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NINA Report

Testing UAV surveying for mapping freshwater pearl mussel populations

Pilot project on UAV mapping of freshwater pearl mussels

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Norwegian Institute for Nature Research

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Hedger, R.D., Gosselin, M.-P. & Larsen, B.M. 2023. Testing UAV surveying for mapping freshwater pearl mussel populations. NINA Report 2353. Norwegian Institute for Nature Research.

Trondheim, November, 2023

ISSN: 1504-3312
ISBN: 978-82-426-5154-9

AVAILABILITY
Open

PUBLICATION TYPE
Digital document (pdf)

QUALITY CONTROLLED BY
Malte Willmes

SIGNATURE OF RESPONSIBLE PERSON
Assistant research director: Tonje Aronsen (sign.)

CLIENT(S)/SUBSCRIBER(S)
NINA

CLIENT(S) REFERENCE(S)
NINA SATS 22-26 Hedger

COVER PICTURE
UAV image of the River Borråsaleva, showing a dense aggregation of embedded adult freshwater pearl mussels © Richard Hedger

KEY WORDS
- Borråselva, Trøndelag, Norway
- Freshwater pearl mussel, *Margaritifera margaritifera*
- UAV remote sensing
- Light environment

NØKKELORD
- Borråselva, Trøndelag, Norway
- Elvemusling, *Margaritifera margaritifera*
- UAV fjernmåling
- Lysmiljø

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Abstract

Hedger, R.D., Gosselin, M.-P. & Larsen B.M. 2023. Testing UAV surveying for mapping freshwater pearl mussel populations. NINA Report 2353. Norwegian Institute for Nature Research.

This report presents a preliminary assessment of the viability of using UAVs (drones) for mapping freshwater pearl mussel (*Margaritifera margaritifera*; FPM) populations. The standard methods for surveying FPM populations – wading or snorkelling through a river and counting the visible adult FPMs on the riverbed – are time-consuming and therefore costly. In contrast, UAVs offer the potential to quickly and efficiently map large stretches of a watercourse at high spatial resolution. Since UAVs have not been used as part of FPM monitoring programmes, an assessment of the strengths and limitations of this technology is required. In the current study, the effectiveness of UAVs to survey adult FPM populations was tested in the River Borråselva, a small, regulated river in Trøndelag, Central Norway, with a well-documented FPM population. Sites with known occurrence of FPMs were selected and a UAV, flying at an elevation of ≈5 m, was used to image the riverbed. UAV imagery was acquired using both photo and video surveying approaches. Photos were merged in WebODM to create orthophotos of the sites; video data were used to test the potential for image processing to remove phenomena that hindered discernment of FPMs (e.g. sunglint, shallow water wave lensing, and refraction from ripples). UAV flights were carried out under different light conditions, and in different sections of the river, to explore possible influences on FPM visibility. The test surveys showed that it is possible to provide a relatively quick indication of FPM distributions. However, two limitations were encountered. First, the area that could be investigated within a single survey for the Borråselva was limited by the difficulty of flying a UAV close to the surface within a narrow stream bounded by fully grown riparian forest, while maintaining line-of-sight to the operator. Secondly, detection of FPMs was strongly dependent on light conditions. We conclude that UAVs have strong potential for use in FPM monitoring programmes. However, careful survey planning is essential to ensure optimal surveying conditions: surveys should only be done during bright, cloud-free weather conditions, and attempts should be made to minimize the presence of shadows and sunglint. Additionally, image processing may be necessary to increase the visibility of FPMs on the riverbed.

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Sammendrag

Hedger, R.D., Gosselin, M.-P. & Larsen, B.M. 2023. Testing av UAV-undersøkelser for kartlegging av elvemuslingpopulasjoner. NINA Rapport 2353. Norsk institutt for naturforskning.

Denne rapporten presenterer en foreløpig vurdering av UAV-er (droner) som verktøy for å kartlegge bestander av elvemusling (*Margaritifera margaritifera*; FPM). Standardmetodene for å kartlegge bestander av elvemusling – vading eller snorkling i en elv og telling av synlige elvemuslinger på elvebunnen – er både tidkrevende og kostbare. I motsetning til dette, tilbyr UAV-er potensialet for å kartlegge effektivt store deler av et vassdrag med høy romlig oppløsning. UAV-er har imidlertid ikke blitt brukt som en del av overvåkingsprogrammer av elvemuslingbestander eller testet for dette før, slik at det i denne sammenhengen kreves en vurdering av både styrker og begrensninger av denne teknologien. I denne studien ble effektiviteten til UAV-er for å kartlegge bestander av elvemuslinger testet i Borråselva, en liten, regulert elv i Trøndelag, Midt-Norge, med en godt dokumentert bestand av elvemusling. Steder med god forekomst av elvemuslinger ble valgt og en UAV, som fløy i en høyde på ≈5 m, ble brukt til å avbilde elvebunnen. UAV-bilder ble anskaffet ved å bruke både foto- og videomålingsmetoder. Bilder ble slått sammen i WebODM for å lage ortofoto av kartlagte områder; videodata ble brukt for å teste potensialet for bildebehandling for å fjerne forstyrrende elementer i bildet (f.eks. reflekser fra sola, bølgelinjer på grunt vann og brytning fra krusninger). UAV-flyvninger ble utført under forskjellige lysforhold, og i forskjellige deler av elven, for å utforske mulig påvirkninger på synlighet av elvemuslinger. Testundersøkelsene viser at det er mulig å gi en relativt rask indikasjon på utbredelsen av elvemusling. Imidlertid ble det funnet to viktige begrensninger. For det første, var området som kunne undersøkes i Borråselva, innenfor en enkelt flyvning, begrenset pga. problemer med å fly en UAV nær overflaten av elva, som hadde fullvokst kantskog langs elvebredden, og samtidig opprettholde siktlinje til operatøren. For det andre, var resultatene sterkt avhengig av lysforholdene under undersøkelsen. Det ble konkludert med at UAV-er har et godt potensial for bruk i undersøkelser og overvåking av elvemusling. God planlegging er imidlertid avgjørende for å sikre optimale undersøkelsesforhold. Undersøkelser bør gjøres under lyse, skyfrie værforhold, samtidig er det viktig å minimere tilstedeværelsen av skygger og reflekser fra sola. I tillegg kan bildebehandling være nødvendig for å øke synligheten til elvemuslinger på elvebunnen.

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Contents

Foreword

One of NINA's key strategic initiatives is the development of new methods in research, mapping and monitoring of nature. This report presents results from a NINA Strategic Initiative (SATS) pilot project (Forskningsrådets prosjektnummer 160022/F40), testing the application of remote sensing for mapping populations of freshwater pearl mussels. We present the results of a preliminary UAV survey of a pearl mussel river in central Norway (Borråselva), discuss the current potential and limitations of this surveying approach, and provide recommendations to plan successful UAV river surveys. Outcomes from this study are relevant to NINA's research portfolio in mapping river ecology as well as improving the application of UAVs within surveying programmes.

Richard Hedger, November 2023

1 Introduction

1.1 The freshwater pearl mussel *(Margaritifera margaritifera)*

The freshwater pearl mussel (*Margaritifera margaritifera*), hereafter referred to as the FPM, is a freshwater bivalve, found within unpolluted fast-flowing streams and rivers in the Holartic. Its ecology is well documented (Bauer 1987, Geist 2010, Skinner et al. 2003, Tamario et al. 2022). Four FPM life-stages have been defined:

(1) **Larvae.** Larvae (glochidia) disperse downstream, entrained in the river flow. Most are swept out to sea, where they die, but larvae encountering salmonids (Atlantic salmon, *Salmo salar* L. or brown trout, *Salmo trutta* L.) may be inhaled into the fish gills. The larvae then close their shells to attach to the gills.

(2) **Glochidia attached to the fish gills.** After attachment, glochidia grow as parasites in the oxygen-rich gill environment until the following summer, where they drop off (as juveniles).

(3) **Juveniles.** Juveniles burrow into sandy or gravel substrates, and slowly grow for ≈10-15 years to reach maturity (adults).

(4) **Adults**. Adults remain embedded in the substrate. Each year, males release sperm into the water, which may be filtered by females to fertilize eggs in the female’s breeding pouch. Eggs develop into larvae within the breeding pouch and are released as larvae. Adults may reproduce for >75 years.

The FPM’s habitat requirements, complex biology, and dependence upon Atlantic salmon or brown/sea trout as host fish (Larsen 2018), makes the species easily susceptible to the impacts of human activities, both directly and indirectly (e.g. Höfler et al. 2023). The fact that individuals live stationary on the river substrate also means that water quality and the quality of the habitat in the immediate vicinity of FPM individuals is especially important. Due to its specific habitat requirements and sensitivity to environmental changes, the FPM is considered an indicator species, thus providing an indication of overall ecosystem health (Geist 2010).

The FPM has declined dramatically within its range, both in North America and Europe (Araujo & Ramos 2000, Geist 2010, Lopes-Lima et al. 2017). This has led to the species being classified by the IUCN as critically endangered (Cuttelod et al. 2011, Moorkens 2011). In large parts of central Europe, the species has disappeared from its original distribution range. Norway holds the largest population of FPMs in Europe, and hosts ca. 25% of the remaining European FPM populations (Larsen 2018). The FPM is found in over 419 Norwegian rivers and is distributed over >150 km of Norway’s total river length (Larsen & Magerøy 2019a). Although the decline has not been so dramatic in Norway, the FPM has disappeared from a minimum of 25% of the known historical sites (Larsen & Magerøy 2019a) and recruitment is so limited in many watercourses that the species is in danger of disappearing from >50% of the remaining sites. Populations have become extinct in more than 100 Norwegian rivers, and recruitment is weak or non-existent in the majority of the remaining FPM rivers in south-eastern and central Norway surveyed by Larsen (2010). The species has been classified as vulnerable in the Norwegian red list for endangered species and declared a “national responsibility species” in Norway, with its own dedicated conservation and management plan (Larsen 2018). Mapping and monitoring of these populations have been given high priority (Larsen & Magerøy 2019a), and a national monitoring plan is in place for the species that includes 40 rivers (e.g. Larsen & Magerøy 2023).

