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Evaluating the suitability of aerial photo surveys for assessing Atlantic salmon habitat in Norway

Aerially surveying Norwegian Atlantic salmon habitat

Richard Hedger
Line Sundt-Hansen
Anders Foldvik

NINA

Norwegian Institute for Nature Research

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COVER PICTURE
Norge i bilder image of the River Børsa, with contours showing LiDAR surface elevations, and an inlet panel showing a UAV orthomosaic. © Richard Hedger, Anders Foldvik and Pål Kvaløy

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CONTACT DETAILS

NINA head office
P.O.Box 5685 Torgarden
NO-7485 Trondheim
Norway
P: +47 73 80 14 00

NINA Oslo
Sognsveien 68
0855 Oslo
Norway
P: +47 73 80 14 00

NINA Tromsø
P.O.Box 6606 Langnes
NO-9296 Tromsø
Norway
P: +47 77 75 04 00

NINA Lillehammer
Vormstuguvegen 40
NO-2624 Lillehammer
Norway
P: +47 73 80 14 00

NINA Bergen:
Thormøhlens gate 55
NO-5006 Bergen.
Norway
P: +47 73 80 14 00

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Abstract

Hedger, R.D., Sundt-Hansen, L.E. & Foldvik, A. 2022. Evaluating the suitability of aerial photo surveys for assessing Atlantic salmon habitat in Norway. NINA Report 2105. Norwegian Institute for Nature Research

Remote sensing has been increasingly applied to researching the river habitat of fishes such as Atlantic salmon over the last few decades. Advances in remote sensing, such as the development of new platforms (UAVs), new methods for processing data, and better infrastructure for integrating data with additional GIS data sources, means that application of remote sensing to river science is becoming increasingly effective. This report assesses the capabilities and limitations of using aerial photo surveys for assessing Norwegian Atlantic salmon habitat. This habitat is extensive, so ground-based surveys are unable to provide synoptic coverage. This study shows how this coverage can be achieved via remote sensing, relying on the two principal photo survey data sources available to NINA: Norge i bilder and UAVs. The two approaches are complementary: Norge i bilder can be used to provide large-scale coverage, and allows for examination of long-term historical change, but is limited by sometimes poor quality imagery; UAVs allow for collection of novel, detailed information, but are limited in range. The successful application of these aerial photo survey approaches to Atlantic salmon habitat within Norway is somewhat limited by the light environment of Norwegian Atlantic salmon reaches, characterized by high cloud cover, low solar elevations or darkness in winter, and shadows from topography or bank-side trees. However, a full awareness of limitations (both those related to the remote sensing approach and those related to the light environment) allows optimal application of the remote sensing. This report, therefore, provides recommendations for a structured approach to aerial photo surveying of Norwegian Atlantic salmon habitat, incorporating Norge i bilder and UAV images and ancillary GIS datasets.

Richard Hedger, Line Sundt-Hansen, Anders Foldvik. Norwegian Institute for Nature Research – NINA, P.O.Box 5685 Torgard, NO-7485 Trondheim. Email: richard.hedger@nina.no

Sammendrag

RD Hedger, LE Sundt-Hansen, A Foldvik 2022. Evaluering av flyfotoundersøkelsers egnethet for vurdering av laksehabitat i Norge NINA Report 2105. Norsk institutt for naturforskning.

I de siste tiårene har fjernmåling i økende grad blitt brukt til å forske på elvehabitatet til atlantisk laks. Bruken av fjernmåling til elvekartlegging blir stadig mer effektiv på grunn av stadig nye fremskritt innen fjernmåling, slik som utvikling av nye plattformer (droner), nye metoder for behandling av data og bedre infrastruktur for integrering av data med ytterligere GIS-datakilder. I denne rapporten ser vi på mulighetene og begrensningene knyttet til flyfotoundersøkelser når det gjelder å vurdere leveområdet (habitatet) for atlantisk laks. Habitatet til atlantisk laks er omfattende i Norge. Dette betyr at bakkebaserte feltundersøkelser ikke er i stand til å gi god dekning. Denne rapporten viser hvordan bedre dekning kan oppnås ved bruk av fjernmåling, basert på foto Norge i bilder og fra droner. De to tilnærmingene er komplementære: Norge i bilder kan brukes til å gi storskala dekning, og gir mulighet for undersøkelse av langsiktige historiske endringer, men kan være begrenset av bildekvalitet. Droner tillater innsamling av ny, detaljert informasjon, men er begrenset i rekkevidde. Vellykket anvendelse av flyfoto og dronebilder er delvis begrenset av lysmiljøet, som i Norge som er preget av høyt skydekke, lave solhøyder eller mørke om vinteren, og skygger fra topografi eller sidetrær. Bevissthet om begrensninger (både de som er relatert til fjernmålingstilnærmingen og de som er relatert til lysmiljøet) er nødvendig for optimal anvendelse av fjernmåling. Denne rapporten gir anbefalinger for en strukturert tilnærming til flyfotoundersøkelse av laksehabitat i Norge, ved bruk av Norge i bilder og dronebilder og tilhørende GIS-datasett.

Richard Hedger, Line Sundt-Hansen, Anders Foldvik. Norsk institutt for naturforskning (NINA), Postboks 5685 Torgard, NO-7485 Trondheim. E-post: richard.hedger@nina.no

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Foreword

A key strategic initiative of NINA is the development of new methods in research, mapping and monitoring. This report presents research from a NINA Strategic Initiative (SATS) project (project financing: Forskningsrådets prosjektnummer 160022/F40) assessing the ability of using aerial photo surveys (principally archived aerial photographs from Norge i bilder and newly acquired UAV images) for assessing Norwegian Atlantic salmon habitat. The report documents potentials and limitations of photo survey approaches, and suggests methods for optimizing their application. Outcomes from this study are relevant to NINA's research portfolio in a number of areas, particularly with regard to research on wild salmonids and conditions that affect them.

Richard Hedger, January 2022

1 Introduction

1.1 A river science approach to Atlantic salmon habitat

The Atlantic salmon (*Salmo salar* L.) is an anadromous, cold-water fish species that spends its early life-stages (eggs, alevins, fry and parr) within rivers in the northern hemisphere ranging from ≈ 43ºN in northern Spain (Almodovar et al. 2019) to ≈ 70ºN on the northern coast of Norway (Jensen et al. 2014). The physical and biological properties of rivers that support the survival and reproduction of the Atlantic salmon (see Table 1) determine the extent of available habitat of the species. Characterization of such habitat is necessary for effective examination of controls on Atlantic salmon populations and management of stocks. Traditionally, habitat has been characterized by ground-based surveys conducted along-side surveys of Atlantic salmon populations, often by sampling the habitat via wading through the river or observing the river from the river bank. However, given the spatial extent of such habitat, and its dynamically changing properties, characterization of habitat via ground-based surveys alone may be time-consuming and expensive.

River science is a rapidly developing interdisciplinary field integrating the natural sciences, engineering and socio-political sciences (Gilvear et al. 2016). It uses research in hydroecology, ecohydrology, eco-hydromorphology and ecogeomorphology "to provide the methods and knowledge required to sustainably manage some of the planet's most important and vulnerable ecosystems" (Serlet et al. 2020). River science is growing as a discipline because of an increased need for data to document spatial and temporal variation in river systems, evolving technologies that enable lower cost acquisition from reach to continental scale, and an increasing use of Geographic Information Science (GIS) (Marcus & Fonstad 2010). Developments in river science, utilizing the developing technologies of remote sensing and GIS, may offer the potential to achieve a more efficient, comprehensive and robust characterization of Atlantic salmon habitat.

Table 1. Key properties of Atlantic salmon physical habitat.

Property	Principle functional effect on Atlantic salmon
Riverbed substrate size *	Gravel for spawning Pebbles, cobbles, boulders for cover from predators
Channel depth	Deep areas offer cover from predators and suboptimal temperatures
Flow velocity	Supply of prey items Energy expenditure
Riparian vegetation	Cover from predators Cover from excess summer temperatures
Woody material	Shelter
Temperature	Growth, susceptibility to mortality from heat stress or ice formation
Channel cross-sectional profile, mesohabitat, sedimentary link	Heterogeneity in functional effects listed above

* Substrate categories referenced in this report follow a modified Wentworth scale (Wentworth 1922): sand (< 2 mm), gravel (2-32 mm), pebble (32-64 mm), cobble (64-256 mm), boulder (>256 mm)

1.2 Spatiotemporal characteristics of river habitat

River habitat (defined here as *fish habitat within rivers*) varies across a range of spatial and temporal scales. Pioneering work by Frissell et al. (1986) presented a system for defining and classifying river habitat at different spatiotemporal scales, associated with watershed geomorphic features and events. This system allowed for a spatiotemporal nesting of habitat across a range of system levels – stream, segment, reach, pool/riffle, microhabitat – each with a characteristic spatial dimension over which the level exists, and a characteristic temporal dimension describing the time-ranges over which changes occur. The nature of the habitat at all scales will affect what occurs at any location. Newson and Newson (2000) concluded that biological patterns respond firstly to the longitudinal zonation of the river but are also affected by the mesohabitat biotype.

1.2.1 Spatial scales

At microscales – the scale of meters or below – river habitat varies in terms of water velocity, water depth, riverbed substrate size, and water temperature. These may affect phenomena such as prey supply and energy expenditure (dependent on velocity), the ability to hide from predators (dependent on depth and substrate size), and growth rate (dependent on temperature). In addition to being a scale where there is a direct and immediate impact of the habitat on the individual fish, this scale lends itself to easy investigation in the field because researchers do not need to cover a large geographic distance to observe it. There has therefore been much research at the microscale, leading to, for example, functional relationships being derived between Atlantic salmon occurrence/abundance and microhabitat properties, including the development of preference curves that describe these relationships (Armstrong et al. 2003, de Jalon & Gortazar 2007, Hedger et al. 2005).

At mesoscales (over tens or hundreds of meters), the spatial configuration of microscale habitat properties may be used to classify reaches into mesohabitat types – pool/riffle, rapids, sills etc. – that may better characterize the range of environmental properties experienced by individual fish. Atlantic salmon individuals use multiple locations, both within the same life-stage, and across the ontogenetic development of the individual. For example, spawning adults may require gravel substrates for building redds, whereas juveniles may require medium sized substrates for shelter (Armstrong et al. 2003). Juveniles often only disperse over short distances downstream of the spawning redd (Beall et al. 1994, Einum & Nislow 2005) so a stretch consisting of substrates suitable for spawning in close proximity to substrates suitable for rearing may support a greater Atlantic salmon abundance than a stretch where areas suitable for spawning and rearing are distant from one another.

At macroscales, up to the entire length of the river, longitudinal variation in properties control where mesohabitats and microhabitats occur. A range of models have been used to describe longitudinal changes in rivers: e.g. the Hjulström (Hjulström 1935) and Schumm (Schumm 1977) models. Typically, rivers have longitudinal profiles, beginning with a steep, narrow channel that becomes progressively gentler and wider toward the river mouth. Riverbed substrate tends to become progressively finer further downstream due to shallower gradients and increasing discharges. Rivers may be compartmentalized into two zones: the upstream “rithron” and the downstream “potamon” zone. The rithron zone is characterized by generally steep channels with fast flowing waters, and may have alternating segments consisting of steep and narrow rapids and riffles or flatter and wider pools and glides. The potamon zone is characterized by wide, flat, meandering channels. Local phenomena may cause other macroscale structure to be superimposed on this pattern. For example, tributaries or underlying geology may structure the river into a series of sedimentary links (see Lapointe 2012). Alternatively, human activity such as hydropower dams and weirs may cause punctuated changes in flow, sediment transport and sedimentation, and cross-channel profile. Macroscale variation in habitat may have a large influence on where Atlantic salmon are found. For instance, sedimentary links may control where spawning occurs (Davey & Lapointe 2007), and hydropower dams may prevent migration of Atlantic salmon to upstream parts of the watercourse (Thorstad et al. 2008).

1.2.2 Temporal scales

Temporal variation in river habitat may originate from natural causes (e.g. weather or climate patterns, or channel erosion and deposition) or anthropogenic causes (e.g. building of dams for hydropower or channel modification). Both are pertinent to Norwegian Atlantic salmon rivers: climate change is expected to cause large variations in discharge regimes (Sundt-Hansen et al. 2018) and there is extensive ongoing anthropogenic modification of Norwegian watercourses (Lia et al. 2015).

River habitats vary over time-periods from minutes to multi-millennia. Frissell et al. (1986) characterized the temporal scales of rivers as increasing within increasing spatial scale of the system, so time scales of continuous potential persistence would be: <0.1 – 1 years (microhabitat), 1 – 10 years (pool/riffle), 10 – 100 years (reach), 1000 – 10000 years (segment) and >10 000 years (stream). Short-term variation in discharge, from natural floods or anthropogenic activity within regulated rivers (such as hydropeaking) may cause variation in velocity, depth and wetted area over timescales of minutes to days (Sauterleute et al. 2016). These variations may be aperiodic and unpredicted, such as in the case of natural floods, or episodic, in the case of managed flows in regulated rivers. The fact that Norwegian Atlantic salmon rivers are prone to developing surface ice during winter may cause intra-annual variation in habitat properties with consequent effects on Atlantic salmon survival (Hedger et al. 2013). Long-term variations in discharge patterns, on the decadal scale, may be a response to changes in catchment characteristics, or discharge regimes within regulated rivers. This may become a more pertinent issue with ongoing climate change (Sundt-Hansen et al. 2018). Changes in channel characteristics and substrate may also occur over a range of timescales. Near-instantaneous changes may occur from flooding or from river management activities (for example, the addition of spawning gravels), but long-term changes will also affect Atlantic salmon habitat (for example, long-term sedimentation of spawning habitat).

1.3 Research on Norwegian Atlantic salmon rivers

The Atlantic salmon is a culturally and economically important fish across Scandinavia (Ignatius & Haapasaari 2018, Liu et al. 2011). Norway has circa 440 Atlantic salmon rivers (see Forseth et al. 2017) (Figure 1). However, Norwegian Atlantic salmon populations are at historically low levels (Hindar et al. 2010), with declines resulting from escaped farmed Atlantic salmon and salmon lice, the freshwater parasite *Gyrodactylus salaris*, freshwater acidification, and hydropower and habitat modification (Forseth et al. 2017). This has created an impetus for characterizing both populations and the watercourses that support them.

1.3.1 Characterizing populations

Given the cultural significance of Atlantic salmon within Norway, it is a well-studied fish. For example, from a topic search for “Atlantic salmon”, Web of Science lists Norway in first place as country of origin (>5 600 articles). Most research has lacked a detailed spatial component. However, over the last two decades, there has been an increase in research that has taken into consideration the spatial characteristics of Norwegian Atlantic salmon populations. Johansen et al. (2005) established relationships between juvenile Atlantic salmon density and invertebrate density in tributaries of one of Norway’s largest salmon rivers, the River Tana in Northern Norway. Finstad et al. (2010) used snorkeling and bankside observations to study the distribution of spawning Atlantic salmon for eight rivers (Eidselva, Stryn, Nausta, Gaula, Lærdal, Aurland, Flåm and Nærøydal) to conclude that the distribution of spawners would have strong implications for river accessibility to young-of-the-year parr. The importance of the ability of juveniles to migrate was identified in a study by Foldvik et al. (2012) based on 205 electrofishing parcels in a ≈ 5 km stretch of the River Skauga. While these studies have provided useful information, they have not used a full river science approach, and have not incorporated the potential benefit from remote sensing / GIS approaches for characterizing habitat. In contrast, studies on temporal aspects of salmon populations in Norway are much more prevalent. This has ranged from long-term studies in individual rivers (Erkinaro et al. 2019, Ugedal et al. 2008) to reports summarizing nation-wide populations (Thorstad et al. 2020).

Figure 1. Norwegian Atlantic salmon reaches (blue lines) used in this report (N = 432).

1.3.2 Characterizing rivers

Given the challenges faced with regard to watercourse management, there has been an increase in the development of formalized approaches for characterizing rivers. These have ranged from simple methods for compartmentalizing rivers into distinct mesohabitats to decision support tools for classifying based on the river's ability to sustain fish populations.

Compartmentalizing watercourses. A system for the compartmentalization and classification of Norwegian watercourses into distinct mesohabitat units was proposed by Borsányi et al. (2004). Development criteria for this were that: (1) it was applicable to all Norwegian Atlantic salmon rivers; (2) it required no prior expert knowledge; and (3) it required no specialized or sophisticated instrumentation. This system uses a classification decision tree based on certain river properties to compartmentalize the watercourse (Table 2). Properties are as follows:

1) surface pattern: smooth/rippled (wave height < 0.05 m) versus broken/unbroken standing waves (wave height > 0.05 m)
2) surface gradient: moderate (< 4 %) versus steep (> 4 %)
3) surface velocity: slow (< 0.5 m s^{-1}) versus fast (> 0.5 m s^{-1})
4) water depth: shallow (< 0.7 m) versus deep (> 0. 7 m)

Table 2. Mesohabitat classification system of Borsányi (2004).

Property				**Code**	**Mesohabitat**
Surface pattern	Gradient	Surface velocity	Water depth		
Smooth or rippled	Steep	Fast	Deep	A	Run
	Mild	Fast	Shallow	B1	Shallow glide
	Mild	Fast	Deep	B2	Deep glide
	Mild	Slow	Deep	C	Pool
	Mild	Slow	Shallow	D	Walk
Broken or unbroken standing waves	Steep	Fast	Deep	E	Rapid
	Steep	Fast	Shallow	F	Cascade
	Mild	Fast	Shallow	G	Splash
	Mild	Slow	Shallow	H	Rill

Harby et al. (2018) suggested a system for classifying hydromorphological conditions in Norwegian watercourses based on quantifying (1) variation alongside the river (e.g. erosion protection or bankside vegetation), (2) variation along the river (e.g. barrier effects or fragmentation), (3) variation within the river (e.g. substrate types and river classes), and (4) hydrological conditions (e.g. changes in discharge and water level). Additionally, Harby et al. detailed other important characteristics pertinent to Norwegian river systems such as variation in water temperature, straightening of watercourses, the presence of dead wood and vegetation in the river, and changes in ice conditions.

Decision support tools. A system allowing watercourse characterization with a view to improving Atlantic salmon populations in regulated rivers while taking hydropower interests into account was presented in the *Handbook for environmental design in regulated rivers* (Forseth & Harby 2014). With regard to modelling Atlantic salmon populations, this system allows for the identification of habitat-related bottlenecks and hydrological bottlenecks. Habitat-related bottlenecks, usually defined at a segment scale (500 – 1000 m long), are identified from spawning habitat and shelter. Spawning habitat is classified based on the size of the spawning area within the segment, and distance between spawning habitats across segments. Shelter can be assessed from field-based measurements. Combinations of spawning habitat and shelter classification can then be used to determine (1) probable habitat bottlenecks and (2) segment productivity. Hydrological bottlenecks, usually defined at the reach scale (a reach being defined as part of the river system which has a uniform impact from regulation), are identified from flow conditions and water temperature. An alternative decision support system, designed for commissioning and operating hydropower plants with regard to mitigation measures and developing cost-efficient solutions and strategies for enhancing fish populations and avoiding fish damage, has been developed within the *Fithydro* project (Dewitte et al. 2018) (see https://www.dss.fithydro.wb.bgu.tum.de/home/ui). Here, hydropower impacts and potential mitigation methods are assessed with regard to habitat, environmental flows, sediments, and fish migration.

There is, thus, a growing awareness of the need to use a more formalized framework within Norway to characterize watercourses, particularly so that the impacts from river regulation can be minimized. Approaches used so far have relied mostly on collecting information on rivers by on-site visits. There is, however, the potential for using remote sensing to increase the amount of information obtained and to improve the robustness of river habitat characterization.

1.4 Remote sensing of rivers

1.4.1 Development within the field

With advances in remote sensing – the process of obtaining information about the physical characteristics of an area from a distance, typically from aircraft or satellite, using reflected or emitted radiation – opportunities have arisen to examine river habitat at a variety of spatial and temporal scales. Aerial survey applications to river systems stretch back to the first half of the 20th century (Rich 1941). Satellite-based surveys are much more recent, with relatively little published research before the 1980s. These remote sensing surveying approaches have provided information on river habitats over large areas, sometimes at fine spatial resolutions: for instance, aerial photography from a low-flying helicopter platform may have spatial resolutions as fine as ≈ 0.03 m (Carbonneau et al. 2005a); high resolution QuickBird-2 satellite images can provide spatial resolutions of ≈ 1 m (Xu et al. 2004). Technological advances within the last decade have greatly increased the potential of remote sensing in river habitat studies via the development of new platforms (i.e. Unmanned Aerial Vehicles, UAVs), the development of algorithms for processing remote sensing data, and the development of procedures for disseminating and integrating remote sensing and GIS data.

UAVs. With the development of UAVs, otherwise known as Unmanned Aerial Surveillance Systems (UASSs) or drones, a new technology now exists that has high potential for examining river habitat. A range of platforms (multi-rotors, fixed-wing and combined rotor/fixed-wing) and sensor types exist, which can be selected with respect to survey demands. UAVs have greatly extended the informative ability of remote sensing to quantify river properties. Firstly, spatial resolution from UAVs may be several orders of magnitude higher – a pixel size of < 1 cm^2 (Figure 2) – than aerial photographs from crewed aircraft flying at higher altitudes, enabling the better detection of fine substrates (gravel and smaller). UAV resolutions are such that it is possible to map locations of spawning redds directly from the imagery (Harrison et al. 2020). Secondly, the ability to image from multiple angles using UAVs offers the potential to obtain depth structure (for instance, using *Structure from Motion*, SfM, approaches). This allows for the creation of orthomosaics (georegistered images) and digital surface models (DSMs) which can be used to map the distribution of river morphology (Tamminga et al. 2015). Thirdly, the ease of repeat imaging allows for examination of temporal change over short timescales, such as change in water-covered area at different discharges (Niedzielski et al. 2016). Finally, and importantly, UAVs allow the operator full control over how and when the site is imaged, allowing an operational responsiveness that may be unavailable from crewed aircraft or satellites, and allowing the site to be imaged at optimal times. UAVs have the potential to provide more valuable information than traditional remote sensing approaches (at least over small spatial ranges). However, end-users have often used the same methods as those used in traditional remote sensing, although there is now on-going development in UAV-specific techniques such as object detection and real-time tracking (Yao et al. 2019).

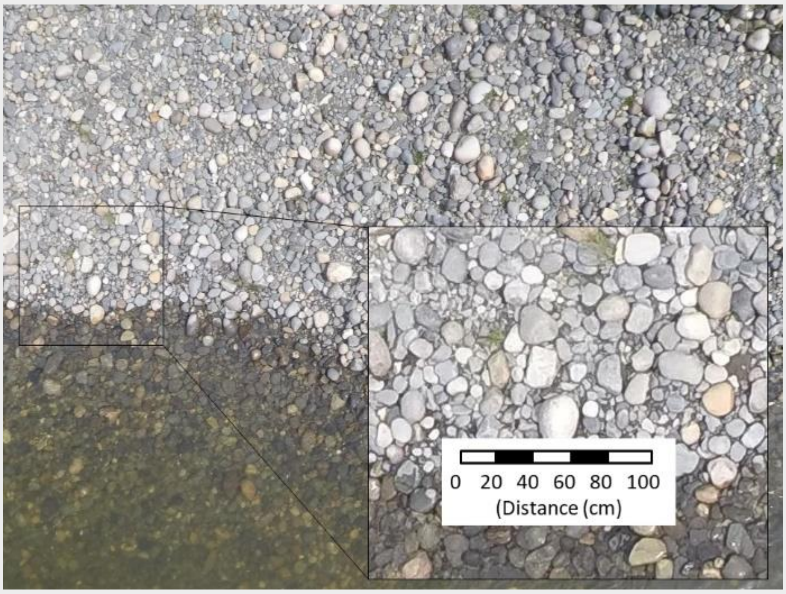

Figure 2. Example of UAV imagery obtained from a multi-rotor UAV operating at an elevation of less than 10 m (River Gaula, Vassdrag Nr: 122.Z). Pixel length is < 3 mm.

Algorithm development. There has been considerable development of new algorithms to process the type of information that may be obtained from remote sensing, some of which has application to river science. The most significant developments with regard to UAVs has been SfM, allowing the generation of orthomosaics and DSMs from overlapping UAV images. With regard to extracting information from remote sensing data on river habitats, there have also been developments in algorithms that can minimized some of the confounding factors: for example, fluid lensing to reduce the prominence of waves on the water surface (Chirayath & Earle 2016). However, possibly the most significant development is the incorporation of artificial intelligence techniques: (1) *machine learning* techniques such as supervised and unsupervised learning algorithms; and (2) *deep learning*, a type of machine learning based on artificial neural networks (ANNs). These offer the potential to deal with the complexity existing in imagery of river habitats (Casado et al. 2015, Hamann et al. 2014, Harrison et al. 2020), regardless of the source of the remote sensing imagery.

Data availability, dissemination and integration. There has been a large increase in the availability of remote sensing data from archived data sources, alongside GIS databases. R allows access to online data through the *rnaturalearth*, *osmdata*, and *getSpatialData* libraries. GIS packages, including open-source packages such as QGIS, Saga and GRASS, often link to online databases from which remote sensing and GIS data can be obtained. Platforms such as *Norge i bilder* allow for the download of orthomosaics covering all of Norway (see Section 3). A wide range of additional remote sensing and GIS data are available, both from Norwegian and European sources (see Appendix 10.1).

1.4.2 Basic river properties

Many applications of remote sensing towards river research have focused on directly extracting basic river properties such as water-covered area, flow conditions, velocity, depth, substrate size, channel vegetation/debris and ice/water temperature. Applications of remote sensing within this area have mostly been developed by individual researchers or research teams, rather than being part of coordinated agency research programs, which has led to a diversity in approaches and applications, but has made the development fragmented and has limited discussion (Marcus & Fonstad 2010).The following gives a brief overview of some of the studies.

Water-covered area. Water-covered area can be derived from orthophotos/orthomosaics by identifying parts of the imagery covered by water, using data obtained from a variety of platforms from UAVs (Niedzielski et al. 2016) to satellites (Xu et al. 2004).

Flow conditions. Approximate estimates of flow conditions (e.g. whether the flows are smooth or rapid) can be obtained from visual observation of surface conditions of the river in single images. For example, fast flows are associated with surface ripples or white water. To accurately estimate velocity from aerial imaging, however, requires tracking moving features on the water surface. The ability to acquire multiple successive images from UAVs over very short timescales allows for pattern matching of surface features and can be used to estimate surface velocity (Detert & Weitbrecht 2015, Tauro et al. 2016a, Tauro et al. 2016b).

Water depth. The depth of the water column within the river channel can be estimated by either analysis of image spectra or photogrammetry. The former approach involves establishing a relationship between digital number (DN) values in one or more image channels and water column depth measured from ground-surveying, and then using this relationship to estimate depth in the imagery (Legleiter et al. 2009). This relies on the fact that deeper parts of the channel have more attenuation of upwelling irradiance and are typically darker in images taken from above. This approach has been used across a range of imagery types including aerial photographs from *Norge i bilder* (Flener 2013) and very high resolution UAV imagery (Lejot et al. 2007). Importantly, this approach has been used successfully with panchromatic images so is applicable to archived aerial photographs (Lane et al. 2010). DN values are also affected by substrate (Legleiter et al. 2009) and periphyton (Gilvear et al. 2007) so these may, however, bias estimates. The alternative approach is to acquire overlapping images from multiple-view angles and use photogrammetry. UAVs can acquire imagery that is highly suitable for this approach (see for example Tamminga et al. 2015), given that they can easily acquire overlapping images with a changing view-angle as the UAV flies along the river stretch. Both approaches – spectral analysis and photogrammetry – require the ability to image the channel bed, so cannot be used if the river is too deep, too turbid, or has turbulence-induced surface white water.

Substrate size. Substrate size determination is dependent on the resolution of the imagery. Coarse resolution imagery (e.g. spatial resolution >0.1 – 1 m), may be used to distinguish between broad categories based on manual interpretation or spectral analysis (Camenen et al. 2013). Fine resolution imagery (e.g. spatial resolution ≈ 0.01 m) can be used to quantify substrate size using a variety of approaches that quantify spatial variation in DN, such as (1) image texture analysis and (2) image segmentation. Image texture analysis techniques have been based on statistical analysis of autocorrelation (Buscombe 2008, Buscombe et al. 2010, Rubin 2004, Warrick et al. 2009) or variance as a function of distance (Camenen et al. 2013, Carbonneau et al. 2005a, Carbonneau et al. 2005b). Image segmentation involves identifying individual substrate particles by classifying the image into clusters of bright areas (each cluster representing a substrate grain) surrounded by dark areas (shadows in the interstices between grains). Usually, this is done through a mixture of high-pass filters, segmentation, thresholding and mathematical morphology (Butler et al. 2001, Graham et al. 2005a, Graham et al. 2005b, Sime & Ferguson 2003).

Channel vegetation and woody debris. Submerged aquatic vegetation may be determined using image color (Flynn & Chapra 2014). UAV remote sensing is a suitable technique for mapping woody debris, which requires high resolution imagery (MacVicar et al. 2009).

River ice and temperature. River ice can be detected using a range of platforms from UAVs (Lin et al. 2012) to satellites (Li et al. 2020), using image clustering/segmentation approaches or spectral indices. The thickness, spatial extent and volume of surface ice can be mapped by applying an SfM approach to UAV imagery (Alfredsen et al. 2018). The water temperature of the river surface may be obtained through the use of thermal infrared cameras mounted on helicopters (Dugdale et al. 2013) or UAVs (Wawrzyniak et al. 2013).

1.4.3 From basic properties to habitat

Once basic properties have been established, it is possible to use their spatial configuration to determine characteristics of the river system, up to meso- and macro-scales (see Marcus & Fonstad 2008, Marcus & Fonstad 2010). This is typically associated with attempts to identify and map river features relevant to how fish species may use the river. At the mesoscale, Hamann et al. (2014) used an object-oriented approach to classify aerial photographs into run, riffle and pool habitats, and then identified transitional areas where runs or riffles were contiguous with pool habitat. Casado et al. (2015) used an ANN to classify a river stretch into a series of substrate features (e.g. bars), water features (e.g. riffles), and vegetation types (e.g. vegetated banks). Over larger-scales, aerial photographs have been used to aid in compartmentalizing rivers into sedimentary links (see Davey & Lapointe 2007).

