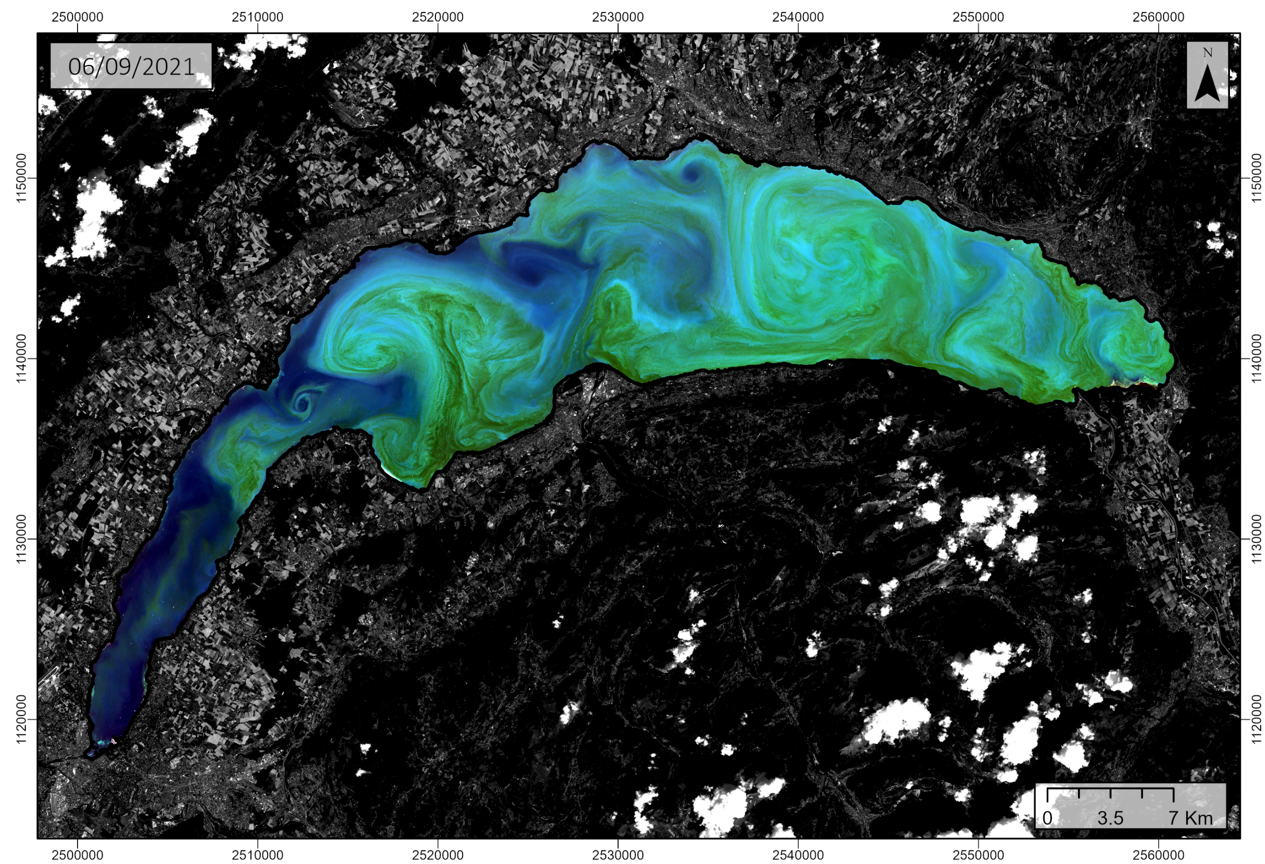
Switzerland from space

Travail de mémoire

Certificat complémentaire en Géomatique



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Abstract

The work presented here is the creation of an atlas of Switzerland from space using images obtained by different satellites orbiting the Earth. We use remote sensing to show how climate change is affecting Swiss landscapes and to illustrate how humans can also directly shape these landscapes. Readers are taken on a journey through some of the country's most emblematic places, discovering the spectacular scenery that Swiss nature has to offer.

For the creation of the images presented in this work we have employed different image processing techniques, widely used in the field of remote sensing to characterize and study the Earth's surface and its changes over time.

Résumé

Le travail ici présenté est la création d'un atlas de la Suisse depuis l'espace en utilisant des images obtenues à partir de différents satellites en orbite autour de la Terre. Nous utilisons la télédétection pour montrer comment le changement climatique affecte les paysages suisses, et pour illustrer comment l'homme peut aussi façonner directement ces paysages. Les lecteurs sont également emmenés dans un voyage à travers certains des lieux les plus emblématiques du pays, à la découverte des paysages spectaculaires que la nature suisse a à offrir. Pour créer les images présentées dans ce rapport, nous avons utilisé différentes techniques de traitement d'images, largement utilisées dans le domaine de la télédétection pour caractériser et étudier la surface de la Terre et ses changements au fil du temps.

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1. Introduction

Remote sensing is a technology that allows acquiring information from Earth's surface and its atmosphere using sensors/cameras installed on satellites, drones and airplanes. These devices measure reflected and emitted electromagnetic energy (EM) at specific wavelengths from the visible spectrum to the thermal infrared and more (Fig. 1). The information collected can be used for a variety of purposes, such as environmental monitoring, natural resource management, agriculture, natural disaster prediction, and mapping [1, 2].

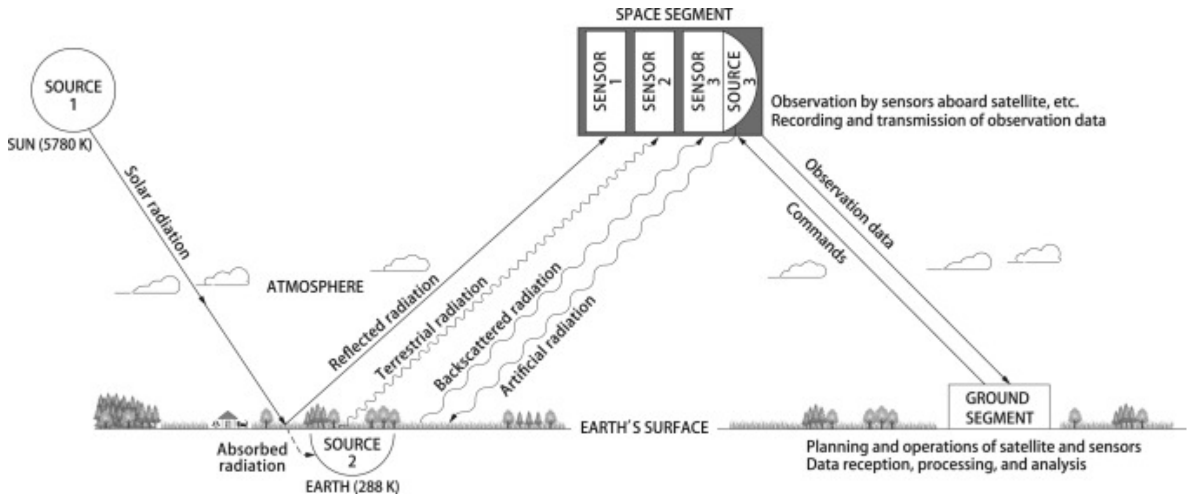


Figure 1: Schematic illustration of the remote sensing technology and its different components [3]

Several satellites currently orbit the Earth and measure the emitted or reflected radiation at different wavelength intervals, called bands. For each wavelength range, an image (also called a spectral band) of a specific location on Earth's surface is obtained. The space resolution of the images varies between satellites and sensors, ranging from 30 cm to 500 m per pixel.

Every object on the surface of the Earth has its unique spectral reflectance, which means that has its own way to interact with the incident radiation. For example, water bodies reflect radiation at wavelengths within the visible range of the EM spectrum, while vegetation does it in the near and intermediate Infrared range (Fig. 2). In remote sensing, the combination of different spectral bands allows to obtain highly detailed information about land cover, land use, vegetation, soil moisture, surface temperature, snow coverage, etc. [4].

Aided by the global positioning system (GPS), remote sensing satellites know their orbital position precisely. The frequency with which an image of a particular location is captured depends on the orbital period of the satellite (the amount of time that the satellite takes to complete one orbit around the Earth). Acquiring temporal image sequences of specific positions is of high utility since it allows tracking over time.

Thus, remote sensing imagery is a game-changer for environmental monitoring and management, as well as an extremely useful tool for mapping purposes [4-6].

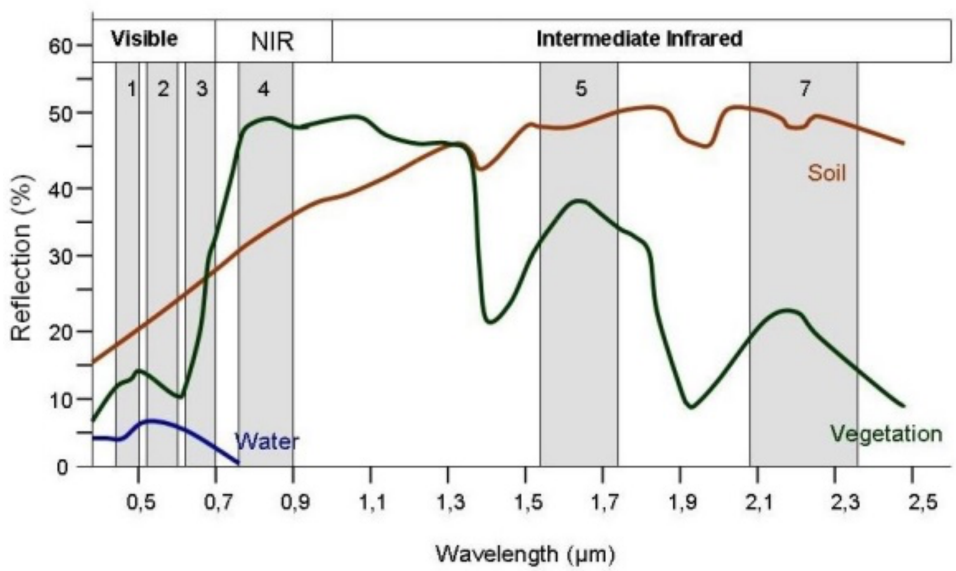


Figure 2: Spectral signatures of soil, vegetation, and water [7]

Monitoring environmental changes driven by climate change is one of the main applications of remote sensing [8]. It serves as an essential tool in assessing various phenomena such as glacier retreat, shifts in sea surface temperature, flood occurrences, alterations in terrestrial ecosystems, and numerous other impacts [4].

It has been proven that mountainous landscapes are undergoing major changes due to climate change [9]. In a mountain-dominated country like Switzerland, these changes are becoming more and more evident over time [10-12]. The use of remote sensing allows us to follow in depth the landscape evolution of this country.

2. Aim of the project

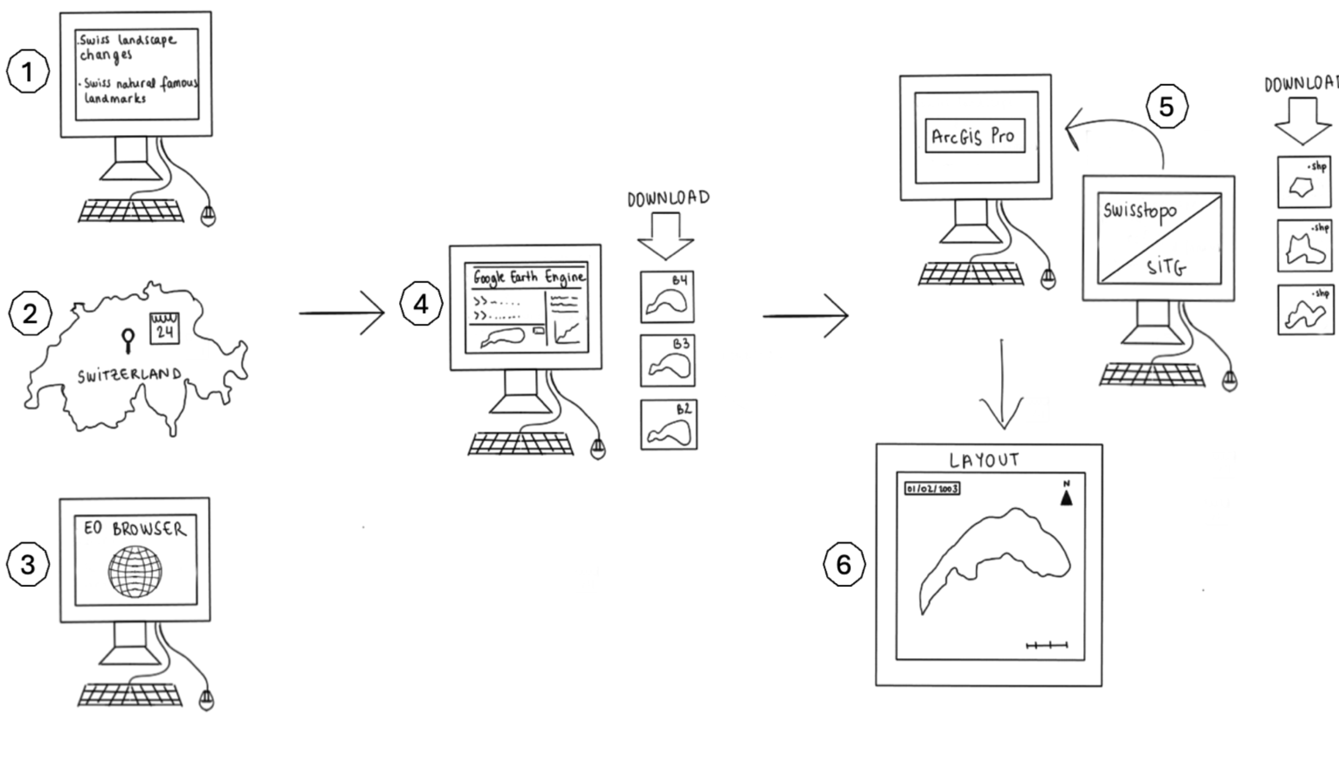
The United Nations Environment Program (UNEP) launched in 2005 the book "One planet, many people: Atlas of our changing environment" [13], in collaboration with organizations such as the US Geological Survey and NASA. In this book, satellite images and ground photographs were presented to describe and analyze humanity's impact on our environment. Inspired by this atlas, we aimed to leverage the diverse capabilities of remote sensing to create an atlas of Switzerland from space. Our objective is to process and present a series of satellite images illustrating:

- Significant transformations in the Swiss landscape over recent years, possibly triggered by climate change.
- Human influence on Swiss landscape dynamics.
- Most emblematic places of this country.

Through the creation of this work, we also want to discover the potential of remote sensing and its limitations.

3. Methods

3.1. Workflow



1. Gathering information about (1) Swiss landscape changes over time and (2) natural famous landmarks (official reports, scientific papers, newspapers, etc.).
2. Identification of (1) dates and places of interest regarding a specific change in Swiss landscape and (2) most emblematic locations of the country.
3. Checking if the identified landscape changes can be detected through satellite images using the Sentinel-Hub EO Browser portal.
4. Collecting images from different satellites and processing them using the tool Google Earth Engine (GEE) Code Editor.
5. Final processing using ArcGIS Pro (e.g. addition of layers from swissTopo and SITG, raster calculation, creation of clipped layers, band composites, etc.).
6. Images and map layout creation using ArcGIS Pro.

3.2. Information collection for identification of areas and dates of interest

Prior to the image gathering for the creation of this atlas, different sources of information were consulted in order to identify places and dates where major changes in the Swiss landscape took place. Additionally, information was also sought about the most relevant places in the country that are worth showing in this work. Among the different sources of information consulted, we included official sources (e.g. the Swiss Government and Cantonal websites and reports), reports from Swiss environmental commissions and associations, online newspapers, audio-visual resources (e.g. Swiss television news and documentaries), and peer-reviewed research articles.

3.3. Image collection, analysis, and layout

Image collection was performed using the online tool Google Earth Engine (GEE) Code Editor, working with the programming language JavaScript. Before starting the image collection, a preliminary investigation was carried out with the help of EO Browser from Sentinel Hub (https://apps.sentinel-hub.com/eo-browser/), in order to select the most suitable satellites, image collections, dates of acquisition of the images, and band combinations.

3.3.1. Satellites and image collections - Google Earth Engine

This atlas has been created with image collections provided by the satellites Modis (MOD09A1 MODIS Surface Reflectance 8-Day L3 Global 500m), Landsat 5 (USGS Landsat 5 Level 2, Collection 2, Tier 1), Landsat 8 (USGS Landsat 8 Collection 2 Tier 1 TOA Reflectance), and Sentinel-2 MSI (Harmonized Sentinel-2 MSI: MultiSpectral Instrument, Level-1C). The image collections used to create each image presented in this atlas are listed in their respective captions.

The mentioned satellites are equipped with different optical and/or thermal sensors that can capture information in various spectral bands (Tab. 1 to 4).

Modis			
Band Number	Description	Wavelength	Resolution
sur_refl_b01	Surface reflectance for band 1	0.620-0.670 µm	500 meter
sur_refl_b02	Surface reflectance for band 2	0.841-0.876 µm	500 meter
sur_refl_b03	Surface reflectance for band 3	0.459-0.479 µm	500 meter
sur_refl_b04	Surface reflectance for band 4	0.545-0.565 µm	500 meter
sur_refl_b05	Surface reflectance for band 5	1.230-1.250 µm	500 meter
sur_refl_b06	Surface reflectance for band 6	1.628-1.652 µm	500 meter
sur_refl_b07	Surface reflectance for band 7	2.105-2.155 µm	500 meter

Table 1: List of available bands and their associated wavelength ranges in Modis

Landsat 5			
Band Number	Description	Wavelength	Resolution
Band 1	Visible blue	0.45 - 0.52 µm	30 meter
Band 2	Visible green	0.52 - 0.60 µm	30 meter
Band 3	Visible red	0.63 - 0.69 µm	30 meter
Band 4	Near-Infrared	0.76 - 0.90 µm	30 meter
Band 5	Short-wave Infrared 1 (SWIR-1)	1.55 - 1.75 µm	30 meter
Band 6	Thermal	10.4 -12.3 µm	120 meter
Band 7	Short-wave Infrared 2 (SWIR-2)	2.08 - 2.35 µm	30 meter

Table 2: List of available bands and their associated wavelength ranges in Landsat 5

Landsat 8			
Band Number	Description	Wavelength	Resolution
Band 1	Coastal aerosol	0.433–0.453 µm	30 meter
Band 2	Visible blue	0.450–0.515 µm	30 meter
Band 3	Visible green	0.525–0.600 µm	30 meter
Band 4	Visible red	0.630–0.680 µm	30 meter
Band 5	Near-infrared (NIR)	0.845–0.885 µm	30 meter
Band 6	Short-wave infrared 1 (SWIR-1)	1.560–1.660 µm	60 meter
Band 7	Short-wave infrared 2 (SWIR-2)	2.100–2.300 µm	30 meter
Band 8	Panchromatic	0.500–0.680 µm	15 meter
Band 9	Cirrus	1.360–1.390 µm	30 meter
Band 10	Thermal Infrared 2 (TIRS-2)	10.6-11.2 µm	100 meter
Band 11	Thermal Infrared 2 (TIRS-2)	11.5-12.5 µm	100 meter

Table 3: List of available bands and their associated wavelength ranges in Landsat 8

Sentinel-2 MSI			
Band Number	Description	Wavelength	Resolution
Band 1	Coastal Aerosol	0.433–0.453 µm	60 meter
Band 2	Visible blue	0.458–0.523 µm	10 meter
Band 3	Visible green	0.543–0.578 µm	10 meter
Band 4	Visible Red	0.650–0.680 µm	10 meter
Band 5	Red Edge 1	0.698–0.713 µm	20 meter
Band 6	Red Edge 2	0.733–0.748 µm	20 meter
Band 7	Red Edge	0.733–0.793 µm	20 meter
Band 8	Near Infrared (NIR)	0.785–0.900 µm	10 meter
Band 8a	Near Infrared narrow (NIRn)	0.855–0.875 µm	20 meter
Band 9	Water vapor	0.935-0.955 µm	60 meter
Band 10	Short Wave Infrared (SWIR) /Cirrus	1.360-1.390 µm	60 meter
Band 11	Short Wave Infrared 1 (SWIR-1)	1.465-1655 µm	20 meter
Band 12	Short Wave Infrared 2 (SWIR-2)	2.100-2.280 µm	20 meter

Table 4: List of available bands and their associated wavelength ranges in Sentinel-2 MSI

3.3.2. Image preparation and analysis - Google Earth Engine

For the creation of this atlas, satellite bands were combined in multiple ways, depending on the feature that had to be characterized on the images (Fig. 3, Tab. 5). The different band combinations used to create the images presented here are listed in their respective image captions.

