Contactless river discharge from Unmanned Aerial Systems hydrometry: Performance evaluation using a large and diverse set of river cross sections

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Background

The river discharge measuremet is important, but it is…

Hard to reach

Time-consuming

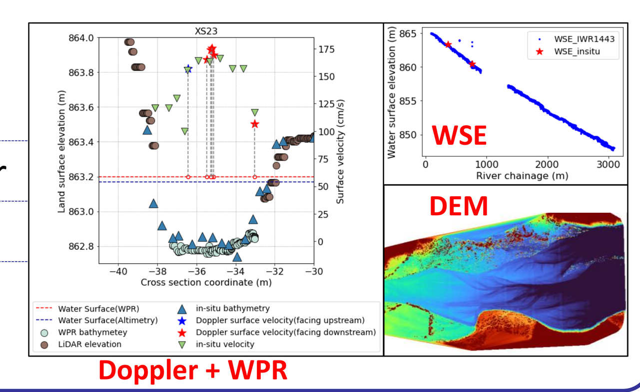
Even dangerous

Solution: Unmanned Aerial Systems (UAS) hydrometry[1]

Algorithm framework

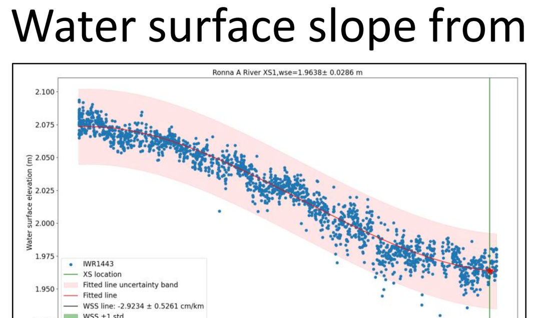
1 UAS hydrometry [2] :

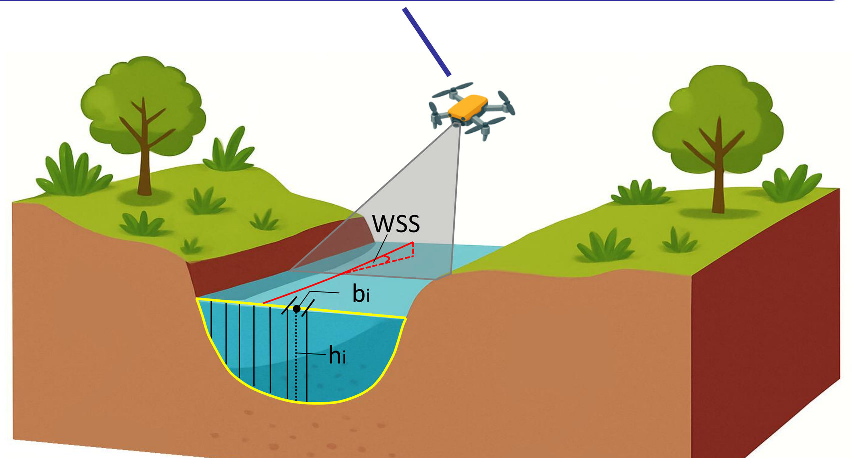
- Surface velocity: Doppler radar
- River bathymetry: Water penetrating radar
- Water surface elevation (WSE): Radar altimetry
- DEM elevation: LiDAR



2 Data processing:

- Surface velocity to bulk velocity
  - 0.85 model[3]
  - Power law model[4]
  - Log law model[5]
  - Entropy model[6]
- Water surface slope from WSE



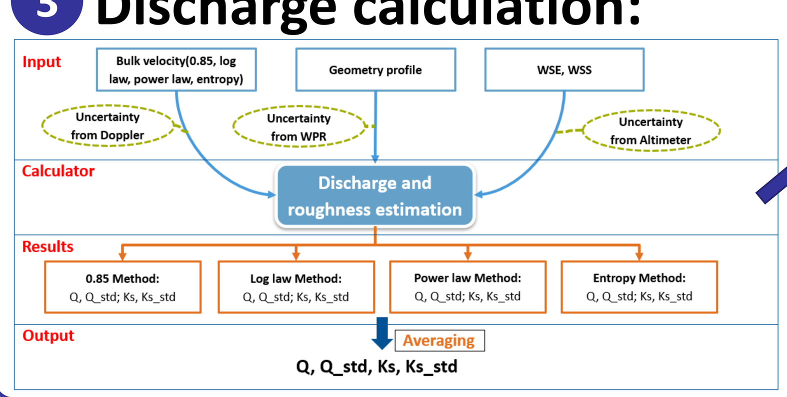


h_i - water depth of i_{th} segment

b_i - column width of i_{th} segment

WSS- Water surface slope from water surface elevation: equals to friction slope under diffusive wave approximation

