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Sensitivity analysis of a hydro-morphological index (HMID) to the optimization of the roughness coefficient in a 2D numerical model

Meander of Hauterive Abbey (Sarine, Fribourg)

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Contents

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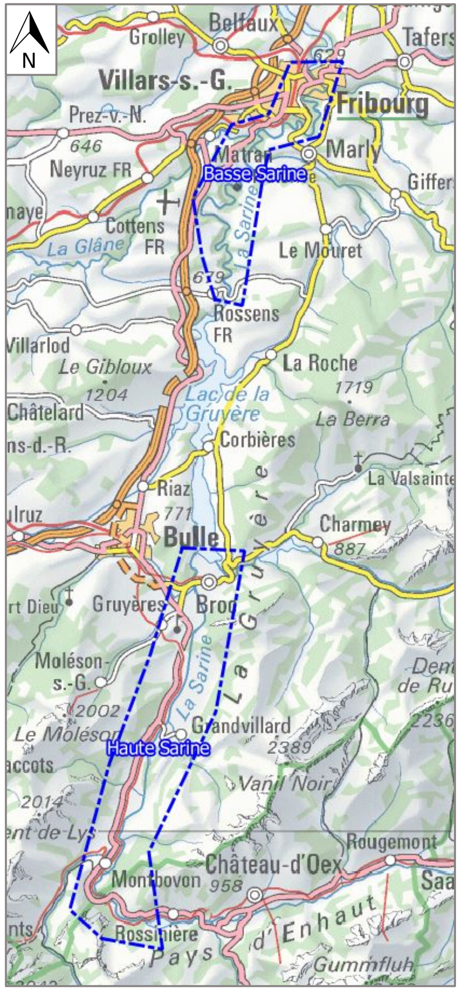
Introduction	
Objectives	
Meander of Hauterive Abbey	
Data	River geometry and flow characteristics
	Grain size distributions
Numerical model "HyApp"	Generation
	Calibration
	Simulations
Evaluation method	HMID
Results	HMID with the HyApp model
Conclusion	



Source base map: Swiss National Map 1:500'000

Introduction

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- In Switzerland, hydropower counts for more than 50% of the total energy production

- Hydropower infrastructures have negative impacts on the exploited rivers
  - Residual flow
  - Hydropeaking

- New Swiss law on the Protection of Waters (2011) obligates the prevention or elimination of those negative impacts

- The Swiss National Science Foundation has launched the *HyApp* project to create a 2D model to allow the prediction of ecological changes and to optimize the integrated management in complex floodplains

Objectives

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- In the framework of the HyApp project, this Master thesis had the following objectives:

  - **Creation of a 2D model for the meander of Hauterive Abbey, in the residual flow section of the Sarine river**
  - **Development and computation of the Hydro-Morphological Index of Diversity (HMID)**
  - **Analysis of the potential effects of an artificial flood on the morphology of the meander, based on the HMID criterion**

Meander of Hauterive Abbey

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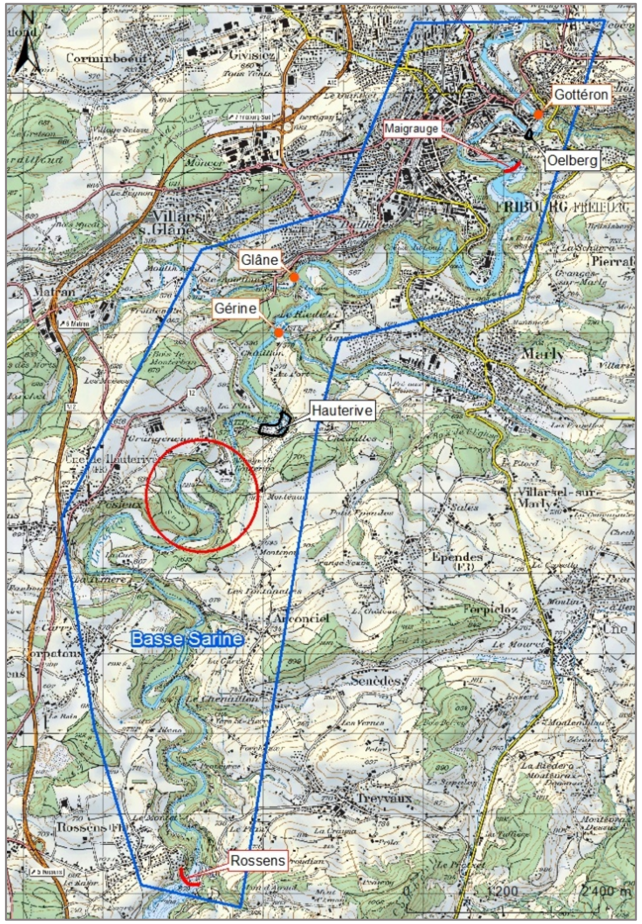

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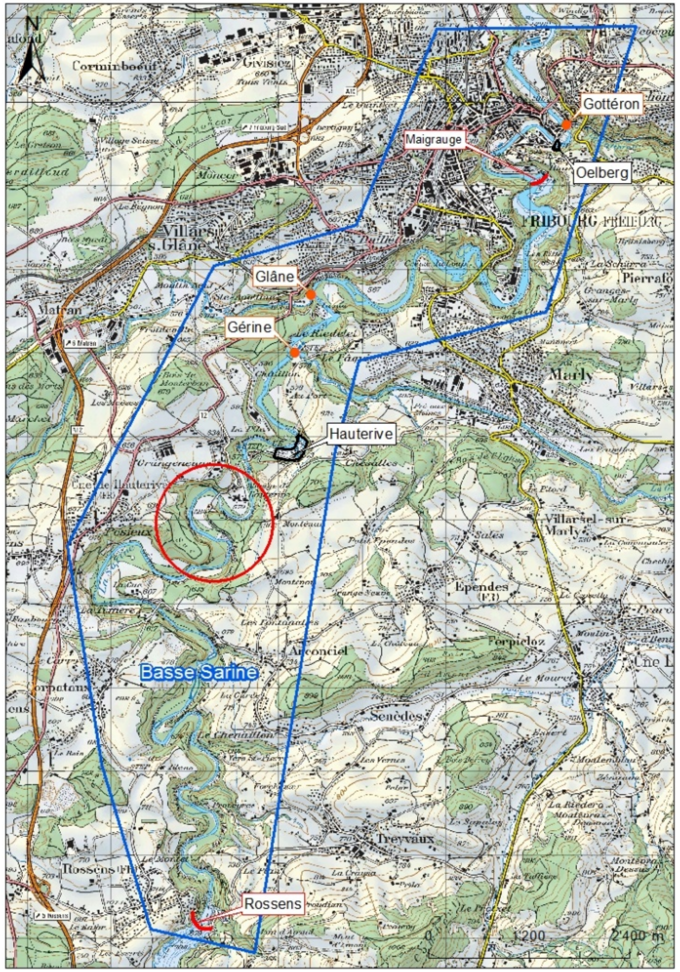
- Located in the *Basse Sarine*, between the dam of Rossens and the power station of Hauterive
- Residual flow
  - 2.5 m^3/s in winter (October – May)
  - 3.5 m^3/s in summer (June – September)
- Sequences of pools and riffles
- Special features: island, alluvial forest, gravel bars, vegetated gravel bars, disconnected secondary channels
- No real changes in morphology since the construction of the dam
- High development of the vegetation
- Progressive incision of the river in the main channel due to the lack of entering sediments

