Using Remote Sensing to Detect Suspended Sediment

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Glacier-fed hydrological systems in high latitude regions experience high seasonal variation in meltwater runoff. The peak in runoff usually coincides with the highest air temperatures which drive meltwater production. This process is often accompanied by the release of sediments from within the glacier system that are transported and suspended in high concentrations as they reach the proglacial realm. Sediment-laden meltwater is later transported to the marine environment and is expressed on the surface of fjords and coastal waters as sediment plumes. Direct monitoring of these processes requires complex and time-intensive fieldwork, meaning studies of these processes are rare.

sediment plumes | glacier meltwater | remote sensing | Sentinel-2 | suspended sediment concentration | glacial lake | fjord | Arctic

1. Sediment Plumes

Sediment plumes are common features in the fjords and coastal waters of the archipelago of Svalbard [1]. They regularly surface in the summer months between June–August and are a product of meltwater runoff suspending sediment produced during the process of erosion at the ice-bed interface, and lateral areas of glaciers and ice caps [2], or from the remobilisation of previously deposited sediment in the proglacial realm [3]. Sediment plumes can form at the margins of marine-terminating glaciers, where buoyant sediment-laden water sourced from the englacial and subglacial channel networks is evacuated [4]. They can surface at multiple locations across a glacier calving front and, dependent on their magnitude, extend substantial distances into fjords [5]. However, not all sediment plumes are linked to marine-terminating glacier systems, with a large number being formed from glacier-fed subaerial rivers. These are often thinner plumes, as they are delivered onto the fjord surface; as a result they are smaller in scale, but still transport significant volumes of sediment-laden meltwater to fjords and coastal environments [6]. Sediment plumes can impact upon a number of processes, dependent on whether they form at marine-terminating glaciers or from terrestrial glacier-fed rivers, and their size, including calving and submarine melt rates [7], marine biogeochemistry [8], fjord circulation [9], glaciomarine sedimentation [10] and marine and bird life [11].

The researchers' understanding of sediment plumes in Svalbard comes from a combination of modelling [12][13], surface observations [2][14] and the collection of oceanographic data in areas close to where they form [15]. Remote sensing datasets are often used to supplement in situ measurements, but because of the climate regime of the archipelago, cloud cover is very often a limiting factor [16][17]. More recently, higher temporal and spatial resolution datasets, such as Sentinel-2 have been launched, providing improved coverage of the region. These improvements allow the researchers to better understand the behaviour of sediment plumes over shorter time periods [18][19].

Sediment plumes have been well studied in Svalbard, with a large number of in situ studies in two of the most well-known fjord complexes, Isfjorden and Kongsfjorden. However, there have also been studies undertaken in other areas of the archipelago, such as Austfonna in the far Northeast [13]. This research has focussed on various aspects of the glaciological and oceanographic realm, including using sediment plumes to determine volumes of meltwater being delivered to fjords by a marine-terminating glacier [1], to calculate sedimentation rates at a glacier ice front [10], to better understand rapid changes in subglacial hydrology linked to supraglacial processes [14], and more recently using CTD instruments attached to Ringed Seals to understand plume behaviour [20].

Sediment plumes occur as a result of enhanced meltwater runoff. The main source of water available for runoff is connected to the melting of glaciers. Glacier melt is highly dependent on atmospheric conditions and is also affected by long-term climate fluctuations [21]. In Svalbard, the climate is changing on average 2–6 times faster than in other regions of the world. [22][23]. This is demonstrated mainly through the intensive transformation of the landscape, of which glaciers and (especially in recent years) glacial lakes are an important element. Changes in glacier mass balance based on oblique aerial photographs dating from the 1930s have recently been published by a team led by Geyman et al. [24]. This research showed a correlation between areas where temperatures have increased the most over recent decades and where the greatest glacier recession has occurred. Overall, the glacierized area of Svalbard has decreased by about 14.8% [24]. Retreating glaciers leave space in the proglacial area for the development of glacial lakes, the largest number of which on Svalbard are moraine-dammed lakes (52%) [25]. Moraine dams, due to their unconsolidated structure, are dams that are often subject to seasonal changes. It is also common for dams to collapse due to melt-out of dead ice found within them [26]. This can lead to seasonal drainage of moraine-dammed lakes or, in certain situations, to catastrophic Glacial Lakes Outburst Floods (GLOFs). The retreat of glaciers after the Little Ice Age (LIA) led to the development of a large number of glacial lakes that often serve as deposition centres for fine grained fluvio-glacial sediments in Svalbard [27].