Band	Natural color	Geology	Urban areas	Burn areas	Water
R	Red	SWIR-2	NIR	SWIR-2	NIR
G	Green	SWIR-1	Red	NIR	SWIR-1
B	Blue	Blue	Green	Red	Red

Table 5: Band combinations used in this atlas.

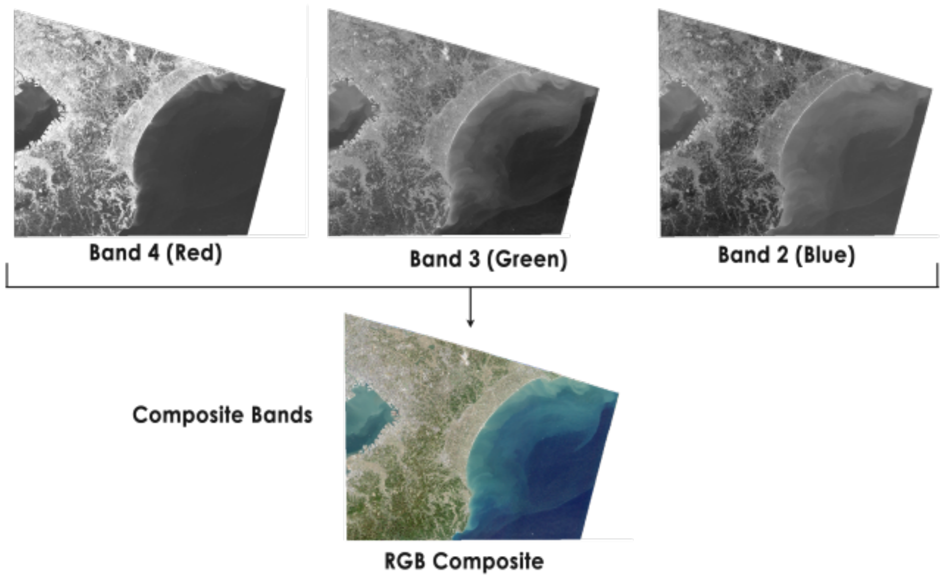


Figure 3: Example of a natural color band combination in Sentinel-2 MSI [14]

Index calculation

Different indices were also calculated such as the Normalized Difference Vegetation Index (NDVI) to assess health and density of vegetation, the Normalized Difference Snow Index (NDSI) to identify snow, and the Normalized Difference Water Index (NDWI) for water body detection (Tab. 6). The different indexes calculated to create the images presented in this atlas are listed in the respective captions.

Index	Formula
NDVI	(NIR - Red) / (NIR + Red)
NDSI	(Green - SWIR) / (Green + SWIR)
NDWI	(Green - NIR) / (Green + NIR)

Table 6: Indices used in this atlas and their respective formulas.

Multi-Temporal composite

In some cases, multi-temporal composites were created. For the preparation of this atlas, we obtained composites for a specific time frame and location where each pixel value was the median of all the pixels from the image stack.

Cloud masking

To avoid having cloud interferences when creating multi-temporal composites, different cloud masking algorithms were applied depending on the image collection. We used the algorithms provided by GEE.

Pan-sharpening (Landsat 8)

When comparing images between Landsat 8 and Sentinel-2 MSI collections, differences in band resolution could be a problem. Indeed, resolution of Landsat 8 bands are 30 m versus 10/20 m for Sentinel-2. To solve this problem, we performed pan-sharpening of Landsat 8 bands, which is a process that enhances the resolution of the bands by fusing them to the panchromatic band of Landsat 8 (which is the only one having a high spatial resolution of 15 m). In GEE, the pan-sharpening process was possible by using two methods: rgbToHsv () and hsvToRgb ().

3.3.3. Google Earth Engine Code Editor Scripts

All the generated codes for image collection and analysis are available here.

3.3.4. Vector addition, raster calculator, clipping, and band adjustment – ArcGIS pro

Exported images from GEE were then processed with the software ArcGIS Pro. In some cases, the software was used to add vector features, mainly to show geographical limits of areas of interest. These files were first downloaded from the database of the territorial information system of Geneva (SITG) and the Federal Office of Topography (swisstopo).

Several tools provided by ArcGIS Pro were very useful for the image geoprocessing. For glacier retreat assessment, the Raster Calculator tool was used, allowing to perform a subtraction between two monoband layers. The Clip Raster function tool was also used to cut raster images within a specific polygon (here we used it to clip Lake Geneva, and Geneva and Vaud cantons).

3.3.5. Projected coordinate system – ArcGIS Pro

The projected coordinate system selected to prepare the images and maps presented in this atlas is the CH1903+_LV95, which is the Swiss official reference system since the beginning of 2017. The "absolute" accuracy of the coordinates throughout Switzerland is within 1 to 2 centimeters for the horizontal component, and 2 to 3 centimeters for the ellipsoidal height [15].

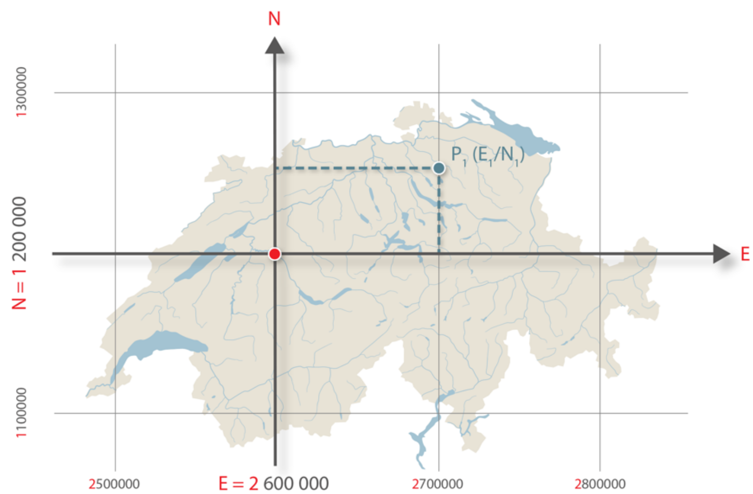


Figure 4: Image of Switzerland with the CH1903+_LV95 coordinate system [15]

Although images obtained with GEE had the WGS84 reference system, it was possible to change it to the CH1903+_LV95 using ArcGIS Pro.

4. Results

Results are presented as a small atlas of Switzerland, including an introduction (section 4.1.), and three main sections: 4.2. Impact of climate change on Swiss landscape, 4.3. Nature-human interactions, and 4.4. Swiss natural wonders.

4.1. Introduction

Switzerland, in the heart of Europe, is a country of breathtaking landscapes. Majestic mountains, serene lakes, verdant forests and meadows make this country a unique place in terms of biodiversity and natural resources.

Due to its topography and wide range of altitudes, Switzerland presents many microclimates and hosts a wide variety of plant and animal species (approximately 50,000 species of plants, fungi, and animals) [16]. The country is divided in six main biogeographic regions: Jura, Central Plateau, Northern Alps, Eastern Alps, Western Alps, and Southern Alps (Fig. 5). The mountain ranges Alps and Jura, are a fundamental part of the Swiss identity, occupying two-thirds of the country.

Switzerland is not only defined by its natural environment. It is also the country of 8.8 million inhabitants, living in the 26 cantons that compose the Swiss Confederation (Fig. 6). Most inhabitants are mainly settled in the Central Plateau, where we found the biggest cities: Zurich, Geneva, Basel, Lausanne, and Bern (in decreasing order of number of inhabitants) (Fig. 5). Swiss urban development tries to coexist with nature preservation. However, the rapid growth of urban areas, as well as climate change, are exerting constant pressure on the Swiss natural environment. From retreating glaciers to more frequent flooding episodes, Swiss landscapes and urban areas are undergoing rapid evolution, presenting important challenges for conservation and adaptation.

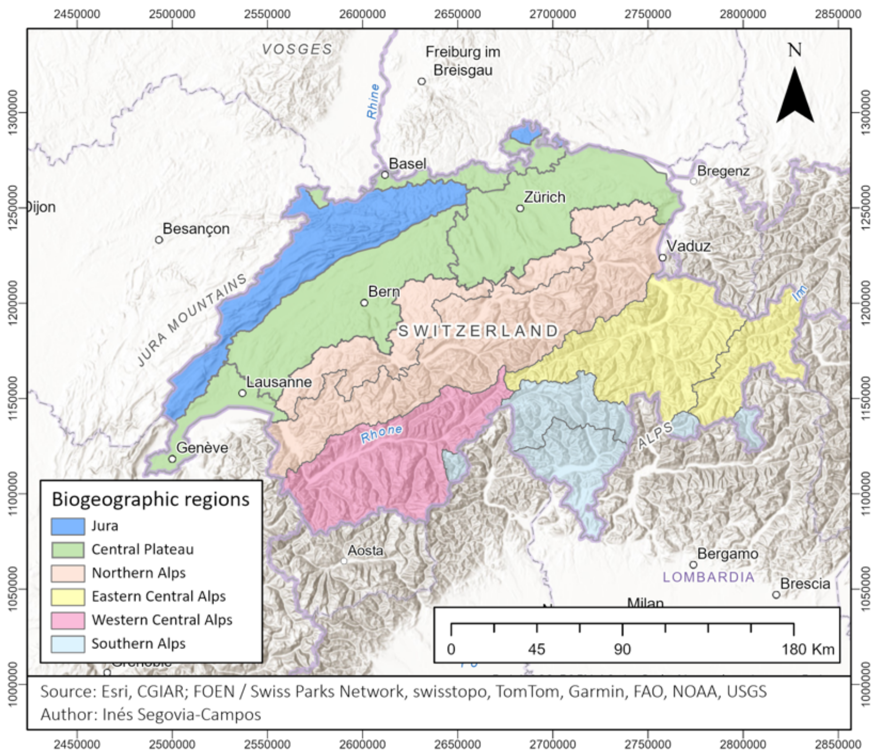


Figure 5: Biogeographic regions of Switzerland

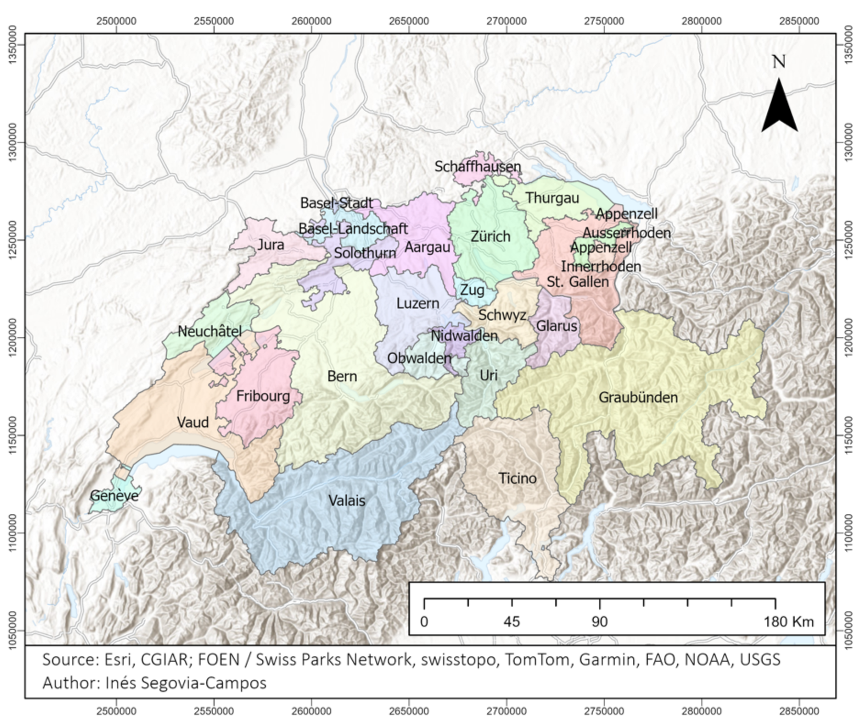


Figure 6: Cantons of Switzerland

4.2. Impact of climate change on Swiss landscape

4.2.1. Glacier retreat

Glaciers play a crucial role in regulating water resources and supporting biodiversity [17]. They also influence local and regional climate dynamics through their role in the hydrological cycle and their capacity to reflect light (albedo effect) [18]. However, excessive glacier melting and retreating are part of the current consequences of global climate change, triggering methane emissions, landslides, catastrophic rockfall, sea-level rise, but also contributing to the acceleration of climate change itself [18-20]. Unfortunately, Swiss glaciers are not spared from this phenomenon, as the rapid retreat of the country's major glaciers has clearly been observed over the last years [21].

4.2.1.1. Rhône Glacier

Rhône Glacier is located in canton of Valais, in the Urner Alps. It is the primary water source of the Rhône River and Lake Geneva. Despite human effort to slow down its retreat by installing UV-resistant fleecy white blankets [22], this glacier is also suffering from global warming. Since the early 1990s, the Rhône Glacier has steadily retreated. Since 2006, a lake has formed at the end of the glacier tongue, which increases in size every year [23] .

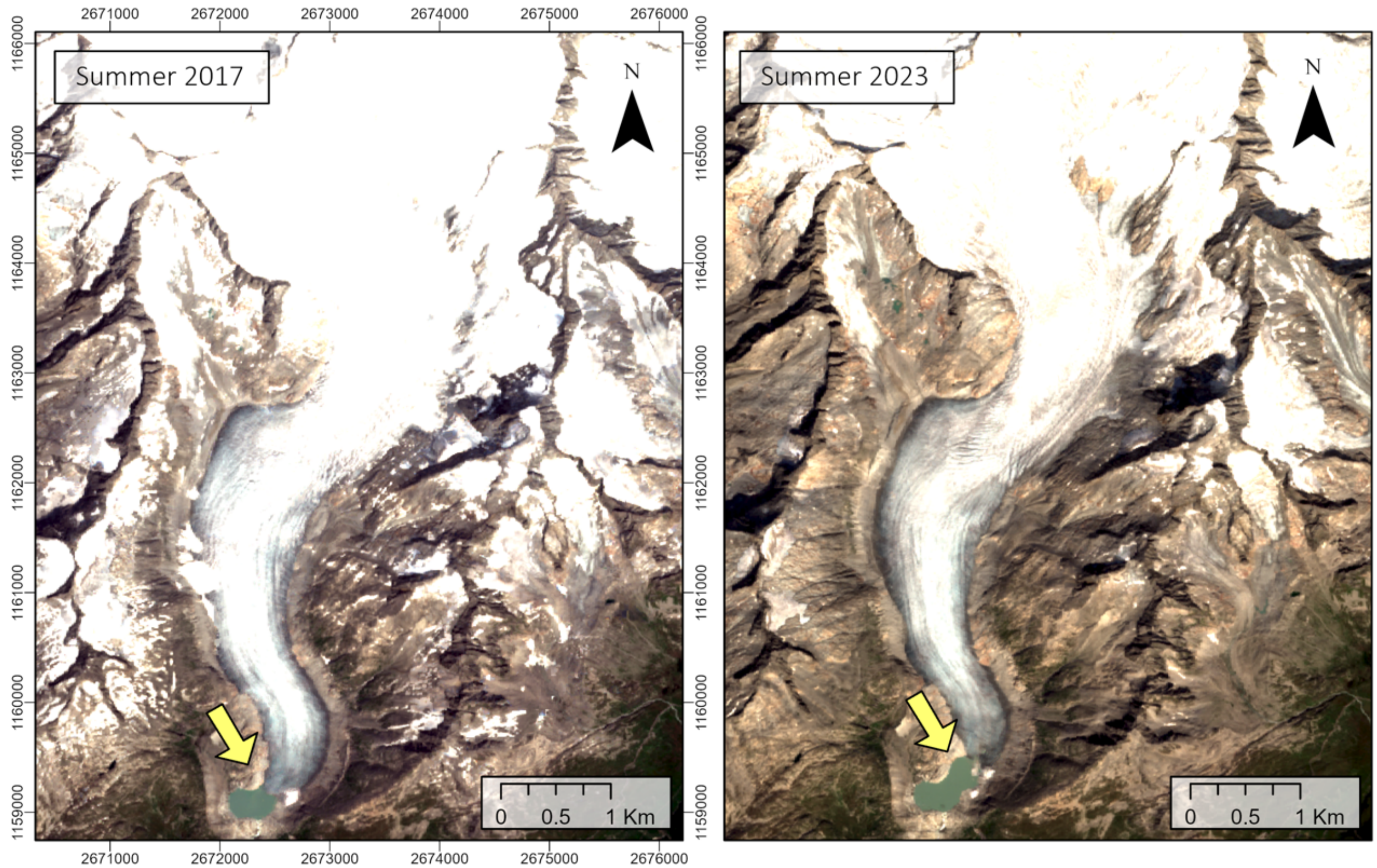


Figure 7: Rhône glacier - Summer 2017 vs summer 2023

These Sentinel-2 images were obtained by the combination of bands 4 (red), 3 (green), and 2 (blue) to obtain the natural color of multi-temporal composites where median values were calculated from images acquired between July 1 to September 30, 2017 and July 1 to September 30, 2023. Cloud masking was applied.

→ We can easily notice the retreat of the ice tongue, resulting in the growth of the lake surface.

