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DATA DESCRIPTOR

UAS hydrometry: contactless river water level, bathymetry, and flow velocity – the Rönne river dataset

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High-resolution monitoring of rivers becomes important because more frequent and severe flooding and drought events are expected in the future, caused by climate change. Some key hydrometric variables (water surface elevation, bathymetry, and water surface velocity) can be acquired at high spatial resolution and in a contactless and noninvasive way using Unoccupied Aerial Systems (UAS). This paper presents a large publicly available UAS hydrometric dataset surveyed within a 10 km stretch of Rönne Å in Sweden from 28 August to 1 September 2023. The data were acquired using UAS radar altimetry for water surface elevation mapping, UAS water penetrating radar and UAS sonar for bathymetric mapping, and UAS Doppler radar for surface velocity monitoring. All data are divided into three processing levels: the raw data (Level 1), processed point data (Level 2), and point data referenced to a reference river centerline/reference cross section line (Level 3). *In-situ* ground truth and legacy UAS hydrometry payload data are included for comparison and validation. Good consistency indicates that the new UAS hydrometry payloads provide satisfactory datasets.

Background & Summary

High-resolution river monitoring has become more important because frequent and severe floods are caused by climate change and extreme events in the age of global warming¹. *In-situ* station-based monitoring infrastructure is vulnerable and often fails during extreme flooding events when the value of information is very high. Station-based monitoring networks lack spatial resolution and have been declining in many regions, particularly in remote and hard-to-reach areas². Data accessibility is increasingly restricted because of growing conflicts between countries over water resource allocation. To solve these problems, effective, contactless hydrometric monitoring solutions (e.g., water surface elevation, bathymetry, and water surface velocity) deployed using Unoccupied Aerial Systems (UAS), are a frontier of current research and development in river hydrometry³. Because these methods are deployed airborne and contactless, integrating both the airborne platform and the geophysical sensors (e.g., altimetry radar, sonar, water penetrating radar, and Doppler radar), they are ideally suited for remote and hard-to-reach areas and extreme physical conditions.

Water surface elevation (WSE) is an important hydrometric parameter, which is used to calibrate hydraulic and hydrological models^{4–6}, predict floods^{7–9}, and assess climate change impacts. A UAS radar altimetry payload was developed at the Technical University of Denmark that delivers 3 cm accuracy in the vertical and has been demonstrated to outperform competing lidar and photogrammetry methods in the Danish operational environment characterized by small and heavily vegetated streams¹⁰. However, a commercial drone radar altimetry solution for WSE mapping in Arctic, alpine, and tropical operational environments in Europe and beyond is currently not available on the market. Therefore, a new commercial UAS radar altimetry payload based on the Geolux radar altimetry instrument was developed in the UAWOS project¹¹.

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Detailed bathymetry maps of riverbed and floodplain areas are essential for assessing flood hazard^{12–14} and predicting sediment transport and streambed morphological evolution^{15–18}. UAS tethered sonar payloads are an alternative for deeper and more saline inland water bodies. Bandini *et al.*¹⁹ measured accurate water depths using a UAS tethered sonar in a lake and in two different rivers located in Denmark and obtained bathymetry with an accuracy of ca. 2.1% of the actual depth for observations up to 35 m¹⁹; however, stability and accurate positioning of the sonar sensor is still a challenge, especially in fast-flowing rivers and wavy inland water environments. UAS water penetrating radar (WPR) technology has been demonstrated for mapping riverbed geometry in freshwater environments with low electric conductivity, delivering accurate bathymetry results with an average MAE of approx. 8 cm (thus similar to the vertical resolution of the radar at the frequency of ca. 80 MHz) compared to *in situ* RTK GNSS²⁰. However, noise caused by surface clutter commonly contaminates the early portions of the radargrams of drone-borne WPR. In waterbodies with soft clayey beds, UAS WPR performance degrades compared to ground-truth. Sonar and WPR technology still need to be extensively validated and demonstrated for a range of operational river environments, especially in vegetated water bodies and remote and hard-to-reach areas.

River surface flow velocity is essential to evaluate sediment deposition, erosion processes, and discharge^{21–25}. Currently, the most widely used methods for contactless airborne water velocity measurements are optical tracking methods based on time-lapse imagery, also called Particle Image Velocimetry (PIV)^{26–28} and Space-Time Image Velocimetry (STIV)^{29,30}. However, such methods have several drawbacks in operational settings, such as seeding, daylight, and river width requirements³¹. Doppler radar shares the advantages of largely automatic data acquisition and processing workflows to obtain a cross-sectional profile of surface flow velocity. It has been widely used in static instruments mounted on bridges etc.^{32,33}. The stationary measurements were shown to be accurate to within ca. 10 cm/s when compared with *in situ* measurements. However, Doppler data from moving airborne platforms is still scarce, and airborne deployment leads to several new challenges. Only a few studies report actual UAS deployment of a Doppler radar, which shows unreliable results for rivers with low water surface roughness and poor repeatability^{34,35}.

In summary, radar altimetry, sonar/WPR bathymetry, and Doppler radar velocimetry payloads have been demonstrated for selected operational environments only (not Arctic/alpine/tropical), at the proof-of-concept level. There is a need to share UAS hydrometry datasets in the public domain to be used as proof of concept/validation of UAS-based measurement technologies for stream monitoring under both normal and extreme conditions to establish the technologies as viable and widely accepted alternatives to ground-based techniques^{19,20,23,36,37}. The purpose of this dataset is to demonstrate that UAS hydrometry can achieve accuracy comparable to *in-situ* measurements while offering cost advantages and superior coverage and resolution. To this end, we included datasets from the new UAS hydrometry sensors, selected airborne legacy sensor datasets and traditional *in-situ* ground-truth datasets. When applied to other sites and conditions, UAS hydrometry can contribute significantly to climate adaptation by enabling managers to collect more detailed and comprehensive data at a lower cost. In this dataset, we present the drone (DJI Matrice 300) GNSS positioning data with the radar altimeter (Geolux LX-80) for measuring WSE, with sonar (ECT400s) and WPR (Zond Aero LF) for measuring the river depth, and with Doppler radar (Geolux RSS-2-300W) for measuring the river surface flow velocity. The UAS hydrometry payloads are being developed and commercialized in the UAWOS project funded by the European Commission under Horizon Europe. The surveyed river is Rönne Å in South Sweden, and field data were collected from 28 August to 1 September 2023. To validate the contactless UAS hydrometry datasets acquired using the UAWOS payloads, *in-situ* measurement techniques and legacy UAS hydrometry payloads were deployed concurrently. Statistical analyses of the datasets reveal small error margins and deviations within acceptable thresholds, which demonstrates the reliability of the UAS hydrometry payloads developed in UAWOS.

Methods

This section describes the sensors and surveying workflows used to acquire various hydrometric parameters. Field-measured data were collected from 28 August to 1 September 2023 at Rönne Å in South Sweden. Six cross-sections (XSs) were surveyed (see Fig. 1), and XS taglines, which are set up perpendicular to the flow direction, are established to mark each XS in the river. The right and left banks are determined by convention by looking towards the downstream direction (Fig. 2).

In this field survey, we applied 4 different types of drones: DJI Matrice 300 (M300), DJI Matrice 600 (M600), DJI Phantom 4 Pro, and Hydrohex (DTU own development). The M300 and M600 platforms were integrated with SPH Engineering's UgCS SkyHub - a small, powerful onboard computer with special software, which is used to maintain a constant altitude of the drone over the surface using data from the radar altimeter, and also to control and store georeferenced raw sensor data. Furthermore, during the field measurement process, the M300 and M600 drones, equipped with the UgCS software and its specialized add-on, enable seamless mission planning with precise flight height control. Operators set the desired flight altitude and speed, then activate the True Terrain Following mode. The system handles navigation autonomously, ensuring accurate and efficient operations. In contrast, the DJI Phantom 4 Pro and Hydrohex are operated manually. To verify the datasets acquired by the new UAS hydrometry sensors, some legacy UAS sensors and *in-situ* measurement techniques are applied. Table 1 summarizes the different combinations between UAS platforms and sensors used in the survey. In Fig. 3, a schematic of a representative stream cross-section is presented, depicting the flight altitudes and trajectories of various sensors mounted on the UAS.

