Quantifying SSC variability in sediment-laden meltwater plumes using in-situ data and simulated satellite remote sensing bandwidths

Guy David Tallentire¹, Jeffrey Evans¹, Richard Hodgkins¹, and Eleanor F Darlington²

¹Loughborough University
²National Oceanography Centre

November 24, 2022

Abstract

Sediment-laden meltwater plumes are commonly observed in the fjords and coastal waters of Svalbard. Plumes are present at the margins of marine-terminating glaciers, and the mouths of glacier-fed subaerial rivers. They can influence fjord circulation, are useful proxies for meltwater runoff and can be used to infer a glacier’s hydrological system. Plumes often cover large areas of open water, meaning they are visible in satellite imagery. Passes by satellites provide an insight into what is occurring at a point in time, but satellite timeseries can also provide a longer temporal window than in-situ measurements. To determine how suspended sediment concentration (SSC) varies in plumes at two sites in Kongsfjorden, over three melt seasons (2012, 2019, 2021), we use in-situ and satellite-equivalent techniques. We find that SSC-reflectance relationships in a subaerial river plume are variable across three melt seasons, meaning relationships are not transferable from season-to-season. At a marine-terminating system, we find relationships remain stable across two melt seasons, however a small, non-significant dataset means there is low confidence in extrapolating these results. We also find that plumes from these subaerial and marine-terminating systems are not directly comparable due to differing geology and contrasting methods of meltwater delivery. Our findings suggest more research should be conducted into the relationship between SSC-reflectance at plumes in Svalbard, focussing on a system’s hydrology and lithology, whilst accounting for retreat at marine-terminating glaciers. Furthermore, new methods for interrogating cloud-impacted satellite scenes should be devised, reducing the reliance on short fieldwork windows for understanding plume variability.

Hosted file

Guy D. Tallentire¹*, Jeffrey Evans¹, Richard Hodgkins¹ and Eleanor F. Darlington²

¹Geography and Environment, Loughborough University, Loughborough, LE11 3TU, UK
²National Oceanography Centre, European Way, Southampton, SO14 3ZH, UK.

Corresponding author: Guy Tallentire (G.D.Tallentire@lboro.ac.uk)

Key Points:
- MODIS Band 2 and respective satellite bandwidths are a better tool for predicting SSC using in-situ reflectance than Band 1 equivalents
- Empirical relationships determined at the same site over three separate melt seasons are not temporally transferable
- Data from two separate sampling sites are not spatially transferable due to variable geology and contrasting meltwater delivery methods

Abstract

Sediment-laden meltwater plumes are commonly observed in the fjords and coastal waters of Svalbard. Plumes are present at the margins of marine-terminating glaciers, and the mouths of glacier-fed subaerial rivers. They can influence fjord circulation, are useful proxies for meltwater runoff and can be used to infer a glacier’s hydrological system. Plumes often cover large areas of open water, meaning they are visible in satellite imagery. Passes by satellites provide an insight into what is occurring at a point in time, but satellite time-series can also provide a longer temporal window than in-situ measurements.

To determine how suspended sediment concentration (SSC) varies in plumes at two sites in Kongsfjorden, over three melt seasons (2012, 2019, 2021), we use in-situ and satellite-equivalent techniques. We find that SSC-reflectance relationships in a subaerial river plume are variable across three melt seasons, meaning relationships are not transferable from season-to-season. At a marine-terminating system, we find relationships remain stable across two melt seasons, however a small, non-significant dataset means there is low confidence in extrapolating these results. We also find that plumes from these subaerial and marine-terminating systems are not directly comparable due to differing geology and contrasting methods of meltwater delivery. Our findings suggest more research should be conducted into the relationship between SSC-reflectance at plumes in Svalbard, focussing on a system’s hydrology and lithology, whilst accounting for retreat at marine-terminating glaciers. Furthermore, new methods for interrogating cloud-impacted satellite scenes should be devised, reducing the reliance on short fieldwork windows for understanding plume variability.

Plain Language Summary

Melting glaciers are raising global sea levels. In the Arctic, glacier melt combines with sediment, to form ‘sediment plumes’. These features can tell us about the
interior of a glacier and how it is responding to climate change. Sediment plumes can be viewed from space using satellites, but our understanding of them is primarily based on measurements collected in person. In our study we measured sediment concentration and surface reflectance at two sites: Bayelva and Blomstrandbreen in Kongsfjorden, Svalbard, over several melt seasons and compared this with wavelengths that various satellites measure in. We found that the correlation between sediment concentration and surface reflectance at Bayelva across three melt season was different and could not be compared. The correlations between two datasets from Blomstrandbreen were similar, but data collected in 2019 was from a single day reducing our confidence to compare them. We also found that different rock types and the way meltwater and sediment reach the fjord meant that the two sites could not be compared. Our study highlights the need for further field research of sediment plumes, and ways to remove clouds from satellite images, in order to better understand their behavior in space and time.

1 Introduction

The Arctic is warming at between two and six times the global average, resulting in the melting and retreat of glaciers and ice sheets throughout the region (IPCC, 2019; Wawrzyniak and Osuch, 2020), with the potential to rise sea level significantly (Overland et al., 2019; IPCC, 2021). In Svalbard, many of the glacier systems are marine-terminating, extending into fjords or coastal waters, with glacier fronts in some cases reaching many hundreds of metres below the water surface (Hagen et al., 1993; Blaszczzyk et al., 2009; Nuth et al., 2013; Lindbäck et al., 2018). However, these glacier systems are retreating and are expected to terminate on land within the next century (Torsvik et al., 2019). A transition to land-terminating glaciers will have various impacts upon: fjord circulation, marine biogeochemistry, glaciomarine sedimentation, and the wider Arctic ecosystem (Schuler et al., 2020; Hopwood et al., 2020; Meslard et al., 2018; Descamps et al., 2017). This transition will also result in significant topographic changes, including, increased fjord lengths and the expansion of proglacial areas (Hodgkins et al., 2009; Blaszczzyk et al., 2013; Grabiec et al., 2018).

