Bathymetric mapping in turbid braided mountain streams using SfM-MVS photogrammetry and statistical approaches

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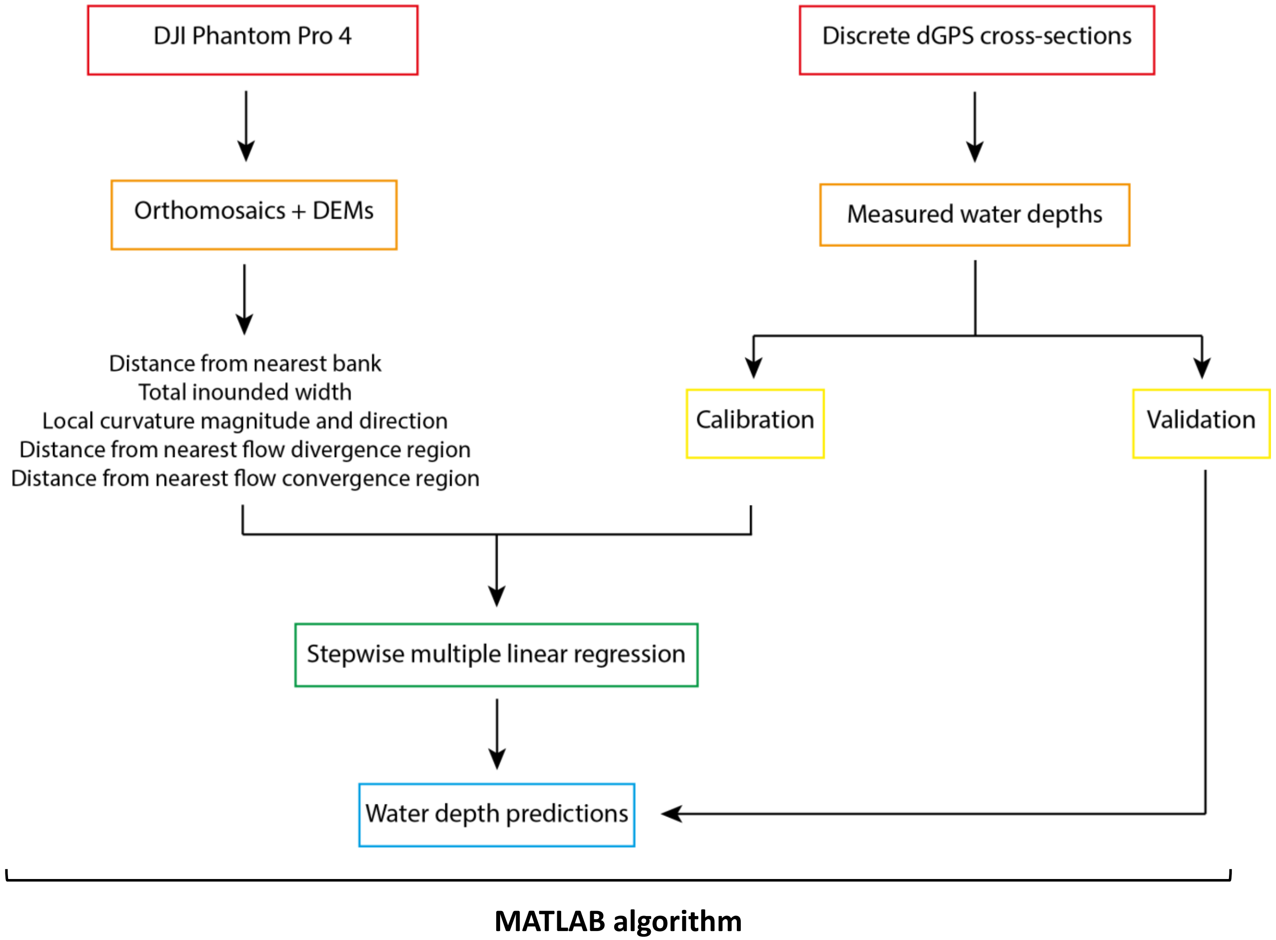
1. Introduction

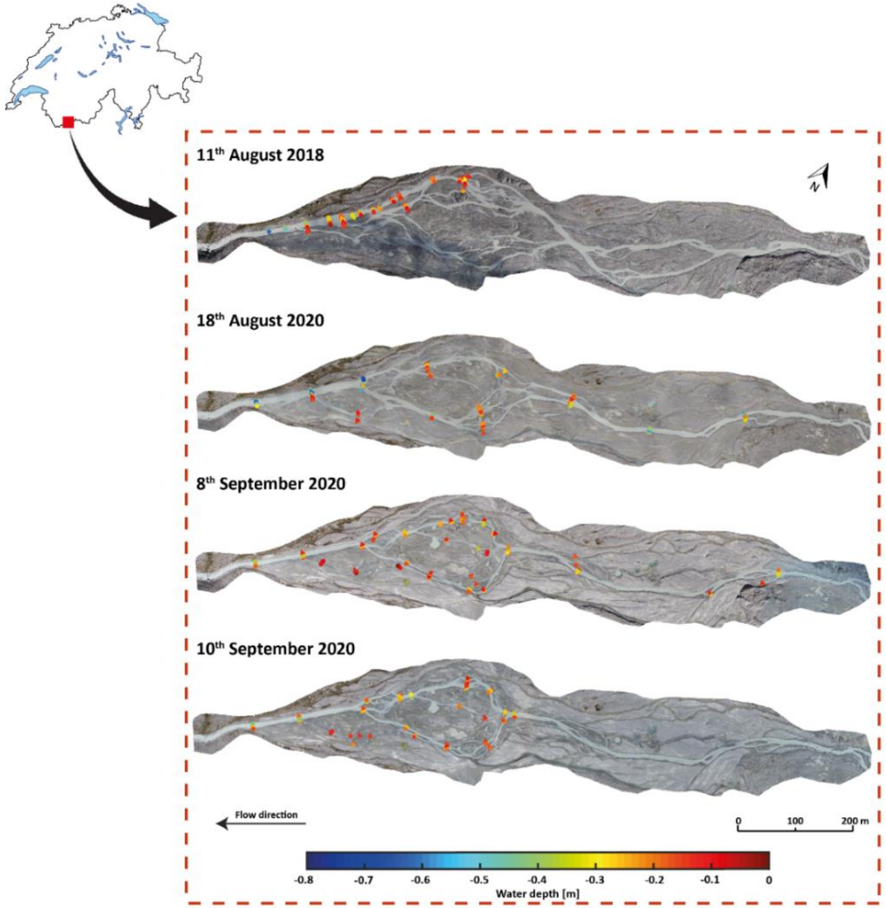
- Traditional techniques to collect bathymetric data in shallow rivers:
  - Total station
  - Differential GPS systems

  Time consuming + point density vs. survey extent
  - Through-water photogrammetry (correct light reflection due to the water-air interface; e.g. Dietrich, 2017)

- Aim: Test if it possible to predict water depth distribution in a shallow braided stream having high suspended sediment content from basic morphometric information