Meander of Hauterive Abbey



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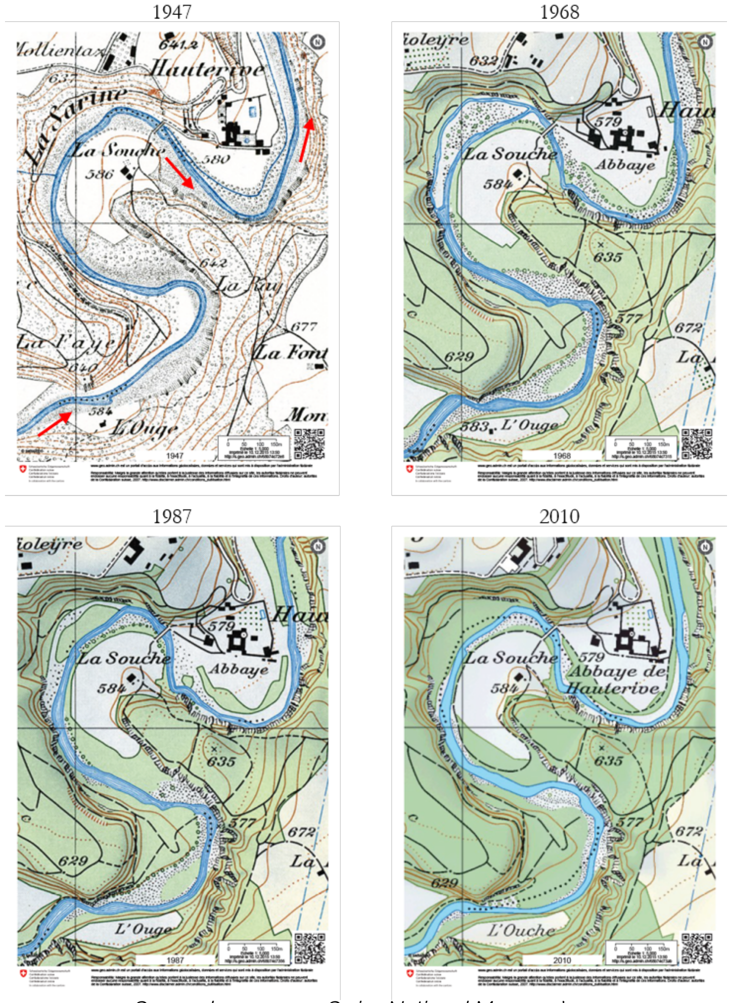
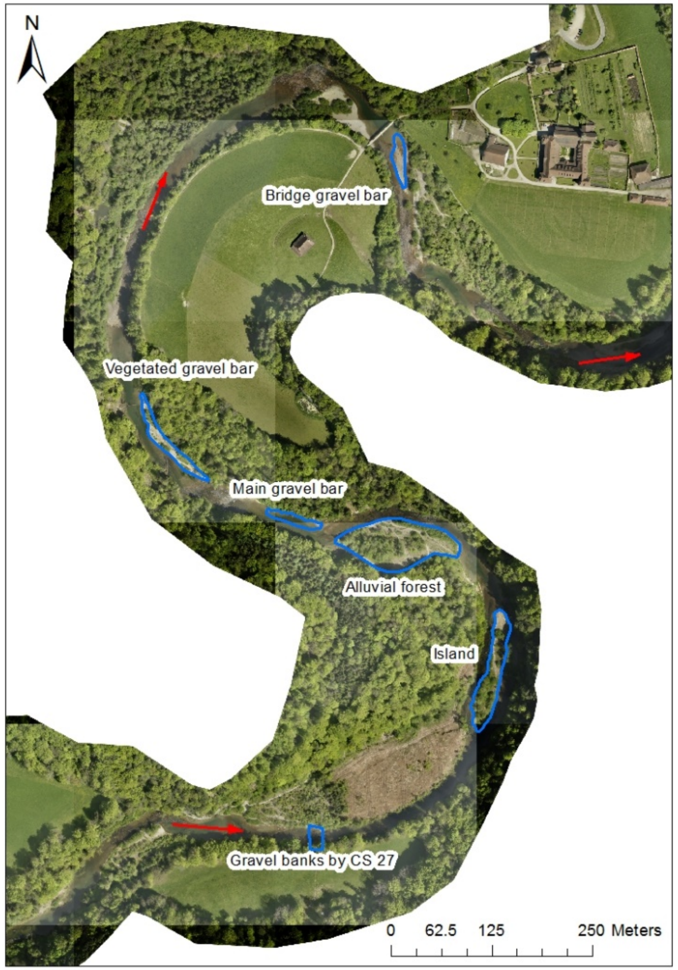
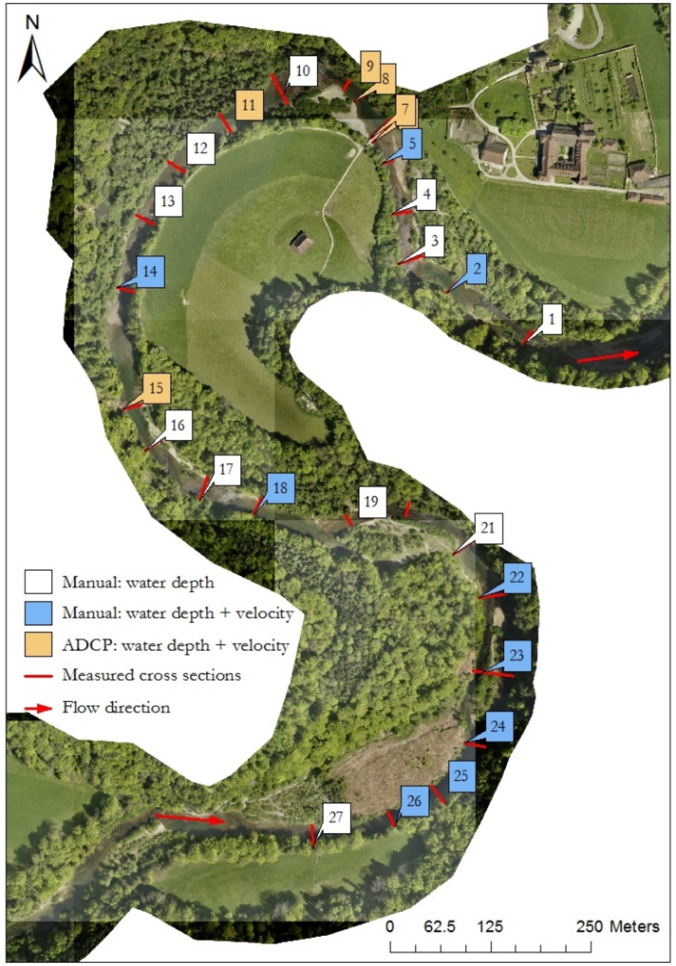


Source base maps: Swiss National Map 1:25'000



Source base map: e-dric.ch

Data – river geometry and flow characteristics



Measured cross sections with different measurement methods
Source base map: e-dric.ch

- 27 measured cross sections
  - Every ± 80 m
  - 21 manually measured
  - 6 with the ADCP boat
- Measurements
  - Water depth (for all cross sections)
  - Flow velocity (for 15/27 cross sections)
  - Location of all measuring points
- Grain size distribution
  - 18 samples collected along the meander
  - Comparison between two counting methods

Data – grain size distribution

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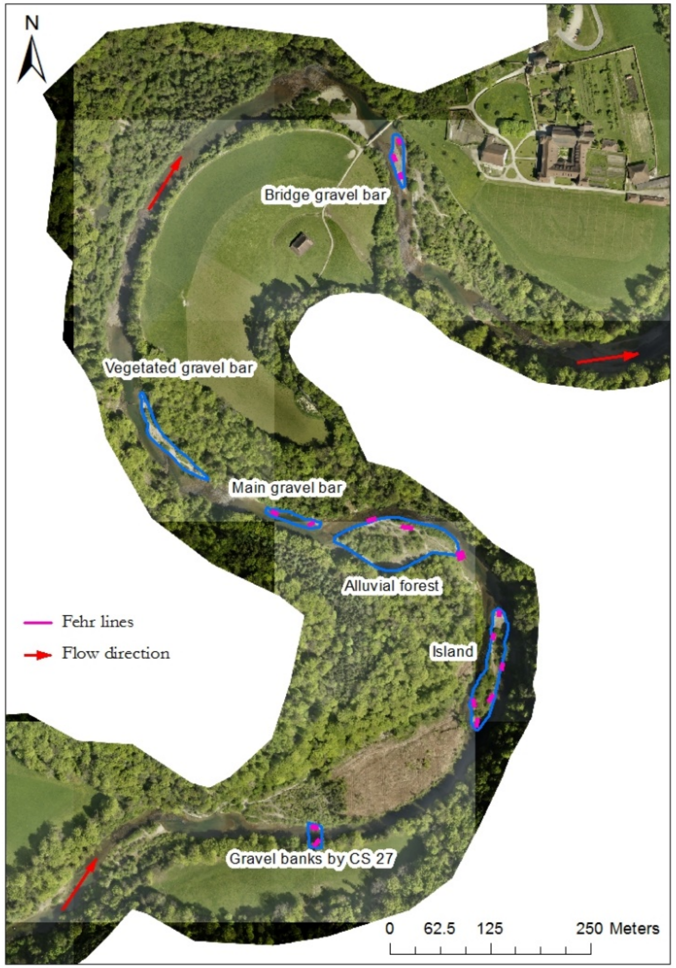