Svalbard’s marine-terminating glaciers release large volumes of meltwater during the summer melt season. This meltwater entrains sediment before being discharged at the glacier’s grounding line into fjords or coastal waters where they are expressed as sediment-laden meltwater plumes which are buoyant and spread laterally across the water surface (Mugford and Dowdeswell, 2011; Hewitt, 2020). Much the same process is seen at subaerial rivers on the archipelago, very often fed from partially glacierized catchments with small cold-based or polythermal glaciers (Repp, 1988; Bogen and Bønsnes, 2003; Nowak and Hodson, 2013). When the sediment-laden meltwater reaches the coast, it is instead discharged directly onto the water surface, also resulting in a sediment-laden meltwater plume, albeit often at a smaller scale (e.g. Dowdeswell and Cromack, 1991; Chu, 2014). Sediment-laden meltwater plumes are very good proxies for meltwater runoff and can be used to better determine the hydrological sensitivity
of both terrestrial and marine-terminating glaciers to increasing global temperatures (McGrath et al., 2011; Chu et al., 2012; Schild et al., 2016). They have been comprehensively studied throughout the Arctic (e.g. Chu et al., 2009), pan-Arctic (Hodgkins et al., 2016) and in Svalbard (e.g. Schild et al., 2017) using a combination of field-based and remote sensing studies. More recently, given the marked increase in the availability of remote sensing data from private companies (e.g. Planet Team, 2022) and non-satellite sources, on top of that already provided by space agencies (McCabe et al., 2017), it has become far easier to study the variability of these phenomena in space and time remotely. As well as an uptick in platforms, there have been improvements in the spatial and temporal resolution of the data, which for a region like the Arctic where cloud cover can be an impediment to observation-based studies (e.g. Marshall et al., 1993) improves the likelihood of a cloud free pass and greater time series data. Superior spatial resolution is also highly beneficial when working with features such as sediment-laden meltwater plumes, which can be difficult to resolve when using lower resolution optical imagery such as that provided by the Moderate Resolution Imaging Spectroradiometer (MODIS) (500 m) instrument compared with ultra-high resolution (3 m), sub-daily imagery available from Planet Labs (hereafter, ‘Planet’).

In this paper we use in-situ measurements from three field seasons (2012, 2019 and 2021) and apply simulated satellite remote sensing bandwidths from several public and commercial platforms to better understand the empirical relationships between SSC and surface reflectance (L) at two contrasting sediment-laden meltwater plumes in Kongsfjorden, Svalbard. By determining these relationships, we can better establish the volumes of sediment being transported by glacier-fed rivers and marine-terminating glaciers, which is then expressed on the fjord surface, through the use of satellite remote sensing. We also show how different satellite remote sensing platforms can influence empirical relationships and discuss their impact in retrieving SSC from reflectance in space and time. Furthermore, we describe when sediment-laden meltwater plume (hereafter also referred to as ‘plumes’) onset and shutdown occurs across each melt season, to better understand their variability from year-to-year, and how this might impact upon sediment reaching the fjord, as global temperatures increase further with climate change.

2 Study Site and Methods

The study sites are situated in the Kongsfjorden region of Svalbard, in the northwest of the main island of Spitsbergen, where the two sites lie across the fjord from each other (see Figure 1). The, the first is the Bayelva River which drains two cold-based terrestrial glacier systems, Austre and Vestre Brøggerbreen, which cover ~50% of the 32 km² Bayelva catchment (Bogen and Bonsnes, 2003 and Nowak and Hodson, 2013; 2014). The glacier-fed river flows across the Brøggerhalvøya peninsula, initially over a small floodplain before being constrained by a narrow bedrock channel; it flows into the southern side of Kongsfjorden close to the international research station at Ny-Ålesund, forming
the Bayelva River sediment-laden meltwater plume. The second site is Blomstrandbreen on the northern side of Kongsfjorden is a small marine-terminating glacier, draining an area ~80 km$^2$, with multiple tributaries, the glacier flows southwest into Kongsfjorden into a small embayment that is separated from the main section of the fjord by Blomstrandhalvøya, an island, previously thought to be a peninsula (Sund and Eiken, 2010, Mansell et al., 2012; Burton et al., 2016). The Blomstrandbreen sediment-laden meltwater plume enters the fjord directly from below the partially submerged bed of the glacier.

1. Main image: RGB Landsat 8 image (06/07/2021) of the northwest of Spitsbergen, the largest island of the archipelago of Svalbard, including Kongsfjorden and its surrounding glaciers. Landsat 8 image courtesy of the U.S. Geological Survey. Top right: Study location highlighted relative to the archipelago of Svalbard. Map courtesy of OpenStreetMap contributors’ data available under Open Database License (licensed as CC BY-SA).

2.1 Field Methods

2.1.1 Suspended sediment sampling
Surface water samples were collected at two distinct locations in Kongsfjorden across three summer melt seasons between 2012 – 2021. The majority of samples were taken in the shallow waters of the Kolhamna basin, where the glacier-fed Bayelva River drains into the southern side of Kongsfjorden (Figure 2, Table 1). The additional sampling sites were the open waters between Blomstrandhalvøya and the margin of Blomstrandbreen, a marine-terminating glacier system, on the northern side of Kongsfjorden. Here samples were collected in 2019 and 2021 (Figure 2, Table 2).
2. RGB Planet image (27/07/2019) of a section of Kongsfjorden, NW Spitsbergen (Planet Team, 2022). The two red boxes highlight the main study sites. (a) The glacier-fed Bayelva River sediment-laden meltwater plume, draining into Kolhamna, southern Kongsfjorden and (b) the Blomstrandbreen sediment-laden meltwater plume draining into northern Kongsfjorden, between the glacier’s calving front and Blomstrandhalvøya (the large island situated to the south of the glacier and stretching out into the fjord).

**Table 1.** Surface water samples collected in Kolhamna, Kongsfjorden and the Julian days the samples were collected on.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total number of surface water samples collected</th>
<th>Day of year</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>22</td>
<td>195, 198, 201, 204, 206, 207</td>
</tr>
<tr>
<td>2019</td>
<td>48</td>
<td>187, 192, 197, 200</td>
</tr>
<tr>
<td>2021</td>
<td>129</td>
<td>170, 172, 173, 174, 175, 176, 179, 180, 182, 185, 186, 187, 188, 190, 191</td>
</tr>
</tbody>
</table>

**Table 2.** Surface water samples collected from open water between Blomstrandhalvøya and the margin of Blomstrandbreen and the Julian days the samples were collected on.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total number of surface water samples collected</th>
<th>Day of year</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>10</td>
<td>194</td>
</tr>
<tr>
<td>2021</td>
<td>72</td>
<td>174, 179, 186, 189, 191</td>
</tr>
</tbody>
</table>

Suspended sediment samples were taken at regular intervals along transects of varying angles from the mouth of the Bayelva River, and parallel and perpendicular to the ice front of Blomstrandbreen during the 2019 and 2021 field campaigns. (see Figure 3). In 2012, a sampling grid was employed where each of the points were revisited on the respective sampling days (Figure 3). Sampling locations at each site were both inside and outside the sediment-laden meltwater plume in areas with limited or no floating ice. The sampling periods covered episodes of both high and low meltwater runoff in each of the three summer melt seasons. Samples were taken by hand from the surface layer of the fjord over the side of a Polarcirkel boat at the point furthest from the outboard motor, to avoid disturbance of the sediment layer. In all cases a GPS unit was used to acquire an accurate position of where a sample had been collected.
3. Example surface water and reflectance sampling locations from each of the three field campaigns. (a) The sampling grid was used in 2012 and revisited on each of the six days measurements were taken in the Kolhanna basin. (b) Sampling locations during the 2019 field campaign in the same area as in panel (a), measurements were also made here using the same method during 2021. (c) All sampling locations distal and proximal to the Blomstrandbreen margin during the 2021 field campaign. For further details on the sampling methods, see text.