2. Methodology

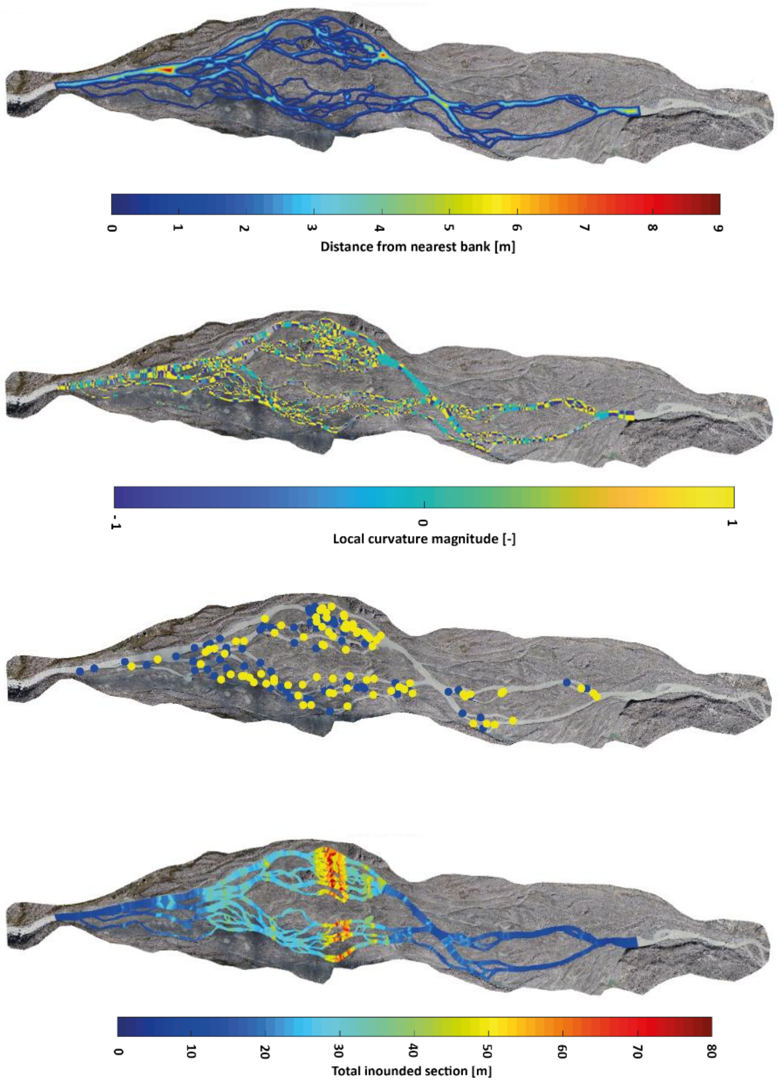




Date	UAV and dGPS acquisition time	dGPS measurements	
		Total points	Cross-sections
11.08.2018	08:50 - 10:50	176	20
18.08.2020	09:00 - 12:55	206	23
08.09.2020	09:40 - 12:11	259	37
10.09.2020	08:55 - 11:12	157	25

2. Methodology

Calculation of explanatory variables:



Input data:

1. Photogrammetrically-derived orthomosaics and DEMs

Date	Acquisition time	Total number of images	GCPs RMS error [pix]
11.08.2018	08:50 - 10:50	1072	0.53
18.08.2020	09:00 - 12:55	2629	0.74
08.09.2020	09:40 - 12:11	1959	1.59
10.09.2020	08:55 - 11:12	1849	1.26

2. Water depth measurements of discrete stream cross-sections

	Total		Calibration		Validation	
Date	Number of points	Cross-sections	Number of points	Cross-sections	Number of points	Cross-sections
11.08.2018	176	20	92	10	84	10
18.08.2020	206	23	112	12	94	11
08.09.2020	259	37	136	19	123	18
10.09.2020	157	25	82	13	75	12

Water depth prediction model

2. Methodology

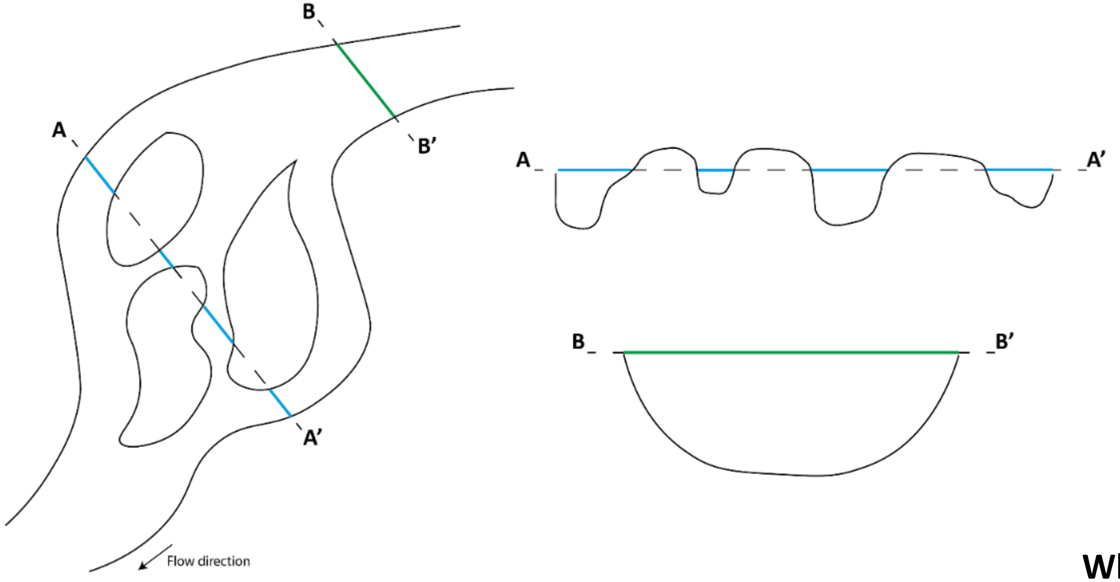
- Variable: Distance from nearest bank

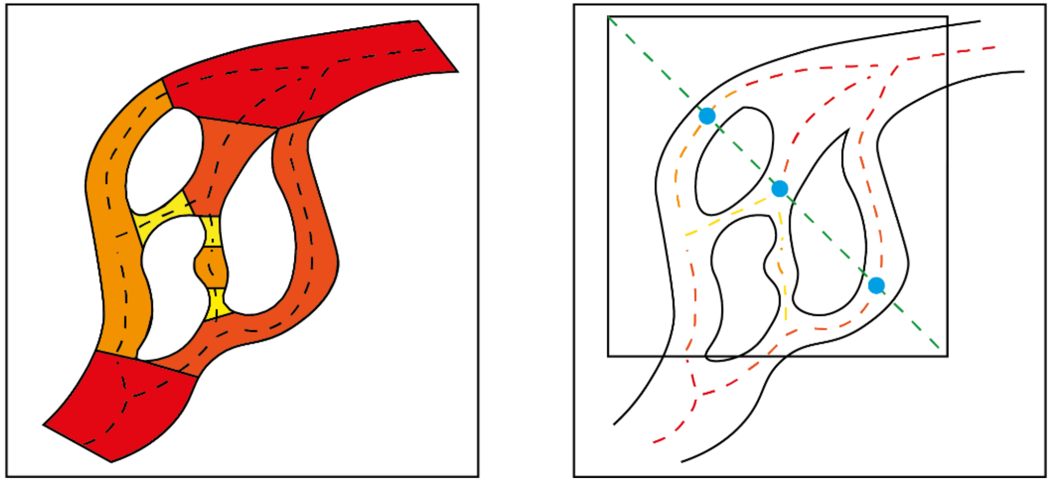
$$DnB_i = bwdist[bwmorph(IA_i)]\ x\ Res$$

