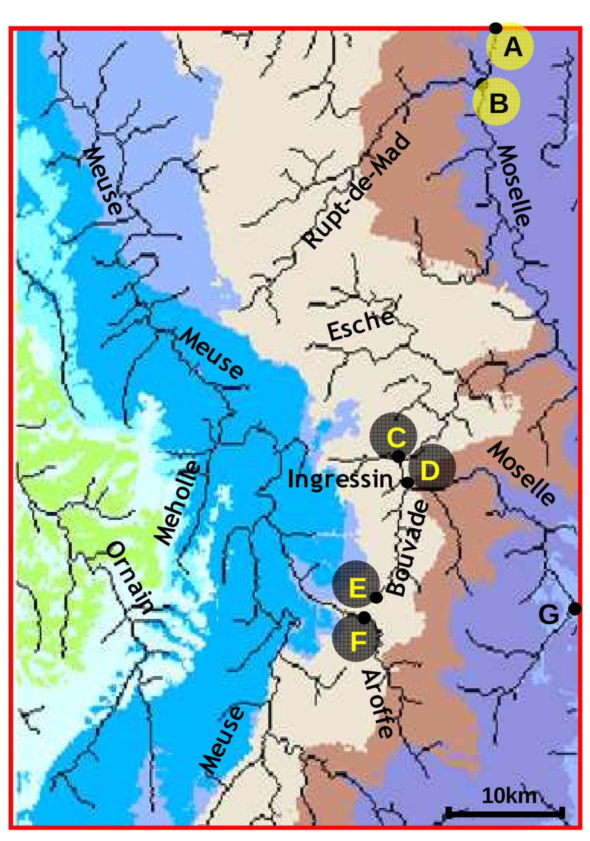
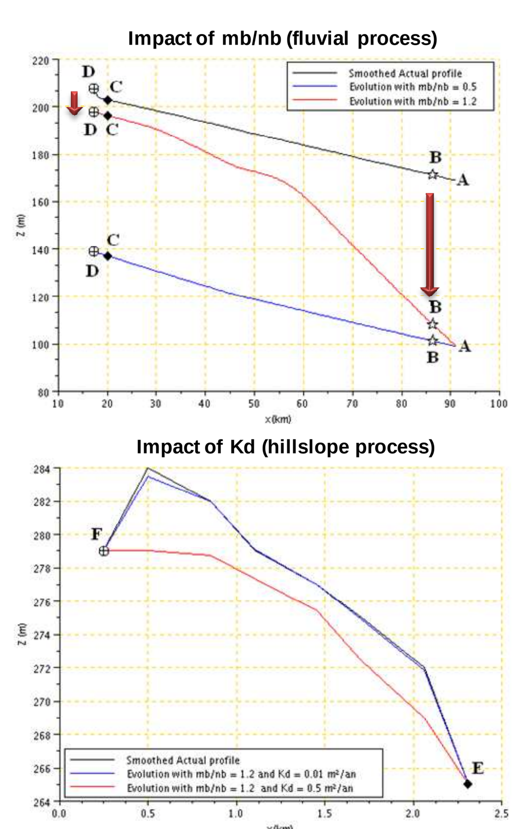


Illustration of scenarios:





The increase of **mb/nb** (fluvial process) promotes the upstream piracies. In our case, if **mb/nb>1** the piracy of the Meuse by the Ingressin does not occur.

The increase of **Kd** (hillslope process) may promote piracies in regions with weak relative hillslope elevation. In our case, if **Kd>0.5m²/y** the Aroffe is captured by the Bouvade independently of the fluvial process.