Mapping the distributions of FPM populations is required for their successful conservation. Observations of adult FPMs, which are typically found either embedded in sand/gravel substrates, are conducted in Norway either through observation from above the water surface (Figure 1), observation from just beneath the water surface using a partly submerged aquascope (Figure 2), or by snorkelling in the case of deep river sections not accessible by wading. Traditional survey methods obey a strict standard, documented in the European *Water quality - Guidance standard on monitoring freshwater pearl mussel (Margaritifera margaritifera) populations and* *their environment* (CEN 2017). The drawback to these traditional approaches, however, is that they can be time-consuming and therefore costly in labour-hours. This limits the spatial range of these surveys, reducing the ability to correctly assess the spatial distribution of the population and the possible changes that occur from year to year resulting from, for example, major flow events. Wading through the river to survey FPMs may also potentially damage FPM beds in areas of high FPM density.

Figure 1. Example photographs of adult freshwater pearl mussels taken from above the surface in the River Borråselva, Trøndelag. Pictures: Marie-Pierre Gosselin.

Figure 2 Mapping of a freshwater pearl mussel population using an aquascope. Picture: Bjørn Mejdell Larsen.

1.2 UAV remote sensing

Unmanned aerial vehicles – UAVs – are a remote sensing technology that has potential for mapping of FPM populations. Indeed, this technology has been already successfully used for the mapping of riverbed properties such as substrate (Arif et al. 2016) and filamentous algae and rooted macrophytes (Kislik et al. 2020). UAVs have also been used for the monitoring of riverscape features, as well as the outcome of river restoration projects (Langhammer et al. 2023, Marteau et al. 2017). For surveying FPM populations, UAVs offer two major advantages over traditional aerial photography from higher flying crewed aircraft: high spatial resolution and full control over imaging parameters:

- **Spatial resolution.** It is not possible to use traditional aerial photography (e.g. the type available through *Norge i bilder, https://www.norgeibilder.no/*) to detect FPMs. The highest resolution of *Norge i bilder* imagery is 10 cm which is insufficient for the dimensions of FPMs embedded in the substrate [≈10-120 mm; see Larsen (2017)]. UAVs can provide resolutions as fine as several mm making it possible to discern FPM populations. For example, Figure 3 shows the same area imaged by aerial photography (a 10 cm resolution *Norge i bilder* image) and by a UAV (<1 cm resolution). Fine-scale detail is absent in the *Norge i bilder* image, whereas the UAV image shows the brown homogenous sand/gravel substrate of the river, with FPMs evident as small, dark patches on the brown substrate.
- **Control over imaging.** It may be impossible to view the channel using traditional aerial photography. The river channel may be obscured by trees unless the camera is positioned directly above the channel, something that may not be possible using a crewed aircraft flying high above a meandering stream. The full control over the positioning of the UAV allows for direct line-of-sight between the imaging sensor and the water surface. Additionally, if the research relies upon archives of aerial photographs (e.g. *Norge i bilder*), there is no control over the light conditions when the imagery was acquired (see Hedger et al. 2022). Conducting the survey under optimal conditions (e.g. relating to cloud cover and solar position) may provide more informative imagery. This is best achieved using UAVs. For example, the *Norge i bilder* image in Figure 3 was acquired under light conditions leading to reflections from the water surface, resulting in no detail on the riverbed being apparent; the UAV image in Figure 3 was taken at a time of day when the water surface was under direct sunlight, and reveals much more detail on the riverbed, including FPMs.

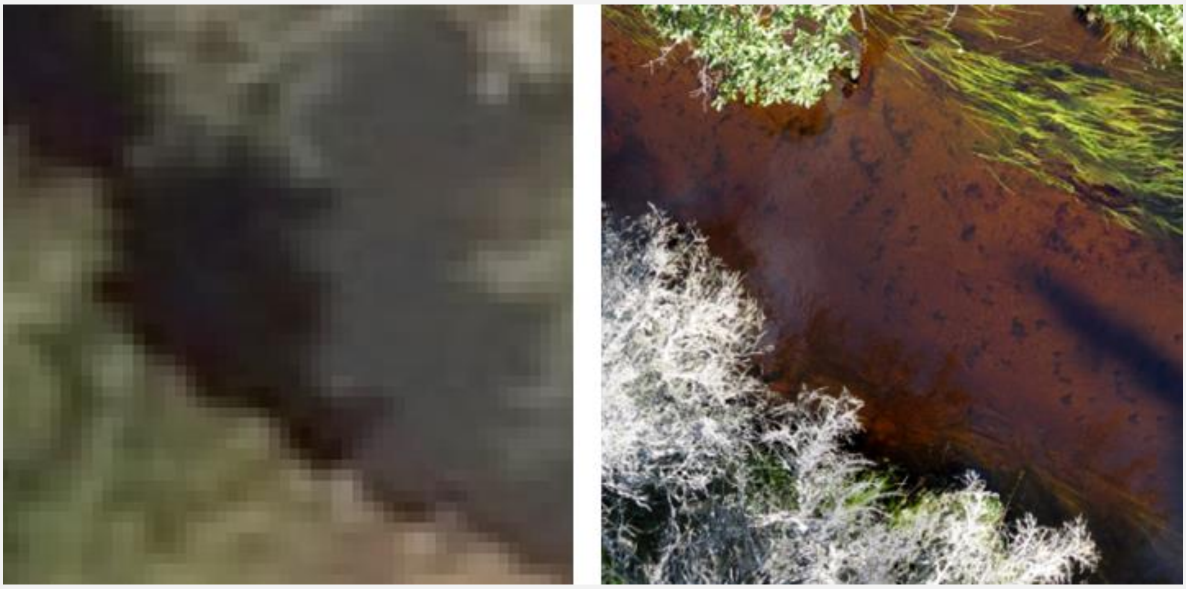

Figure 3. Traditional aerial photograph from Norge i bilder (left panel) and UAV image (right panel) of part of the River Borråselva.

Selection of optimal conditions for imaging the riverbed can be challenging. Water bodies are optically complex, and this results in challenges associated with light reflection from the water surface (Overstreet & Legleiter 2017), refraction (Bird et al. 2010), and absorption (Carbonneau et al. 2006), all of which need to be considered when surveying the riverbed. Moreover, rivers present the additional challenge that riparian vegetation is often present and well developed along the banks, which may lead to shadows on the water surface. Such issues may hinder the ability to delineate adult FPMs on the riverbed. They must, therefore, be accounted for or minimized when possible. UAV images are sensitive to ambient light conditions, in turn dependent on weather conditions.

- When imaging the river under overcast conditions, reflections of clouds from the water surface may dominate the outgoing signal (Figure 4; left panel), completely obscuring the riverbed. In contrast, imaging under direct sunlight during cloud-free conditions may allow detail on the riverbed to be observed, including FPMs (Figure 4; right panel).
- Imaging under conditions of direct sunlight, however, makes imagery susceptible to a range of effects including sunglint and shallow water wave lensing (Figure 5). Sunglint results from specular reflection of sunlight off the water surface into the imaging sensor, which obscures the riverbed beneath affected areas. Wave lensing is caused by the convex regions of waves focusing light on the riverbed in shallow water bodies, which superimposes a textured pattern on the riverbed (Veal et al. 2010).

These phenomena should be considered when using UAVs to image FPM beds. It may be possible to select an optimal time to minimize these phenomena, and/or to use image processing procedures to remove them.

Figure 4. UAV images acquired under overcast (left panel) and cloud-free (right panel) conditions.

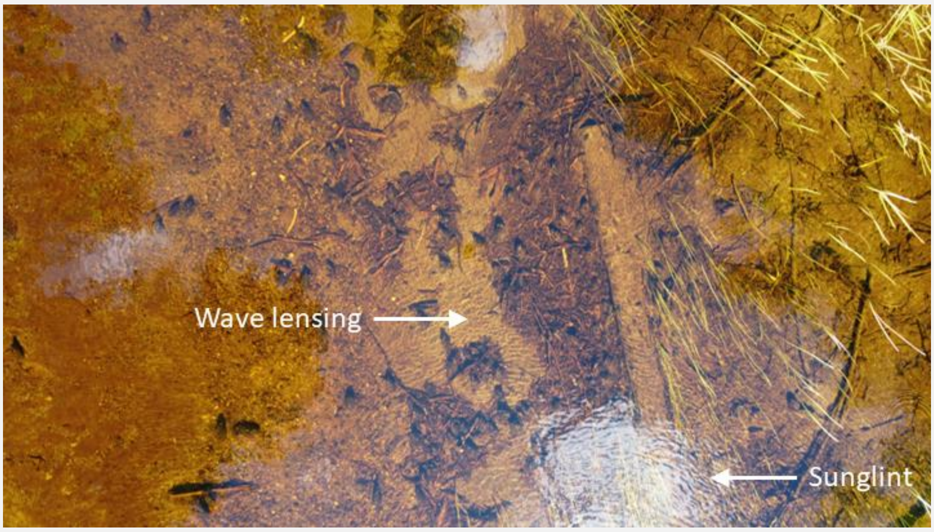

Figure 5. UAV image showing sunglint and shallow water wave lensing.

1.3 Research objectives

The overall objective of this study is to assess the suitability of UAV surveying for the mapping of FPM populations. We test the ability to detect adult FPMs using UAVs, assess weather and light conditions over which this can be done, identify potential sources of error and constraints, and examine imaging techniques with respect to both their informative potential and their limitations.

Specifically:
(1) We assess the ability of UAVs to provide **maps** (orthophotos) of FPMs.
(2) We identify **optimal imaging windows** in terms of weather conditions and time of day.
(3) We identify the potential for better detection of FPMs via **image processing**.

2 Methods

2.1 Study river – Borråselva

The River Borråselva (63.54ºN, 11.02ºE; NVE vassdragsnr 124.2Z) is a low gradient river in Trøndelag, central Norway (Figure 6) that is part of the regulated River Gråelva, flowing between the Ausetvatnet and Almovatnet lakes. The river supports a population of brown trout, which is the host fish for FPM larvae (Larsen 2017, Larsen & Magerøy 2019b). The Borråselva has been included in Norway's National Monitoring Programme for FPMs since 2000 (Larsen 2017, Larsen & Magerøy 2019a) and, as such, has been investigated every 6 years. Consequently, the population of FPMs in the River Borråselva is well known and the locations of the sites with the highest densities of FPMs are well identified, making this river an ideal case study to evaluate the use of UAVs.