UAS radar altimetry and *in-situ* WSE. The UAS radar altimetry payload enables mapping of WSE in rivers and streams at very high spatial resolution (less than one meter) and high accuracy (less than 3 cm). The main principle of UAS radar altimetry is using a radar to measure the distance between the radar and the water

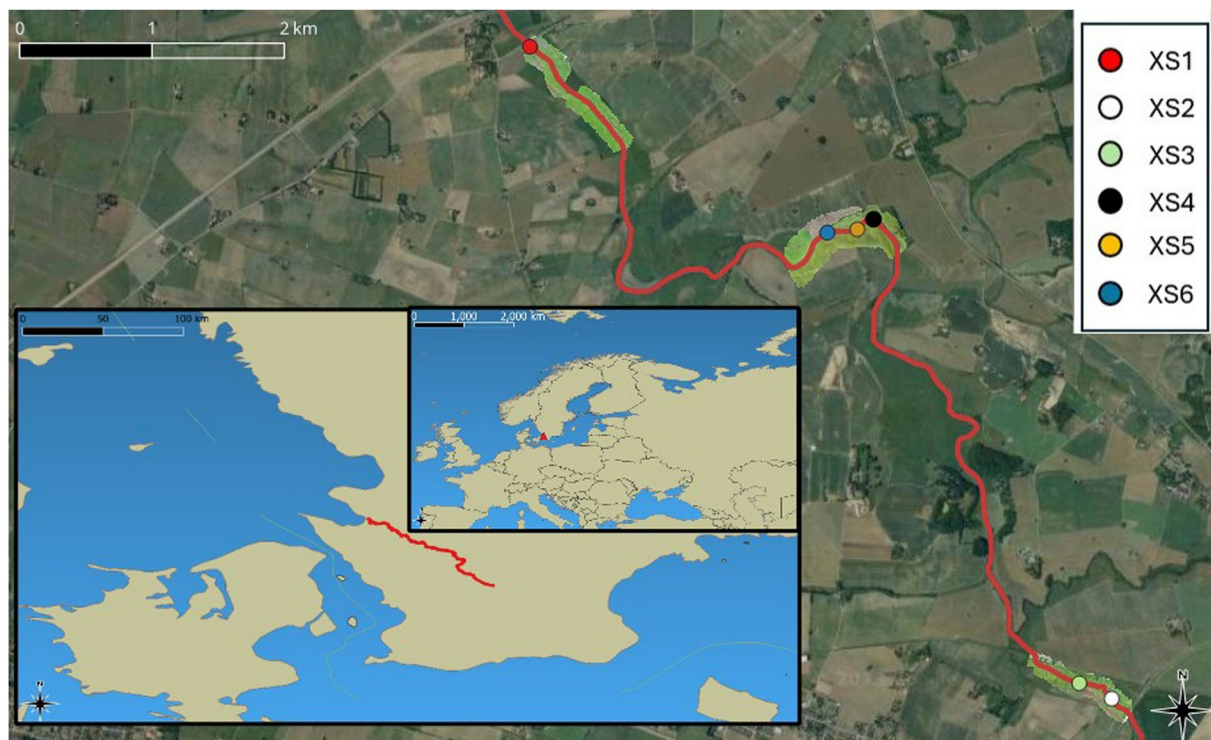


Fig. 1 The red triangle and red line in inserted overview map show the measured river location of Rönne Å in Sweden (source for the inset map is from natural earth data). Selected 6 cross-sections (XSs) measured in this study are shown using solid circles. Red line indicates the river survey centerline⁴⁷.

surface (range) and using GNSS (Global Navigation Satellite System) to measure the accurate RTK/PPK (Real Time Kinematic/Post-Processed Kinematic) position of the sensor. By subtracting the range to water surface from the GNSS-derived altitude, WSE can be determined. The accuracy of WSE measurements is a combination of the accuracy of both the ranging sensor and the GNSS system¹⁰.

In this paper, WSE surveys were carried out using the drone M300 with a radar altimeter sensor Geolux LX-80 (LX80) ranging radar platform, which is a frequency-modulated continuous wave radar sensor that operates in W-band, at frequencies between 77 GHz and 81 GHz. The UAS radar measures along the river centerline with a measurement rate of 10 Hz. The maximum detection distance is 30 m, and the measurement resolution is 0.5 mm. The sensor LX80 has been re-engineered to allow simple installation on the UAS, to allow integration with the UAS on-board computer, and to ensure that the measured data is transferred in real-time since the payload is attached to the moving platform. The radar altimeter payload delivers the data through two communication interfaces simultaneously. The first interface is RS-232 serial line, which delivers processed radar data with 10 samples per second sampling rate, stored as ASCII-encoded csv files. The second interface is CAN bus, which delivers seg-y format files for full radar echo curve output, at up to 1 sample per second sampling rate. In this survey, because the radar altimeter was not stabilized using a gimbal, we had to take measured drone pitch and roll angles into account to calculate the nadir range to the water surface from the recorded slant range.

For validation, we also surveyed WSE using the drone M600 equipped with the legacy radar altimeter sensor IWR1443^{10,38}. The radar was configured with 1 transmitting antenna and 2 receiving antennas, with the chosen chirp configuration resulting in a bandwidth of 4 GHz, a measurement rate of 5 Hz, 1024 range bins, maximum unambiguous range of ca. 30 m, and vertical resolution of ca. 0.036 m. Crucially, and unlike the LX80, the IWR1443 sensor was mounted on a gimbal.

In addition, *in-situ* WSE measurements were taken using a [EMLID REACH RS2+](#) GNSS receiver along the river chainage.

UAS sonar, UAS WPR, and ground truth bathymetry. A sonar payload enables mapping of riverbed elevation/bathymetry in rivers and streams at very high spatial resolution (less than one meter) and high accuracy (less than 10 cm). Bathymetry mapping with the sonar payload combines datasets from the drone GNSS system and a sonar sensor^{19,20}. The main principle is measuring the travel time of ultrasound waves through the water column and determining the depth using the known speed of sound in water (approx. 1500 m/s), which varies moderately with water temperature and salinity^{39,40}. As an established reference technology for measuring depth in water bodies, the sensor must be in contact with the water during the measurement period.

In this paper, we chose the drone M300 equipped with the sonar sensor ECT400s, in which the sensor is a single beam echo-sounder with 450 kHz frequency, as the main sonar bathymetry surveying system. The sensor has a tethered arrangement to attach the sensor to the drone, which is equipped with integrated tilt sensors,