All samples were filtered in the laboratory using a Nalgene Filter kit and vacuum pump. Each filter paper (47 mm diameter, 0.45 m ashless, cellulose nitrate membrane) was weighed before and after filtration using a 1.00 × 10⁻⁵ g precision balance. SSC was then calculated in g L⁻¹.

2.1.2 In-situ surface reflectance measurements

At each position a surface water sample was collected (Figure 3), spectral reflectance was measured using a FieldSpec HandHeld 2 Spectroradiometer. The handheld spectroradiometer acquires raw digital number (DN) surface measurements that were calibrated before and after each measurement using a 92 mm, high-reflectance spectralon white reference panel. All measurements were made
from approximately 10 mm above the fjord surface, on the sunlit side of the boat. This meant that measurements of upwelling spectral radiance were not affected by shadow. However, with all in-situ surface reflectance measurements being taken above the water surface, the values from the measurements include radiance from specular reflection. To further avoid the effects of variable imaging geometry and water surface motion including wave action during windier periods, multiple measurements (4 - 10) were made at each location that a surface water sample was collected.

2.1.3 Processing of in-situ reflectance measurements

Prior to analysis each reflectance profile was reviewed by manual plotting of data in a spreadsheet programme. Any erroneous data identified during this process was removed. Profiles were then averaged together to form one reflectance profile for each location in which a surface water sample was collected.

In-situ surface reflectance data were then correlated to in-situ SSC. After relationships between these two variables were determined, various linear and non-linear models were fit to the data. We opted not to alter the Line of Best Fit, for example, by log transform, or by setting the intercept of the linear model at 0, of any of our in-situ SSC and reflectance relationships for each of the melt seasons, as previous similar studies have done. The reason we use a standard linear model fit is to account for the fact that ambient fjord water has nonzero reflectivity, and as such, it is very unlikely there will be an occasion where both SSC and reflectance are equal to 0. Phytoplankton, among other biotic components of the ecosystem, along with the possible movement of the water surface through wave action, will likely be captured in in-situ reflectance measurements of fjord water, and therefore result in a value greater than 0 being recorded. We can provide evidence of this through our surface water samples from areas of ambient fjord water outside of the sediment-laden meltwater plumes, where small amounts of other suspended matter are captured during filtration (for further details see SSC in Table 4).

2.2 Remote sensing-based methods

2.2.1 Satellite remote sensing

Sediment-laden meltwater plume characteristics were extracted from various satellite derived surface reflectance data and optical imagery, varying in temporal and spatial resolution (Table 3). Cloud cover (see Section 4.4) impacted many of the images, and therefore the surface reflectance values, limiting the quality of data. Many of the cloud free images used throughout the study do not align with days when in-situ measurements were made, and therefore no direct comparison of in-situ and satellite reflectance is made, however we apply band designations from various satellites to our in-situ datasets.

MODIS on NASA’s Terra and Aqua satellites offers daily passes of the two study areas with seven bands in the visible and near-infrared at 500 m spatial resolution, and two bands at 250 m spatial resolution. Bands 1 and 2 of MODIS
250 m surface reflectance product (MOD09 and MYD09) (Vermote and Wolfe, 2015) corrected for atmospheric conditions e.g. gasses, aerosols and Rayleigh scattering were applied in this study.

Top of the Atmosphere (ToA) reflectance data from the Landsat 8 Operational Land Imager (OLI) were also utilized in this study, (Vermote et al., 2016). These data are limited by a 16-day repeat interval, although imagery is acquired at faster rates over the Polar Regions than previous Landsat missions (USGS, 2022). This data has significantly better spatial resolution of 30 m, than MODIS. For this study bands 4 and 5 are used, as these are the closest spectral band equivalents to MODIS bands 1 and 2. Very little Landsat 7 ETM+ data was available in 2012 as there were very few satellite passes that coincided with in-situ measurements, and none which were cloud or stripe free (USGS, 2022). Instead, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data were used as a cloud free pass coincided with the fieldwork period (NASA/METI/AIST/Japan Spacesystems and U.S./Japan ASTER Science Team, 2001). These data have a spatial resolution of 15 m and bands 2 and 3N/B in the Visible and Near-Infrared (VNIR) were used as these bandwidths compare well with MODIS.

Sentinel-2 MultiSpectral Instrument (MSI) Level-1C ToA data were also acquired for this study (Copernicus Sentinel-2, 2021). These data are limited to a 10-day repeat interval, with one satellite, but when data from the two satellites (Sentinel-2A and 2B respectively) is combined, this repeat interval is reduced to only five days. These two satellites provide three different levels of spatial resolution across their 13 spectral bands, with four bands in the visible and VNIR offering a very high spatial resolution of 10 m. There are six bands in the VNIR and Shortwave Infrared (SWIR) that have a 20 m spatial resolution. There are three bands in the visible, VNIR and SWIR that have a coarser spatial resolution of 60 m. For this study, Sentinel-2 bands 4 and 8 (10 m resolution) are utilized as their spectral bands fit most closely to those of MODIS bands 1 and 2. Sentinel-2 spectral bands are narrower than other satellite platforms. This limits the influence of atmospheric constituents, such as water vapour (ESA, 2015). Sentinel-2 also varies from other platforms in that each band has a central wavelength, i.e. 664.6 nm and a given bandwidth 20 nm, meaning there is slight variation between S2A and S2B. However in bands 4 and 8 this difference is less than 0.4 nm, we therefore assume their bandwidths to be the same in this paper.

Planet’s surface reflectance product has also been examined by this study. This product is derived from their standard Analytic product and is processed to ToA reflectance, prior to being atmospherically corrected to Bottom of the Atmosphere reflectance (Planet Team, 2022). PlanetScope (RapidEye) scenes were primarily used. These data have a fast repeat interval, with at least one overpass of the study areas each day, and have very high spatial resolution, of ~3 m. The red and near-infrared from the 4-band multispectral images were used as their bandwidths compare well with the MODIS equivalents. The data from Planet
are limited by a short temporal period (2017 – present) and by the Education and Research package which the authors used, in which a maximum of 5,000 km² of images can be downloaded each month.