Fehr lines locations and main morphological structures
Source base map: e-dric.ch

$$Strickler\ formula:\ k_{st} = \frac{21.1}{\sqrt[6]{d}}\ ; d \in \{d_m, d_{90}\}$$

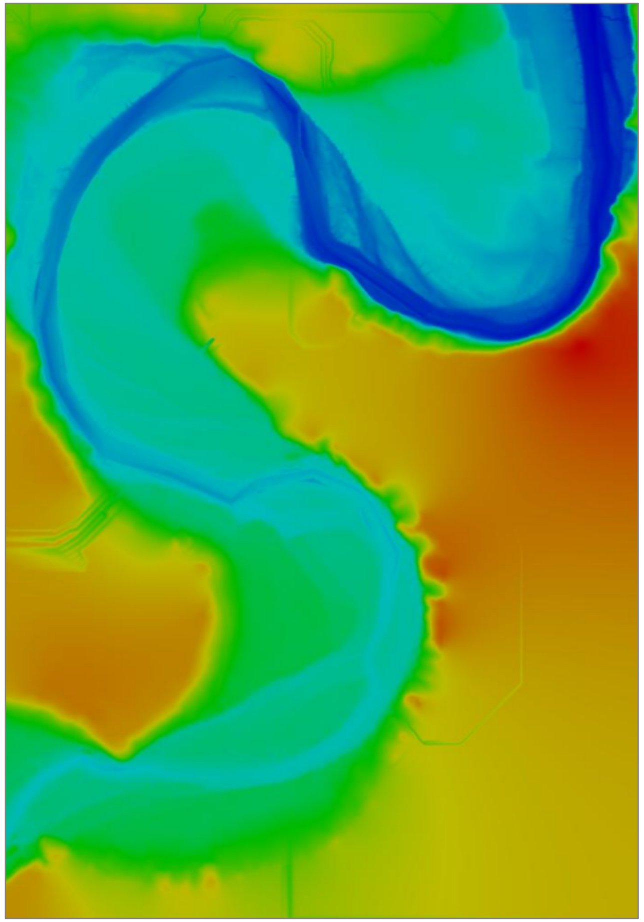
FEHR LINE ANALYSIS

Spot	d_m cm	d_{90} cm	k_{St} (d_m) $m^{1/3}/s$	k_{St} (d_{90}) $m^{1/3}/s$
Cross section 27	6.4	13.0	33.4	29.6
Island	5.6	9.9	34.1	31.0
Alluvial forest	4.9	9.1	34.9	31.5
Main gravel bar	6.4	12.8	33.4	29.7
Bridge gravel bar	5.2	9.5	34.5	31.2
BASEGRAIN				
Main gravel bar	6.2	12.8	33.5	29.7
Bridge gravel bar	5.4	12.2	34.4	30.0
Average	**5.7**	**11.3**	**34.0**	**30.4**

Data – river geometry and flow characteristics

Longitudinal profile evolution, elevation of the riverbed. Comparison between 2000, 2006 and 2015

HyApp model - mesh generation



DEM generated with ArcGIS. Cell size 30 x 30 cm..

- Interpolation of the measured cross sections every 2 meters
- Creation of a Digital Elevation Model (DEM) with ArcGIS
  - Interpolated riverbed geometry
  - LIDAR survey from e-dric.ch (2014)
  - Cell size: 30 x 30 cm
- Conceptual model
- Mesh generation
  - 1 meter grid-mesh
  - 2 meters grid-mesh

HyApp model - conceptual model

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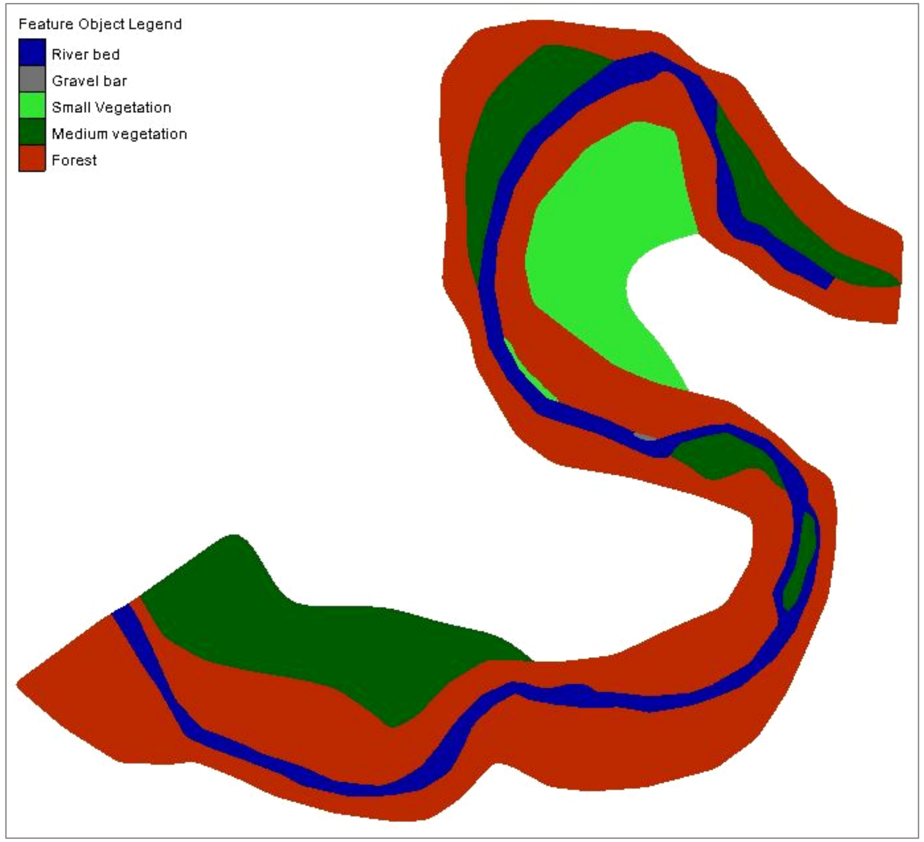

Conceptual model for the mesh generation and material index

Zone	**Strickler coefficient K_{St}** $[m^{1/3}/s]$
Riverbed (assuming paving layer)	30.4
Gravel bar	34
Small vegetation	20
Medium vegetation	16.7
Forest	10