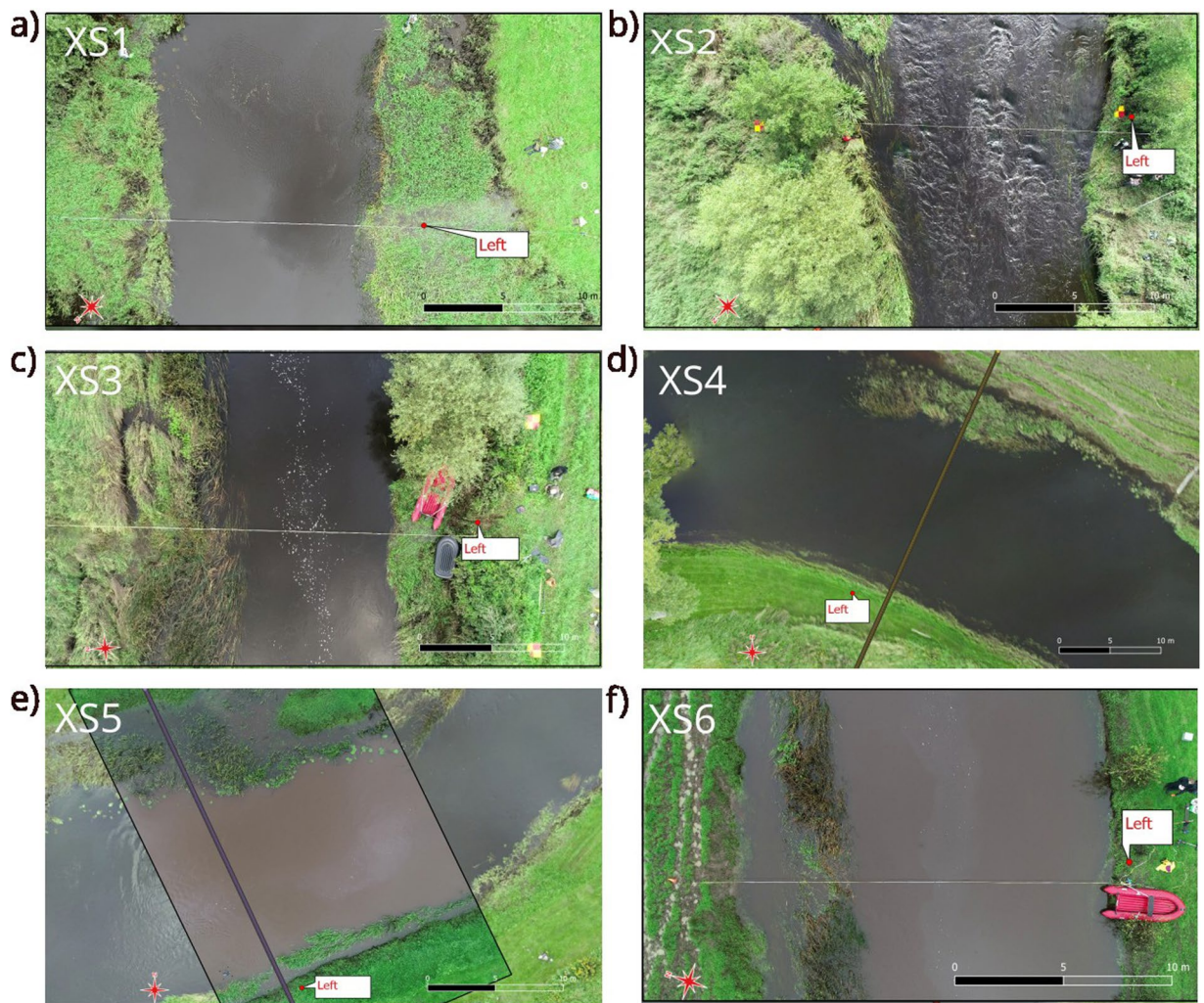


Fig. 2 The top view figures of 6 XSs, in which white and brown lines indicate the taglines of XSs, the left bank selected according to the conventional method of looking towards the river flow direction. From (a) to (f), XS1, XS2, XS3, XS4, XS5, XS6 are shown in sequence.

allowing to reject data when the sensor attitude is not close to vertical, and a temperature sensor. Tilt angles and water temperature are logged along the depth. The nominal accuracy of ECT400s is 0.2% of the depth, and the depth resolution is < 1 mm. An alternative surveying system is the Hydrohex floatplane, equipped with the sensor [ECT400](#). For data collection, the Hydrohex lands on water and navigates along the chosen survey line. As a third technique we use a legacy approach⁴¹, which is based on the drone M600 and the single beam sensor [Deeper Smart Sonar CHIRPplus](#). This sonar is a single beam echo-sounder with Narrow CHIRP 675 kHz (7° cone angle), Medium CHIRP 240 kHz (20° cone angle) and Wide CHIRP 100 kHz (47° cone angle) frequencies. In this survey, we use the narrow beam (675 kHz) because of its ability to penetrate through vegetation^{19,41}. The sonar payload is mounted on the UAS with a rigid, foldable telescopic-arm solution, the UAS was flown along each XS with the sensor always staying on the water surface.

Water penetrating radar (WPR) is the preferred solution for contactless bathymetry measurements because, unlike sonar, it can be deployed without direct contact to the water surface at low flight altitude of drone by transmitting and receiving reflected electromagnetic (EM) waves. Moreover, WPR penetrates through submerged vegetation to map the true riverbed, also in densely vegetated lowland streams. A UAS WPR bathymetry survey enables mapping of bathymetry in rivers and streams at very high spatial resolution (less than one meter) and high accuracy (less than 10 cm). The acquired WPR traces are geotagged by synchronization between the high-precision GNSS carried by UAS and WPR sensors and river bottom reflections are extracted from the radargrams. Further, the water depth is converted to elevation using the known elevation of the water surface.

Here, we adopted the drone M300 equipped with the sensor [Zond Aero LF](#) system as the main UAS WPR bathymetry technique, in which the sensor is a single-channel receiver with an unshielded dipole antenna. The radar sensor antenna center frequency can be adjusted by adjusting the length of the dipole antenna. During the measurement, we assessed 3 different frequencies (100 MHz, 150 MHz, and 300 MHz) with various antenna directions (parallel or perpendicular to the stream). The UAS was flown along each XS while keeping a constant low altitude with the WPR antenna approx. 0.2–1.0 m above the water surface. An alternative legacy approach²⁰

Parameters	Platform	Sensor	Sensor type	Measurement rate	Accuracy	Cross sections	Date of survey
WSE	M300	Radar (Geolux LX-80)	new	10 Hz	less than 3 cm		08/28/2023 08/29/2023
	M600	Radar (IWR1443)	legacy	5 Hz	3 cm		08/28/2023 08/29/2023
	<i>In-situ</i>	EMLID REACH RS2+	ground truth	Real-time	RTK: H: 7 mm + 1 ppm V: 14 mm + 1 ppm		08/28/2023
Bathymetry	M300	WPR (Zond Aero LF)	new	100/150/ 300 MHz	less than 10 cm	XS2/3	08/30/2023
						XS4/5/6	09/01/2023
	M600	WPR (Gekko 80)	legacy	80 MHz	10 cm	XS1	08/29/2023
						XS3	08/30/2023
						XS4/5/6	08/31/2023
	M300	Sonar (ECT400S)	new	450 kHz	less than 10 cm	XS1	08/29/2023
						XS2/3	08/30/2023
						XS4/5/6	09/01/2023
	Hydrohex	Sonar (ECT400)	new	450 kHz	less than 10 cm	XS1	08/29/2023
						XS2/3	08/30/2023
						XS4/5/6	08/31/2023
	M600	Sonar (DeeperCHIRPplus)	legacy	675 kHz	10 cm	XS1	08/28/2023
						XS2/3	08/30/2023
						XS4/5/6	08/31/2023
	Boat	ADCP (Teledyne RiverPro 1200)	ground truth	Slant: 1228.8 kHz; Vertical: 614.4 kHz	± 1%	XS1	08/29/2023
	Boat	ADCP (SonTek RS5)	ground truth	3.0 MHz	1% ± 0.005 m	XS2/3	08/30/2023
						XS4/5/6	09/01/2023
	<i>In-situ</i>	EMLID REACH RS2+ and ruler	ground truth	Real-time	RTK: H: 7 mm + 1 ppm V: 14 mm + 1 ppm	XS1	08/29/2023
						XS2/3	08/30/2023
						XS4/5/6	08/31/2023
Land elevation	M300	DJI Zenmuse L1 Livox Lidar	legacy	240,000 pts/s	cm level	XS1	08/29/2023
						XS2/3	08/30/2023
						XS4/5/6	08/31/2023
Flow velocity	M300	Doppler radar (RSS300)	new	10 Hz	less than 10 cm/s	XS1	08/29/2023
						XS2/3	08/30/2023
						XS5/6	08/31/2023
	DJI Phantom 4 Pro	video-camera GoPro Hero 5	legacy	59.94 frames/s	15–20 cm/s	XS1	08/29/2023
						XS2/3	08/30/2023
						XS5/6	08/31/2023
	<i>In-situ</i>	OTT MFPro	ground truth	Real-time	± 2% ± 0.015 m/s (0 - 3 m/s) and ± 4% ± 0.015 m/s (3 - 5 m/s)	XS1	08/29/2023
						XS2/3	08/30/2023
						XS5/6	08/31/2023

Table 1. Platform and sensor settings for measuring different hydrological parameters along each XS in this study.

deployed for validation is based on the drone M600 and the sensor [Gekko 80](#). The adopted antenna center frequency is 80 MHz. And the sensor antenna direction is perpendicular to the stream. The UAS was flown over each XS while keeping a constant low altitude with the WPR antenna approx. 0.5–0.6 m above the water surface.

Ground truth bathymetry was collected using a remote controlled ADCP boat and RTK ruler surveys. The ADCP bathymetry was performed based on sensors [Teledyne RiverPro 1200](#) (for XS1) and [SonTek RS5](#) (for XS2–XS6) equipped on a boat. The [EMLID REACH RS2+](#) was also used to measure WSE elevation at each XS to subtract the sonar/WPR depth and get the bathymetric profiles. Meanwhile, we used conventional XS measurements with both RTK GNSS and ruler measurements as ground truth observations.

