FEATURED DATA SOURCES AND NORMALISED INDICES OF USE IN SMALL ARCTIC CATCHMENT RESEARCH

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ABSTRACT: The development of remote sensing instruments and methods has revolutionised work practices worldwide, resulting in a new field of research. Remote sensing has significantly expanded the possibilities for detailed research, spanning from biological to urban studies, by constantly imaging the Earth. Numerous photogrammetric campaigns and satellite missions have been increasing the possibilities for conducting research that includes larger areas and time scales while minimising the need for fieldwork. This is particularly useful in polar regions, where fieldwork is complicated by harsh weather conditions, hard-to-reach research areas, polar nights, and the need for high funding and logistical support. Here available algorithms that help to track environmental shifts in the small Arctic catchments, such as changes in ice, snow, vegetation, and water are presented.

KEY WORDS: remote sensing, satellite sources, normalised differences indices, Arctic

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Introduction

Aerial or satellite images have been used for mapping since their first release (e.g. Schöner, Schöner 1997, Tonkin et al. 2016). They are used initially for their own country or navigational studies, and then gradually for scientific use. As a result, today, we have invaluable materials about some areas, especially Svalbard, which enables us to analyse studies in the period as far back as the end of the Little Ice Age (LIA). The first use of photogrammetric materials in polar research started at the end of the 19th century and the first thematic mapping based on aerial photographs was conducted in 1905 in Alaska (Furmańczyk, Jania 1981). In the 1930s few photogrammetric in Arctic campaigns took place which focused on Franz Joseph Land, Severnaya Zemlya, Taymyr Peninsula, and Novaya Zemlya (the German-Soviet expedition, 1931) used for making topographic overview maps (Schneider 1974, Furmańczyk, Jania 1981), photogrammetric overflights of Spitsbergen, Bear Island and eastern Greenland (the Norwegian expeditions, 1930s) (Schneider 1974, Furmańczyk, Jania 1981, NPI 2014, Geyman et al. 2022) and over Labrador, Canadian Arctic and Greenland (Furmańczyk, Jania 1981). Based on Alfred Hoel Svalbard's photogrammetric campaign, Geyman et al. (2022) provided an orthophotomap of Svalbard for the years 1936/38. This dataset captures the environment shortly after the LIA when most of the

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Svalbard glaciers reached their last maximal extent. Other flights over Svalbard took place in the 1960s, 1990s, and 2010s. Firstly, these data serve as snapshots of landscape state and therefore as data for the generation of orthophotomap and numerical terrain models.

Climate change is undoubtedly associated with its faster pace in polar regions due to the Arctic Amplification (Nordli et al. 2014, 2020, Isaksen et al. 2022, Rantanen et al. 2022). Since the end of the LIA when the last glacial maximal extent was recorded, rapid landscape changes have been seen in the sea ice loss (Serezze et al. 2007), glacier retreat (Martín-Moreno et al. 2017) or within small catchments (Lønne, Lyså 2005). In Svalbard, located between 74°N and 81°N and between 10°E and 30°E, the LIA lasted until the 1900s (Szczuciński et al. 2009, Kavan 2020, Dudek et al. 2023). Since then, for over 100 years, the archipelago has recorded the constant retreat of most of the glaciers and shift in environmental settings within small catchments. Therefore glacial retreat and thinning have been widely observed on Svalbard (e.g. Nuth et al. 2013, Martín-Moreno et al. 2017, Morris et al. 2020, Schuler et al. 2020, Hugonnet et al. 2021, Dudek, Pętlicki 2023) and at the same time, the activation and intensification of mass processes have occurred influencing the topography of glaciers forelands (e.g. Lyså, Lønne 2001, Lønne, Lyså 2005, Lukas et al. 2005, Schomacker 2008, Schomacker, Kjaer 2008, Evans et al. 2012, Tonkin et al. 2016, Midgley et al. 2018, Błaszkiewicz et al. 2023, Dudek et al. 2023). Moreover, the retreating glaciers provided space for lakes (e.g. Schöner, Schöner 1997, Dudek et al. 2023), vegetation (e.g. Wietrzyk et al. 2018), and fauna succession (Ziaja 2006). Even though Schuler et al. (2020), pointed out that Svalbard is an ideal field laboratory due to its developed and long-lasting research infrastructure and being relatively easy to reach there are still some obstacles during maintaining fieldwork. The main difficulties researchers encounter while working in the field are harsh environmental conditions (e.g. unpredictable weather, strong wind), long polar nights, difficulties in access from research stations or settlements study sites as they are too far in distance, high costs, and challenging logistics. This is where remote sensing studies can help. Fortunately, the period between the end of the LIA and today coincides with the development of terrestrial and then aerial photogrammetry, and more recently with the launch and expansion of satellites. Remote sensing devices and methods have advanced significantly in the last 60 years along with various applications of remotely derived data. The newly uncovered landscape is experiencing the succession of vegetation, the development of drainage systems, and lakes, or the activation of slope processes, and these processes can be tracked with the use of remote sensing data.