1.4.4 Application to Norwegian Atlantic salmon rivers

While remote sensing may provide useful information on river properties, its potential use for resolving Atlantic salmon habitat within Norway is less substantiated. Firstly, it is necessary to match the surveying technique to the spatial extent of the habitat and the dynamic change within the habitat, while ensuring that the technique provides information of sufficient quality. This requires investigation of the spatiotemporal scales of variation in habitat so that the remote sensing approach can be optimized. Secondly, Norwegian rivers are challenging for remote sensing. Boreal environments are characterized by low solar irradiance relative to more southern latitudes, limiting the utility of a passive optical remote sensing method reliant on solar irradiance. Atlantic salmon rivers may also be in mountainous areas or have tall riparian vegetation that may further affect the light environment. Finally, from a remote sensing perspective, rivers are information-heavy environments, which hinders the extraction of useful habitat features. Despite the problems associated with remote sensing of rivers within Norway, there has been an increasing application of this technique over the last decade: see for example mapping of bathymetry (Flener 2013, Sundt et al. 2021, Zinke & Flener 2013) and river ice (Alfredsen et al. 2018).

1.5 Study objectives

In this study, we evaluate the suitability of aerial photo surveys for assessing Atlantic salmon habitat within Norway (see Tables 3, 4 and 5 for an explanation of abbreviations, a glossary of remote sensing terms, and a glossary of how river science terms are used in this report).

- We begin by examining how the spatial and temporal characteristics of Atlantic salmon habitat lend themselves to being resolved from aerial photo surveys, both through the use of traditional, high altitude archival aerial photographs from *Norge i bilder* and through the use of novel, low altitude UAV surveys.
- We then examine, for selected rivers, the type of information that can be obtained from *Norge i bilder*-archived aerial photographs and UAV images, and we assess their respective informative potential with regard to characterizing Atlantic salmon habitat. We also describe alternative photo surveying approaches.
- We then examine issues related to aerial photo surveys of Atlantic salmon habitat within Norway, both in terms of image acquisition and image quality.
- We then suggest approaches for optimizing aerial photo surveys of Atlantic salmon habitat, both for *Norge i bilder* and for UAVs, and for integrating them with GIS data.

We focus on aerial photo surveys based on passive optical remote sensing, using true color (red, green, blue) camera sensors that are used for the bulk of aerial photography available through *Norge i bilder* or in relatively inexpensive UAV systems, rather than arguably less relevant (due to cost, and a high application-specificity) sensors such as multi-spectral cameras, hyperspectral sensors and thermal infra-red sensors (see summary of applications, benefits and costs in Yao et al. 2019). Where appropriate, however, we also reference satellite imagery, alternative remote sensing approaches (e.g. LiDAR), and the wide-range of GIS data available that may be used to supplement information from photo surveys.

Table 3. Abbreviations used for terms in this report.

Abbreviation	Term
ANN	Artificial neural network
DN	Digital number (the pixel value of a single channel of an image)
DSM	Digital surface model (elevation of features plus topography)
DTM	Digital terrain model (elevation of topography with features removed)
FOV	Field of view
GIS	Geographic information science/system
GCP	Ground control point
GPS	Global positioning system
Masl	Meters above sea level
NIR	Near-infra red
UAV	Unmanned aerial vehicle
SfM	Structure from motion
LiDAR	Laser imaging, detection, and ranging

Table 4. Glossary of remote sensing terminology used in this report.

Term	Meaning
Aerial photo	Image acquired from an aerial platform (e.g. airplane, helicopter or UAV)
Angular FOV	Angle (degrees) through which camera receives light
Crewed aircraft	An aircraft with a crew, either fixed wing (of the type used for acquiring *Norge i bilder* images) or helicopter
Image artefact	A feature present in the image that is not inherent to the surface being imaged (e.g. shadow, reflection)
Irradiance	Intensity of electro-magnetic radiation (W m^{-2})
Look-angle	Angle from nadir at which the sensor looks at the surface
Linear FOV	Ground swath width
Orthophoto	A single geometrically corrected image
Orthomosaic	A geometrically corrected image composed of multiple mosaiced images
Orthorectification	The process of removing image perspective and relief from terrain to create a planimetrically image with constant scale
Passive RS	Remote sensing reliant upon a radiation source other than the remote sensing instrument: i.e. reflected solar radiation or emitted radiation
Platform	The vehicle (e.g. crewed aircraft, UAV) on which the sensor is mounted
Solar insolation	Amount of solar energy over time (Wh m^{-2}) that is incident on a surface
Solar zenith	Angle (degrees) of sun from vertical
Solar elevation	Angle (degrees) of sun above horizon (= 90º – solar zenith)
True-color	Imagery where blue, green and red wavelengths are mapped into blue, green and red channels

Table 5. Glossary of river science terminology as used in this report.

Term	Meaning
Segment	A stretch of river, approximately 500 – 1000 m in length
Reach	A stretch of river with uniform impact from regulation
Sedimentary link	A distinct part of the river, created by geological discontinuities or large tributaries, that results in macroscale structure in gradient, and bed material.
The salmon reach	The area of a watercourse that is accessible to and supports population of Atlantic salmon
Watercourse	A course of flowing surface water, including all rivers and tributaries

NB: Frissell's use of the terms "Reach" and "Segment" (Frissell et al. 1986) are not used here.

2 Spatial and temporal characteristics of Atlantic salmon habitat in Norway

2.1 Introduction

Effective aerial photo surveying requires matching of the imaging system with what is being imaged, both spatially and temporally. Here, we describe the spatial and temporal characteristics of Atlantic salmon habitat throughout Norway, and the implications these have for aerial photo surveys. We first investigate the spatial distribution of Atlantic salmon habitat across Norway: its geographical distribution and its proximity to human infrastructure. This distribution has implications both for the potential quality of imagery and the ease of access for UAV photo surveying. We then investigate the spatial characteristics of Atlantic salmon reaches, such as length, topography, and mesoscale and macroscale variability (e.g. the existence of “sedimentary link”-like features). Such characteristics can be used to establish the degree to which novel UAV data could be used to complement existing *Norge i bilder* archived imagery. We also examine temporal characteristics: long-term variation in watercourse structure, which pertains to the usefulness of using archived *Norge i bilder* aerial photographs; changes in discharge, and the seasonal presence of ice-cover, which pertains to the usefulness of the operational flexibility of UAV surveys.

2.2 Data sources and processing

The Norwegian rivers which support Atlantic salmon populations have been documented (Forseth et al. 2017), as have the spatial limits within each river that support Atlantic salmon (referred to henceforth as “Atlantic salmon reaches”) (https://lakseregisteret.fylkesmannen.no/). The upper parts of these Atlantic salmon reaches are usually constrained by waterfalls or hydropower dams. This Information was used to constrain our analysis to known Atlantic salmon reaches across Norway.

The courses of Atlantic salmon rivers were extracted from the *NVE-Elvenett* database of all rivers in Norway. This is a vector line database, in which center lines have been digitized running approximately midway between the banks of the channel. Each line in the database has IDs referencing the river (*Elvenavn*, *elvID*, *vassdragNr*), plus some additional information (e.g. stream order, whether the line refers to a river or a lake). Atlantic salmon rivers were then clipped so that they only contained the reaches that support and are occupied by Atlantic salmon (including both the main channel and large tributaries). In total, we used 432 Atlantic salmon rivers. Although this approach allowed us to make a general summary of features of Norway’s Atlantic salmon supporting reaches, the list of reaches is not necessarily 100% exhaustive. Atlantic salmon may be present in additional rivers, or potentially absent from some of the rivers listed if there has been recent population extirpation.

Atlantic salmon reaches were then examined with reference to spatial distribution (i.e. where they are) and spatial and temporal characteristics. Such information has relevance to aerial photo surveys with regard to light environment (critically important for passive optical remote sensing), and accessibility for UAV surveys (which require on-site presence). Additionally, spatial and temporal characteristics affect the optimal imaging platform (crewed aircraft or UAV) (see Section 2.4).

2.2.1 Spatial distribution of Atlantic salmon reaches

The spatial distribution of Atlantic salmon reaches was examined in regard to their geographical distribution across Norway and their proximity to roads and settlements.

- Geographical distribution was examined in relation to latitude and administrative county (Fylke)
- Proximity to human infrastructure (to the nearest road and to the nearest settlement) was calculated from raster datasets created by NINA (Olsen et al. 2020).

2.2.2 Spatial characteristics of Atlantic salmon reaches

Spatial characteristics of Atlantic salmon reaches were examined with respect to length, topography, mesoscale structure, and macroscale structure.

- The total Atlantic salmon reach length within each Atlantic salmon river (N = 432) was calculated using the *NVE-Elvenett* derived reaches
- Topography (elevation and gradient) was calculated by integrating the Atlantic salmon reaches with a Digital Terrain Model (DTM). Elevation along the reaches was extracted from a 50 m DTM (obtained from https://hoydedata.no/, *Kartverket*) at the vertices of *NVE-Elvenett* vector line database. This approach will overestimate elevation in narrow reaches surrounded by steep valleys because the value in the 50 × 50 m DTM will also be influenced by valley slopes around the river, but was considered to be satisfactory for providing a crude estimate of Atlantic salmon reach elevation across Norway (and use of a higher resolution DTM for all of Norway would have been too computationally demanding).
- Mesoscale structure was examined for 15 Atlantic salmon rivers where we had available data on mesohabitat (Hindar et al. 2019). These rivers have been compartmentalized into mesohabitat units based on a river habitat classification system used in Norway (see Borsányi et al. 2004). These mesohabitat units characterize river habitat with regard to features that are salient to supporting salmonid populations, such as pools, glides, and rapids.
- Macroscale structure was investigated for two large Atlantic salmon rivers – the River Alta and the River Gaula. Longitudinal variation in characteristics was examined to determine whether they showed evidence of sedimentary links. Characteristics examined were elevation, gradient and sinuosity (derived from a DTM and the *NVE-Elvenett*-derived reaches), and channel maximum wetted width (derived from *N50 Kartdata*). Changes in channel characteristics were also examined with respect to underlying geology using *NGU*'s *løsmasse* map.

2.2.3 Temporal characteristics of Atlantic salmon reaches

Temporal characteristics of Atlantic salmon reaches were explored with regard to decadal, seasonal and diurnal variation:

- Long-term decadal-scale variation in watercourses was assessed by analyzing the development of human infrastructure on watercourses (a major source of variation in river characteristics such as discharge, erosion, sedimentation etc. over the last century). Data on the construction of dams and securing measures (e.g. bank modification) were obtained from *NVE*. To illustrate the effects of river regulation on discharge, patterns were examined for the River Nidelva, a regulated river where discharge base-flows and hydropeaking regimes have been altered over the last century since hydropower development.
- Seasonal and diurnal variation in discharge was examined using *NVE* datasets for a selected river (the River Nidelva).
- Seasonal variation in ice cover, and limitations regarding the ability to quantify this, was examined with reference to *NVE* datasets and satellite-based estimates of river and lake ice extent from the EU's *Copernicus Land Monitoring Service*

2.3 Distribution and characteristics of Norwegian Atlantic salmon reaches

2.3.1 Spatial distribution of Atlantic salmon reaches

Geographical distribution. Atlantic salmon reaches are distributed across Norway from the southern to the northern coast. Three peaks in the distribution occur, centered on 59.5, 63.5 and 69ºN (Figure 3A). The southern peak coincides with Rogaland and Vestfold og Telemark, the central peak coincides with More og Romsdal and Trøndelag, and the northern peak coincides with northern Nordland and Troms og Finnmark. Nearly 30% of Norway's Atlantic salmon reach length is within Troms og Finnmark (Figure 3B). Atlantic salmon reaches are absent from the landlocked county of Innlandet.

Proximity to human infrastructure. Most of the length of Atlantic salmon reaches within Norway is situated close to roads and settlements (see Figure 4 for maps of Trøndelag, showing main watercourses only). Across Norway, nearly 85% lies within 1 km of the nearest road, and ≈ 37% lies within 5 km of the nearest settlement (Figure 5).

2.3.2 Spatial characteristics of Atlantic salmon reaches

Length. Most Norwegian Atlantic salmon reaches stretch from several km to 10 km. Of all selected rivers, ≈ 40% have an Atlantic salmon supporting reach length > 10 km, and ≈ 10% a length > 40 km (Figure 6A). The longest Atlantic salmon reach is 852.5 km (the River Tana, 234.Z). Reach length is variable among all counties other than Oslo (Figure 6B), with county medians ranging between 2 and 30 km.

Topography. Most of the total length of the Atlantic salmon reaches within Norway is at low elevation (Figure 7A): ≈ 55% is < 50 masl and ≈ 75% is < 100 masl. Most Atlantic salmon reaches have a low maximum elevation (Figure 7B): for example, ≈ 60 % of Atlantic salmon reaches do not extend to > 100 masl. The Atlantic salmon reach extending to the highest elevation is the River Driva (109.Z) (≈ 720 masl). Atlantic salmon reaches tend to have shallow gradients, with nearly 65% of Norway's total Atlantic salmon reach length having a longitudinal gradient of < 0.5 % (i.e. < 50 cm fall over 100 m) (Figure 8A). Gradients tend to decrease in the downstream, lower elevation parts of the watercourses (Figure 8B).

Mesoscale structure. Of the Norwegian rivers for which data were available on mesohabitat units, mesohabitat unit lengths typically range between 100 and 300 m (Figure 9A). The length of the defined mesohabitat units tend to be longer in long rivers: for example, the small River Imsa has a median mesohabitat length of ≈ 40 m whereas the large River Alta has a median mesohabitat length of ≈ 400 m. Lengths of the defined mesohabitat units vary according to mesohabitat type (Figure 9B): cascades tend to be shortest (median length = 134 m), whereas glides tend to be longest (median = 192 m). However, inferences based on these with regard to structural relationships should take into account that there is some subjectivity in defining distinct mesohabitat units, so there may be bias with respect to river or mesohabitat type.

Mesohabitat units can reveal longitudinal structural changes but do not show information on habitat variation within the mesohabitat unit. For example, the mesohabitat classification of the River Stryn (Figure 10) shows a longitudinal sequence of mesohabitat units dominated by rapids, cascades and splashes in the upper watercourse to pools and rapids in the lower water course. However, surface features suggest heterogeneity within individual mesohabitat units: for example, some mesohabitat units classified as pools also contain patches of white water, which may be indicative of short cascade-like features.

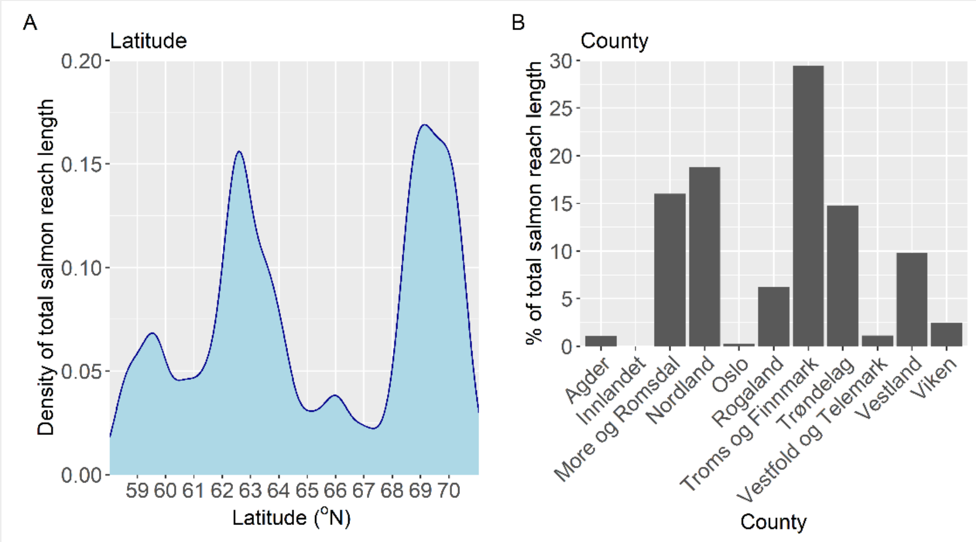

Figure 3. Distribution of Norwegian Atlantic salmon reaches (N = 432): (A) density distribution by latitude; (B) % of Norway's total Atlantic salmon reach length per county. In A, density has been calculated using the geom_density function of ggplot using default settings.

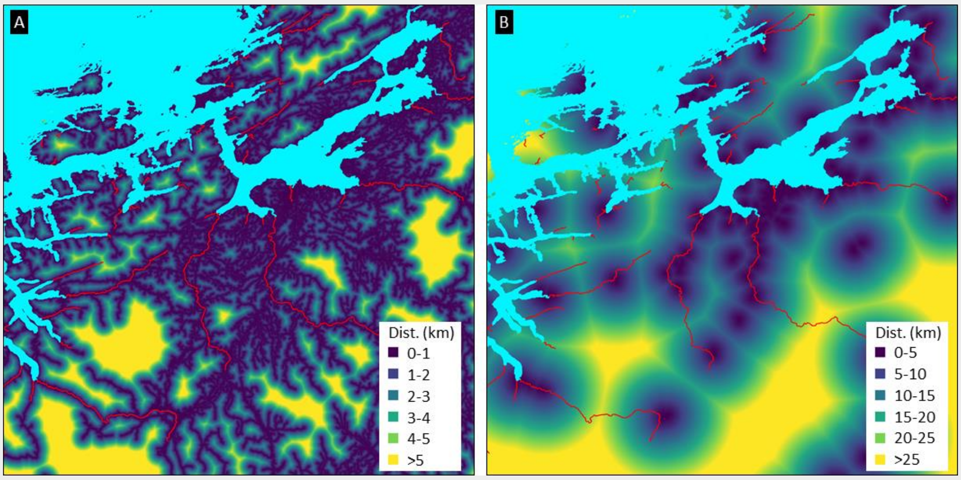

Figure 4. Proximity to infrastructure for Atlantic salmon reaches in a selected area of southern Trøndelag: (A) distance to nearest road; (B) distance to nearest settlement.

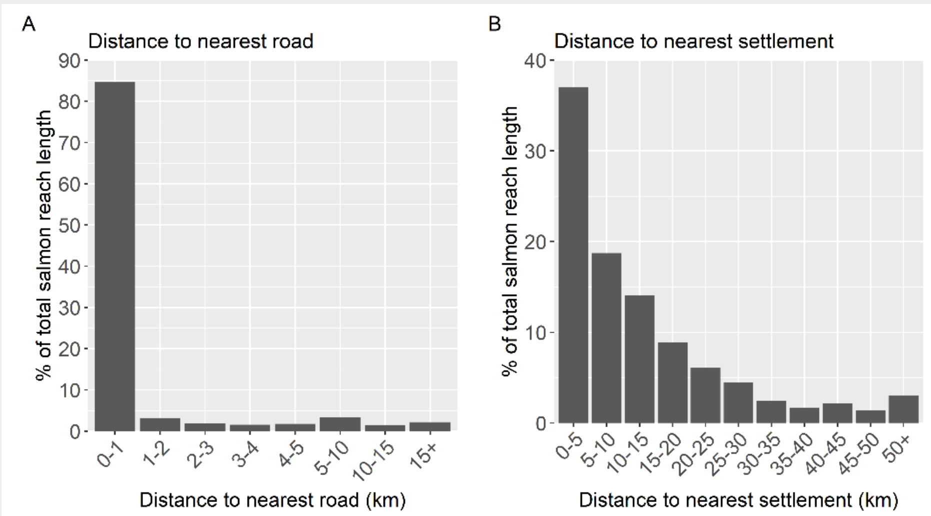

Figure 5. Proximity to infrastructure of Norway's total Atlantic salmon reach, for all Atlantic salmon rivers in Norway (N = 432): (A) % of Norway's total Atlantic salmon reach length according to distance to nearest road; (B) % of Norway's total Atlantic salmon reach length according to distance to nearest settlement.

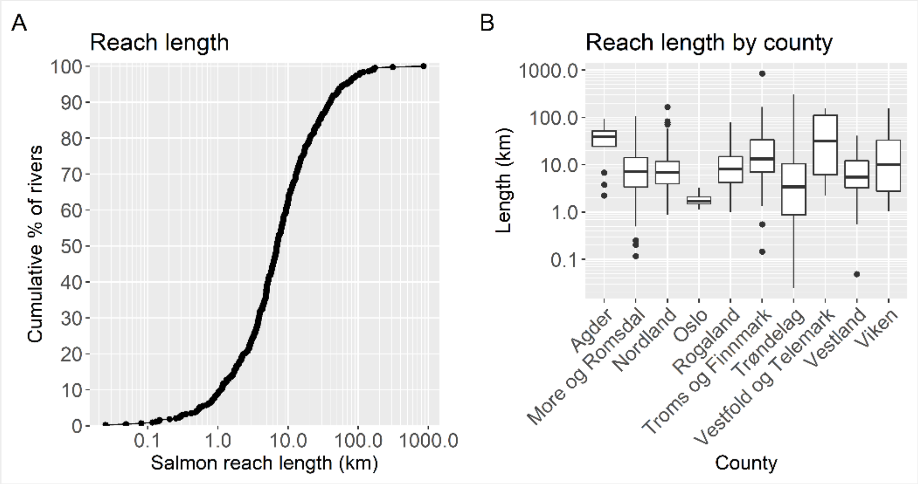

Figure 6. Lengths of Norwegian Atlantic salmon reaches (N = 432): (A) length distribution; (B) length distribution by county. In (B), rivers crossing county borders are presented twice (one observation for each county containing the river).

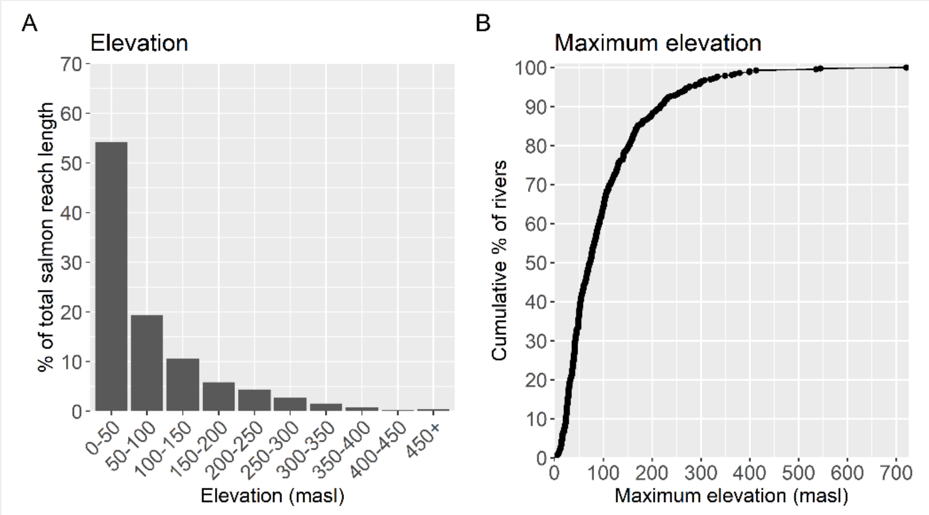

Figure 7. Elevation of Norwegian Atlantic salmon reaches (N = 432) derived from a 50 m DTM: (A) % of Norway's total Atlantic salmon reach length according to elevation class; (B) maximum elevation of each reach.

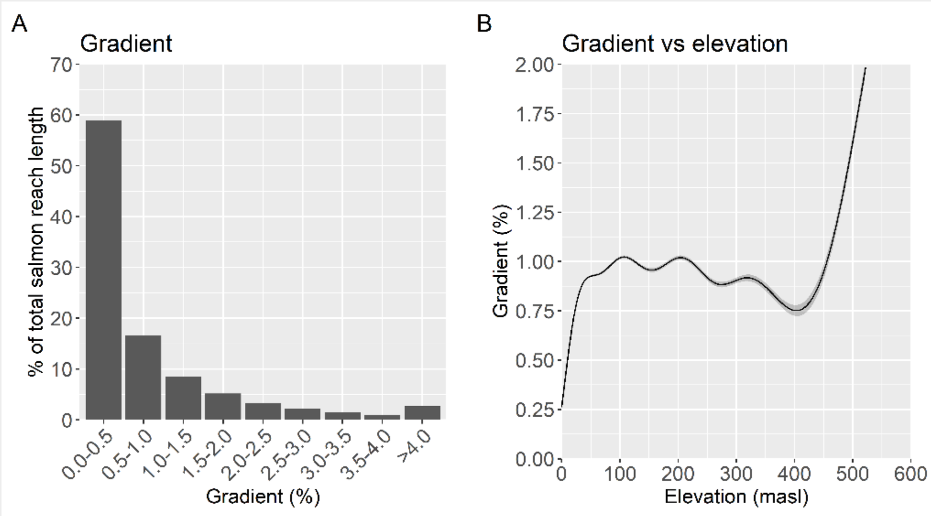

Figure 8. Gradients of Norwegian Atlantic salmon reaches (N = 432): (A) % of Norway's total Atlantic salmon reach length according to gradient class; (B) GAM plot of gradient vs elevation. In (B), the ribbon shows the 95% confidence intervals.

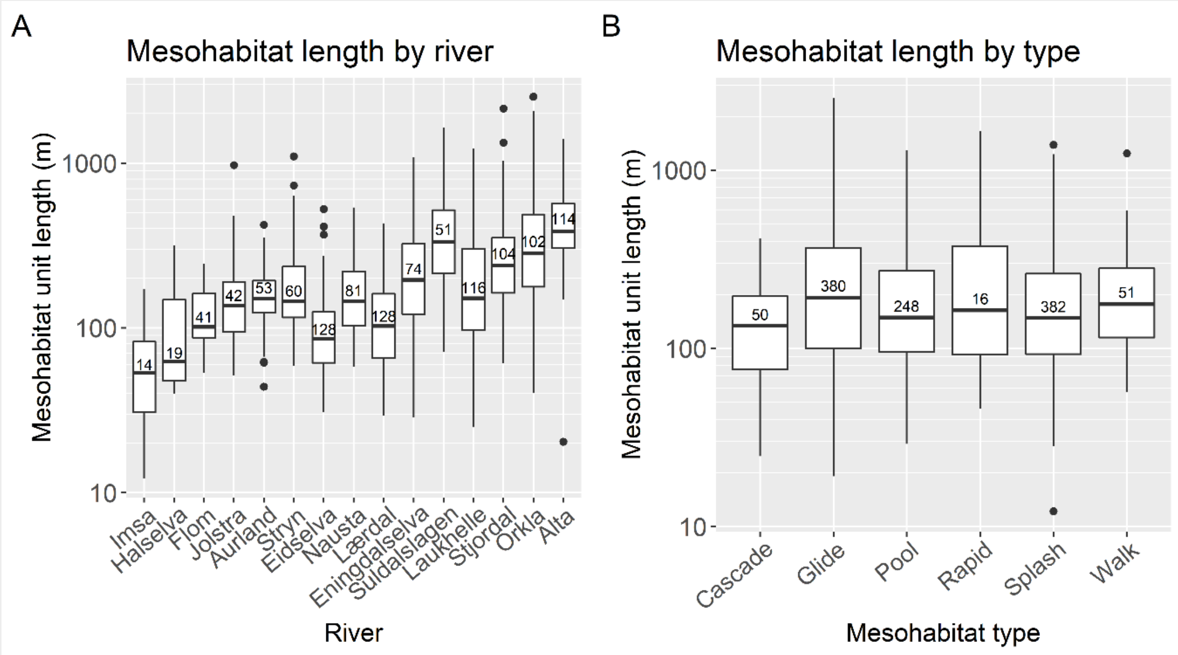

Figure 9. Mesohabitat unit lengths for selected Norwegian rivers: (A) mesohabitat length by river; (B) mesohabitat length by mesohabitat type. Numbers of observations are shown above the median for each box. In (A), rivers are arranged in order of total length of Atlantic salmon supporting reach from short (left) to long (right).

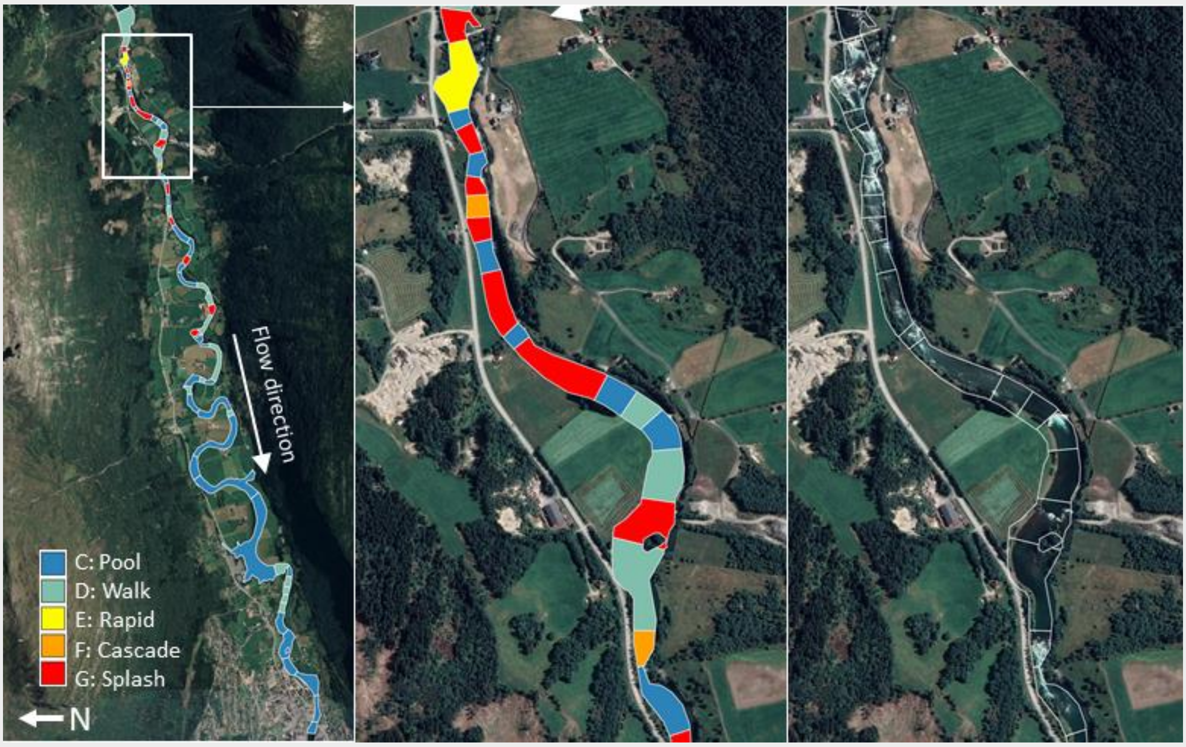

Figure 10. Mesohabitat types in the River Stryn (088.Z).