Initial Strickler coefficients used in the model

HyApp model – mesh comparison

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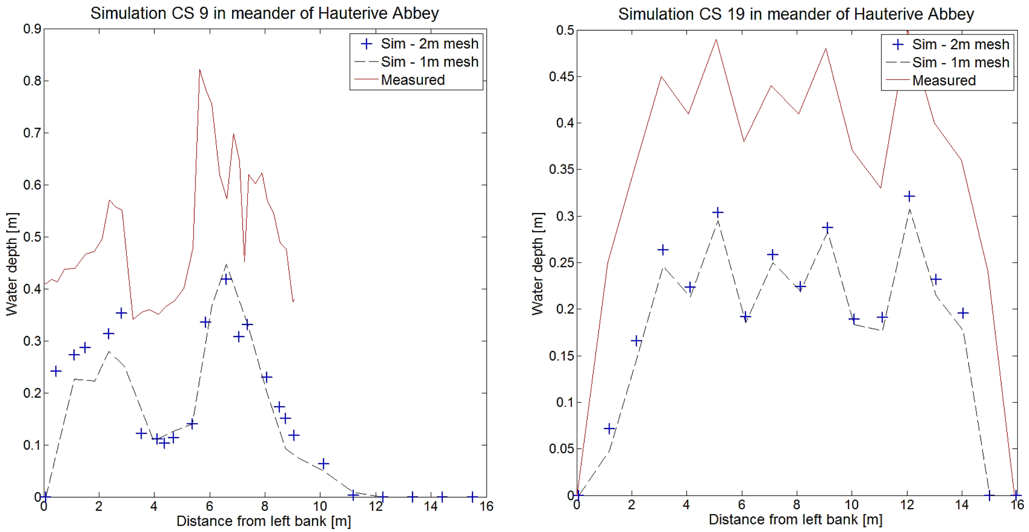
- Mesh comparison
  - Riverbed Strickler coefficient K = 30.4 $m^{1/3}/s$
  - Constant incoming discharge Q = 2.5 m^3/s
  - Accuracy depends on the measurement method
  - General shape respected



Mesh comparison for two cross sections, measured with the ADCP boat (CS9) and with the manual method (CS19)

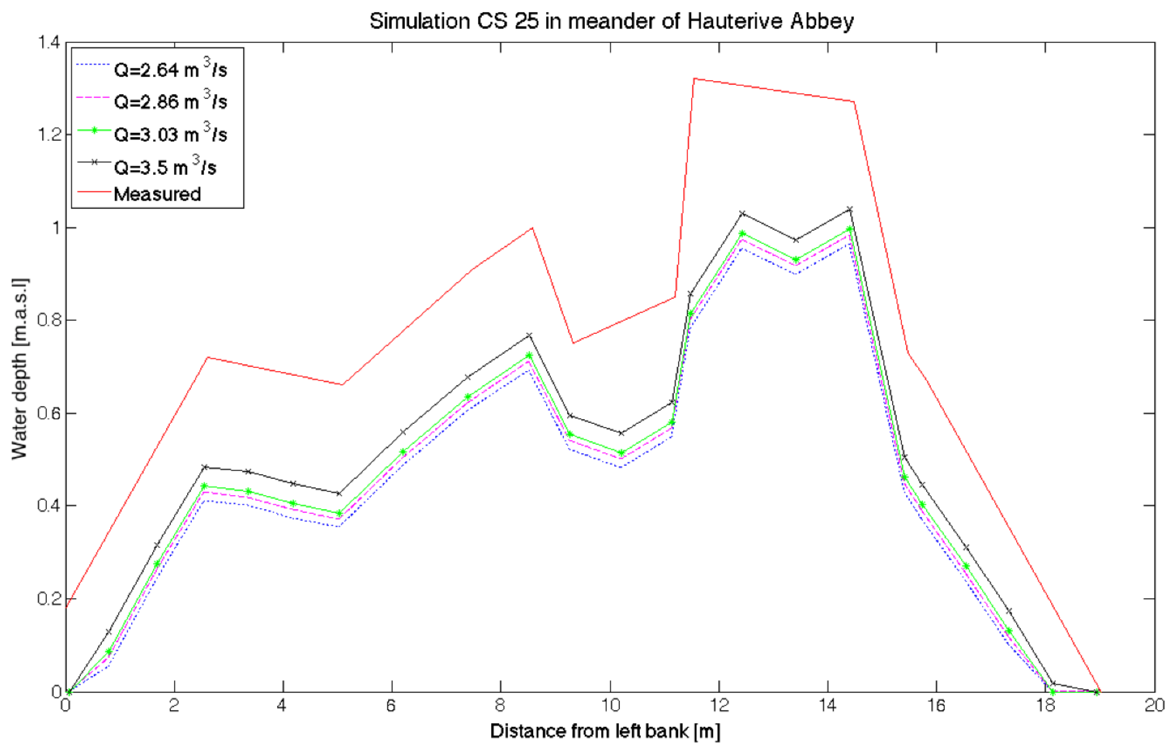
Cross-section	Max difference $[m]$	Mean difference $[m]$
27	0.082	0.013
25	0.126	0.022
22	0.019	0.005
19	0.023	0.011
16	0.182	0.012
13	0.027	0.004
9	0.088	0.040
7	0.112	0.005
4	0.021	0.006
1	0.005	0.002
Global		0.012

Differences of water depths simulated with the 1 meter and 2 meters-grid at 10 CS

HyApp model - calibration

- First simulation with Strickler K = 30.4 $m^{1/3}/s$ and Q = 2.5 m^3/s
  - Average absolute error equal to 20 cm
  - Simulated water depths lower than the measured ones

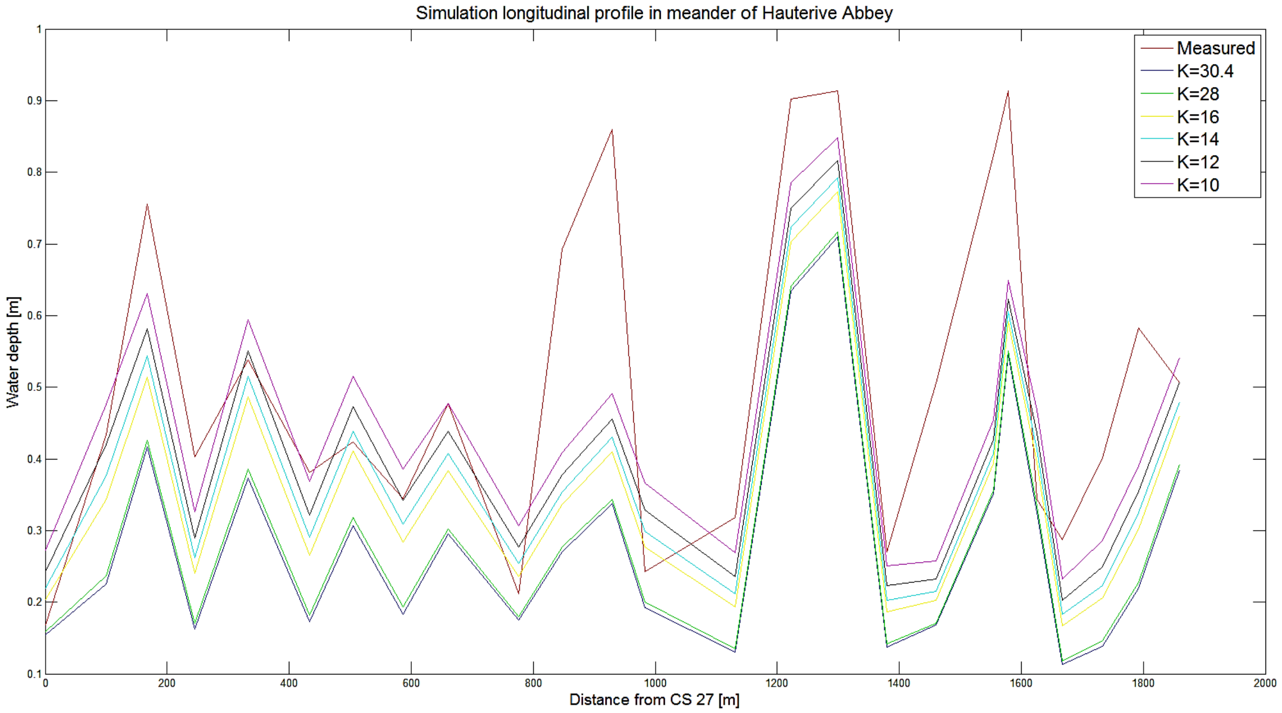
- Sensitivity of the water depth to small variations of the discharge
  - Incoming discharge: $2.6 \leq Q \leq 3.5$ m^3/s
  - K = 30.4 $m^{1/3}/s$