Archival maps and images enable us to track glacier fluctuations (including surges) to follow their reaction to climate change (Schöner, Schöner 1997, Eiken, Sund 2012, Dudek, Pętlicki 2023). Photogrammetric methods such as structure from motion (SfM) enable the creation of point clouds and digital elevation models (DEMs) based on aerial photographs (stereopairs). This method is widely used and described in many studies on both geomorphology and polar research (e.g. Westoby et al. 2012, Gomez et al. 2015, Eltner et al. 2016, Mosbrucker et al. 2017, Kavan 2020, Holmlund 2021). DEMs from different years or periods can be subtracted to track changes in surface elevation. Difference of DEMs (DoD) shows the loss or gain of glacier thickness (Eiken, Sund 2012, Geyman et al. 2022, Małecki 2022) or landforms degradation (e.g. Tonkin et al. 2016, Morris et al. 2020, Błaszkiewicz et al. 2023). The data can be processed by manual mapping or automatic image classification (especially for larger areas and quantitative applications) which is also faster and may serve for long-term studies (Kääb 2005). Remote data has been widely used for mapping, e.g. terrain topography (e.g. Chandler et al. 2018, Ewertowski, Tomczyk 2020, Allaart et al. 2021, Wołoszyn, Kasprzak 2023), hydrography (lakes, streams, surface melting spots and primarily glaciers (e.g. Kavan 2020, Kavan et al. 2022a, Wieczorek et al. 2023) or vegetation (Wołoszyn, Kasprzak 2023, Zmarz et al. 2023), using various algorithms can be crucial for more objective studies, especially of hard-to-reach regions. Moreover, it enables the creation of multi-temporal analysis and provides a source for comparable future studies in similar areas.

The main objective of this paper is to provide a review of remote sensing approaches for studies in the Arctic, also relevant in small catchments, based on the example of Spitsbergen, Svalbard.

This paper lists the available data sources and normalised difference indices that can contribute to the understanding and tracking of environmental responses in spatiotemporal studies.

Data and indices

The number of freely available satellite and photographic data has been increasing as are different applied methods. One of the oldest is, currently declassified, intelligence satellites — Key Hole mission mainly with CORONA satellite system (USGS 2008). The mission was carried out from June 1959 till October 1980 and provided >990,000 photographs of the Earth, with polar regions covered up to ca. 85° North and South — coverage map available at USGS (2023). Data provided by the above-mentioned mission have resolutions ranging from 1.8 m to 7.7 m. Although the lack of georeferencing and varying radiometric quality limits their usability (Shahbandeh et al. 2023) nevertheless they served as the basis for geomorphological, archaeological, technical, or land use and land cover as well as glaciological analyses (Lauzon et al. 2023). The high resolution of the data allows for its use in spatial analyses of smaller areas as opposed to the older data e.g. Landsat 1–3 satellite images with a resolution of 80 m, thus pixel covering 6400 m^2 (Ustin, Middleton 2021). For smaller areas such as small catchments, the resolution is highly important as it affects the interpretation of the datasets. Therefore, the oldest satellite data, apart from the intelligence satellites, should not be considered as precise but can be useful for spatiotemporal analysis over the region. With the growing spatial and spectral resolution more detailed analysis can be performed. Since the 1970s, when Landsat started operating the continuous evolution of sensors as well as the increasing number of satellites is pushing further the possibilities of use of the data they provide.