Macroscale structure. Some of the larger Norwegian rivers show evidence of macroscale structure in the form of possible sedimentary links. For example, Figure 11 shows longitudinal-channel characteristics of the Atlantic salmon supporting reach of the main branch of the River Alta. A sharp fall in elevation and therefore an increase in gradient occurs ≈ 7.9 km downstream from the river source where the superficial deposits change from landslide material to that classified as bare mountain. Channel sinuosity and gradient is often higher in the landslide material than in the bare mountain superficial deposits. It is reasonable to suggest that the transition in channel metrics at ≈ 7.9 km downstream marks a transition between two sedimentary links. Likewise, the transition to fluvial glacial deposits is associated with a marked increase in sinuosity, associated with a meandering channel. This is suggestive of an additional sedimentary link in the lower watercourse. Figure 12 shows longitudinal characteristics of the River Gaula. Relatively steep drops in elevation occur at ≈ 2, 14, 53 and 77 km downstream along the Atlantic salmon reach which may be associated with the upstream parts of distinct sedimentary links.

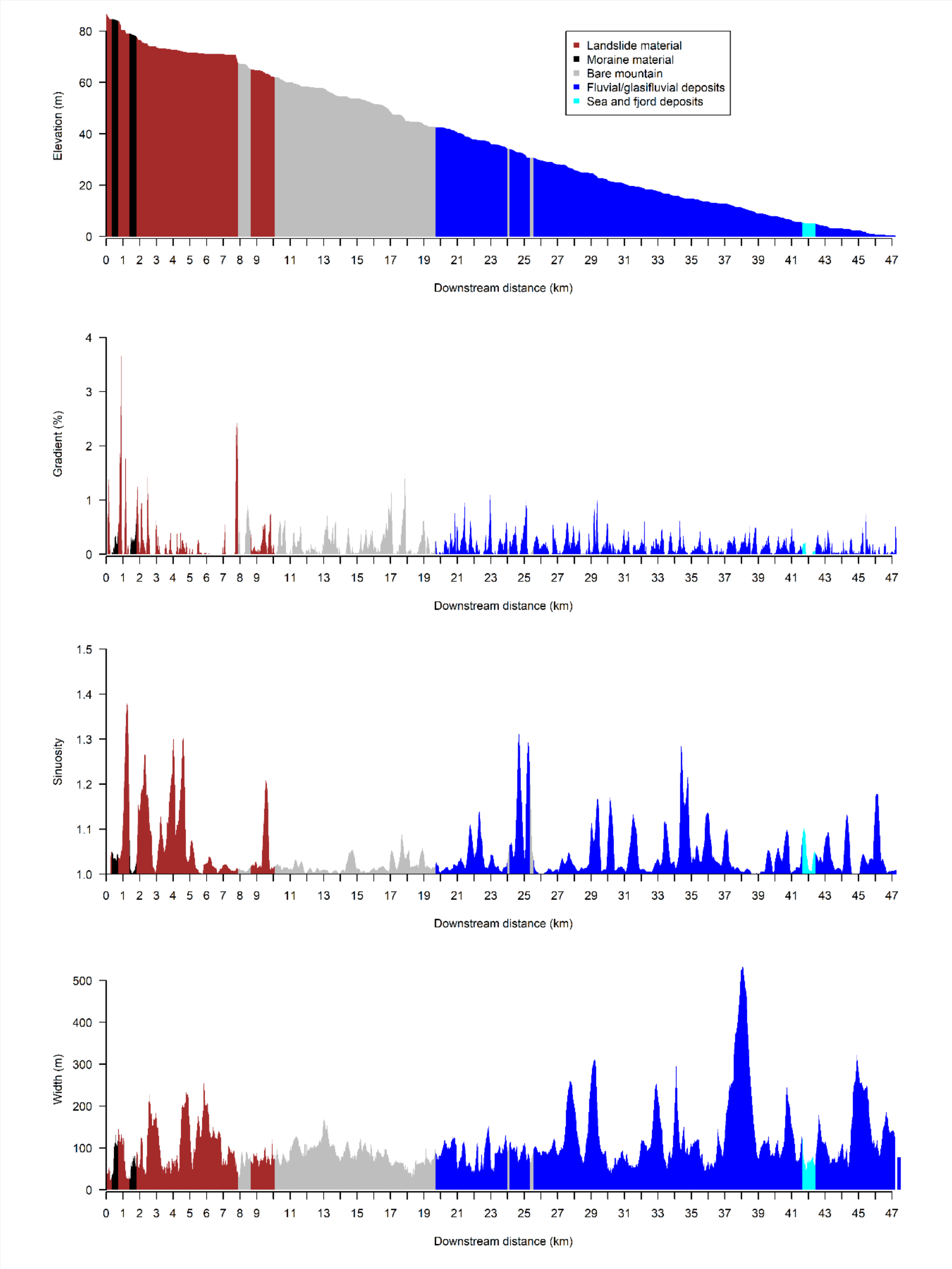

Figure 11. The Atlantic salmon reach of the River Alta (212.Z). Gradient has been derived from DTM elevations along the NVE watercourse; sinuosity has been derived from the NVE watercourse; superficial deposits were obtained from NGU; width was derived from N50 Kartdata.

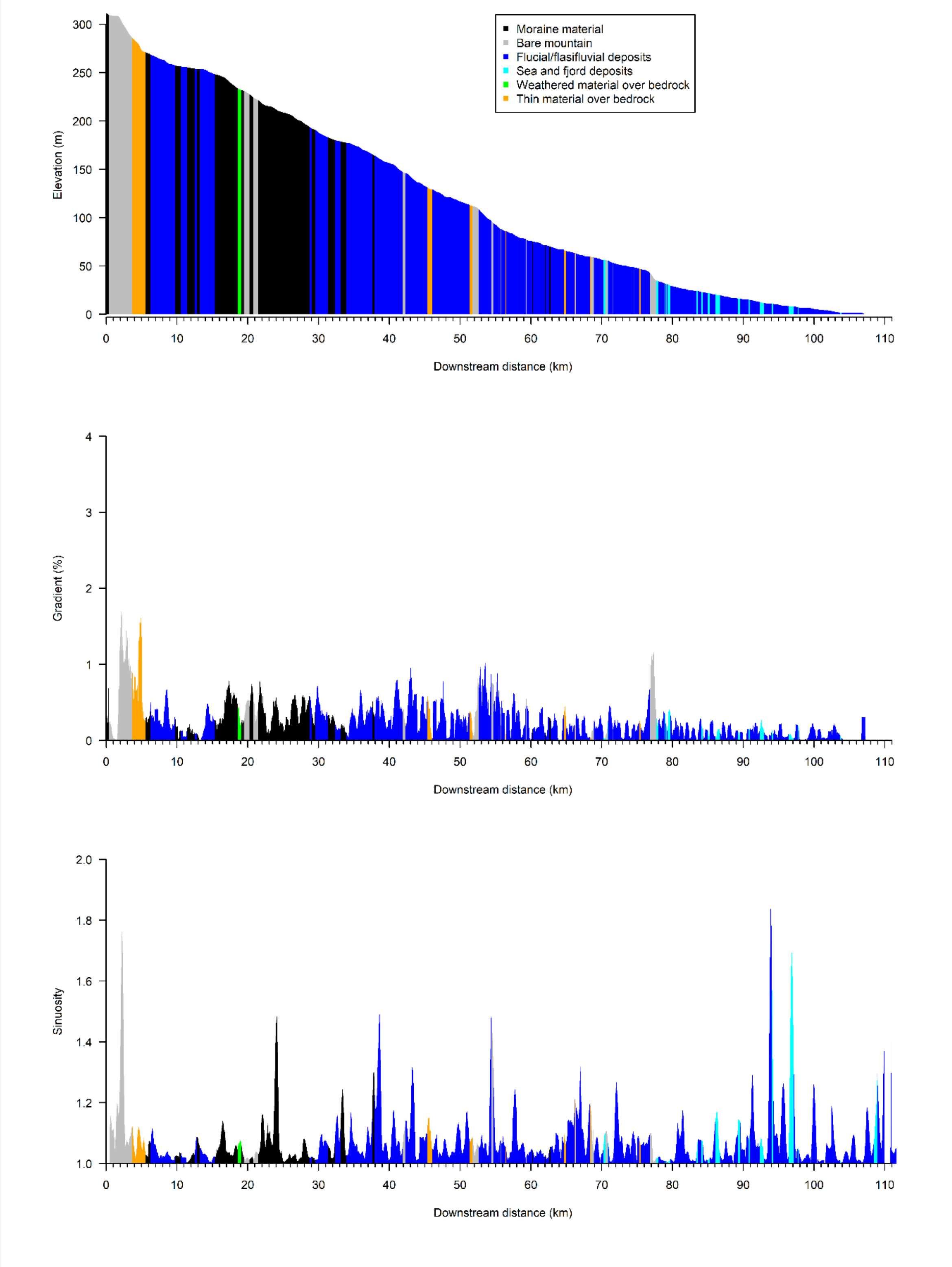

Figure 12. The Atlantic salmon reach of the River Gaula (122.Z). Gradient has been derived from DTM elevations along the NVE watercourse; sinuosity has been derived from the NVE watercourse; superficial deposits were obtained from NGU.

2.3.3 Temporal characteristics of Atlantic salmon reaches

Long-term variation in watercourse structure. Norway's watercourses have undergone extensive modification resulting from the construction of hydropower dams (Figure 13A) and securing measures such as anti-erosion and anti-flooding channel modifications (Figure 13B). Modifications of watercourses extend back to the 17th Century, but there has been a large increase in the rate of modification in the 20th Century.

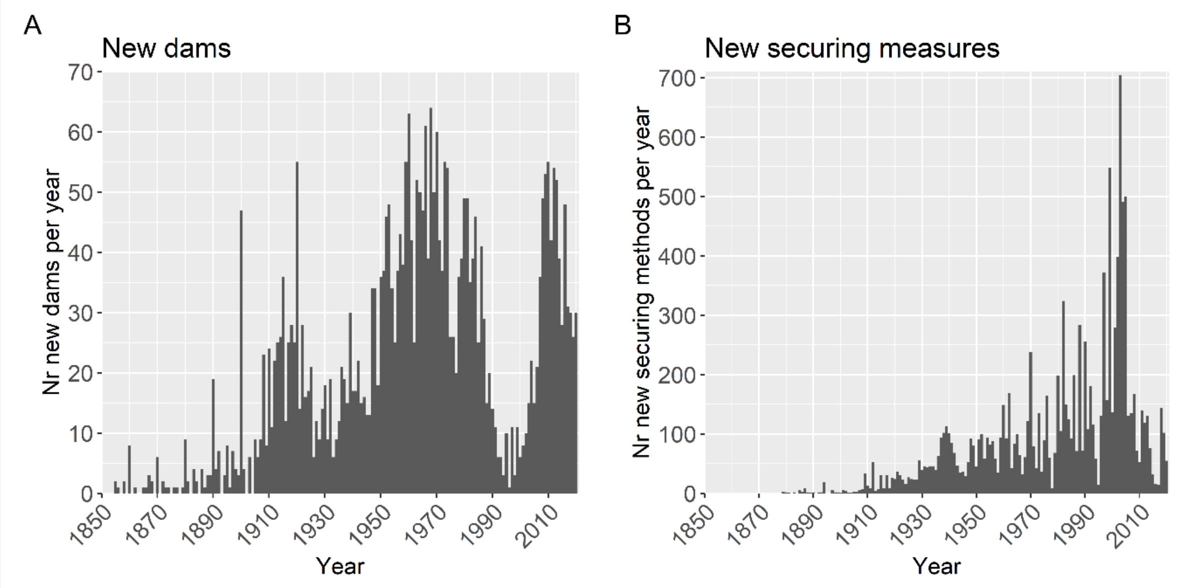

Figure 13. Infrastructure development in Norwegian watercourses: (A) dams; (B) securing measures. NB: Only dams or securing measures that have a registered construction date have been included.

River modifications have a large effect on river discharge. For example, Figure 14 shows how median discharge has increased in the River Nidelva since the construction of a hydropower dam in 1910, in which operating regimes have been implemented that have increased the median yearly discharge (Figure 14A) but reduced the coefficient of variation within the year (Figure 14B). With changes in discharge from hydropower dams, there will be consequent changes in a range of properties pertinent to Atlantic salmon habitat such as flow velocity, wetted area, sedimentation, and erosion.

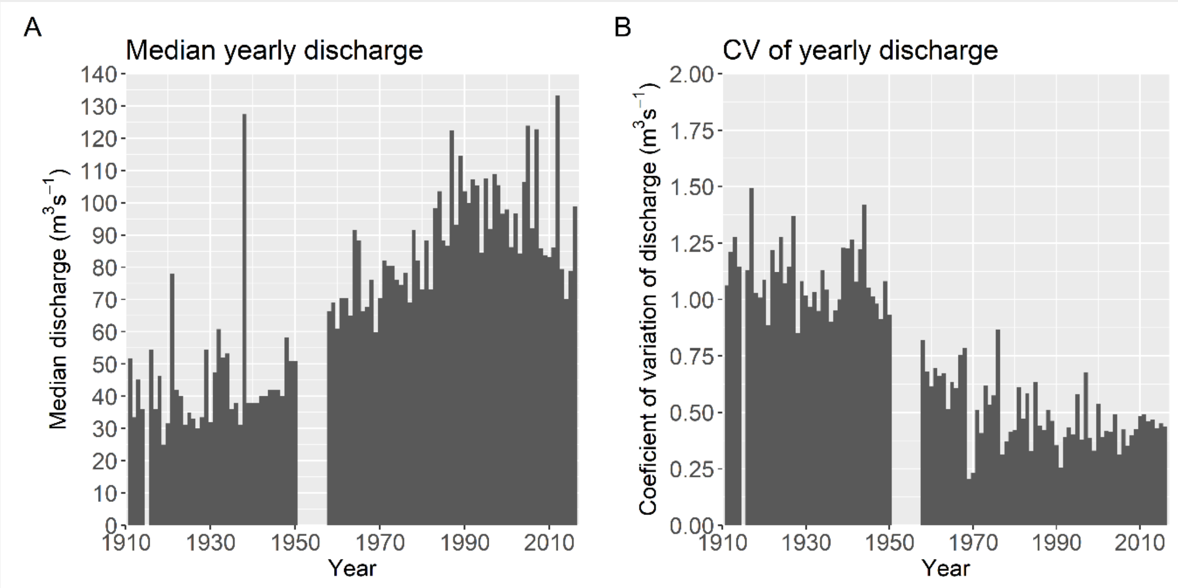

Figure 14. Yearly discharge in the River Nidelva (123.Z): (A) mean; (B) coefficient of variation. Data from the early 1950s were not available.

Seasonal and diurnal variation in discharge. Norwegian rivers are dynamic in terms of discharge, over a range of scales. Within a year, the melting of catchment snow and ice in spring can cause a peak spring discharge (see Figure 15A). In regulated rivers subject to hydropeaking, large variations in discharge can occur over time periods of several hours (Figure 15B).

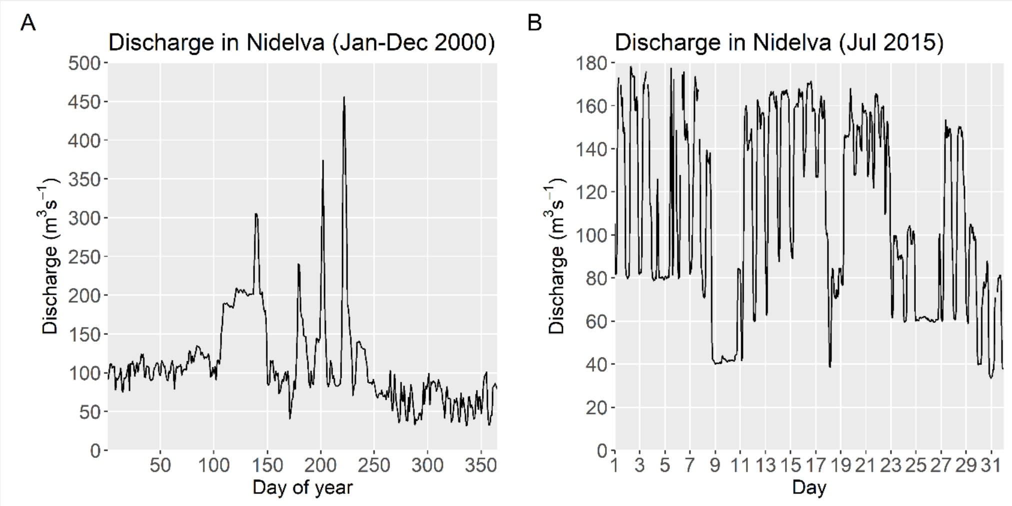

Figure 15. Selected discharge hydrographs for the River Nidelva (123.Z): (A) over a year; (B) over a month.

Seasonal variation in ice cover. Many Norwegian rivers experience ice cover during winter. Information on freeze- and break-up dates for Norwegian rivers is not comprehensive (Gebre & Alfredsen 2011), although freeze- and break-up dates for selected river locations are available from "HYDRA II" of *NVE*. Spatiotemporal patterns of snow and ice within rivers may be obtained from *Copernicus*'s *River Lake Ice Extent* mapping, based on satellite imagery (Sentinel 2 sensor). These images may be used to delineate snow- and ice-covered gravel banks and open water in the deeper, faster flowing channel (Figure 16A) or ice-covered versus ice-free conditions (Figure 16B). However, such maps are infrequently produced so have limited utility in monitoring programs. For example, a search of the vicinity of the River Alta only provides 5 images from 2019-12-02 to 2020-03-01. Additionally, they have a 20 m spatial resolution so can only be used in larger rivers. Therefore, although Norwegian rivers show seasonal variation in ice cover, the full temporal pattern across the country is difficult to describe because of limited data.

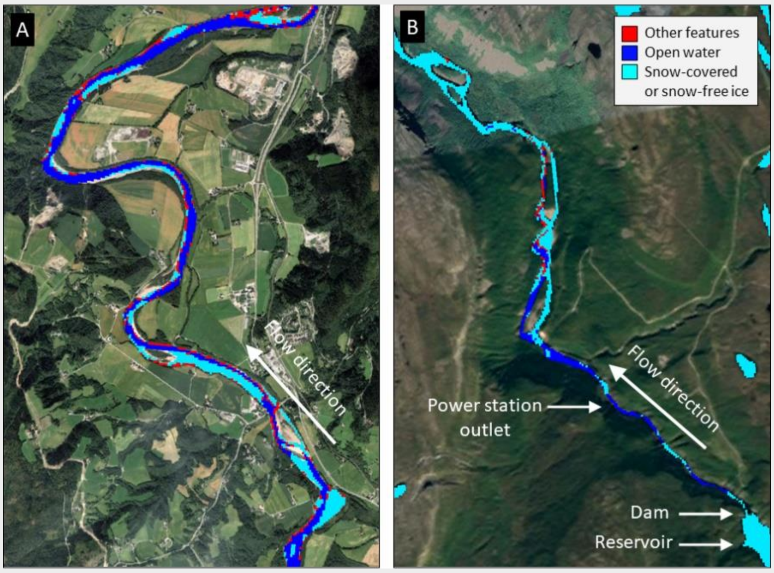

Figure 16. Snow/ice cover from River Lake Ice Extent (RLIE), obtained from the EU's Copernicus Land Monitoring Service; (A) River Gaula (122.Z) (2020-03-16); (B) River Alta (212.Z) (2019-02-22).

2.4 Implications for aerial photo surveys

Norwegian Atlantic salmon habitat is distributed across the country, may extend over long river stretches, is characterized by variation over a range of spatial scales, and is temporally dynamic. Its spatial distribution and spatial and temporal characteristics will have strong implications for how aerial photo surveys should be conducted. Potential limitations are addressed in detail in Section 6, with suggestions for optimizing the remote sensing methodology in Section 7, but the main implications of the distribution and characteristics of Norway's Atlantic salmon rivers for successful aerial photo surveys can be summarized as follows:

Spatial distribution. The high latitude of Norway and the typically high amount of tall riparian vegetation have implications for obtaining a reasonable light-environment for imaging rivers through passive optical remote sensing (see Section 6). Photo surveying may provide better imagery in a more southerly river (with higher solar elevation) in an area with little surrounding vegetation (with fewer shadows on the river surface), than in a northerly river running through forest (with lower solar elevation and shadows across the river surface). Image quality has particularly relevance for *Norge i bilder* aerial photographs which are generally not acquired with the objective of ensuring an optimal light environment for river remote sensing. Accessibility for UAV-based photo surveying, which requires access to the site, is generally high, with ≈ 85% of Norway's total Atlantic salmon reach lying within 1 km of the nearest road, and most Atlantic salmon reaches being near settlements which may aid survey logistics. A potential difficulty is that a lot of Norway's total Atlantic salmon reach is situated in northern Norway, so may be distant from research institutions, but field work is regularly conducted in these northern rivers, and UAVs are easily transportable, so this does not preclude their use. However, the presence of infrastructure beside the Atlantic salmon reach may somewhat restrict the legal operation of UAVs in more urbanized areas (see Section 6.3.3).

Spatial characteristics. Many Atlantic salmon reaches are long and outside the operational range of UAVs. Additionally, many Atlantic salmon reaches lie within forested habitat, so the presence of tall riparian vegetation may obstruct direct line-of-site between operator and platform when flying UAVs at low altitudes (see Section 6.3.3). Use of traditional aerial photography (i.e. from *Norge i bilder*) may therefore be required for surveys of the entire watercourse (see Section 3). Heterogeneity within the mesohabitat unit is at a suitable scale for UAV operation, so UAVs have the potential for providing high spatial resolution imagery over relatively small scales (several 100 m) (see Section 4), and supplementing traditional aerial photography.

Temporal aspects. Atlantic salmon reaches are temporally dynamic. The *Norge i bilder* image repository may be used in long-term monitoring from the 1930s until present (see Section 3). UAV-based surveying offers greater flexibility for collecting new imagery, allowing the same part of the reach to be imaged multiple-times over short time periods (see Section 4). For regulated rivers with hydropeaking, variation in discharge can occur over short timescales, so monitoring this with traditional aerial photography from high-altitude crewed-aircraft is not possible due to the time required to plan and execute a survey. In contrast, UAVs allow imaging when required, so it is possible to conduct repeat imaging to see how flow conditions change over short time periods. Additionally, surveys of ice-cover may require the use of UAVs due to the absence of available *Norge i bilder* aerial photographs obtained during the winter.

3 *Norge i bilder aerial photography*

3.1 Introduction

The *Norwegian Mapping Authority* (*Kartverket*) in collaboration with the *Norwegian Public Roads Administration* and the *Norwegian Institute of Bioeconomics (NIBIO)*, provides orthomosaic aerial photography (alongside orthomosaic satellite imagery) covering the whole of Norway through the *Norge i bilder* ("Norway in Pictures") portal. Data are compartmentalized into ≈ 1800 image projects, with each project being composed of multiple images that can cover a large geographical area. The *Norwegian Mapping Authority* has additionally scanned and orthorectified 20 000 historical images from its archive. In total, over 120 Tb of data are stored. The imagery has a long temporal range, from 1937 until present, with increasing availability toward the present-day (Figure 17).

Aerial photographs from *Norge i bilder* are mostly true-color from the 1990s onwards, with panchromatic (black and white) aerial photographs being more prevalent in former decades. There is also some availability of near-infrared aerial photographs. The spatial resolution ranges between 0.04 m and 1 m, although aerial photographs with a resolution higher than 0.1 m are rare. For each image, the *Norge i bilder* portal provides information on date of image acquisition, owner, spatial resolution, image type, color bit depth, image sensor, and original image format.

Imagery is suitable for application to assessing Atlantic salmon habitat because of its long-term range, allowing long-term study of watercourse changes, and its relatively high spatial resolution (in comparison to satellite imagery), allowing identification of habitat features. Additionally, the fact that date of image acquisition is provided allows easier integration of imagery with temporal datasets such as river discharge.

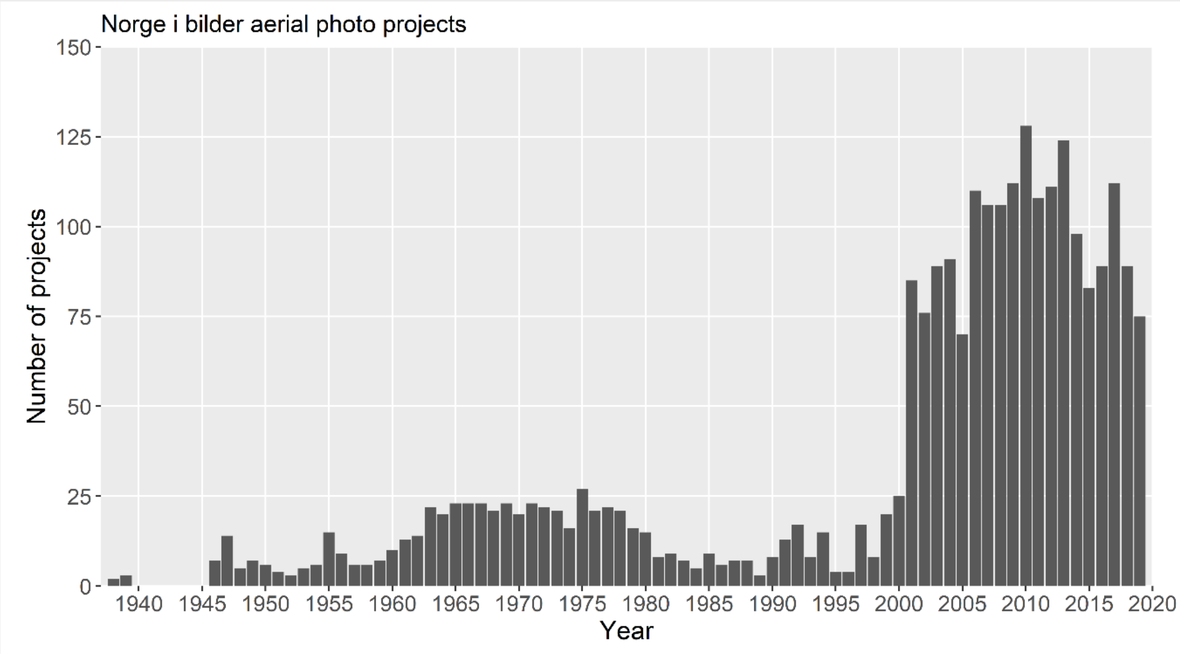

Figure 17. Number of Norge i bilder aerial photo projects per year.

3.2 Resolving Atlantic salmon habitat

3.2.1 Observing historical changes

The long temporal coverage provided by the *Norge i bilder* repository allows observation of long-term, large-scale historical changes in channel structure (e.g. channelization), and identification of historical changes of within-channel infrastructure (e.g. booms, weirs). For example, Figure 18 shows how part of the downstream stretch of the River Orkla has changed from the mid-20th Century to present-day. Changes identified in the imagery show a deterioration in the watercourse in terms of optimal Atlantic salmon habitat. The watercourse is now more channelized, rather than meandering, and parts of the braided section have been sedimented. Additionally, small channels are no longer so well defined, which may impact on other parts of the watercourse ecology, including brown trout (*Salmo trutta*) spawning areas. The effect of river regulation and watercourse modification is easily apparent using the *Norge i bilder* repository. Figure 19 shows how the upstream part of the Atlantic salmon supporting watercourse of the River Nidelva has changed between 1937 and 2020. Both images were acquired during the period when the Nidelva's flow regime has been regulated by hydropower, but the earlier image was obtained when the flow regime was much more relaxed with both lower minimum discharges (≈25 $m^3 s^{-1}$) and higher maximum discharges (>750 $m^3 s^{-1}$) than the current regime (where discharges typically vary between 35 and 115 $m^3 s^{-1}$). Additionally, the latter image was acquired after watercourse modification associated with road building. The earlier image shows dewatered beaches, which become flooded at greater discharges (evident from the lack of vegetation). The latter image shows a smaller dewatered area, indicative of a higher discharge when the image was acquired. It shows well-established trees on what is now an island, indicative that this does not become flooded. It also shows major modification of part of the western bank, associated with road-building. *Norge i bilder* aerial photographs may also be used to track measures implemented to minimize adverse effects of river regulation on Atlantic salmon populations. Figure 20 shows changes that were made within part of the River Mandalselva as a result of hydropower development. In the mid-20th Century, this part of the watercourse had higher flows, and more habitat heterogeneity including gravel bars (Figure 20A). Conversion of this into a minimum-flow stretch reduced discharges, so weirs were constructed to maintain a high wetted area (Figure 20B). It is evident from the imagery that these weirs have had a large effect on riverbed morphology.

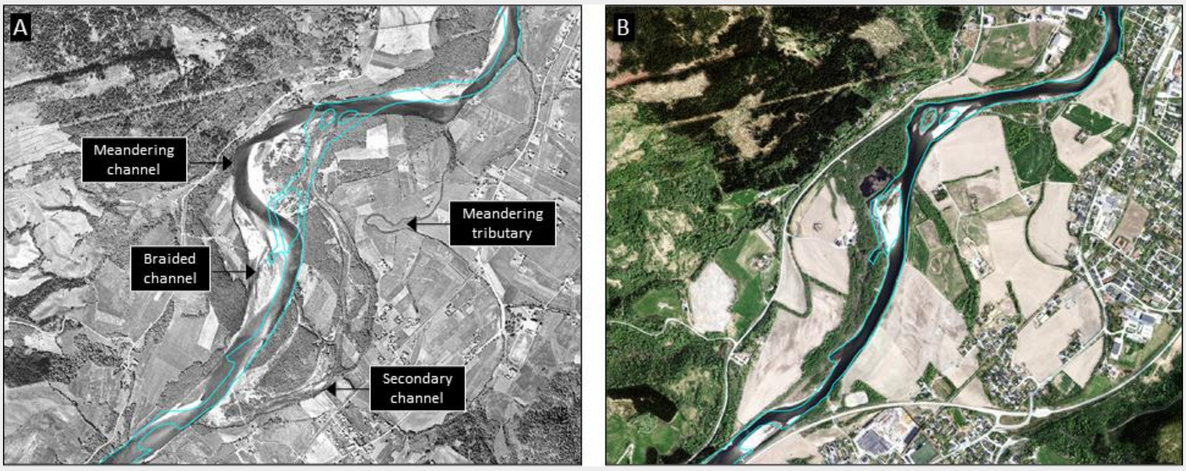

Figure 18. Norge i bilder images of the River Orkla (122.Z): (A) 1957; (B) 2018. The superimposed blue line shows the present-day river watercourse from N50 Kartdata.