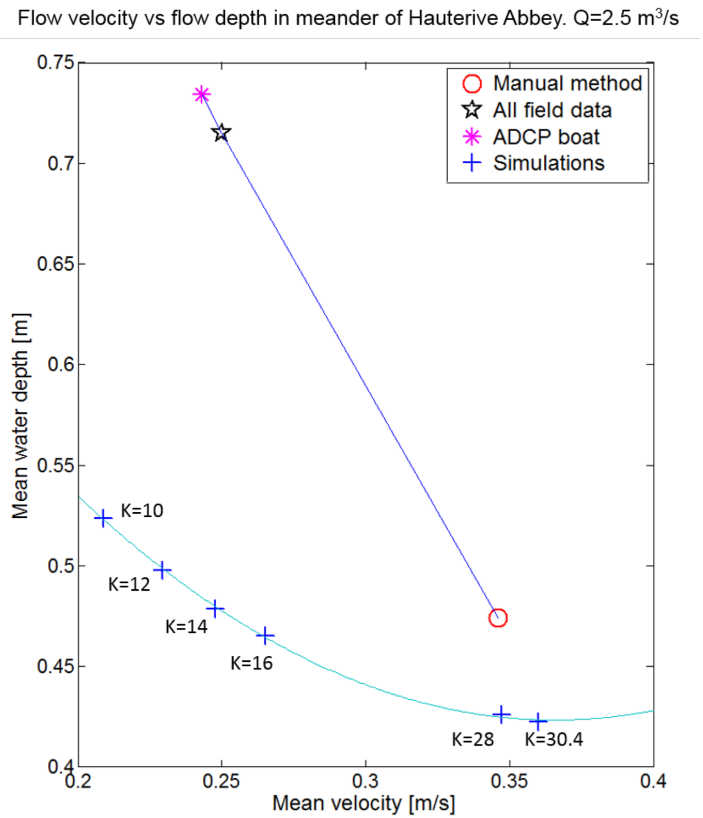
Sensitivity of the water depth to small discharge changes at CS25

HyApp model - calibration

- Strickler coefficient
  - $10 \leq K \leq 30.4\ m^{1/3}/s$
  - Constant incoming discharge: $Q = 2.5\ m^3/s$



Mean water depths along the longitudinal profile with different riverbed Strickler coefficients



Relation between flow depth, flow velocity and Strickler coefficient at constant discharge

HyApp model - calibration

– Chézy coefficient

$$C = \frac{\sqrt{R_h \cdot J}}{v}$$

$$C = k_{St} \cdot R_h^{1/6} = 30.4 \cdot 0.0634^{1/6} = 19.2\ \mathrm{m}^{1/2}/\mathrm{s}$$

R_h: *hydraulic radius (mean value of all measured cross sections)*

J: *friction slope*

v: *mean velocity*

k_{St}: *Strickler coefficient (calculated value assuming paving layer)*

HyApp model - calibration

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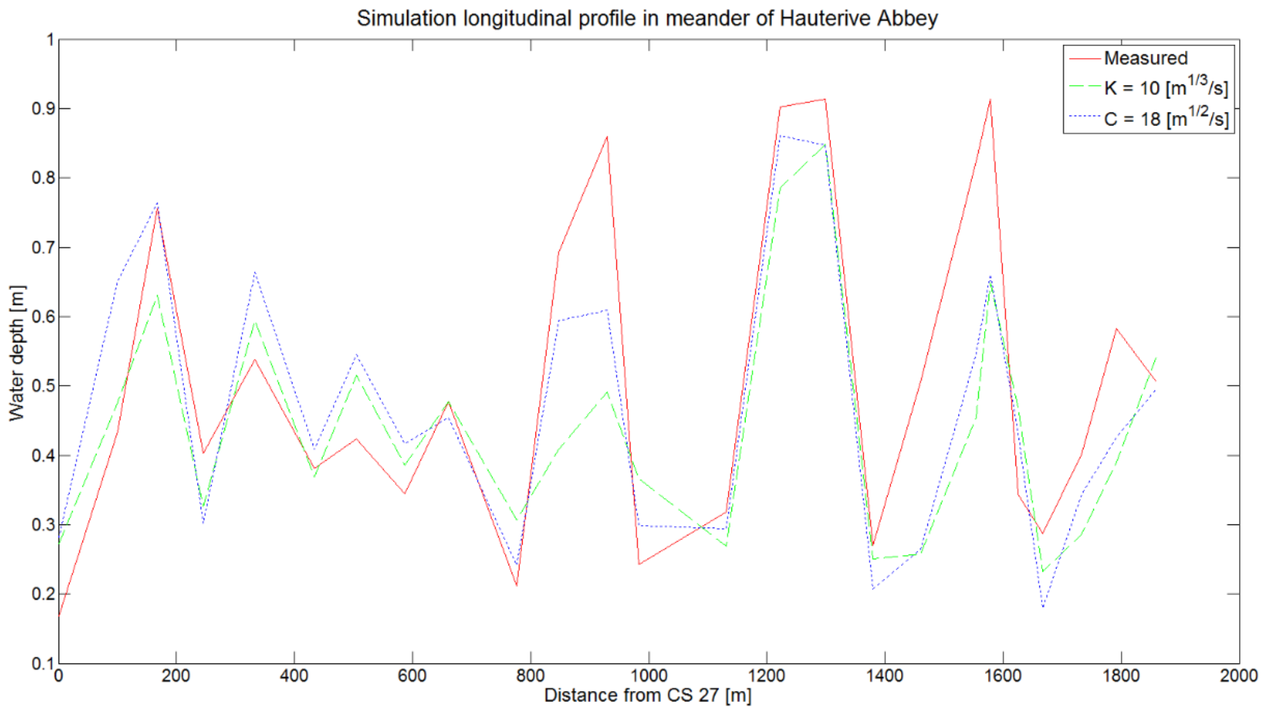
- Chézy coefficient
  - $12 \leq C \leq 18\ m^{1/3}/s$
  - Constant incoming discharge: $Q = 2.5\ m^3/s$



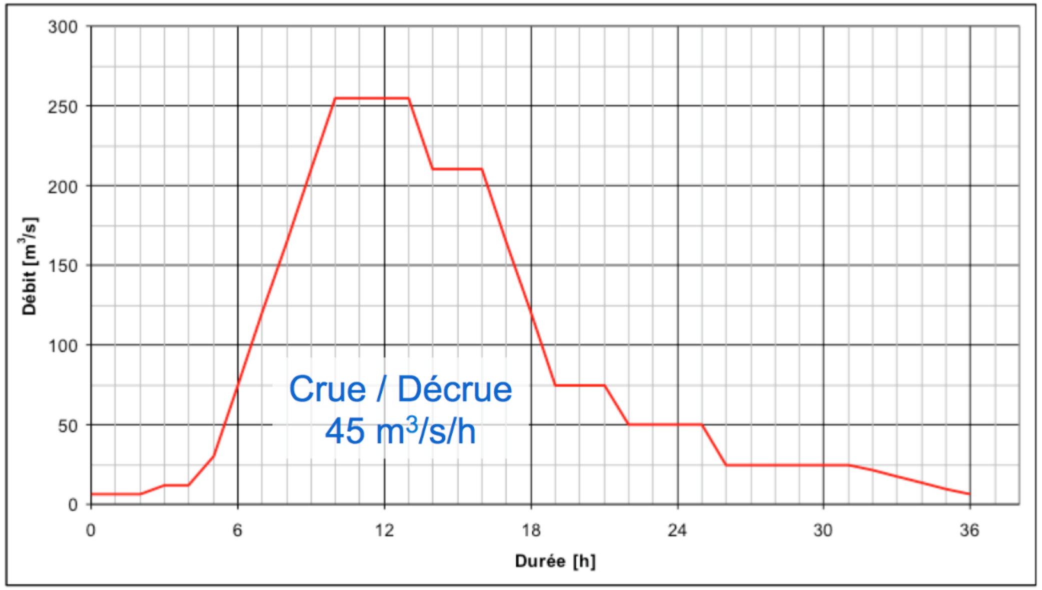
Mean water depths along the longitudinal profile with different riverbed Chézy coefficients