The below-mentioned satellites (Table 1) can be used for spatiotemporal analysis over small catchments in an almost 80-year timespan. The newest images, with higher resolution, enable more detailed analysis of various things, e.g. creeks, small water ponds, water stagnation areas, or geomorphological features such as patterned ground on smaller areas. Their analysis can have an impact on either modelling or predicting other similar environments around the world including populated regions.

The sensors on the satellites have changed and are advanced in technology, which led to variations in the algorithms used. Satellite data is composed of different bands that can be used for specific analyses. Some of them as red, green, or near-infrared bands are available from the beginning of the Landsat land observation data – since 1972, which allows us to have a 50-year-long remote analysis of the environment. The collection of freely available data with their bands can be found in the Table 2.

Even though the aforementioned Landsat and Sentinel images have a low resolution compared to commercial satellites, their availability and long measurement series make them highly valued. The Planet satellite images have high resolution (up to <4 m) and for research purposes can, upon prior justification, be made available at no charge. After the Landsat 7 Scene Line Corrector failure (Ustin, Middleton 2021), there was no well-functioning sensor therefore there was either a gap in data or other malfunctions (strips on images) which typically prevented research on their path. It is important to mention that wavelengths of certain bands differ as they become slightly narrower with progress in sensors (Ustin, Middleton 2021).

As a result of multispectral imaging, the unique properties of different environmental features allow for observation of e.g. ice, snow, water, and vegetation as their spectral response makes it possible to distinguish between them (Kääb 2005). The multi-decadal dataset enables to observation of the spatiotemporal trends over research areas and the creation of databases, e.g. vegetation (Ustin, Middleton 2021). The above-mentioned product – bands have been used to create algorithms, among which, one of the most popular methods is the analysis of normalised indices.

Normalised differences indices (NDI) are formed based on the following equitation,

$$NDI_{ij} = \frac{R_{ij} - 1}{R_{ij} + 1} = \frac{(DN_i - DN_j)}{(DN_i + DN_j)} \quad (1)$$

where DN of i and j are digital numbers of two bands (Schowengerdt 1997, Kääb 2005).

Table 1. Examples of potential data sources for polar studies based on Svalbard.

Data provider	Type of product/device	Start	Stop	Sensors	Repeat coverage [days]	Resolution	Extra information
NPI	Aerial photos	1936	1938	Panchromatic film	NA	18 × 18 cm film Geyman et al. (2022)	NPI dataset
NPI	Aerial photos	1960	1961	Panchromatic film	NA	1,270 dpi or 1,800 dpi (NPI aerial image archive)	NPI aerial image archive – available for purchase
NPI	Orthophotomap	2008	2012		NA	40 cm	The orthophotomap is freely available as WMS or WMTS in NPI dataset
USGS	CORONA (KH-1 to KH-4B)	1959	1972			1.8–7.7 m	From KH-4, thanks to panchromatic cameras, it is possible for DEM Dashora et al. (2007), Iacone et al. (2022) and Shahbandeh et al. (2023). Available for purchase at (earthexplorer.usgs.gov)
USGS	Landsat 1	23.07.1972	6.01.1978	RBV, MSS	18	80 m	
USGS	Landsat 2	22.01.1975	5.02.1982	RBV, MSS	18	80 m	
USGS	Landsat 3	5.03.1978	31.03.1983	RBV, MSS	18	80 m	
USGS	Landsat 4	16.07.1982	15.06.2001	TM, MSS	16	30 m/80 m	
USGS	Landsat 5	1.03.1984	01.2013	TM, MSS	16	30 m/80 m	
USGS	Landsat 7	15.04.1999	2022	ETM+	16	15 m/30 m/80 m	Error in scan line corrector (May 2003, Ustin, Middleton 2021)
USGS	Landsat 8	11.02.2013	Still operating	OLI, TIRS	16	15 m/30 m	
USGS	Landsat 9	27.09.2021	Still operating	OLI-2, TIRS-2	16 (overlap with L8)	15 m/30 m	
ESA	Sentinel 1A	3.04.2014	Still operating	SAR	6		Radar imaging
ESA	Sentinel 1B	25.04.2016	2022				
ESA	Sentinel 2A	23.06.2015	Still operating	MSI	5	10 m/20 m/60 m	Multispectral high-resolution imaging
ESA	Sentinel 2B	7.03.2017					
ESA	Sentinel 3A	16.02.2016	Still operating	The SLSTR, The ocean and land colour instrument, SAR	27		Multi-instrument
ESA	Sentinel 3B	25.04.2018					