UAS lidar land elevation. Lidar data, which is the state of the art approach for measuring land elevation adjacent to the river channel, were collected using the drone M300 and the sensor [DJI Zenmuse L1](#). The sensor integrates a Livox solid-state Lidar module, GNSS receiver, an IMU, and a 20 MP camera featuring a 1-inch CMOS sensor. All mounted on a stabilized three-axis gimbal to capture the real-time three-dimensional data. This enables efficient and accurate reconstruction of complex structures, resulting in accurate models. During the flights, the manufacturer-recommended altitude of 50 m was applied to ensure optimal accuracy. The data was collected with 50% overlap, in triple return mode with repetitive scanning, and with RGB coloring enabled. The Livox Lidar module scanned the area at a 160 kHz sampling rate in a repetitive scanning pattern, supporting a

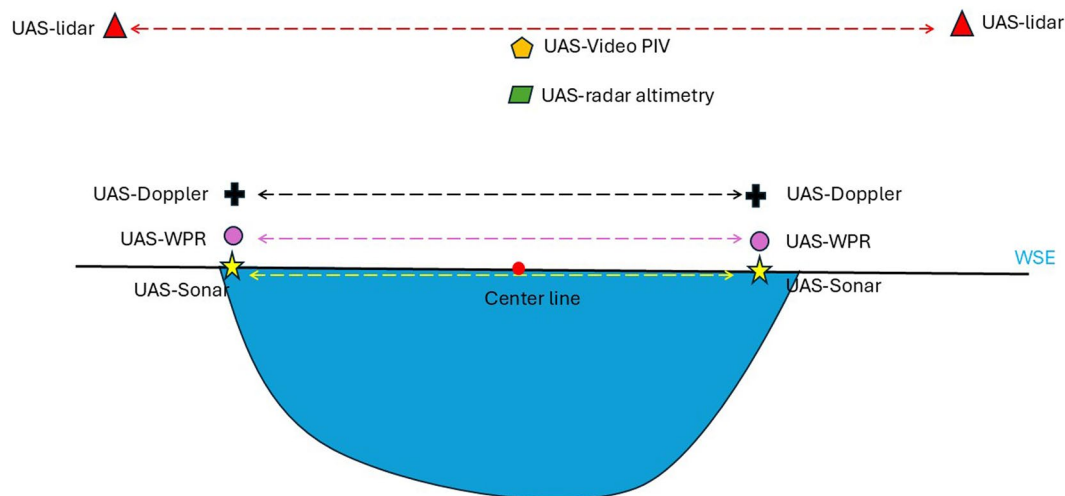


Fig. 3 Presents a schematic illustrating the various UAS-mounted sensors and their corresponding flight trajectories. The footprint trajectory of the UAS-lidar, flying at a height of 50 m above the WSE, is represented by the red dashed line, with the effective area restricted to non-submerged regions. The UAS-video system hovers in a fixed position at an approximate height of 35 m for at least 1 minute to capture steady footage for PIV calculations. To measure WSE, the UAS-radar follows the river's centerline at an altitude of a max height of 30 m. For UAS-Doppler measurements, several waypoints are designated along the black dashed tagline. At each waypoint, the sensor remains stationary for at least 1 minute at varying altitudes ranging from 1.5 m to 6.1 m, always oriented upstream. UAS-WPR and UAS-sonar are used to measure river depth. The primary difference is that the UAS-WPR operates at a height of approximately 0.2 m to 1.0 m above the WSE, while the sonar must remain in direct contact with the water. Both sensors follow similar flight trajectories.

maximum of 3 echo returns^{42,43}. **DJI Terra** software was used for the post-processing of the Lidar flight data. The drone M300 leveraged RTK georeferencing to conduct an accurate survey using this sensor.

UAS Doppler radar velocimetry. River surface velocity can be measured using contactless Doppler radar sensors³⁵. Due to the Doppler effect, the frequency shift between the transmitted and reflected electromagnetic waves will be proportional to relative velocity between the radar instrument and the water surface^{44–46}. Keeping the radar instrument in a static position while the measurement is being made, the frequency shift will be proportional solely to the river flow velocity of the water at the surface. Deploying the Doppler radar payload on UAS platform provides a measurement of surface flow velocity in rivers and streams at a spatial resolution of the Doppler radar footprint size⁴⁷. In this paper, the Doppler radar payload is the **Geolux RSS-2-300W** surface velocity radar mounted on the drone M300. The sensor is a continuous-wave (CW) Doppler-radar operating in K-band, at 24.125 GHz center frequency f_0 and with a wavelength of 12.5 mm when traveling in the air. Here, we applied 45 degrees as the incidence angle of the transmitted radar signal on the water surface. The radar works for river surface velocities between 0.02 m/s to 15 m/s with a velocity resolution of 7.3242 mm/s, a sampling rate of 10 sps (samples per second), and a small measurement repeatability error ($<1\%$) of the true measured value⁴⁷. During the planned flight for each XS, the UAS equipped with the Doppler radar was hovering at each waypoint to retrieve observations for measurement periods of about 1 min. The flight direction between two waypoints was planned to keep the UAS nose pointing perpendicular to the river flow. During the radar measurements, the radar was always looking against the flow direction. Finally, we acquired Doppler data in the 5 selected XSs with 5 different flight altitudes (1.5 m, 2.1 m, 4.1 m, 5.1 m, and 6.1 m).

Image velocimetry and *in-situ* velocimetry. To verify the Doppler radar results, the video-camera GoPro Hero 5 in 1080p HD with 60 frames per second⁴⁸ mounted on the drone **DJI Phantom 4 Pro** was used for recording the selected 5 XSs. Particle Image Velocimetry (PIV)^{49–51} was used to post-process the acquired videos. For XS1, the water surface did not contain enough natural particles for successful PIV analysis, thus artificial seeding (woodchips) was thrown into the water by two operators standing on two banks of the river.

In addition, the *in-situ* velocimetry along XSs was measured using the electromagnetic flow sensor **OTT MF Pro** (OTT HydroMet, Kempen, Germany). In the measurement process, the sensor head needs to be fully submerged in the flow, so observations could not be acquired exactly at the surface level but a few centimeters below the water surface^{23,52}. The interval point of measurement was 1 m and a Fixed Period Average velocity with a default period of 30 seconds was applied.

Data Records

In this study, UAS hydrometry datasets and *in-situ* (ground)/boat hydrometry datasets for validation and benchmarking of UAS datasets were collected. All datasets are stored in the repository named Roenne Aa Survey, Sweden⁵³, and are in open-source binary formats such as seg-y or in ASCII file formats such as NMEA or csv. Auxiliary GIS datasets are stored in common geospatial data formats such as kml and geotiff. This project

Filename	Processing level			Description
	Level 1	Level 2	Level 3	
Roenne Aa.kml	x			Site kml file
GNSS_Base_Station_Data.zip	x			GNSS base station data
Orthophotos_##.zip	x	x		UAS-orthophotos data
Ground_truth_water_surface_elevation_RTK_##.zip	x	x	x	<i>In-situ</i> RTK WSE
Radar_altimetry_water_surface_elevation_M600_IWR1443_##.zip, Radar_altimetry_water_surface_elevation_M300_LX80_##.zip	x	x	x	UAS-radar WSE
Ground_truth_bathymetry_##.zip	x	x	x	<i>In-situ</i> RTK and stick bathymetry
Acoustic_Doppler_bathymetry_##.zip	x	x	x	Boat ADCP bathymetry
Sonar_bathymetry_M300_ECT400S_##.zip, Sonar_bathymetry_M600_DeeperCHIRPplus_##.zip, Sonar_bathymetry_Hydrohex_ECT400_##.zip	x	x	x	UAS sonar bathymetry
Water_penetrating_radar_bathymetry_M300_ZondAeroLF_##.zip, Water_penetrating_radar_bathymetry_M600_Gekko80_##.zip	x	x	x	UAS WPR bathymetry
Lidar_land_elevation_##.zip	x	x	x	UAS Lidar land elevation
Ground_truth_velocimetry_OttMFPPro_##.zip	x	x	x	<i>In-situ</i> ground truth velocimetry
Image_velocimetry_##.zip	x	x	x	UAS video camera velocimetry
Doppler_radar_velocimetry_M300_RSS300_##.zip	x	x	x	UAS Doppler radar velocimetry

Table 2. Contents of the storage datasets are located at the repository⁵³. Note, ## represents various processing levels: Level_1, Level_2, Level_3.

stores datasets that can be divided into three different processing levels according to the terminology of [NASA's EOSDIS repository](#): (1) Level 1 data are the raw data as they come from the sensors; (2) Level 2 data are point x, y, z data in chosen coordinate system and vertical reference; (3) Level 3 data are point data projected to river centerline/across river coordinate. All dataset details can be found in Table 2.