Where:
bwdist = Matlab “distance transform of binary” function
bwmorph = Matlab “morphological operations on binary images” function
DnB_i = distance from nearest bank for the inounded cell i
IA_i = binary image of the inounded area
Res = orthomosaic resolution (i.e. 0.20 m)

2. Methodology

- Variable: Total inunded width





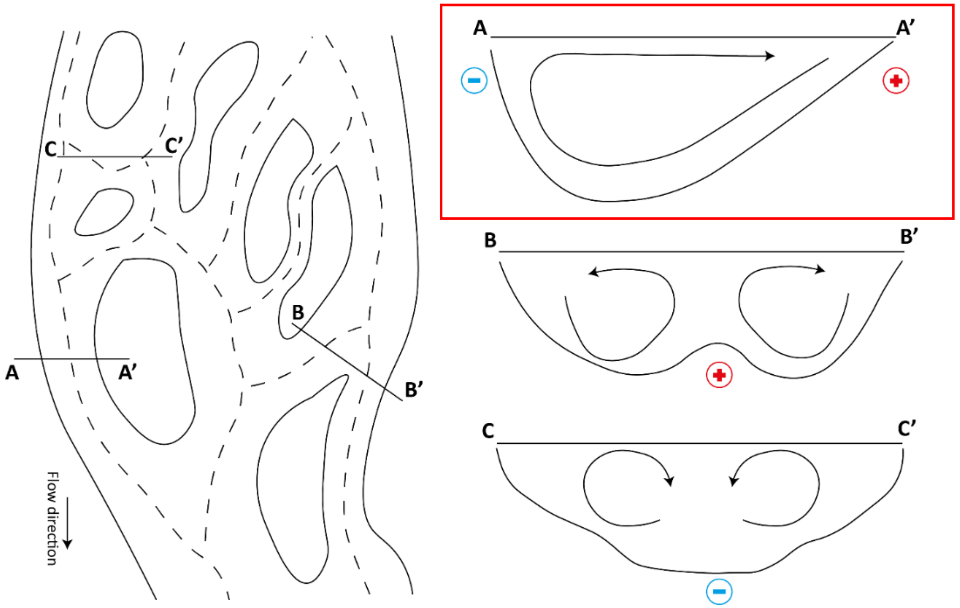
$$TIW_i = min_{ij}[\sum_{n=1}^{1400} d_j\,(lw)]$$

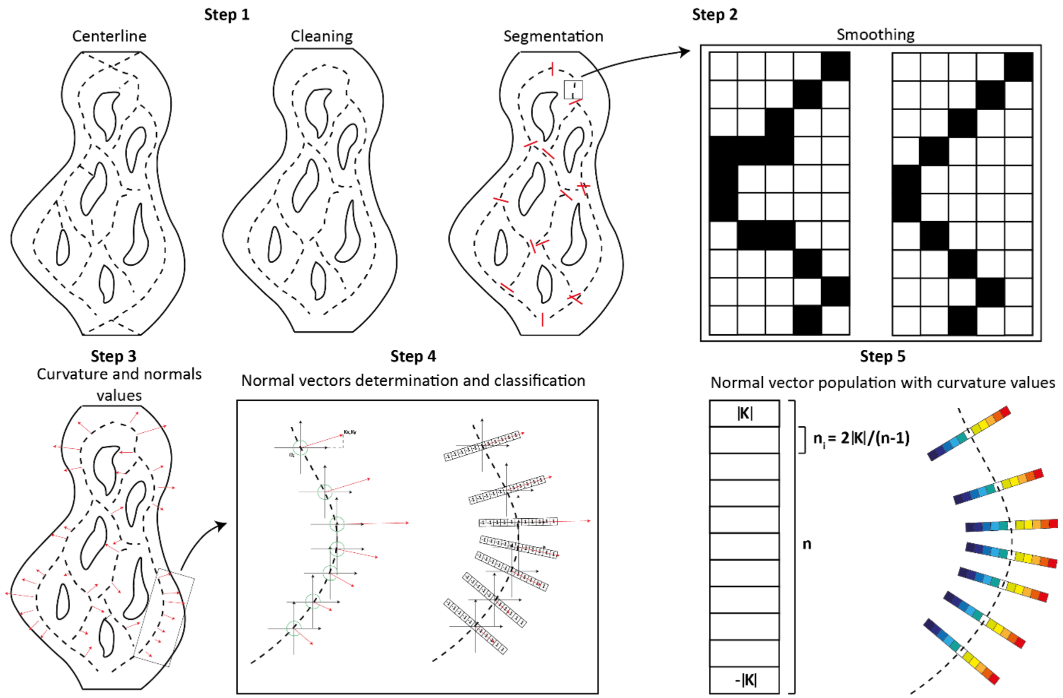
Where:

TIW_i = Total inounded width associated to the inounded cell i
min_{ij} = nearest distance between the inounded cell i and the centerline cell j
d_j (lw) = ones diagonal matrix associated to the centerline cell j summing all local channel width values along the diagonal.

2. Methodology

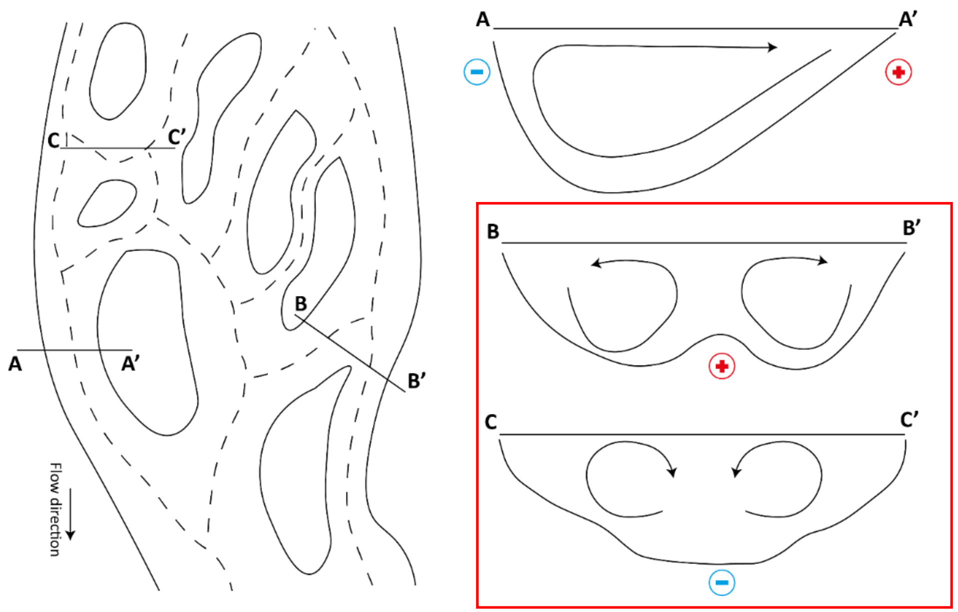
- Variable: Total inunded width





2. Methodology

- Variable: Distance from nearest flow divergence and convergence regions



$$D_{dci} = min_{ij}[bwdist[bwmorph(DC_j)]\ x\ Res]$$

Where:

D_{dci} = Distance from nearest divergence and convergence region for inounded cell i
min_{ij} = nearest distance between the inounded cell i and the divergence or convergence region j
DC_j = Empty matrix associated to the divergence or convergence region j
Res = Orthomosaic resolution (i.e. 0.20 m)
bwdist = Matlab "distance transform of binary" function
bwmorph = Matlab "morphological operations on binary images" function

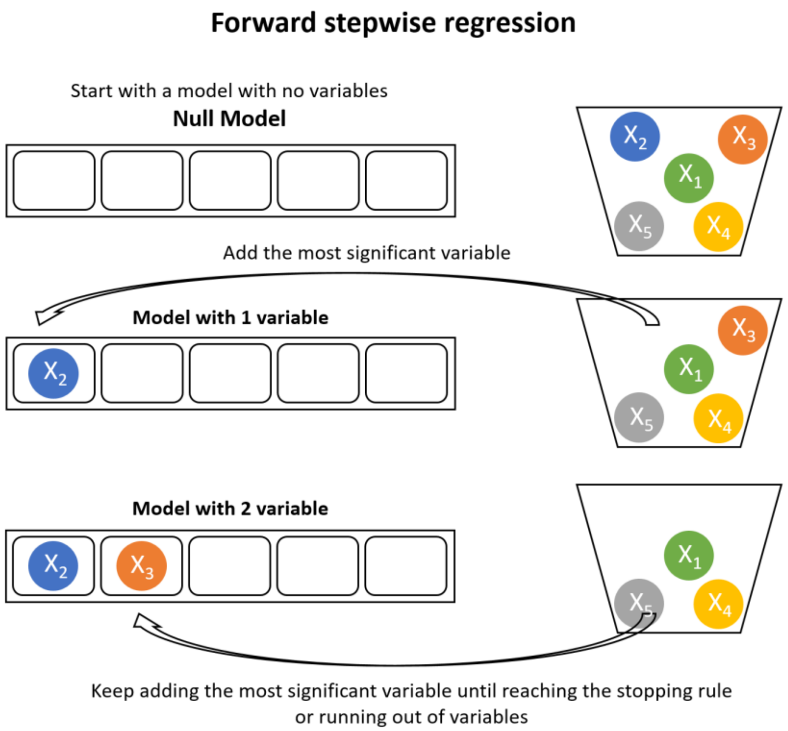
Methodology

- Post-processing
  - Stepwise approach to calibrate a multiple regression
  - 5 variables:
    - Distance to nearest bank
    - Total inounded width
    - Local stream curvature magnitude and direction
    - Distance to nearest flow divergence region
    - Distance to nearest flow convergence region

Water depth $= a_0 + a_1 \times (X_1) + a_2 \times (X_2) + a_3 \times (X_3) + a_4 \times (X_4) + a_5 \times (X_5)$

Rule: p-value > 0.05 (α) -> model vs. candidate predictors

  - Aim:
    - + R2 between response and explanatory variables
    - - SD between observations and predictions



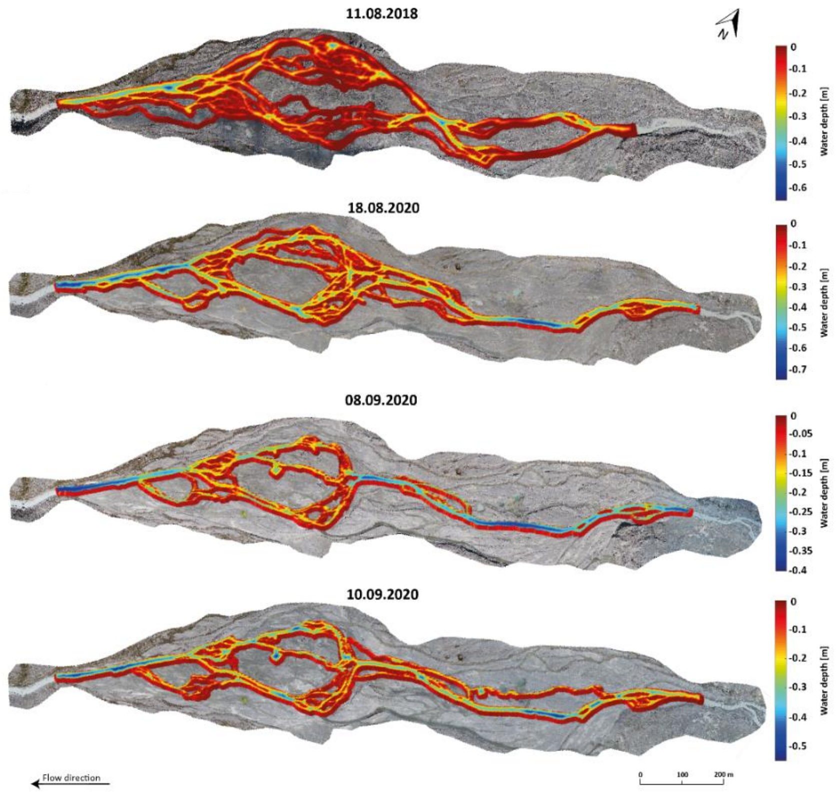
3. Results

- Calibration: forward stepwise multiple linear regression

Water depth = $a_0 + a_1 \times (X_1) + a_2 \times (X_2) + a_3 \times (X_3) + a_4 \times (X_4) + a_5 \times (X_5)$

Date	Step	Variable	Coefficient a						p-value	R^2	SDE
			a_0	a_1	a_2	a_3	a_4	a_5			
11.08.2018	1	**Total Width**	0.490	-0.010					4.1×10^{-11}	0.346	0.102
	2	**+ Dist. nearest bank**	0.377	-0.008	0.037				0.001	0.486	0.090
	3	**+ Convergence**	0.446	-0.009	0.047	-0.006			9.7×10^{-4}	0.574	0.082
	4	**+ Divergence**	0.287	-0.005	0.054	-0.005	0.003		6.5×10^{-4}	0.625	0.077
18.08.2020	1	**Dist. nearest bank**	0.190	0.093					2.2×10^{-9}	0.375	0.138
	2	**+ Divergence**	0.144	0.069	0.004				4.7×10^{-9}	0.545	0.118
08.09.2020	1	**Total Width**	0.371	-0.012					7.3×10^{-7}	0.367	0.081
	2	**+ Dist. nearest bank**	0.305	-0.010	0.033				7.2×10^{-4}	0.450	0.075
	3	**+ Convergence**	0.261	-0.008	0.026	8.8×10^{-4}			0.002	0.489	0.072
10.09.2020	1	**Dist. nearest bank**	0.148	0.076					1.3×10^{-11}	0.434	0.088
	2	**+ Divergence**	0.134	0.064	0.001				2.3×10^{-6}	0.537	0.079
	3	**+ Convergence**	0.138	0.069	0.003	-0.003			2.6×10^{-4}	0.610	0.073