Surface reflectance for MODIS, ASTER, Landsat 7 ETM+ and 8 OLI, Sentinel-2 and Planet sensors was calibrated using measurements collected in the field, through the development of an empirical relationship between in-situ reflectance and in-situ SSC. Field spectra were first compared with the spectral response of MODIS bands 1 and 2. Many previous studies (e.g. Chu et al., 2009; Hudson et al., 2014; Hodgkins et al., 2016) have found these bands to have the optimal response for distinguishing sediment-laden water from ambient fjord water. Based on the bandwidths of the MODIS sensors, the equivalent or closest bandwidths for the five alternative satellites were determined and applied. An empirical model was then developed to test and identify a best-fit regression model to relate the various satellite bands and their bandwidths to SSC.

<table>
<thead>
<tr>
<th>Sensor name</th>
<th>Bands used by study</th>
<th>Wavelengths of bands used (nm)</th>
<th>Spatial resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS</td>
<td>1, 2</td>
<td>620 – 670 and 841 – 876</td>
<td>250</td>
</tr>
<tr>
<td>ASTER</td>
<td>2, 3N/B</td>
<td>630 – 690 and 860 – 890</td>
<td>15</td>
</tr>
<tr>
<td>Landsat 7 ETM+</td>
<td>3, 4</td>
<td>630 – 690 and 770 – 900</td>
<td>30</td>
</tr>
<tr>
<td>Landsat 8 OLI</td>
<td>4, 5</td>
<td>640 – 670 and 850 – 880</td>
<td>30</td>
</tr>
<tr>
<td>Sentinel-2 MSI</td>
<td>4, 8</td>
<td>650 – 680 and 785 – 900</td>
<td>10</td>
</tr>
<tr>
<td>PlanetScope</td>
<td>3, 4</td>
<td>590 – 670 and 780 – 860</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3. Summary of the satellite remote sensing platforms used in the study, including their respective bands, wavelengths and spatial and temporal resolution.

2.2.2 The Google Earth Engine Digitisation Tool

The Google Earth Engine Digitisation Tool (GEEDiT) (Lea, 2018) was used in the study to determine the onset and shutdown of sediment-laden meltwater plumes at the two locations in-situ measurements were collected in 2019 and 2021, and to establish the timing of plume onset at other marine-terminating glaciers in Kongsfjorden. The tool was originally designed for the digitization of glacier margins, but now has a polygon tool (version 2.02), meaning that whole features can be digitized. GEEDiT also has the entire Sentinel-2 image series, meaning imagery at 10 m spatial resolution can be utilized when checking for the expression of sediment on the surface of the fjord. Further to this, it has a cloud cover filter (which was set to <20%), which can be used to reduce the number of images that require interrogation.

2.3 Additional datasets

2.3.1 Bayelva meltwater runoff

A monitoring station operated by the Norwegian Water Resources and Energy
Directorate (NVE) is located approximately 0.7 km from where the Bayelva River enters Kongsfjorden (Sund, 2008). The position of the monitoring station allows for measurements of all meltwater runoff from the Bayelva catchment, including glacier melt from both Austre and Vestre Brøggerbreen (Nowak and Hodson, 2013; 2014). The station consists of an artificial concrete flume, with a crump weir; water level is measured using a system which includes a float, counterweight and encoder, and data are stored on a logger (Zhu et al., 2016). Meltwater runoff is eventually calculated using a rating curve. In 2012, runoff data were collected between 15 June (167) and 1 October (275), and in 2019, between 24 June (175) and 1 November (305), as for the remainder of each year data collection was not possible either due to river flows not exceeding the height of the float or due to freezing over of the river system. In 2021, no data were collected at the station as a result of damage to the structure; thawing of the permafrost below the 0.5 – 1.5 m thick active layer that occurred during the 2020 melt season (Songe, pers. comm). These data have been used to better understand when meltwater runoff is flowing through the Bayelva catchment into the final section of river and to therefore determine melt onset and shutdown.

2.3.2 Meteorological data

A consistent meteorological dataset collected at the German-French Arctic (AW-IPEV) Research Station has been recording observations of air temperature, relative humidity, wind speed at 2 m, and air temperature and wind speed at 10 m in Ny-Ålesund, Svalbard since the late summer of 1993 (Maturilli et al., 2013; 2013; Maturilli, 2020). Meteorological data has been used in this study to understand when melt onset and shutdown takes place in the Kongsfjorden region. These data are available in separate tab-delimited text files for each month of the year during this 28-year period.

3.0 Results

3.1 Plume characteristics

The SSC of surface water samples collected across the three melt seasons at the Bayelva River sediment-laden meltwater plume ranged from 0.02 – 0.48 g L$^{-1}$. At the Blomstrandbreen sediment-laden meltwater plume, SSC collected in surface water samples in 2019 and 2021 ranged from 0.02 – 0.28 g L$^{-1}$ (Table 4). Reflectance at Bayelva also varied by melt season and location with a range of 0.01 – 0.43 in band 1, and 0.01 – 0.30 in band 2. In band 1 at Blomstrandbreen, reflectance ranged between 0.01 – 0.41, whilst in band 2, there was a small range of 0.01 – 0.12.

<table>
<thead>
<tr>
<th>Suspended sediment concentration (g L$^{-1}$)</th>
<th>Bayelva</th>
<th>Blomstrandbreen</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SSC$_{\text{max}}$</strong></td>
<td>0.18</td>
<td>0.29</td>
</tr>
<tr>
<td><strong>SSC$_{\text{mean}}$</strong></td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>SSC$_{\text{min}}$</strong></td>
<td>0.06</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Reflectance, 620 – 670 nm (L)
<table>
<thead>
<tr>
<th></th>
<th>Bayelva</th>
<th>Blomstrandbreen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2012</td>
<td>2019</td>
</tr>
<tr>
<td>Suspended sediment concentration (g L(^{-1}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(L_{\text{max}})</td>
<td>0.22</td>
<td>0.43</td>
</tr>
<tr>
<td>(L_{\text{mean}})</td>
<td>0.11</td>
<td>0.24</td>
</tr>
<tr>
<td>(L_{\text{min}})</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td><em>Reflectance, 841 – 876 nm (L)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(L_{\text{max}})</td>
<td>0.10</td>
<td>0.30</td>
</tr>
<tr>
<td>(L_{\text{mean}})</td>
<td>0.05</td>
<td>0.11</td>
</tr>
<tr>
<td>(L_{\text{min}})</td>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Table 4.** Suspended sediment concentration (SSC) and reflectance (L) statistics from measurement of plumes in each of the melt seasons samples were obtained. Reflectance statistics are based on MODIS bands 1 and 2.

