Stream-piracy impact on the long-term evolution of the Meuse basin. Physical approach "modeling with GOLEM"

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European Geosciences Union
General Assembly 2012
Vienne | Austria | 22 – 27 April 2012

This poster participates in OSP

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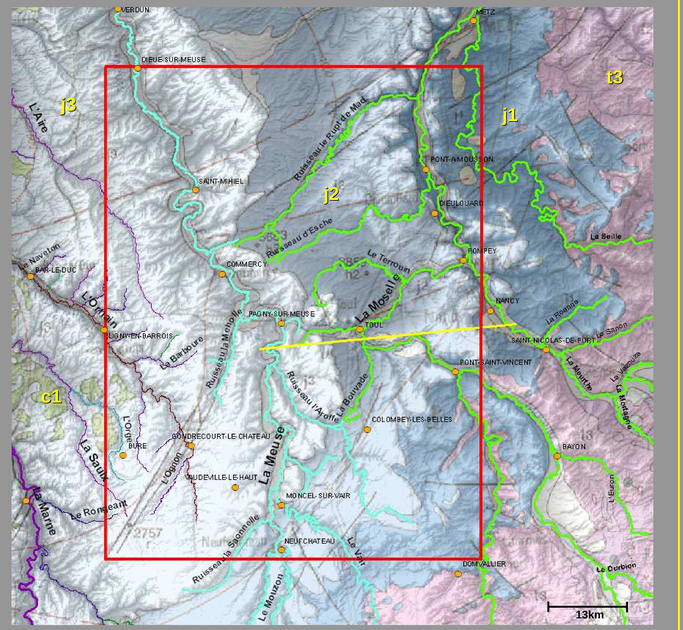
Motivations:

The river Meuse is famous (since Davis 1895), because of all the piracies that happened during the last million years: at the south-east, the well-known capture of the Haute-Moselle by a tributary of the Meurthe near Toul; at the north-west, the capture of the river Aire by the Aisne...

The on-going evolution suggests that similar events can be expected in the long-term future. Where and when next streams piracies could occur, what consequences may be expected?

Our approach is to simulate the dynamic evolution of the landscape with an improved version of GOLEM (Geomorphic / Orogenic Landscape Evolution Model - LEM), a software developed by Tucker & Slingerland in 1994. The LEM characterizes the erosion by incorporating diffusion and advection equations whose parameters must be fixed, according to local conditions.

Geomorphologic settings and background:

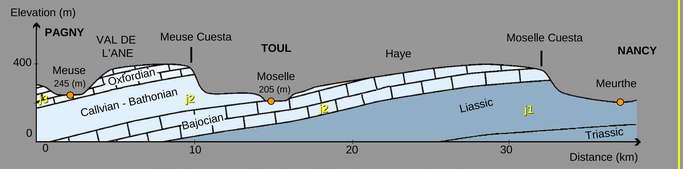


The MEUSE river
20km narrow basin (cuestas)
valley ~+50m relative elevation
10 to 25m deposit

The last My
erosion stopped at Monthermé
4 captures, 3 spots :
1 Aisne, Aire ~ -0.9,-0.4Ma
2 Gespunsart ~ -0.9Ma
3 Haute-Moselle ~ -0.3Ma

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

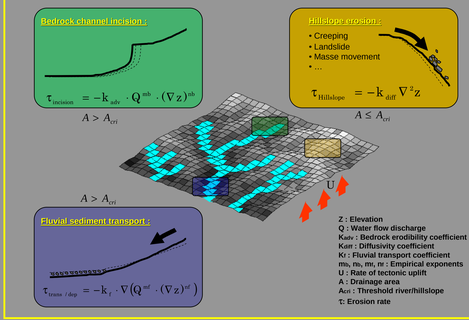
Next Capture ?
Where & when ? Impact ?
topography analysis gives limited results