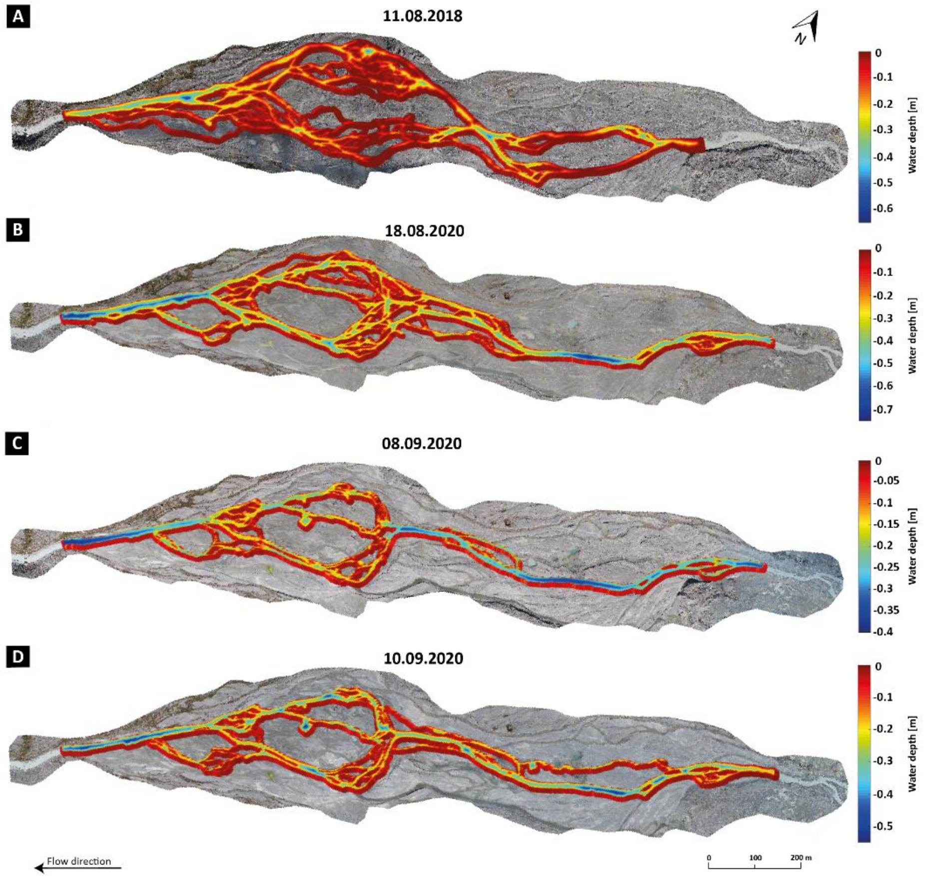
+ R^2
- SDE



Rule: p-value < 0.05 (α) -> model vs. candidate predictors

3. Results

- Predictions

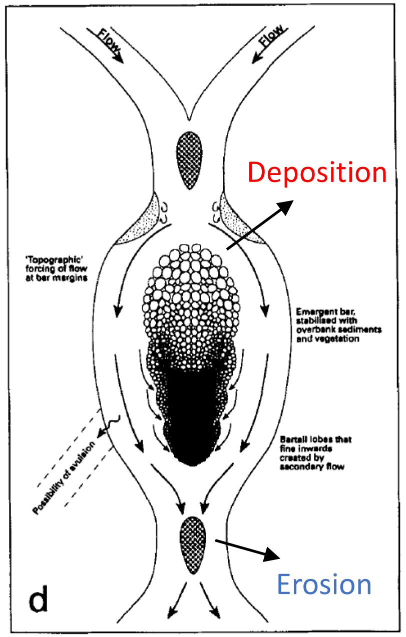


Basic hydraulics theories are respected:

i) Water depths are deeper in straight channel patterns

ii) Convergence = incision = deeper

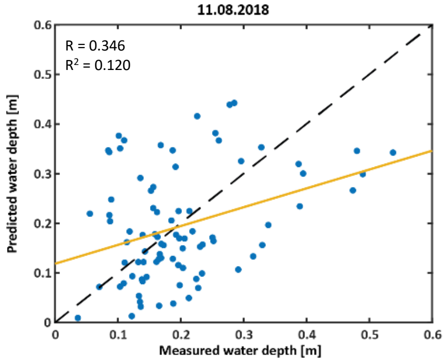
iii) Divergence = deposition = shallower

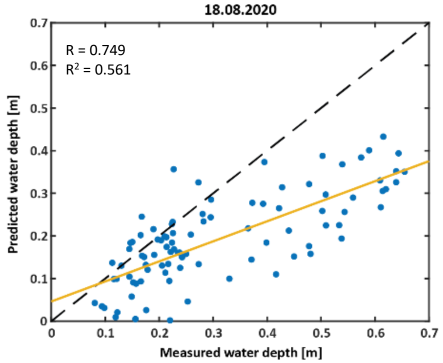


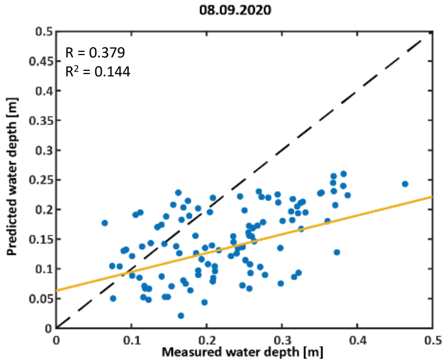
Ashworth (1996)

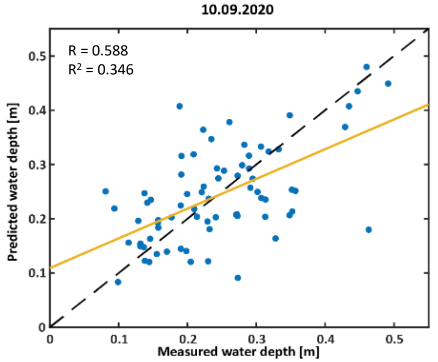
3. Results

• Validation





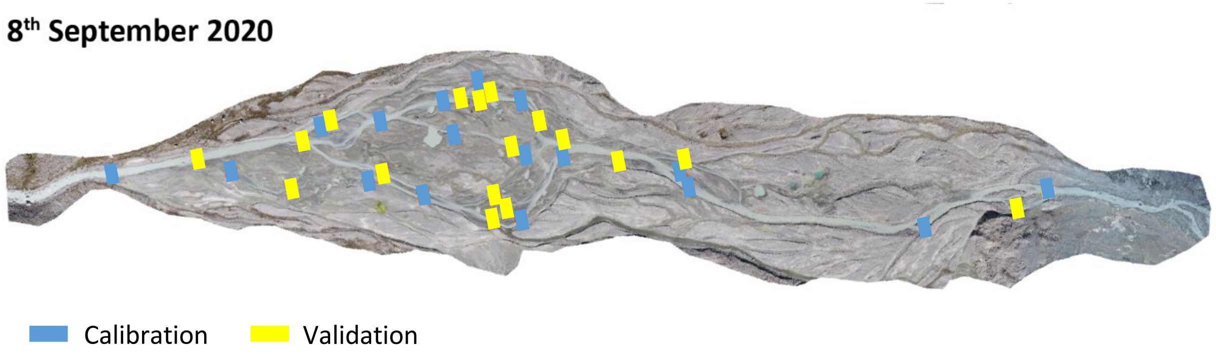




Results are largely to be significant (R^2 << 0.6)