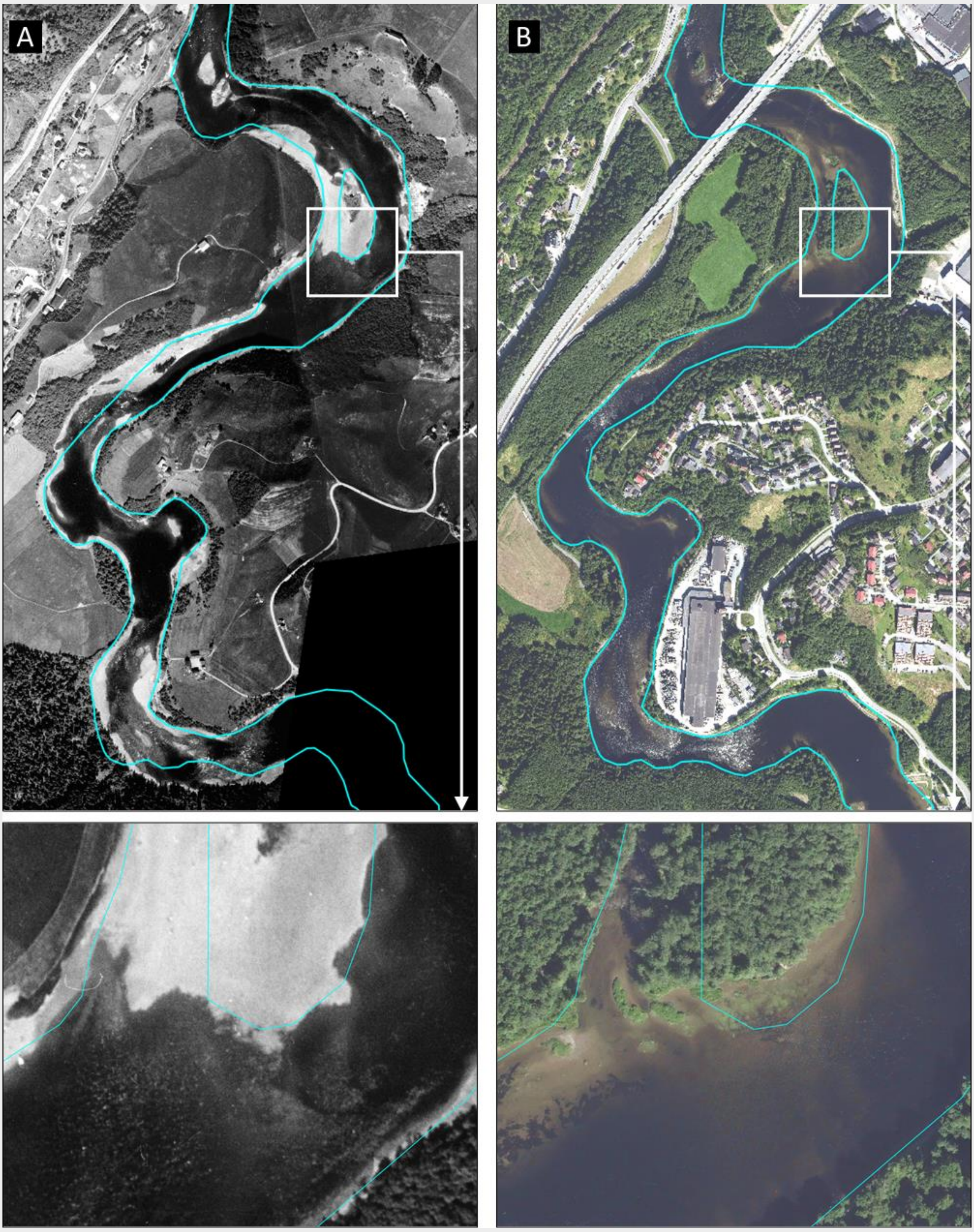

Figure 19. Norge i bilder images of the River Nidelva (123.Z): (A) 1937; (B) 2020. The superimposed blue line shows the present-day river watercourse from N50 Kartdata.

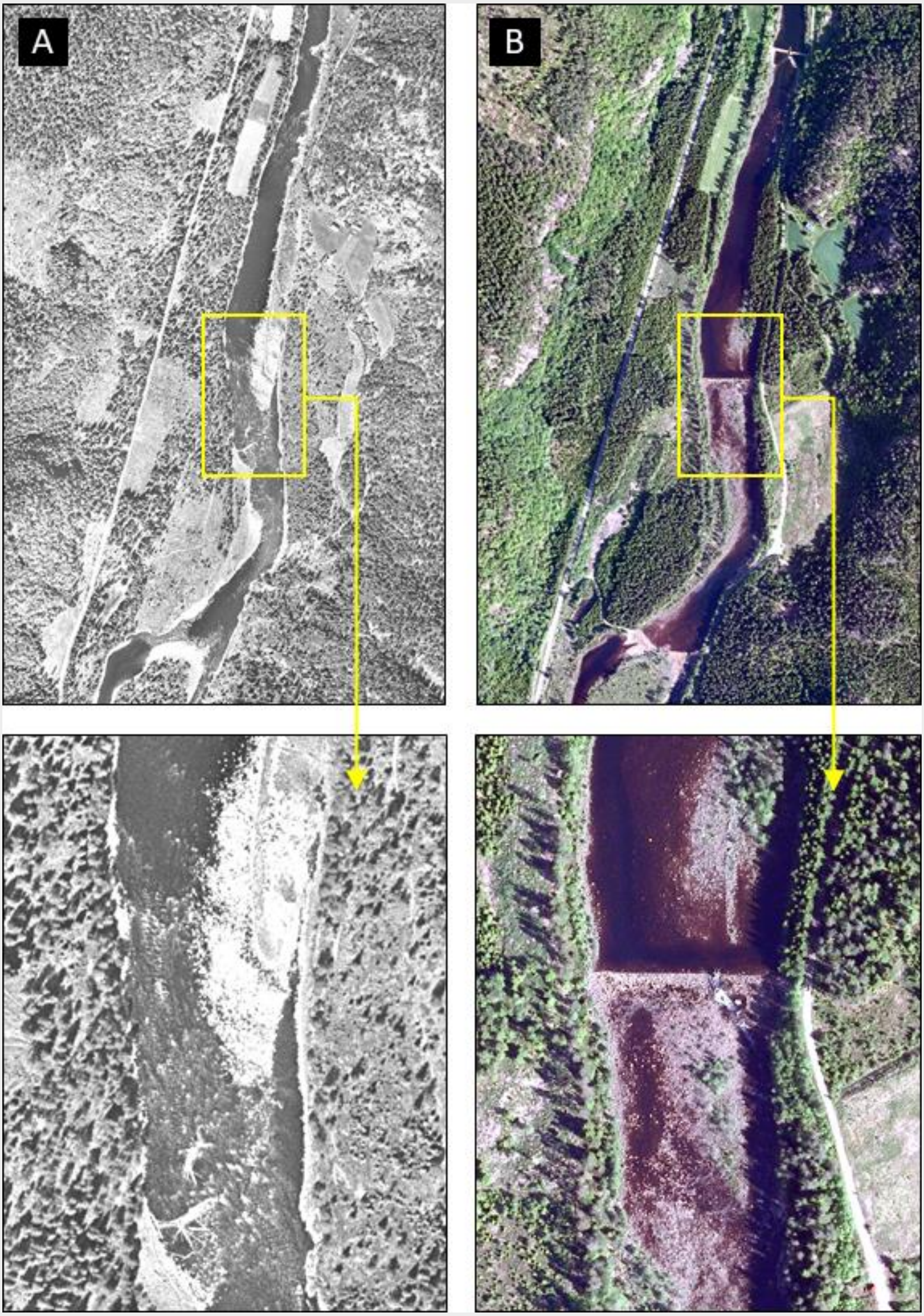

Figure 20. Norge i bilder images of the River Mandalselva (022.Z): (A) 1959; (B) 1999.

3.2.2 Observing habitat properties

Cross-sectional profile. Measurements of channel wetted width from *Norge i bilder* aerial photographs acquired at different discharges may be used to provide information on channel cross-sectional profile. Figure 21 shows manual measurements of wetted width of the River Nausta from aerial photographs obtained at high and low discharges. Such measurements can be used to determine a wetted width-discharge relationship (Figure 22A), or determine how parts of the channel may be dewatered at lower discharges (Figure 22B).

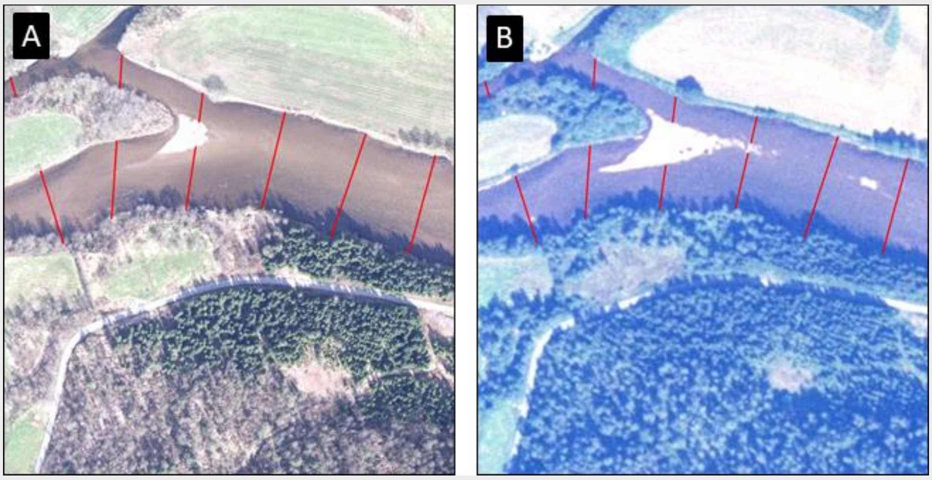

Figure 21. Surveys of wetted width of the River Nausta (084.7Z) using Norge i bilder images: (A) discharge = 20.1 m³ s⁻¹; (B) discharge = 5.2 m³ s⁻¹.

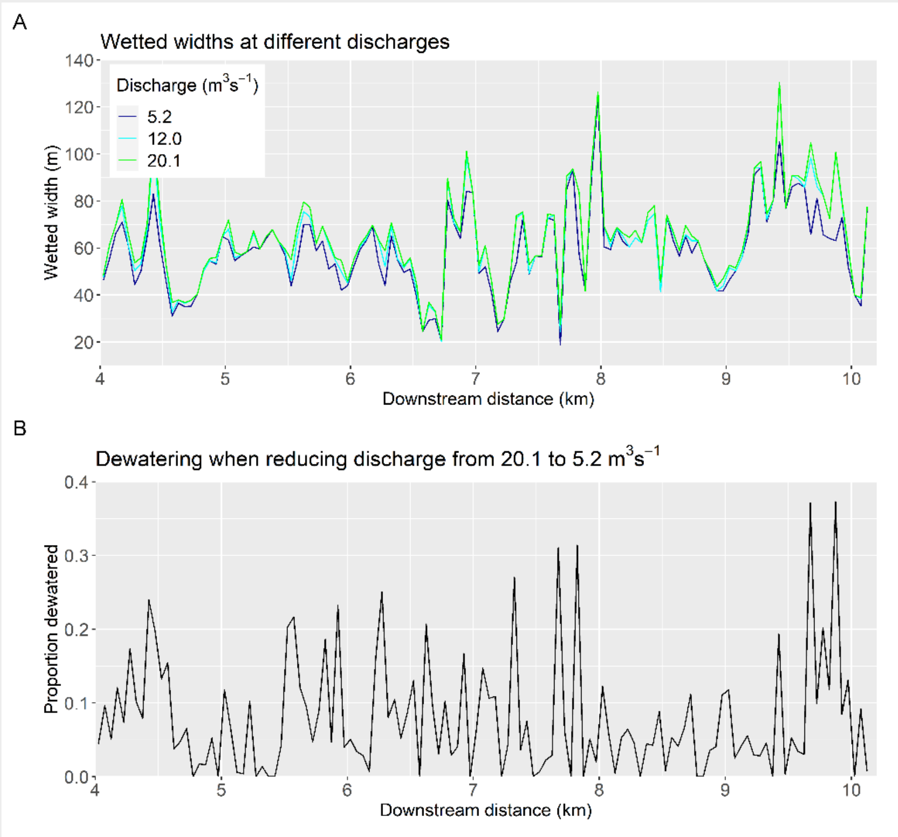

Figure 22. Cross-sectional profile of the River Nausta (084.7Z) as determined from Norge i bilder imagery: (A) discharge – wetted width relationships; (B) proportion dewatered at low discharge.

This method is reliant on a sufficient number of images taken over a range of discharges. If multiple images are available, it may be possible to fit a model between discharge and wetted width such that the model may be used to interpolate wetted widths at different discharges. Discharge-wetted width relationships tend to be non-linear in channels that approximate a “U”-shaped profile. For example, at low discharges, a small discharge increase may cause a large rise in wetted width as dewatered areas become water-covered. An equivalent discharge increase at high discharges may cause a negligible increase in wetted area because the discharge range is within the limbs of the “U”-shape. Therefore, imagery acquired at lower discharges may often be more useful for describing the across-channel profile than images acquired at high discharges. However, this method is limited in terms of accuracy. Firstly, the time of day of *Norge i bilder* imagery may not be available, so if discharge varies much within a day such as in hydropeaked rivers, it may be difficult to determine the discharge when the image was acquired. Secondly, under conditions of temporally-varying discharge in regulated rivers, longitudinal variation in discharge may exist due to lag effects. For example, a discharge change in the upper watercourse may be manifested as a lagged and reduced amplitude change in the lower watercourse. This may give a biased estimate of discharge when the image was acquired.

Depth. Some *Norge i bilder* images are suitable for extraction of depth, or proxies for depth, from analysis of single images. Figure 23A shows the lower watercourse of the River Nidelva. Dark areas within the watercourse concur with estimated depths based on hydrodynamic modelling and a green-LiDAR derived bathymetry (Figure 23B). This concurrence is greatest downstream of the upper most bridge crossing the river. For example, it is possible to identify shallow areas mid-channel. Upstream of this bridge, identification of depth becomes more difficult due to the presence of a section of the channel that was partially dewatered when the aerial photograph was acquired. While it may be possible to obtain a depth proxy based on image DN, estimation of actual depth would require ground truth measurements.

Figure 23. Lower watercourse of the River Nidelva (123.Z): (A) Norge i bilder image (2006); (B) predicted water column depth from a HEC-RAS simulation at a discharge of 135 m^3 s^{-1} (Source: Ana Juarez, NTNU). In A, the area within the river confines (yellow polygon) has been contrast enhanced.

Mesohabitat. Many of the flow features used by the Borsányi classification system for mesohabitat (Borsányi et al. 2004) are obtainable from *Norge i bilder* aerial photographs. It is possible to obtain (1) surface pattern (whether the water is smooth/rippled or has broken/unbroken standing waves) and (2) water depth. Surface gradient and surface velocity is harder to obtain directly from aerial photographs. However, gradient may be derived from LiDAR surveys. Velocity may be estimated from information on the surface gradient, discharge and channel characteristics. Figure 24 shows a preliminary classification of part of the River Nidelva based on features apparent in a *Norge i bilder* aerial photograph alongside information on gradient derived from a LiDAR DSM. The upstream and downstream stretches are classified as *pool* based on them having a smooth surface, having a mild gradient (determined from a LiDAR DSM), and appearing to be deep (the riverbed is not visible). The *cascade* classification is based on the surface having standing waves, the gradient being steep, surface velocity appearing to be fast (with lots of surface turbulence), and the water depth being shallow. The *splash / rill* classification is based on the surface having standing waves, the gradient being mild, and the water depth being shallow (the bed is sometimes visible). NB: this approach to mesohabitat classification can be automated using a deep learning approach (see Section 7.2.4).

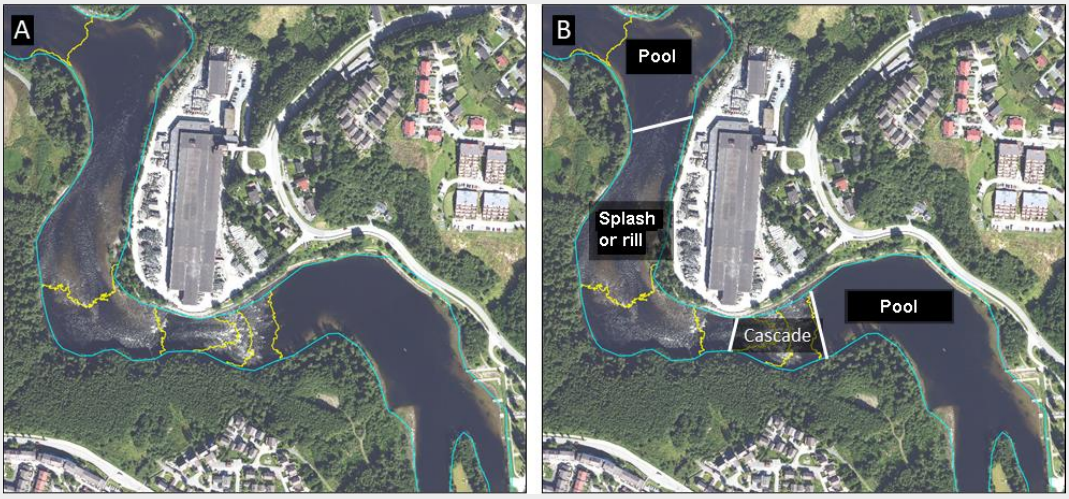

Figure 24. Classification of part of the River Nidelva (123.Z) into mesohabitat units: (A) Norge i bilder image (2010); (B) mesohabitat classifications. Yellow contours show LiDAR-derived surface elevation (contours are at 0.5 m intervals).

3.3 Summary

The *Norge i bilder* repository provides abundant and (relatively) high resolution aerial photographs, covering all of Norway and acquired over a long time span, at zero cost to researchers. It is thus useful for observing historical changes and obtaining information on habitat properties.

Observing historical changes. The long-temporal range of *Norge i bilder* imagery, stretching back to the 1930s, makes it very useful for categorization of historical changes in Atlantic salmon rivers. This is obviously not possible using UAVs which come from a recent technological development (post ≈ 2010).

Observing habitat properties. *Norge i bilder* imagery can be used to derive a range of habitat properties including cross-section profile, depth and mesohabitat. This may be done along the entire length of the watercourse if needed. The imagery is thus useful in ongoing programs about the contemporary nature of Norwegian Atlantic salmon habitat.

The limitation to using *Norge i bilder* aerial photographs is that image quality is not necessarily optimal for determining Atlantic salmon habitat.

- Although the spatial resolution is high, it is not high enough for detection of most substrate types or spawning redds.
- Images are not taken with the sole aim of resolving Atlantic salmon habitat, and thus may have been acquired at non-ideal times, both with regard to identifying ephemeral features of the habitat and minimizing potential artefacts (e.g. shadows from riparian vegetation). Images are not taken in winter, so the ability to determine aspects of winter habitat (e.g. the formation of river ice) is absent.
- There may be gaps of several years between successive aerial photographs. Thus *Norge i bilder* aerial photographs are not suitable for examining short-term variation.

These limitations are addressed in Section 6. How the use of *Norge i bilder* aerial photographs in habitat surveys can be optimized is addressed in Section 7.2.

4 UAV aerial photography

4.1 Introduction

UAV surveys conducted by or in collaboration with NINA have utilized both fixed-wing UAVs and multi-rotors (small quadcopters) (Figure 25). Fixed-wind UAVs have a greater geographical range than multi-rotors but fly at higher elevations so provide lower spatial resolution data. Additionally, fixed-wind UAVs may require some infrastructure for take-off, and require much more take-off and landing space than multi-rotors. Thus, their imaging capabilities lie between that of traditional aerial photography from crewed-aircraft and multi-rotors. In the following, we focus on the use of multi-rotors for surveying Atlantic salmon habitat as we consider this platform type to have the greatest potential in this field. This is largely due to multi-rotors being suitable for flying close to the ground, thereby providing high spatial resolution, in river stretches where there are obstructions from bankside trees.

Figure 25. UAV types and associated imagery: (A) fixed-wing UAV, and (B) multi-rotor UAV. Photo source: A. Foldvik.

In the following, we illustrate how UAV photo surveys can be used to provide both qualitative and quantitative information on Atlantic salmon habitat, using selected salmonid rivers in Trøndelag.

4.2 Resolving Atlantic salmon habitat

4.2.1 Photo surveys

Initial UAV surveys were conducted on parts of the rivers Børsa, Homla and Nævra in the spring/summer of 2014. Imagery was acquired using a GoPro Hero3+ Black Edition camera, mounted on a multi-rotor – the Type X8 from 3DR robotics (https://3dr.com). Given that GoPro cameras have a wide field-of-view, images from this camera show "barrel" distortion. Distortion was reduced using a python algorithm (based on https://tannerhelland.com/2013/02/11/simple-algorithm-correcting-lens-distortion.html) and then stitched using Microsoft Image Composite Editor. Further UAV surveys were conducted In the rivers Gaula and Nidelva in summer/winter 2017. Imagery was acquired using a Phantom 3 UAV. The Phantom 3 camera has a narrow Field of View so suffers less geometric distortion, meaning that further geometric correction was not required prior to image merging. Imagery from these surveys was used to create orthomosaics with OpenDroneMap.

4.2.2 Qualitative information

The stretch of the River Børsa that was imaged consisted of an upstream pool mesohabitat separated from a downstream shallow glide by a weir structure (Figure 26). The upstream pool had a bed material largely composed of sand, and no surface ripples were present, suggesting slow flow speeds. Bed material within the shallow glide was dominated by cobbles and boulders, but also included sand and gravel. Downstream of the weir, ripples were present, suggesting faster flowing water. The stretch was imaged during overcast skies and when riparian vegetation was undeveloped (i.e. imaged in spring so no leaves on trees). Therefore, shadows on the water surface were minimal. However, view angle-affects were evident in the stitched image.

The stretch of the River Nævra that was imaged was immediately downstream of a waterfall, which was the most upstream site accessible by anadromous fish in this river (Figure 27). The habitat was highly complex. The upstream part of the imaged stretch consisted of pool mesohabitat. Downstream of this, walk mesohabitats were present. The lower part of the imaged stretch consisted of habitats with faster flowing waters – either cascades or rapids – but were largely dewatered due to low flows when the imagery was obtained, with water constrained in a gorge. A range of substrate sizes were evident from gravel, through cobble to boulders. Also evident was the presence of woody debris. The watercourse was not imaged at an optimal time with regard to the light-environment, and shadows from riparian vegetation crossed much of the stitched image.

The stretch of the River Homla that was imaged was downstream within the river (Figure 28), and as such, contained a bank that was dewatered for the discharge when the image was acquired; this would have been water covered at higher discharges, as evident from the limited vegetation present on this bank. The water-covered part of the watercourse contained a pool-riffle structure. Imagery acquired from the River Homla showed many of the issues associated with optical remote sensing of water bodies: shadow, reflection from riparian vegetation and isolated clouds, and sunglint.

Qualitative interpretation can be improved using SfM approaches. Figure 29 shows a dewatered gravel bank on the River Gaula. The SfM orthomosaic reveals small changes in elevation which can be used to identify potential stranding areas. Figure 30 shows an orthomosaic and DSM generated via SfM of part of the River Nidelva, immediately upstream of the most downstream hydropower station. The presence of surface ice is evident in both orthomosaic and DSM, suggesting the SfM analysis of UAV imagery may be useful for monitoring river ice.

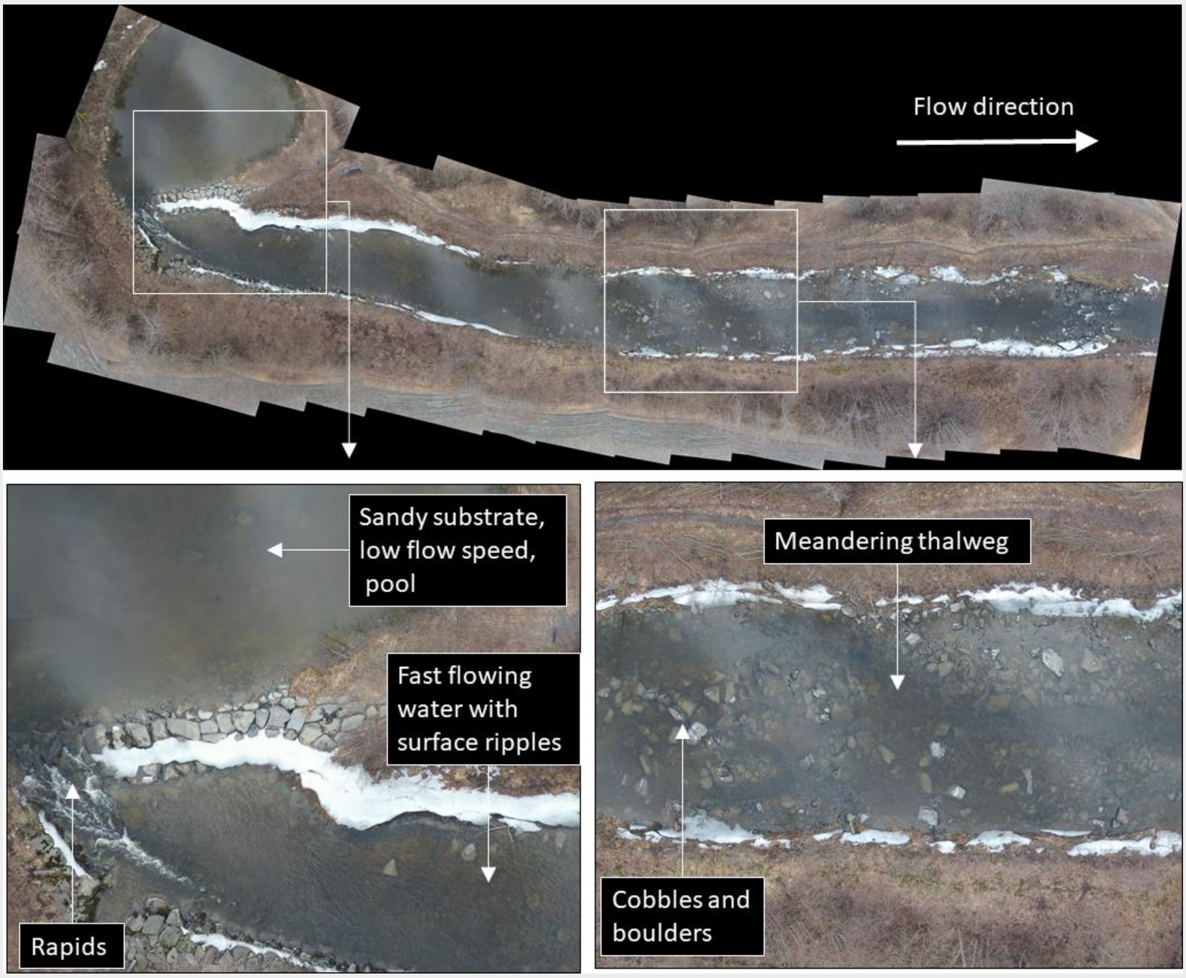

Figure 26. UAV survey of the River Børsa (122.1Z).

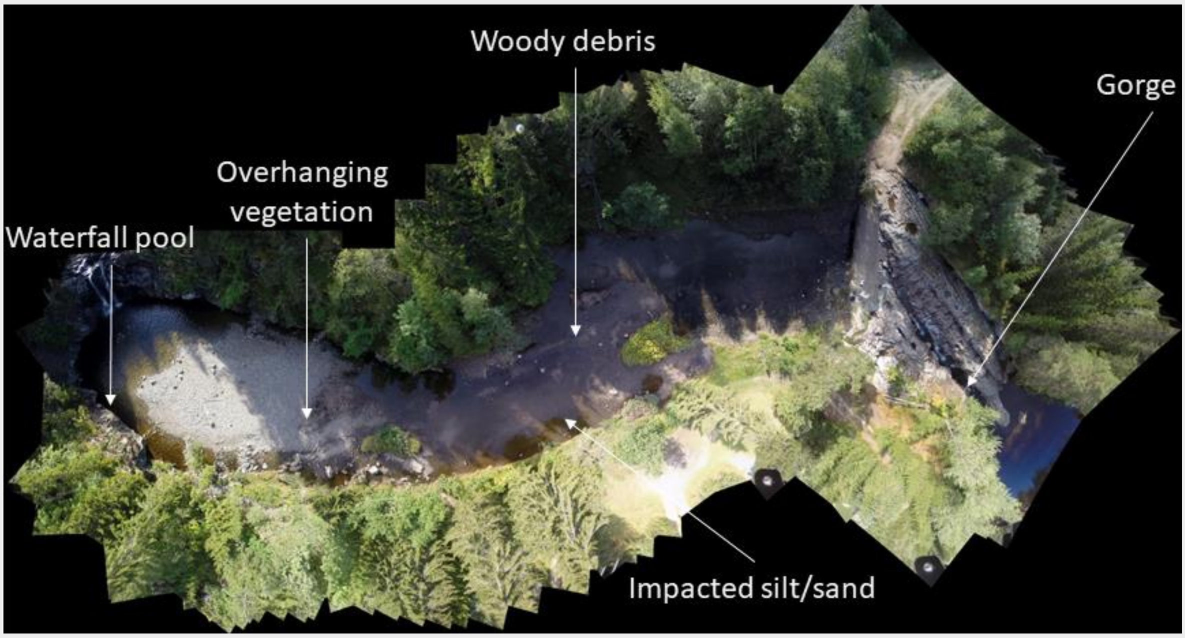

Figure 27. UAV survey of the River Nævra (123.4AZ).

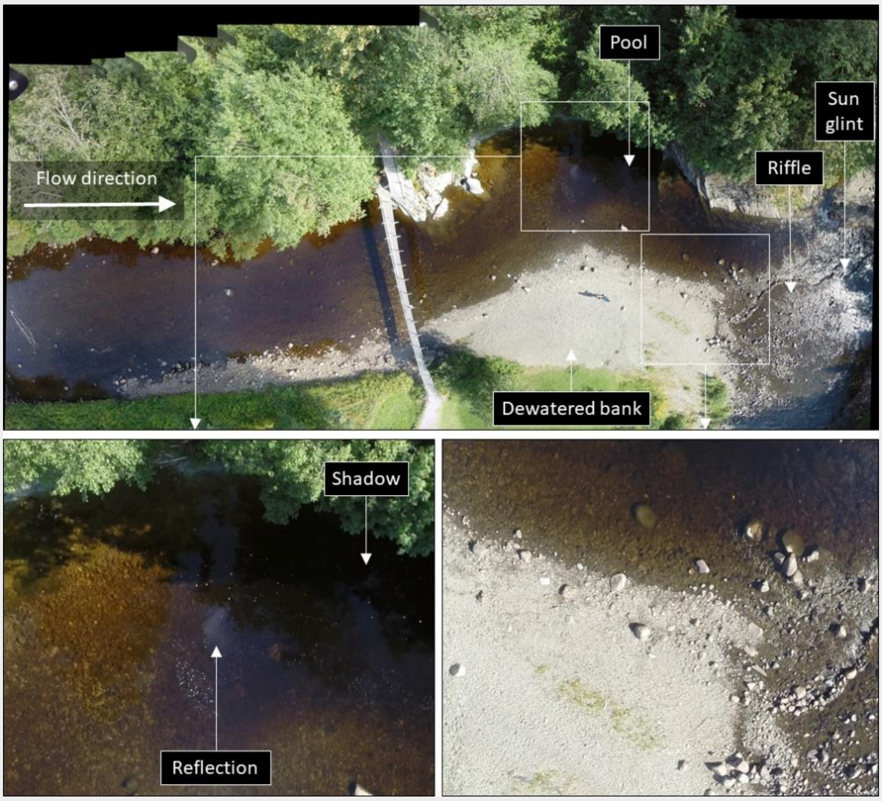

Figure 28. UAV survey of the River Homla (123.4Z).