3 Discharge calculation:



$$Q = K_s A R^{2/3} {S_f}^{1/2} \quad (1)$$

$$Q = \sum_{i=1}^{n} U_{m,i} b_i h_i \quad (2)$$

$\rightarrow \boxed{Q, K_s}$

- $\boldsymbol{Q}$ - discharge
- $\boldsymbol{K_s}$ - Gauckler-Manning-Strickler coefficient
- $\boldsymbol{R}$ - hydraulic radius: $R = A/P$ (P is wetted perimeter)
- $\boldsymbol{S_f}$ - friction slope: equals to WSS under diffusive wave approximation
- $\boldsymbol{A}$ - cross-sectional area
- $\boldsymbol{U_{m,i}}$ - vertical mean velocity of i_{th} water column

Study sites

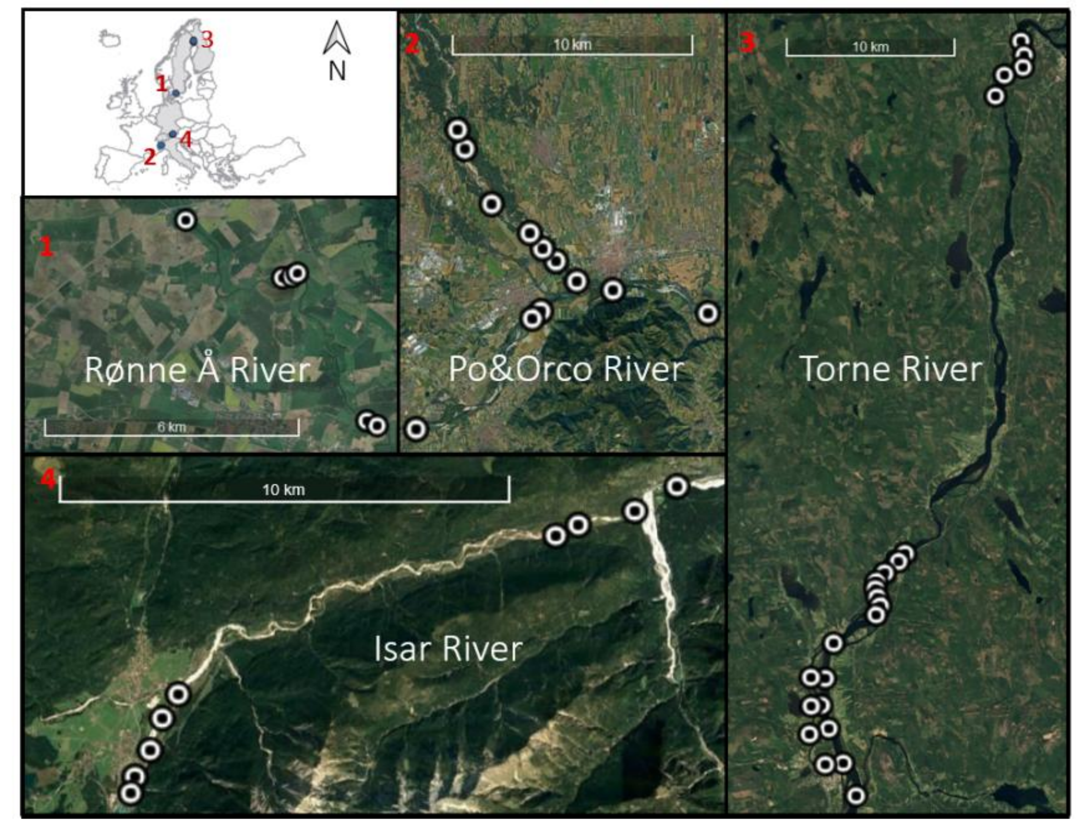


Fig1 Overview of measured cross-sections.