The reflectance measurements made simultaneously to surface water samples vary with wavelength, but at all locations there is a consistent response between ~600 – 700 nm (equivalent to a red band in the visible spectrum) and ~750 – 900 nm (equivalent to the very near or near-infrared). This response corresponds with MODIS bands 1 (620 – 670 nm) and 2 (841 – 876 nm) and equivalent bands from other research and commercial satellites i.e. Landsat and Planet. SSC and surface reflectance are generally well correlated in these respective wavelength windows at both the Bayelva and Blomstrandbreen plumes. The regressions between in-situ sampled SSC and reflectance in MODIS bands 1 and 2, and equivalent wavelengths (\(B_{1\text{eqv}}\) and \(B_{2\text{eqv}}\)) from the other optical satellite platforms, give us confidence that the \(B_{1\text{eqv}}\) and \(B_{2\text{eqv}}\) reflectances can be calibrated to values of SSC using the example relationships shown in Figure 4. Calibrations of all relationships for 2012, 2019 and 2021 for each of the field sites can be found in Tables 5 and 6 in Section 4.3.
4. Multiple regression plots of suspended sediment concentration (SSC) on in-situ reflectance (L). (a) and (b) SSC-L of 2012 in-situ data collected at Bayelva applied to 630 – 690 nm and 780 – 860 nm windows, equivalent to ASTER B1 and B2; (c) and (d) SSC-L of 2019 in-situ data collected at Bayelva applied to 640 – 670 nm window and 850 – 880 nm windows, equivalent to Landsat 8 B1 and B2; (e) and (f) SSC-L of 2021 dataset collected at Bayelva applied to 650 – 680 nm and 785 – 900 nm windows, equivalent to Sentinel-2 B1 and B2; (g) and (h) SSC-L of 2021 dataset collected at Blomstrandbreen applied to 590 – 670 nm window and 780 – 860 nm window, equivalent to Planet B1 and B2.

3.2 Effects of bandwidths

The relationships between in-situ sampled SSC and B1\textsubscript{eqv} and B2\textsubscript{eqv} are variable across the satellite platforms utilized by the study. This variability comes from the different ranges of frequencies along the electromagnetic spectrum that space agencies and Earth imaging companies apply to their imagery. Earlier satellites carried only one sensor on board, resulting in broader bandwidths, whereas more modern satellites often operate with two or more sensors on board, meaning there are more image bands in narrower wavelengths, e.g. Landsat 8 OLI has 11 bands from 430 – 12510 nm compared to its predecessor Landsat 7 ETM+ which had eight bands between 450 – 900 nm. This variation in bandwidth creates an opportunity to understand if in-situ sampled SSC and reflectance measurements map better to a very precise bandwidth, or whether empirical relationships are improved by a broader, less narrow bandwidth which encompasses a greater range of the electromagnetic spectrum. Variations in bandwidth are most obvious in B1\textsubscript{eqv} when comparing Planet with Sentinel-2 and Landsat 8. Planet opted for a B1\textsubscript{eqv} of 590 – 670 nm, a bandwidth of 80 nm. Although bandwidths are extremely variable in B2\textsubscript{eqv} across the chosen satellite platforms, for example, Sentinel-2 has a bandwidth of 115 nm, MODIS 35 nm, and Landsat 8 a bandwidth of 30 nm, there is far less impact on the regressions between in-situ SSC and L. In 2019 at Bayelva, R\textsuperscript{2} is the same for all regressions of SSC-L irrespective of satellite platform, equal to 0.61. This suggests that B2\textsubscript{eqv} is a better tool for calibrating reflectance using SSC in this location compared with B1\textsubscript{eqv} during this particular melt season. On the whole, B2\textsubscript{eqv} is considerably better at calibrating in-situ L using SSC across the three melt seasons at Bayelva, and in 2019 and 2021 at Blomstrandbreen. This makes this study different from those that have previously worked in these environments, as they have often avoided applying these bandwidths and relied solely on B1\textsubscript{eqv}.
3.3 Sediment-laden meltwater plume onset and shutdown

The sediment-laden meltwater plumes at Bayelva and Blomstrandhreen have variable onset and shutdown periods across the three melt seasons. We have aimed to determine date ranges for when both melt and plume onset occur, and provide the closest date to plume shutdown to better understand how these features vary in space and time and how this variability may impact relationships between SSC and L.

Various datasets were used to undertake this analysis, including optical imagery from Landsat 7 for 2012, and Sentinel-2 and Planet (Planet Team, 2022) for 2019 and 2021. Sentinel-2 images were examined using GEEDiT for the two
more recent melt seasons applying a maximum cloud cover of <20% to all available scenes. In addition to this, the 2 m and 10 m air temperature data from the nearby meteorological station in Ny-Ålesund was used as a proxy for snow and ice melt, whilst gauging station data from the Bayelva River provided by NVE was used to indicate when discharge was being routed through the narrow bedrock channel.

To determine the melt onset period, observations of water pooling, and filling of channels and crevasses either in the Bayelva River floodplain, and upon Blomstrandbreen were made. When no imagery was available, meteorological data was used, where available, with a period of five days over 0°C assumed as initiating melt. However, because of the different characteristics of each site i.e. glacier-fed river and marine-terminating glacier system, it is not possible to further refine the temporal range. The plume onset period was determined by the first visible sediment expression on the fjord surface from satellite imagery. The plume season was determined by regular plume surfacing in the fjord at both sites, whilst shutdown was determined when sediment was no longer being transported to, or expressed on, the surface of Kongsfjorden at either site. This period usually coincided with an extended period of temperatures below 0°C, fresh snow being visible in satellite imagery, or a distinct reduction in meltwater runoff at the Bayelva hydrometric station to values less than 0.5 m³/s for more than three days. By determining these periods, we can see how increasing temperatures may be influencing plume surfacing from year-to-year. The length of a plume season and the period in which they surface also impacts the volume of sediment transported to fjords and coastal waters, which can have knock-on effects on fjord circulation, and marine biogeochemistry.

The Bayelva plume onset tends to occur in the first three calendar weeks of June (Figure 6), with some variability across the three melt seasons. Despite increases in average annual air temperatures in the region in the most recent decade (Wawrzyniak and Osuch, 2020), plume onset at this location in 2012 occurred earlier than in either 2019 or 2021, this is likely the result of unseasonably warm temperatures exceeding 4°C in the middle of May, initiating melt much earlier in the year. These warm temperatures may be linked to 2012 having the minimum spring ice extent in the period between 2003 – 2016 in Kongsfjorden (Pavlova et al., 2019). In each of the years, a date for plume shutdown has been determined, with the latest occurring in 2021 on day 280, the end of the first week in October, and the earliest shutdown occurring in 2019 on day 265, a result of early snow down to sea level. On average, the plume season at this location is 110 days, with both 2012 and 2021 having plume seasons of 114 days and 2019 having a shorter plume season of 103 days.
Figure 6. Melt season timeline, with a broken $x$ axis, for each of the three melt seasons at the Bayelva River sediment-laden meltwater plume, describing when melt first occurs, when plumes surface on the fjord, the length of the ‘plume season’ and when plumes shutdown (see text for further detail).