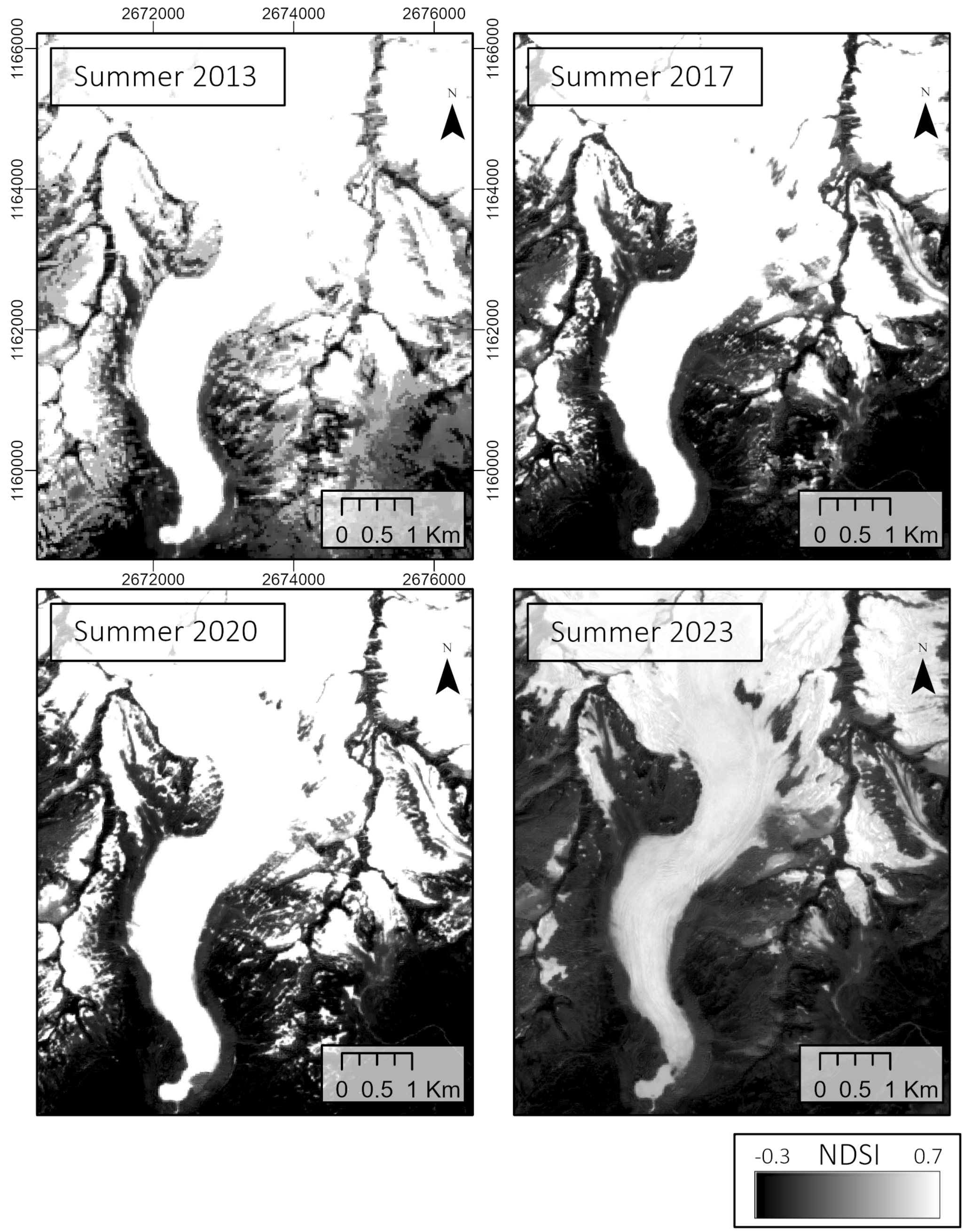


Figure 8: Rhône Glacier - Evolution of the summer NDSI from 2013 to 2023

The summer 2013 image was obtained by calculation of the Normalized Difference Snow Index (NSDI) with Landsat 8 images, using bands green (B2) and SWIR-1 (B6). A pan-sharpening was applied to improve the resolution before creating a multi-temporal composite where median values were calculated from images acquired between July 1 and September 30, 2013. Cloud masking was applied.

Images for summer 2017, 2020, and 2023 were obtained from the Sentinel-2 collection. The Normalized Difference Snow Index (NSDI) was also calculated using bands green (B3) and SWIR-1 (B11). These images are also the result of a multi-temporal composite where median values were calculated from images acquired between July 1 and September 30, 2017, 2020, and 2023. Cloud masking was also applied.

→ A decrease in snow and ice cover over the years can be easily observed.

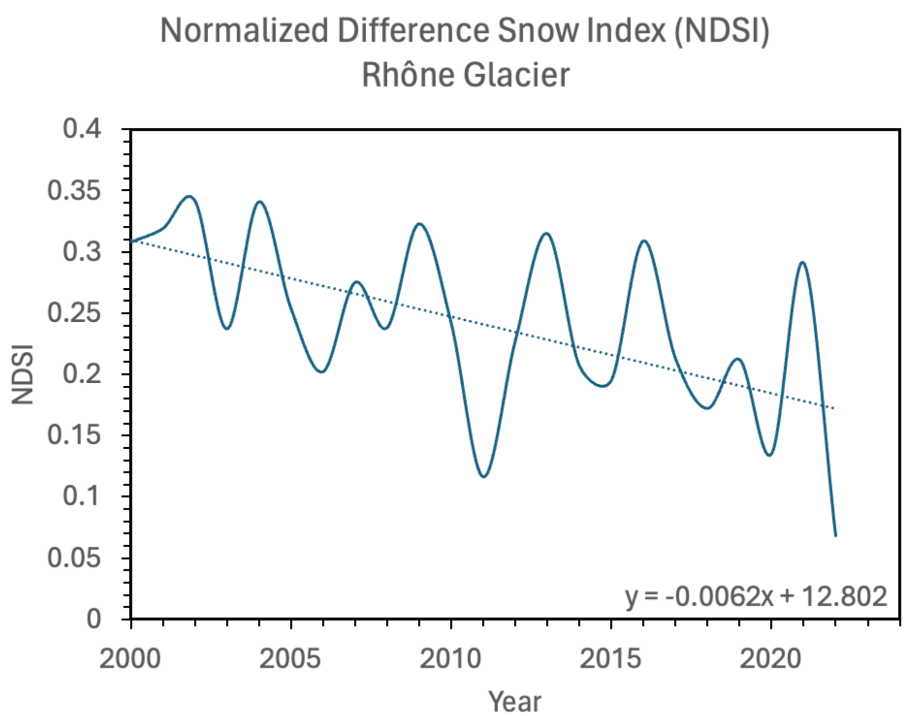


Figure 9: NDSI evolution of Rhône Glacier from summer 2000 to summer 2022

This graph was created from MODIS images. It includes the mean of the NDSI values calculated for the first week of August from 2000 to 2022 in the Rhône Glacier area.

→ A clear decrease of NDSI values can be observed over time.

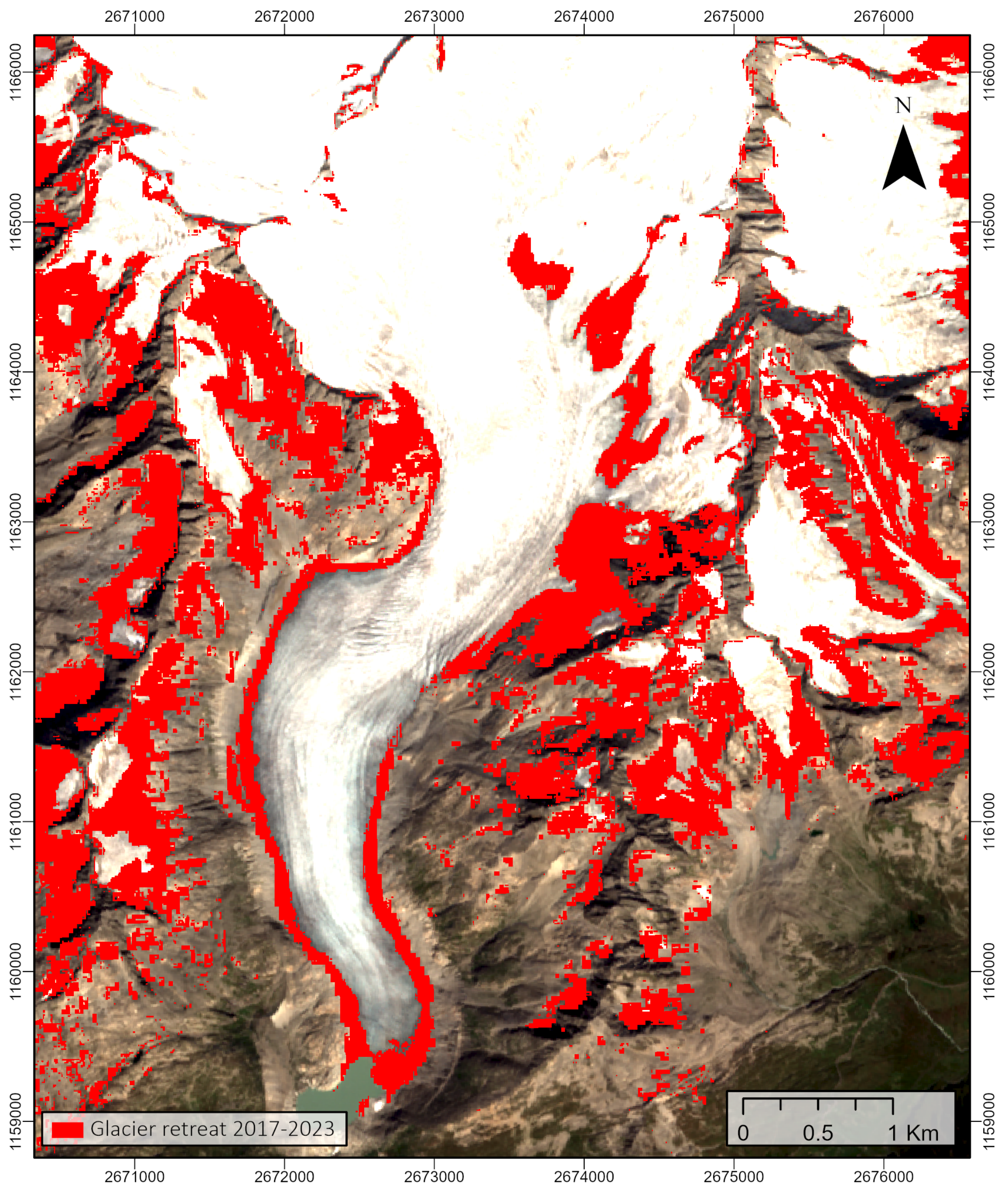


Figure 10: Rhône Glacier retreat between summer 2017 and summer 2023

This image was obtained by subtracting the 2023 NDSI raster to that obtained for 2017 (both in Fig. 8) using ArcGIS pro. Red areas correspond to those pixels where the difference of the subtraction was greater than 0.6. The base image is the one obtained for summer 2023 with the natural color band combination presented in Fig. 7.

→ The glacier retreat over the last five summers is clear.

4.2.1.2. Great Aletsch Glacier

Also located in canton Valais, the Great Aletsch Glacier is the largest glacier of the Alps. It stretches over 23 km and covers an area of about 81 km^2. The Great Aletsch Glacier is an UNESCO World Heritage Site and a popular destination for mountaineers. Over the past 40 years, the end of the glacier has shrunk by 1.5 km [24, 25]

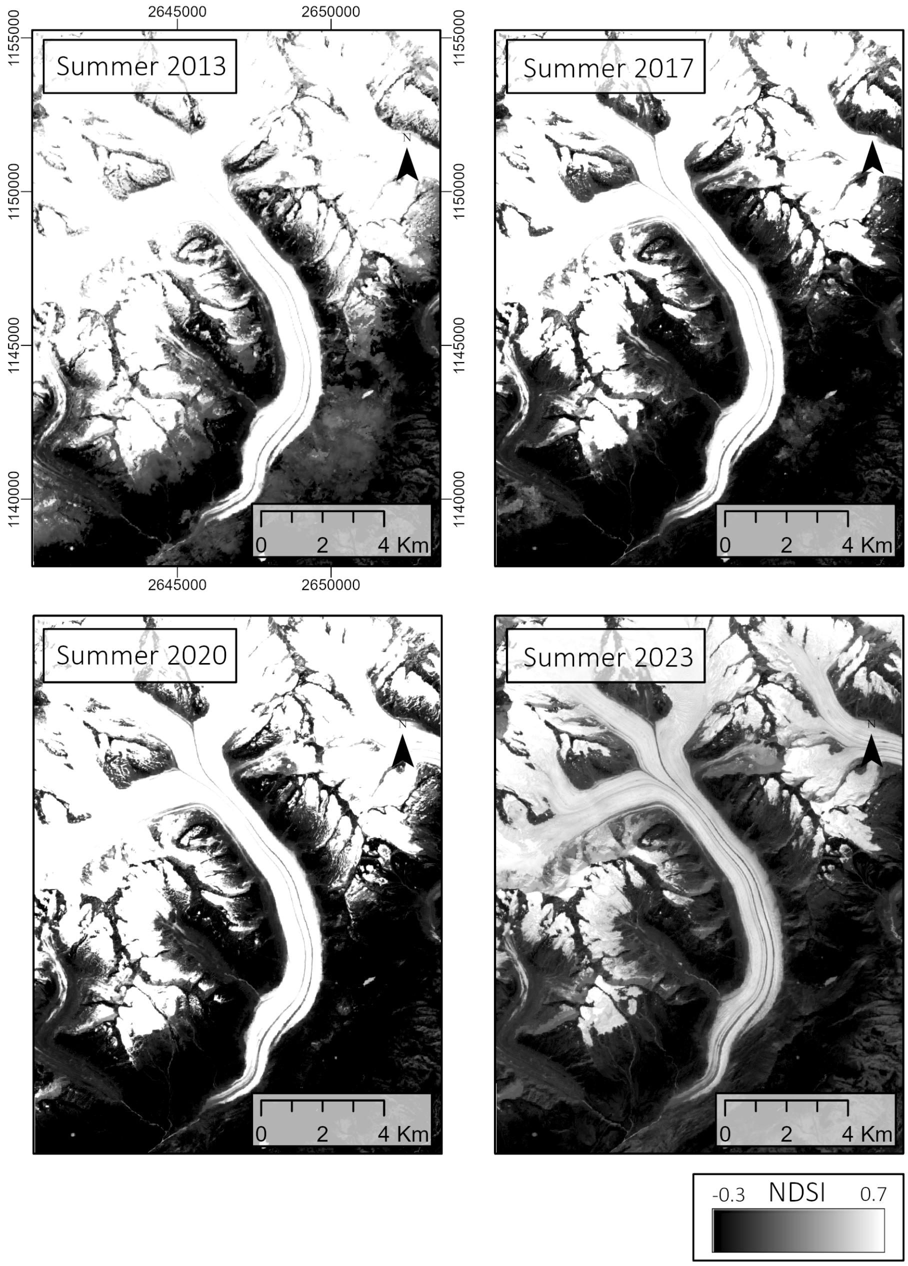


Figure 11: Great Aletsch Glacier - Evolution of the summer NDSI from 2013 to 2023

As for Rhône Glacier, the summer 2013 image was obtained by calculation of the Normalized Difference Snow Index (NSDI) using Landsat 8 images. For this index calculation, bands green (B2) and SWIR-1 (B6) were used. A pan-sharpening was applied to improve the resolution before creating a multi-temporal composite where median values were calculated from images acquired between July 1 and the September 30, 2013. Cloud masking was applied.

Images for summer 2017, 2020, and 2023 were also obtained from the Sentinel-2 collection. In this case, the Normalized Difference Snow Index (NSDI) was calculated using bands green (B3) and SWIR-1 (B11). These images are also the result of a multi-temporal composite where median values were calculated from images acquired between July 1 and September 30, 2017, 2020, and 2023. Cloud masking was also applied.

→ The decrease in snow and ice cover over the years can be easily observed.

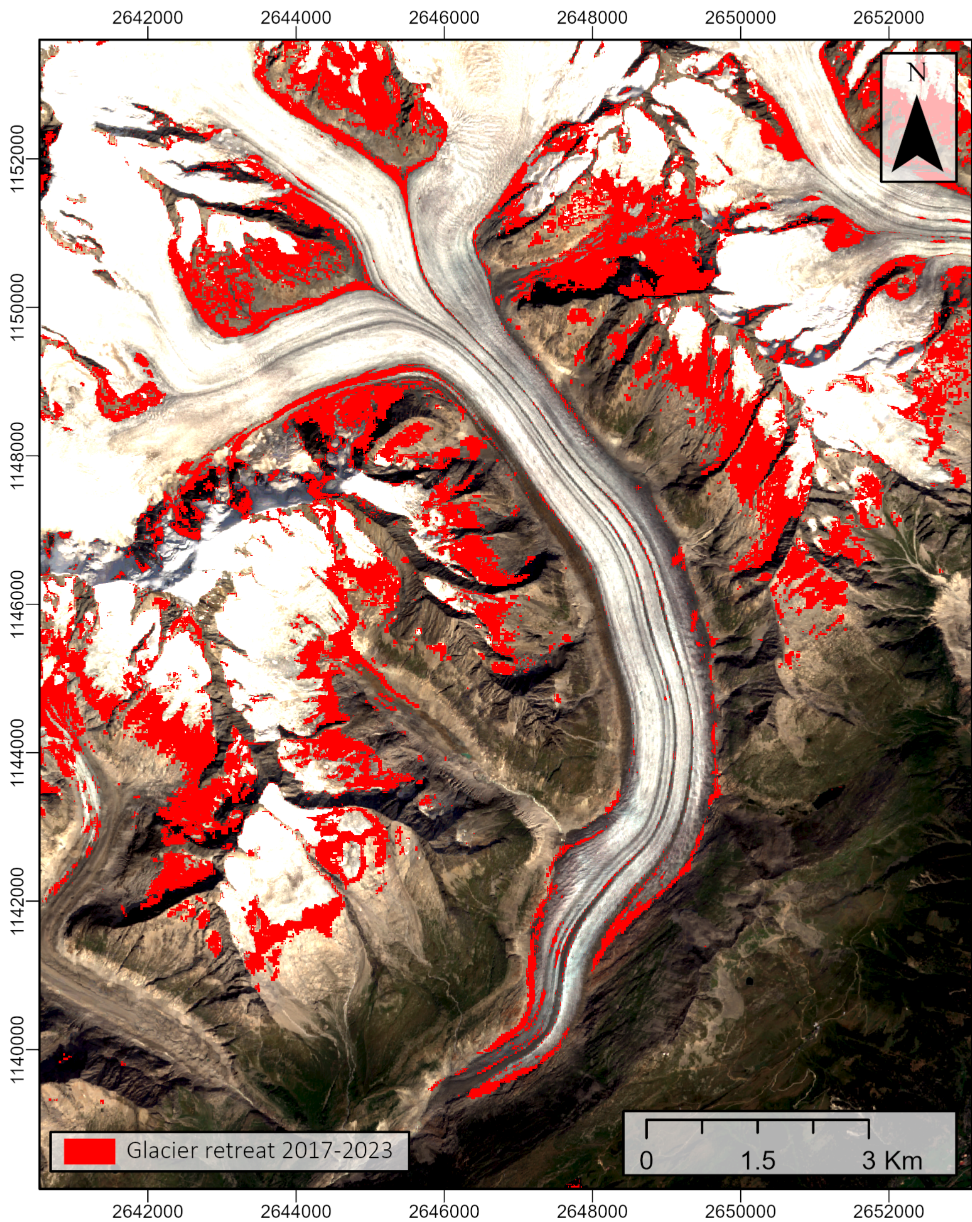


Figure 12: Great Aletsch Glacier retreat between summer 2017 and summer 2023

Same as Rhône Glacier, this image was obtained by subtracting the 2023 NDSI raster to that obtained for 2017 (both in Fig. 11) using ArcGIS pro. Red areas correspond to those pixels where the difference of the subtraction was greater than 0.6. The base image was obtained from the Sentinel-2 image collection. It was created with the natural color band combination red (B4), green (B3), and blue (B2) of a multi-temporal composite where median values from images acquired between July 1 and September 30, 2023 are shown. Cloud masking was applied.