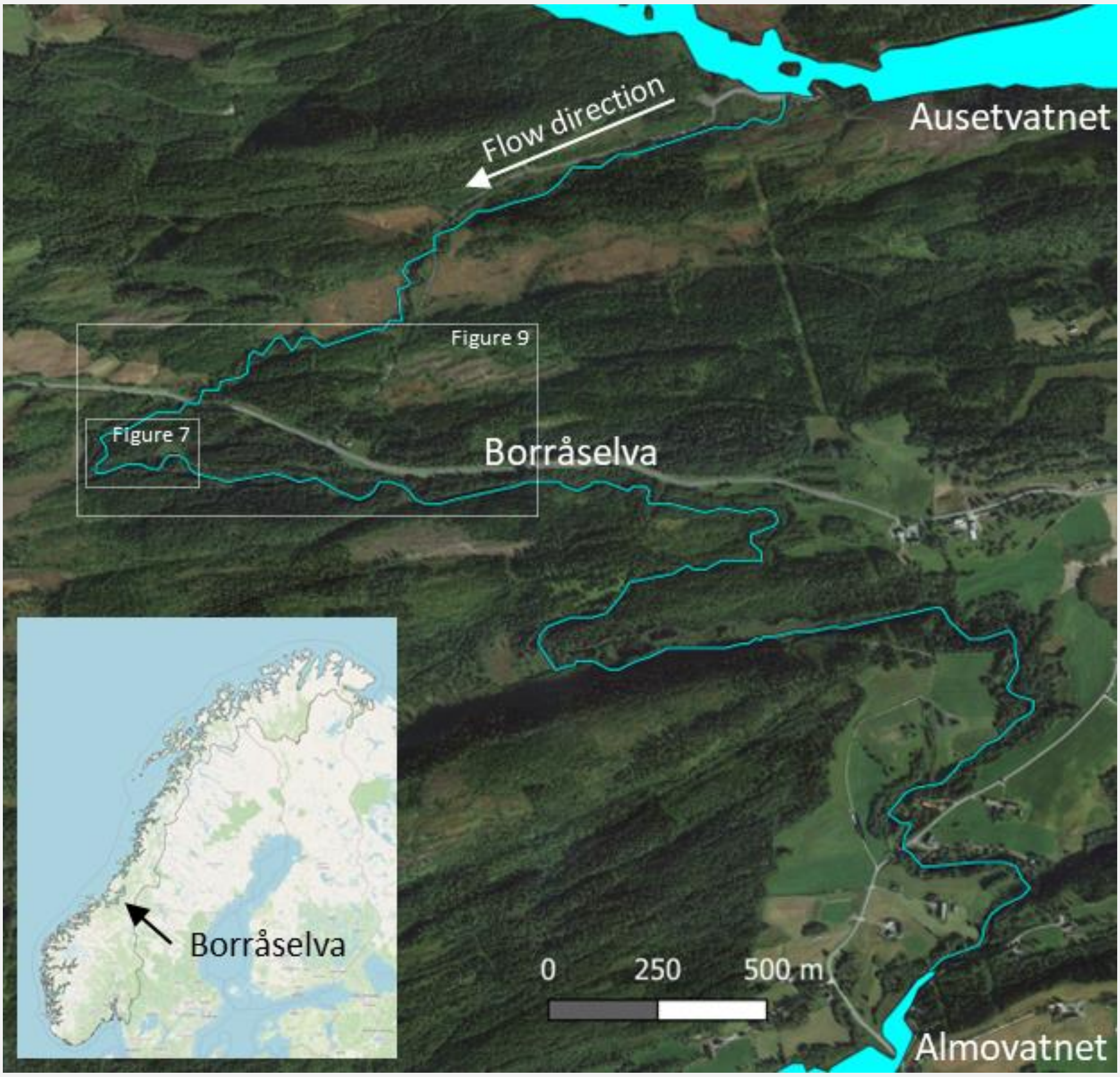

Figure 6. Map of the River Borråselva. White boxes show areas covered in Figure 7 and 9.

The Gråelva catchment, to which the Borråselva belongs, is largely forested (75.8%) (https://nevina.nve.no/), and much of the Borråselva riverbank is lined by trees (Figure 7). This means that the river is often under shadow, particularly at low solar elevations and when the solar azimuth is perpendicular to the channel orientation (Figure 8).

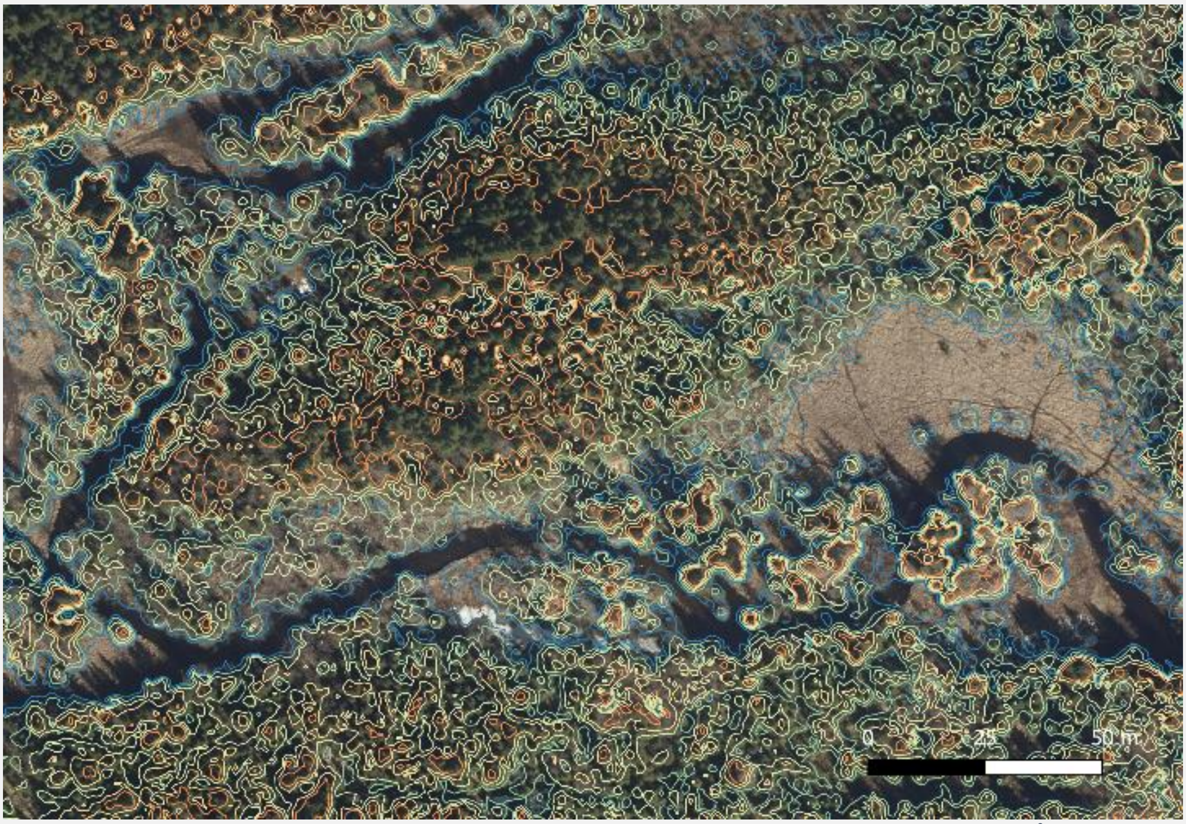

Figure 7. Elevation of riparian vegetation (contour interval = 2.5 m) around part of the River Borråselva, as derived from topographic lidar data (riparian vegetation elevation = DSM elevation – DTM elevation).

Figure 8. Photo of the River Borråselva, taken by a UAV. Note the presence of shadow across most of the water surface.

2.2 UAV surveys

UAV surveys were conducted using an off-the-shelf DJI Mini 2 (https://www.dji.com/no/mini-2/specs). This UAV was chosen for several reasons: (1) it is small and relatively inexpensive while (2) it has sufficient camera capabilities for imaging rivers. Being small, it can be operated in narrow channels; being inexpensive (≈6 000 – 13 000 NOK, depending on specification), it is an acceptable expense relative to potential loss of the UAV due to (for example) tree collision. Imaging is done by a 1/2.3" CMOS sensor in a 12 MP camera, with a fixed-aperture F2.8 lens with an 83º FOV, and an ISO range of 100-3200. With a selected 4/3 aspect ratio, this provides imagery with dimensions of 4000 by 3000 pixels, either as single images (which can be obtained at a preset time interval) or video (25 frames per second). Images and video are geo-referenced with GPS positions stored in the image Exif data. However, this UAV does not include Real-time kinematic (RTK) positioning, so estimated positions may have an error of several meters.

Sites for UAV surveys within the Borråselva were selected based on known locations of FPMs as monitored by Larsen (2017) as part of Norway's National Monitoring Programme (Figure 9). Two survey sites were selected ≈50-100 m upstream of Monitoring Station 6 (*Site 6a* and *Site 6b*), and two were selected ≈50-100 m downstream (*Site 6c* and *Site 6d*). A further site was selected between monitoring stations 7 and 8 (*Site 7-8*). Exact locations were based on availability of access for using the UAV and on FPMs being visible from the bank. Surveys were conducted on several occasions in the late spring / summer of 2022 (Table 1). This season was chosen to ensure that solar elevations were suitably high, and depths and turbidity were relatively low (after the spring floods), allowing better visibility of the riverbed. The study sites were surveyed under a range of weather conditions and solar elevations, allowing evaluation of effects on imaging.

Surveys were conducted by flying the UAV directly over the water surface, within line-of-sight of the operator, and at low above-surface elevation (typically 5-10 m). For an elevation of ≈5 m, DJI Mini 2 camera properties (an aspect ratio (r) of 4/3 and FOV of 83º) provided images of 7 m width and 5 m height. For image dimensions of 4000 × 3000 pixels, this gave an average pixel resolution of ≈2 mm. Two surveying approaches were used:

Photo surveys. Surveys were conducted by flying the UAV in transects along and above the river channel. The UAV was flown along the channel across the study site at low speed (<0.5 m s^{-1}), and downward-looking images (camera aimed perpendicularly at the water surface) were acquired at the minimum possible time interval (2 s) with auto-exposure. Flight speed was kept low to ensure (1) that images were free from motion blur, and (2) that there was a sufficient overlap between successive images (ideally >70%) to enable ortho-registration. This approach was used for the construction of orthophotos of short stretches (40-50 m in length) of the river.