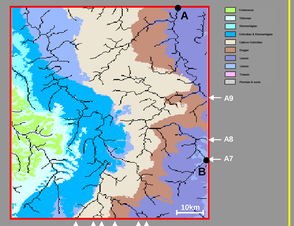
Simplified cross section through the Meuse and Moselle cuestas

- t3 : Upper Triassic
- j1 : Lower Jurassic
- j2 : Middle Jurassic
- j3 : Upper Jurassic
- c1 : Lower Cretaceous

Model and simulation parameters:



Z : Elevation
Q : Water flow discharge
K_{adv} : Bedrock erodibility coefficient
K_{diff} : Diffusivity coefficient
K_f : Fluvial transport coefficient
m_b, m_s, m_f, n_f : Empirical exponents
U : Rate of tectonic uplift
A : Drainage area
A_{cri} : Threshold river/hillslope
τ: Erosion rate



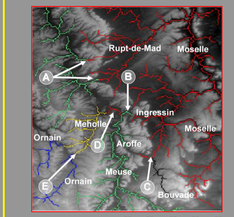
Description	Value
Grid size (cell)	327x245
Cell size (m)	250
Tectonic uplift (m/My)	10
Boundary conditions	NO FLUX
Incision rate A (m/My)	70

A1 :Saonelle A =77km²
A2 : Meuse A =430km²
A3 : Mouzon A=409km²
A4 : Frezelle A =22km²
A5 : Vraine A =92km²
A6 : Vair A =214km²
A7 : Madon A =796km²
A8 : Moselle A =2030km²
A9 : Meurthe A =3059km²

Sensitivity analysis:

1) Erodability coefficient (K_{adv})?

- A_{cri} = 0 km² - K_{diff} = 0 m²/y
- (K_{adv}, m_b, n_b) = (**10**, 0.5, 1)

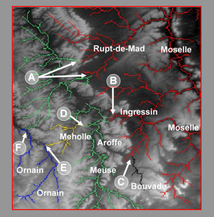


Piracies order : C B D A E

- Piracies location and order are unchanged.
- Age of piracies are proportional to K_{adv}

2) Flux and slope powers (m_f,n_f)?

- A_{cri} = 0 km² - K_{diff} = 0 m²/y
- (K_{adv}, **m_b, n_b**) =(10, **0.3**, 1)

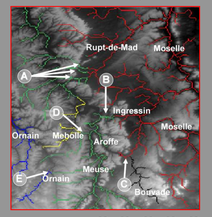


Piracies order : C B A F D E

- Flux and slope powers don't impact piracies location and order.

3) Diffusivity (K_{diff}). ?

- A_{cri} = 1 km² - **K_{diff} = 0.1 m²/y**
- (K_{adv}, m_b, n_b) = (10, 0.5, 1)

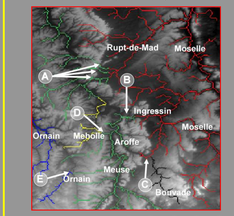


Piracies order : C B D A E

- Diffusivity does not impact piracies location and order.

4) Threshold river initiation (A_{cri}) ?

- **A_{cri} = [0.125 ; 1] km²** - K_{diff} = 0.01 m²/y
- (K_{adv}, m_b, n_b) = (10, 0.5, 1)

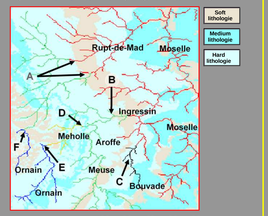


Piracies order : C B D A E

- Threshold river initiation does not impact piracies location and order.
- Age of piracies are proportional to A_{cri}

5) Lithological impact ?

- A_{cri} = 0 km² - K_{diff} = 0 m²/y
- (K_{adv} **{S, M, H}**, m_b, n_b) = ({**5,2,1**},0.5, 1)



Piracies order : C B D A E

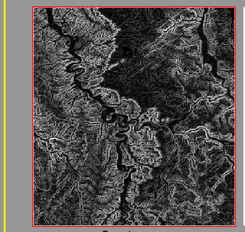
- Lithological heterogeneity does not impact piracies location and order.