→ The glacier retreat over the last five summers is clear.

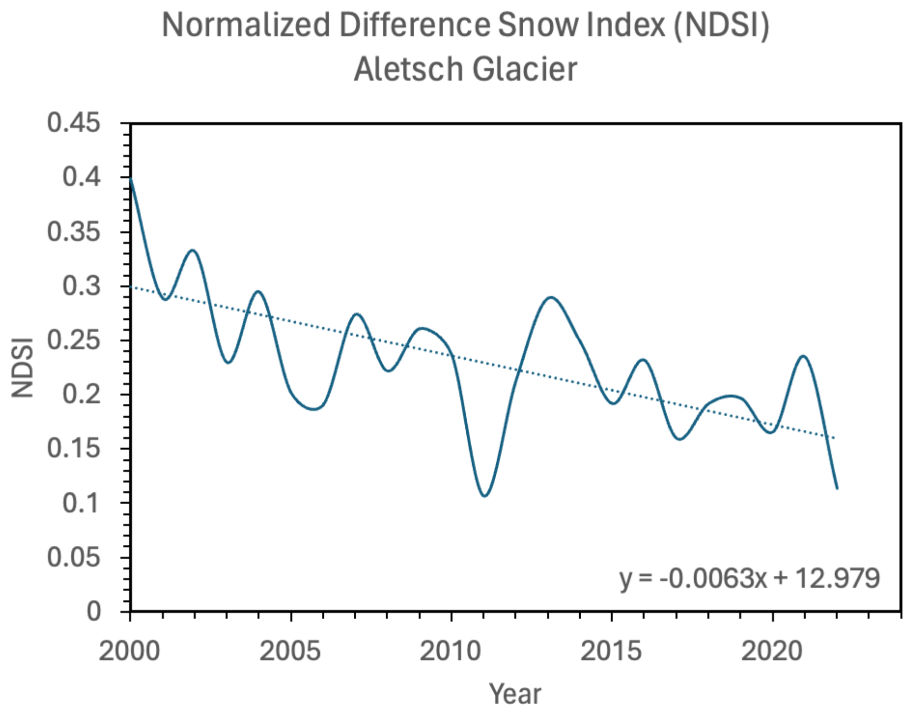


Figure 13: NDSI evolution of the Great Aletsch Glacier from summer 2000 to summer 2022

Like Rhône Glacier, this graph was obtained from MODIS images. It includes the mean of the NDSI values calculated in the first week of August from 2000 to 2022 in the Great Aletsch Glacier.

→ A decline of NDSI values over time is evident, mirroring a comparable trend seen in the Rhône Glacier during the same period.

4.2.2. Floods

As a mountainous water-rich country, Switzerland has a history of significant floods, which are expected to recur. Floods represent one of the most impactful natural hazards in the country, and their frequency is projected to rise due to climate change [26]. These events typically result from a combination of several factors, including heavy rainfall, rapid snowmelt, and saturated soil conditions. Furthermore, the increase in population density and infrastructure development in flood-prone areas increase the risk posed by flooding.

4.2.2.1. August 2005

In August 2005, torrential rains fell for days on vast regions of the northern slopes of the Alps, locally surpassing all previously recorded rainfall measurements. Within hours, the water level of certain lakes rose to unprecedented levels, streams and rivers turned into devastating torrents, and slopes began to slide. Several persons lost their lives and the material damages amounted to three billion Swiss francs [27].

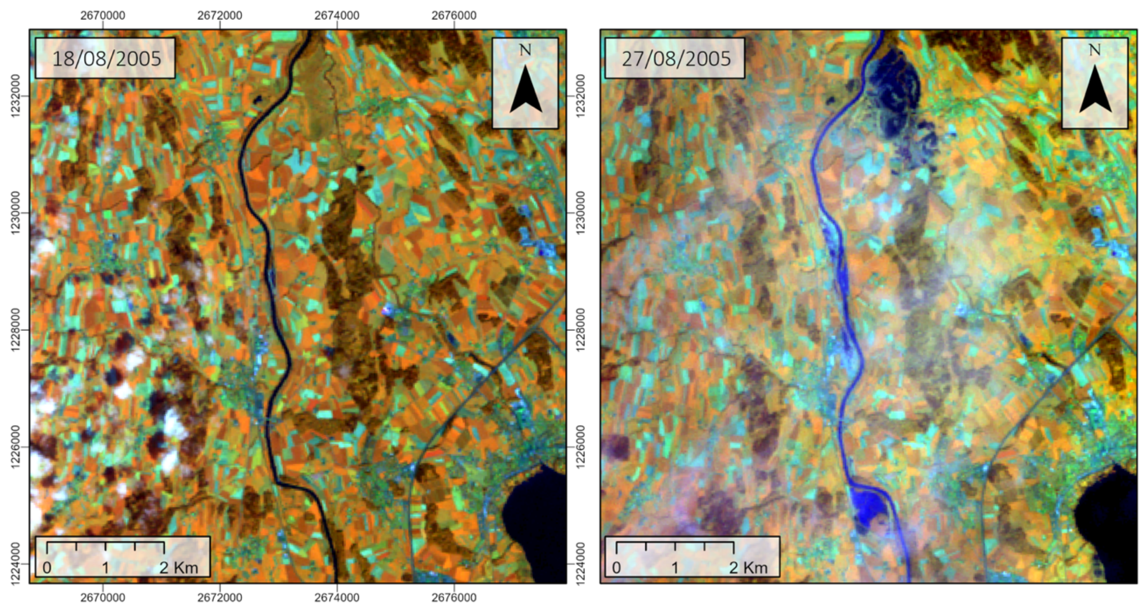


Figure 14: Flood in Oberrüti (Canton of Aargau) due to the overflowing of the Reuss river. Water bodies appear in dark blue and/or black

These images were taken by the Landsat 5 satellite on August 18 and 27, 2005. They were obtained by combining band B4 (NIR), B5 (SWIR-1), and B3 (red). No cloud masking was applied.

→ Despite the presence of clouds, large, flooded areas can be detected on the Reuss riverbank on August 27, 2005.

4.2.3. Landslide

A landslide is the movement of a mass of rock, debris, or earth down a slope under the direct influence of gravity. Mudflows (also called mudslides), together with rockfalls, are the most common landslide events occurring in Switzerland, frequent in all the country due to its mountain-dominated landscape, but also to the effect of climate change, including melting glaciers, thawing permafrost, and heavy rainfalls [28, 29].

4.2.3.1. Randa rockfalls

Between April and May 1991, the municipality of Randa, in Valais canton, was hit by massive rockslides. They occurred on the east face of the Weisshorn, a prominent mountain in the Pennine Alps near Randa.

The rockslides resulted in the displacement of more than 45 million cubic meters of rock, creating a major debris flow that descended into the valley below. The event caused widespread damage to infrastructure, including roads and buildings, and resulted in the loss of livestock. Fortunately, no human deaths were reported, as the area had been evacuated prior to the event due to concerns about the stability of the mountain [30].

The rockfalls in Randa serve as a reminder of the geological hazards present in mountainous regions and underscores the importance of monitoring and mitigating such risks to protect lives and property.

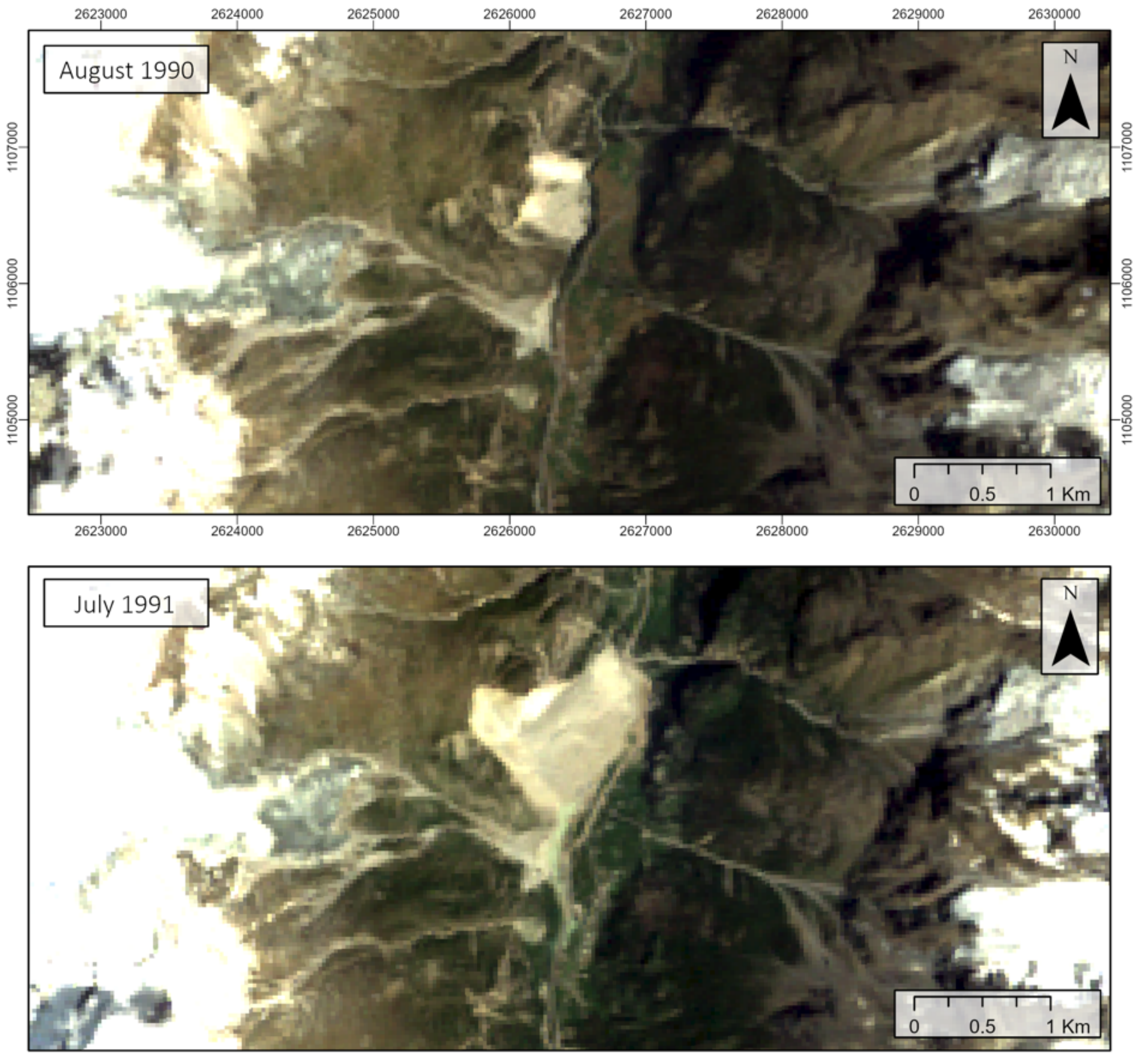


Figure 15: Randa rockfall - Before and after.

Landsat 5 images captured on August 2, 1990 and July 4, 1991. Natural color band combination (B3 (red), B2 (green), and B1 (blue)) was applied.

→ A surface increase of the detachment niche on the Weisshorn side is clearly visible after the rockslides of April and May 1991.

4.2.3.2. Bondo rockslide

A catastrophic rockslide also occurred on August 23, 2017 in the Swiss village of Bondo, located in the Grisons canton. The landslide was triggered by a combination of heavy rainfall and thawing permafrost, resulting in massive amounts of rock and debris tumbling down the Piz Cengalo Mountain. The landslide passed through the village of Bondo, destroying buildings, roads, and infrastructure in its path. Unfortunately, several hikers lost their lives [31].

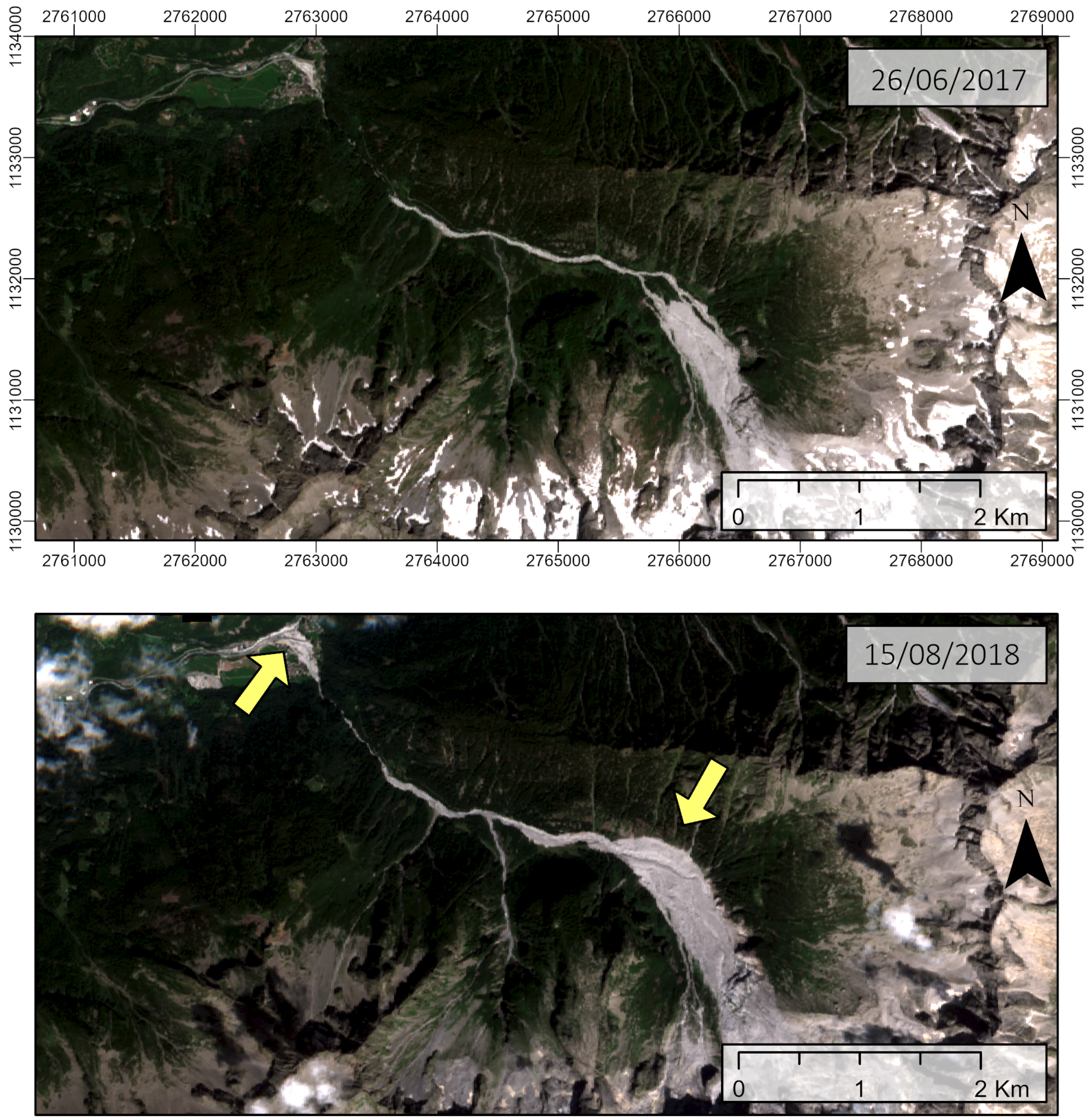


Figure 16: Bondo rockfall - Before and after

Sentinel-2 images were captured on June 26, 2017 and the July 4, 1991. Natural color band combination red (B4), green(B3), and blue (B2) was applied.

→ Deposition of rock debris are visible on the mountainside of the the Piz Cengalo as well as in the village of Bondo after the rockslide of August 2017.

4.2.4. Drought

Even the country of water is more and more frequently suffering from drought, especially during the summer. Indeed, a slight decrease in precipitation and an increased evaporation due to global warming are contributing to more frequent recurrence of these events [32]. Ecosystems, agriculture, forestry, and power stations are affected to a greater or lesser extent, depending on the duration of the event.

In summer 2022, Switzerland went through a historic drought. Lakes and watercourses experienced alarming reductions in water levels and flows, agriculture faced severe challenges, glacier retreat was accelerated, and forest fire risk increased [33]

4.2.4.1. Lac des Brenets

Several Swiss lakes are facing a decline in water levels attributed to prolonged periods of heat and dryness, particularly evident during late spring, summer, and early autumn. In Neuchâtel Canton, situated on the border between Switzerland and France, Lac des Brenets has already borne the brunt of drought conditions. Carved out during the Quaternary period by a glacier slide, this lake was nestled within a limestone and marl-limestone region of the Jura massif. Since the European drought of 2018, water levels of this lake have been significantly impacted, leading to complete drying out during the summer of 2022 [34].