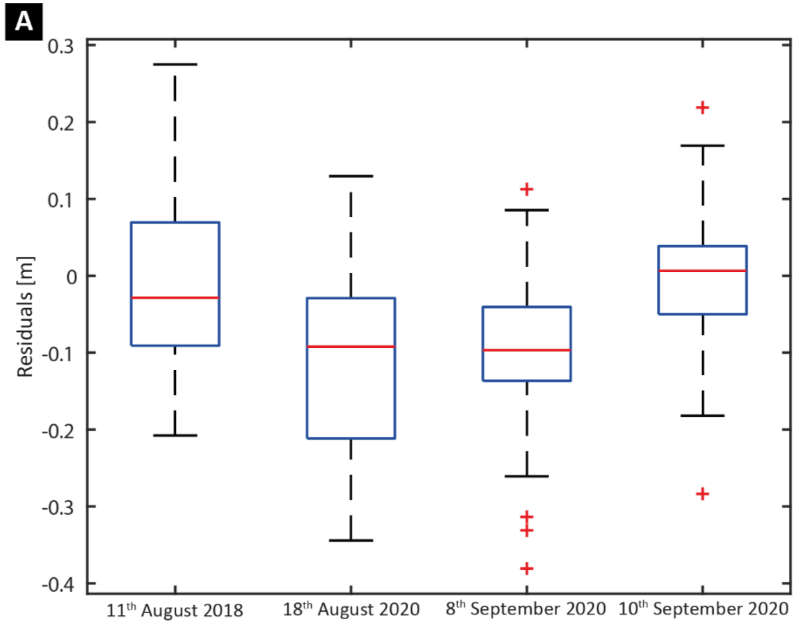
↓

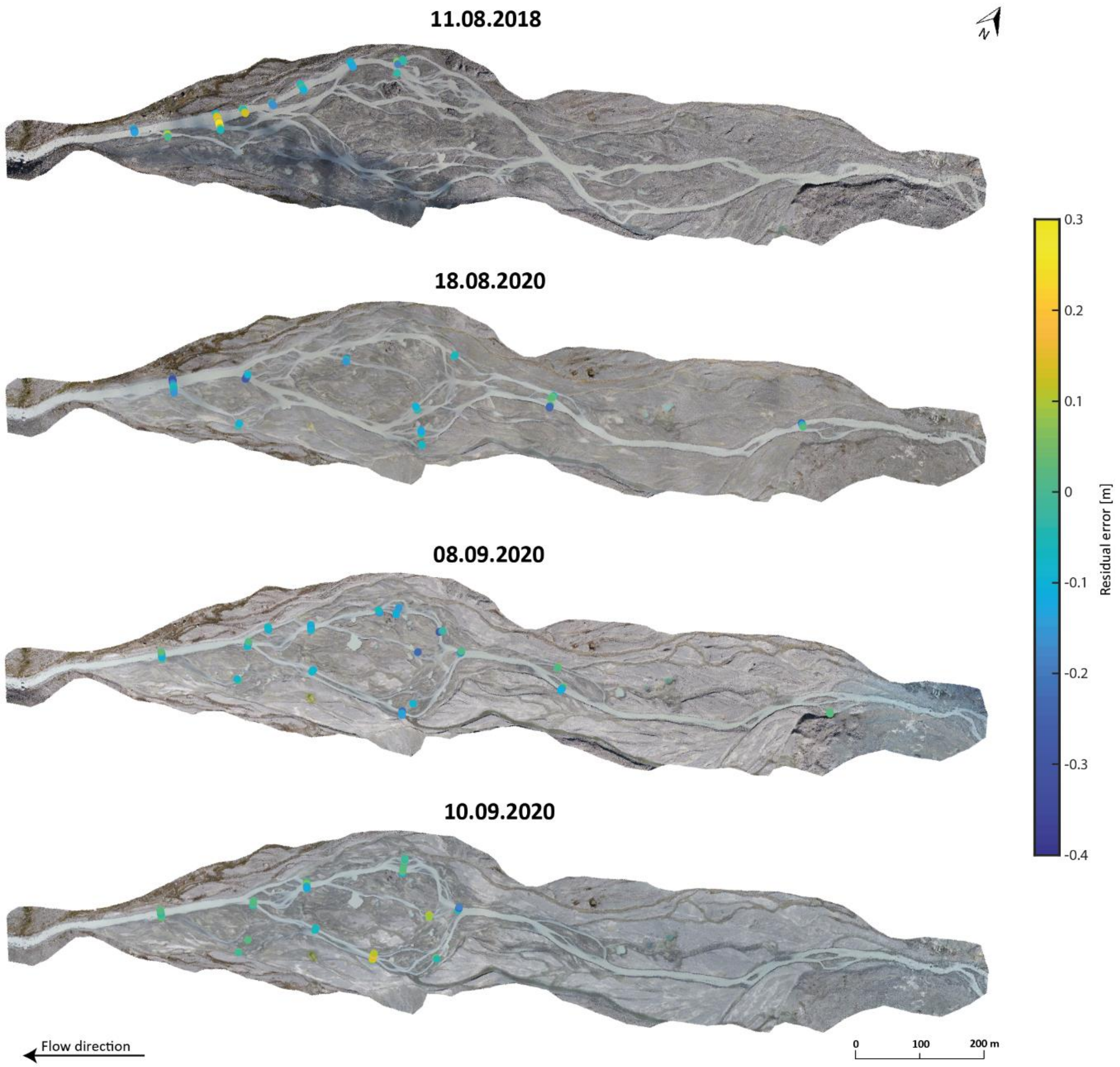
Number of observations + water depth measurements (main and secondary channels) for both validation and calibration process