Video surveys. Video was acquired at selected locations by flying the UAV to a fixed position over the channel, and then holding this position while a downward-looking video of the location was obtained (typically lasting 5-10 s) using auto-exposure. This approach was used to examine the ability to account for temporally varying aspects of the environment (e.g. changes in sunglint, shallow water wave lensing, and distortion by waves on the river surface) to enhance imagery of the riverbed. The image processing method used (see Section 2.4) requires auto-alignment of video frames, so video was acquired ensuring that some part of the video included the (stationary) land surface surrounding the river to aid in auto-alignment.

Given that light reflected off a water surface tends to be polarized, a polarized filter may be used to reduce the effect of surface reflection that contributes to sunglint (Dietrich 2017). However, polarizing filters are most effective when perpendicular to the sun. This is difficult to achieve when flying a UAV over a river, and our preliminary investigation of this has shown them to be ineffective, so we did not use a polarizing filter in the current study.

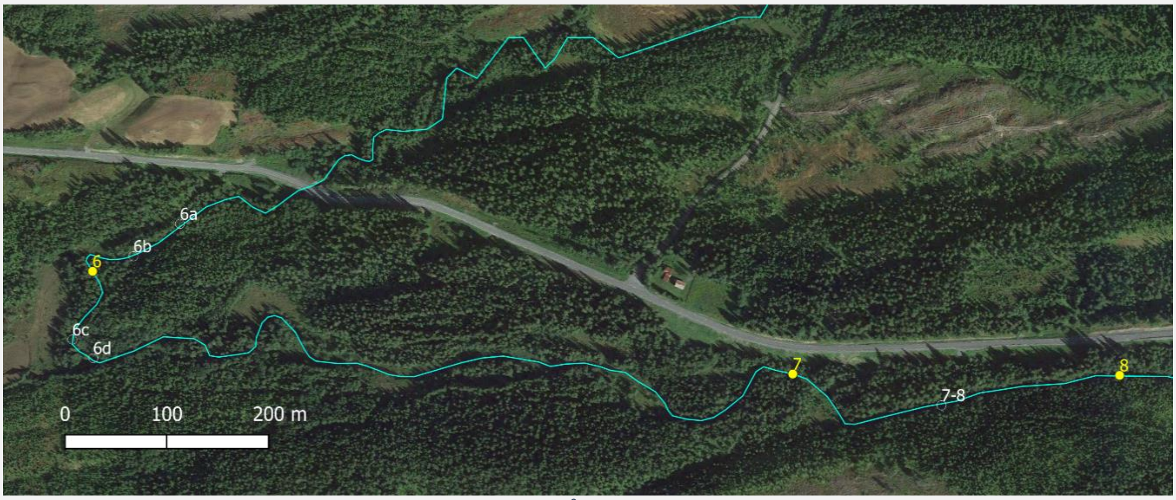

Figure 9. Distribution of study sites on the River Borråselva (Sites 6a, 6b, 6c, 6d and 7-8; shown in white). Site numbers are based on their proximity to Sites 6, 7 and 8 in Larsen (2017) (shown in yellow).

Table 1. UAV surveys conducted in the River Borråselva in 2022. Average solar elevation was estimated from the mid-point of the survey time using R function sunAngle{oce}; https://cran.r-project.org/web/packages/oce/index.html.

Date	Study site	Time of survey	Weather conditions	Presence of shadow	Average solar elevation (°)
May-31	6b	13:24 – 13:29	Overcast	Moderate	48.3
	6c	13:41 – 13:45	Overcast	Moderate	48.1
	6d	13:53 – 14:13	Overcast	Moderate	47.6
June-30	7-8	14:37 – 15:22	Cloud-free	Moderate	46.4
	6a	15:50 - 15:54	Cloud-free	Moderate	42.4
August-18	6d	11:57 – 12:04	Cloud-free	Heavy	37.6
	6c	12:21 - 12:24	Cloud-free	Heavy	38.5
	7-8	12:52 - 12:57	Cloud-free	Heavy	39.3

2.3 Mapping freshwater pearl mussels

Orthophotos were constructed from geopositioned UAV images using WebODM (Toffanin 2019). These were produced at the highest resolution possible (≈3-5 mm). Geopositioning errors in orthophotos were further corrected by georegistering orthophotos with existing geospatial data administered by the Norwegian Mapping Authority: aerial photographs from the *Norge i bilder* data portal (https://www.norgeibilder.no/) and topographic LiDAR-derived surface elevation from the *Høydedata* data portal (https://hoydedata.no/LaserInnsyn2/). Georegistering was done using the QGIS *Freehand Raster Georeferencer* plug-in by moving the orthophoto so that the channel banks evident in the orthophoto overlaid those evident in the aerial photograph and LiDAR data.

2.4 Image processing

The potential for image processing to make FPMs more discernible was tested by applying **temporal filters** (see Partama et al. 2018) to videos. Imagery acquired in the photo surveys often contained phenomena caused by the interaction of light and the water surface, such as sunglint, shallow water wave lensing, and ripples. These phenomena were often transient and ephemeral: for instance, the lensing pattern caused by ripples changes rapidly over timescales of less than a second. By identifying these phenomena within individual video frames, it may be possible to filter them. Then, filtered frames can be combined to construct an image of the area with these ephemeral, transient phenomena removed. To test this approach, we used the following method (done in Photoshop 2022 (version 23)):

1) **Frame extraction.** Frames were extracted from the video. Typically, we used ≈4 s of video, corresponding to ≈100 frames.
2) **Frame auto-alignment.** Frames were then auto-aligned, using transformation parameters that were auto-selected by photoshop. For successful auto-alignment, it was necessary for imagery to contain features that were temporally stable to fulfil the pattern matching requirements of the software. We therefore ensured imagery covered some of the bank surrounding the river, rather than just the river channel.
3) **Frame stacking.** The auto-aligned stack of frames was used to create a final image, where each pixel value in the final image was selected from the pixels in the stack corresponding to that pixel. Two types of stacking functions were used: median and minimum. These functions selected, respectively, the pixel with the median or minimum value of all pixels in the stack corresponding to the location.
4) **Image sharpening.** The images constructed after stacking were sharpened. This was done because constructed images were slightly blurred in comparison to individual frames, probably resulting from slight errors in auto-alignment and temporal change in refraction at the water surface between frames. Sharpening was done using an *Unsharp mask* algorithm.

3 Results

3.1 Mapping freshwater pearl mussels

The UAV surveys allowed the construction of high-resolution orthophotos of the study sites (Figure 10, Figure 11 and Figure 12). The requirement to maintain line-of-sight when flying the UAV at low elevation below the crown of trees along the banks constrained the maximum survey lengths to ≈40-50 m, limiting the area covered by individual orthophotos. Additionally, overhanging tree branches acted as obstacles to flying, and this further limited the range of individual flights. This was particularly the case for Site 6a, which was located in a tree-covered part of the stream, making it difficult to fly the UAV, reducing the survey length to 10 m.

The visibility of the riverbed was strongly dependent on weather conditions. Orthophotos produced from imagery acquired on May 31 (Figure 10) showed virtually no detail on the riverbed because of cloud reflection from the water surface. In contrast, orthophotos produced from imagery acquired during cloud-free conditions on June 30 (Figure 11) and August 18 (Figure 12) showed more riverbed detail, but the images were also affected by shadows from riparian vegetation.

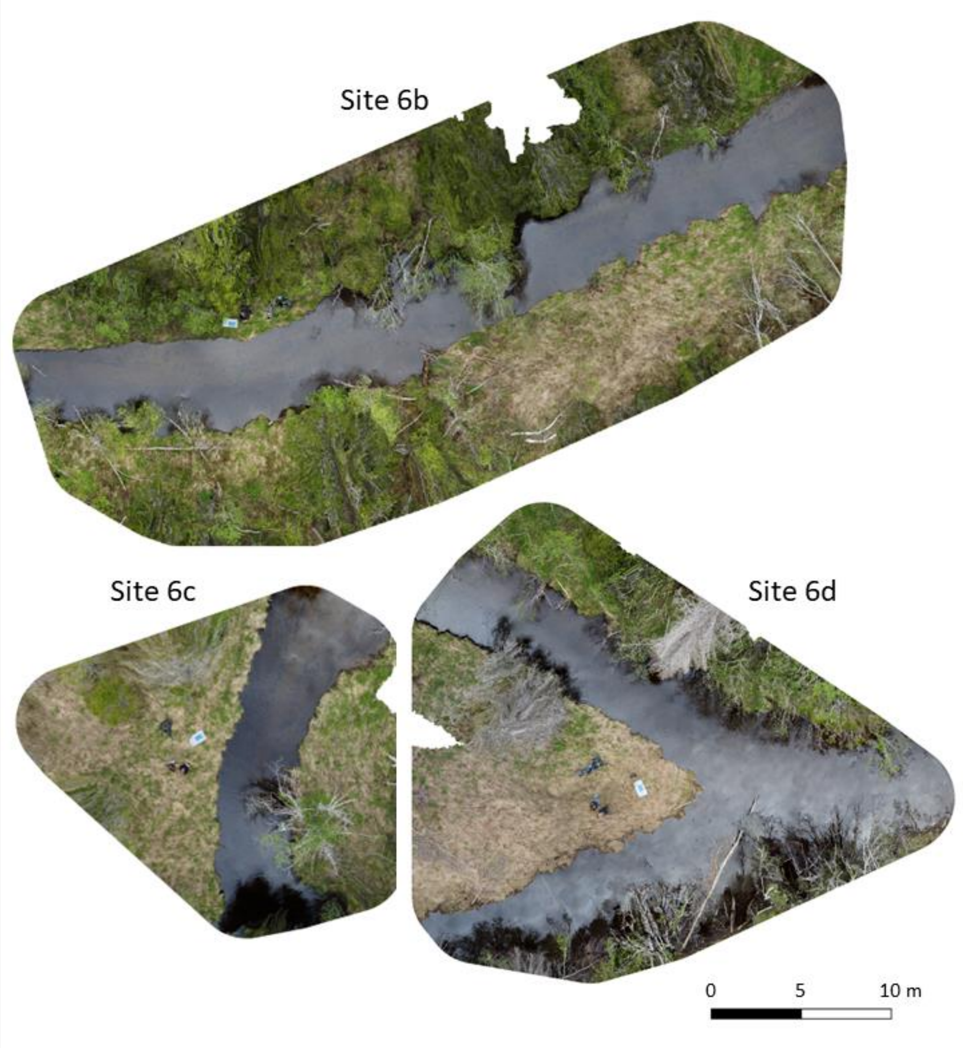

Figure 10. Orthophotos from imagery acquired on May 31 during overcast conditions.