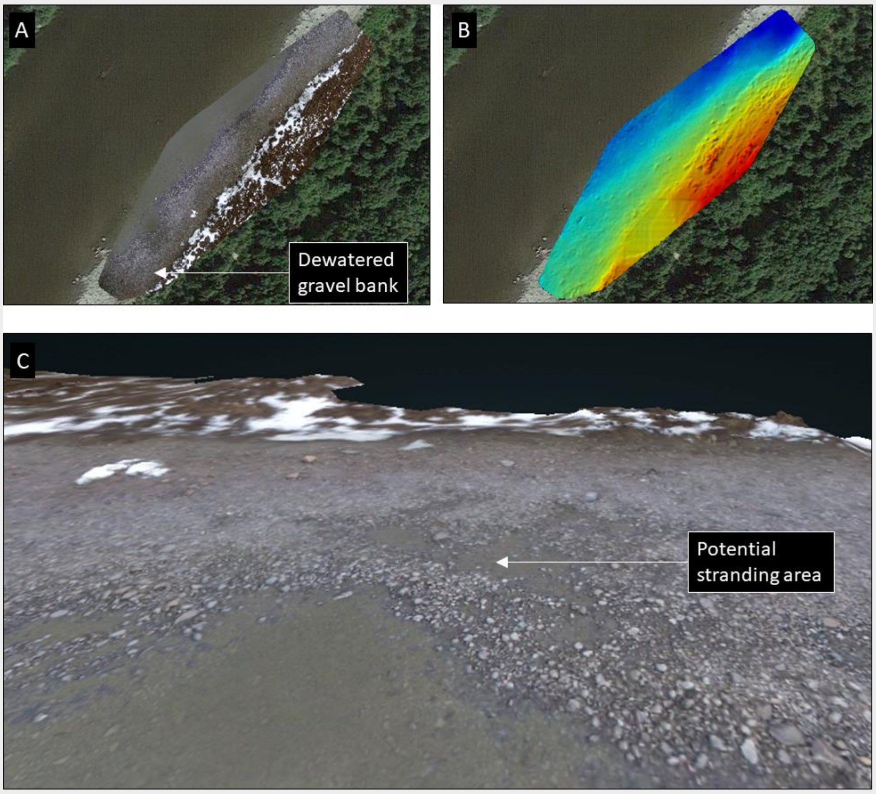

Figure 29. UAV survey of the River Gaula (122.Z): (A) orthomosaic; (B) digital surface model (DSM) created through structure from motion (SfM); (C) oblique view of draped surface.

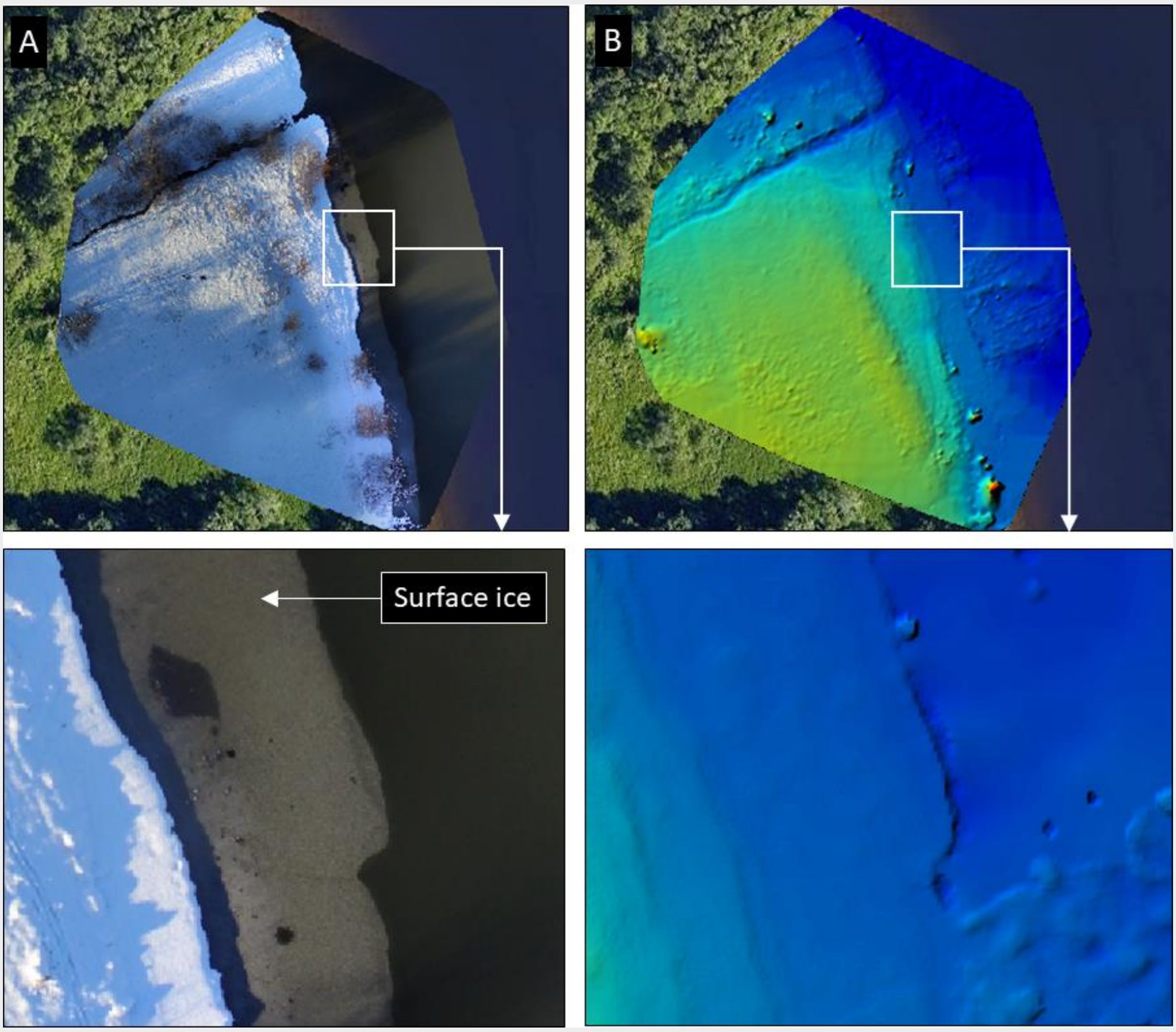

Figure 30. UAV survey of the River Nidelva (123.Z): (A) orthomosaic; (B) digital surface model (DSM) created through Structure from Motion (SfM).

4.2.3 Quantitative information

Here we provide examples of some of the procedures that can be applied to extract quantitative information from UAV imagery, focusing on methods for acquiring information on depth and substrate size.

Depth. Depth can be estimated from single UAV-derived images using a spectra-based approach, using the same procedure as that which can be used for *Norge i bilder* images (Section 3). The multi-view angle provided by UAV imagery, however, also allows for depth estimation via generation of a DSM of the riverbed topography using SfM (Figure 31). This method works for both dewatered areas and shallow water-covered areas, although the accuracy of the latter needs to be assessed because of the problems associated with observing the riverbed when water-covered: attenuation and diffusion reduce the ability to match features in overlapping images, and refraction of light at the water-air medium may cause problems in the photogrammetric method that SfM uses.

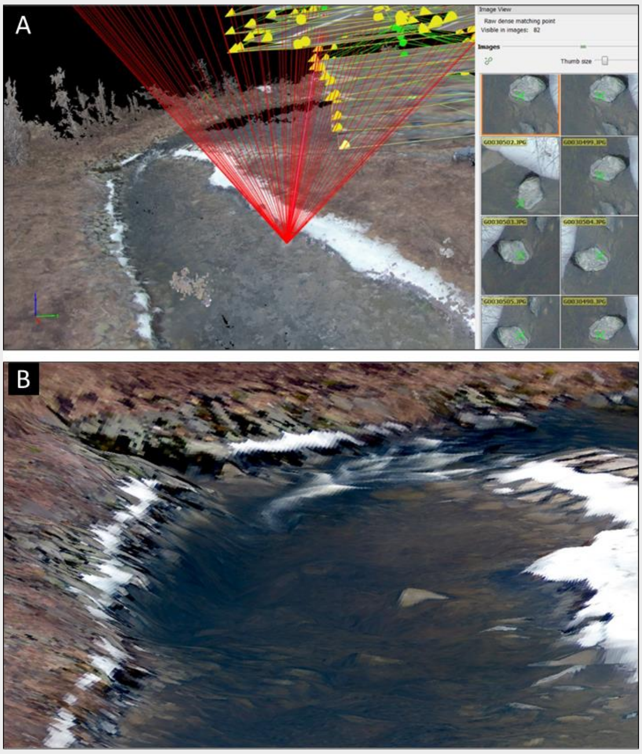

Figure 31. Structure from motion (SfM) depth extraction from UAV images of the River Børsa (122.1Z): (A) reconstructed image overlain on digital surface model (DSM) generated from multiple images; (B) zoomed-in area showing stretch immediately downstream of the weir.

Substrate size. Quantification of substrate size requires the substrate grains (e.g. gravels, pebbles, cobbles) to be visible. Visibility of the riverbed declines with water column depth due to light absorption and scattering so delineation of substrate grains in submerged areas can be difficult (Figure 32A). Absorption increases with wavelength. Conversely, scattering declines with wavelength, so longer wavelengths (red as opposed to blue) are more useful for delineating substrates in submerged areas. Further detail can be enhanced by simple image processing. For example, Figure 32B shows the application of rank equalization to the red channel, resulting in substrate material on the riverbed being much more evident than in the unenhanced original imagery. The observed bed material is mostly compose of cobbles and boulders. Patches exist, however, where no large bed material is observable in the imagery, and it is uncertain whether this represents a true absence of large grains, or whether the channel in these patches is too deep for light to penetrate and return to the surface due to absorption within the water column.

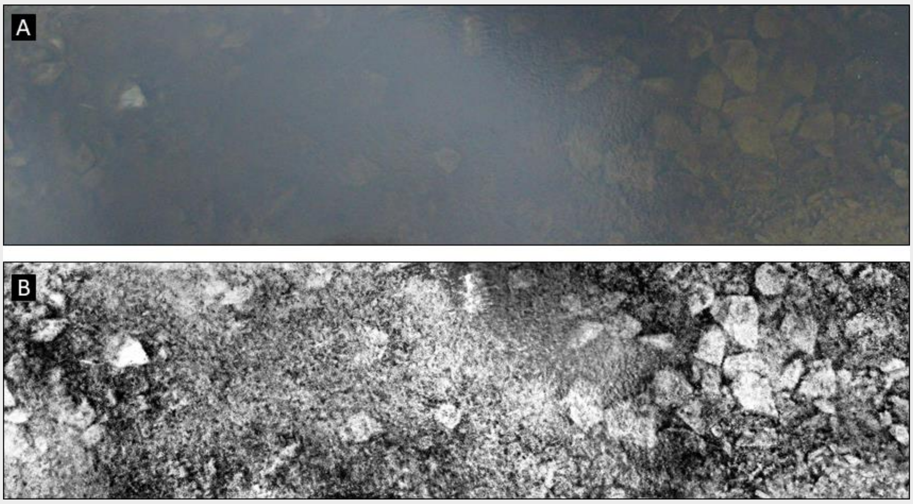

Figure 32. Riverbed substrate visible in a UAV image of the River Børsa (122.1Z): (A) original image; (B) rank equalized red channel.

A range of methods exist for extracting substrate size. Here we present two methods: geostatistics and mathematical morphology. The geostatistical method determines the variance in pixel DN as a function of lag (distance of separation) using an empirical variogram. Parameters of models fitted to the empirical variograms can be related to substrate size, allowing mapping of substrate size across the water course (Figure 33B). The mathematical morphological approach involves identifying contiguous pixels with similar DNs (the substrate grains), and segmenting them from the background (the interstitial space between grains) (Figure 33C).

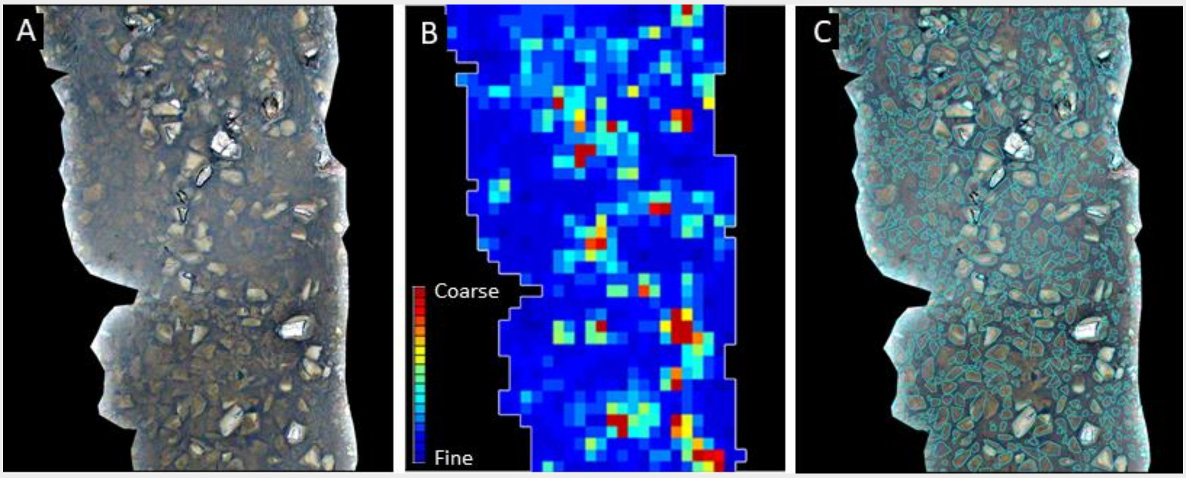

Figure 33. Texture-based classification of substrate size in a UAV image of the River Børsa (122.1Z): (A) original image; (B) geostatistical approach; (C) mathematical morphological approach.

In the example shown, both approaches were able to quantify relative substrate size. However, the explanatory power was low when comparing estimates with manual measurements from photo-sieving (Figure 34). Most studies on photo-based substrate size quantification have been taken under ideal conditions: that is, imaging of dewatered gravel bars consisting of non-cohesive unlithified clastic material, often involving imaging from a camera attached to a fixed mount several meters above the surface (see Butler et al. 2001, Warrick et al. 2009). Further research is necessary to examine how effective these methods are for more operational settings, such as submerged gravel beds.

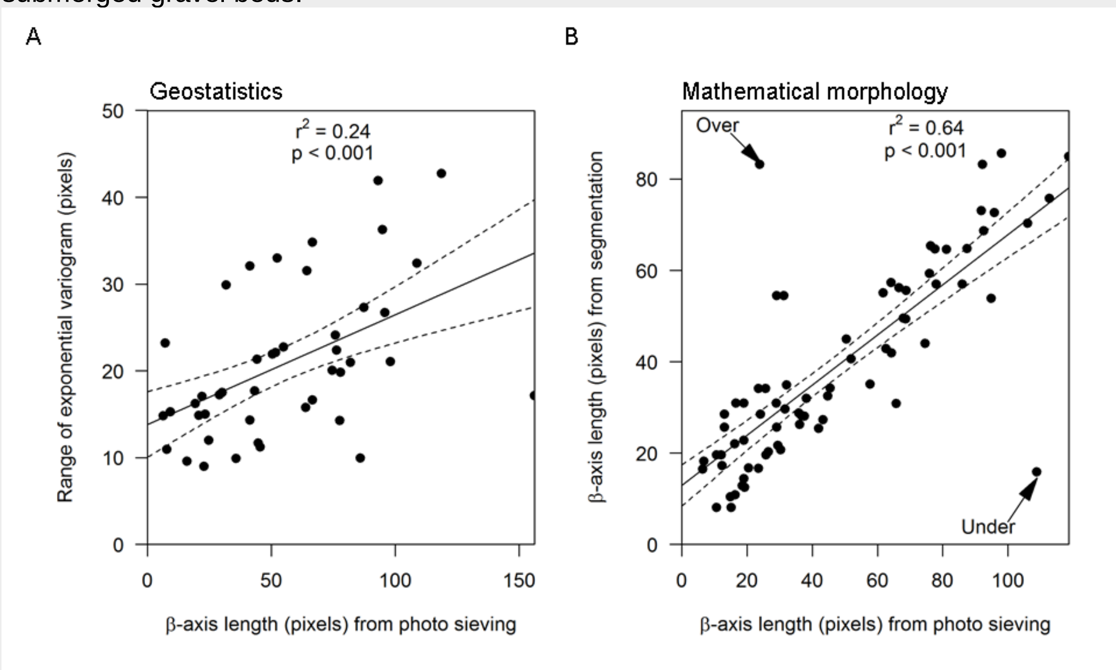

Figure 34. Comparison between estimated substrate size and manual measurement from imagery from photo sieving: (A) geostatistical approach; and (B) mathematical morphological approach.

4.3 Summary

Using UAV images acquired in Norwegian Atlantic salmon rivers, we have shown that UAVs have strong potential for providing information on Atlantic salmon habitat, both qualitatively and quantitatively. However, they also show certain limitations

Potentials. The main advantages of UAVs shown here are that they provide high resolution imagery, from multiple view angles. Spatial resolutions provided are sufficient to derive many habitat features that are not present within coarse resolution *Norge i bilder* images. For instance, it is possible to delineate the full range of substrate sizes pertinent to Atlantic salmon. Being able to image from multiple view angles is advantageous for extracting information on river morphology. UAVs are easy to use and provide a method of obtaining imagery, that with a simple application involving limited further image processing, can provide qualitative information that can contribute to knowledge on the Atlantic salmon habitat by providing a “top-down” view.

Limitations. The examples shown here have also shown some of the limitations involved. Firstly, imaging is dependent on the light environment. Images of the River Nævre were strongly affected by shadow from riparian vegetation; and those in the River Homla were affected by a range of factors, including sunglint and reflection. While it was still possible to obtain useful qualitative information, these image artefacts could potentially make quantitative analysis less effective. Secondly, extraction of quantitative information was not easy or always effective. SfM could be used to determine river morphology. However, it is questionable how effective this would be in deeper areas. Additionally, the approaches used for quantifying substrate size provided some information, but had low explanatory power.

Effective application of UAVs to Atlantic salmon habitat surveying requires more attention to image acquisition and image processing. We provide more detail about some of the issues associated with successful imaging in Section 6, and provide suggestions for optimizing UAV surveys and image analysis in Section 7.3.

5 Alternative photo surveying approaches

5.1 Introduction

The two sources of aerial photo survey data focused upon in this report – *Norge i bilder* and UAVs – have been shown to have strong potential for characterizing Norwegian Atlantic salmon habitat. However, there are limitations to both sources. *Norge i bilder* as a data source requires the user to rely on the datasets that are available. There may be long gaps between image acquisition, there is a lack of winter coverage, and images are typically not acquired to explore important features of Atlantic salmon habitat so may be of sub-optimal suitability (e.g. low resolution). UAVs have limited range, their use may be restricted by no-fly zones, and they may be difficult to operate in small, tree-lined streams. Three further forms of photo surveying techniques – helicopter photo surveys, ground-based photo surveys and underwater photo surveys – may complement *Norge i bilder* and UAVs as sources of information on Atlantic salmon habitat.

5.2 Helicopter photo surveys

Surveying from a helicopter provides an intermediate remote sensing approach between using *Norge i bilder* aerial photographs and using UAVs. Helicopter-based surveys have the advantage over *Norge i bilder* of increased flexibility (the user has control over when and how the imagery is acquired), and increased resolution (the helicopter can fly closer to the ground than a fixed-wing crewed aircraft). They have the advantage over UAVs of increased range, with no issues with maintaining line-of-site between operator and platform, and fewer issues with avoiding infrastructure on the ground as they can fly higher than UAVs. The largest drawback with helicopter-based surveys is the financial cost.

Helicopter photo surveys offer the ability to monitor changes made within watercourses. For example, Forseth et al. (2019) used helicopter surveys to monitor the channel characteristics of the River Mandalselva during a period of habitat remediation that involved removal of weirs (Figure 35) and the addition of coarse substrate for supporting fish (Figure 36). Here, aerial photographs were taken from oblique angles to aid qualitative interpretation of changes; acquiring helicopter aerial photograph from a perpendicular angle to the surface is more suitable if the objective is quantitative mapping.

Figure 35. Oblique aerial photographs of the River Mandalselva (022.Z) obtained from a helicopter survey: (A) before removal of a weir; (B) after removal of a weir. See https://brage.nina.no/nina-xmlui/bitstream/handle/11250/2657971/Forseth%20Mandalselva%202020.pdf?sequence=1&isAllowed=y. Source: Tor Kviljo

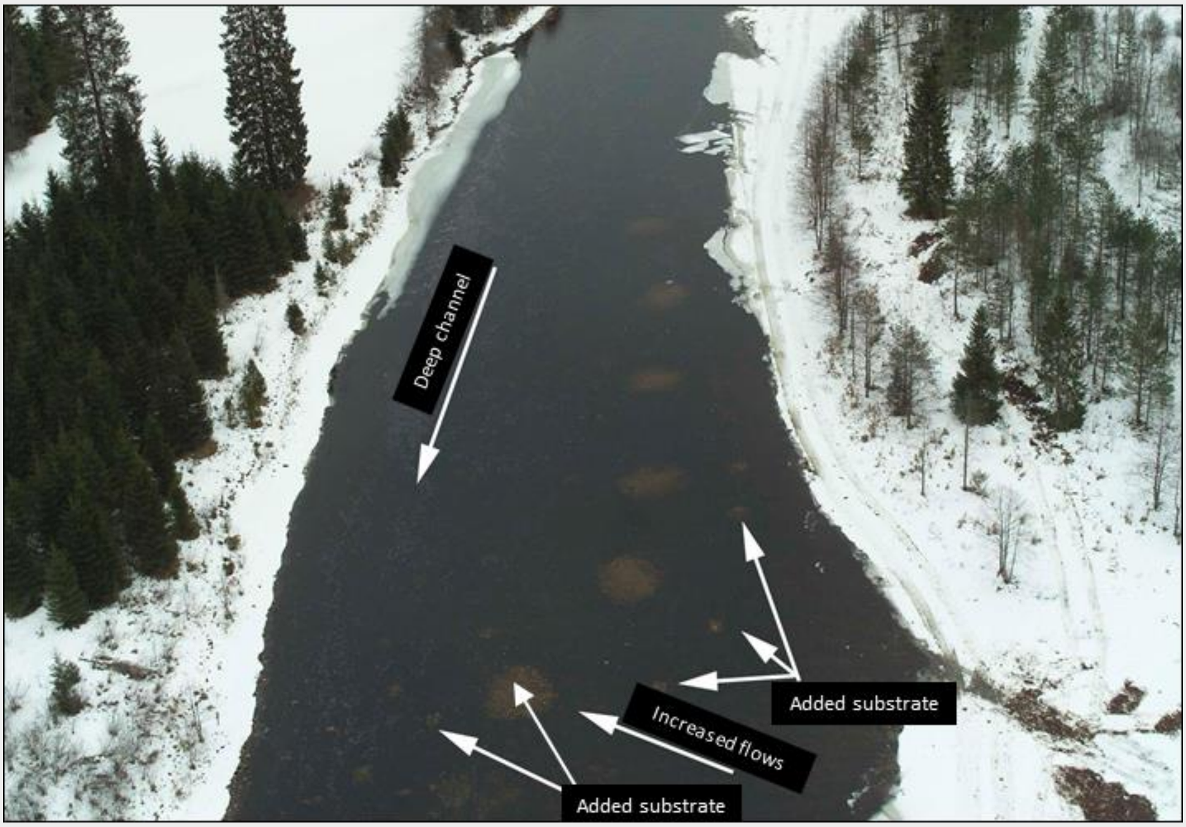

Figure 36. Oblique aerial photograph of the River Mandalselva (022.Z) obtained from a helicopter survey showing substrate additions and improved flow conditions. Source: Tor Kviljo.

5.3 Ground-based photo surveys

In cases were UAVs are operationally restricted from use, high resolution and multi-view angle photo surveys of rivers can be obtained from ground surveys using cameras suspended above the river. Methods of suspending the camera vary according to research team. For example, Bird et al. (2010) used a gimbal-mounted camera suspended from a 10 m pole above the river surface from the river bank. In the ground-based photo surveys conducted at NINA, a field operative takes multiple downward images from a camera elevated above the surface at 2-3 m above the water surface while wading through the river (Figure 37). The camera is attached to the pole using a fixed bracket rather than a gimbal so that it points downward but not necessarily perpendicular to the water surface. Images are then merged through stitching or orthorectification software to provide a photo survey of the area of river covered by the wader (Figure 38). Due to the increased geometric deformation caused by the low elevation of the camera, orthorectification based on an SfM point-cloud approach is recommended. Given that the operator and camera pole are often present in the images, this approach may require image cropping to remove them before the orthorectification, alongside possible removal of areas of sunglint. This method has been found to be effective for mapping habitat in shallow, wadable rivers. While it retains the main advantages of UAV surveying – full control of imaging time, and high resolution and multi-view angle imagery – the method is expensive in terms of labor cost, and is not applicable in reaches that are not wadable due to waters being too fast flowing or too deep. Thus, it is limited in its overall applicability to Norwegian rivers, and is more suitable for use in small, shallow and slow flowing streams.

Figure 37. Photo surveying conducted by wading through the River Vigda (122.2Z) using a pole-mounted camera. Source: R. Hedger.

Figure 38. Results of ground-based photo surveying: (A) single image; and (B) stitched images. Source: A. Foldvik.

5.4 Underwater photo surveys

Photo surveys of riverbed substrate and vegetation may be conducted using a camera in a waterproof casing, held beneath the water surface (Figure 39). If a reference scale is available within the image (e.g. from a tape measure laid along the riverbed), feature dimensions can be calculated. The advantage of this approach over above-surface photo surveys is that imagery is less affected by features on the surface of the water (such as white-water). Images must be acquired at a short distance to the riverbed, so geometric distortion in the imagery will be high, and successful merging of images may require an SfM approach. However, ripples on the surface may be evident as bright streaks on the bottom, and changes in their locations between successive images may make SfM approaches difficult. Finally, the requirement to position the camera beneath the water surface while wading through a river reduces the effective practical range over which this approach can feasibly be applied.

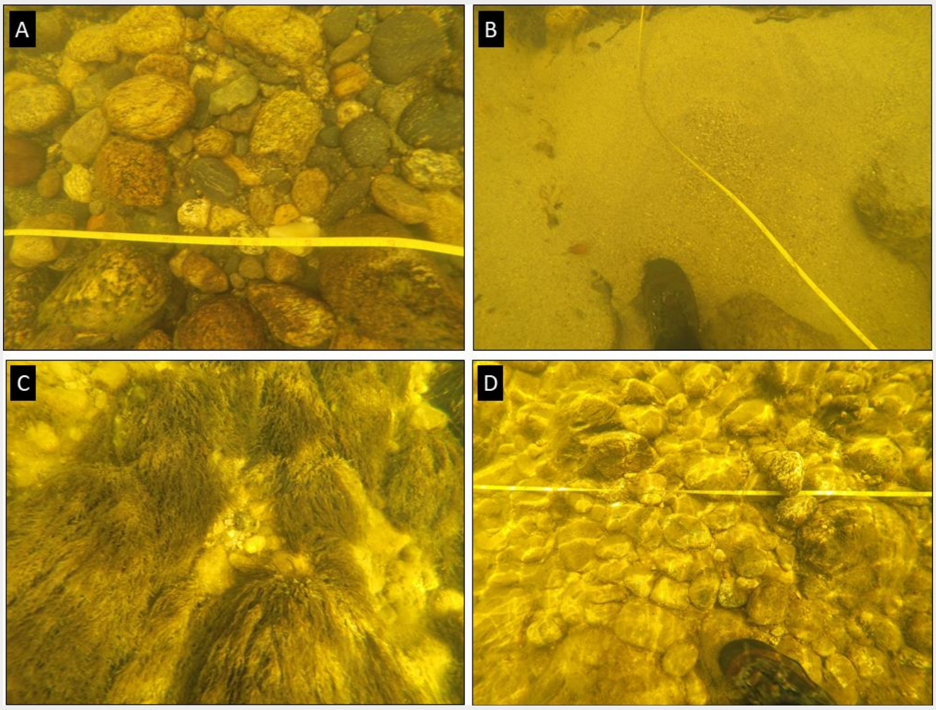

Figure 39. Sample images acquired from an underwater photo survey conducted in the River Skjoma (174.5Z). Source: A. Foldvik.

5.5 Summary

The three approaches shown here can be used to complement the use of *Norge i bilder* and UAVs:

Helicopter photo surveys. These provide an intermediate remote sensing methodology between crewed fixed-wing aircraft and UAVs, allowing for long-distance coverage, operational flexibility, and high spatial resolution, but with the drawback of the high financial cost involved.

Ground-based photo surveys. These can provide very high resolution data and can be used in areas inaccessible to UAVs, but have the drawback of limited spatial range and inapplicability to deep water stretches.

Underwater photo surveys. These provide the highest resolution possible, can be used in areas inaccessible to UAVs, and do not suffer from potential artefacts caused by imaging the air-water surface interface, but have even more restricted range than ground-based photo surveys.

6 Issues affecting image acquisition and quality

6.1 Introduction

Effective airborne surveying of Norway's Atlantic salmon rivers is dependent upon both being able to acquire images and for these images to be of sufficient quality to provide usable scientific information. Both image acquisition and image quality present challenges.