3. Results

- Predictions - validation





3. Results

- Pool calibration: 2020 datasets

1. Water depth measurements:

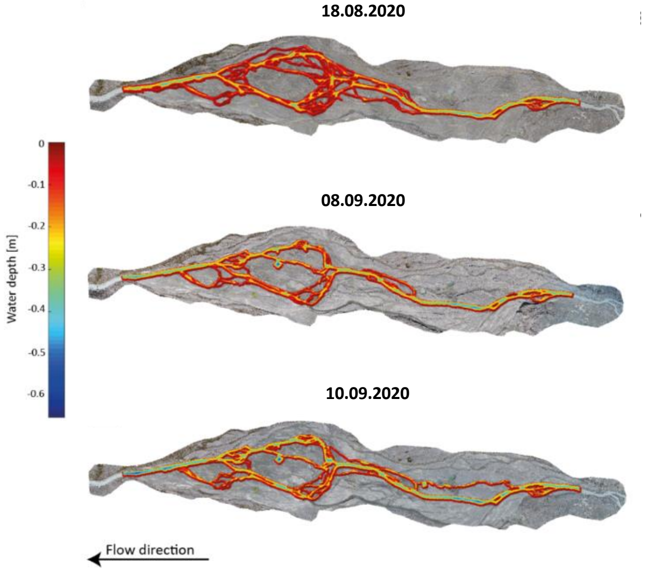
	Total	Calibration	Validation
Date	Number of points	Number of points	Number of points
18.08.2020	206	112	94
08.09.2020	259	136	123
10.09.2020	157	82	75
Total	622	330	

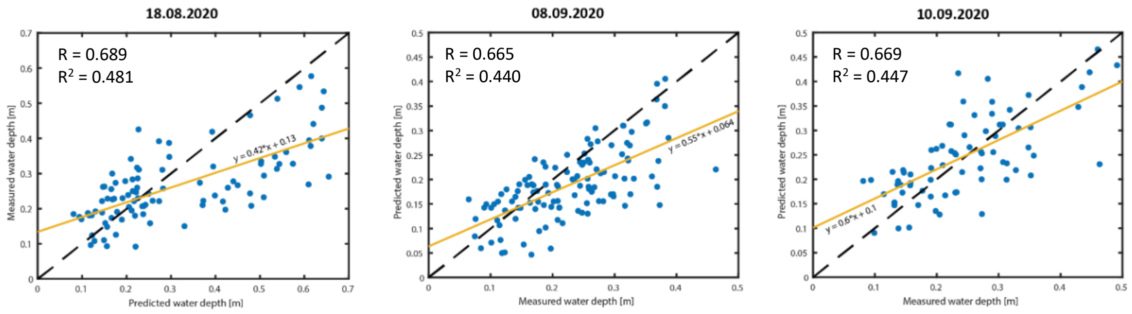
2. Stepwise regression: **Water depth** = $a_0 + a_1 \times (X_1) + a_2 \times (X_2) + a_3 \times (X_3) + a_4 \times (X_4) + a_5 \times (X_5)$

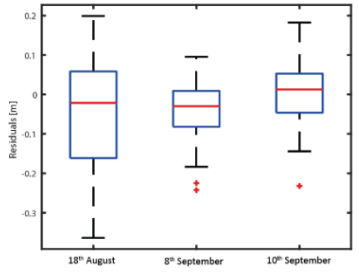
Step	Variable	Coefficient a						Statistics			
		a_0	a_1	a_2	a_3	a_4	a_5	R	R^2	SDE	p-value
1	Dist. nearest bank	0.147	0.083					0.596	0.355	0.118	2×10^{-26}
2	+ Divergence	0.132	0.073	0.001				0.751	**0.560**	**0.113**	8×10^{-8}