Minimum, maximum, median and mean values of cross-sectional properties

River		Area(m^2)	Depth (m)	Hydraulic radius(m)	Width (m)	Froude	Width/Depth ratio	Wetted perimeter (m)	Water surface slope(cm/km)
Torne	Min	24.404	0.421	0.420	56.562	0.066	64.507	34.471	3.960
	Max	1121.810	3.001	2.990	675.678	0.295	592.445	342.634	166.440
	Median	464.893	1.369	1.367	286.995	0.129	189.386	141.468	10.930
	Mean	505.764	1.517	1.515	335.186	0.142	248.541	181.046	35.623
Rönne å	Min	9.032	0.531	0.525	16.135	0.068	13.566	11.664	2.923
	Max	48.710	1.771	1.700	37.275	0.359	31.804	17.188	193.804
	Median	30.259	1.189	1.135	25.707	0.104	22.089	14.168	20.898
	Mean	31.171	1.188	1.140	24.621	0.143	22.347	14.202	86.465
Isar	Min	1.170	0.143	0.143	5.893	0.263	16.941	4.159	110.742
	Max	5.172	0.348	0.338	31.498	0.883	219.802	13.375	534.695
	Median	2.834	0.197	0.196	14.891	0.450	55.086	8.105	257.474
	Mean	3.096	0.231	0.228	14.837	0.502	80.347	8.600	291.125
Orco	Min	21.074	0.470	0.469	25.737	0.134	12.839	15.800	222.454
	Max	51.716	2.005	1.831	63.321	0.570	134.652	46.280	409.053
	Median	32.572	0.777	0.766	34.262	0.323	45.940	23.796	337.969
	Mean	35.720	0.981	0.942	41.246	0.344	58.258	25.928	326.307
Po	Min	101.004	1.047	1.040	78.866	0.096	61.685	44.740	10.706
	Max	360.522	1.661	1.651	216.693	0.434	130.429	157.775	129.370
	Median	116.839	1.157	1.147	107.910	0.324	103.095	71.774	90.115
	Mean	164.649	1.245	1.236	125.286	0.283	99.076	84.454	76.795

Torne River

Rönne River

Isar River

Orco River

Po River

Results

Algorithm performance in discharge calculation

Accuracy of calculated discharge compared to gauge station records

River	Percentage bias (%)	0.85	Log law	Power law	Entropy	average
All together	Max	46.95	50.09	48.03	72.88	47.84
	Min	-53.71	-71.43	-61.50	-54.28	-56.44
	Median	-3.94	-34.60	-20.06	8.40	-13.50
	Absolute Mean	22.83	34.13	26.68	25.06	24.45
Torne	Max	43.66	50.09	48.03	49.59	47.84
	Min	-30.19	-61.61	-50.47	-19.03	-40.03
	Median	-3.94	-34.60	-18.13	10.81	-12.82
	Absolute Mean	15.94	31.71	22.78	16.15	19.63
Rönne å	Max	46.95	41.81	40.01	72.88	40.14
	Min	11.88	-39.29	-42.07	-28.05	-21.84
	Median	28.31	-14.92	14.56	39.10	18.99
	Absolute Mean	29.00	26.79	23.41	42.18	22.71
Isar	Max	-31.93	-35.21	-34.82	-32.72	-33.67
	Min	-53.71	-71.43	-61.50	-54.28	-56.44
	Median	-44.23	-50.41	-49.92	-39.09	-47.43
	Absolute Mean	42.80	51.61	47.76	40.15	45.58

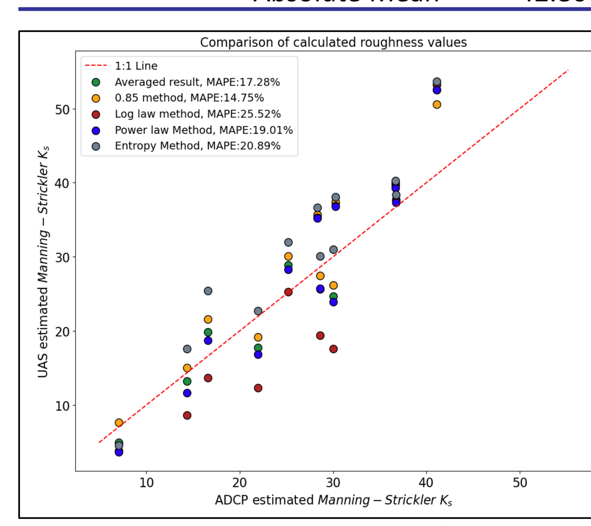


Fig2 Comparison of UAS-based and ADCP-based roughness values, evaluated using mean absolute percentage error (MAPE).