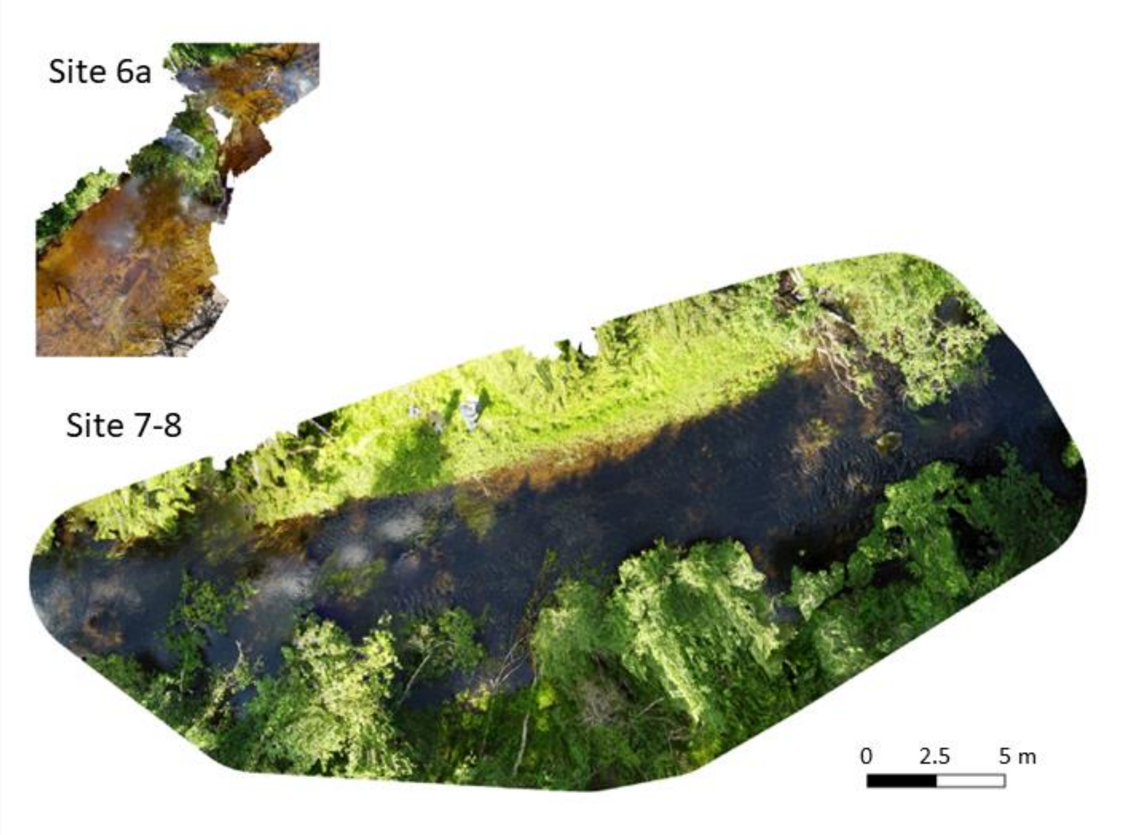

Figure 11. Orthophotos from imagery acquired on June 30 during cloud-free conditions. NB: the orthophoto for Site 6a was constructed from two short flights because overhanging vegetation in the centre of the site prevented continuous flying and imagery acquisition.

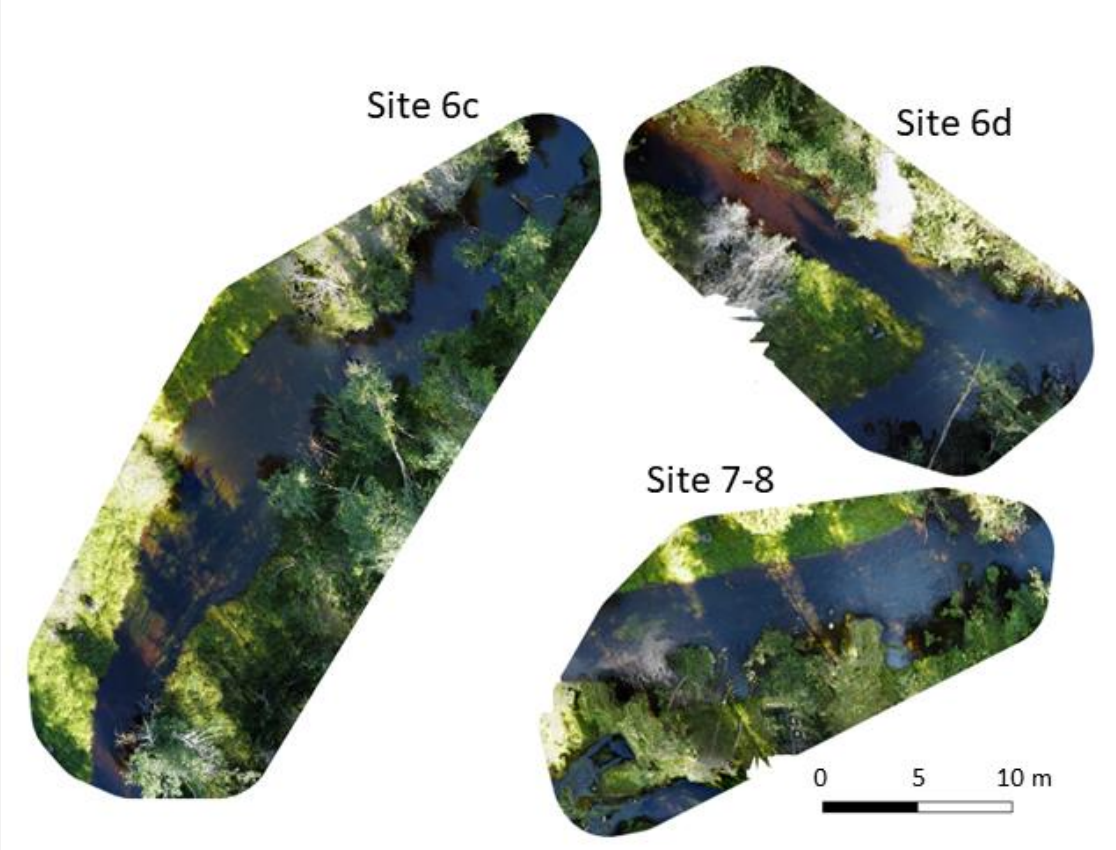

Figure 12. Orthophotos from imagery acquired on August 18 during cloud-free conditions.

FPMs were clearly visible in individual images and associated orthophotos when surveys were conducted during cloud-free conditions. Both dense and sparse aggregations are shown in Figure 13. FPMs are identifiable as a dark swath of touching shells in the dense aggregation (Figure 13; upper panel), and are identifiable as dark objects against the lighter sandy riverbed in the sparse aggregation (Figure 13; lower panel)." The visibility of FPMs was strongly dependent on local light conditions (Figure 14), In particular, sunglint (Figure 14; upper panel) and shadow (Figure 14; lower panel) hindered the ability to see FPMs.

Figure 13. Pearl mussel aggregation: dense aggregation (Site 7-8; acquired June 30) (upper panel), and sparse aggregation (Site 6a, acquired June 30) (lower panel).

Figure 14. Sparse pearl mussel aggregations showing sunglint (Site 6a, June 30) (upper panel) and shadow (Site 6b, acquired August 18) (lower panel).

3.2 Image processing

Application of a temporal filter to videos (see Section 2.4) produced images where obscuration of the riverbed by sunglint, wave lensing and ripples was reduced in comparison to single frames (Figure 15, Figure 16, and Figure 17). This made for easier identification of individual FPMs. Figure 15 shows a site affected by sunglint, which makes discernment of sparsely distributed FPMs among the woody debris more difficult. Also evident are streaks of light on the riverbed caused by wave lensing. Figure 16 shows a site with a rougher surface where sunglint, surface ripples and wave lensing reduce the visibility of individual FPMs in a dense FPM aggregation. In both cases, application of a temporal filter improved the visibility of FPMs. We found that the effectiveness of temporal filters was, however, reduced when there was a large amount of distortion of the riverbed from one video frame to the next caused by a very uneven, and constantly changing surface. Figure 17 shows an example where there was high distortion caused by downwash from the UAV rotors. While application of a temporal filter increased overall visibility (for instance, FPMs in the centre of the image became more visible), some areas were blurred due to the temporal filter not being able to filter differences in the geometric distortion from one frame to the next.

The optimal type of filter function (median or minimum) depended on what features were being removed. In most cases, a temporal filter with a median pixel value selected (e.g. Figure 16 and Figure 17) was found to be most appropriate. Use of the minimum pixel value tended to produce darker and less informative images. However, using the minimum pixel value (e.g. Figure 15) occasionally produced clear images.