+ R^2
- SDE

3. Prediction and validation:

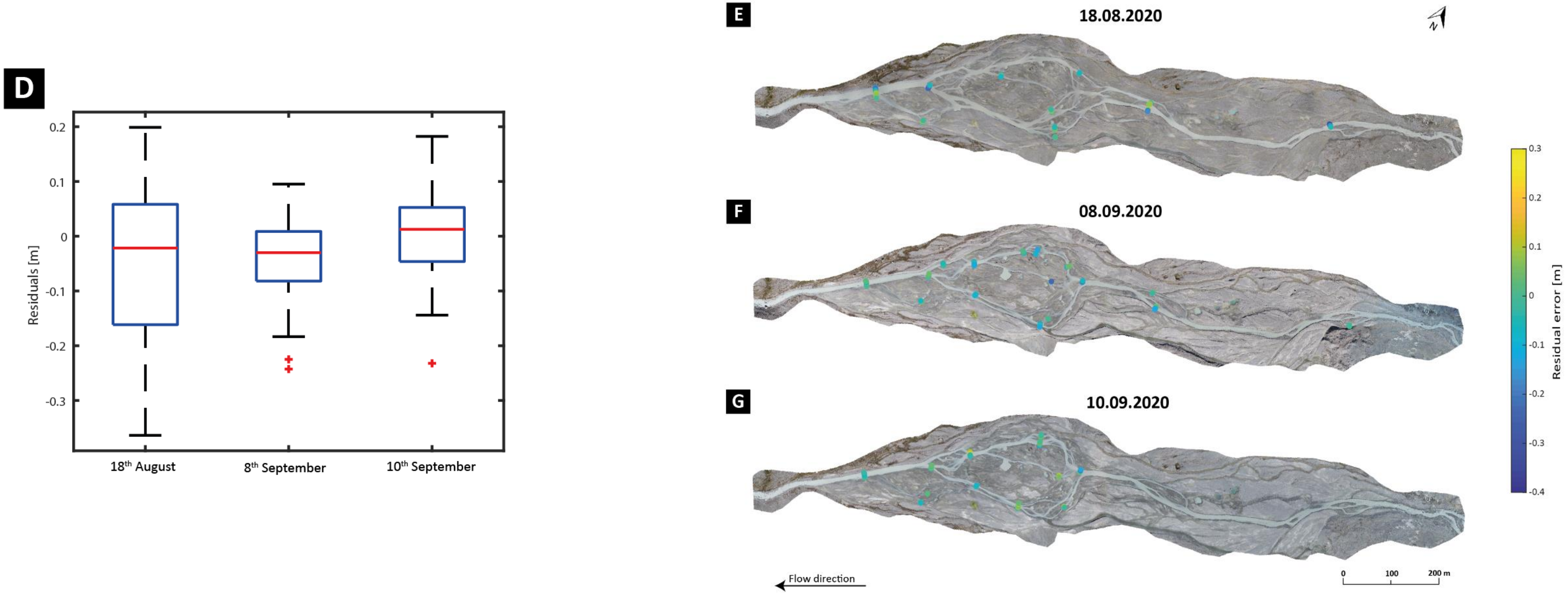






3. Results

- Pool calibration: residual error



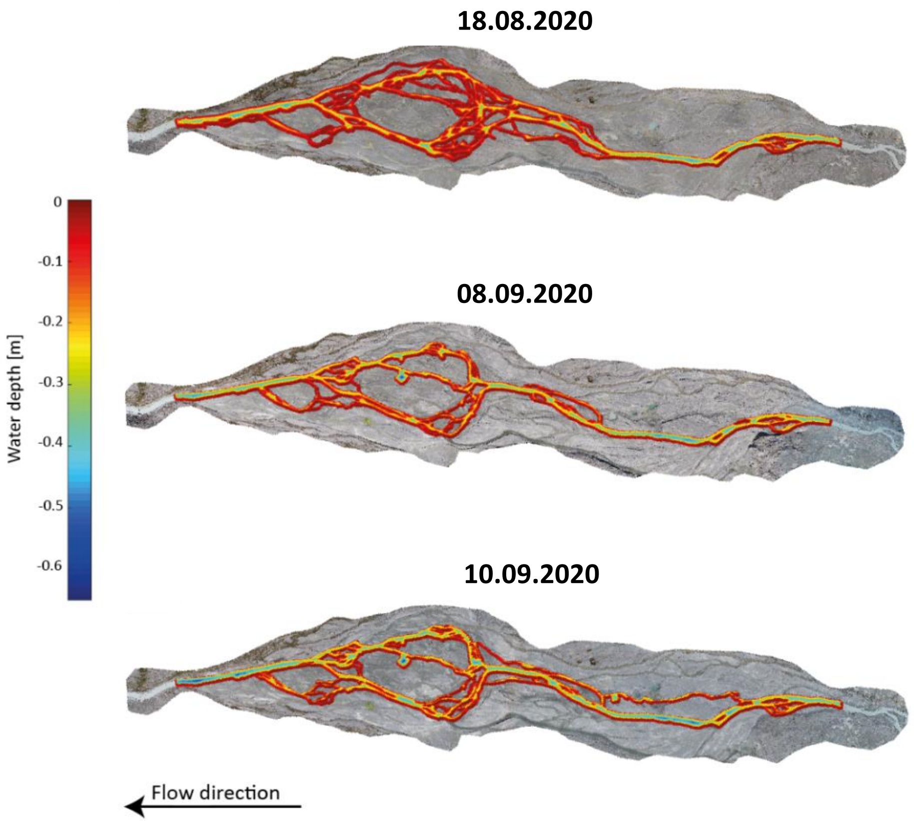
3. Results

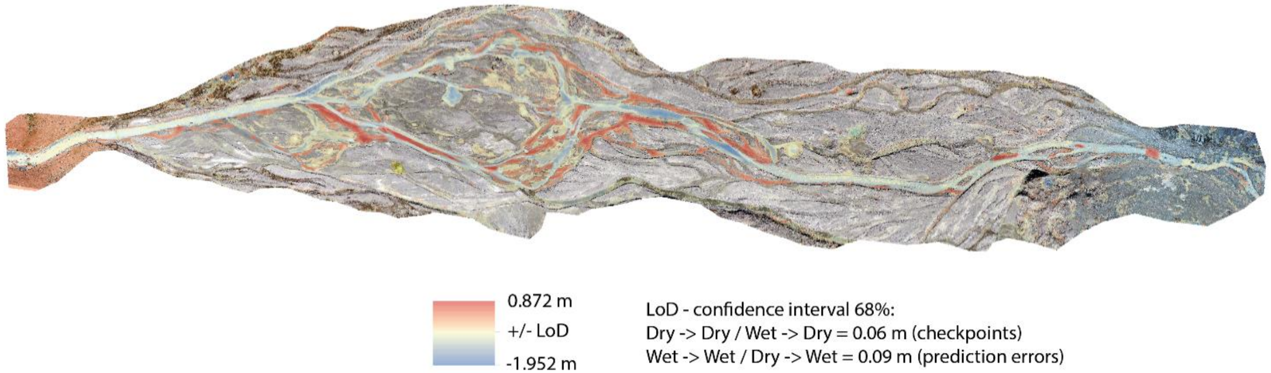
- Residual error distribution: single calibrated models vs. pool calibration

Date	Statistics	Specific models	Generalized model	% Difference
18th August	Median	-0.092	-0.022	-70.21
	Mean	-0.118	-0.052	-55.52
	SDE	0.114	0.122	+12.54
8th September	Median	-0.097	-0.030	-68.64
	Mean	-0.092	-0.030	-67.17
	SDE	0.086	0.064	-25.90
10th September	Median	0.006	0.012	-60.32
	Mean	0	0	0
	SDE	0.083	0.073	-10.84

3. Results

- DEMs of Difference





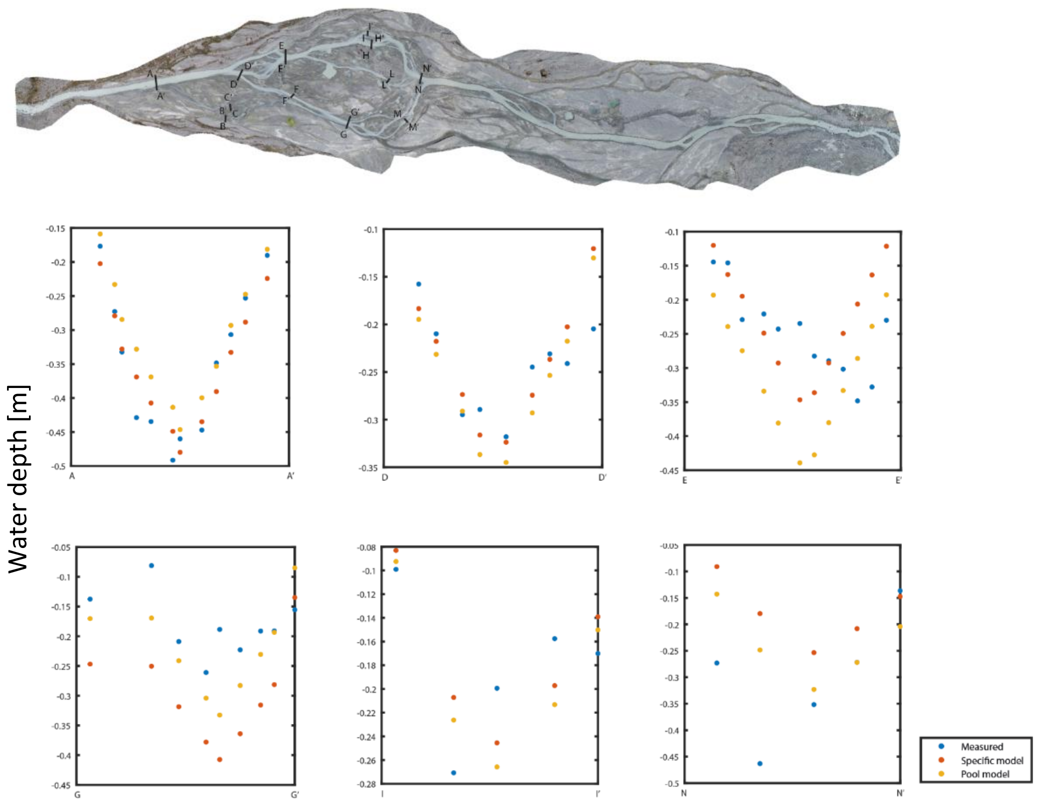
Inclusion into DEMs of dry region

4. Conclusions

- Take home messages:
  1. Basic morphometric information can be used to estimate water depth distribution in braided streams
     - ➢ Even with over -/ under- estimations the general shape of the channel is kept
  2. The pool model seems to have a higher predictive capacity compared to single calibrated models
     - ➢ Higher R^2 values and contained residual errors
  3. Water depth prediction maps are in line with basic hydraulic theories (e.g. Leopold and Maddock, 1953; Ashmore, 1991; Ashworth, 1996)
     - ➢ Water depth is deeper in straight and channelized reaches (i.e. main channel)
     - ➢ Flow divergence regions = shallower -> deposition
     - ➢ Flow convergence regions = deeper -> erosion

     Secondary channels

8th September 2020



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