2. Production and Transport of Sediment

The enhanced melting of Svalbard glaciers and ice caps during the Holocene has released large amounts of sediment previously eroded by the flow of ice over its bedrock. Meltwater has consequently transported the material from land to the coast where it has started to be deposited, reworked, and transported along the shore. One of the most striking and visible examples of such processes is the formation of delta systems. Lønne and Nemec [28] describe the formation of a delta system during the early phase of the Holocene in central Svalbard. The timing of the delta system’s formation was very likely related to the phase of intensive deglaciation between 3000–9000 BP [29]. The greatest sediment transport period occurred during “peak water” when meltwater production was highest [30]. After this point, runoff has steadily declined and so has the transport capacity of glacier-fed rivers. The largest delta systems were formed in the head of Svalbard's fjords. The relatively shallow environment and protection from the erosive action of waves and long-shore currents created favourable conditions for sediment deposition [31]. Svalbard has a high elevation gradient with potential for transporting a large amount of material towards the coast. This, together with relatively intense glacial isostatic uplift after deglaciation, also promoted the progradation of delta systems. A similar trend of delta progradation in recent conditions was observed by Bendixen et al. [32] in western Greenland, where the glaciers are generally much larger and are still on the rising limb of "peak water" [30].

The volume of material transported from land to sea also depends upon the distance it will be entrained for. Generally, the longer the distance to the coast, the smaller the volume of material that will reach this point. Zajączkowski [33] also demonstrated the difference in the source providing the material, as well as in the bed topography of the fjord, using Adventfjorden and Kongsfjorden, Svalbard as examples. Whereas the sediment transport over the shallow tidal flat of a delta was relatively short and resulted in reactivation of previously deposited material, the transport distances in a marine-terminating glacier-dominated fjord were substantially longer. Zajączkowski and Włodarska-Kowalczuk [34] reported the highest concentration (826 mg L^{-1}) of suspended sediments at the edge of the tidal flat and over the upper slope of the delta in Adventfjorden. Kim et al. [35] reported possible progradation of a delta system in Dicksonfjorden which is very likely linked to high input of suspended sediments from the large glacier-fed basin. Lateral movements of sediment spits were reported in only a short period of time.

3. Using Remote Sensing to Detect Suspended Sediment in Fjords and Coastal Waters

Apart from a handful of in situ research campaigns, direct monitoring of sediment transport in the Arctic is often restricted by logistical and financial barriers. Satellite remote sensing is therefore widely used for monitoring and assessment of the quality of surface waters and the dynamics of the hydrosphere [36], with more specific studies taking place in the Arctic region [37][38][39]. Early studies focused on the relationship between reflectance coefficients obtained from the analysis of satellite images and the concentration of suspended sediments, as well as other water quality parameters [39]. Initially, Landsat satellites were key satellites for this type of research. However, with the addition of Sentinel, they are now often used together. In addition, a number of previous studies successfully used data from the MODIS satellite [40]. However, the problem of the latter is its spatial resolution (250 m per pixel), which makes it unsuitable for research in shallow bays, rivers, lakes, and other relatively spatially limited water bodies.

Finding the relationship between suspended sediment concentration (SSC) in water and surface reflectance was a key step in using remote sensing data. In this case, research on detecting indicators of the SSC in water, as well as the calculation of chlorophyll-a, were key (e.g., [41][42]). The reflection coefficient of solar radiation in the visible and infrared parts of the spectrum and the amount of sediment in the water can be directly related. In general, the higher the SSC, the higher the reflectance coefficient in the specific spectrum [43].

The system for calculating many of the above indicators is based on the selection of the necessary combination of channel reflectivity. To begin with, an image undergoes pre-processing, including atmospheric correction, more often by the DOS method [44]. Then, the values of the raster pixels (digital numbers) are converted into the spectral reflectivity coefficient [45][46].