In the survey, the applied horizontal and vertical coordinate reference systems (CRS) are SWEREF 99 TM⁵⁴ and the SWEN17 RH2000 geoid model ([Swedish geoid-models](#)); the time reference system is Coordinated Universal Time (UTC). During the field measurements, the river level was high compared to the normal level for the season. Dry weather and low wind were observed on 28, 29, and 30 August 2023. Strong rainfall and flooding occurred on 31 August and 1 September 2023. The survey dates of different XSs based on UAS are described in Table 1. All relevant metadata are stored in the readme files on the repository⁵³.

UAS radar altimetry and *in-situ* WSE. The primary UAS radar altimetry WSE data was acquired based on M300_LX80 (Fig. 4a) along the river centerline with the flight path shown in Fig. 6a (red points). The output includes raw measured data including csv files and seg-y format files (Fig. 5a, Level 1, No.4 and No.3). In addition, RINEX files for rover GNSS output (Fig. 5a, Level 1, No.1) and csv format log files for drone position and orientation (Fig. 5a, Level 1, No.2) were stored. In Level 2 dataset, we stored PPK files, which are used to correct the drone positions, and stored csv format files containing different column contents (see Fig. 5a, Level 2). Here, we only stored the data when LX80 slant range was less than 30 m. In addition to the LX80, the M300 drone also carried the NRA24 radar altimeter, which was used for true terrain following navigation. NRA24 ranges were recorded along with pitch and roll angles measured by the drone inertial measurement unit (IMU). LX80 and NRA24 slant ranges were subsequently projected into nadir ranges using the recorded pitch and roll angles, which resulted in 4 different WSE estimates, using slant and nadir ranges from both the LX80 and the NRA24, respectively. In Level 3, these csv files were generated based on Level 2 results by adding 2 columns (see Fig. 5a, Level 3), where we adopted a chainage interval with 3.5 m to calculate the standard deviation of WSE values.

The legacy UAS radar WSE measurement was based on M600_IWR1443 (Fig. 4b) with the flight path shown in Fig. 6a (yellow points). This radar records full waveform data at high frequency, which was stored in binary format files (Fig. 5a, Level 1, No. 3), and synchronization files providing the match between GNSS time stamp and IWR1443, which were stored in ASCII format files (Fig. 5a, Level 1, No. 4). In addition, RINEX files for rover GNSS output were also stored in Level 1. In Level 2, the csv format files contain a column named 'MaxPower', which contains the return max power (e.g. in Decibels) of the range bin corresponding to the peak¹⁰. In Level 3, we only stored measured points with both max power value ≥ 70 dB and distance from centerline ≤ 10 m. Also, a chainage interval with 3.5 m was used for calculating the standard deviation of the WSE values.

The *in-situ* WSE was measured along the chainage points of the river centerline from 65031 m to 69590 m on 28 August 2023 by using EMLID REACH RS2+ (Fig. 4c), in which 44 points were selected and measured. The *in-situ* WSE results were stored in a csv format file.

UAS sonar bathymetry. In this section, 3 different UAS sonar bathymetry data were measured along the taglines in 6 XSs (Fig. 2).

The primary UAS sonar bathymetry data was acquired using M300_ECT400s (Fig. 4d). As shown in Fig. 5b, the acquired Level 1 dataset consists of RINEX files for rover GNSS output, seg-y files for full sonar echo curve output (in some cases, the NMEA format was used for raw sonar output), and csv format log files for



Fig. 4 (a–c), (g,m), and (n) show M300_LX80, M600_IWR1443, EMLID REACH RS2+, M300_Zenmuse L1 (integrating a Livox Lidar module and a camera), DJI Phantom 4 Pro (upper) and GoPro Hero 5 (down), and OTT MF Pro, respectively. (d–f) and (h–l) show the measurement processes of M300_ECT400s, Hydrohex_ECT400, M600_DeeperSmartSonarCHIRPplus, M300_Zond Aero LF, M600_Gekko 80, Boat_Teledyne RiverPro 1200, Boat_SonTek RS5, and M300_RSS300, respectively.

combining drone position, drone orientation, sonar depth, and sonar trace with time stamp. In Level 2 datasets, the post-processed results were stored in csv files with different column contents (see Fig. 5b, Level 2). In Level 3, we added 3 columns (see Fig. 5b, Level 3) based on Level 2, where we adopted an interval with a 0.5 m distance along the tagline to calculate the standard deviation.

The secondary UAS sonar bathymetry data was based on Hydrohex_ECT400 (Fig. 4e). In Level 1, the dataset includes RINEX files for rover GNSS output, csv-formatted files for sonar depth measurements with timestamp

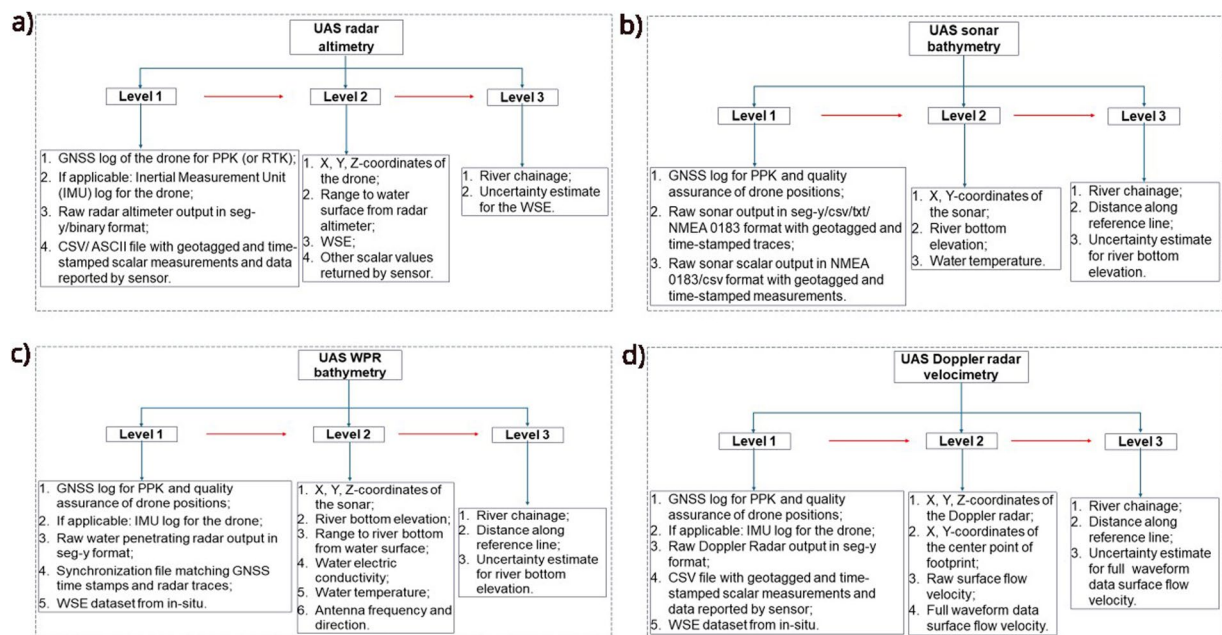


Fig. 5 Shows the components in the Level 1 datasets and the columns of generated csv files in Level 2 and Level 3. **(a)** Indicates UAS radar altimetry dataset. **(b)** Is the UAS sonar bathymetry dataset. **(c)** Is UAS WPR bathymetry dataset. **(d)** Shows UAS Doppler radar velocimetry dataset.

outputs, and csv-formatted files for sonar sensor coordinates with timestamps. In Level 2 and Level 3 datasets, the column contents are the same as M300_ECT400s.

The legacy UAS sonar bathymetry was collected using M600_DeepSmartSonarCHIRPplus⁴¹ (Fig. 4f). The Level 1 datasets contain RINEX files for rover GNSS output, txt files with NMEA 0183 format for sonar depth measurements with timestamp out, and txt files for sonar GNSS data and the NMEA sentence. In Level 2 and Level 3 datasets, the column contents are the same as M300_ECT400s and Hydrohex_ECT400.