DEM – digital elevation model; ETM+ – enhanced thematic mapper+; MSI – multi-spectral instrument; MSS – multi-spectral scanner; NIR – near-infrared; NPI – Norwegian Polar Institute; RSV – return beam Vidicon; SAR – synthetic aperture radar; SLSTR – sea and land surface temperature radiometer; TM – thematic mapper.

Table 2. Assignment of spectral bands to satellite individual bands.

	MSS	TM	ETM+	OLI and TIRS	Sentinel-2
Red	L1–L3 (Band 5), L4–L5 (Band 2)	Band 3	Band 3	Band 4	Band 4
Green	L1–L3 (Band 4), L4–L5 (Band 1)	Band 2	Band 2	Band 3	Band 3
Blue	NA	Band 1	Band 1	Band 2	Band 2
NIR	L1–L3 (Band 6 and 7), L4–L5 (Band 3 and 4)	Band 4	Band 4	Band 5	Band 8
SWIR1	NA	Band 5	Band 5	Band 6	Band 11
SWIR2	NA	Band 7	Band 7	Band 7	Band 12
TIR (TIRS 1 and TIRS 2)	NA	Band 6	Band 6	Band 10 – TIRS 1 Band 11 – TIRS 2	NA
PAN panchromatic	NA	NA	Band 8	Band 8	NA
Cirrus	NA	NA	NA	Band 9	NA
Coastal aerosol	NA	NA	NA	Band 1	NA

ETM+ – enhanced thematic mapper+; MSS – multi-spectral scanner; NIR – near-infrared; SWIR – short-wave infrared; TIR – thermal infrared; TM – thematic mapper.

One important dimension is that NDIs and band ratios partly limit the influence of the atmosphere and topography as they influence the bands alike (Holben, Justice 1981, Kääb 2005). The NDIs aim to highlight the presence of particular features in the images (McFeeters 1996) and their value ranges from −1 to 1.

Below are selected algorithms for tracking the changes in the environment, such as vegetation, glaciers, drainage systems, and snow cover.

For vegetation tracing the Normalised difference vegetation index (NDVI) with the following formula was established (Tucker 1979, Raynolds et al. 2008, Johansen, Tømmervik 2014, Urbański 2022):

$$NDVI = \frac{NIR - red}{NIR + red} \quad (2)$$

The NDVI is the oldest and one of the most popular indices in vegetation research, and it can be also used for water detection, e.g. creeks, as it has negative values. Here, the time of an image is crucial depending on flora flourishing. Therefore, conducting this index in unknown and uncharted areas can be tricky and may lead to some misinterpretations. One important factor is that some species with high chlorophyll may significantly alter the obtained values, e.g. algae in the polar regions (Zmarz et al. 2023). Moreover, in case of high reflectance on one side and shadow influence on the other in a research area the obtained values can be much higher/lower than that of the actual vegetation. On the other hand, the presence of vegetation or differences in its intensity can prove the stability, or instability - when no vegetation cover, of a ground (Kääb 2005, Kasprzak et al. 2020) which is useful in terrain analyses.