- Overall, the average discharge accuracy (MAPE) across four methods is 24.45%. The average accuracy (MAPE) of roughness is 17.28%.
- At the river scale, the Torne River (large, flat) shows the best performance with the 0.85 method; the Isar River (small, braided) performs the worst. For the Rönne å River (small, flat), the power law method is best, with power law and log law outperforming 0.85 and entropy methods.
- At the cross-section scale (Fig. 3), the accuracy of the 0.85 and entropy methods improves with larger cross sections, while the accuracy of the log law and power law methods increases with higher WSS.

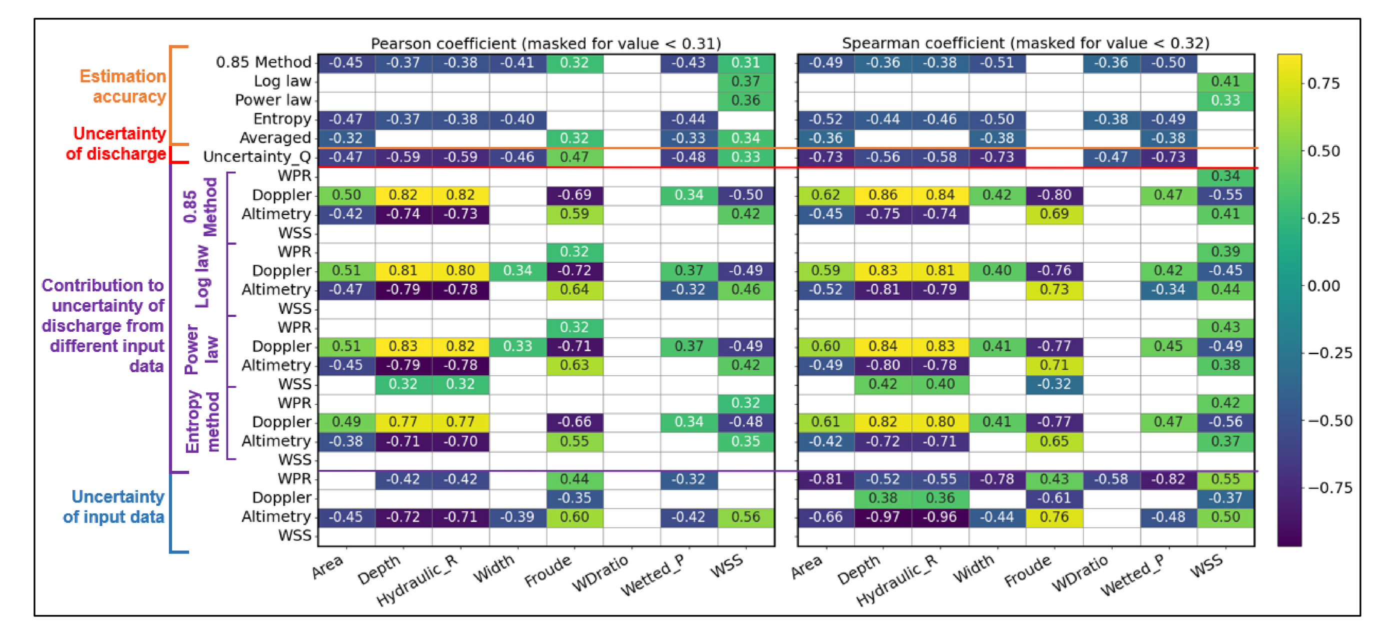


Fig3 Pearson (left) and Spearman (right) correlation coefficients between cross-section properties and (i) algorithm accuracy, (ii) discharge uncertainty, (iii) contributions of input uncertainties to discharge uncertainty, and (iv) input uncertainties. WPR represents river bathymetry measurements; Doppler refers to water surface velocity; altimetry indicates water surface elevation; WSS denotes water surface slope.On the x-axis, Hydraulic_R is the hydraulic radius, WDratio is the river width-to-depth ratio, Wetted_P is the wetted perimeter, and WSS is the water surface slope.