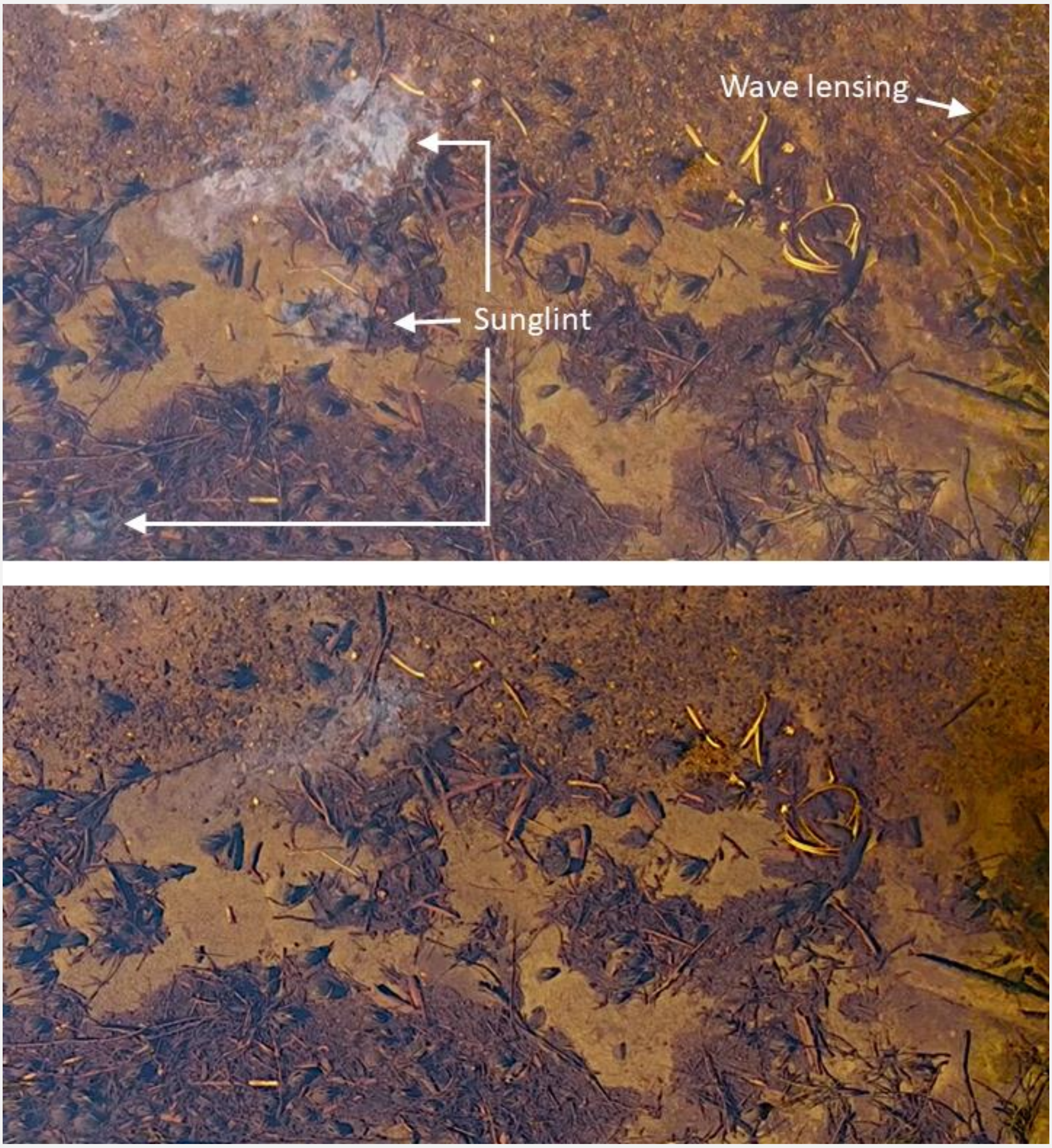

Figure 15. Application of a temporal filter (Site 6a, acquired June 30): a single video frame (upper panel), and an image constructed from a temporal filter (Nr video frames = 50, function = "minimum") (lower panel). The constructed image has been sharpened.

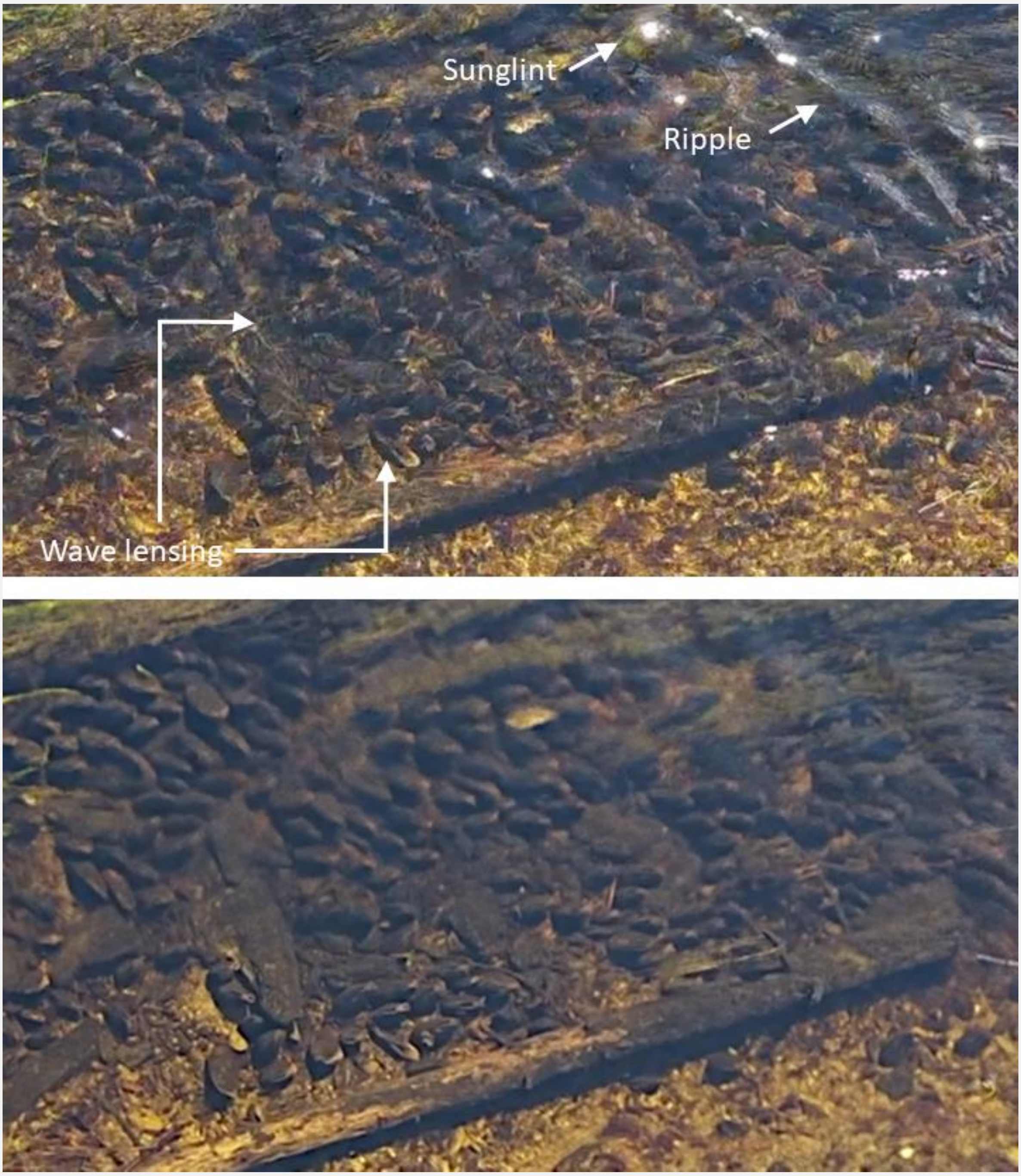

Figure 16. Application of a temporal filter (Site 7-8, acquired June 30): a single video frame (upper panel), and an image constructed from a temporal filter (Nr video frames = 50, function = "median") (lower panel). The constructed image has been sharpened.

Within composite images produced by a temporal filter, the FPMs were more discernible after image sharpening. For example, Figure 18 shows an example of sharpening (Photoshop "Unsharp Mask", amount = 100%, Radius = 30 pixels, Threshold = 0) applied to a dense aggregation of FPMs. FPMs in the unsharpened image are difficult to discern; sharpening increases the local contrast at the shell edges, facilitating discernment of individual FPMs.

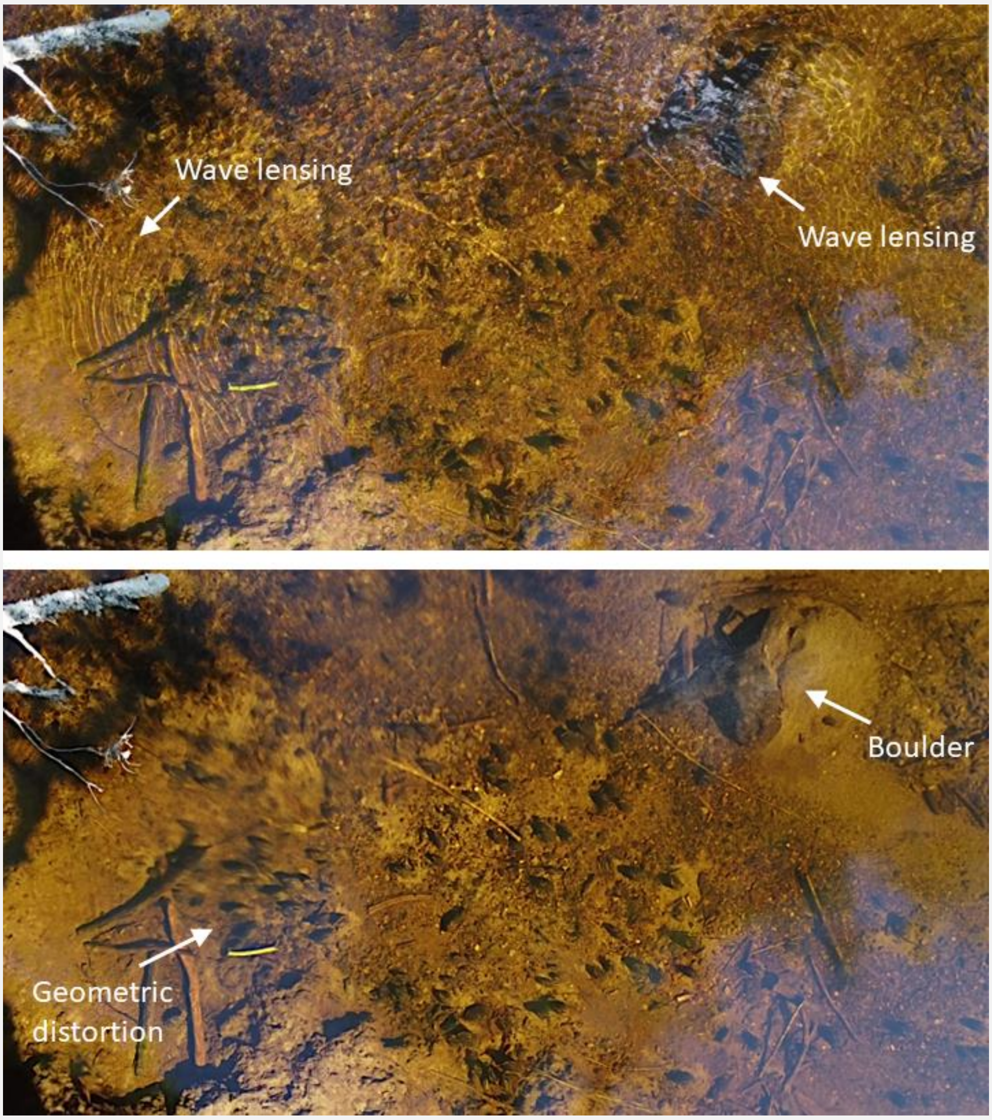

Figure 17. Application of a temporal filter (Site 6a, acquired June 30): a single video frame (upper panel), and an image constructed from a temporal filter (Nr video frames = 50, function = "median") (lower panel). The constructed image has been sharpened.