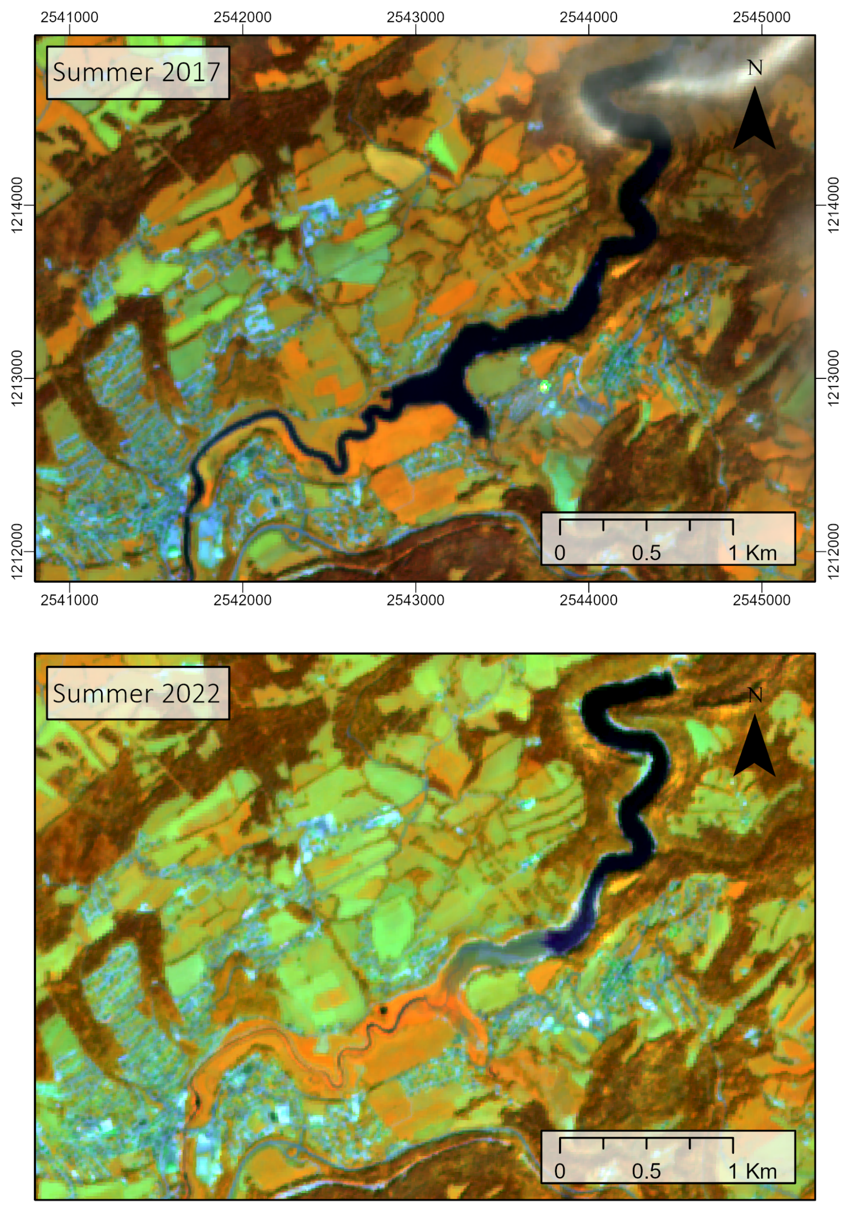


Figure 17: Drough in Lac des Brenets - Before and After. Water bodies appear in dark blue and/or black

Multi-temporal composites showing median values of Sentinel-2 images taken between July 1 and the September 30, 2017 and 2022. The selected band combination is B8 (NIR), B11 (SWIR-1), and B4 (red). Cloud masking was applied.

→ It can be clearly observed that the Lac des Brenets dried up in summer 2022.

4.2.4.2. Drought impact on agriculture

The severe drought of summer 2022 (especially during July) had diverse impacts on Swiss agriculture. Mountain agriculture, particularly in the Jura and several regions of the Prealps like the Bernese Oberland and the canton of Fribourg, suffered from it. Indeed, some farmers had to anticipate the descent from the mountain pastures (known as "désalpe" in French), while others had to bring up extra fodder to feed their livestock in the alpine pastures [33].

Some types of fruit and vegetable crops were also affected. Losses were also observed in potato cultivation, with a decrease of around 10% compared to the five-year average. The apple harvest also saw a decline of 6.5% compared to the ten-year average [33, 35].

On the other hand, this drought was a victory for winegrowers, since their production increased by 63% over the previous year. This abundant harvest marked an important milestone, as the last equally abundant harvest dates back to 1957.

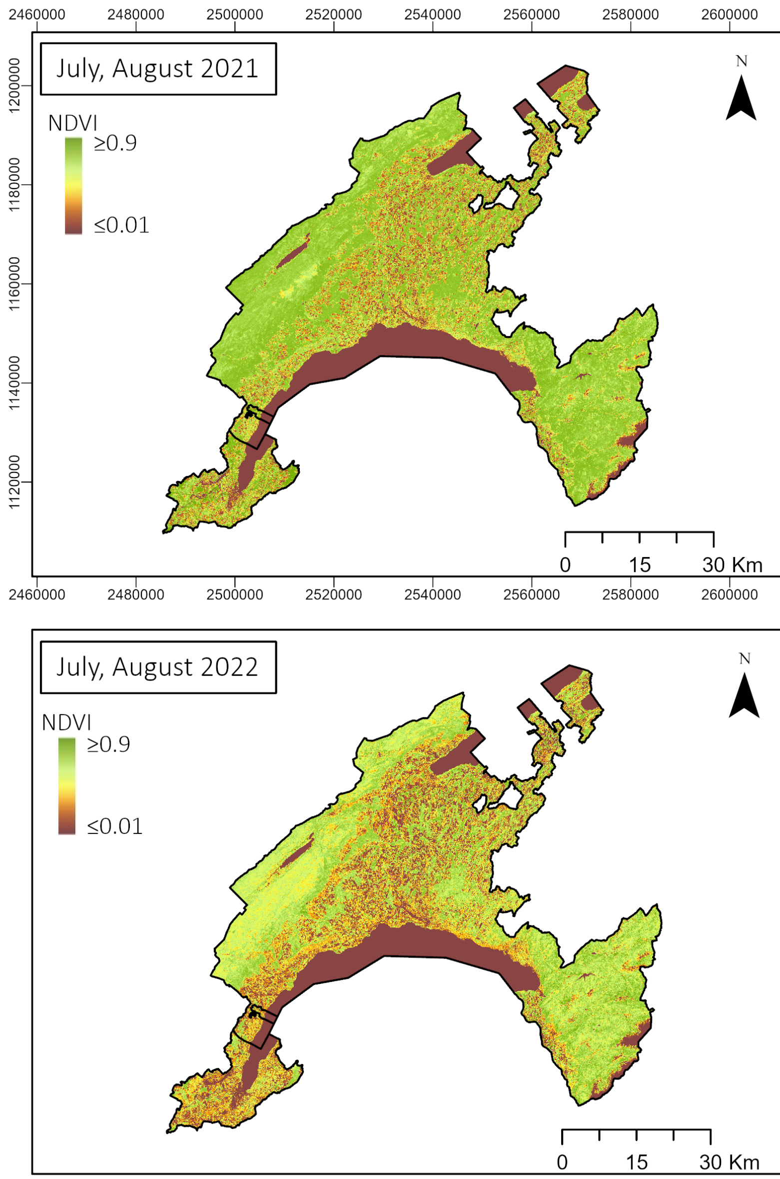
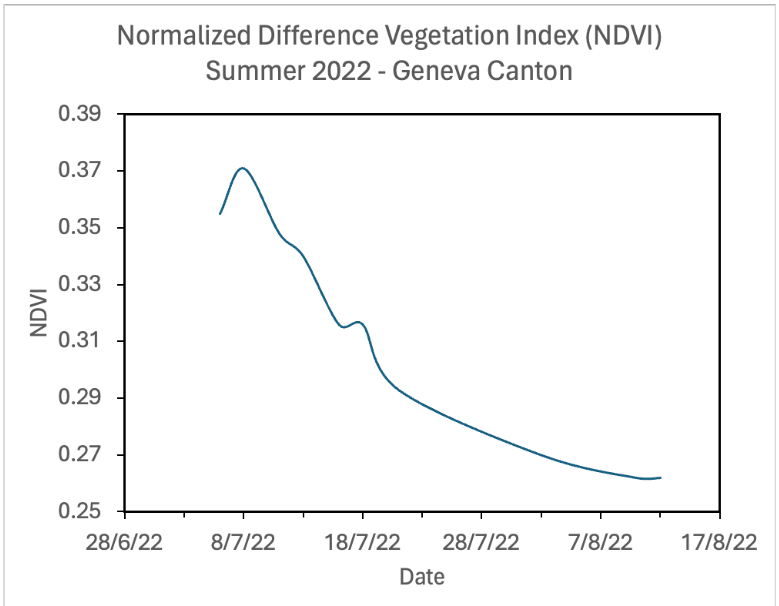


Figure 18: Summer NDVI in Western Switzerland (Geneva and Vaud cantons) - 2021 vs 2022

These multi-temporal composites show the median values of the Normalized Difference Vegetation Index (NDVI) calculated with Sentinel-2 images captured between July 1 and the August 31, 2021 and 2022. A cloud mask was applied. Images were clipped within the geographical limits of Geneva and Vaud cantons (downloaded from swisstopo database).

→ A decrease of NDVI values is clearly observed for the summer 2022 compared to 2021, in both agriculture and mountainous areas.



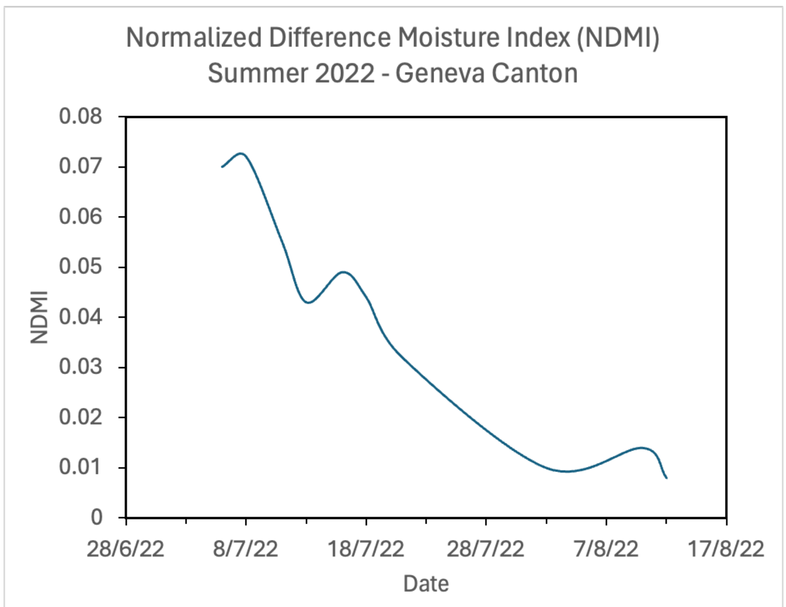


Figure 19: NDVI and NDMI evolution during summer 2022 - Geneva and Vaud

Both graphs have been obtained from Sentinel-2 images captured between July 6 and August 12, 2022 in the Geneva and Vaud region. Mean NDVI and NDMI values of the region are plotted over time. Cloud masking was applied.

→ Both indices strongly decreased over summer 2022, showing the severity of the drought in this region of Switzerland.

4.2.4.3. Forest fires – Leuk

Proliferation of forest fires is also a consequence of drought during summer. On August 13, 2003, a fire, started by one person, quickly spread through the Leuk forest (Valais canton), burning 200,000 trees in 450 hectares [36].

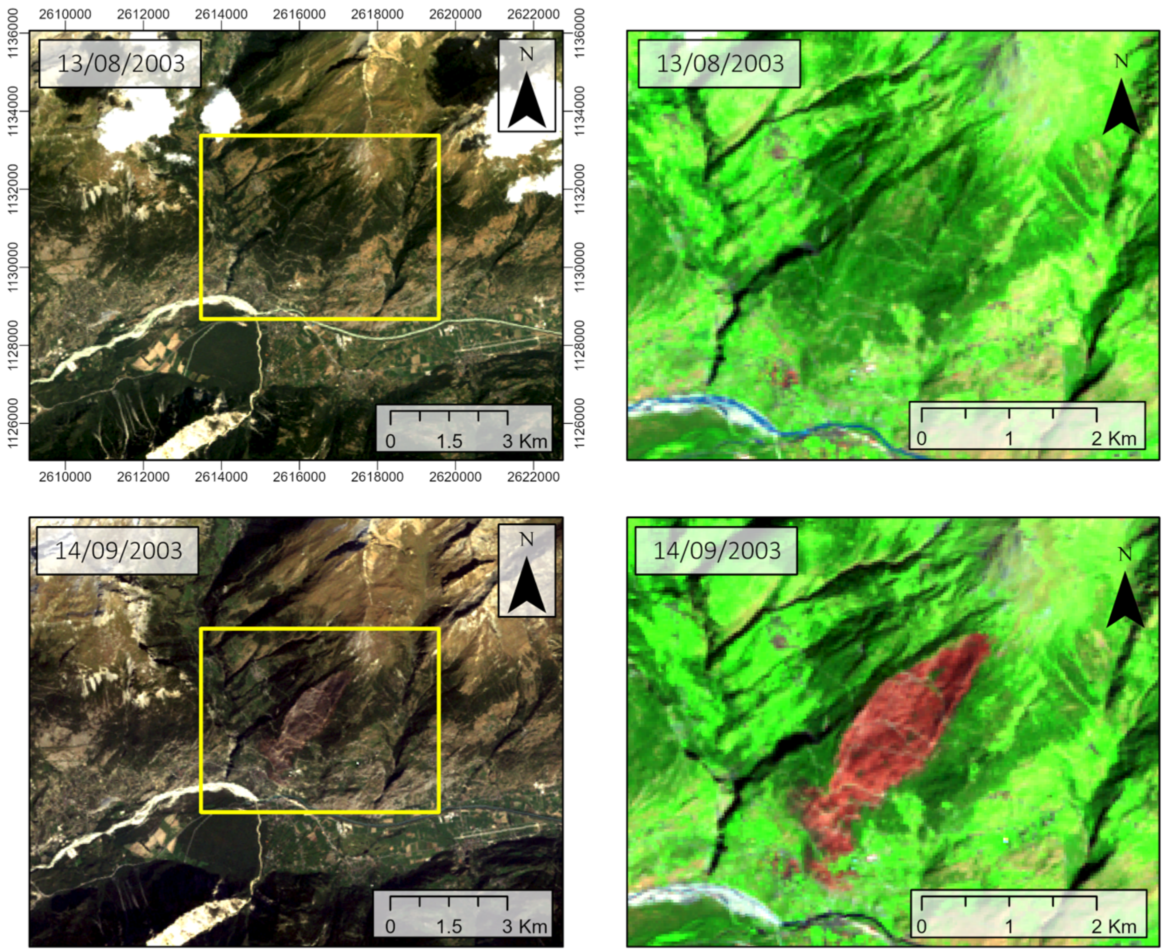


Figure 20: Leuk forest fire - Before and after

Landsat 5 images captured on August 13 and September 14, 2003. Images on the left present the natural color band combination red (B3), green (B2), and blue (B1). Yellow rectangles indicate the zoomed area shown in left images that were created by combining bands SWIR-2 (B7), NIR (B4), and red (B3) to highlight the burned forest.

→ In the image captured on September 14, 2003 we can observe that the fire affected approximately a 3-km long surface of forest.

4.2.4.4. Forest fires- Bitsch

Another example of summer forest fires is the fire that took place in July 2023 in the forest located in the municipality of Bitsch, in the canton of Valais. Active for three weeks, the flames affected an area of 132 hectares, including approximately 35 hectares of steep terrain. Around three-quarters of the trees (mainly spruce trees) were burned in the affected area [37]

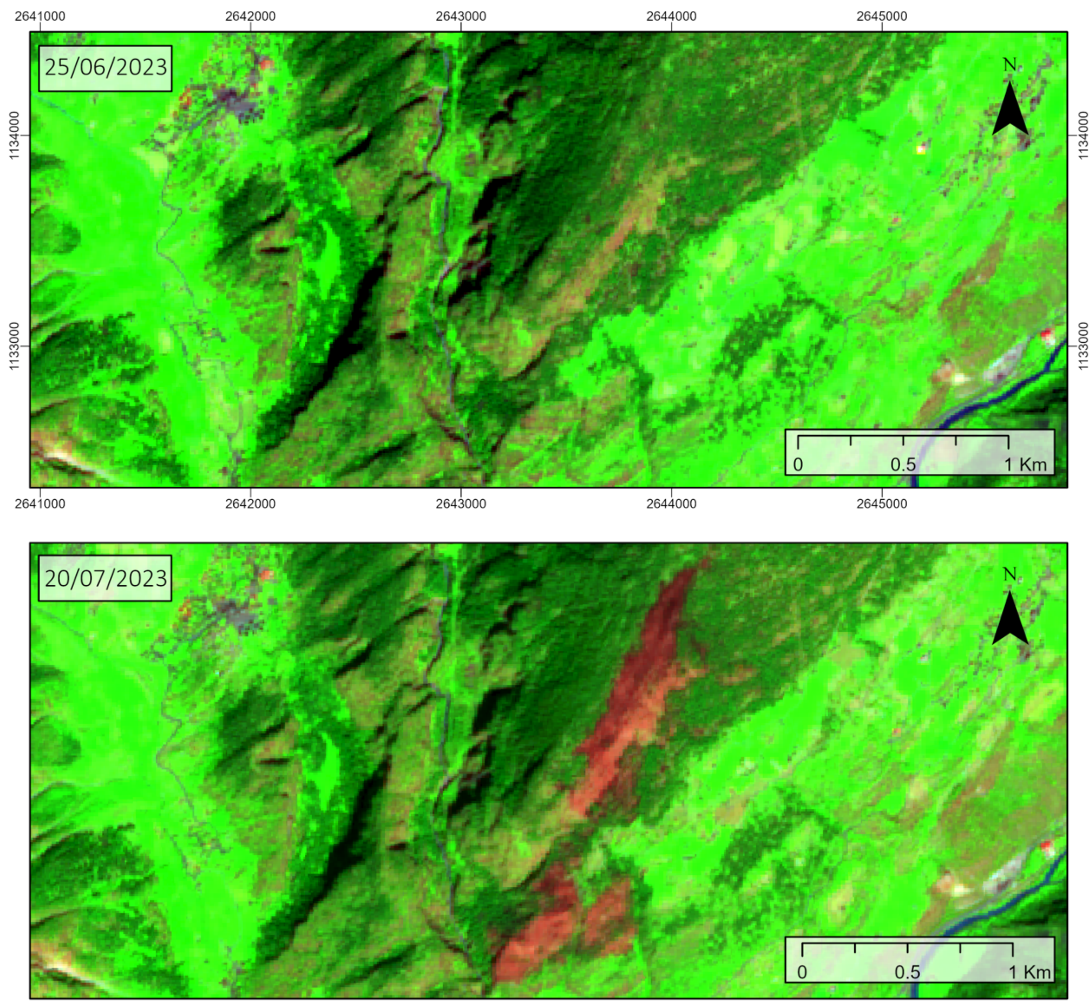


Figure 21: Bitsch forest fire- Before and after

Sentinel-2 images captured on June 25 and September 20, 2023. To highlight the burned area, the band combination SWIR-2 (B12), NIR (B8) and red (B4) was applied.