In order to accurately calculate different environmental indicators, it is usually necessary to use the coefficients obtained as a result of in situ sampling. The necessary coefficients are then calculated using a linear regression method that compares in situ data with remote-sensing-derived measurements [45]. However, the sequence of data over one single study site can provide the researchers with reasonable outcomes, even without in situ calibration. The obtained index cannot be attributed to an absolute value of SSC, but multi-temporal comparison is possible. A similar operation is performed, for example, when calculating the vegetation index NDVI [47].

References

1. Darlington, E.F. Meltwater Delivery from the Tidewater Glacier Kronebreen to Kongsfjorden, Svalbard; Insights from in-situ and Remote-Sensing Analyses of Sediment Plumes. Doctoral Dissertation, Loughborough University, Loughborough, UK, 2015.
2. Schild, K.M.; Hawley, R.L.; Chipman, J.W.; Benn, D.I. Quantifying suspended sediment concentration in subglacial sediment plumes discharging from two Svalbard tidewater glaciers using Landsat-8 and in situ measurements. Int. J. Remote Sens. 2017, 38, 6865–6881.
3. Porter, P.R.; Vatne, G.; Ng, F.; Irvine-Fynn, T.D. Ice-marginal sediment delivery to the surface of a high-Arctic glacier: Austre Brøggerbreen, Svalbard. Geogr. Ann. Ser. A Phys. Geogr. 2010, 92, 437–449.
4. Hewitt, I.J. Subglacial plumes. Annu. Rev. Fluid Mech. 2020, 52, 145–169.
5. Meslard, F.; Bourrin, F.; Many, G.; Kerhervé, P. Suspended particle dynamics and fluxes in an Arctic fjord (Kongsfjorden, Svalbard). Estuar. Coast. Shelf Sci. 2018, 204, 212–224.
6. Bogen, J.; Bønsnes, T.E. Erosion and sediment transport in High Arctic rivers, Svalbard. Polar Res. 2003, 22, 175–189.
7. How, P.; Schild, K.M.; Benn, D.I.; Noormets, R.; Kirchner, N.; Luckman, A.; Vallot, D.; Hulton, N.R.; Borstad, C. Calving controlled by melt-under-cutting: Detailed calving styles revealed through time-lapse observations. Ann. Glaciol. 2019, 60, 20–31.
8. Jørgensen, B.B.; Laufer, K.; Michaud, A.B.; Wehrmann, L.M. Biogeochemistry and microbiology of high Arctic marine sediment ecosystems—Case study of Svalbard fjords. Limnol. Oceanogr. 2021, 66, S273–S292.

9. Torsvik, T.; Albretsen, J.; Sundfjord, A.; Kohler, J.; Sandvik, A.D.; Skarðhamar, J.; Lindbäck, K.; Everett, A. Impact of tidewater glacier retreat on the fjord system: Modeling present and future circulation in Kongsfjorden, Svalbard. Estuar. Coast. Shelf Sci. 2019, 220, 152–165.
10. Kehrl, L.M.; Hawley, R.L.; Powell, R.D.; Brigham-Grette, J. Glacimarine sedimentation processes at Kronebreen and Kongsvegen, Svalbard. J. Glaciol. 2011, 57, 841–847.
11. Lydersen, C.; Assmy, P.; Falk-Petersen, S.; Kohler, J.; Kovacs, K.M.; Reigstad, M.; Steen, H.; Strøm, H.; Sundfjord, A.; Varpe, Ø.; et al. The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway. J. Mar. Syst. 2014, 129, 452–471.
12. Mugford, R.I.; Dowdeswell, J.A. Modeling glacial meltwater plume dynamics and sedimentation in high-latitude fjords. J. Geophys. Res. Earth Surf. 2011, 116, F01023.
13. Dowdeswell, J.A.; Hogan, K.A.; Arnold, N.S.; Mugford, R.I.; Wells, M.; Hirst, J.P.P.; Decalf, C. Sediment-rich meltwater plumes and ice-proximal fans at the margins of modern and ancient tidewater glaciers: Observations and modelling. Sedimentology 2015, 62, 1665–1692.
14. How, P.; Benn, D.I.; Hulton, N.R.J.; Hubbard, B.; Luckman, A.; Sevestre, H.; van Pelt, W.J.J.; Lindbäck, K.; Kohler, J.; Boot, W. Rapidly changing subglacial hydrological pathways at a tidewater glacier revealed through simultaneous observations of water pressure, supraglacial lakes, meltwater plumes and surface velocities. Cryosphere 2017, 11, 2691–2710.
15. Holmes, F.A.; Kirchner, N.; Kuttenkeuler, J.; Krützfeldt, J.; Noormets, R. Relating ocean temperatures to frontal ablation rates at Svalbard tidewater glaciers: Insights from glacier proximal datasets. Sci. Rep. 2019, 9, 9442.
16. Marshall, G.J.; Rees, W.G.; Dowdeswell, J.A. Limitations imposed by cloud cover on multitemporal visible band satellite data sets from polar regions. Ann. Glaciol. 1993, 17, 113–120.
17. Østby, T.I.; Schuler, T.V.; Westermann, S. Severe cloud contamination of MODIS Land Surface Temperatures over an Arctic ice cap, Svalbard. Remote Sens. Environ. 2014, 142, 95–102.
18. Kavan, J.; Haagmans, V. Brief communication: Hydrologic connectivity of a tidewater glacier characterized with Sentinel-2 satellite images–a case study of Nordenskiöldbreen, Svalbard. Cryosphere Discuss. 2022. preprint.
19. Tallentire, G.D.; Shiggins, C.J.; Rawlins, L.D.; Evans, J.; Hodgkins, R. Observing relationships between sediment-laden meltwater plumes, glacial melt and a retreating terminus. Int. J. Remote Sens. in prepint.
20. Everett, A.; Kohler, J.; Sundfjord, A.; Kovacs, K.M.; Torsvik, T.; Pramanik, A.; Boehme, L.; Lydersen, C. Subglacial discharge plume behaviour revealed by CTD-instrumented ringed seals. Sci. Rep. 2018, 8, 13467.