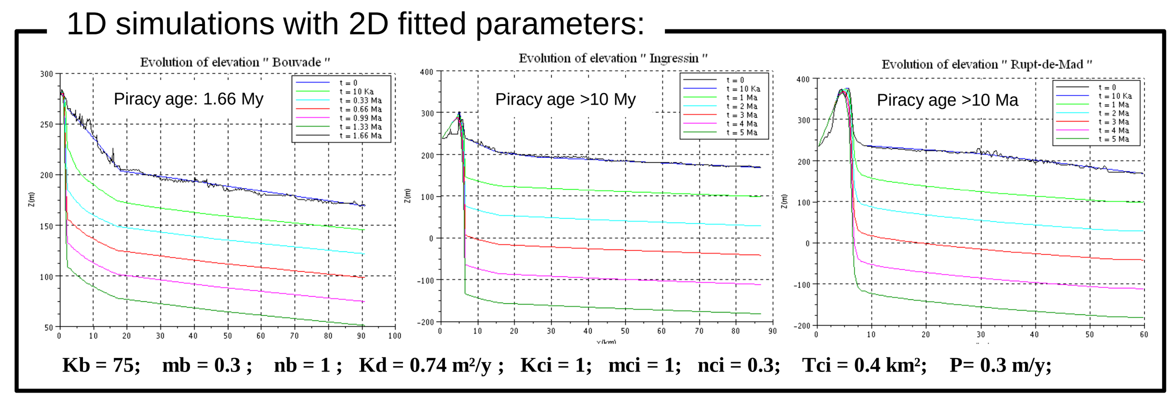
Estimation of piracies ages and parameters calibration

First, GOLEM is calibrated according to most cited methods in literature (*Odoni, 2007*). The simulation shows that the piracies ages are very important (more then 10 My). More complex simulations (Meuse filling, Karst process, etc.) are then realized with a developed 1D model.

The rate of the Meuse avulsion was fixed to 10m/My (ref).

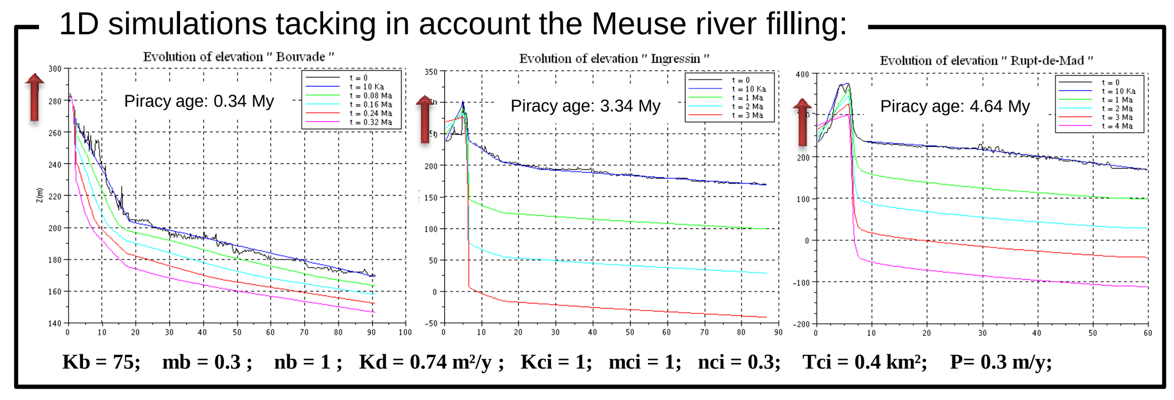
The Karst process had been considered by estimating the ratio between the water flux and drainage area (P=Q/A) for all rivers. Q is based on the hydrologic stations measurement and A is estimated by DEM analysis.

1D simulations with 2D fitted parameters:



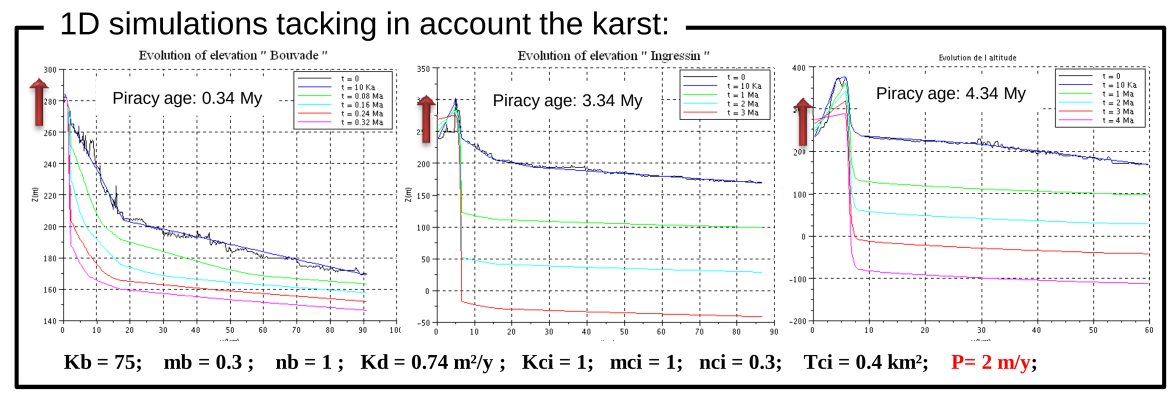
Kb = 75; mb = 0.3 ; nb = 1 ; Kd = 0.74 m²/y ; Kci = 1; mci = 1; nci = 0.3; Tci = 0.4 km²; P= 0.3 m/y;