Strickler		
K_{St} $[m^{1/3}/s]$	**Max difference** $[m]$	**Mean difference** $[m]$
30.4	0.453	0.196
28	0.448	0.189
16	0.407	0.124
14	0.393	0.107
12	0.375	0.093
10	0.349	0.087
Chézy		
C $[m^{1/2}/s]$	**Max difference** $[m]$	**Mean difference** $[m]$
18	0.339	0.080
16	0.389	0.116
14	0.964	0.280
12	0.844	0.339

Calibration of the friction coefficient. Errors between the measured and the simulated mean water depth along the longitudinal profile for a constant discharge of $2.5\ m^3/s$

Simulations

- HyApp model
  - Constant incoming discharges
  - Q = 2.5, 3.5, 10, 25, 50, 100, 150, 200, 250 m^3/s
  - Strickler coefficients
    - K_{St} = 10 $m^{1/3}/s$ for Q ≤ 100 m^3/s
    - K_{St} = 30.4 $m^{1/3}/s$ for Q ≥ 100 m^3/s
- e-dric model
  - «Before» and «after» the flood
    - Constant incoming discharges
    - Q = 2.5, 3.5, 10, 25, 50, 100 m^3/s
    - Use of the original e-dric parameters
  - Flood event
    - Flood hydrograph (based on flood of July, 2014)
    - Use of the corrected parameters



Artificial flood hydrograph
Source : e-dric.ch

Evaluation method – HMID

- Developed by W. Gostner (2012) to assess and predict the morphological diversity in river engineering projets
- Based on simple statistical parameters (variabilities of flow depth and flow velocity)

$$Coefficient\ of\ variation:\ CV_i = \frac{\sigma_i}{\mu_i} \qquad Partial\ diversity:\ V_i = (1 + CV_i)^2$$

$$HMID_{Site} = V_h \cdot V_v = \left(1 + \frac{\sigma_h}{\mu_h}\right)^2 \cdot \left(1 + \frac{\sigma_v}{\mu_v}\right)^2$$

- 3 categories:
  - × HMID < 5 : "channelized or heavily altered sites, with uniform cross-section and minor geomorphic patches"
  - × 5 < HMID < 9 : "sites showing limited variability to near natural morphology. Patterns of intact natural state are not developed yet"
  - × HMID > 9 : "reference sites with fully developed spatial dynamics and the full range of hydraulic habitats"

Evaluation method – HMID

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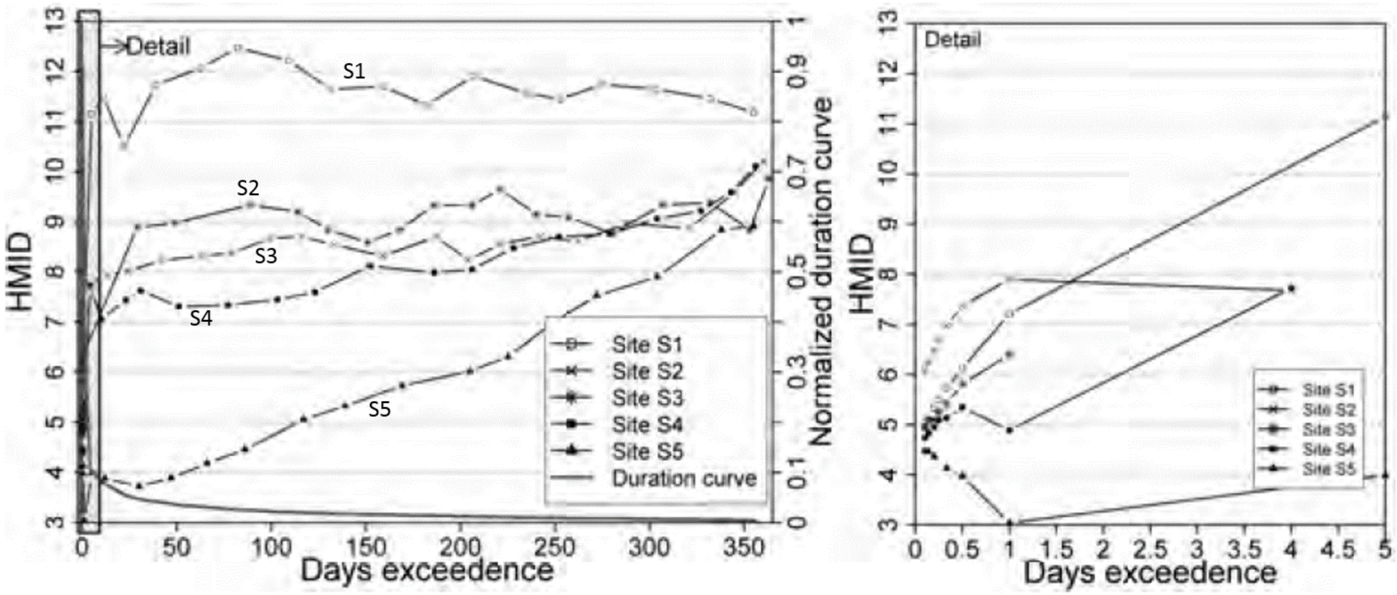
- Time variability of the HMID also important to assess the morphological quality of a river reach
  - HMID calculated under different discharges
  - Natural profiles (S1) have a better temporal stability than channelized ones (S5)
  - HMID values of all types of river morphologies tend to be similar for small and big discharges
  - Comparison between sites ideally on mean flow stages (100-250 days exceedence)



Time variability for different river sections measured during the elaboration of the HMID
Source: W. Gostner

Results – HMID with the field data

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		Manual method	ADCP boat	All field data
v[**m/s**]	μ_v	0.346	0.243	0.250
	σ_v	0.300	0.224	0.232
	CV_v	0.868	0.922	0.926
	V_v	3.489	3.695	3.709
h[**m**]	μ_h	0.474	0.734	0.715
	σ_h	0.325	0.422	0.422
	CV_h	0.686	0.575	0.589
	V_h	2.841	2.482	2.526
	HMID	9.91	9.17	9.37

HMID calculated with the measured data

Results – HMID with the HyApp model

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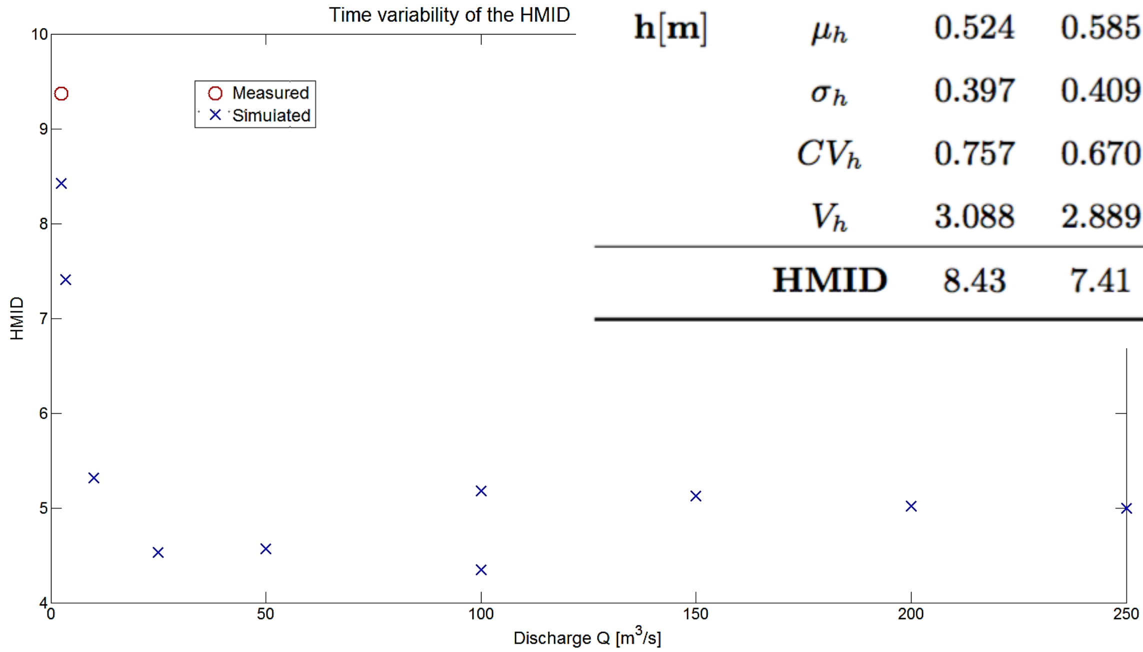