UAS WPR bathymetry. The primary UAS WPR bathymetry data acquired was based on M300_Zond Aero LF (Fig. 4h). 5 XSs (except XS1) were measured. As shown in Fig. 5c, the Level 1 datasets consist of RINEX files for rover GNSS output, seg-y files for full radar echo curve output, and csv files for time-stamped drone position and trace number. In Level 2 dataset, the post-processed results were stored in csv files with different columns (see Fig. 5c, Level 2). In Level 3, we added 3 columns (see Fig. 5c, Level 3) based on Level 2, where an interval with a 0.5 m distance along the tagline was used to calculate the standard deviation.

The legacy UAS WPR bathymetry was using M600_Gekko 80²⁰ (Fig. 4i). 5 XSs (except XS2) were measured. In Level 1, RINEX files for rover GNSS output, seg-y files for full radar echo curve, and txt files for time-stamped drone position and trace number were stored for XS1 and XS3; while only seg-y files were stored for XS4, XS5, and XS6. In Level 2 and Level 3 datasets, the post-processed results were stored in csv files with the column contents the same as M300_Zond Aero LF.

Ground truth bathymetry. The *in-situ* bathymetry measurements were acquired with an EMLID REACH RS2+ and ruler along 6 XSs. Meanwhile, WSE values were measured for 6 XSs by using the EMLID REACH RS2+ to be reference values in estimating UAS sensor data. In Level 1, csv files for correspondence between RTK and tagline coordinates, RTK bathymetry points, ruler bathymetry points, and WSE observations were stored for each XS. In Level 2 and Level 3, csv-formatted files combining RTK bathymetry and ruler bathymetry were stored. Due to heavy rainfall on 31st August, the WSE values in Level 1 were remeasured on 1 September for XS4, XS5, and XS6.

For XS1, the used ADCP bathymetry sensor was Teledyne RiverPro 1200 (Fig. 4j). In Level 1 datasets, 5 groups pre-processed sensor output were recorded at the same time, then the average value of these values were calculated and shown in Level 2 and Level 3. For XS2-XS6, the sensor SonTek RS5 sensor (Fig. 4k) was applied for bathymetry. In 3 different Levels datasets, the SonTek RS5 results can be divided into 2 situations: (1) 'BT.Depth.RH2000' is bottom elevation calculated based on average of 4 slanted beams; (2) 'VB.Depth.RH2000' means bottom elevation calculated based on vertical beam. All ADCP bathymetry results were stored in csv-formatted files.

UAS lidar land elevation. One of UAS auxiliary measurements in this survey was based on M300_DJI Zenmuse L1 (Livox Lidar module, Fig. 4g). The resulting data was managed by DJI Terra and exported in LAS format in Level 1 for processing in the point cloud to derive the results. The generated dense point cloud was further processed to create the digital elevation model (DEM) using the open-source software CloudCompare⁵⁵. Essentially, the dense cloud was rasterized into a gridded digital terrain model with tif format (in Level 2).

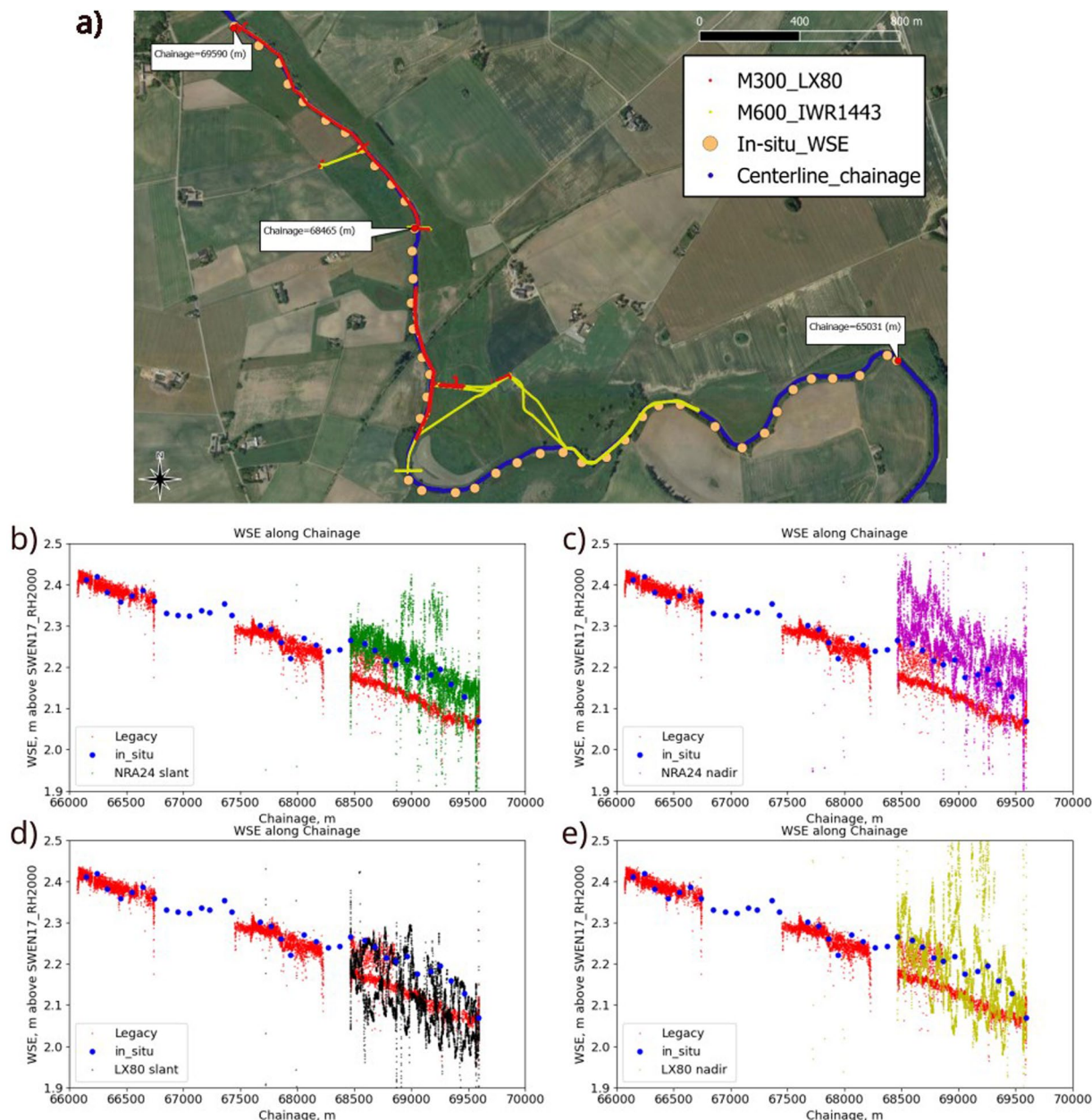


Fig. 6 (a) Shows the drone fly path based on M300_LX80 (red points, new sensor) and M600_IWR1443 (yellow points, legacy sensor, part path was covered by red points). The *in-situ* WSE measured points are shown by orange circles (ground truth sensor), and blue points represent the river centerline chainage. (b–e) show comparisons of *in-situ* WSE results (blue points), M600_IWR1443 WSE results (red points), and M300_LX80 WSE results, where the legacy WSE values were corrected by plus 0.1 m offset. Based on different offsets, the M300_LX80 WSE results are divided into 4 different results, which are NRA24 slant results (green points, in b), NRA24 nadir results (magenta points, in c), LX80 slant results (black points, in d), and LX80 nadir results (yellow points, in e).

Moreover, we sampled the DEM along the individual XS in QGIS to obtain csv files (in Level 3) containing land elevation value along each XS.