21. Marshall, S.J. Regime Shifts in Glacier and Ice Sheet Response to Climate Change: Examples From the Northern Hemisphere. Regime Shifts in Glacier and Ice Sheet Response to Climate Change: Examples From the Northern Hemisphere. Front. Clim. 2021, 3, 702585.
22. Nordli, Ø.; Przybylak, R.; Ogilvie, A.E.J.; Isaksen, K. Long-term temperature trends and variability on Spitsbergen: The extended Svalbard Airport temperature series, 1898–2012. Polar Res. 2014, 33, 21349.
23. Isaksen, K.; Nordii, Ø.; Førland, E.J.; Łupikasza, E.; Eastwood, D.; Niedźwiedź, T. Recent warming on Spitsbergen—Influence of atmospheric circulation and sea ice cover. J. Geophys. Res. Atmos. 2016, 121, 3446–3464.
24. Geyman, E.; van Pelt, W.; Maloof, A.; Aas, H.; Kohler, J. Historical glacier change on Svalbard predicts doubling of mass loss by 2100. Nature 2022, 601, 374–379.
25. Wieczorek, I.; Strzelecki, M.C.; Stachnik, Ł.; Yde, J.C.; Małecki, J. Inventory and classification of the post Little Ice Age glacial lakes in Svalbard. Cryosphere Discuss. 2022. preprint.
26. Schomacker, A.; Kjaer, K.H. Quantification of dead-ice melting in ice-cored moraines at the high-Arctic glacier Holmstrombreen, Svalbard. BOREAS 2008, 37, 211–225.
27. Ewertowski, M. Recent transformations in the high-Arctic glacier landsystem, Ragnarbreen, Svalbard. Geogr. Ann. Ser. A Phys. Geogr. 2014, 96, 265–285.
28. Lønne, I. Nemec WHigh-arctic fan delta recording deglaciation and environment disequilibrium. Sedimentology 2004, 51, 553–589.
29. Fjeldskaar, W.; Bondevik, S.; Amantov, A. Glaciers on Svalbard survived the Holocene thermal optimum. Quat. Sci. Rev. 2018, 199, 18–29.
30. Huss, M.; Hock, R. Global-scale hydrological response to future glacier mass loss. Nat. Clim. Chang. 2018, 8, 135–140.
31. Kvam, M.H. Deposits and Processes on the Tide-Influenced Fjord-Head Delta in Dicksonfjorden, Svalbard. Master's Thesis, Deptartment of Geosciences, UiT—The Arctic University of Norway, Tromsø, Norway, 2018.
32. Bendixen, M.; Lønsmann Iversen, L.; Anker Bjørk, A.; Elberling, B.; Westergaard-Nielsen, A.; Overeem, I.; Barnhart, K.R.; Khan, S.A.; Box, J.E.; Abermann, J.; et al. Delta progradation in Greenland driven by increasing glacial mass loss. Nature 2017, 550, 101–104.
33. Zajączkowski, M. Sediment supply and fluxes in glacial and outwash fjords, Kongsfjorden and Adventfjorden, Svalbard. Pol. Polar Res. 2008, 29, 59–72.
34. Zajączkowski, M.; Włodarska-Kowalczuk, M. Dynamic sedimentary environments of an Arctic glacier-fed river estuary (Adventfjorden, Svalbard). I. Flux, deposition, and sediment dynamics. Estuar. Coast. Shelf Sci. 2007, 74, 285–296.