Image acquisition is limited when the site is obscured, is unilluminated, or is outside the area accessible to the sensor. Panchromatic or true-color aerial photographs are obtained via passive optical remote sensing which is reliant on reflected solar irradiance, and as such, require a direct line-of-site and illumination. Cloud cover is an issue for optical remote sensing in Northern Europe because the frequency of cloud cover is typically greater than 75% (see Wilson & Jetz 2016). The presence of cloud cover obscures the ground from high altitude aircraft (it is not possible to see through thick cloud in visible wavelengths), preventing imaging. Additionally, the absence of sunlight during the long winter nights in northern latitudes may restrict imaging. Finally, UAVs also experience operational restrictions governing where they can be used. According to Luftfartstilsynet, https://luftfartstilsynet.no/en/drones/, UAV pilots must: (1) maintain a visual line-of-site, (2) not fly within 5 km of an airport or airfield without permission, (3) be considerate of people's privacy, and (4) not fly within a preset distance of people, buildings or traffic. The rules applied depend on operational category, UAV class and UAV mass (see https://luftfartstilsynet.no/droner/). For the type of UAV used by NINA (C2, mass < 2.5 kg), the UAV cannot be flown within a 30 m distance of a structure such as a road or building.

Image quality is dependent on solar elevation. Low solar elevations (prevalent in Norway during winter) reduce the intensity of incoming irradiation, resulting in less outgoing irradiation and darker imagery. Low solar elevations also increase the proportion of light that is reflected off a flat water surface. Both of these phenomena may reduce the ability to extract features in the river channel. Image quality also depends on a range of other factors relating to how water surfaces are illuminated and imaged, including shadows from topography and riparian vegetation, reflections from features above the water surface, and sunglint. This is a particular problem if imagery is acquired under direct sunlight, where most incoming irradiance is direct rather than diffuse.

In the following sections, we quantify and qualify how significant these limits on image acquisition and image quality are for Norway's Atlantic salmon rivers.

6.2 Data sources and processing

6.2.1 Image acquisition

Limitations on the ability to acquire imagery were conducted with respect to cloud cover, day length and solar elevation, and operational restrictions governing the use of UAVs.

- Cloud cover across Norway was determined from Aqua/MODIS satellite data, obtained through the NASA Earth Observations portal (https://neo.sci.gsfc.nasa.gov/). This provided mean cloud cover per month at a spatial resolution of 0.1º.
- Day length was calculated across the latitudinal range of mainland Norway throughout the year using R function *suncalc{suncalc}*. Given that imaging is restricted not only by the absence of daylight, but also by low solar elevations, solar elevation at noon was also calculated (using the R function *sunAngle{oce}*).
- UAV operational restrictions were investigated with reference to the ability to avoid no-fly zones. Thirty meter no-fly zones were calculated around all major roads (type R, K, E and F) and all railroads, derived from N50 Kartdata (*Kartverket*, https://kartkatalog.geonorge.no/) and the percentage of Atlantic salmon supporting habitat (by length) that was within these zones was calculated. Potential limitations resulting from the requirement to maintain a line-of-site between UAV and operator were then illustrated for

a selected river (River Børsa) using a *Norge i bilder* aerial photograph and information of tree height from LiDAR data.

6.2.2 Image quality

Potential controls on image quality were examined with reference to image brightness, shadow, reflections from features above the water surface, and sunglint.

- Image brightness was assessed with regard to solar elevation. Solar elevation was calculated using the R function *sunAngle{oce}.* The effect of solar elevation on solar irradiance (W m^{-2}) was estimated using R function *insolation{insol}* (parameters: masl = 0, visibility = 28 km, relative humidity = 60 %, air temperature (K) = 278.15, ozone thickness = 0.02 m, and albedo = 0.2). The effect of solar elevation on reflectance from the water surface was determined using Fresnel equations (see http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/freseq.html)
- Shadows from topography as a function of solar elevation were calculated using R function *doshade{insol}* for all Atlantic salmon supporting reaches in Norway,
- Other artifacts of the light environment (shadows from riparian vegetation, reflections and sunglint) were examined for UAV aerial photographs of the River Homla/Nævre.

6.3 Image acquisition

6.3.1 Cloud cover

Norway experiences a large amount of cloud cover. Cloud cover is greatest on the northern coast in Finnmark and in the south-east in Rogaland, Hogaland, and Sogn og Fjordane, but there is no region with less than ≈ 70% cover (Figure 40A). Cloud cover is prevalent throughout the year, with all months having a medium cloud cover of > 75% (Figure 40B). The prevalence of cloud cover across Norway throughout the year therefore severely limits the flexibility of imaging from high altitude aircraft. UAVs, flying under the cloud, may be used, but with potentially reduced image quality.

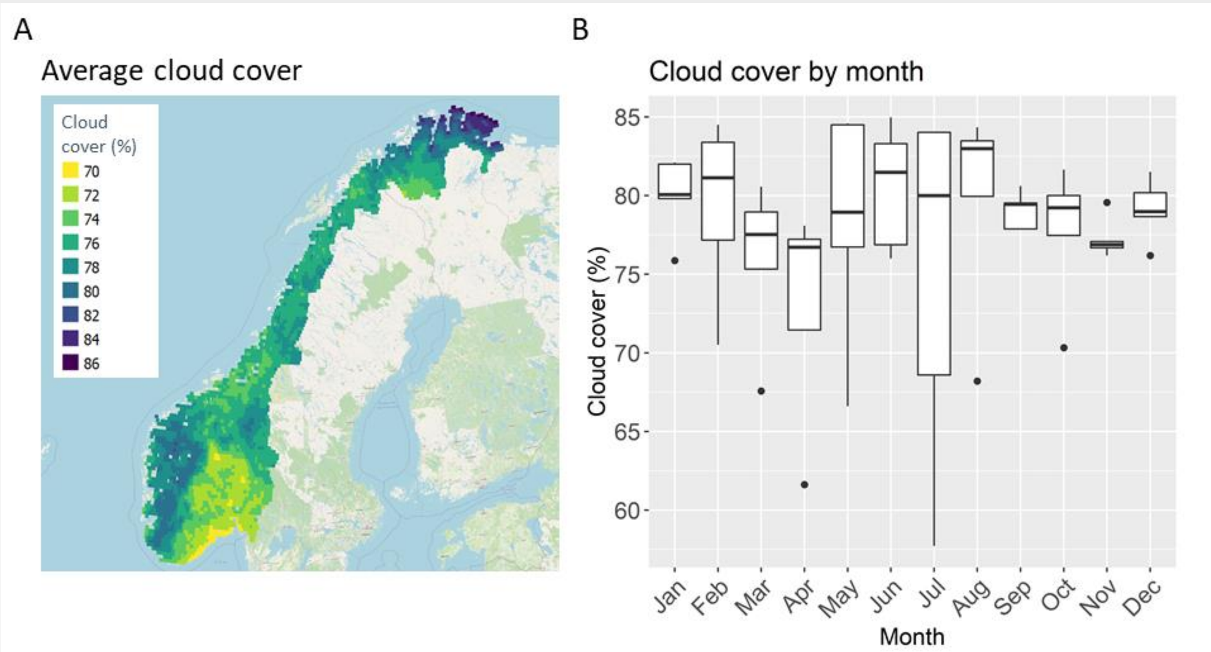

Figure 40, Cloud cover for mainland Norway (2015-2019): (A) map of average cloud cover; (B) average cloud cover according to month of year for all of mainland Norway.

6.3.2 Daylength / solar elevation

Norway's high latitude causes long daylengths during summer but short daylengths during winter, with the intra-annual variation in daylength increasing with latitude (Figure 41A). Summer is characterized by a long daily imaging window (June daylength varies from >18 h in the south to 24 h in the north). However, winter is characterized by a very short daily imaging window (December daylength varies from <7 h in the south to < 1 h in the north). The imaging window is not solely dependent on the presence of daylight but also on having a sufficient solar elevation (low solar elevations lead to relatively dark images). The ambient light environment of Norwegian Atlantic salmon habitat is often characterized by low solar elevations. Even in June, solar elevation will not exceed 45º for habitat north of 68.5ºN (Figure 41B). During December, solar elevation will be less than 10º across all of Norway, resulting in very low solar irradiance. This light environment therefore presents highly sub-optimal conditions for optical remote sensing in winter. Aerial surveys of Norway conducted by government-contracted agencies (of the type available through *Norge i bilder*) are acquired only under "good" light conditions, so there is a constraint on when they are acquired – due to the presence of night or low solar elevation – and surveying during winter is rare.

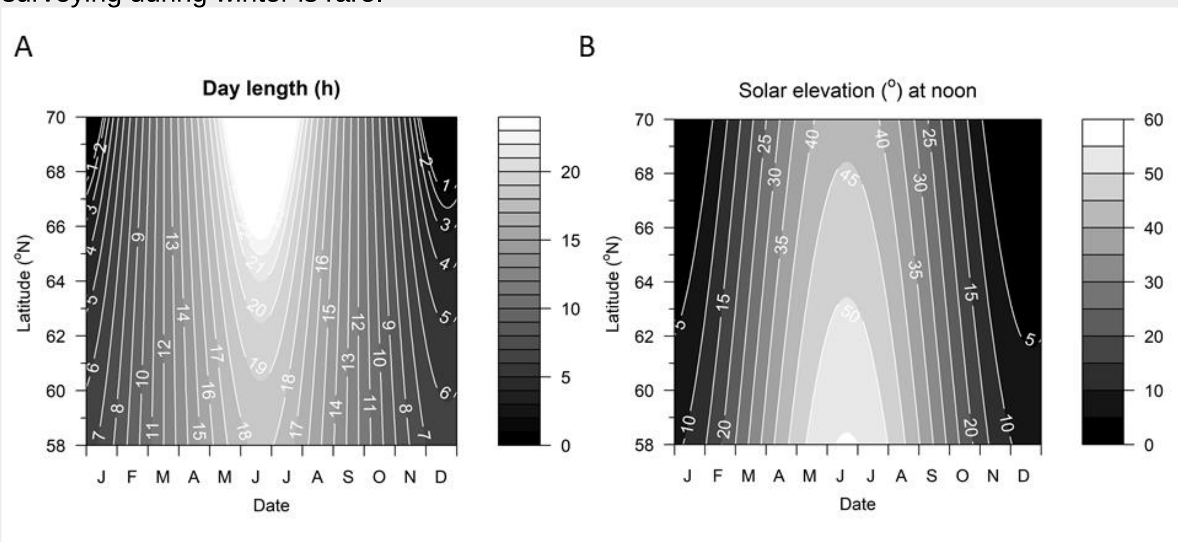

Figure 41. Light environment for Norway across latitudes and dates of the year: (A) day length; (B) solar elevation at noon. Daylength was calculated using R-function suncalc{suncalc} (using longitude = 1.83ºE). Solar elevation was calculated using R-function sunAngle{oce}.

6.3.3 UAV operational restrictions

No-fly zones. Circa 4.5% of the total length of Norway's Atlantic salmon reach lies within the 30 m no-fly zone surrounding roads and railways. No-fly zones tend to be a greater limitation for UAVs in the more south (Agder, Rogland Vestland, Viken, with the urbanized Oslo county being particularly effected) than in the north (Troms og Finnmark) (Figure 42). Given the relatively small length of Norway's salmon reach that lies within a no-fly zone from roads and railways, this will not have a significant impact on UAV surveying within Norway (but must be included in the planning of surveys). However, there are a large number of additional restrictions to where UAVs can be flown, including areas in proximity to other infrastructure (such as airports, hospitals, prisons and schools), and nature conservation areas (see safetofly.no). Additionally there may be no-fly zones associated with power lines crossing the river.

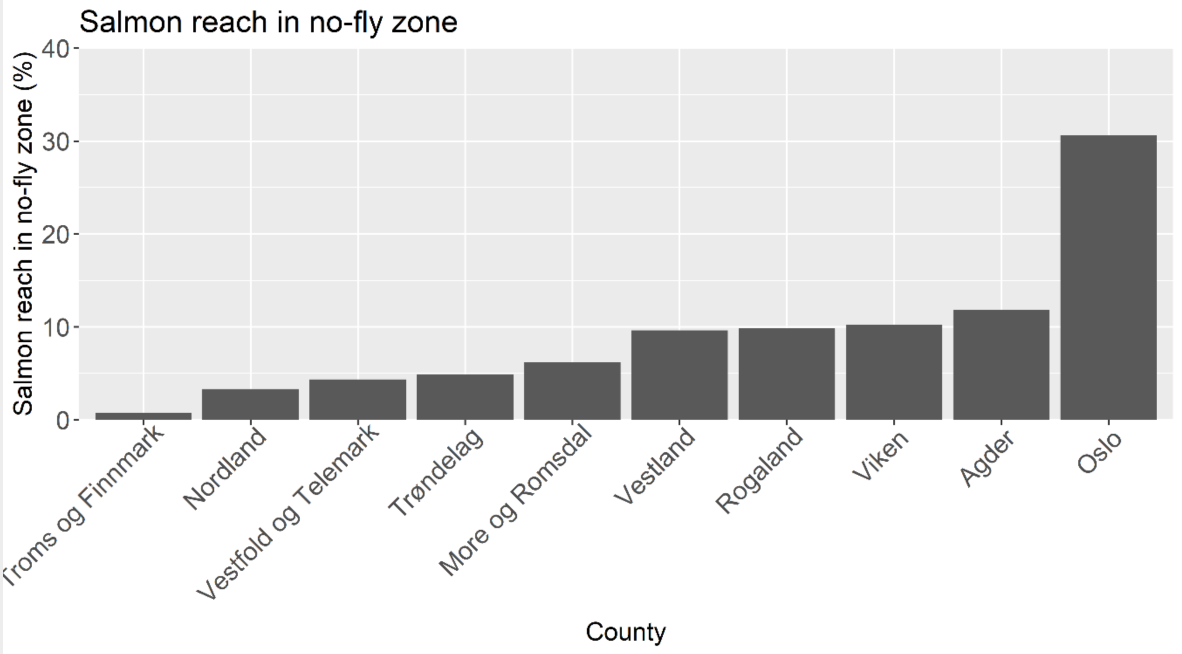

Figure 42. Atlantic salmon reach in no-fly zone (%) from major roads and railways per county. Bars show total no-fly zone length per county over total Atlantic salmon reach length per county, expressed as a percentage.

Line-of-site. Much of Norway's Atlantic salmon habitat is surrounded by forests, and habitat in non-forested area often has tall riparian vegetation lining the riverbanks, so achieving line-of-site may be difficult when using UAVs. For example, Figure 43 shows riparian vegetation along the banks of the River Børsa. For this case, line-of-site UAV imaging could be achieved in the straight part of the channel (upper right part of figure), but the meandering channel limits the potential for line-of-site imaging elsewhere (lower part of figure).

Figure 43. Riparian vegetation along the banks of the River Børsa (122.1Z) as shown by a Norge i bilder image (2016) draped over an estimate of surface feature elevation (difference between LiDAR-derived DSM and DEM).

6.4 Image quality

6.4.1 Image brightness

Norway experiences lower solar elevations and lower solar irradiance than more southerly latitudes. Elevations and irradiance will be particularly low away from the summer solstice. For example, solar irradiance at noon in southern Norway may exceed 1000 W m^{-2} on the summer solstice but be nearer to 800 W m^{-2} by the autumn (Figure 44). In addition to reducing solar irradiance, low solar elevations have a particularly large effect on optical remote sensing of water bodies because surface reflectance from the water body surface increases at low solar elevation (following Fresnel equations). This means that there is less remaining irradiance to penetrate the water column, reducing the ability to discern, for example, riverbed features. Below solar elevations of 20°, which are typically for Norway from November to February, > 10 % of incoming irradiance will be reflected from the water surface. Thus, due to low solar elevation, images may be dark and lack detail on riverbed properties when taken away from noon or outside summer, particularly in more northerly locations.

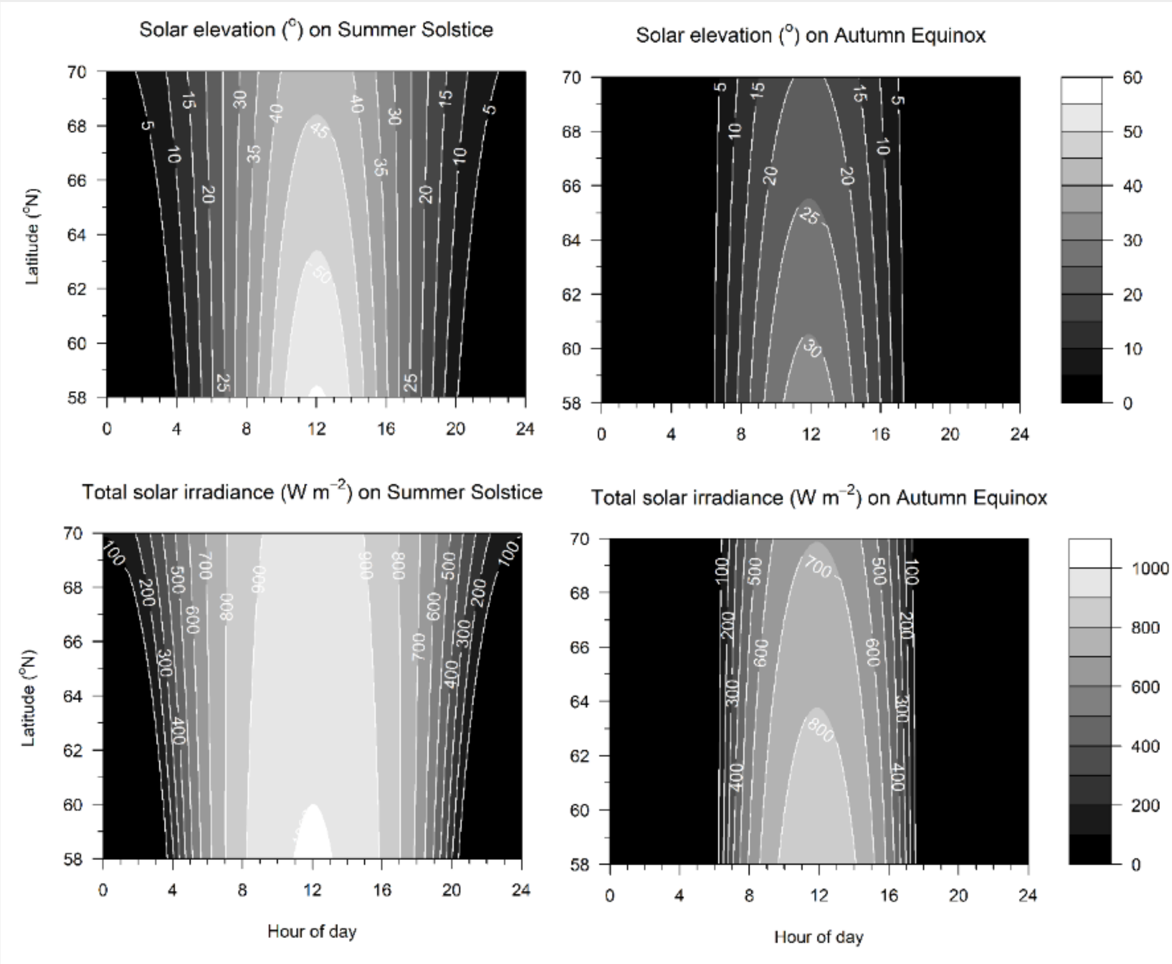

Figure 44. Solar elevation and total solar irradiance on the summer solstice and autumn equinox for different times of the day at different latitudes. Solar elevation was calculated using R-function sunAngle{oce}. Solar irradiance was calculated using R-function insolation{insol}.

6.4.2 Shadow

The local light environment of Norway's Atlantic salmon rivers is often characterized by shadows caused by the obstruction of direct solar irradiance, due to the presence of mountains (topographic shadow), or riparian vegetation such as trees. Topographic shadow affects > 15% of Norway's total Atlantic salmon reach length at a solar elevation of 20º, and ≈ 45% at a solar elevation of 10º (Figure 45A). Shadow is a particular problem in parts of the watercourse that are more East-West aligned (e.g. see the western part of the River Alta which is more affected by shadow than the eastern part; Figure 45B). Tall riparian vegetation may also cast shadows across the watercourse (e.g. Figure 46), adding image artefacts that may obscure features of the habitat. The overall effect of this is expected to be high, given that much of Norway's Atlantic salmon reach has tree-lined riverbanks.

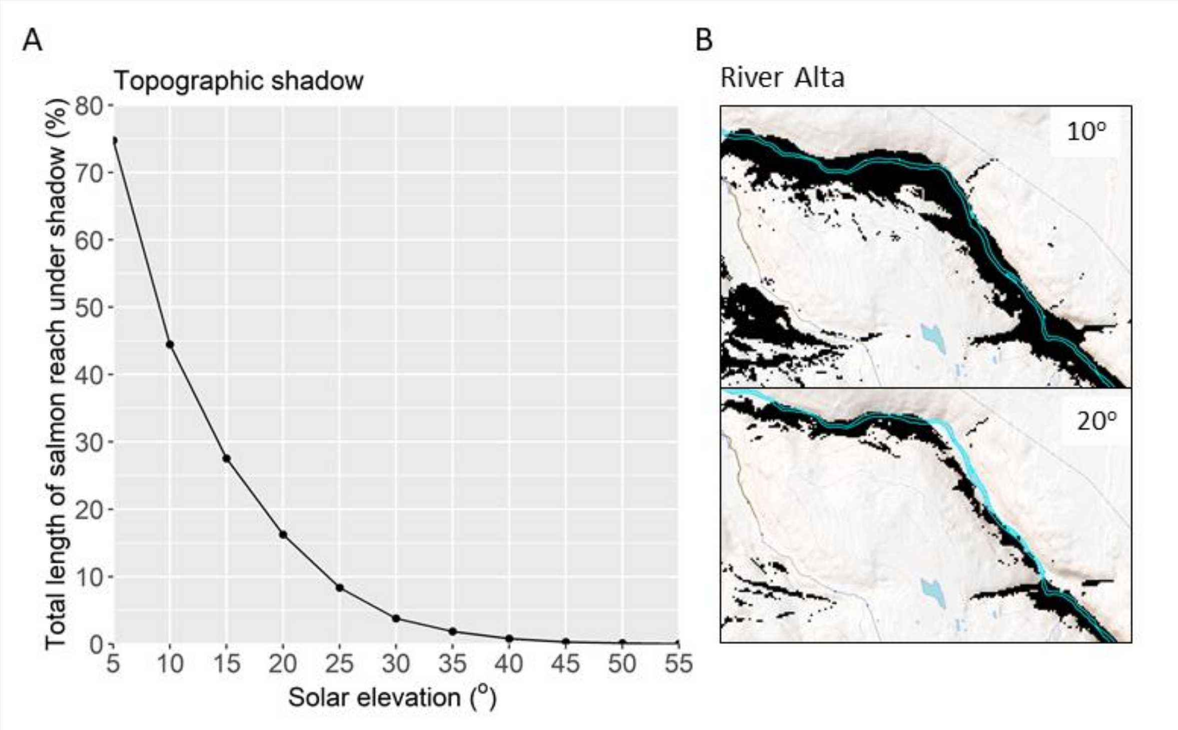

Figure 45. Topographic shadow: (A) total length of Norwegian salmon reach under topographic shadow (%) for different solar elevations; (B) predicted topographic shadow (black pixels) over the River Alta (212.Z) at 12:00 hrs with a solar elevation of 10º and 20º.

Figure 46. Shadow from riparian vegetation in a Norge i bilder image of the River Nævre (123.4AZ).

6.4.3 Reflections

Reflections on the water surface can originate from a variety of sources: for example, riparian vegetation, bankside infrastructure, or isolated clouds (Figure 47). The position of reflections within images depend on the relationship between solar incident angle and view-angle. Reflections from cloud are transitory in nature, and their locations within images will change as the cloud moves. This means that there is potential to minimize reflections by careful selection of view angles and imaging times when UAV surveying.

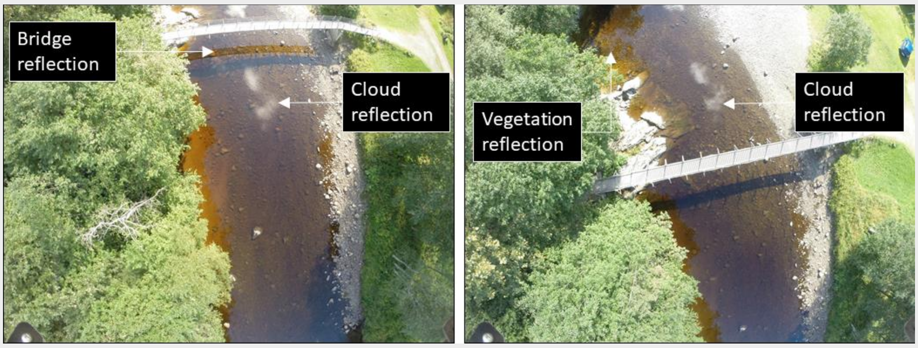

Figure 47. Reflections in UAV images of the River Homla (123.4AZ).

6.4.4 Sunglint

Sunglint occurs when sunlight reflects off the water surface at the same angle at which the sensor is viewing the surface. This results in the obscuration of detail below the surface. Given that sunglint is dependent on view angle, imaging the same area from different angles will change the position and amount of sunglint present in the image (Figure 48). For example, feature “a” is visible on both images because it is in a dewatered bank, but the submerged substrate around features “b” and “c” is largely obscured in the image where there is sunglint around these features (Figure 48A).

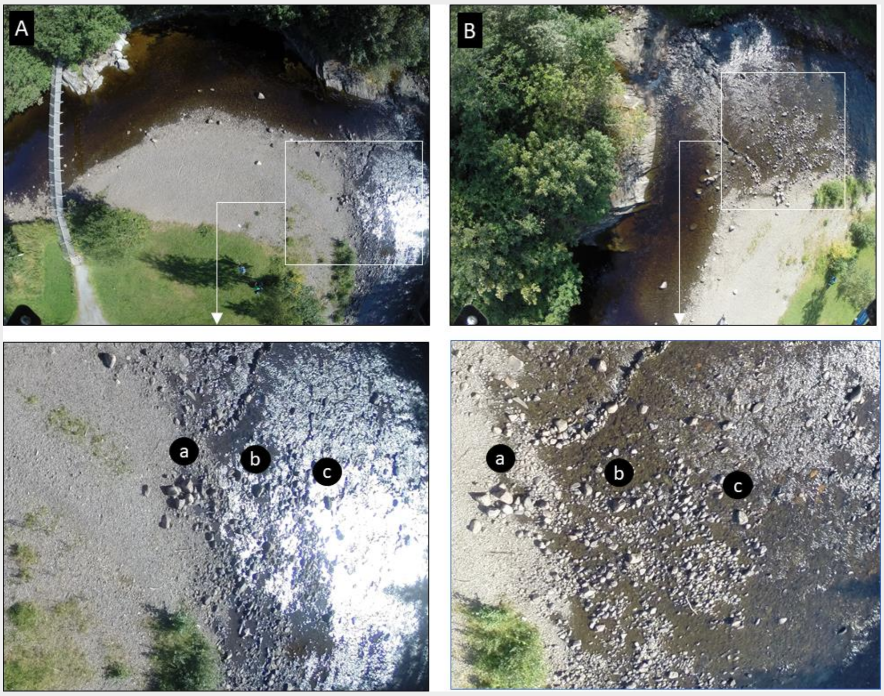

Figure 48. Sunglint in UAV images of the River Homla (123.4Z), taken at different view angles: (A) view angle leading to heavy sunglint; (B) view angle leading to less sunglint.

6.5 Implications for aerial photo surveys

Image acquisition. Norway's light environment restricts when effective surveying can be conducted. The presence of cloud cover prevents imaging by high altitude aircraft, reducing the operational flexibility of habitat surveying using this platform. Images may be acquired from low altitude UAVs under the cloud cover, but the light environment will be relatively dark, involving reductions in solar irradiance in the order of ≈70-90% compared to cloud free conditions (Matuszko 2012). This leads to lower outgoing irradiance, and darker images with a lower signal-to-noise ratio, making extraction of salient features of the river habitat such as depth or substrate size more difficult. The limited availability of daylight in Norway's northern latitude in winter also restricts imaging, such that government-mandated surveys of the type that are available from *Norge i bilder* are rarely conducted during winter. In particular, *Norge i bilder* aerial photographs are acquired at the wrong time of year for monitoring river ice (which is an important phenomenon affecting over-winter survival of Atlantic salmon). UAVs may be used in winter, but low solar elevations pose a problem in terms of image quality. Legal restrictions on the use of UAVs pose only a slight problem: acquisition of imagery of Norwegian rivers from UAVs of the size typically used by NINA (< 2.5 kg) is generally not greatly constrained by the presence of no-fly zones other than in the more urbanized counties (e.g. Oslo), but it is essential to consider this in pre-flight planning.

Image quality. The distribution of Atlantic salmon reaches across Norway has strong implications for acquiring images under optimal light conditions. Firstly, the high latitude of many Atlantic salmon reaches may be lead to low solar elevation, particularly during winter, resulting in dark images where features such as riverbed substrate are more difficult to discern. Secondly, Atlantic salmon reaches are often shaded by mountains or trees, which may result in reduced image quality. Thirdly, cloud cover reduces image quality from UAVs. Finally, there is a range of other factors that makes the light environment challenging – shadows, reflections, sunglint – all of which may make extraction of information on Atlantic salmon habitat difficult. Photo surveys of the type available through *Norge i bilder* (Section 3) are not done with the primary objective of extracting information on Atlantic salmon habitat so the photo survey planning does not attempt to minimize confounding factors for Atlantic salmon rivers. Consequently, images available through *Norge i bilder* may be sub-optimal for investigating Atlantic salmon habitat. UAV surveying (Section 4) offers greater ability to image the habitat when the light environment is more optimal.

7 A structured approach to aerial photo surveys of Atlantic salmon habitat

7.1 Introduction

This study has shown that: (1) the resolving abilities of aerial photo surveys match the spatial and temporal scales of Norwegian Atlantic salmon habitat; (2) both *Norge i bilder* aerial photographs and UAV surveys provide useful habitat data; but (3) Norway's environment creates challenges for aerial photo surveys of rivers, necessitating careful planning of the survey mission and treatment of survey data.

In the following we present a formalized method for aerial photo surveying of Norwegian Atlantic salmon habitat. We begin with recommendations for optimizing the use of *Norge i bilder* imagery (Section 7.2). We then provide recommendations for how to optimize the acquisition and processing of imagery from UAVs (Section 7.3). We then discuss how imagery from these two approaches can be integrated with one-another, alongside ancillary GIS datasets (Section 7.4).