For Normalised difference snow index (NDSI), the following formula (Keshri et al. 2009, Hagolle et al. 2017, Florath et al. 2022, Urbański 2022) is used:

$$NDSI = \frac{green - SWIR1}{green + SWIR1} \quad (3)$$

Urbański (2022) presents $NDSI_{modyfied}$ where the multiplication by near-infrared (NIR) band is added to distinguish water from snow and ice. The formula is as follows:

$$NDSI_{modified} = \frac{green - SWIR1}{green + SWIR1} \times NIR \quad (4)$$

Normalised difference water index (NDWI) proposed by McFeeters (1996) stands as follows:

$$NDWI = \frac{green - SWIR1}{green + SWIR1} \quad (5)$$

NDSI and NDWI have a common area which causes misclassification of snow/water. Therefore Raghubanshi et al. (2023) subtracted MDWI from NDSI to receive only snow pixels.

NDWI was modified by Xu (2006) as

$$NDWI_{modified} = \frac{green - SWIR1}{green + SWIR1} \quad (6)$$

The NDWI was established based on the NDVI and aimed to obtain an image where the soil and land vegetation would have negative or 0 values so that water had positive ones (McFeeters 1996). It is important to mention that water turbidity on Svalbard varies among the archipelago and it makes e.g. lakes' detection harder, but using this knowledge can be auxiliary to asses general water turbidity (McFeeters 1996). The NDWI was used apart from the high influence on the results of a shadow, e.g. Svalbard lakes classification (Urbański 2022) or inventory (on Svalbard – Wieczorek et al. 2023 or on Greenland – How et al. 2021).

For sediment estimation input of inner catchment circulation to the environment, the Normalised Difference Suspended Sediment Index was introduced by Hossain et al. (2010) and used by Kavan et al. (2022b) to estimate the sediment release into the fjord in glacier-lake-fjord system in the High Arctic and the formula is as follows.

$$NDSSI = \frac{NIR - blue}{NIR + blue} \tag{7}$$

Normalised difference moisture index (NDMI) for remote sensing of liquid water in vegetation (Gao 1996, Wilson, Sader 2002, Xu 2006) is given by

$$NDMI = \frac{NIR - SWIR1}{NIR + SWIR1} \tag{8}$$

Wilson and Sader (2002) and Xu (2006) use thematic mapper (TM) band 5 for middle infrared (MIR). Therefore, the MIR was replaced with short-wave infrared (SWIR1) in the equations, and on Sentinel Hub, the components of the equation are NIR and SWIR1 as well (SCS n.d.)

Normalised difference glacier index (NDGI) (Keshri et al. 2009, Florath et al. 2022) is given by

$$NDGI = \frac{green - red}{green + red} \tag{9}$$

Normalised difference snow ice index (NDSII) (Keshri et al. 2009, Florath et al. 2022) is given by

$$NDSII = \frac{green - NIR}{green + NIR} \tag{10}$$

Normalised Difference Bare Ice Index in Sentinel 3 (Kokhanovsky et al. 2019) is given by

$$NDBI = \frac{blue - NIR}{blue + NIR} \tag{11}$$

The NDSI was used to distinguish snow and ice from the surrounding environment (debris) although the problem of supraglacial mapping was still existing (Keshri et al. 2009). The NDGI and NDSII were established for supraglacial mapping – distinguishing ice from snow and different snow cover used in glacier research in the Himalayas (Keshri et al. 2009) or Patagonian Icefield (Florath et al. 2022). Performing NDBI has been possible since the thematic mapper started operating. The bare ice index aimed to again distinguish the snow from the ice on glaciers (Kokhanovsky et al. 2019) which is a tipping point in glaciers melting. The application of this index on small glaciers, in my opinion, is rather uncertain as such areas may not be well visible and big enough to be detected. The indices are first calculated and then the results are interpreted, classified, or given a threshold (when using the hard classification approach, Kääb 2005) to obtain the final environmental results. The threshold determining is one of the classification methods (Kääb 2005), but as spectral reflectance highly varies in different regions, settings, data sources and time of the year (Florath et al. 2022) it is rather hard to show one universal value for the specific NDIs in different research areas. Florath et al. (2022) used four different classifications for snow and ice classes, among which a rule-based classification with experimentally set thresholds was applied for the indices. The above-presented data sources and difference indices can positively affect the studies carried out in polar and high-mountain sites.