Plume onset at Blomstrandbreen in the two melt seasons covered by this study tends to be later than at Bayelva and many of the other tidewater glaciers in Kongsfjorden, determined by interrogating optical imagery (see Section 2.2.2), with the occurrence of sediment close to the glacier margin beginning in the third and fourth calendar weeks of June. The shutdown of plumes at Blomstrandbreen occurs at a similar time to Bayelva in both years. In 2021, a very large plume can still be observed on day 267 which corresponds to warm temperatures at this late stage in September. Only after a sustained period of cold weather can discharge begin to slow and plumes stop, hence day 280 is provided as the date for plume shutdown. At Blomstrandbreen the average plume season (2019 and 2021) is slightly shorter than Bayelva at 103 days, but there is a distinct difference in the length of the seasons, in 2019 the season was 94 days and in 2021 the season was 111 days.

4.0 Discussion

4.1 SSC-reflectance relationships

The stability of the in-situ SSC and surface reflectance relationships is key to
determining their possible transferability and use in predicting SSC beyond a single melt season, or plume location within Kongsfjorden, across the archipelago of Svalbard, and throughout the wider Arctic region. Our results have covered three separate melt seasons at the Bayelva River sediment-laden meltwater plume between 2012 – 2021 and two periods of sampling at the Blomstrandbreen sediment-laden meltwater plume in 2019 and 2021. The measurement periods on all these occasions have varied, although the majority of sampling has taken place in the final calendar week of June and the first two calendar weeks of July. Earlier measurements were taken at both of the study sites in 2021, during the middle of June, whilst some sampling occurred later in July during the 2012 season. However, we consider the period between late June to the middle of July as critical for measurements as this captures the peak of the melt season, especially from the Bayelva catchment, as this encompasses both melt of winter snow in the floodplain, and glacier ice melt from Austre and Vestre Brøggerbreen.

4.2 Spatial transferability

The two sampled systems lie in relatively close proximity across Kongsfjorden, however, there are various differences which mean the datasets collected at these sites are not comparable with one another. The bedrock geology at the two locations is markedly different; the Bayelva River and the glaciers which feed it cut across a large number of stratigraphic units on the Brøggerhalvøya peninsula. The lithology of the catchment varies spatially; with a combination of phyllite, quartzite, dolomite, limestone, anhydrite, carbonate breccia, sandstone, shale, conglomerate, coal, and other carbonate rocks being present beneath and in the lateral zones of the two glaciers. After its formation from glacier meltwater runoff and other non-glacial sources, the Bayelva River is fed through a combination of formerly deposited glacio-fluvial sediments, but also flows through other stratigraphic units which include sandstone, shale, siliceous shale, chert, siltstone, conglomerate, dolomite, limestone, anhydrite, and carbonate breccia before reaching its delta and flowing into Kongsfjorden. In comparison, the lithology at the margins of Blomstrandbreen is less complex, with a combination of mica schist, banded marble, migmatite, granitoid rocks and granitic orthogneiss mapped by the Norsk Polarinstitutt (NPI, 2020). The respective lithology at each site results in significant color differences in the sediment-laden meltwater that surfaces on the fjord, this is visible from satellite remote sensing (Figure 1, 3), but the difference is most significant during the process of filtering the surface water samples. Samples collected from the Bayelva River plume are much redder in color, likely a result of iron oxide or other impurities in the large sedimentary rock deposits in the catchment, such as sandstone, shale and siltstone. Whilst samples collected in the Blomstrandbreen sediment-laden meltwater plume have a grey-brown shade, influenced by the underlying lithology which is primarily made up of igneous and metamorphic rocks, such as migmatite and mica schist. Lithology plays a key role in the color of the suspended sediments which surface on the fjord. Sediment color along with particle size are two properties which are known to influence in-situ and remotely sensed
reflectance and have been well researched (e.g. Novo et al., 1989).

The two systems also differ in the method that they deliver sediment-laden meltwater to Kongsfjorden. The Bayelva River is a subaerial, glacier-fed river which flows for ~3 km before reaching the Kolhamna basin. Here, suspended sediment is delivered directly onto the surface of the fjord (see Section 2.1.1). In contrast, Blomstrandbreen is a marine-terminating glacier, that derives much of its sediment-laden water from the subglacial and englacial hydrologic systems. Although the glacier has retreated significantly in the last 50 years (Sund et al., 2010), and some sections of the terminus lie close to the grounding line, the southeast portion of the glacier remains marine-terminating. This means much of the plume is delivered below the surface of the water, or in a combination of below the water line and surface delivery, like at Bayelva. These alternate methods of delivering suspended sediment mean that the sediment-laden meltwater plumes have contrasting thicknesses. This can impact upon both in-situ and satellite surface reflectance measurements, in particular where the sediment-laden layer is thin e.g. delivered by subaerial, glacier-fed river, because a boat’s outboard motor, or high winds are easily able to disrupt this layer and can result in unrepresentative sampling of SSC and reflectance. Where the sediment-laden layer is thicker, and more stable at a marine-terminating system, outboard motors and wind have less impact, and instead glacier calving will likely play the greatest role in disrupting the surface layer.

We believe that both bedrock geology and the method of plume delivery make these two systems non-comparable. The lithology of the respective catchments impacts upon individual spectral responses as suspended sediments from Bayelva are both brighter, and redder in color than at Blomstrandbreen. Additionally, the thickness of the sediment-laden meltwater makes comparing these systems unviable, as it is delivered to Kongsfjorden in very different ways; on the surface at the Bayelva River mouth, compared with partial or completely subglacial at Blomstrandbreen. As such, future studies may look to compare sites where bedrock geology is similar, and in which sediment-laden meltwater plumes reach fjords or coastal waters in the same way.

4.3 Temporal transferability

Empirical relationships of in-situ SSC and surface reflectance determined from data collected over multiple field seasons can be used to establish whether sediment-laden meltwater plumes vary or remain stable from year-to-year. Should these relationships remain constant the need for time and cost-intensive field sampling could be reduced, and the relationships previously obtained can be transferred directly to satellite remote sensed reflectance to calculate SSC, without the need for regular calibration or validation using in-situ measurements.