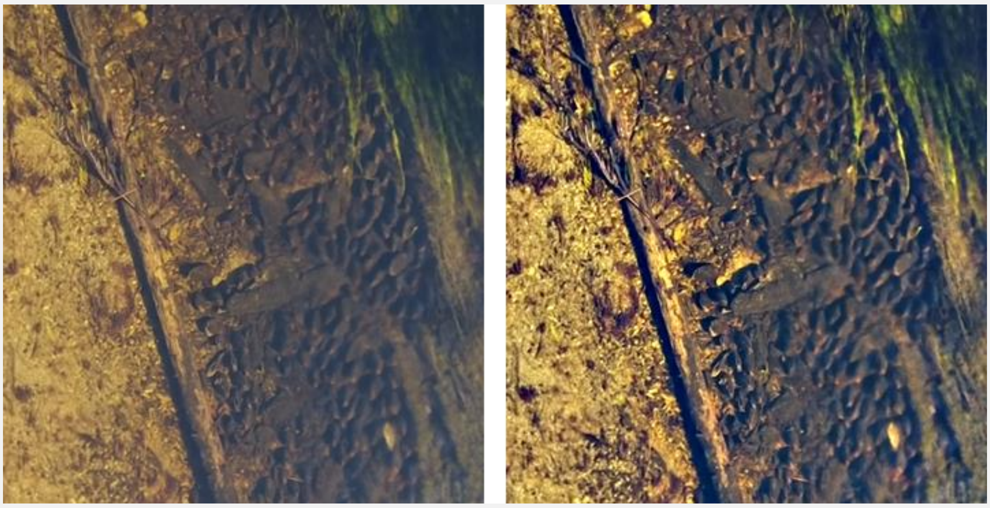

Figure 18. Application of an image sharpening filter (Site 7-8, acquired June 30): unsharpened image produced by a temporal filter (left panel), and a sharpened image (right panel).

4 Discussion

UAV remote sensing was found to be an effective method to survey FPMs in the River Borråselva and to provide information on the relative density of FPMs at the different sites. However, we experienced numerous surveying problems. In the following sections, we discuss the key issues and challenges, and present recommendations for optimizing the procedure for detecting and mapping FPMs, both regarding surveying and data processing. We then provide an overall assessment of the potential for this approach to be further used in Norway.

4.1 Key issues and challenges

This pilot project has revealed certain key issues and challenges with respect to using UAVs to survey FPMs:

Survey length. The Borråselva is a narrow, meandering stream with dense riparian forest, with tree branches overhanging the watercourse. This strongly limited the length that could be surveyed within an individual flight while maintaining both a low elevation above the river (flight elevation ≈5 m) and line-of-sight. The maximum single flight line achievable was ≈50 m, and for Site 6a, which had dense riparian vegetation and overhanging branches, the maximum flight line was ≈10 m.

Surveying conditions. The visibility of FPMs was strongly dependent on light conditions. Surveying was completely ineffective under cloudy conditions, due to reflection of clouds off the water surface which obscured the riverbed. However, surveying during sunny conditions also led to imaging problems: shadows from topography and riparian vegetation as well as from sunglint and wave lensing for parts of the water surface under direct sunlight. FPMs were not detectable in areas under shadow because the riverbed was not reflecting enough light for them to be distinguishable in the images. FPMs were not visible either under sunglint due to the reflected sunlight saturating the signal. FPMs were visible in the presence of wave lensing (although the added texture could potentially interfere with subsequent processing).

Local instream conditions. There was a wide variation in FPM visibility depending on local FPM densities and their surrounding habitat. Firstly, densities of FPMs varied greatly. FPMs in sparse aggregations tended to be individually more visible because the dark shells of the FPMs contrasted sharply with the lighter sand/gravel surrounding them. Those in dense aggregations were, individually, less easy to identify because of a lack of contrast between touching FPM shells. Secondly, riverbed properties had a strong effect on FPM visibility. Dead tree matter on the riverbed was darker than the surrounding substrate, and similar in colour to FPMs. When present, instream vegetation completely obscured the riverbed, making it impossible to discern if FPMs were present or not. Finally, flow circulation patterns had a strong effect on FPM visibility. FPMs were more visible when the flow was less turbulent (e.g. Site 6d on August 18) than when there were more turbulent conditions with ripples and standing waves (e.g. Site 7-8 on July 30).

Image processing. The visibility of FPMs could be enhanced using image processing. The effect of sunglint, wave lensing and some of the distortion caused by ripples could be reduced via the application of temporal filtering applied to video. However, the results of temporal filtering are dependent on how much geometric distortion there is among the video frames used, and we found that this approach smoothed riverbed detail under a strongly rippled surface. Further image processing such as sharpening of images constructed by temporal filtering of video also improved the discernment of individual FPMs in dense aggregations. Overall, image processing was worthwhile, but involved additional effort to ensure the collection of suitable imagery, such as ensuring the presence of enough of the bank within the video to enable accurate auto-alignment of individual video frames. The requirement to take videos from stationary positions would hinder, but not prevent, mapping of long river stretches.

4.2 Recommendations for surveying and image processing

From the analysis of our UAV data in the Borråselva, and from experience in other rivers (see Hedger et al. 2022), we recommend several procedures (see below, and summary in Box 1) to optimize surveying of FPM populations with UAVs.

Survey only under sufficient light levels. Surveying during winter is not recommended due to a short daylength and low solar elevations leading to dark conditions, and a low reflection from the riverbed. It is recommended that surveying is done during the brighter light conditions of late-spring to early-autumn, and at a time of day when solar elevation is high (although this may lead to problems with sunglint; see below).

Survey only under sunny conditions. Overcast conditions lead to reflections of cloud from the water surface that potentially dominate the outgoing signal from the river and obscure the riverbed. Imagery acquired under cloud cover in the current study (May 21) showed no riverbed detail and were not suitable for mapping FPMs. Researchers should make use of forecasts from the Norwegian Meteorological Institute (www.yr.no), and alternative forecasts such as WeatherRadarLive (https://weather-radar-live.com/cloud-cover-map/) to identify cloud conditions when planning survey times. Attention should also be paid to the type of cloud forecasted: thin high-altitude clouds will be less detrimental to effective surveying than thick low-altitude clouds.

Survey to minimize shadow. Shading from topography or riparian vegetation also obstruct direct sunlight and darken imagery of the riverbed. Surveys can minimize the presence of shadows on the water surface via imaging at a time when the channel is aligned with the solar azimuth. The likely positions of shadows can be predicted using a GIS-based approach – applying a shade prediction algorithm (e.g. R function *doshade{insol}; https://cran.r-project.org/src/contrib/Archive/insol/*) to DTM/DSM maps from the Norwegian Mapping Agency (http://hoydedata.no) – or by using one of the available mobile apps (e.g. *Sun Locator Lite*). If the source of shadow is deciduous trees, it may be advisable to survey during early spring (if light levels permit) before the development of the leaf canopy.

Survey to minimize sunglint. While high solar elevations are generally advised for imaging, these can increase the prevalence of sunglint. Sunglint on a flat water surface will probably not occur for imagery acquired from a DJI Mini 2 at high latitudes because maximum solar elevation is too low for sunglint to be within the FOV of the sensor. However, sunglint on ripples was apparent in the Borråselva at solar elevations >20º. When surveying unsmooth river surfaces, it may therefore be advisable to image at lower surface elevations, during morning or evening hours, if there is sufficient illumination to see the riverbed.

Survey when discharge is low. High discharge leads to (1) a deeper water column, potentially with increased suspended sediments and dissolved organic material, resulting in more absorption and scattering of light, and therefore a darker and less defined riverbed, and (2) an increase in the prevalence of ripples/white water surface flow patterns that may obscure the riverbed. Low flow periods can be identified by monitoring rainfall levels (e.g. using data from the Norwegian Meteorological Institute, www.yr.no) and water gauges if available (e.g. data from the Norwegian Water Resources and Energy Directorate – NVE, https://sildre.nve.no).

Survey at appropriate flight elevations and speeds. Successful identification of FPMs requires high resolution imagery. Flying near to the water surface is a requisite for achieving the necessary resolution. Flying at an elevation of 10 m will provide an approximate average resolution of 0.5 cm for DJI Mini 2 images (Figure 19; left panel). We recommend a minimum above surface elevation of ≈5 m to (1) avoid the creation of ripples on the water surface from the downwash of the UAV rotors and (2) minimize the risk of losing control of the UAV (DJI recommends a minimum above surface elevation of 3 m when flying a UAV over water). Swath width increases with elevation (Figure 19; right panel). Therefore, to cover a river from bank-to-bank may require obtaining imagery at a lower resolution than is desirable. In wide streams (e.g. >10 m across), it may be necessary to survey the two banks separately at high resolution, and then later combine imagery into an orthophoto. Elevation also affects the speed at which a UAV can be flown. Firstly, images are more prone to blurring at low elevation due to the movement of the camera relative to the ground surface, so flight speeds should be low at low elevations. Secondly, it is necessary to have sufficient overlap between images for orthophoto construction, so flight speeds need to be low at low elevation to ensure overlap. The distance a UAV moves between image acquisition can be calculated from its velocity over the imaging interval, and this can be used to estimate an acceptable speed to ensure a sufficient overlap.