Discussion

The difficult question is how to classify the data, which relies entirely on remote sensing. The interpretation of remote sensing data alone can be a cause for concern. It is imperative to carry out field studies synchronised with remote sensing to define the exact values of indicators in a given area. Nevertheless, the aforementioned indicators and the subjective classification of study areas are currently considered reliable, relatively fast and low cost.

Mountain environments, including the High Arctic catchments, are characterised by a large variation in land cover, so their spectral response cannot be interpreted straightforwardly and may differ from other scenes (Kääb 2005). Exact delineation of boundaries in the environment and therefore on NDIs is not always possible as a result of ongoing processes such as mass movements, ice melting or vegetation advances. It is worth noting that the bigger areas covered with certain features, e.g. snow, plants or debris within one pixel the more dominant feature will directly influence the result (Kääb 2005). The study of permafrost is an important aspect that should be mentioned. Even though it is hard to directly study the permafrost, via satellite images, it can be traced by characteristic features such as rock glaciers, thaw lakes or polygons (Lewkowicz, Duguay 1999, Frauenfelder et al. 2005, Frohn et al. 2005, Kääb 2005).

Remote sensing has been developing rapidly and the possibilities of applications are constantly increasing and both the technical and methodological possibilities are constantly evolving. Even though the spectral and spatial resolution is improving, many problems still occur. Some indexes have different modifications and some of them even refer to the same equations as NDSI and NDWImod.

Frequent cloud cover is one of the problems in Svalbard and some new methods were established to avoid or cope with small clouds (e.g. Gawlikowski et al. 2022, Yin et al. 2022) but the presence of a shadow is still an issue. The exclusion of such shadowed areas is essential. Nevertheless, this poses a challenge for spatio-temporal analysis, especially when comparing scenes from other satellites passing at different angles. Therefore, one could take, for example, the percentage area covered by vegetation from the undisturbed part of the scene. However, this brings in the fact that it is impossible to carry out a quantitative analysis, only a qualitative one. Here, using scenes from the same instrument, date and hour when the picture was taken would be the best method to avoid small disturbances in analysis. Nevertheless, when analysing multitemporal datasets it is almost impossible to prevent such situations. This results in a noticeable problem for a holistic approach to the catchments in an environmental approach and is a sticking point in remote sensing of small areas. As the Svalbard Archipelago is characteristic with its high mountain landscape, repeating shading is often visible especially within small catchments as the area in the shadow can be a significant of the total area. This means that these fields either cannot be used or must be included as disturbed reflection areas. What is more, the other sight of the catchment, which is under sunlight has – on the contrary – very high reflection which also alters the results. Therefore, the best catchments for remote sensing analysis would be the ones with an aspect which does not influence shadow-making with the flight path of a satellite – which is rare in mountainous areas. Unfortunately, when using multiple satellite data, they differ in the angle at which they fly above. It should be noted that this limits our study and restricts the study area, although it may contain important environmental data.

Conclusions

In summary, the use of aerial and satellite data is becoming increasingly applicable, particularly for inaccessible terrain. Algorithms for calculating significant environmental features can also be applied in Arctic or high alpine regions. NDIs can complement field surveys and enable analysis of larger areas, facilitating regional-scale studies. Some of these can be used with older satellite data to investigate temporal and spatial features, such as vegetation advance or rates of glacial recession. Obstacles such as frequent cloud cover or shade are inevitably encountered during surveys. Additionally, the polar night in the Arctic limits the time available for data collection. However, there are many opportunities, and research is greatly facilitated by the use of both old and new aerial and satellite data.

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