1D simulations tacking in account the Meuse river filling:



Kb = 75; mb = 0.3 ; nb = 1 ; Kd = 0.74 m²/y ; Kci = 1; mci = 1; nci = 0.3; Tci = 0.4 km²; P= 0.3 m/y;

1D simulations tacking in account the karst:



Kb = 75; mb = 0.3 ; nb = 1 ; Kd = 0.74 m²/y ; Kci = 1; mci = 1; nci = 0.3; Tci = 0.4 km²; P= 2 m/y;

Conclusions and limitations:

The fitted parameters stay in the range of variations given in the literature (*Odoni 2007*, etc.). In the other hand, the piracies ages are not in agreement with the geologists predictions (*Le Roux & Harmand, 1997*), when they think that a capture by the Ingressin will occurs in less than 100Ky.

Considering the Meuse avulsion, reduce significantly the piracies ages, but they remain important (more than 3 My for the Ingressin and the Rupt-de-Mad).

The way the Karst process is simulated (impact only the water flux Q) modify the rivers profiles but the ages remain unchanged.

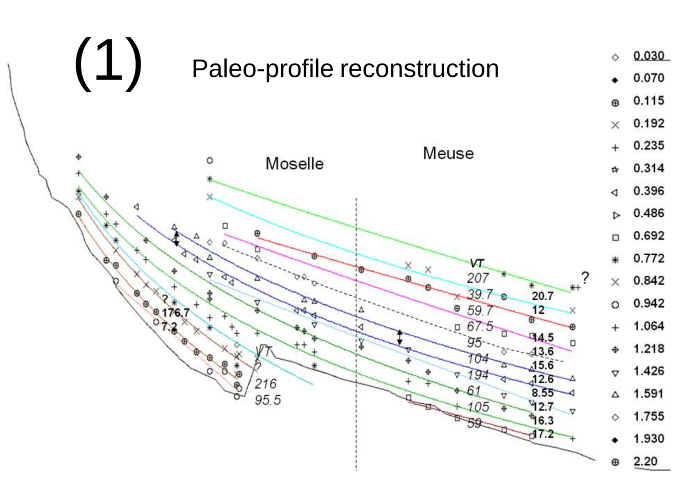
New approach for parameters calibration:

Calibration approach :

This approach is based on the exploitation of the recorded data in the rivers terraces. For this, 3 steps are required:

1. The reconstruction of the Paleo-rivers. We fit a curve by using an optimization method(MLS, etc.).
2. Determination of an Upper and Lower bound for the Paleo-topography.
3. Find by inverse method a set of parameters leading the reconstructed Paleo-profiles (Upper and Lower bounds) to the actual profile.