At the Blomstrandbreen plume, two periods of fieldwork were undertaken. In 2019, a dataset of 10 measurements was collected on a single day. On the whole, B2$_{eqv}$ predicts SSC using in-situ reflectance much better than B1$_{eqv}$ at
this location (Table 5). \( R^2 \) values range from 0.34 – 0.52 dependent on the band designations of the satellites, the relationship between in-situ SSC and reflectance is not statistically significant at \( p \leq 0.05 \) for ASTER, MODIS and Landsat 8. However, the relationship is significant in Planet and Sentinel-2 band designations where \( p = 0.02 \), respectively. The 2021 dataset is much larger and covers a wider temporal period. In total, 72 in-situ SSC and reflectance measurements were collected by the study. During this melt season, both \( B_1_{eqv} \) and \( B_2_{eqv} \) predict SSC well using in-situ reflectance measurements; \( R^2 \) values in \( B_1_{eqv} \) (0.51 – 0.55) are very similar for all five satellite platforms with only a small amount of variation, whilst in \( B_2_{eqv} \) \( R^2 \) values are between 0.68 – 0.72, suggesting bands in the very near- to near-infrared predict SSC better. In all band designations, both \( B_1_{eqv} \) and \( B_2_{eqv} \), \( p \leq 0.05 \), confirming that all of the relationships are statistically significant.

**Table 5.** Statistics from regressions of in-situ SSC and surface reflectance collected at the Blomstrandbreen sediment-laden meltwater plume, applied to \( B_1_{eqv} \) and \( B_2_{eqv} \) of five satellite remote sensing platforms. Regression equations are in the form of \( L = m(SSC) + c \), unless stated. Regressions where \( p \leq 0.05 \) are marked by an asterisk.

<table>
<thead>
<tr>
<th>Satellite Platform</th>
<th>( m )</th>
<th>( c )</th>
<th>( R^2 )</th>
<th>( m )</th>
<th>( c )</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODIS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( B_1_{eqv} )</td>
<td>0.23</td>
<td>0.02</td>
<td>0.34</td>
<td>*</td>
<td>−0.003</td>
<td>0.68</td>
</tr>
<tr>
<td>( B_2_{eqv} )</td>
<td></td>
<td></td>
<td></td>
<td>0.42*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( B_1_{eqv} )</td>
<td>0.35</td>
<td>0.02</td>
<td>0.52</td>
<td>*</td>
<td>−0.01</td>
<td>0.72</td>
</tr>
<tr>
<td>( B_2_{eqv} )</td>
<td></td>
<td></td>
<td></td>
<td>0.59*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat 8 OLI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( B_1_{eqv} )</td>
<td>0.24</td>
<td>0.01</td>
<td>0.37</td>
<td>*</td>
<td>−0.002</td>
<td>0.68</td>
</tr>
<tr>
<td>( B_2_{eqv} )</td>
<td></td>
<td></td>
<td></td>
<td>0.40*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sentinel-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( B_1_{eqv} )</td>
<td>0.30*</td>
<td>0.02</td>
<td>0.49</td>
<td>*</td>
<td>−0.003</td>
<td>0.71</td>
</tr>
<tr>
<td>( B_2_{eqv} )</td>
<td></td>
<td></td>
<td></td>
<td>0.50*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( B_1_{eqv} )</td>
<td>0.35*</td>
<td>0.02</td>
<td>0.53</td>
<td>*</td>
<td>−0.01</td>
<td>0.72</td>
</tr>
<tr>
<td>( B_2_{eqv} )</td>
<td></td>
<td></td>
<td></td>
<td>0.59*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

When comparing coefficients between the two melt seasons in Sentinel-2 \( B_2_{eqv} \), which are both statistically significant relationships, the 2019 regression model...
has a coefficient of 0.30 (t-stat = 2.8), and the 2021 regression model has a coefficient of 0.50 (t-stat = 12.9). This indicates that for every 0.1 g L⁻¹ increase in SSC, L will increase by 0.03 and 0.05, for 2019 and 2021, respectively. The large t-stat value from the 2021 regression suggests a precise coefficient which is likely a result of the wide range of in-situ SSC and reflectance measurements. These coefficients indicate that these relationships are not transferable from one year to the other. However, based on the difference in the number of measurements collected in each of the years, we can postulate that with a larger dataset, these relationships would be more comparable as they would account for a wider variability in SSC and surface reflectance throughout the melt season, as was achieved by the sampling undertaken in 2021.

Three datasets from 2012, 2019 and 2021 have been analyzed to understand the variability of SSC at the Bayelva River sediment-laden meltwater plume (Figure 7). As a number of the more modern satellite systems have only been introduced in the last ~5 years, temporal comparison between datasets at this location will be made using MODIS band designations as this satellite has been in operation since 2002 and continues to collect data from onboard the Aqua and Terra satellites.

Although a small dataset was collected in 2012 (18 measurements), the relationship between in-situ SSC and reflectance is statistically significant (p < 0.05) for all three satellites, and the B1_eqv and B2_eqv band designations the in-situ data has been applied to. B1_eqv \( R^2 \) values vary between 0.44 – 0.47, whilst B2_eqv predicts SSC slightly less well with \( R^2 \) varying from 0.35 – 0.46 (Table 6). In comparison, B2_eqv predicts SSC far better in both the 2019 (46 measurements) and 2021 (129 measurements) datasets, with \( R^2 \) values of 0.61 across all five satellite platforms in 2019, and range between 0.32 – 0.39 in 2021 (Table 6). This is compared to values ranging between 0.33 – 0.39 in 2019 and 0.20 – 0.24 in 2021 when predicting SSC from reflectance using B1_eqv. The relationship between these two variables is also statistically significant (p < 0.05) in both B1_eqv and B2_eqv designations from the five satellites used in 2019 and 2021.

![Figure 7](image)

**Figure 7.** Regressions of suspended sediment concentration (SSC) and in-situ reflectance (L) in the 841-876 nm window, or B2_eqv, from each of the three melt...
seasons (2012, 2019 and 2021), samples were collected in the Bayelva River sediment-laden meltwater plume.

The 2012 regression model has a coefficient of 0.46 (t-stat = 2.9), whilst the 2019, and 2021 models have coefficients of 0.42 (t-stat = 8.3) and 0.14 (t-stat = 8.0) respectively. These data reveal that for every 0.1 g L\(^{-1}\) increase in SSC, in-situ reflectance (L) will increase by 0.046, 0.042 and 0.014, respectively, in each of the three melt seasons. This suggests that there is some similarity in the datasets collected in 2012 and 2019, albeit the sampling in 2012 did not account for much variability in SSC, hence a lower R\(^2\) of 0.35, compared with a R\(^2\) value of 0.61 in 2019 and a much wider range of SSC values (see Table 4). The t-stat generated by the 2012 regression also points to a less precise coefficient, which could be easily altered had there been additional samples across the melt season. The 2021 coefficient is far lower at 0.14 and suggests a very different relationship between SSC and L than in 2012 and 2019; the t-stat for the 2019 and 2021 regressions are both in excess of 8.0 which indicates the coefficient is fairly accurate, based on the number of samples collected. The greatest difference between these field seasons is the range of in-situ SSC measurements which can be seen in Figure 7. Despite this, there was very little variation in the in-situ reflectance measurements in 2021, which has the greatest impact upon the empirical relationships.