- **Piracies location and order are not parameter-sensitive**
- **Ages** of piracies: they are proportional to K_{adv} (1) and A_{cri} (4), nonlinearly dependency otherwise. Sensitivity to DEM limits and boundary conditions. In (1), if K_{adv} =10, all piracies occur between 0,5My and 0.8 My.

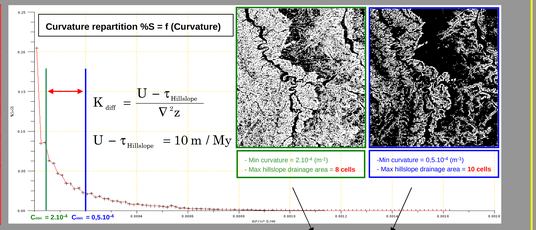
There is no capture if diffusion is not sufficient on hillslope.

Parameters fitting:

Diffusivity and threshold river initiation ? Topography analysis to determinate diffusivity (K_{diff}) and threshold river initiation (A_{cri}).

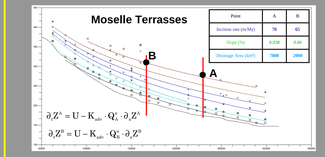


Curvature map
- Min curvature = 0 (m⁻¹)
- Max curvature = 16.10⁻⁴ (m⁻¹)



- K_{diff} = 6,25.10⁻² m²/y
- A_{cri} = [0.5 ; 0.625] km²

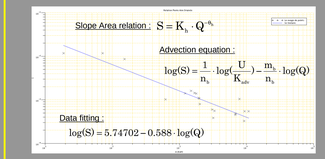
Erodability coefficient (1) ?



Point	A	B
Incision rate (m/My)	70	65
Slope (%)	0.110	0.06
Drainage Area (km²)	2000	2000

n_b	m_b	K_{adv}
0.50	0.22	22.73
0.75	0.30	24.08
1.00	0.40	25.51
1.25	0.47	27.03
1.50	0.56	28.63
1.75	0.65	30.03
2.00	0.72	32.15

Erodability coefficient (2) ?



n_b	m_b	K_{adv}
0.50	0.29	565.0
0.75	0.44	134.3
1.00	0.59	31.92
1.25	0.73	7.594
1.50	0.88	1.801
1.75	1.09	0.429
2.00	1.17	0.102

- No capture is observed for the next 10 millions years with the fitted parameters.
- Even, a 1 or 2 magnitude order error does not induce piracies.
- Fitted parameters stay in the range of variation given in the literature K_{diff} [0.5 5.10⁻⁵] m²/y (Tucker & Slingerland 1997, Odoni 2007, Leyland & Darby 2009) .
- In order to observe piracies during the next million years K_{diff} must be greater than 1 m²/y. This value is not consistent with the range of variation given in the literature.
- Other processes integration in the model may probably lead to the expected results.

Conclusions:

- During the last million years several captures were observed in the Meuse basin. Some are expected in a "near" future and simulations with LEM show that their location and order are not sensitive to the model parameters while the age of these captures varies between 0.1 and 100 million years.
- Fitting parameters to our specific data gives realistic values but simulations give no capture in the next 10 million years. This result seems unrealistic when 3 captures occurred during the last million years… and probably shows that more complex processes have to be taken into account…
- **Further Investigations** :
- Dissolution: limestone rocks are subjected to chemical processes.
- Karst: most authors actually agree that karstic processes may have played an important role in the past capture of the Haute-Moselle. Even if karst localization and modeling remain difficult, a probabilistic approach may be investigated,
- Avulsion: the rate of deposition in the Meuse valley is difficult to estimate and depends on the climate characteristics,
- Climatic fluctuations (glacial-temperate switch) should be integrated into the model to control incision, avulsion and karstic processes and, so, to have a better estimation of the ages of the captures.
- However, we assume that the localization and the order of the captures may remain unchanged.

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