$\mathbf{Q[m^3/s]}$		2.5	3.5	10	25	50	100^1	100^2	150	200	250
$\mathbf{v[m/s]}$	μ_v	0.209	0.244	0.381	0.542	0.668	0.821	1.582	1.765	1.890	1.971
	σ_v	0.136	0.147	0.186	0.235	0.291	0.347	0.823	0.912	0.965	1.014
	CV_v	0.652	0.602	0.489	0.433	0.436	0.422	0.520	0.517	0.510	0.514
	V_v	2.729	2.565	2.217	2.054	2.062	2.023	2.312	2.300	2.281	2.293
$\mathbf{h[m]}$	μ_h	0.524	0.585	0.872	1.265	1.626	2.148	1.490	1.756	2.014	2.271
	σ_h	0.397	0.409	0.479	0.614	0.793	1.001	0.741	0.866	0.974	1.080
	CV_h	0.757	0.670	0.549	0.486	0.488	0.466	0.497	0.493	0.484	0.476
	V_h	3.088	2.889	2.398	2.207	2.214	2.149	2.242	2.230	2.201	2.177
	HMID	8.43	7.41	5.32	4.53	4.56	4.34	5.18	5.13	5.02	4.99

HMID calculated with the HyApp simulations

Results – HMID with the HyApp model

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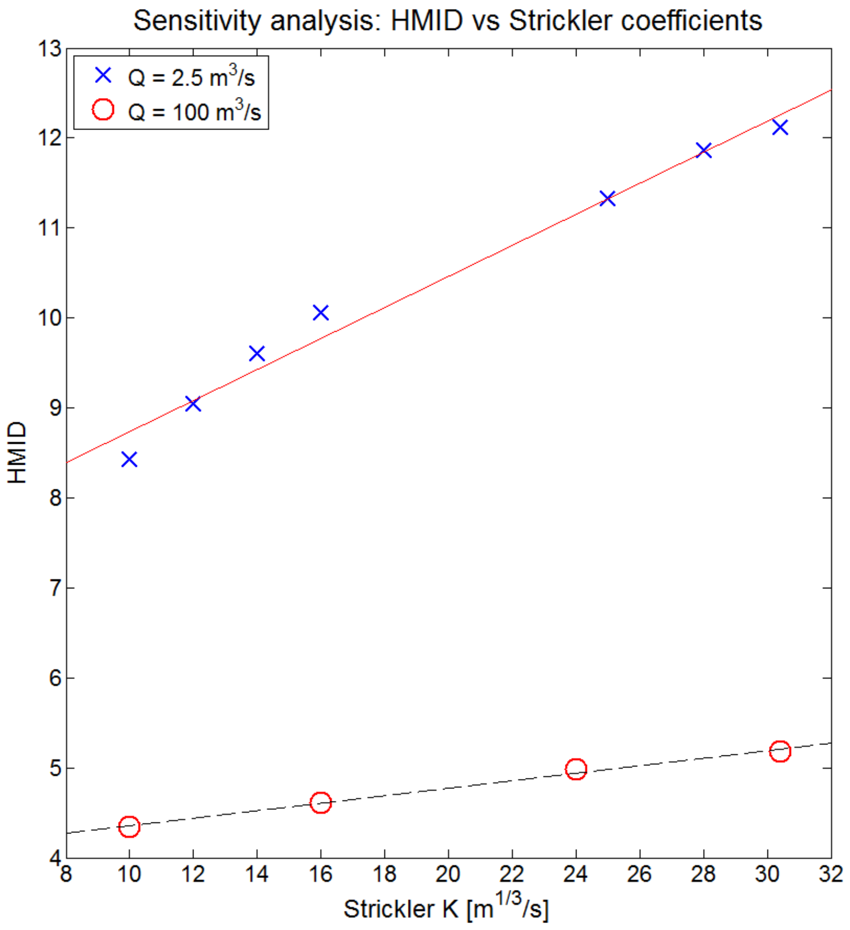
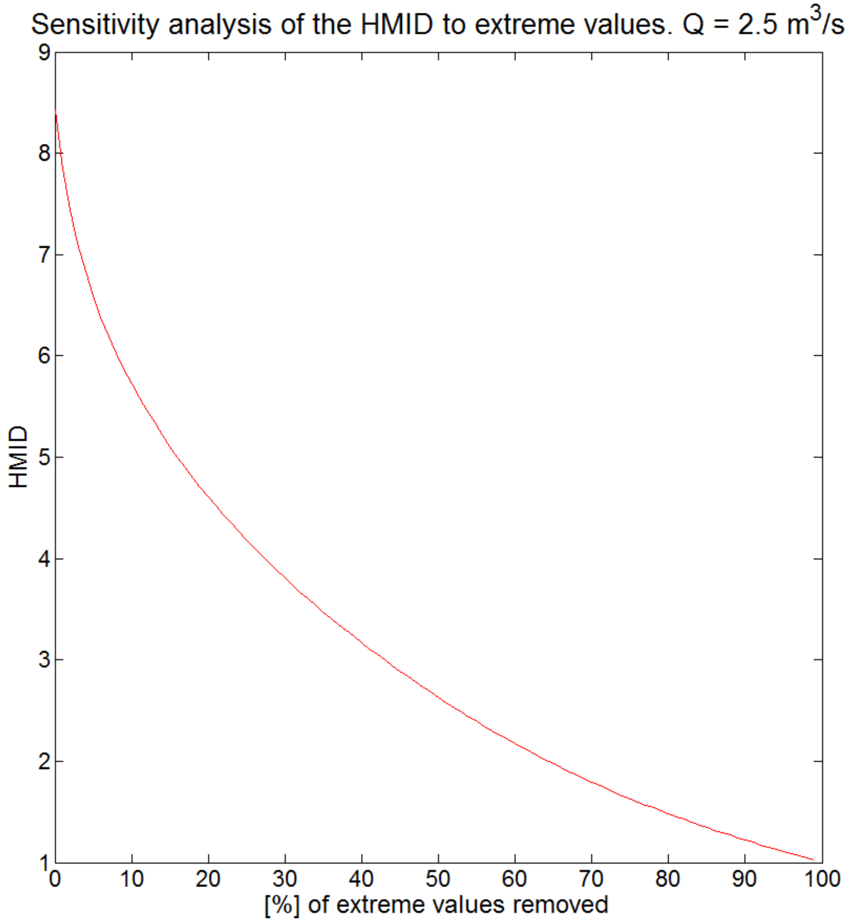
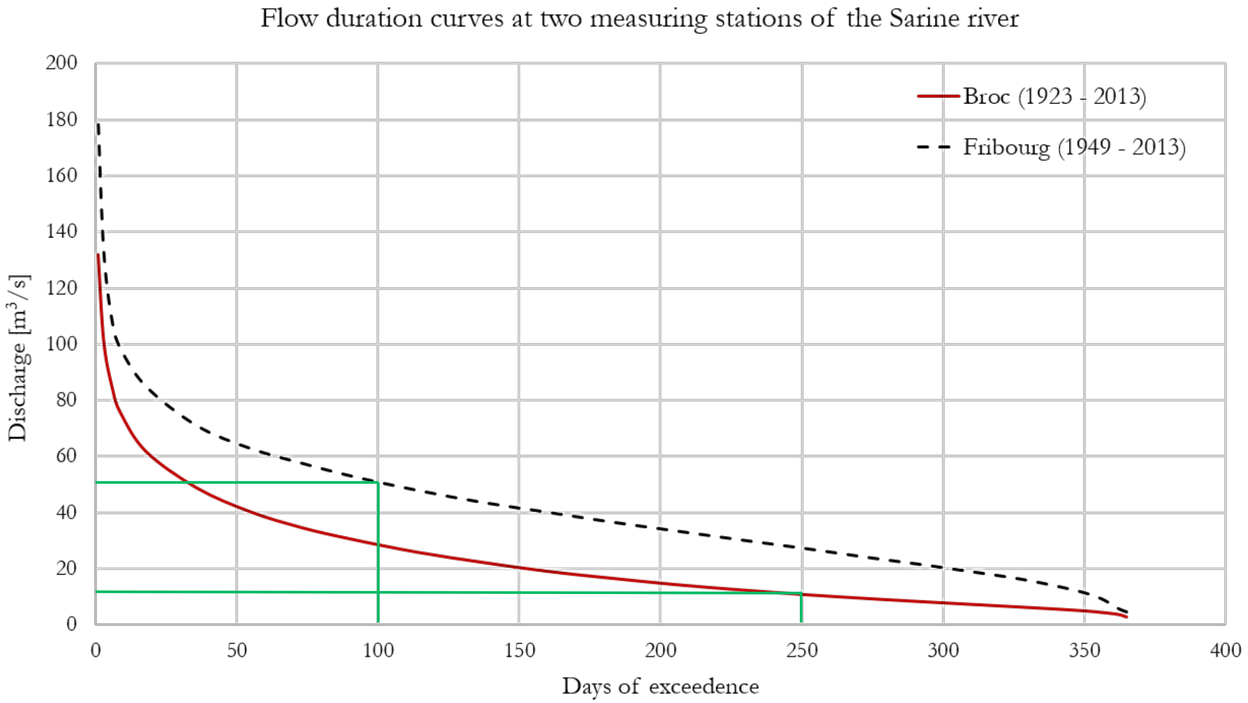