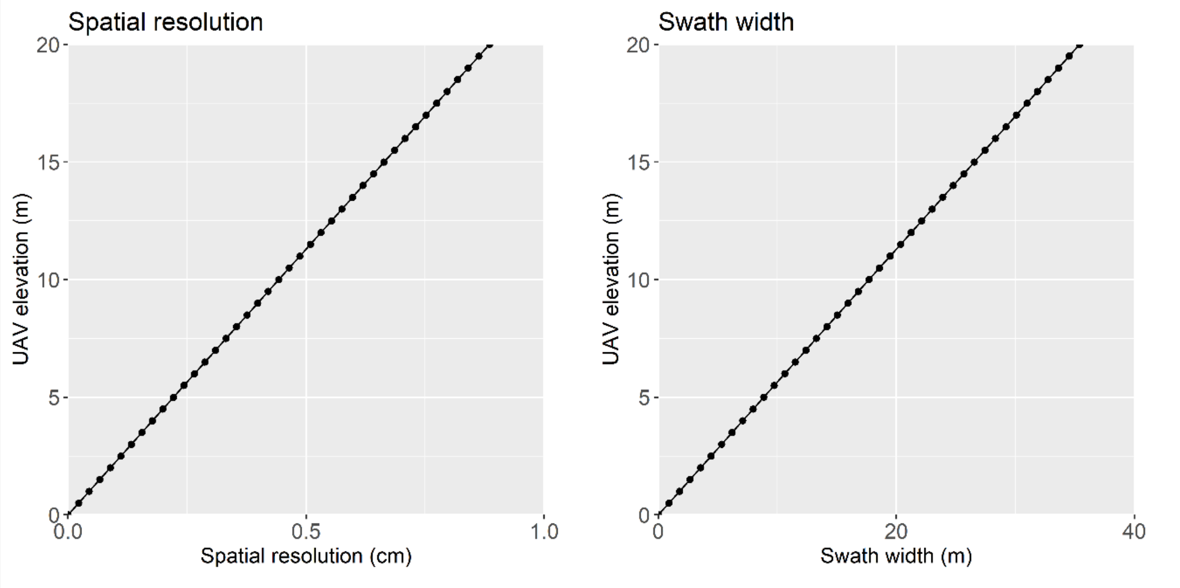

Figure 19. Image spatial resolution (left panel) and swathe width (right panel) as a function of UAV elevation for a 12 MP DJI Mini 2 image.

Survey with a range of imaging techniques. Imaging should involve both photo surveying (i.e., single images taken at a pre-set time-interval) and video surveying.

When photo surveying, both *jpeg* and *raw* data formats should be acquired. The *jpeg* format is appropriate for use in construction of orthophotos using WebODM. *Raw* data offer greater potential for image processing in single images. When acquiring images for construction of orthophotos, we recommend that surveys should include:

- a flight over the study area at low elevation (e.g. 5 m) and low speed with a downward looking viewing angle to acquire high resolution data.
- a flight over the study area at higher elevation (e.g. 10-15 m), above the tree level, with a downward looking viewing angle to aid in geo-registering of low elevation high resolution data, and to provide coverage of the surrounding bankside vegetation.
- a flight over the study area at the same higher elevation but with an oblique viewing angle to assist in geo-registration of data.
- flights along-side the channel to assist in avoiding geometric distortion in the periphery of the channel.

Failure to conduct the photo-surveying correctly may result in artefacts within the constructed orthophotos. In the current study, orthophotos were generally free from artefacts within the river channel, but there were occasional areas of geometric distortion in some parts of the orthophotos in the surrounding banks. For example, Figure 20 shows an orthophoto with very heavy distortion in the periphery of the orthophoto, caused by (1) having a low overlap of images that comprise the orthophoto and (2) a highly variable surface elevation from the presence of trees. Producing realistic orthophotos in this area would require extending the survey so that the UAV is flying alongside the channel, rather than just directly above it.

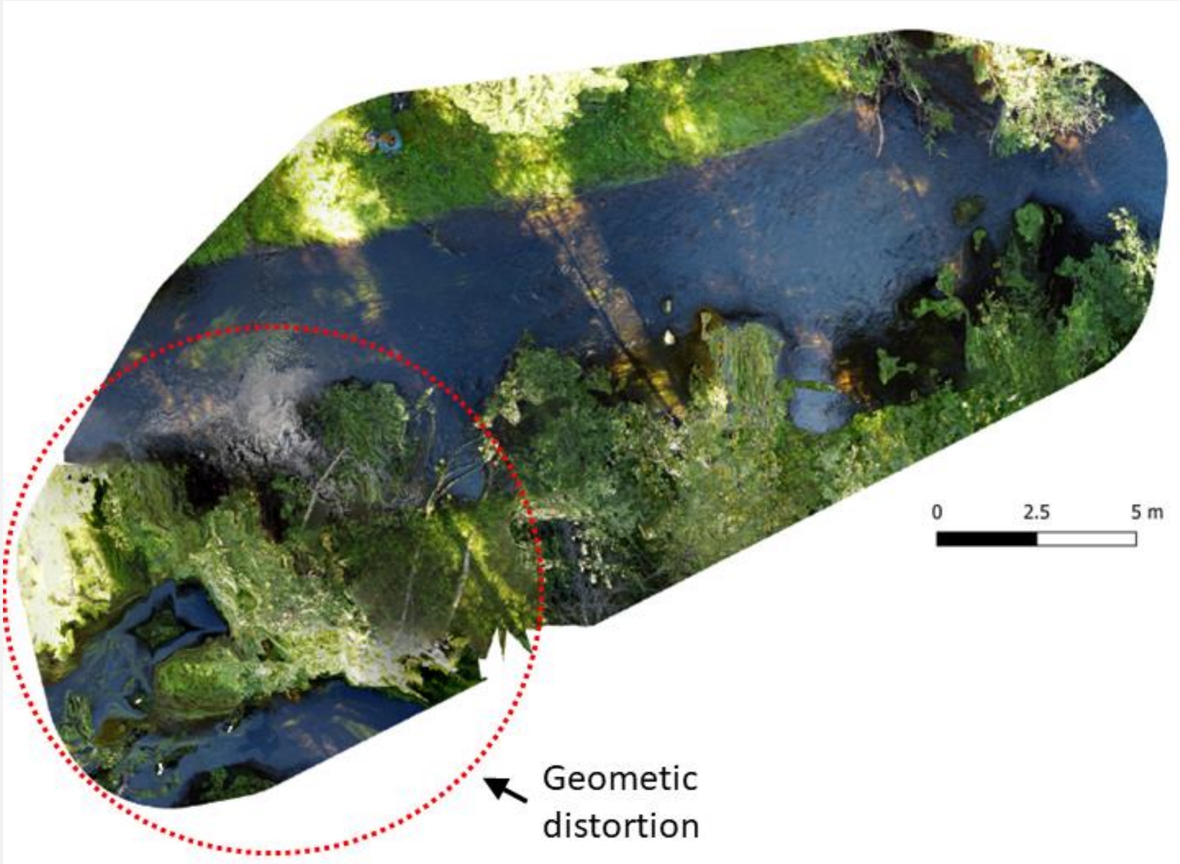

Figure 20. Example of geometric distortion (Site7-8, August 18).

Video offers the opportunity to obtain images (extracted as frames of the video) at a very high rate (e.g. 25 per second). We recommend two approaches for video surveying:

- Firstly, a video survey of the entire river stretch should be made by slowly flying the UAV across the stretch. This guarantees the collection of data for every part of the stretch.
- Secondly, videos of specific locations should be acquired from a UAV held in a fixed position. This ensures acquisition of multiple frames of the same location that can be used to reduce phenomena that obscure the riverbed such as sunglint, shallow water wave lensing, ripples, and foam.

Some of these recommendations imply contradicting survey procedures. For example, imaging under direct sunlight leads to an increased propensity for shadow and sunglint; imaging at low solar elevation to avoid sunglint reduces the incoming irradiance per unit area, resulting in darker images. Additionally, given the practical difficulties involved in surveying, some of the optimizing methods may not be feasible. Thus, an overarching recommendation is that researchers take these issues into account, but are flexible and attempt to achieve a balance to ensure best possible conditions.

Box 1. Key factors to ensure optimal surveying.

1. **Survey during spring to autumn, when light levels are sufficient.**
2. **Survey under direct sunlight, avoiding overcast conditions.**
3. **Survey to minimize shadow.**
4. **Survey under suitable flow conditions.**
5. **Fly at low elevation, and at low speed.**
6. **Acquire as much imagery as possible, using both photo and video surveying.**

Construct orthophotos and remove phenomena obscuring the riverbed. WebODM was sufficient for producing orthophotos of FPM distributions. The software did produce artefacts, typically in the periphery of the orthophotos and in areas of high topographic variation around the river, but the propensity for artefacts can be minimized by surveying a wider area with more images (Section 4.2). ODM performs similarly to commercial packages (Pell et al. 2022) so is the recommended platform. Errors in orthophoto geopositions (typical with those based on DJI Mini images which lack RTK positioning) can be geocorrected using GIS packages. A potential hindrance to orthophoto construction is the presence of ephemeral image phenomena such as sunglint, shallow water wave lensing and ripples. We found a temporal filter applied to video was found to be effective for reducing these phenomena. If the FPM stretch is heavily affected by such phenomena, it may be advisable to construct multiple images from multiple videos, and then merge the constructed images for production of orthophotos.

4.3 Effectiveness of UAVs for freshwater pearl mussel surveying

The current study has shown that UAVs can be used to detect FPMs and produce orthophotos of FPM aggregations in a river. However, application of UAVs to FPM surveying is not without challenges, particularly with respect to (1) selection of a suitable survey time window; (2) the maximum extent of the river that can be surveyed within a particular flight; and (3) FPM visibility. The Borråselva was a particularly difficult river to survey FPMs from a UAV due to steep banks and dense riparian vegetation with a lot of overhanging tree branches, that both limited the length of individual surveys to ≈40-50 m and hindered imaging of the riverbed due to shadows. Given that this is possibly a “worse case” example of a river for UAV surveying, it can be expected that other FPM rivers will yield better results. Thus, we conclude that, although there were challenges to the effective application of UAVs in the current study, UAVs have potential for surveying FPMs and may be a valuable part of FPM monitoring programmes.

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ISSN: 1504-3312
ISBN: 978-82-426-5154-9

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