7.2 Optimizing the use of *Norge i bilder*

Norge i bilder imagery provides full spatial coverage of all Norwegian Atlantic salmon rivers, and snapshots of historical conditions of these rivers, but the imagery was not acquired for the sole purpose of elucidating Atlantic salmon habitat, so suffers from multiple limitations in this respect (relatively low spatial resolution and limited image quality). To extract useful information, we recommend a more formalized approach involving exploiting multiple images of the same habitat, alongside use of ancillary datasets. We also recommend the implementation of a more formalized procedure for qualitatively interpreting habitat characteristics in imagery, and recommend some simple techniques for quantitative image analysis including machine learning.

7.2.1 Exploiting multiple images

Images show widely different features, based on how and when they were acquired (affecting resolution and illumination angle) and temporal changes in the river (discharge, riparian vegetation, channel characteristics, bed material). Analysis of multiple images of the same site allows for better resolving of features and allows identification of temporal changes which may give insight into habitat characteristics. For example, Figure 49 shows imagery of the same part of the River Gaula taken at different discharges. The image acquired at high discharge was taken during better light conditions (with less shadow across the river) and shows interesting flow features, evident from white water around boulders. However, submerged substrate in the image taken at low discharge is more visible due to the lower depth and lower surface turbulence, so also provides useful information. There is also evidence of movement of cobble substrates between the images so use of multiple images can provide information on riverbed sediment dynamics.

Use of multiple images is particularly important for estimating depth. For example, the image acquired of the River Nausta at high discharge (Figure 50A) contains a lot of white water caused by weirs which would prevent depth estimation in these areas. The image acquired at lower discharge (Figure 50B) has less white water, so is more suitable for estimating depth (Figure 50C). However, the image taken at high discharge is useful for assessing the quality of the depth estimation from the low discharge image because it has a higher spatial resolution and can be used to identify features such as patchiness in substrate color (see inset panels) which might cause spurious depth estimates.

Figure 49. Norge i bilder images of the River Gaula (122.Z): (A) image acquired at high discharge; (B) image acquired at low discharge.

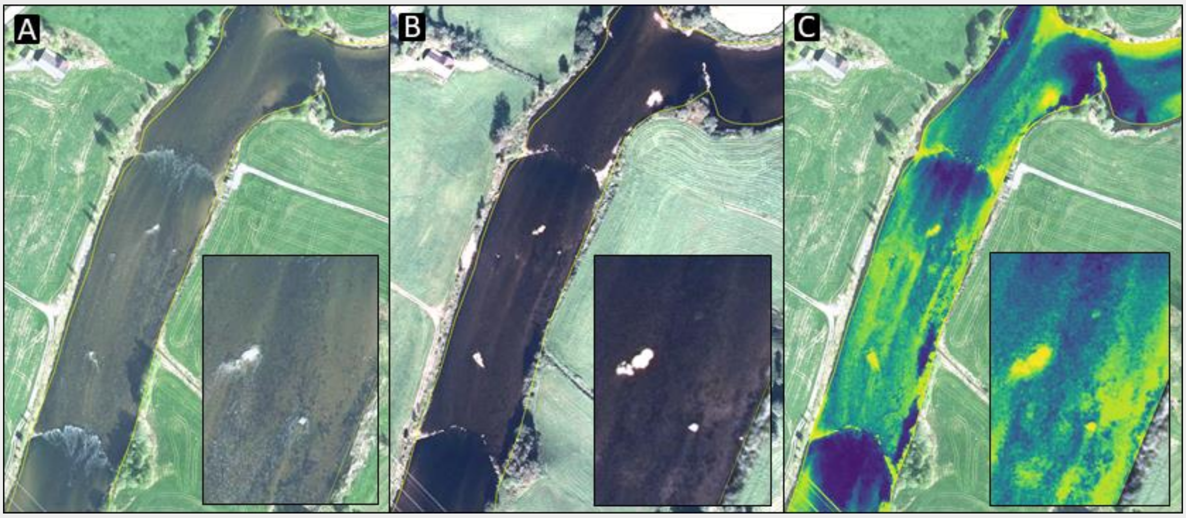

Figure 50. Norge i bilder images of the River Nausta (122.Z): (A) image acquired at high discharge; (B) image acquired at low discharge; (C) red channel of image acquired at low discharge, color coded from blue (low values) through green (medium values) to yellow (high values).

7.2.2 Exploiting ancillary datasets

A wide range of remote sensing/GIS datasets exist (see Section 10.1), which can be used to aid interpretation and analysis of *Norge i bilder* imagery. Discharge data (from *Norge vassdrags- og energidirektorat, NVE*) may be cross-referenced with time of image acquisition to aid in determination of how water-covered area changes with discharge, and may be used to extract cross-channel profile if multiple images are available. *NVE Elvenett* GIS data may be used to locate small tributaries; *Kartverket N50 kartdata* may be used in delineating the main river channels. *Kartverket* LiDAR-derived elevation data may be used to determine changes in river surface elevation and surface gradient, and used to derive the height of tall riparian vegetation. Maps of superficial deposits from *Norges geologiske undersøkelse* may also be useful for interpreting river processes within the context of the surrounding environment. Satellite remote sensing data from the EU's *Copernicus* Earth Observation Programme may be used to assess ice cover. Finally, a wide range of base maps are available on publicly accessible servers (and can for example be imported into QGIS using XYZ Tile Layers).

7.2.3 Qualitative interpretation

An initial qualitative inspection of imagery can be used to identify features of the Atlantic salmon habitat. Dependent on the application, some of the following procedures should be implemented:

- **Identify flow features.** For example, the presence of white water indicates flow turbulence and high speeds. Likewise, slow flowing areas in shallow waters may be inferred by the absence of surface flow features (i.e. no white water or ripples).
- **Identify depth patterns.** Darker parts of the channel in individual images can reveal deeper waters. Comparison of water covered areas among multiple images taken at different discharges can show channel profile.
- **Identify substrate sizes.** Image resolutions will not allow identification of individual grains smaller than large cobbles, but it is possible to delineate the water course into large (large cobble / boulder) and small (pebble and smaller) substrates.
- **Identify hydromorphological features.** Hydromorphological features that can be observed in *Norge i bilder* imagery include side channels, dewatered beaches, pool-riffles, meanders, rapids, and inflows from tributaries.
- **Identify human infrastructure.** These include culverts, weirs, dams, hydropower outlets, and bank modifications.
- **Identify migration barriers.** These include both natural barriers (high gradient stretches or waterfalls) and human infrastructure (dams or culverts).
- **Classify the river into the main mesohabitat types.** *Norge i bilder* imagery is suitable for use in the mesohabitat classification system of Borsányi et al. (2004), providing information on surface pattern and water depth. Additional data sources such as LiDAR, providing longitudinal gradient, may improve the mesohabitat classification.
- **Classify the river into distinct reaches.** The macroscale structure of large rivers may be defined by classifying parts of the water course into rithron and potamon zones, or sedimentary links.

Image enhancement may reveal further detail. Stretching the image contrast can be useful for detecting changes in depth (Figure 51). Image sharpening techniques may enhance the clarity of larger substrates, particularly those in deeper parts of the channel (Figure 52) (although the coarseness of *Norge i bilder* imagery limits these techniques).

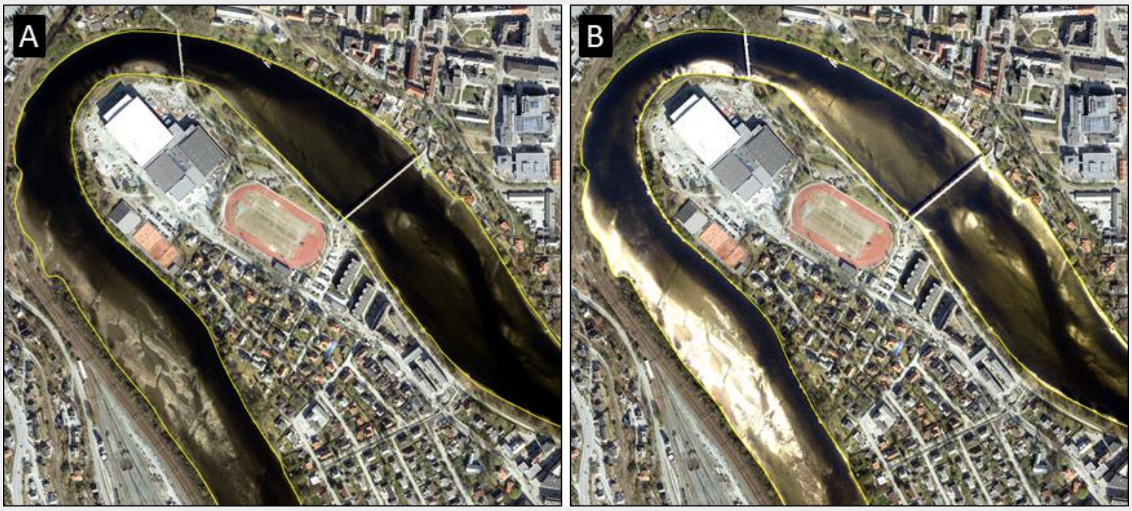

Figure 51. Norge i bilder image of the River Nidelva (123.Z): (A) true color image; (b) true color image contrast stretched within boundaries of the river.

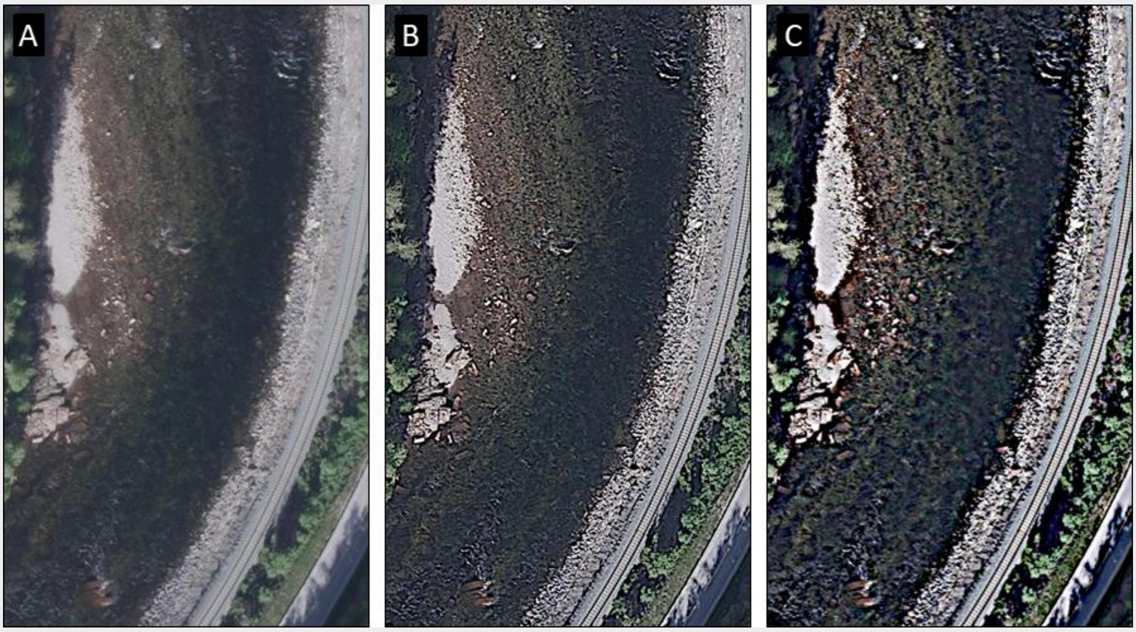

Figure 52. Norge i bilder images of the River Gaula (122.Z): (A) true color image; (B) sharpened image (radius = 4); (C) sharpened image (radius = 16). In (B) and (C), sharpening was done with Gimp sharpen (unsharp mass), radius = n, amount = 3, threshold = 0.

7.2.4 Quantitative analysis

A variety of image processing algorithms can be applied, ranging from traditional (e.g. application of spectral ratios, filters) to leading-edge procedures in image analysis (e.g. machine learning approaches).

Traditional approaches. If the study is solely interested in channel properties, areas that are outside the watercourse can be defined and excluded so that image processing algorithms are constrained to the river channel. For example, a running window used to extract local texture to provide information on substrate size should only be applied to the channel, and not include texture of the riverbank. Habitat characteristics extracted from *Norge i bilder* imagery at NINA include the following:

- **Water-covered area.** This can be directly measured from *Norge i bilder* imagery. Measurements at different discharges may provide information on channel morphology.
- **Depth.** Relative depth can be extracted based on DN values, and absolute depth can be estimated with reference to ground truth data.
- **Substrate size.** Substrate size can be quantified by analysis of image texture (for instance, using a geostatistical approach). The coarseness of *Norge i bilder* imagery however limits this to larger substrates.

Machine learning. Machine learning approaches are suitable for extraction of information from *Norge i bilder* imagery because: (1) there are abundant datasets (images) for training of models; and (2) machine learning is suitable for “noisy” data of the type that is found in *Norge i bilder*. Machine learning is underexploited at NINA with regard to river habitat. However, we show here an example of how a deep learning (neural network) approach could be used for automated classification of a river channel into mesohabitat classes, using imagery from the River Halselva and the River Nidelva for, respectively, training and testing the neural network. As a training dataset, a reach of the River Halselva is segmented into many small cells (cell size = 100 × 100 pixels) and each cell is manually classified into “smooth or rippled” or “standing wave” classes based on surface patterns (Figure 53) (see Borsányi, 2004). These data are then used to train a neural network using TensorFlow with the Keras Application Programming Interface which can then be used to classify surface patterns in new imagery. When these surface pattern classes are combined with additional data (e.g. surface gradient, obtainable from LiDAR data), it is possible to predict mesohabitat (Figure 54). The quality of the mesohabitat prediction could be increased by incorporating a more extensive training set, increasing the number of different class types, adjusting how the neural network is trained, and including additional parameters (surface velocity and water depth) in classification decision rules.

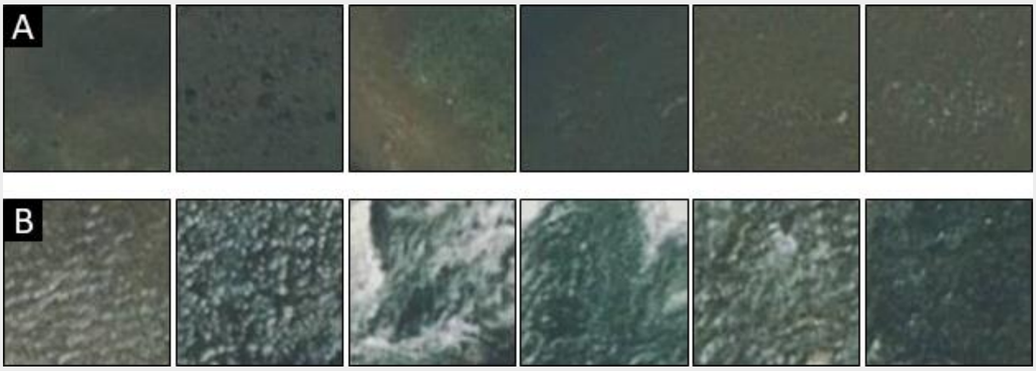

Figure 53. Training classes from the River Halselva: (A) smooth or rippled; (B) standing waves.

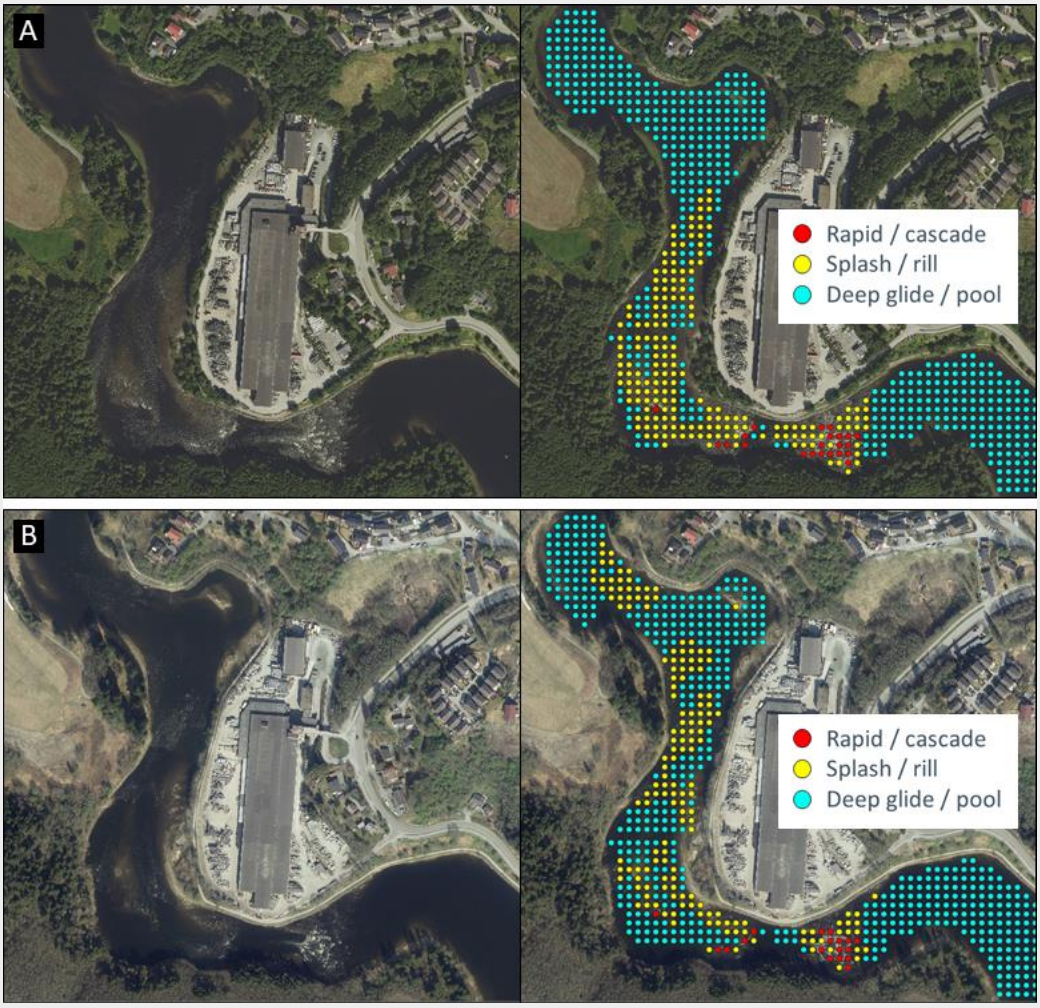

Figure 54. Predicted mesohabitat in the River Nidelva (123.Z): (A) high discharge; (B) low discharge.

Here, we have illustrated the application of neural networks to *Norge i bilder* imagery using a simple objective (classification of imagery into mesohabitat classes), but there are a large number of other potential applications such as mapping of water covered area, depth, or substrate size. These approaches can also be used for the processing of UAV data.

7.3 Optimizing UAV photo surveys

In comparison to traditional *Norge i bilder* imagery, UAV photo surveys allow for much greater operational flexibility, providing researchers full control on when, where and how images are obtained. Additionally, UAV imagery, by virtue of being acquired from low elevations and involving repeat imaging, allows for high resolution multi-angle views, so can potentially provide much more detailed information. However, the limited spatial range of UAVs, plus the potential proximity of the platform to obstructions (e.g. trees), can limit the ability to survey habitat. If the UAV survey is appropriately planned (which is enabled by the high operational flexibility), and the imagery is appropriately exploited, it is possible to overcome some of the constraints on successful imaging of rivers, and fully utilize the potential of UAV surveys. Here, we detail how this can be done, with reference to (1) flight planning, (2) image generation, and (3) image enhancement, interpretation and analysis.

7.3.1 Flight planning

Before visiting the survey site, GIS datasets should be used to identify site-properties affecting image acquisition (e.g. proximity to no-fly zones, obstructions to line-of-site between operator and UAV, take-off and landing location) and image quality (e.g. shadows from topography or riparian vegetation). Flight lines and view angles need to be planned. Image properties (swath width, resolution and overlap) should be estimated pre-flight to ensure flights will collect useful data. Potential ground control points may need to be identified or added in the field. It is also necessary to consider the ambient light-environment (dependent on solar elevation and azimuth when the imagery is to be acquired). Finally, a pre-flight checklist should be used to ensure safe operation of the UAV when surveying.

No-fly zones and obstructions to line-of-site.

No-fly zones can be identified via the safetofly.no service (https://www.safetofly.no) of *UAS Norway* and *Asplan Viak AS* (see Figure 55).

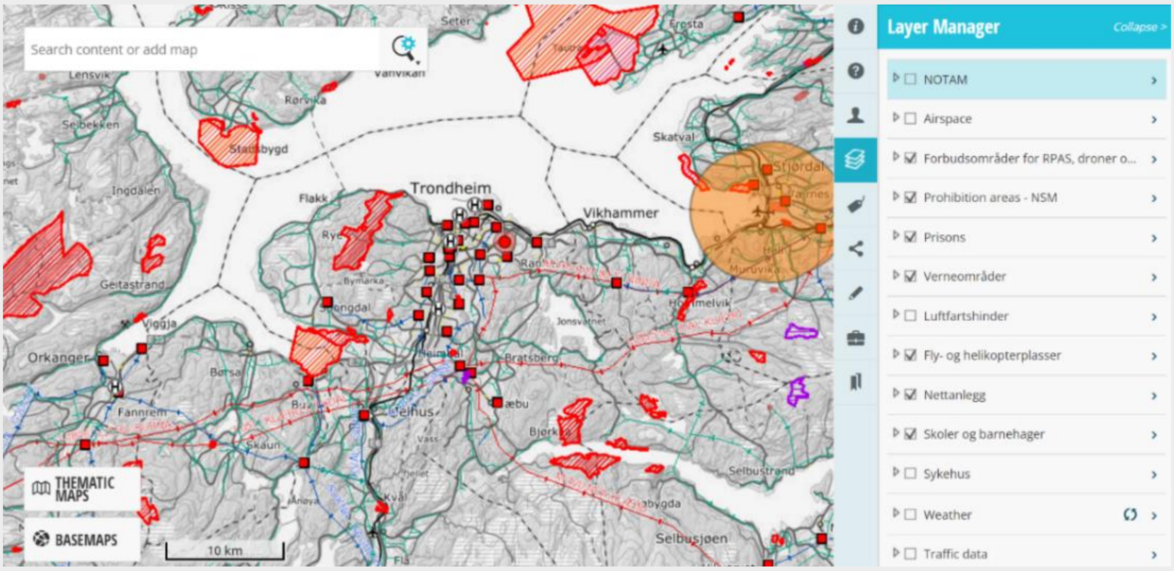

Figure 55. Selected UAV flight restrictions surrounding Trondheim as identified through safetofly.no.

Additional planning for identifying no-fly zones (e.g. areas proximal to roads), potential flight hazards or obstructions to line-of-site can be done before site visits using remote sensing/GIS datasets. For example, powerlines can be identified from *Norge i bilder* images, and potential obstructions to line-of-site from riparian vegetation can be identified from both *Norge i bilder* images and LiDAR data (see Figure 56).

Figure 56. Riparian vegetation along the River Børsa (122.1Z): (A) true color image showing riparian vegetation; (B) height of riparian vegetation as derived from LiDAR data (DSM – DTM) (light colors indicate higher elevation).

Flight lines and view angles. Approximate survey flight lines and view-angles should be established before visiting the site. Flight lines should be planned so that the UAV does not fly close to obstructions such as power lines and bankside trees. When flying in proximity to bankside trees, it is advisable that the operator flies the UAV longitudinally alongside the trees and avoids flying the UAV directly towards them where it is difficult to judge the distance between the UAV and the trees from the operator's point-of-view. Optimal view-angles will depend on the information required. Simple preliminary surveys to enable qualitative characterization of the Atlantic salmon habitat might only require oblique-angle images of the area. Generation of a simple orthomosaic may require overlapping images with a view angle perpendicular to the ground. Generation of a 3D model will benefit from multiple view angles so that (1) no surfaces are obscured and (2) point-cloud generation software can use images with the same feature imaged from multiple view angles.

Imaging parameters: swath width, image resolution, overlap and distortion. With careful planning of the survey, based on the camera type, the UAV altitude, and the imaging frequency relative to how fast the UAV is moving, the likelihood of collecting informative sequences of UAV images is increased. Information on image dimension (calculated from UAV elevation, angular FOV and image aspect ratio; Section 10.3) can be used to estimate if there is a sufficient swath width to cover the channel, and information on image dimensions can be combined with camera pixel resolutions to estimate likely image ground resolution. Additionally, information on image dimensions can also be combined with UAV speed and camera repeat frequency to estimate the degree of overlap between successive images (and therefore determine whether it will be possible to successfully construct orthomosaics or DSMs). Finally, the fact that UAV images are acquired from a low elevation makes them susceptible to geometric distortion, so UAV camera settings should be investigated pre-flight. Narrow camera FOV settings provide images with less geometric distortion, so setting cameras to minimum FOV settings (if available) is desirable. GoPro cameras are wide-angle and should generally be avoided. Some distortion is inevitable, but single images can often be partially corrected by camera software, or by post-processing (Section 10.3), and orthomosaicing packages can correct distortion when merging images (Section 7.3.2).

Ground control points (GCPs). GCPs are locations of features that can be identified both within the imagery and on the ground, which can be used to aid geometric registration of imagery via cross-referencing the image GCP location with the ground location. GCPs will not typically be required if the imaging system provides georeferenced images. However, their use may be necessary if image geopositions are inaccurate or unavailable. GCPs may be established using infrastructure already present in the imagery or by the laying of markers in the field. Structures already present might include corners of roadway intersections etc. Markers should be something of known dimensions that can be clearly identified, and may be something as simple as a colored sheet of plastic, weighed down with a weight (e.g. a rock). Pixel dimensions of the GCP can also be measured, allowing for estimation of image spatial resolution.

Optimal imaging time with regard to light-environment. The flexibility with regard to imaging time when conducting UAV surveys allows image acquisition when the light-environment is the best available. The presence of shadows from topography and riparian vegetation can be minimized by imaging the channel at a time when the solar azimuth is aligned with the channel so that shadows fall alongside rather than across the channel. For example, image acquisition along an east-west aligned channel around noon may result in shadows across the channel, but if imagery is acquired earlier or later in the day (e.g. ≈ 08:00 or ≈ 18:00 hrs), the sun will be in the east or the west, respectively, and shadows will fall parallel with the channel bank rather than into the channel. In such circumstances, it may be better to acquire imagery away from noon, even though solar elevations will be lower. The potential causes of shadows can be identified using the same GIS/remote sensing datasets that can be used for investigating line-of-site issues, and the likely locations of shadows can be predicted using readily available algorithms (see Section 10.2).

Preflight checklist. Pre-flight checklists, conducted immediately before UAV operation, ensure greatest chance of a safe and effective UAV flight. Safety is particularly important when imaging rivers because of the likely presence of infrastructure or people. Avoiding crashes is also particularly important because of the greater likelihood of destroying the UAV and camera when crashing into a water body. A sample checklist is shown in Table 6.

Table 6. Sample pre-flight checklist for safe UAV surveys.

Term	Task
Mission planning	Plan and document all actions and contingencies
	Share mission plans and flight plans with all operators
	Ensure waypoints for automated flight are set (if applicable)
	Obtain flight permission and notify owners and bystanders
	Identify or add ground control points to site
Mission operation	Ensure satisfactory weather conditions
	Discuss flight plans
	Identify take-off and landing zone
	Check for potential alternative landing sites
	Insert batteries and activate UAV and transmitter
	Inspect equipment 1. rotor mounts and rotors 2. camera lens and settings 3. batteries in UAV and transmitter 4. warning systems 5. remote control transmitter
	Ensure adequate telemetry connection
	Ensure line-of-site between operator and UAV
	Flight • Avoid no-fly zones from infrastructure and protected areas • Avoid people, animals, trees, power lines
	Land and deactivate UAV and transmitter
	Remove batteries from UAV and transmitter

7.3.2 Image generation

Individual UAV images cover limited spatial extents, especially if acquired from a platform near to the surface and/or with a camera with a narrow FOV, so it may be necessary to merge multiple images to map the stretches of interest. A wide variety of packages can be used for stitching, construction of orthomosaics, or construction of DSMs. Simple stitching of images requires rotation, offsetting and affine transformations so that image features overlap. SfM approaches, used for orthomosaic or DSM construction, involve many more computational procedures, including creation of a point cloud (a 3D structure consisting of the coordinates generated from the imagery), followed by the construction of a mesh, and then the superimposition of imagery onto the mesh. Depending on the software, point cloud construction can be improved by the inclusion of image geolocations. A range of packages are available. Here we detail the free / open source packages with which we have experience: Image Composite Editor and OpenDroneMap.

Image Composite Editor. The simplest method for merging images is to use Image Composite Editor (ICE) (Microsoft) (https://www.microsoft.com/en-us/research/product/computational-photography-applications/image-composite-editor/). This does not produce orthorectified maps but merely aligns images via offsets and rotation through pattern matching and then merges them together, and stitched images may include artefacts from the stitching process. Pre-processing of UAV images to reduce geometric distortion, such as removal of barrel distortion (see Section 10.3), may minimize the presence of artefacts in the stitched image. ICE is useful as a quick and easy method to produce stitched images for qualitative investigation, and it is possible to subsequently orthorectify ICE images using a GIS if GCPs are available. When georegistering to *Norge i bilder* imagery, it is recommended to examine all *Norge i bilder* images of the study site to identify the image which has the most similarity to the stitched UAV image.

OpenDroneMap. OpenDroneMap (https://www.opendronemap.org/) is an ecosystem of applications designed to process, analyze and display aerial photographs. It is based on ODM, the processing engine, but includes a variety of other applications, such as WebODM, a user-friendly interface. It offers a range of features: SfM, meshing, texturing, georeferencing, DSM production, orthomosaicing, and post-processing. Georeferencing relies on image geolocation information, or in the absence of this, on user-determined GCPs. Processed data can be viewed as 2D orthomosaics or 3D views, and can be exported for use in GIS packages. For a computer with 16 GB RAM, it is recommended that the number of images is limited to 100-200, but this will be sufficient for most UAV-surveys. This offers an inexpensive competitor to commercial packages (and is the one we recommend).