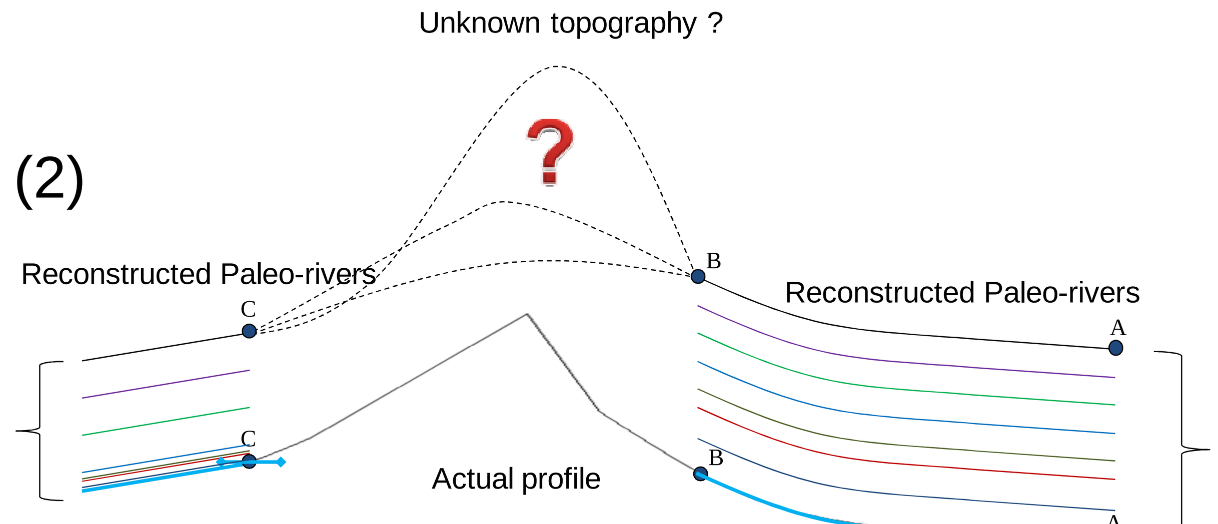
(1) Paleo-profile reconstruction



(Théobald & Gardet, 1932 ; Pissart & Harmand, 1997)

Unknown topography ?

(2)