Sensitivity analysis of the HMID to the model calibration and to the extreme values

Results – HMID with the HyApp model

- Exact HMID values should be interpreted carefully: sensitivity to the model calibration!
- Comparison on mean flow stages:
  - $10 \leq Q \leq 50\ m^3/s$
  - $4.56 \leq HMID \leq 5.32$: "heavily altered sites with uniform cross sections and longitudinal slope"



Conclusion

- Hydropower production coupled with retention infrastructures has negative impacts on the physical and biological environments of the exploited river
- 2D models are a useful tools in projects aiming at eliminating or preventing those negative effects
  - Simulation of the hydraulic parameters for the actual state
  - Predictions for any hydraulic or sediment transport scenarios
- The HMID is an effective tool to for the prediction of the structural diversity in a river reach
  - ! Sensitivity of the HMID to the model calibration
  - Tendencies and ranges of HMID are better indicators than exact values
- HyApp model can be further used for the link with habitat indicators to create a 2D model allowing complete evaluations of the morphological and biological quality of rivers

Thank you for the attention!

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7.2 Evaluation method – Artificial flood

- Evaluation of the artificial flood effects on the morphology of the meander
- Comparison of the HMID values “before” and “after” the flood

Water spill at the dam of Rossens. May 6, 2015
Source: www.lematin.ch

Results – effects of the artificial flood

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- Improvement of the morphological diversity (HMID higher after the flood)

$\mathbf{Q[m^3/s]}$		**2.5**	**3.5**	**10**	**25**	**50**	**100**
$\mathbf{v[m/s]}$	μ_v	0.334	0.396	0.631	0.963	1.235	1.420
	σ_v	0.259	0.297	0.418	0.533	0.674	0.905
	CV_v	0.774	0.750	0.663	0.554	0.546	0.637
	V_v	3.148	3.064	2.765	2.413	2.389	2.681
$\mathbf{h[m]}$	μ_h	0.396	0.436	0.549	0.774	1.007	1.267
	σ_h	0.276	0.287	0.351	0.420	0.517	0.704
	CV_h	0.690	0.660	0.640	0.543	0.513	0.555
	V_h	2.856	2.754	2.689	2.380	2.290	2.419
	HMID	8.99	8.44	7.43	5.74	5.47	6.48

*HMID simulated with the e-dric model **before** the flood*

$\mathbf{Q[m^3/s]}$		**2.5**	**3.5**	**10**	**25**	**50**	**100**
$\mathbf{v[m/s]}$	μ_v	0.227	0.273	0.488	0.792	1.064	1.340
	σ_v	0.213	0.247	0.363	0.492	0.620	0.785
	CV_v	0.938	0.904	0.744	0.621	0.583	0.586
	V_v	3.756	3. 625	3.041	2.628	2.507	2.515
$\mathbf{h[m]}$	μ_h	0.572	0.591	0.698	0.862	1.041	1.293
	σ_h	0.408	0.418	0.459	0.520	0.596	0.725
	CV_h	0.713	0.708	0.657	0.603	0.573	0.561
	V_h	2.935	2.916	2.746	2.568	2.474	2.436
	HMID	11.02	10.57	8.35	6.75	6.20	6.13

*HMID simulated with the e-dric model **after** the flood*

Results – effects of the artificial flood

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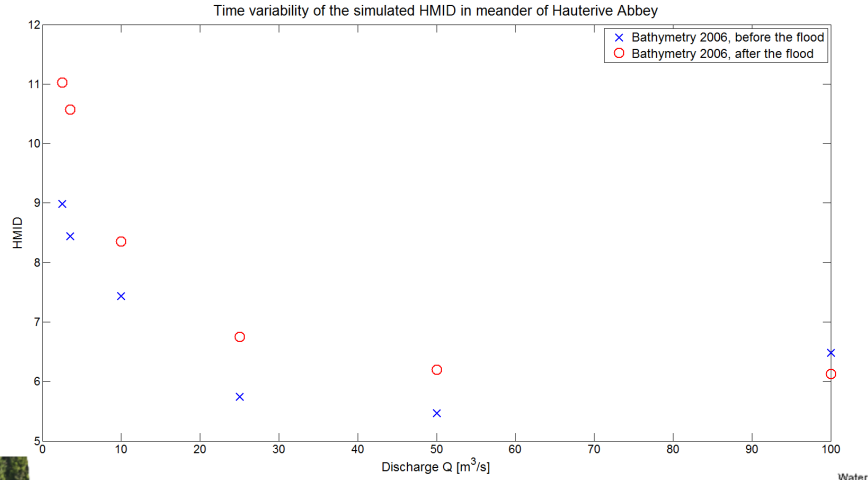
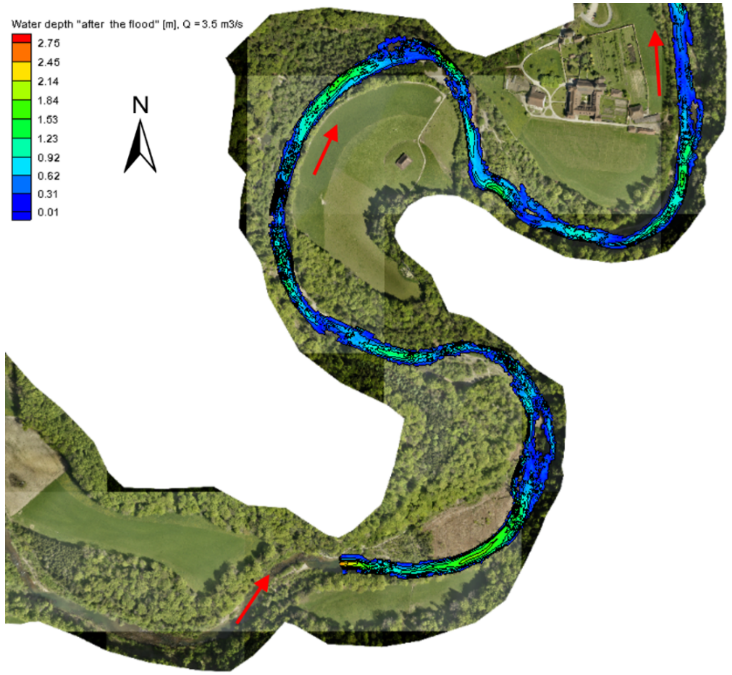


*HMID simulated with the e-dric model **before and after** the flood*

Simulated water depth before the flood, Q = 3.5 m³/s (left)



Simulated water depth after the flood, Q = 3.5 m³/s (right)