→ An extended burned area can be easily observed in the forest of Bitsch after the fire that took place in July 2023.

4.3. Nature-human interactions

Human interactions with nature are diverse, ranging from harmonious coexistence to destructive exploitation. Humans have always depended on nature for resources and sustenance, shaping landscapes and ecosystems in the process.

Especially after the Industrial Revolution, human activities have led to pollution, environmental degradation, and loss of biodiversity. Unfortunately, Switzerland has not been exempted from these impacts, however, there is a growing number of initiatives promoting positive interactions with nature. Establishing projects for the conservation of natural environments, restoring ecosystems, adopting sustainable practices, and the creation of eco—neighborhoods, are among the priorities of the Swiss and cantonal governments to address environmental challenges and promote the long-term health and resilience of ecosystems.

4.3.1. Dam maintenance

Switzerland has more than 200 dams, most of them located at high altitude in the Alps. Their construction boomed after World War II, mainly to create water reservoirs for energy production. Today, the construction of new dams in the country is no longer considered, however, existing dams require regular maintenance [38].

4.3.1.1. Replacement of the Spitallamm dam

The Spitallamm dam was built 90 years ago on Lake Grimsel in the Bernese Oberland. Due to the appearance of a crack in the wall side directly in contact with water, a new dam is being built downstream. The original dam will be submerged but not demolished for environmental reasons (to avoid having to drain the entire lake and dispose of the concrete elsewhere). This maintenance project started in 2019 and will be finished for 2025 [39].

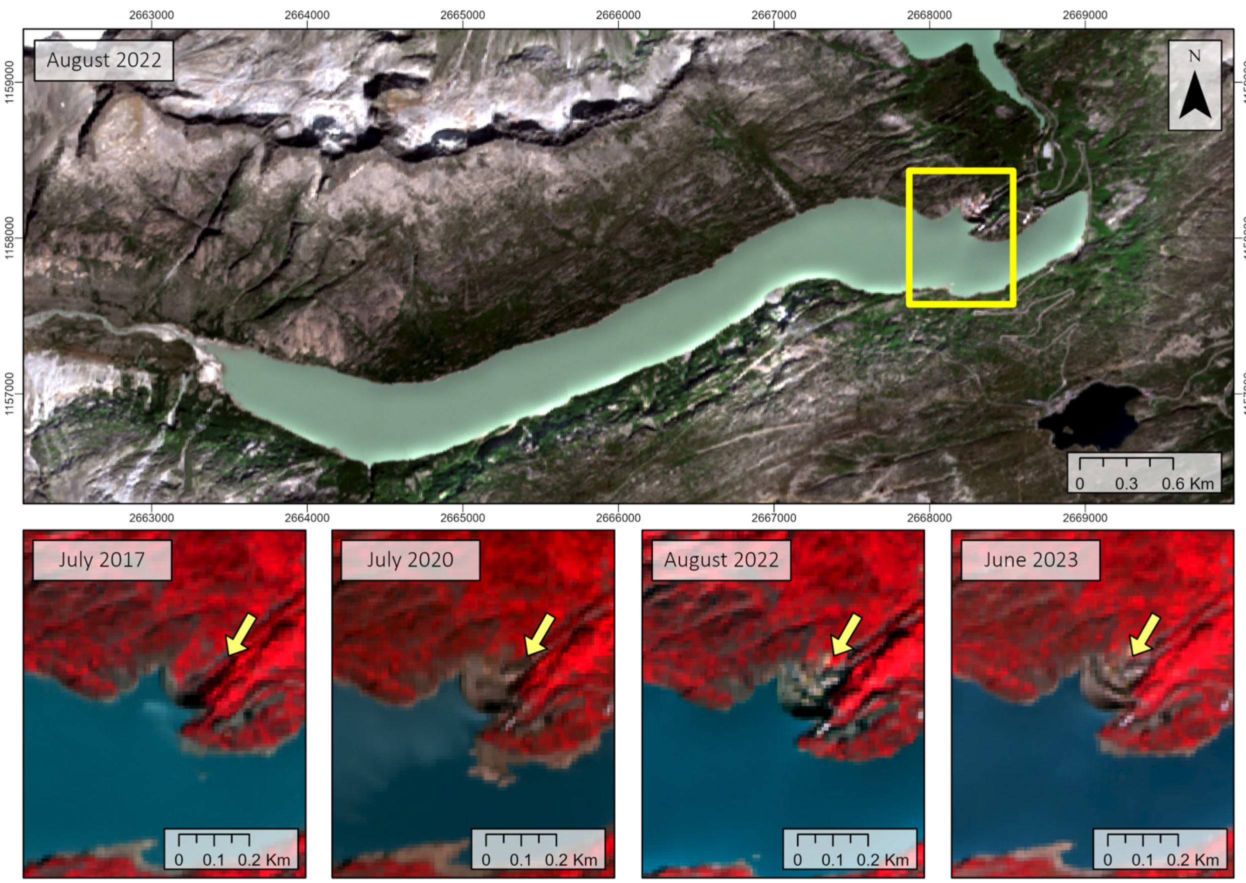


Figure 22: Construction of the new Spitallamm dam

Sentinel-2 images obtained on July 19, 2017, July 9, 2019, August 16, 2022, and June 25, 2023. The image on top presents the natural color band combination red (B4), green (B3), and blue (B2). The yellow rectangle indicates the zoom-in of the images on the bottom, created by combining bands NIR (B8), red (B4), and green (B3) to highlight the dam construction (yellow arrows).

→ We can observe the construction of the new dam over time. It shows a curved structure that may indicate that it is an arch dam similar to the previous one.

4.3.1.2. Emptying the artificial lake retained by the Contra dam (also known as Verzasca dam)

Again, for maintenance reasons, the artificial Lake Vogorno near Locarno, in Ticino canton, had to be completely emptied in 2022. Several submerged parts of the dam (called Contra dam or Verzasca dam) had to be repaired and/or replaced mainly due to corrosion.

As a curious fact, a world-famous scene from the movie GoldenEye (James Bond Series, 1995) was filmed on this 220-m-high dam [40, 41].

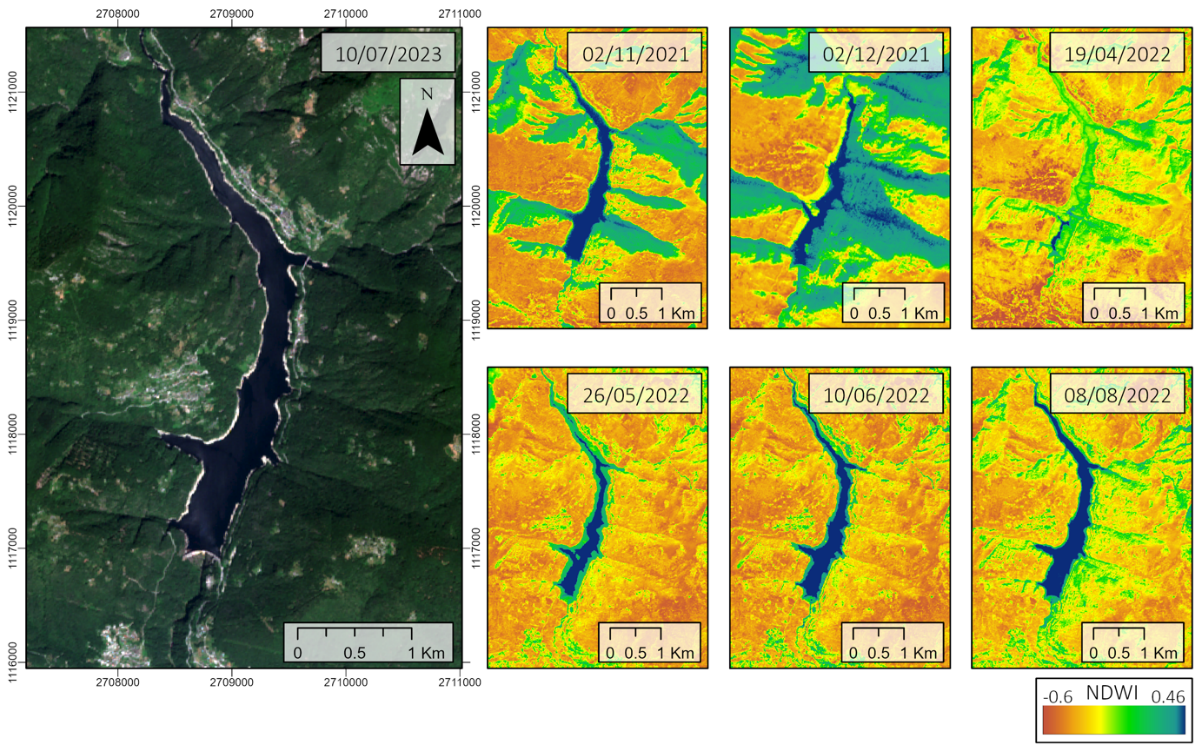


Figure 23: Emptying Lake Vogorno

Sentinel-2 images obtained between end-November 2021 and mid-July 2022.

The image on the left is the result of the natural color band combination red (B4), green (B3), and blue (B2). Images on the right were created by calculation of the NDWI using bands green (B3) and NIR (B8) for the specific dates indicated on the images.

→ The lake was completely empty in April 2022 and came back to normal in August 2022. In December 2021, the presence of snow around the lake difficulted the detection of water. The NDWI calculation and manipulation of the color scale provided the best result for water detection in this specific case.

4.3.2. Renaturation and nature conservation projects

In recent years, Swiss and cantonal governments have been promoting diverse renaturation and nature conservation projects. They aim to restore and preserve natural habitats, particularly in areas affected by human activities such as urbanization, agriculture, and infrastructure development. The ultimate goal of these projects is to promote sustainable ecosystems and preserve their biodiversity [42].

4.3.2.1. River Aire renaturation project

The Aire, in canton of Geneva, is a little river that rises in Mont Salève (France) and flows through the Geneva Basin to join the river Arve in the city of Geneva. In the 19th century, the river was channeled along five kilometers. The idea was to eliminate the threat of flooding while getting fertile farmland from the former wetland. Unfortunately, preserving the biodiversity linked to the natural riverbed was not very important at that time [43].

In 2000, the canton of Geneva started a project competition for the renaturation of the Aire. The winning project put in place a series of strategies to revitalize the natural ecosystem while preserving the man-made waterway. Indeed, by excavating a geometric matrix of channels that formed diamond-shaped islands next to the canal, a large divagation space for the river was created as an alternate path. This pattern allowed the river to naturally find its way among the different excavated channels. The project was successfully completed in 2022.

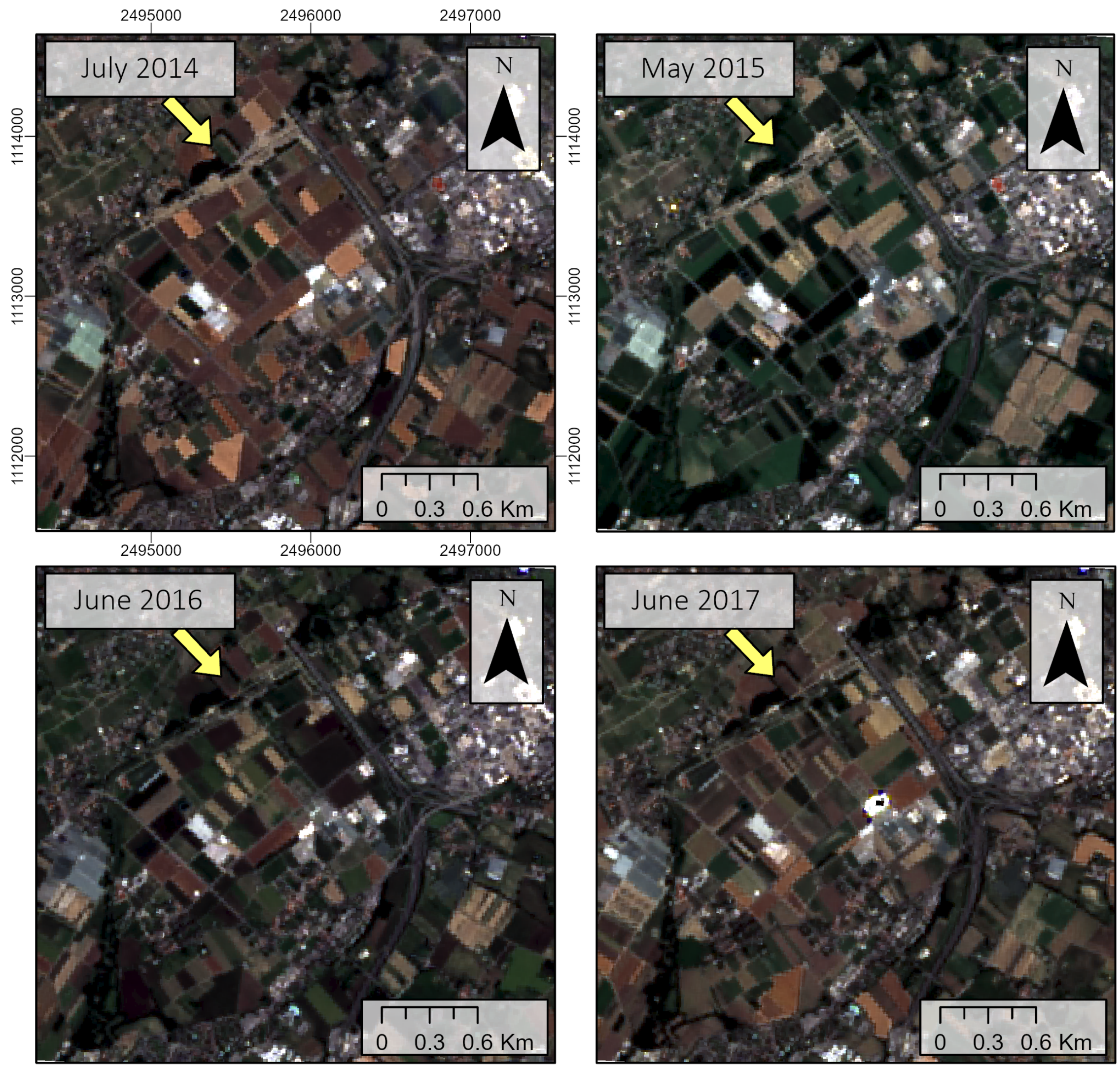


Figure 24: Renaturation of the River Aire

Landsat 8 images obtained on July 1, 2014, May 17, 2015, June 20, 2016, and June 23, 2017. Pan-sharpening was applied in all the images. They present the natural color band composition: red (B4), green (B3), and blue (B2).

→ The presence of bare soil in the riverbed (yellow arrows) in July 2014 and May 2015 images shows that the renaturation project was ongoing. However, there is a clear resolution limitation despite the pan-sharpening.

4.3.2.2. Lake Geneva shoreline renaturation project

In recent years, several renaturation projects have been developed on the shores of Lake Geneva, heavily modified by humans in the past. The main goals of these renaturation projects are three: environmental, by encouraging the development of a rich flora and fauna; Economic, by ensuring the safety of people and property against flooding; Social, by welcoming people to the water's edge (walking, swimming, fishing) and providing quality public spaces [44].

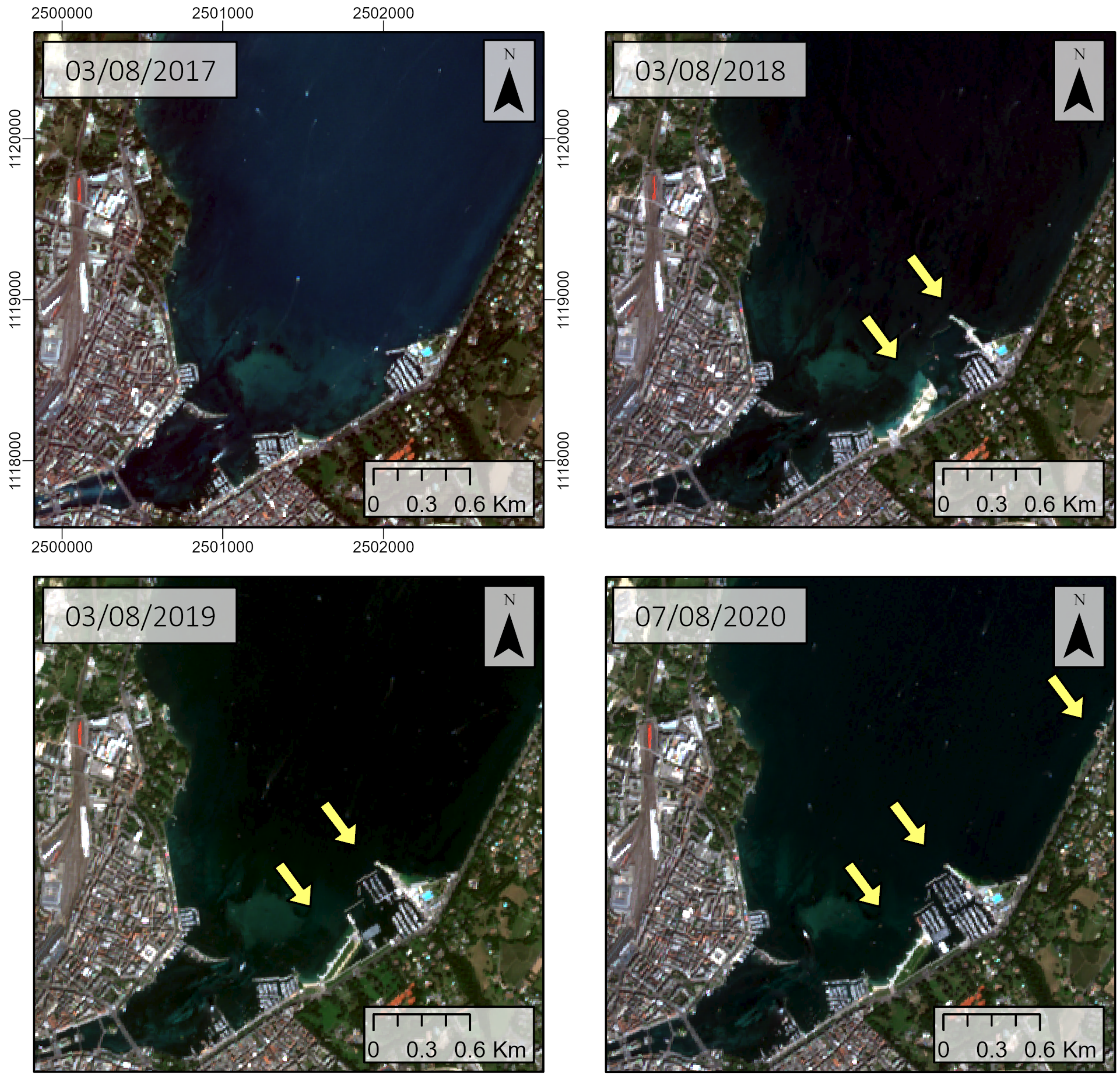


Figure 25: Lake Geneva shore renaturation

Sentinel-2 images from 2017 to 2020. They have been created with the natural color band combination red (B4), green (B3), and blue (B2).