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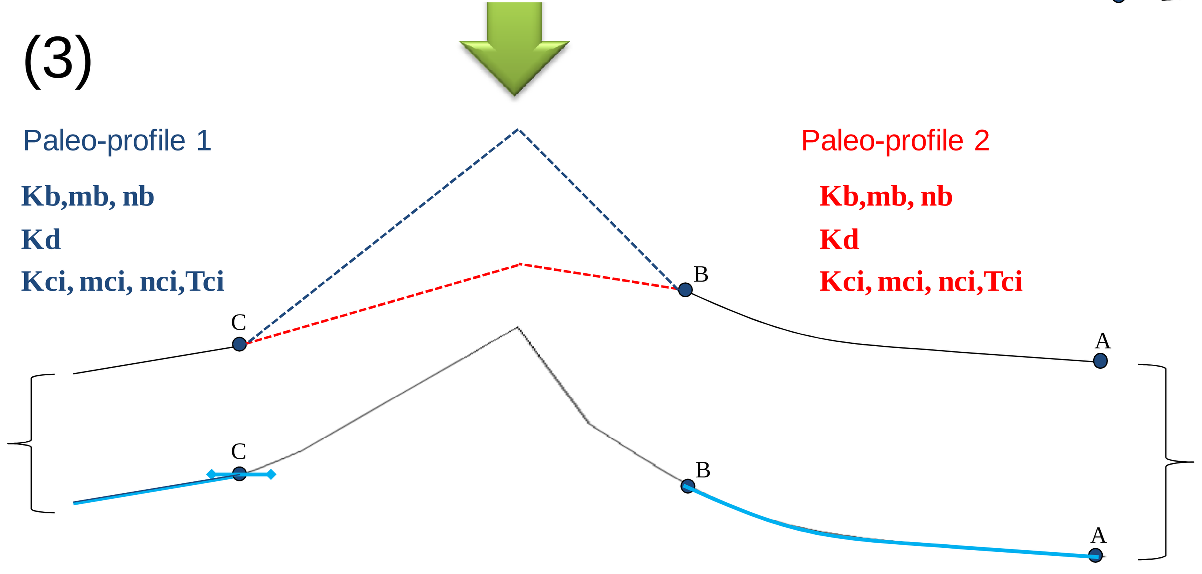
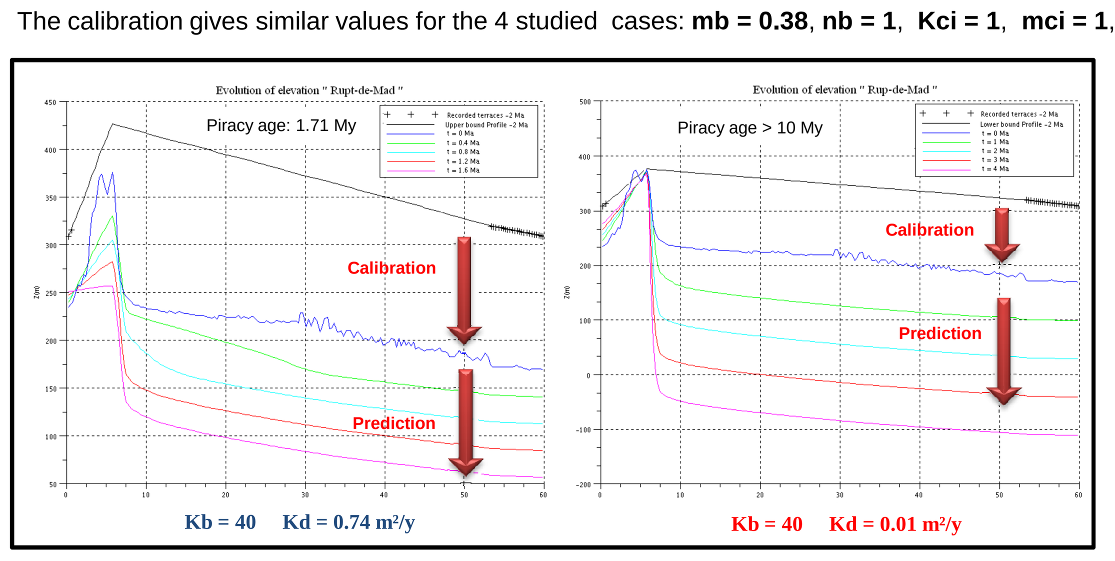
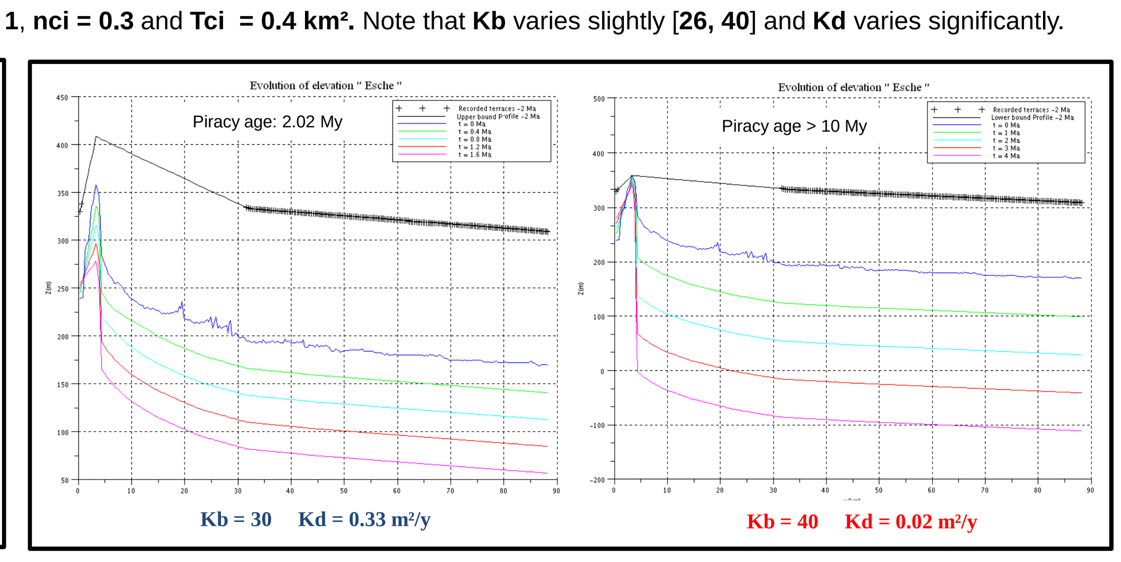
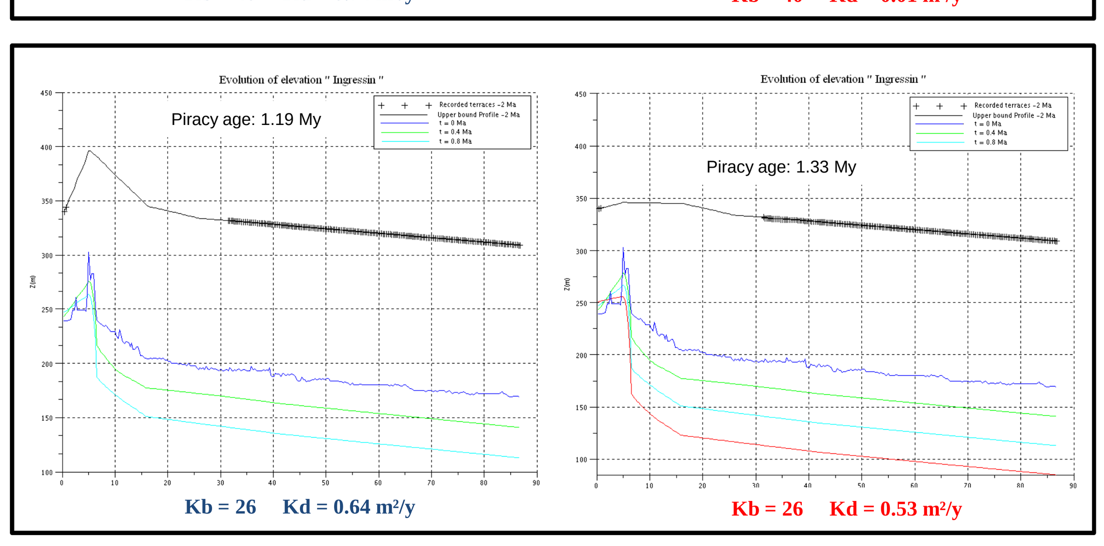