Uncertainty of the discharge calculation

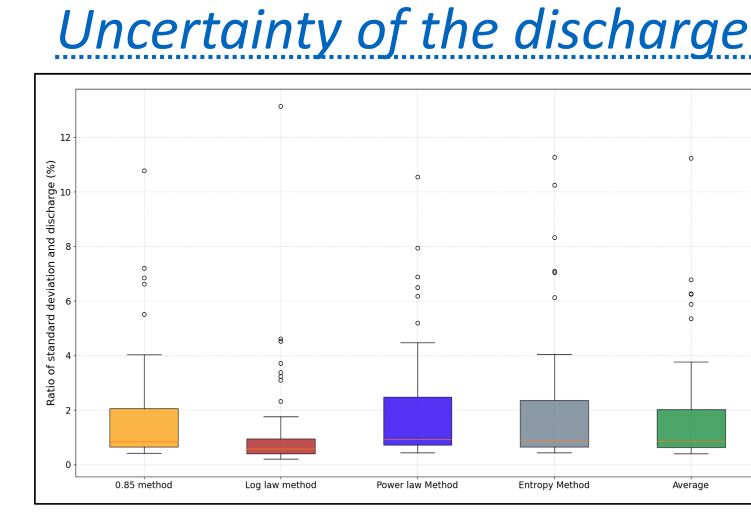


Fig4 Boxplot of uncertainty of calculated discharge.

- The overall discharge uncertainty due to input uncertainties ranges from 0% to 4%, expressed as the standard deviation normalized by the ensemble mean from Monte Carlo simulations (Fig. 4).
- Smaller cross sections tend to exhibit higher uncertainties (Fig. 3).
- The contribution of surface velocity measurements to discharge uncertainty increases with river depth, while the contribution from water surface elevation decreases (Fig. 3).
- Cross sections with greater water depth or lower Froude numbers are associated with higher uncertainties in surface velocity measurements (Fig. 3).

Extreme Scenarios Analysis

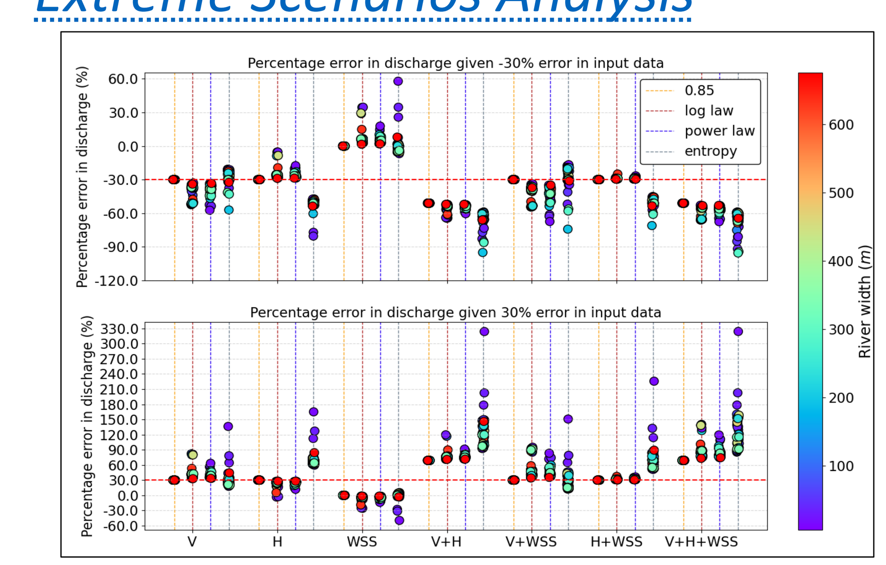


Fig5 Percentage change in calculated discharge under extreme scenarios with ±30% biases applied to different input combinations. V, H, and WSS represent surface velocity, water depth, and water surface slope, respectively. Points are color-coded by river width.

The 0.85 method does not amplify or attenuate input data errors during discharge calculation. The entropy method exhibits the highest variability in error propagation. Extreme error cases for all methods predominantly occur at cross sections with smaller widths.

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