UAS Doppler velocimetry. The UAS Doppler velocity measurement was based on M300_RSS300 (Fig. 4l). 5 XSs (except XS4) were measured. As shown in Fig. 5d, the Level 1 datasets include RINEX files for rover GNSS outputs, seg-y files for full Doppler radar echo curve outputs, csv files with time-stamped drone position and orientation, and csv files containing time-stamped sensor position, velocity, and trace numbers. In Level 2 datasets, the post-processed results were stored in csv files with different columns (see Fig. 5d, Level 2). In Level 3, we

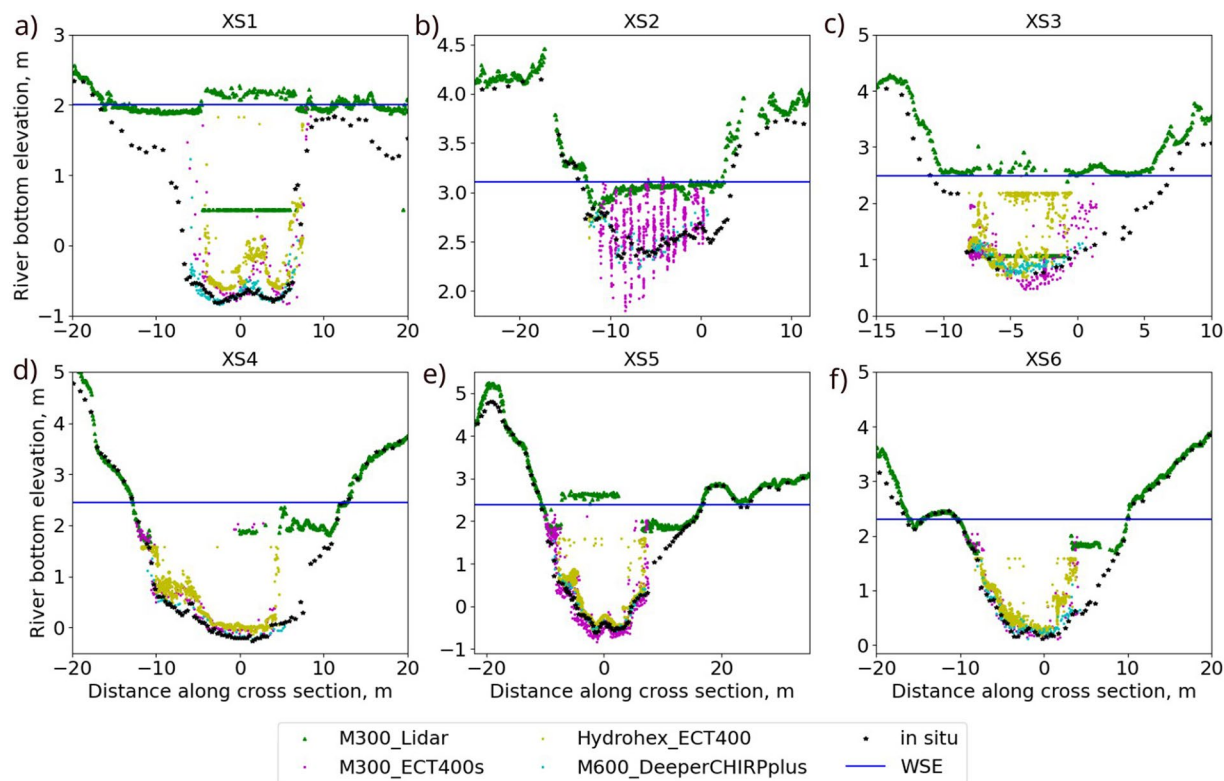


Fig. 7 Shows comparisons of M300_Lidar elevation results (green triangles, legacy sensor), *in-situ* bathymetry results (black stars, ground truth sensor), and 3 different sonar bathymetry results: M300_ECT400s (magenta points, new sensor), Hydrohex_ECT400 (yellow points, new sensor), and M600_DeeperCHIRPplus (cyan points, legacy sensor). The blue solid lines indicate WSE value of XSs. From a) to f), XS1, XS2, XS3, XS4, XS5, XS6 are shown in sequence.

added 3 columns (see Fig. 5d, Level 3) based on Level 2, where an interval with 5 traces within the selected traces at one waypoint was used to calculate the standard deviation.

Image velocimetry. The other UAS auxiliary measurement was based on UAS video camera along 5 XSs (except XS4), in which the UAS platform is DJI Phantom 4 Pro and the video-camera is GoPro Hero 5 (Fig. 4m). In Level 1, the stored datasets consist of mp4 files for video output and csv/txt files for coordinates of ground control points. In Level 2 and Level 3, csv files for velocimetry points derived from PIV were stored.

Ground truth velocimetry. The *in-situ* velocity measurement was using OTT MFPro electromagnetic velocity (Fig. 4n). In Level 1 datasets, csv files for OTT MFPro surface velocity and correspondence between RTK and tagline coordinates were recorded along 5 XSs (except XS4). In Level 2 and Level 3 datasets, the river surface velocity points were stored in csv files format.

Ancillary datasets. The river centerline is extracted from the EU-Hydro River Network Database 2006-2012 (vector)⁵⁶, and stored in the file 'Centerline_chainage.kml'. The centerline was discretized into 1 m chainage intervals using the plugin Qchainage in QGIS. The created chainage started from 59999 m at the most upstream point of the river and ended at 70327 m at the most downstream point of the river with steps of 1 m separation, into which the measured XSs were reprojected so that the zero point of the cross section coordinate falls on top of the river centerline.

To cover the 10 km river reach and the selected 6 XSs, a photogrammetry flight based on M300_DJI Zenmuse L1 (a camera with a 1-inch CMOS on a 3-axis stabilized gimbal, Fig. 4g) was performed to better understand the impact of vegetation density on the XS. The generated file named 'Orthophotos' contains datasets at 2 levels: (1) Level 1 contains csv files for ground control point coordinates and raw JPG pictures; (2) Level 2 contains orthomosaics of the images in geotiff format.

Technical Validation

For computing M300_LX80 WSE results in Level 2 and Level 3, we need to consider different vertical offsets between the GNSS receivers and the two radars (LX80 and NRA24). Different GNSS receivers with different offsets were used in RTK and PPK mode. We measured vertical offsets as: RTK - LX80 = 0.216 m, RTK - NRA24 = 0.09 m, PPK - LX80 = 0.376 m and PPK - NRA24 = 0.25 m. Subsequently 4 different WSE values were

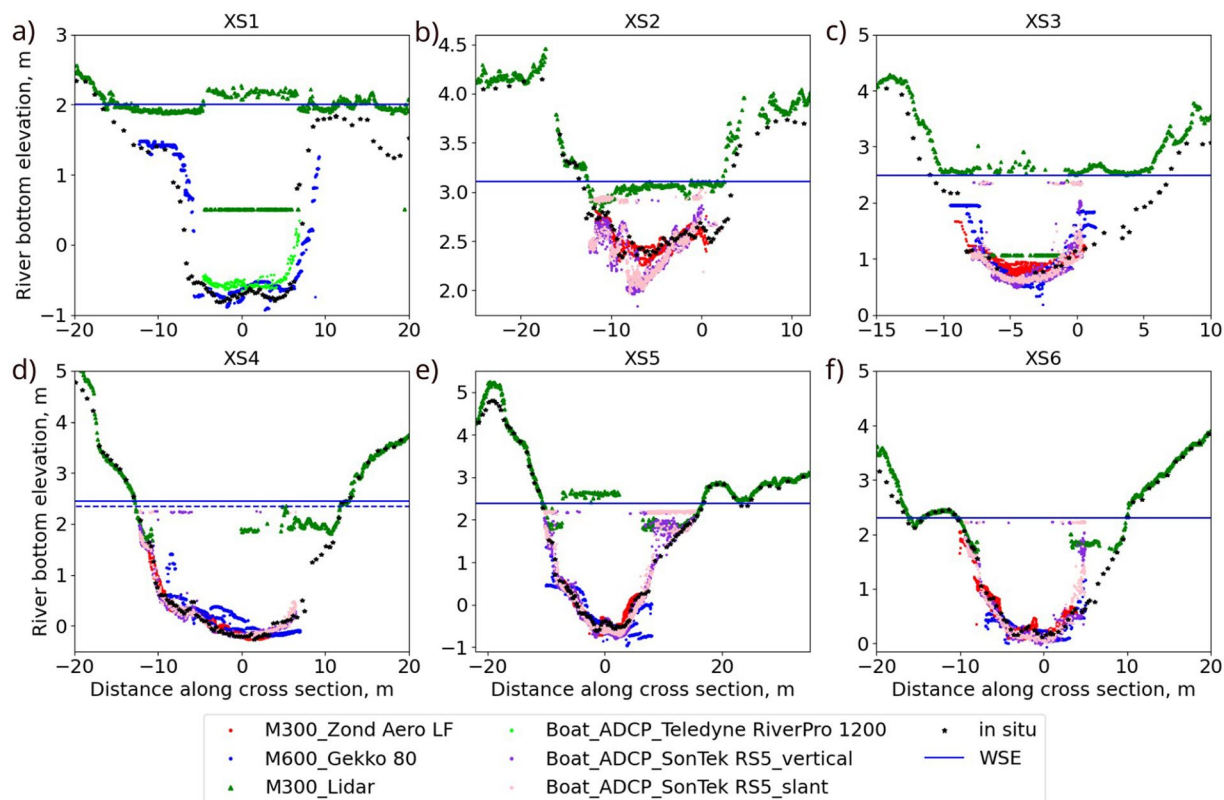


Fig. 8 Shows comparisons of M300_Zond Aero LF bathymetry (red points, new sensor), M600_Gekko 80 bathymetry (blue points, legacy sensor), M300_Lidar elevation (green triangle, legacy sensor), Boat_ADCP bathymetry results (ground truth sensor), and *in-situ* bathymetry results (black stars, ground truth sensor). In which, Boat_ADCP with Teledyne RiverPro 1200 sensor results (lime points) only appeared in XS1, while Boat_ADCP_SonTek RS5 with vertical beam results (blue violet points) and with average of 4 slanted beams results (pink points) can be found in XS2, XS3, XS4, XS5, and XS6. The blue solid lines indicate WSE values of XSs. Note that the blue dashed line in XS4 represents the updated WSE value only used for computing M300_Zond Aero LF bathymetry values. From a) to f), XS1, XS2, XS3, XS4, XS5, XS6 are shown in sequence.