Table 6. Statistics from regressions of in-situ SSC and surface reflectance collected at the Bayelva River sediment-laden meltwater plume, applied to B1\(_{\text{equiv}}\) and B2\(_{\text{equiv}}\), for six satellite remote sensing platforms. Regression equations are in the form of \(L = m(SSC) + c\). Regressions where p \(\neq 0.05\) are marked by an asterisk.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.60*</td>
<td></td>
<td>*</td>
<td>0.52*</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>Not used by study</td>
<td>0.004</td>
<td>0.52*</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>study after introduction</td>
<td>0.41*</td>
<td>0.13*</td>
</tr>
<tr>
<td></td>
<td>Not used by study</td>
<td>study after introduction</td>
<td>0.02</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>0.47*</td>
<td>OLI</td>
<td>*</td>
<td>0.21*</td>
</tr>
<tr>
<td></td>
<td>0.61</td>
<td>OLI</td>
<td>0.01</td>
<td>0.31</td>
</tr>
</tbody>
</table>

We can conclude from these data that empirical relationships between in-situ SSC and surface reflectance at the Bayelva River sediment-laden meltwater plume are not transferable in time from one summer melt season to another. Further field sampling should be undertaken across a larger temporal period,
capturing a similar number of samples as in 2019 and 2021 at this location to better understand this variability. Future work may wish to focus more specifically on the Bayelva catchment, or a similar glacier-fed subaerial river to determine whether sediment remobilization and deposition, and non-glacial water sources in the catchment, influence the sediment-laden meltwater plume.

Regressions produced in this study have lower $R^2$ values than other similar studies, this is because we use a linear relationship without fixing the intercept at 0 (see Section 2.1.3 for further details). We believe this decision is justified, given ambient fjord water is still a reflective surface, and samples from these locations will still contain some suspended matter, albeit not necessarily glacio-fluvial sediments. Further to this, there are some samples which have a clear impact on the regression models, but where possible, we have tried to retain these points to show that this form of in-situ sampling is not fool proof and errors can be introduced at any stage from sample collection, and measurement through to sample processing in the laboratory.

4.4 Impacts of cloud cover

The west of the Svalbard Archipelago is extensively covered by fog and clouds during the summer and early autumn, with very few clear sky days (Shiobara et al., 2003). This makes satellite remote sensing of this region difficult, as most optical sensors, including multispectral instruments, are impeded by cloud cover, in particular low clouds (Marshall et al., 1993, 1994; Østby et al., 2014). As a result, usable satellite remote sensing data in this study are limited to cloud-free periods, which are infrequent, not easy to predict, and highly variable from year-to-year. As such in-situ reflectance measurements have not been directly compared with reflectance data from onboard the selected satellite platforms (Section 2.2.1).

The impacts of cloud cover in the Kongsfjorden region can be demonstrated by the number of Sentinel-2 images GEEDiT (maximum cloud cover <20%) returned for the four month period between 1 June – 30 September in both 2019 and 2021 at the Bayelva River plume, the temporal period the study used to determine the onset and shutdown of plumes (Figure 6). In 2019, 35 images are available to the study, the first being from 01/06/2019 and the last a partially cloud impacted scene from 22/09/2019. In 2021, 61 images were available to the study through GEEDiT, considerably more than in 2019. The first is an image from 06/06/2021, and the last a shadow impacted image in which the Bayelva River continued to deliver sediment-laden meltwater to the fjord from 24/09/2021. These data reveal the difficulty of studying features which require optical imagery in this region, in spite of using a higher temporal resolution, 5-day repeat when both Sentinel’s 2A and 2B are operating and a 10-day repeat when only one is operational, and higher spatial resolution (10 m) satellite platform.

5.0 Conclusions

The relationship between suspended sediment concentration and in-situ
reflectance in sediment-laden meltwater plumes has been examined at both a glacier-fed river and a tidewater glacier in Kongsfjorden, Svalbard. Through this study we demonstrate that MODIS Band 2 (841 – 876 nm) and equivalent bands (B2\text{eqv}) in the very near- or near-infrared from other research and commercial satellites are a far better tool in predicting SSC using in-situ reflectance than Band 1 equivalents (e.g. 620 – 670 nm) at these locations. Previous research has often focussed solely on the use of B1 (e.g. Hudson et al., 2014; Hodgkins et al., 2016) with some earlier studies attributing atmospheric correction issues as the reason for not including B2 in their empirical models (Chu et al., 2009). In this study, however, we have been unable to validate in-situ reflectance measurements with satellite reflectance data, due to cloud impacted scenes and a lack of passes coinciding with the dates of in-situ sampling. We instead focus on simulating respective satellite bandwidths with our in-situ measurements. Another significant finding from this study is that empirical relationships determined for melt seasons at the Bayelva River sediment-laden meltwater plume are not temporally transferable and cannot be applied to satellite surface reflectance products from a different period. We therefore suggest in order to determine plume variability, regular sampling i.e. yearly may be required. Further field sampling at the Blomstrandbreen sediment-laden meltwater plume would offer an insight into whether empirical relationships here are comparable, and therefore transferable from one year to the next. The regressions undertaken on the datasets collected in 2019 and 2021 indicate they are not temporally transferable, however the limited dataset of measurements from 2019 mean that many of the relationships were not statistically significant. We have also determined that our datasets are not spatially transferable from one catchment to another, this is a result of the diverse bedrock geology at each site and the method in which sediment-laden water is delivered to Kongsfjorden. Future work should focus on the impacts of glacier hydrological systems on sediment-laden meltwater plumes, and the impact local lithology has on surface reflectance measurements. These are of particular importance given Svalbard’s diverse bedrock geology, and because many of the region’s tidewater glaciers are expected to retreat onto land this century, which will result in significant changes to the behavior and variability of sediment-laden meltwater plumes across the archipelago.

**Acknowledgements**

The authors are very grateful to Nick Cox of the UK Arctic Research Station and staff of the Kings Bay AS for assistance in undertaking the fieldwork, and for access to laboratory facilities in Ny-Ålesund. We would also like to thank Research in Svalbard for permitting the research (RiS ID: 11298). This research was funded by a UK Research and Innovation Natural Environment Research Council PhD studentship (grant [NE/L002493/1]). Further funding came from a SIOS Research Infrastructure Access project funded by the Research Council of Norway, project number 291644, Svalbard Integrated Arctic Earth Observing System – Knowledge Centre, operational phase, and a Loughborough University Doctoral Researcher Santander Mobility Award.
Open Research

Data Availability Statement

The data used in this manuscript can be accessed via the Loughborough University Research Repository https://doi.org/10.17028/rd.lboro.21186076.v1

References


fjorden, Svalbard (pp. 105-136). Springer, Cham. https://doi.org/10.1007/978-3-319-46425-1_4