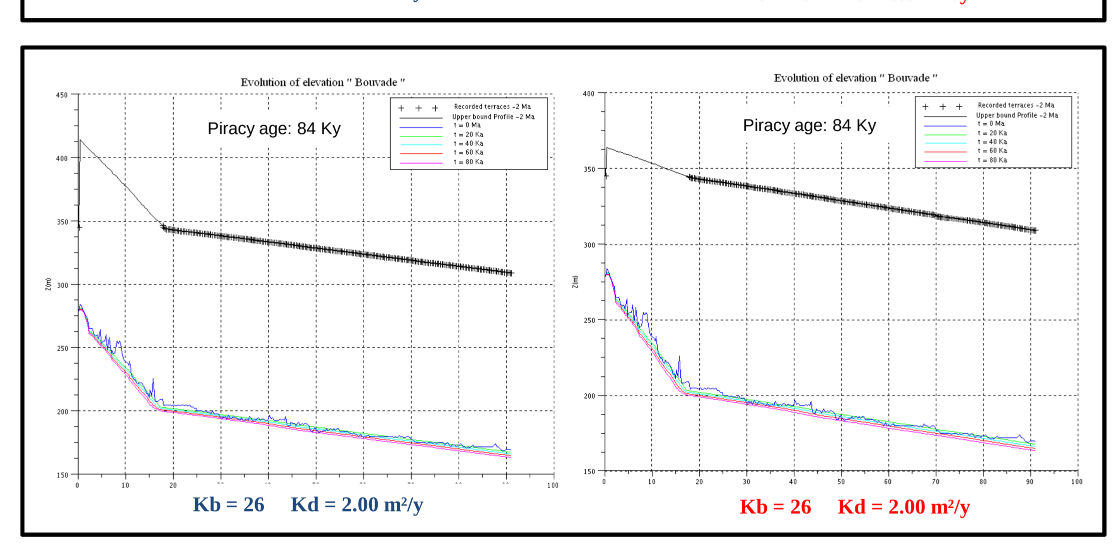
Application on the Meuse basin rivers:

The calibration gives similar values for the 4 studied cases: **mb = 0.38**, **nb = 1**, **Kci = 1**, **mci = 1**, **nci = 0.3** and **Tci = 0.4 km²**. Note that **Kb** varies slightly [**26, 40**] and **Kd** varies significantly.









Conclusions further works:

Meuse basin:

- The sensitivity analysis shows that the piracies are always at the same place at 4 different locations. The impact of parameters variation on piracies order is then quantified.
- The new calibration approach gives more realistic piracies ages according to the geologists estimations than classical approaches (*Odoni 2007*).
- The high value of diffusivity (2m²/y) in the Bouvade/Aroffe profile may be due to the local erosion (several studies show a high karst activity between Aroffe and Bouvade).
- In the Ingressin it's particular, because the valley hillslope is a old valley.
- The obtained results are based on several hypothesis (boundary limits, climate fluctuations, lithology, karst, Meuse avulsion, etc.).

Modelling:

- The models we have explored in this presentation provide a framework for understanding the impact of parameters variation on the stream piracies.
- The 1D calibration method gives a new vision for apprehending landscape evolution models.
- The 1D approach can be used to explore quickly several possibilities once the piracies are localized.

This research opens a number of opportunities that could be developed:

- The integration of karst processes impact on hillslope process.
- The 1D approach can be used to better understand the past captures. Among other things, the parameters calibration can be achieved by relying on the past piracies.
- The analysis could be extended to other regions, which have the same characteristics as the experienced region (geomorphology, history, etc.).