When using an SfM approach to generate orthomosaics or DSMs, attention should be paid to the imaging system, the image coverage, and the optical properties of the feature being imaged to minimize potential errors. Unsuitable camera characteristics and/or view positions and complicated image properties (e.g. the presence of a land-water boundary or shadows) may lead to errors in orthomosaicing. Figure 57A shows a poorly constructed (and obviously incorrect) DSM resulting from surveying a long reach using a GoPro camera which lacked image georeferencing and had a wide FOV with associated barrel distortion in individual images. This resulted in a deformed point-cloud and DSM. Figure 57B shows a DSM where there is high geometric distortion, with the surface curving upward around the edges. Images were only taken along a strip in the central line of the channel, and geometric errors increased with distance away from this line. To minimize this distortion, we recommend using a camera with GPS georeferencing ability and a narrow FOV, and ensuring a sufficiently broad coverage of the area of interest with images taken from beside the channel as well as immediately above. DSM errors may be caused by the optical properties of the study area. Figure 57C shows a DSM where the elevations do not perfectly correspond with surface morphology. For example, the elevation contours cross the boundary of the dewatered bank and the water-covered channel (where elevation should be non-varying, so a generated elevation contour crossing this boundary indicates that something is incorrect). Figure 57D shows a DSM where shadows lead to errors in estimated elevation across the water surface. Minimizing problems resulting from land-water interfaces may be difficult because

SfM software is not designed to deal with this. It may however be possible to minimize problems from shadow by better selection of imaging time.

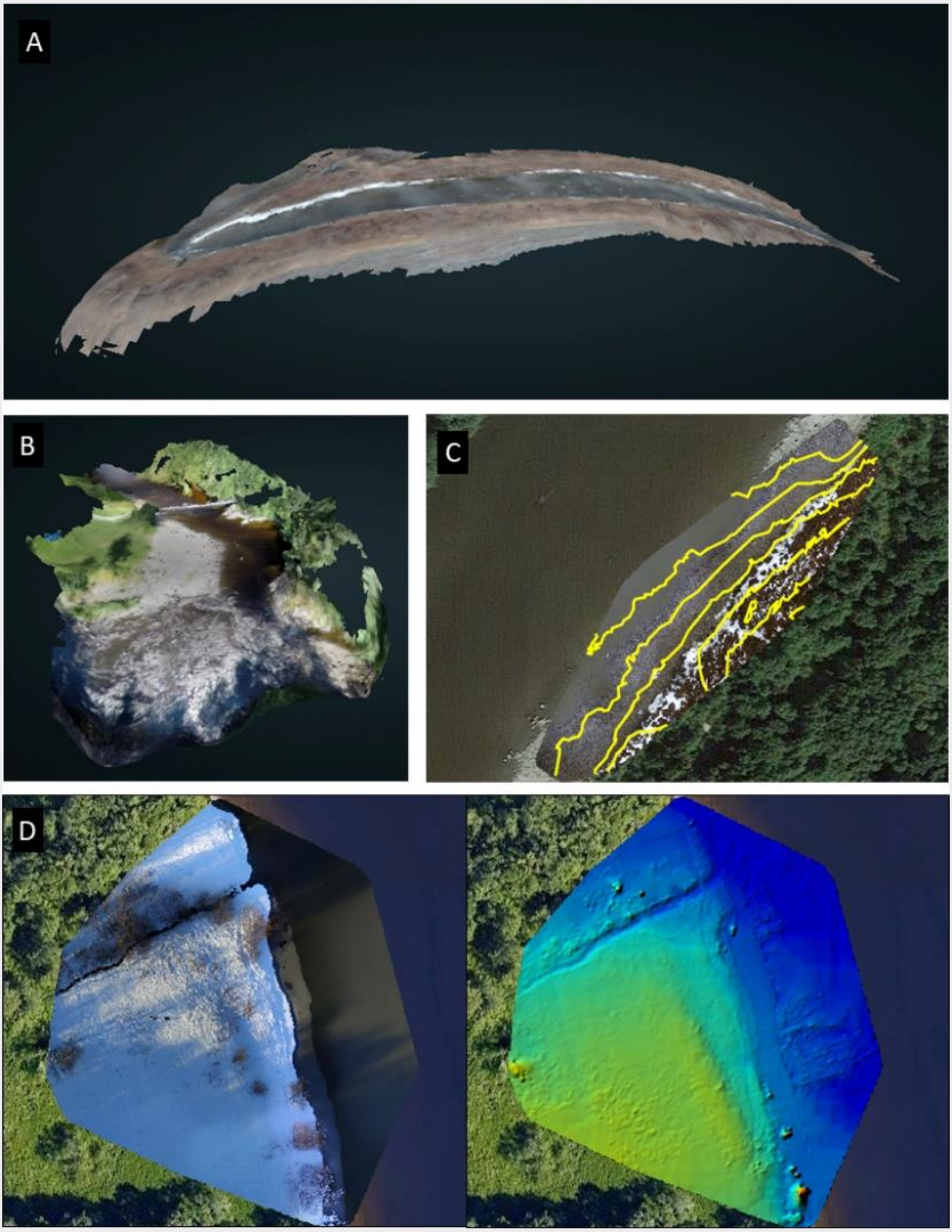

Figure 57. Examples of errors associated with SfM-based generation of DSMs: (A) distortion caused by camera barrel distortion in images without GPS-encoding; (B) distortion at the edges of the area imaged; (C) incorrect estimates of surface elevation across a dewatered/watered interface; (D) incorrect estimates of surface elevation from shadows. All DSMs were created in OpenDroneMap. In (C), yellow contour lines show elevations at 0.5 m intervals.

7.3.3 Image enhancement, interpretation and analysis

The image enhancements that should be applied will depend on the type of information that is desired to be extracted. As a first series of steps, some of the following can be recommended:

Crop images to remove sunglint and reflections. Before orthorectification, imagery may be cropped to remove sunglint and reflections from clouds and riparian vegetation on the water surface. The fact that the positions of these within the images will vary depending on view angle means that it may be possible to produce stitched images or orthomosaics were these have been removed. Imagery should be taken with sufficient overlap to allow removal but ensure a continuous coverage.

Correct geometric distortion. Geometric distortion increases with proximity of the imaging platform to the surface being imaged and with camera FOV (other things being equal). If a surface is being reconstructed using SfM ortho-rectification software, this distortion will be removed automatically. Alternatively, it is possible to manually reduce geometric distortion (Section 10.3).

Crop images to remove areas outside the watercourse. In circumstances where the study is only interested in what occurs within the watercourse, imagery can be cropped. Approximate watercourse boundaries may be obtained from *N50 Kartdata*. These polygons may be overlaid on the UAV imagery in GIS software and manipulated so that they correspond to the watercourse. Features outside the polygon can then be cropped.

Examine differences among image color channels. Band (color channel) ratios may be useful in examining depth, or identifying reflections or shadows on the water surface. For some applications, some channels may be uninformative: blue and green color channels are less useful for extraction of detail on the riverbed than the red channel due to scattering, so can potentially be discarded in studies of riverbed substrate size.

Examine image saturation and contrast. Increasing image saturation has the potential for delineating between dry and wetted sand bars. Contrast can be stretched so that features are more identifiable, which is particularly useful in deeper, and darker parts of the river channel.

Sharpen imagery. A range of procedures (e.g. high-pass filters) can be used to enhance image texture. Image sharpening will be more useful for enhancing habitat characteristics in UAV images than *Norge i bilder* images because the high resolution of UAV images provides the ability to detect fine-scale detail (e.g. individual gravel grains, spawning sites). These may be blurred by light diffusion within the water column, and image sharpening may improve the ability to resolve them.

A wide range of methods exist for interpretation and analysis of UAV imagery. These include methods that can be applied to *Norge i bilder* imagery (see Section 7.2.3 and 7.2.4). In addition, the multi-angle views afforded by UAVs allow for improved ability to determine 3D structure (channel bathymetry, riparian vegetation), so SfM should be applied when using UAVs. Additionally, the high resolution allows for easier quantification of substrate size. For instance, with respect to grain size identification from image segmentation, Sime & Fergusson (2003) found that the method was unreliable for grains smaller than 5 × 5 pixels, and Graham et al. (2005a) concluded that the smallest grain of interest should have a β-axis (second longest axis) of 23 pixels. Grain size determination is therefore more suitable to UAV imagery where pixel resolutions in the order of several mm can be achieved.

7.4 Integrating *Norge i bilder*, UAV and GIS data

Norge i bilder and UAV imagery can be viewed as complementary approaches that provide respective potentials and limitations with regards to the execution of the remote sensing survey (Table 7) and the type of habitat information provided (Table 8). *Norge i bilder* provides large-scale coverage, but only provides snapshots separated by long time intervals and imagery is often sub-optimal in terms of quality. UAVs offer high quality imagery, obtainable with high flexibility, but do not have the range to survey a whole river, or to look at the history of the river.

Table 7. Comparison between Norge i bilder and UAV surveys: operational aspects.

Operational aspect	*Norge i bilder*	UAV
Maximum range	Unlimited	100-200 m per flight
Cost	Free (to end user)	Cheap
Flexibility in mission planning	Low	High
Image quality	Low	High
Legal restraints to imaging	Low	Moderate
Ease of ground-truthing	Low	High
Susceptibility to cloud cover	High	Moderate

Table 8. Comparison between Norge i bilder and UAV surveys: resolvable information.

Feature	*Norge i bilder*	UAV
Flow	Main features (waterfalls, rapids, glides)	Main features plus velocimetry
Depth	DN-based determination	DN or photogrammetry-based determination
Substrate size	Delineation between coarse classes (gravel banks, boulders)	Measurement of grain size from gravel upwards
Spawning sites	Non-identifiable	Identifiable
Channel profile	Qualitative determination from single images Quantitative determination from images at different discharges	SfM-based 3D mapping
Habitat	Watercourse mesohabitat classification	Within-mesohabitat variation

For many studies, it will be beneficial to use both approaches to exploit their relative advantages. UAVs can be used to supplement *Norge i bilder* aerial photographs in a variety of ways:

Examining locations of special interest. Locations of special interest can be examined within the watercourse using UAVs. Such locations might include spawning sites, sites where habitat remediation has been applied, electrofishing sites etc. UAVs allow for observation of such locations at a higher spatial resolution, under a more optimal light environment, and allow repeated observation of the location so that short-term temporal changes can be identified.

Extending the image window. UAVs allow images of the watercourse to be acquired in winter when *Norge i bilder* imagery is typically unavailable, or under conditions of overcast skies when *Norge i bilder* imagery is never available.

Rapid repeat imaging. Rapid, repeat imaging of the river by UAVs allows for better determination of short-term variation: e.g. water-covered area during a hydropeaking cycle.

Increasing the observation frequency. The observation frequency of *Norge i bilder* imagery may be quite low, sometimes with several years between successive images. The use of UAV surveys allows collection of novel data allowing the update of information from the most recently acquired *Norge i bilder* image.

Imaging during optimal flow conditions. UAV surveying of the river at low discharges increases the ability to resolve substrate. At low discharges, the proportion of the riverbed that is dewatered increases, allowing for best determination of substrates, and water depth is reduced in water-covered areas, reducing consequent scattering and attenuation, and making it easier to obtain information on submerged substrates.

Imaging during optimal light conditions. The flexibility of UAVs allows for easier control of the ambient light environment during image acquisition. Imaging can be conducted so that topographic and riparian shadow on the watercourse is minimized.

All relevant *Norge i bilder* imagery should be downloaded and assessed before collection of new UAV imagery. This allows identification of limitations (e.g. areas with insufficient resolution to identify habitat features, areas where shadow is obscuring the habitat) that can be addressed by UAV surveys. For efficient processing, researchers should ensure that all data have the same Coordinate Reference System (CRS), and transform datasets to the same system if necessary. This applies to *Norge i bilder* images, UAV images, associated GIS datasets and GPS georeferenced ground survey data, which will often be registered with different systems. It is recommended to use the *ETRS89* geodetic CRS rather than the *WGS84* Geodetic CRS (e.g. 25833 should be used rather than 32633) because the former is more accurate for Europe. When working with local data, it is more accurate to use a CRS for the UTM zone of the location under investigation. For example it is recommended that researchers use 25832 (UTM zone over western Norway), 25833 (UTM zone over central), 25834 (UTM zone over eastern Norway) for rivers within UTM zones 32, 33 and 34 respectively, rather than to use 25833 (which is often the default for data within Norway) for all zones.

Ancillary GIS and remote sensing datasets (see Section 7.2.2 and Section 10.1) can be integrated with the *Norge i bilder* and UAV data, enabling better interpretation of the habitat and better understanding of influences upon it. Construction of DSMs from UAV imagery is typically done using SfM from the images, but in cases where this is unsuccessful, it may be possible to drape the UAV imagery over a LiDAR DSM (Figure 58).

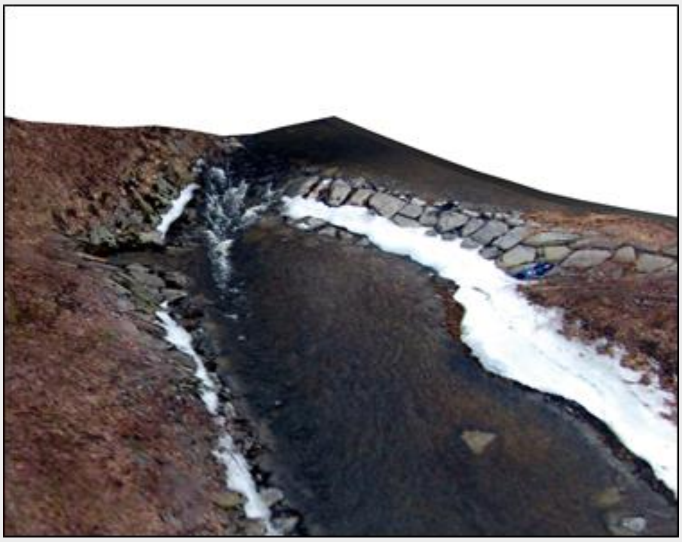

Figure 58. UAV image of the River Børsa (122.1Z) draped over a 1 × 1 m DSM. NB: the z-scale has 2× magnification.

Integrated datasets can be presented in a variety of ways. Oblique-angle views of *Norge i bilder* imagery draped over a DTM, with inlet panels of UAV images showing high resolution detail at sites of special interest, can provide an easily interpretable view of a river stretch (Figure 59A).

Alternatively, geo-registered maps of UAV images of areas of special interest, superimposed on *Norge i bilder* imagery of the surrounding area, with superimposed ancillary data (such as elevation contours) may show both detailed information within sites and the surrounding context for processes occurring within these sites (Figure 59B).

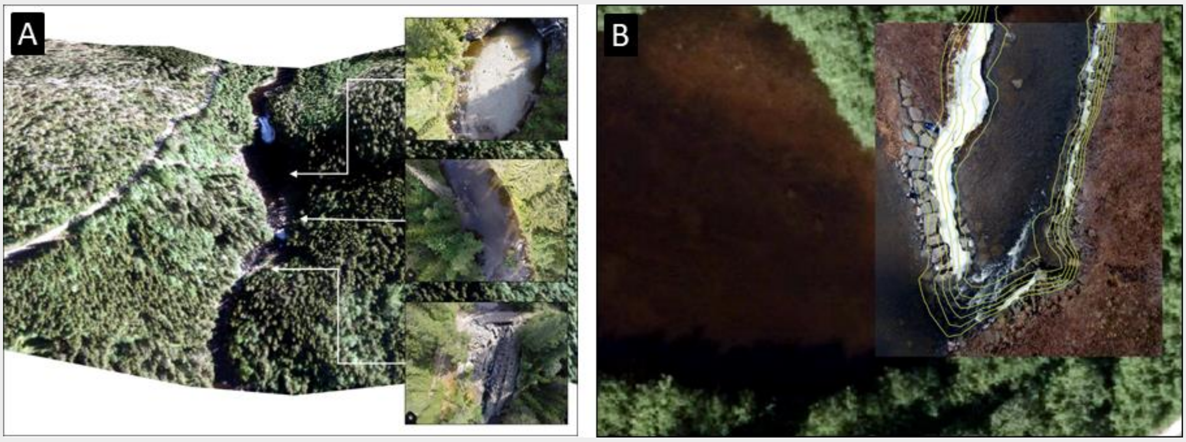

Figure 59. Integration of airborne surveys with GIS data: (A) Norge i bilder image of the River Nævre (123.4Z) draped over a DTM; (B) UAV and Norge i bilder images of the River Børsa (122.1Z). In (A), side panels show UAV images; in (B), contours are at elevation differences of 0.1 m.

8 Conclusion

Aerial photography, either by high altitude aircraft or low elevation UAVs, is a valuable tool suitable for surveying Norwegian Atlantic salmon habitat, with the potential to provide information that extends over large spatial ranges that would be difficult to obtain through ground sampling. The scales over which Norwegian Atlantic salmon habitat vary, both spatially and temporally, are appropriate for aerial surveys, although the optimal surveying technique (from high altitude aircraft or UAVs) will depend on the research objective. However, the ability to obtain useful information from aerial surveys is dependent on the extent to which the multiple confounding factors associated with imaging in a generally poor light environment are accounted for, both during image acquisition and during subsequent image processing. With respect to surveying Norwegian Atlantic salmon habitat, we (1) summarize the main capabilities and limitations of *Norge i bilder* and UAV surveys, (2) outline their main potential areas of application, and (3) suggest how the use of aerial photo surveys can be optimized.

Capabilities and limitations. The two approaches offer markedly different capabilities and have markedly different limitations (Table 9). The *Norge i bilder* archive of aerial photographs provides riverscape overviews. It allows examination of how the habitat has changed historically, and offers the ability to cover the entire riverscape, allowing the watercourse to be analyzed in its entirety and, if necessary, to be compartmentalized into distinct mesohabitats, reaches, or links. However, from the perspective of a NINA researcher, the approach may be limited in terms of (1) spatial resolution and image quality, and (2) image availability. Spatial resolution may be too low (e.g. to discern spawning redds or substrate types). Image quality may be poor (e.g. shadows from topography or trees obscuring features) because images are not acquired prioritizing a perfect light-environment for rivers. Image availability may be an issue: with potentially gaps of years between successive images, short-term changes are missed; and a lack of imaging during winter prevents assessment of winter habitat. In contrast, UAVs provide detailed information but lack spatial range. UAVs can provide study site information – the type of information lying between the scale of a traditional high altitude aerial photo survey and ground sampling. They are useful for resolving the variation within the mesohabitat, and provide fine-scale information that can be used in, for instance, substrate size determination. They provide a high operational flexibility to the end user, so can target features of interest, and allow images to be acquired during optimal light conditions. However, they are not practical over distances of more than ≈ 1 km, and flight restrictions may hinder their use. Limitations in one approach may be compensated for by a capability in another. For example, UAVs may be used to obtain information during the long gaps between *Norge i bilder* surveys, or to provide high spatial resolution data in sites of special interest; *Norge i bilder* surveys provide large-scale data that can put the UAV “study site” data within context of the surrounding environment.

Table 9. Characteristics of Norge i bilder and UAV data.

Characteristic of image source	***Norge i bilder***	**UAV**
Spatial extent	**Large (complete river)**	**Short (100-1000 m)**
Spatial resolution	**Intermediate (≈0.1 m)**	**Fine (≈0.01 m)**
Temporal extent	**Long (1930s +)**	**Short (2010s +)**
Image quality	**Sub-optimal**	**Optimal**
Repeat frequency of imaging	**Very low (years)**	**Very high (minutes)**
End-user (NINA) control on imaging	**None**	**High**
Flight zone restrictions	**Absent**	**Small**

Areas of application. The different capabilities and limitations of the two approaches mean that they have different areas of application to surveying Norwegian Atlantic salmon habitat (Table 10). Large-scale studies – those looking at historical changes or dealing with the complete watercourse – are obviously more suitable to *Norge i bilder;* small-scale studies, requiring high-resolution or high-frequency imaging, are more appropriate for UAVs. Some studies – such as surveying very narrow tree-lined streams or looking at winter habitat – can only be conducted using UAVs. In many cases, a combination of the two approaches is recommended.

Table 10. Atlantic salmon habitat applications for Norge i bilder and UAV images.

Application	Suitability	
	Norge i bilder	UAV
Historical studies of watercourses	**Yes**	**No**
Segmenting watercourses into sedimentary links	**Yes**	**No**
Segmenting watercourses into mesohabitat	**Yes**	**No**
Surveying large rivers	**Yes**	**Limited**
Surveying along-channel profile	**Yes**	**Limited**
Surveying riparian vegetation	**Yes**	**Yes**
Monitoring contemporary changes (e.g. dam removal, flow change, channel modification)	**Limited**	**Yes**
Surveying small channels	**Limited**	**Yes**
Surveying cross-channel profile	**Limited**	**Yes**
Surveying within-channel vegetation	**Limited**	**Yes**
Microscale studies (e.g. quantification of substrate size, detection of redds)	**No**	**Yes**
Surveying winter habitat	**No**	**Yes**
Surveying narrow tree-lined streams	**No**	**Yes**

Optimizing the use of aerial photo surveys. Limitations on extracting information on Atlantic salmon habitat from aerial photo surveys can be partly compensated for by careful UAV survey planning, image processing and data integration:

- **UAV surveys.** UAVs offer enormous potential for microscale to mesoscale studies, but best results are reliant upon having a carefully planned survey. In particular, it is necessary to pay attention to acquiring imagery under the best light-environment possible, and to pre-plan flights carefully to obtain sufficient spatial resolution, and to obtain sufficient image overlap and image coverage to enable successful orthomosaicing of images.
- **Image processing.** Firstly, Structure from Motion (SfM) enables full utilization of the multiple view angles provided by UAVs and should be the default approach when mapping Atlantic salmon habitat with UAV surveys. Secondly, remote sensing image processing methods have developed markedly over the last decade. The older approaches such as band ratios and texture quantification may be limited for analysis of rivers due to the presence of confounding factors such as topographic and riparian shadows. However, a range of machine learning approaches are now available (e.g. TensorFlow + Keras) which should be further utilized because they have the potential to improve the analysis of aerial photo survey imagery, particularly for “noisy” *Norge i bilder* images.
- **Data integration.** Over the last two decades, there has been a massive expansion in the availability of remote sensing and GIS data, alongside software tools for accessing and integrating them. Data integration is key for synoptic studies. We have shown, in particular, that when using *Norge i bilder* and UAVs together, limitations in one approach can be compensated for by a capability in the other. And we have shown that alternative GIS and remote sensing data sources provide valuable information. In particular, as the coverage of green LiDAR expands across Norway, there is increased opportunity to directly and accurately extract habitat depth. Additionally, access to high resolution satellite imagery is becoming increasingly available. These new remote sensing data sources require further integration and utilization in future habitat studies.

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10 Appendix

10.1 Ancillary remote sensing and GIS datasets

A range of GIS datasets are available which can be integrated with aerial photo survey data. Some of those used in this report are listed in Supplementary table 1.

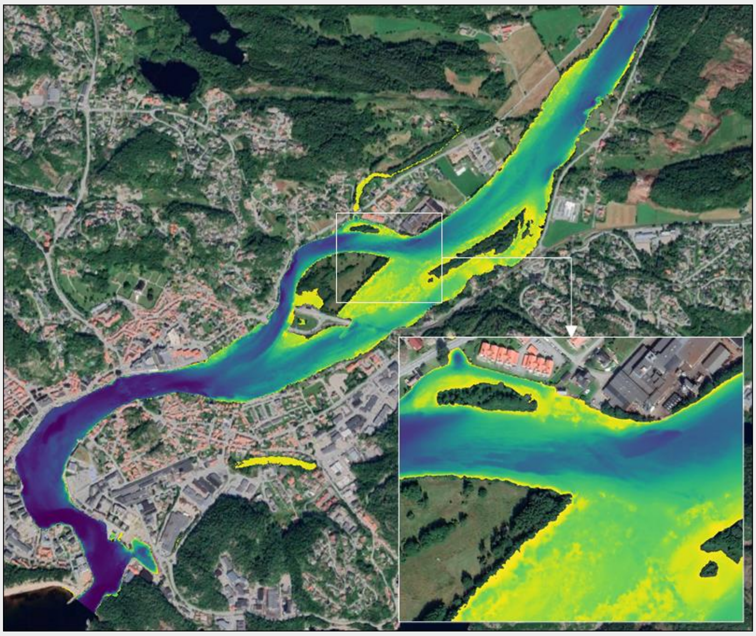
Supplementary table 1. Ancillary remote sensing and GIS datasets

Type	Type (resolution)	Source: dataset name
Watercourse centerlines	Polyline	*Norge vassdrags- og energidirektorat* (*NVE*): nve-Elvenett
Watercourse boundaries	Polygon	*Kartverket*: N50 Kartdata
Salmon supporting reaches	Online	*Miljødirektoratet* Lakseregisteret https://lakseregisteret.fylkesmannen.no/
Discharge, temperature and ice presence time series	Txt files	*NVE*: https://www.nve.no/vann-og-vassdrag/hydrologiske-data/
LiDAR elevation	Raster (1-50 m) LAZ point cloud	*Kartverket*: høydedata https://hoydedata.no/LaserInnsyn/
Superficial deposits "løsmassekart"	Vector	*Norges geologiske undersøkelse* (*NGU*) https://www.ngu.no/emne/datasett-og-nedlasting
River Lake Ice Extent	Raster (20 m)	*Copernicus* (EUs Earth Observation Programme) https://land.copernicus.eu/

There has been increasing application of LiDAR to environmental research in Norway (see Erikstad & Bakkestuen 2017). LiDAR data, available through the Høydedata portal, have proven to be the most useful additional remote sensing data type for integration with air photo survey data in this report. Data are available in the form of point clouds (LAZ files including X, Y, and Z geo-positions) and raster datasets derived from the point clouds. Raster dataset types are (1) a Digital Surface Model (DSM) of the elevation of the surface including surface features such as trees and buildings, and (2) a Digital Terrain Model (DTM) of the elevation of the terrain, with these surface features removed. LAZ point clouds can be processed in (1) QGIS using the *LAStools* plugin which utilizes the LAStools software (*rapidlasso GmbH*), a limited form of which is free for use and in (2) R using the *rlas* library.

Near-infrared (NIR) LiDAR. Near-infrared (NIR) LiDAR data (use for terrestrial mapping) are available across Norway. DTM data can be used to estimate channel elevation and longitudinal profile, and have been used in mapping of migration barriers in streams (Hedger et al. 2020). Additionally, subtraction of the DTM from the DSM may be used to estimate the height of riparian vegetation, which may be used in investigating line-of-site issues and shadows.

Green LiDAR. Data from green LiDAR (used for aquatic mapping because it can penetrate water bodies) are only available for a small number of Norwegian rivers. Supplementary figure 1 shows a bathymetric map of part of the downstream watercourse of the River Mandalselva derived from green LiDAR data (*NVE* Project NR 201603593). It shows the suitability of green LiDAR for underwater mapping, with the caveat that the presence of submerged macrophytes on the riverbed (evident by the stippled pattern in the close-up panel) may reduce the accuracy of depth estimates.



Supplementary figure 1. Bathymetric DEM as derived from a green LiDAR survey of the River Mandalselva (022.Z) near the outlet. The color scheme ranges from dark blue (< -17 masl) to yellow (≈ -2 masl).

10.2 R libraries useful for data processing

A range of R libraries are available for processing geospatial data. Some of the most useful libraries are listed in Supplementary table 2.

Supplementary table 2. R libraries useful for the processing of remote sensing and associate data.

Package	Use
sf, sp, terra, raster, stars	Spatial classes (NB: sf and terra are recommended due to continued development after 2023)
dplyr, rmapshaper	Process attribute tables / geometries
rnaturalearth, osmdata, getSpatialData	Spatial data download
rgrass7, qgisprocess, RSAGA, link2GI	Connect with GIS software
gstat, mlr3, CAST	Spatial data modelling
rasterVis, tmap, ggplot2	Static visualization
leaflet, mapview, mapdeck	Interactive visualization
oce, insol, suncalc	Prediction of solar elevation, solar insolation, and shadows
spatstat, spdep, spatialreg, dismo, landscapemetrics, RStoolbox, rayshader, gdalcubes, sfnetworks	Specialized packages useful for processing georegistered data
Rlas	Processing LAZ point clouds
neuralnet	Deep learning

10.3 Routines for UAV image dimensioning and distortion reduction

Estimation of the area that will be covered from a single UAV image can be calculated from the properties of the UAV elevation and the camera. Geometric distortion (specifically barrel distortion) can be partially removed by transforming pixel positions as a function of their distance from the center of the image.

Estimation of image dimensions. Image dimensions (A and B) for a UAV looking perpendicularly at a flat surface (i.e. looking downwards) can be calculated from the UAV elevation above the surface and the UAV camera specifications as follows (see https://www.techforwildlife.com/blog/2019/1/29/calculating-a-drone-cameras-image-footprint):

$$A = \frac{2 \cdot h \cdot tan(\theta/2)}{\sqrt{(1+r^2)}} \tag{1}$$

$$B = \frac{2 \cdot r \cdot h \cdot tan(\theta/2)}{\sqrt{(1+r^2)}} \tag{2}$$

where h = UAV elevation above the surface, θ = angular FOV of camera and r = aspect ratio. Image resolution can be calculated by dividing the image dimensions by the respective numbers of image pixels.

Reduction of image distortion. Barrel distortion can be reduced by creating a new image, Img_{cor}, where the digital number (DN) for each x and y location is that of the DN of a given position, $x.ori$ & $y.ori$, in the original, distorted image
(see https://tannerhelland.com/2013/02/11/simple-algorithm-correcting-lens-distortion.html):

$$Img_{cor}[x, y] = Img_{ori}[x.ori, y.ori] \tag{3}$$

The original position is calculated as a function of a parameter related to the amount of distortion, θ, and the displacement between the location in the corrected image and the center of the image, i & j:

$$x.ori = X_{cen} + \theta i \tag{4}$$

$$y.ori = Y_{cen} + \theta j \tag{5}$$

where X_{cen} and Y_{cen} are the centers of the image. For a crude distortion removal, this parameter can be adjusted until the image appears to be less distorted (e.g. a straight road appears straight within the corrected image).

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NINA Report

The Norwegian Institute for Nature Research, NINA,
is as an independent foundation focusing on environmental research, emphasizing the interaction between human society, natural resources and biodiversity.

NINA was established in 1988. The headquarters are located in Trondheim, with branches in Tromsø, Lillehammer, Bergen and Oslo. In addition, NINA owns and runs the aquatic research station for wild fish at Ims in Rogaland and the arctic fox breeding center at Oppdal.

NINA's activities include research, environmental impact assessments, environmental monitoring, counselling and evaluation. NINA's scientists come from a wide range of disciplinary backgrounds that include biologists, geographers, geneticists, social scientists, sociologists and more. We have a broad-based expertise on the genetic, population, species, ecosystem and landscape level, in terrestrial, freshwater and coastal marine ecosystems.

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Norwegian Institute for Nature Research
NINA head office
Postal address: P.O. Box 5685 Torgarden,
NO-7485 Trondheim, NORWAY
Visiting address: Høgskoleringen 9, 7034 Trondheim
Phone: +47 73 80 14 00
E-mail: firmapost@nina.no
Organization Number: 9500 37 687
http://www.nina.no

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