→ We can easily observe the construction of a new beach with a natural space between the beach and the shore, the construction of an extension of the nautical harbor, and a donut-shaped swimming area next to a new reed bed (07/08/2020).

4.3.2.3. Forest increase – Bregaglia forest

Forests and other wooded areas cover almost a third of Swiss territory. Between 1985 and 2018, they increased by 589 km^2 (+5%), corresponding to a surface area slightly bigger than Lake Geneva. This increase has been observed especially in mountain regions (higher than 2000 m). It is mainly due to the return of trees to mountain pastures that are no longer exploited, as well as the rise in the upper tree limit due to climate change [45].

An example of this phenomenon can be observed in the forest of Bregaglia, in the canton of Grisons.

Figure 26: Bregaglia forest- Before and after

Landsat 5 images where natural color band combination red (B3), green (B2), and blue (B1) was applied. Time difference between the two images is 20 years.

→ Different band combinations were applied to try to highlight the reforestation over time, however they did not provide better results than the natural color band combination presented here. We can observe that some areas of the forest have been repopulated by trees (yellow arrows) over a 20-year period.

4.3.3. Urbanization

Almost three quarters of Swiss population live in urban areas, where around 80% of all jobs are located. Half of the urban population lives in one of the five largest agglomerations: Zurich, Geneva, Basel, Bern, or Lausanne. Although the growth of residential and infrastructure land has slowed somewhat compared to the 1980s and 1990s, urban sprawl continues, mainly at the expense of agricultural land. Indeed, Swiss population (8.8 million inhabitants) is growing steadily and is likely to reach 10 million by 2040. This will lead further expansion of urban areas, exerting pressure on agricultural areas and landscape conservation [46-48].

4.3.3.1. Geneva urban expansion

The housing shortage is a major challenge in Switzerland, particularly in large cities like Geneva, where less than 0.5% of housing is available for rent [49]. To tackle this housing problem, the canton of Geneva is currently striving to build and/or renovate entire neighborhoods, putting sustainability in the spotlight. An example of recently built neighborhoods are the Quartier de L'Étang near Geneva Airport or the Quartier Belle-Terre in the south-western part of the city.

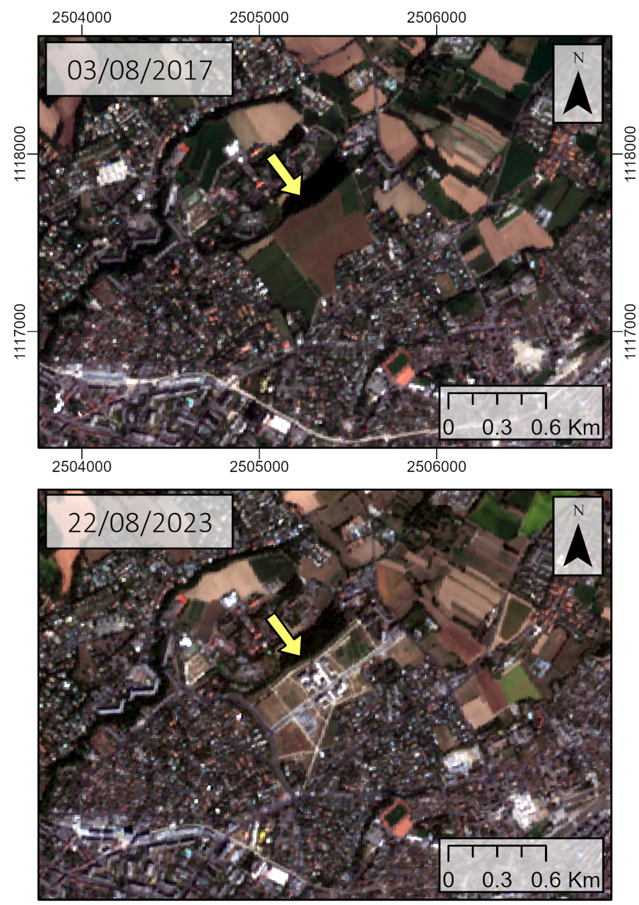


Figure 27: Urban expansion in Geneva - Quartier Belle-Terre

Sentinel-2 images showing the natural color band combination red (B4), green (B3), and blue (B2).

→ We can observe the construction of a new neighborhood (Quartier Belle-Terre) in a former agricultural field over a 6-year period.

4.3.3.2. Zurich

Zurich is the largest city in the Swiss Confederation, with a population of 434,783 inhabitants and a metropolitan area of 1,539,275 inhabitants [50]. It is the capital of the canton of Zurich, and it is located in the Central Plateau, close to the Alps.

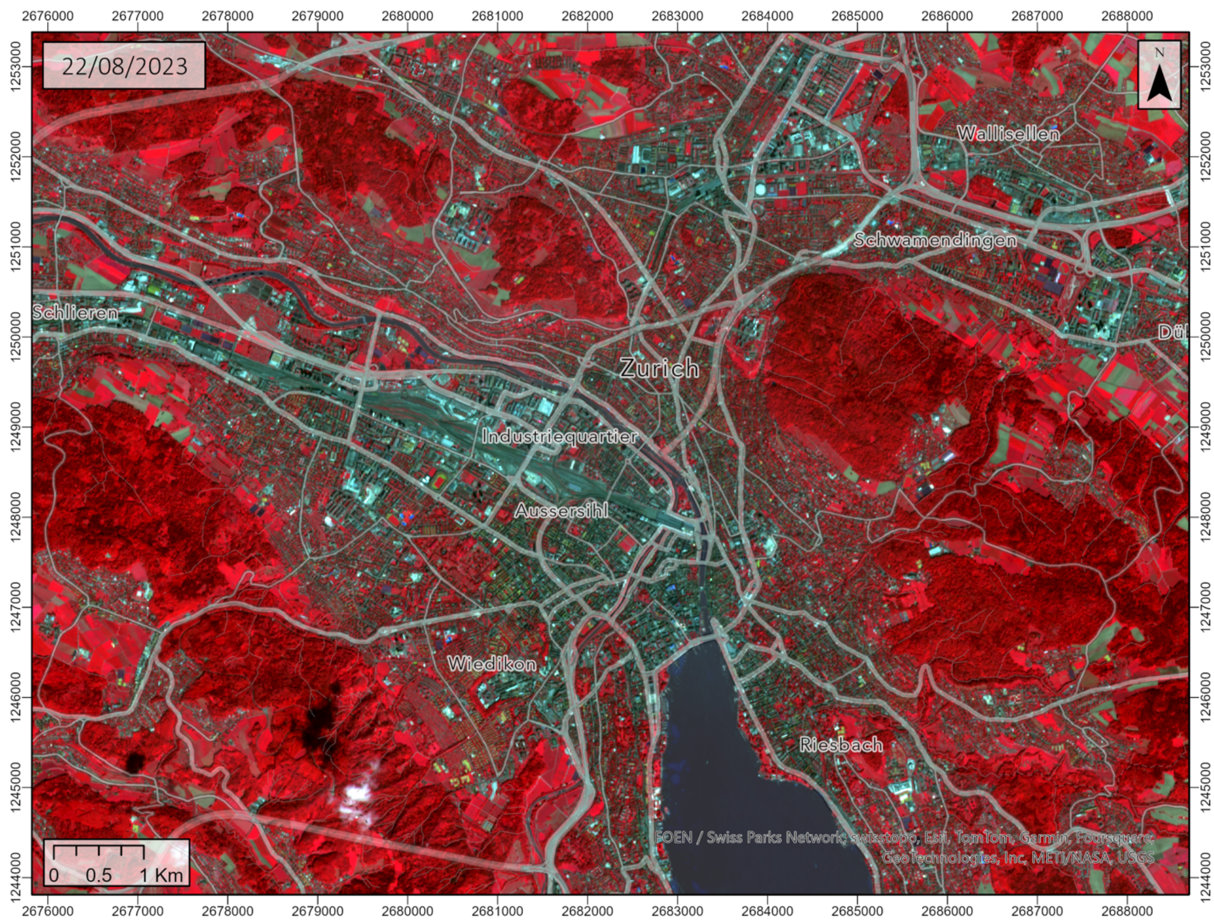


Figure 28: Zurich and its metropolitan area overview

Sentinel-2 image obtained on August 22, 2023. Bands NIR (B8), red (B4), and green (B3) were combined to highlight urban areas. An urban map was added on top using ArcGIS pro.

4.3.3.3. Geneva

Geneva is the second biggest city of the Swiss Confederation and the capital of the canton of Geneva. It is located in the southwest part of the country, near the border with France, at the exit of the Rhone from Lake Geneva. The city has more than 200,000 inhabitants, while the metropolitan area of Geneva (including neighborhoods located in France), has an estimated population of more than 1 million inhabitants [51].

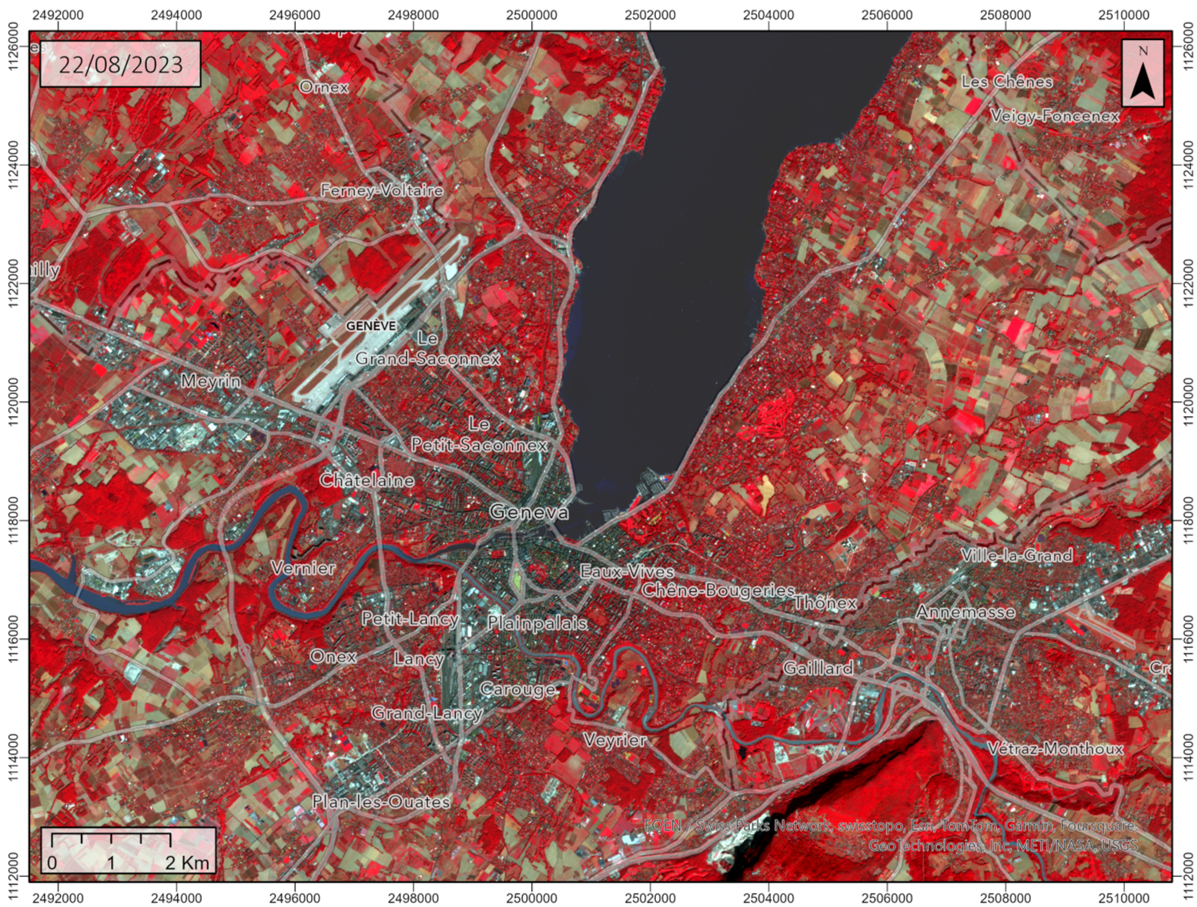


Figure 29: Geneva and its metropolitan area overview

Sentinel-2 image obtained on August 22, 2023. Bands NIR (B8), red (B4), and green (B3) were combined to highlight urban areas. An urban map was added on top using ArcGIS pro.

4.3.3.4. Basel

Basel is the third most populated country of Switzerland with 180,434 inhabitants in the city and 547,000 inhabitants in the metropolitan area. It is located in the canton of Basel City, in northwestern Switzerland, on the banks of the Rhine River. The city borders both Germany and France, however the region of Basel culturally extends into these two countries.

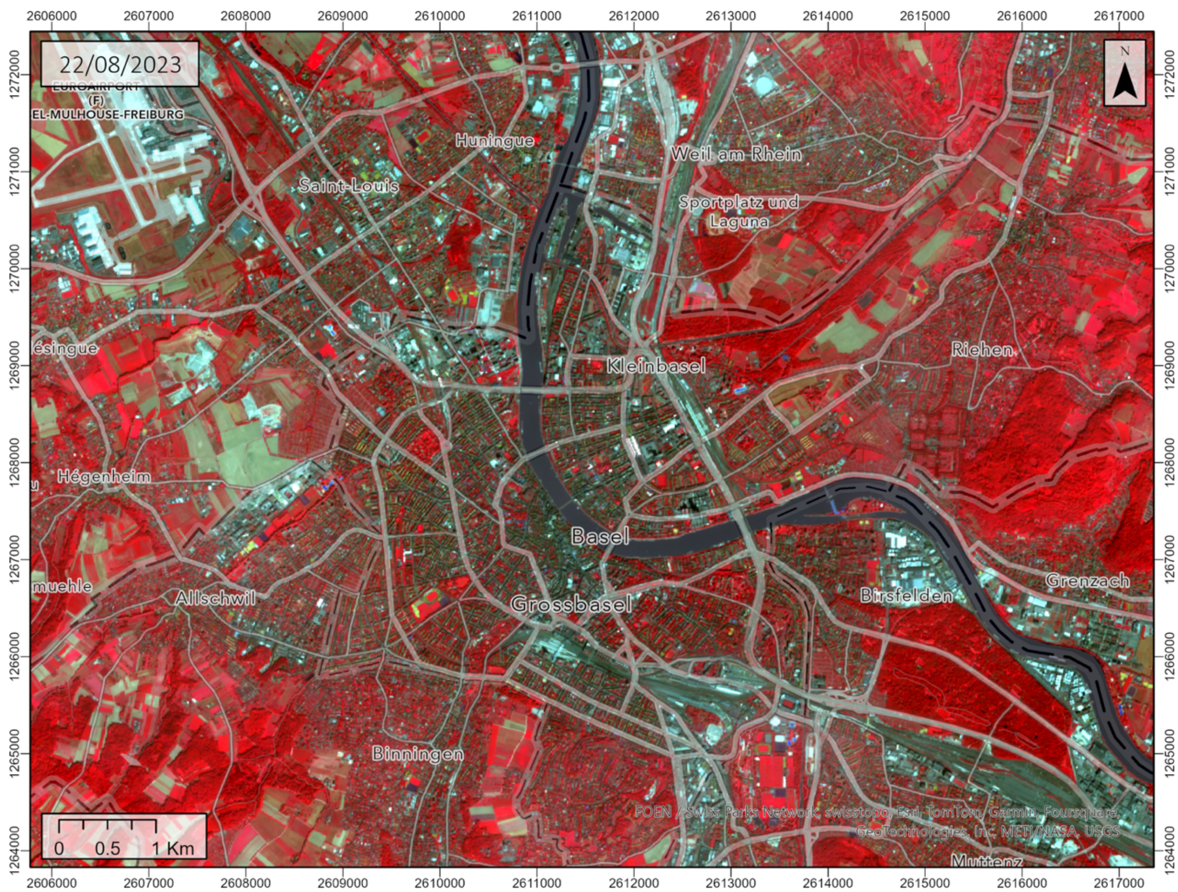


Figure 30: Basel and its metropolitan area overview

Sentinel-2 image obtained on the August 22, 2023. Bands NIR (B8), red (B4), and green (B3) were combined to highlight urban areas. An urban map was added on top using ArcGIS pro.

4.3.3.5. Bern

The city of Bern is a municipality and the capital of the canton of the same name. As the "federal city", it acts as the capital of Switzerland. In 1983, Bern's Old Town was inscribed on the UNESCO World Heritage List. The city has a total population of 134,506 inhabitants, while in the agglomeration of Bern, there is a permanent resident population of 422,706 inhabitants. It is one of the most populated cities of Switzerland after Zurich, Geneva, Basel and Lausanne.

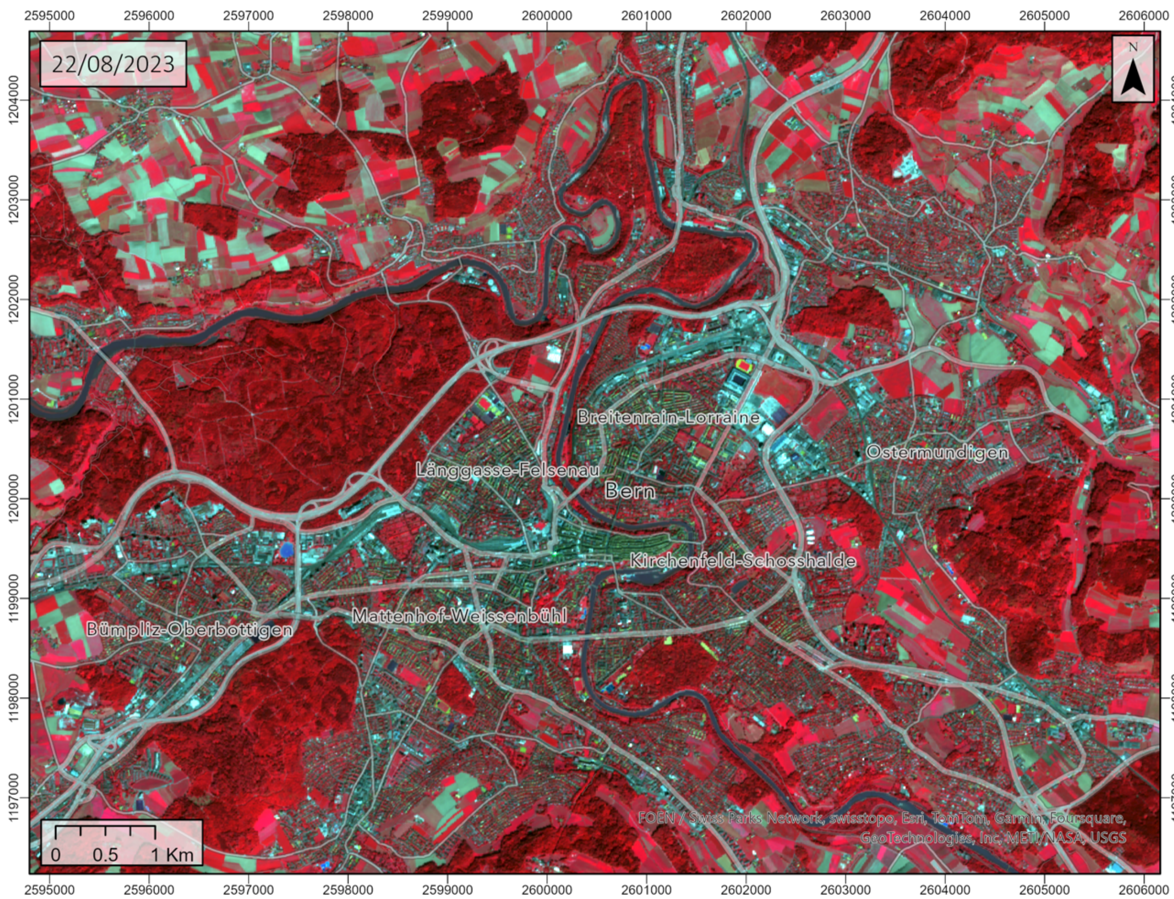


Figure 31: Bern and its metropolitan area overview

Sentinel-2 image obtained on August 22, 2023. Bands NIR (B8), red (B4), and green (B3) were combined to highlight urban areas. An urban map was added on top using ArcGIS pro.