calculated, using nadir and slant ranges from both radar altimeters: ‘WSE LX80 slant’, ‘WSE NRA24 slant’, ‘WSE LX80 nadir’, and ‘WSE NRA24 nadir’. Further, we compared M300_LX80 results with *in-situ* values (blue points) and legacy M600_IWR1443 values (red points) in Fig. 6(b–e). Comparison of results shows that the M300_LX80 WSE did not perform at the expected level (less than 3 cm), presumably because the payload was not gimbaled and the recorded pitch and roll angles were not accurate enough. This prompted the development of a gimbaled version of the LX80 payload, which will be used in upcoming surveys of the UAWOS project.

In Fig. 7, the UAS sonar bathymetry results of M300_ECT400s (magenta points) and Hydrohex_ECT400 (yellow points) are shown and compared. Further, we compared the results with legacy UAS sonar bathymetry values based on M600_DeeperSmartSonarCHIRPplus (cyan points). In addition, the *in-situ* values (black stars) and Lidar land elevation observations (green triangles) based on M300_DJI Zenmuse L1 are shown in Fig. 7, which can be used to verify the river bottom and land elevation adjacent to the river channel with high resolution and accuracy.

In Fig. 8, the primary UAS WPR bathymetry results based on M300_Zond Aero LF (red points, except XS1) are shown along each XS, while the legacy UAS WPR results based on M600_Gekko 80 are shown in blue points (except XS2). The Boat_ADCP bathymetry in XS1 (lime points) and the other 5 XSs (pink points) are shown in different colors because of employing different sensors. Also, the *in-situ* values (black stars) and the Lidar land elevation (green triangles) are shown for verifying consistency.

In Fig. 9, the *in-situ* velocities (OTT MF Pro, black stars) are distributed along the tagline of each XS at 1 m intervals. The PIV results (red points) are calculated and shown as the vector sum of the velocities in both image directions (parallel and perpendicular to the stream). The UAS Doppler can record full waveform signal data shown in Level 1, but it is difficult to determine the river flow velocity from the raw data. A fitting algorithm between the raw data and two alternative models (a Gaussian one peak model, or a Gaussian two peak model) was proposed and applied⁴⁷, which enabled us to obtain the full waveform velocity shown in Level 2 and Level 3. In Fig. 9, we plotted flow velocities derived from M300_RSS300 (triangles) along each XS, different triangle colors indicate different drone fly altitudes.

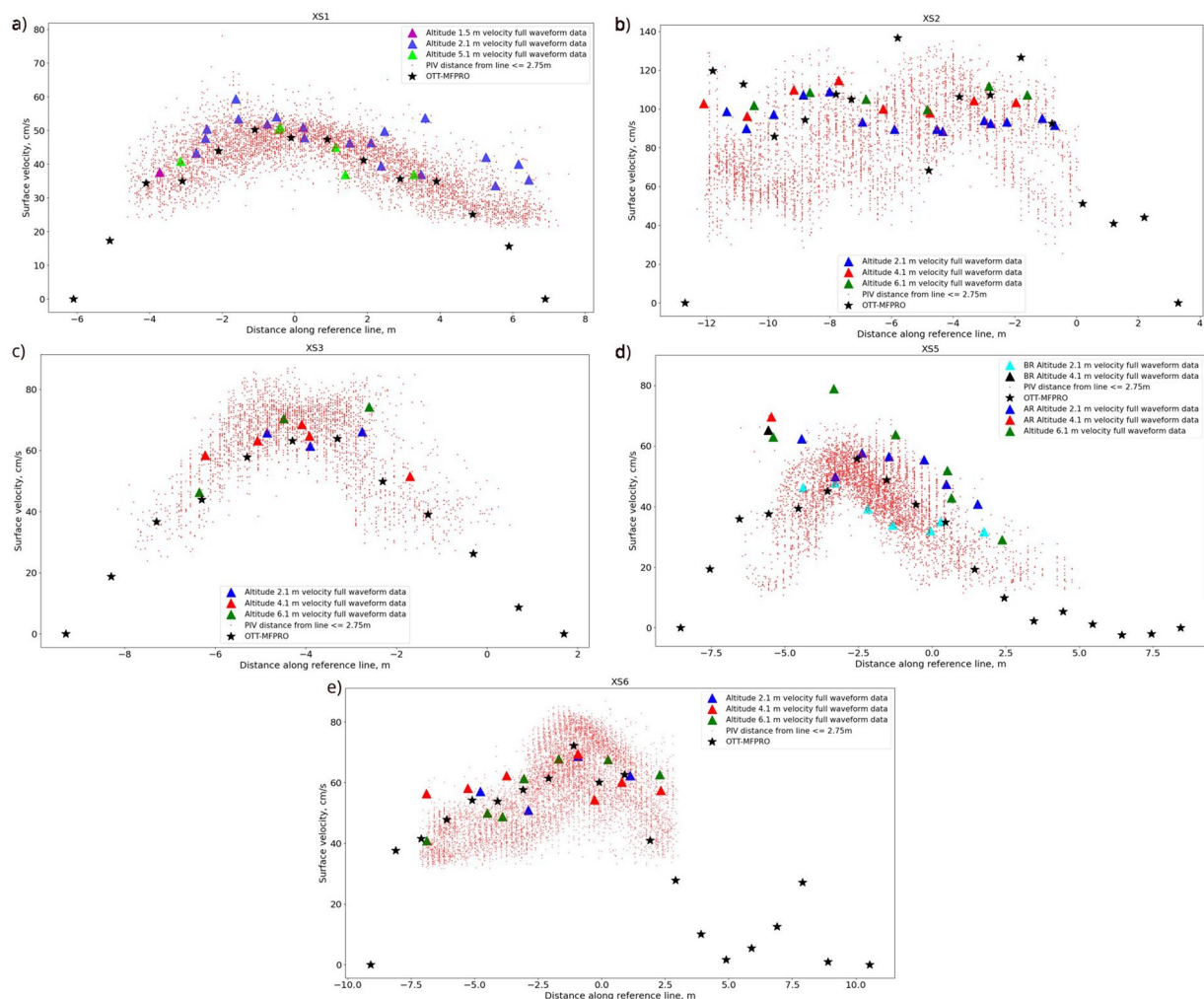


Fig. 9 Shows comparisons of velocities derived from Doppler radar full waveform data (triangle, new sensor), *in-situ* velocities by using OTT MFPRO (black stars, ground truth sensor), and PIV values with distance from the tagline ≤ 2.75 m (red points, legacy sensor). In XS5, the Doppler results are divided into 2 situations under 2.1 m and 4.1 m fly attitudes: before rain ('BR') and after rain ('AR'). A positive value means along the river flow direction. From a) to e), XS1, XS2, XS3, XS5, XS6 are shown in sequence.

Usage Notes

Specialized software is required to process most Level 1 data (e.g., seg-y files), while Level 2/3 data come in standard comma-separated ASCII csv files.

Code availability

The codes for UAS hydrometry parameters solved can be downloaded in the public data repository⁵⁷.

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Author contributions

Z.Z. code in Python, curated the data and wrote the manuscript; L.R., E.A.J., D.H.O., A.R.V., M.C.F., M.L., S.N., D.G., D.W., J.A. and V.F. fieldwork and collected data; P.B. conceptualisation, code in Python, curated the data, repository (meta) data management, and project administration. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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