35. Kim, D.; Jo, J.; Nam, S.; Choi, K. Morphodynamic evolution of paraglacial spit complexes on a tide-influenced Arctic fjord delta (Dicksonfjorden, Svalbard). Mar. Geol. 2022, 447, 106800.
36. Gholizadeh, M.H.; Melesse, A.M.; Reddi, L. A comprehensive review on water quality parameters estimation using remote sensing techniques. Sensors 2016, 16, 1298.
37. Chu, V.W.; Smith, L.C.; Rennermalm, A.K.; Forster, R.R.; Box, J.E. Hydrologic controls on coastal suspended sediment plumes around the Greenland Ice Sheet. Cryosphere 2012, 6, 1–19.
38. Hudson, B.; Overeem, I.; McGrath, D.; Syvistski, J.P.M.; Mikkelsen, A.; Hasholt, B. MODIS observed increase in duration and spatial extent of sediment plumes in Greenland fjords. Cryosphere 2014, 8, 1161–1176.
39. Dekker, A.; Zamurovic-Nenad, Z.; Hoogenboom, H.; Peter, S. Remote sensing, ecological water quality modelling and in situ measurements: A case study in shallow lakes. Hydrol. Sci. J. 1996, 41, 531–547.
40. Li, R.R.; Kaufman, Y.J.; Gao, B.C.; Davis, C.O. Remote sensing of suspended sediments and shallow coastal waters. Geoscience and Remote Sensing. IEEE Trans. 2003, 41, 559–566.
41. Kabir, S.M.I.; Ahmari, H. Evaluating the effect of sediment color on water radiance and suspended sediment concentration using digital imagery. J. Hydrol. 2020, 589, 125189.
42. Smith, B.; Pahlevan, N.; Schalles, J.; Ruberg, S.; Errera, R.; Ma, R.; Giardino, C.; Bresciani, M.; Barbosa, C.; Moore, T. Chlorophyll-a Algorithm for Landsat-8 Based on Mixture Density Networks. Front. Remote Sens. 2021, 1, 5.
43. Long, C.M.; Pavelsky, T.M. Remote sensing of suspended sediment concentration and hydrologic connectivity in a complex wetland environment. Remote Sens. Environ. 2013, 129, 197–209.
44. Rumora, L.; Miler, M.; Medak, D. Impact of Various Atmospheric Corrections on Sentinel-2 Land Cover Classification Accuracy Using Machine Learning Classifiers ISPRS. Int. J. Geo-Inf. 2020, 9, 277.
45. Trinh, L.; Tarasov, M.K. Evaluation of suspended matter concentrations in surface water of the Tri An water reservoir (Vietnam) using the remote sensing data. Vestn. Mosk. Univ. Seriya 5 Geogr. 2016, 2, 38–43. (In Russian)
46. Peterson, K.T.; Sagan, V.; Sidike, P.; Cox, A.L.; Martinez, M. Suspended Sediment Concentration Estimation from Landsat Imagery along the Lower Missouri and Middle Mississippi Rivers Using an Extreme Learning Machine. Remote Sens. 2018, 10, 1503.
47. Hossain, A.K.M.; Yafei, J.; Xiaobo, C. Development of Remote Sensing Based Index for Estimating/Mapping Suspended Sediment Concentration in River and Lake Environments. In Proceedings of the 8th International Symposium on Ecohydraulics (ISE 2010) 0435, Zaragoza, Spain, 12–16 September 2010; pp. 578–585.