4.4. Swiss natural wonders

Nature in Switzerland offers breathtaking landscapes, from the majestic mountains conforming the Alps to countless lakes, rivers, and waterfalls, as well as nature reserves and national parks. Switzerland’s diverse natural landmarks make it one of the favorite destinations of nature enthusiasts, offering a perfect balance between adventure, tranquility, and beauty.

4.4.1. Mountains

The Swiss Alps are renowned worldwide. Peaks like the Matterhorn, Eiger, and Jungfrau offer amazing views and numerous opportunities for outdoor activities such as skiing, hiking, and climbing.

4.4.1.1. Matterhorn, Zermatt

The Matterhorn is probably one of the most famous mountains of Europe. Located in Zermatt, in the canton of Valais, this pyramid-shaped mountain whose summit is 4,478 meters, offers a breathtaking Alpine panorama [52].

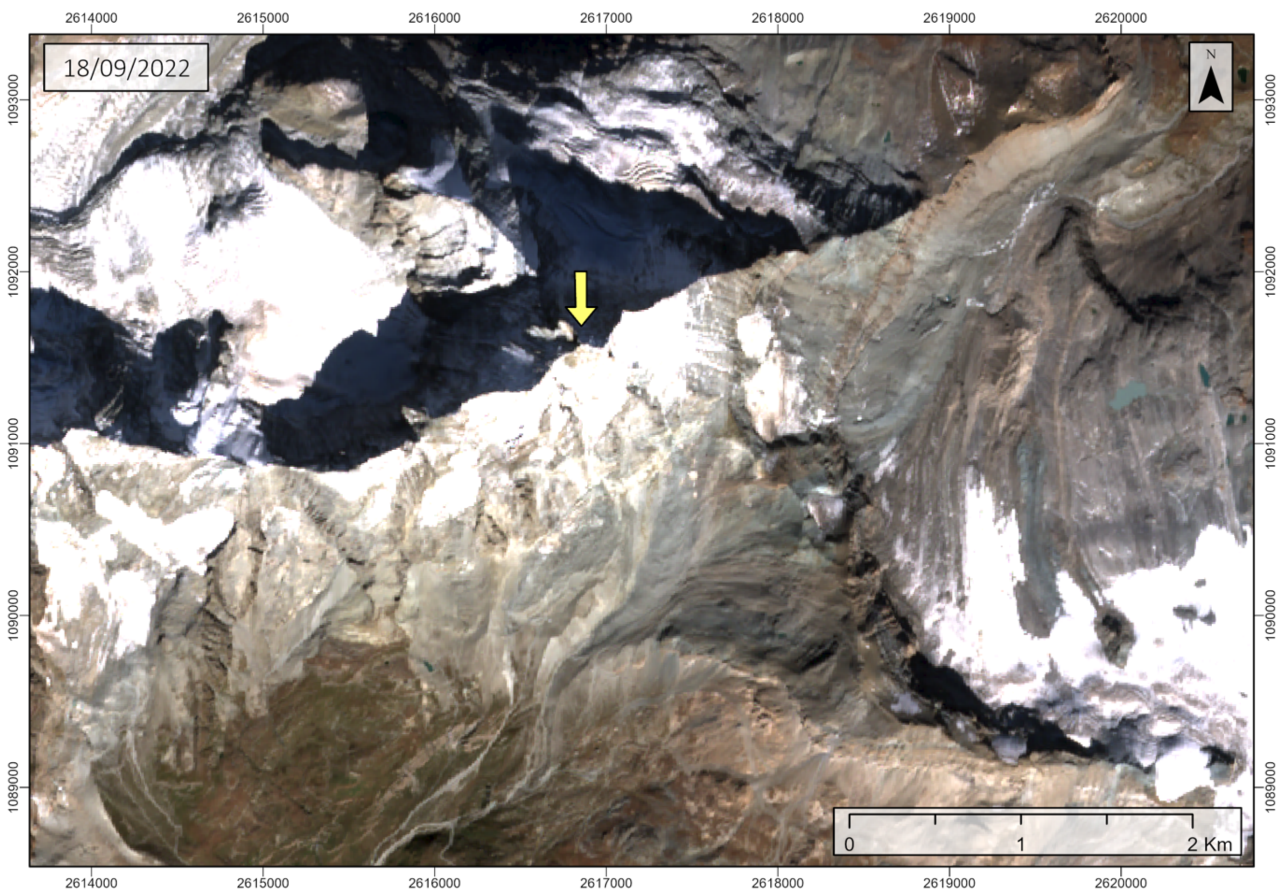


Figure 32: Matterhorn overview

Sentinel-2 image showing the natural color band combination red (B4), green (B3), and blue (B2).

→ The location of the Matterhorn is marked with the yellow arrow. Although it is an imposing peak, its grandeur is not fully captured in this image due to the top-down perspective of the satellite view.

4.4.1.2. Dufourspitze, Zermatt

Also located in Zermatt, the Dufourspitze mountain is the highest (4,634 m) of both Switzerland and the Pennine Alps. It is also the second-highest mountain of the Alps and Western Europe, after Mont Blanc. It is located between Switzerland (Canton of Valais) and Italy (Piedmont and Aosta Valley).

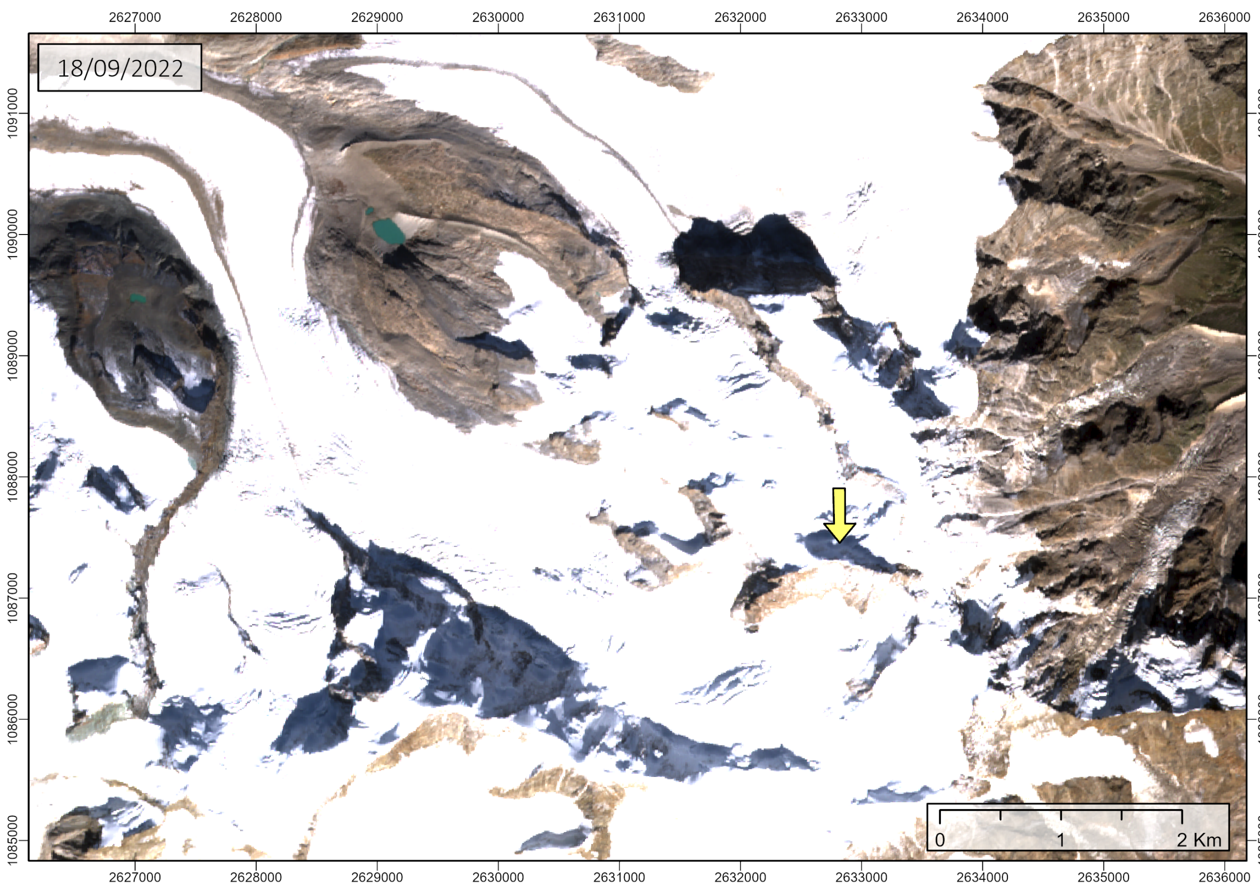


Figure 33: Dufourspitze overview

Sentinel-2 image showing the natural color band combination red (B4), green (B3), and blue (B2).

→ The location of the Dufourspitze is marked with the yellow arrow. Although it is the highest peak of Switzerland, its grandeur is not fully captured in this image due to the top-down perspective of the satellite view.

4.4.2. Lakes and watercourses

Switzerland is home to numerous lakes, including Lake Geneva, Lake Lucerne, Lake Thune and Lake Brienz, and many more. These lakes provide not only scenic beauty but also a variety of recreational activities. Rivers and waterfalls are also a major attraction, highlighting the Rhine Falls, which are the Europe's largest waterfall by volume.

4.4.2.1. Lake Lucerne

Lake Lucerne is the fourth largest lake of Switzerland. This glacial lake is located in five different cantons: Lucern, Uri, Obwald, Nidwald, and Schwytz. It is 38 km long from its mouth to the Reuss dam. It has a surface area of 114 km^2 and a depth of 214 meters [53]. It is a is a monomictic lake, with only one complete overturn every six years [54].

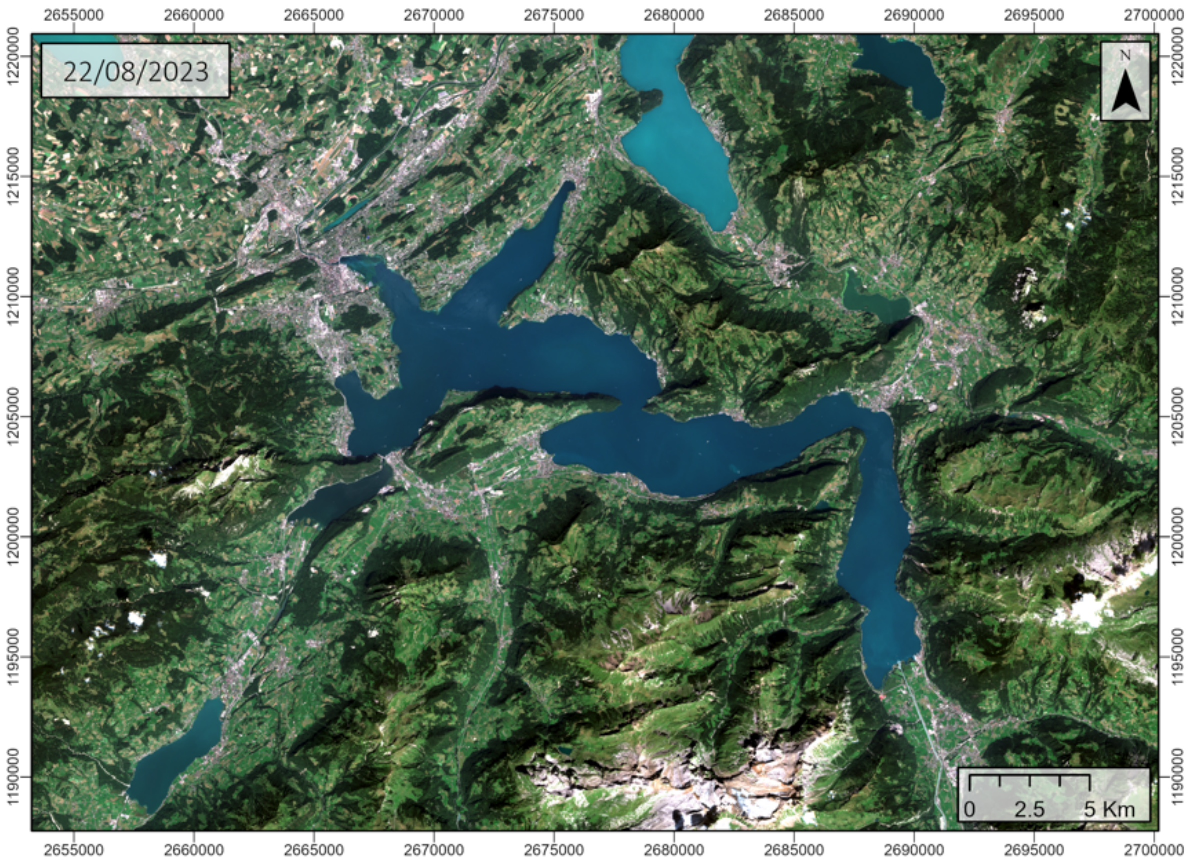


Figure 34: Lake Lucerne overview

Sentinel-2 image presenting the natural color band combination red (B4), green (B3), and blue (B2).

→We can observe the irregular shape of the lake that lies in four different valleys.

4.4.2.2. Lake Thun and Lake Brienz

Lake Thun and Lake Brienz are located in canton of Bern. One next to the other, they are separated by the town of Interlaken. Lake Thun presents a surface of approximately 48.3 km^2 while Lake Brienz has a surface area of 29 km^2.

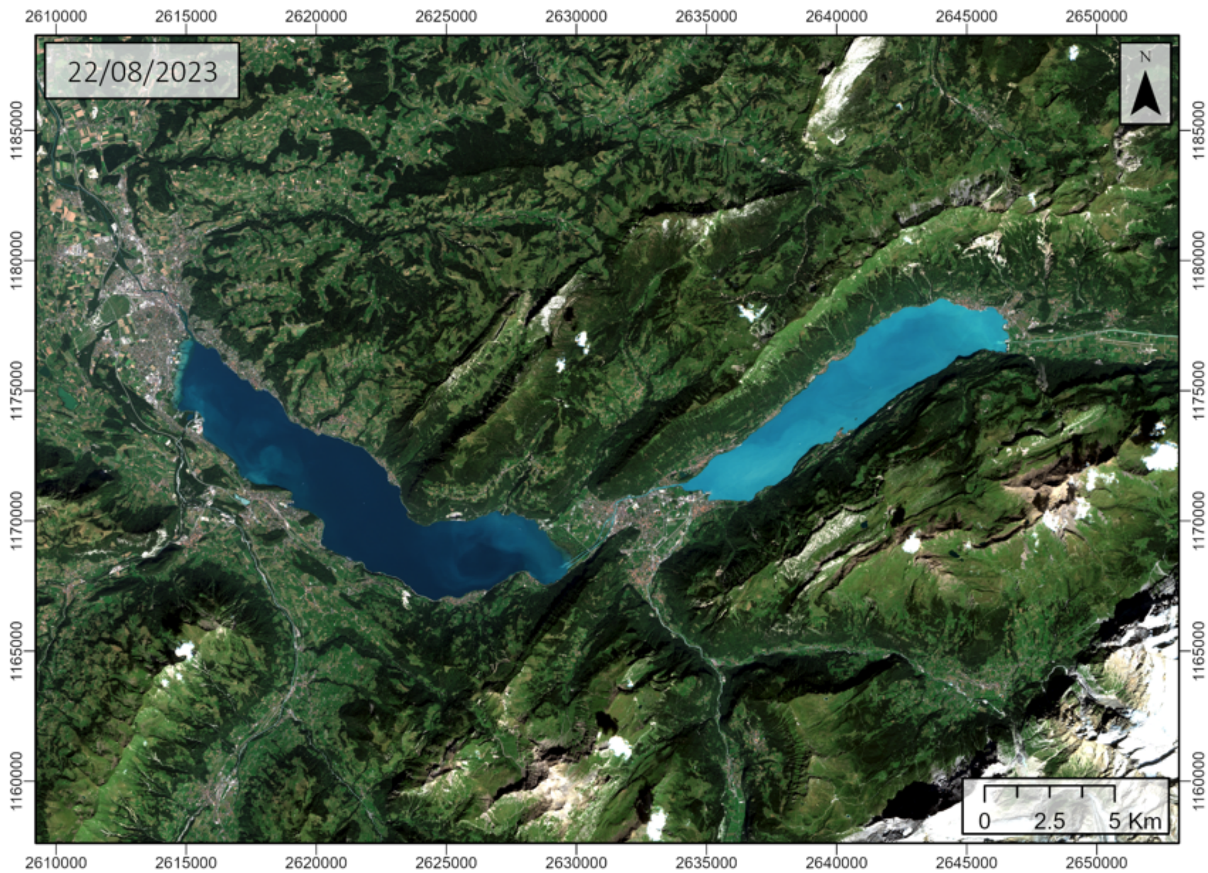


Figure 35: Lake Thun and Lake Brienz overview

Sentinel-2 image presenting the natural color band combination red (B4), green (B3), and blue (B2).

→We can observe the characteristic color difference between these two lakes: While Lake Thun (on the left) presents a dark blue color, Lake Brienz (on the right) shows a turquoise color. We can also observe the town of Interlaken, located between the two lakes.

4.4.2.3. Three Lakes region

Lake Neuchâtel, Lake Bienne, and Lake Morat are located at the foot of the Jura, conforming the Three Lakes region that lies in the cantons of Bern, Fribourg, Neuchâtel and Vaud.

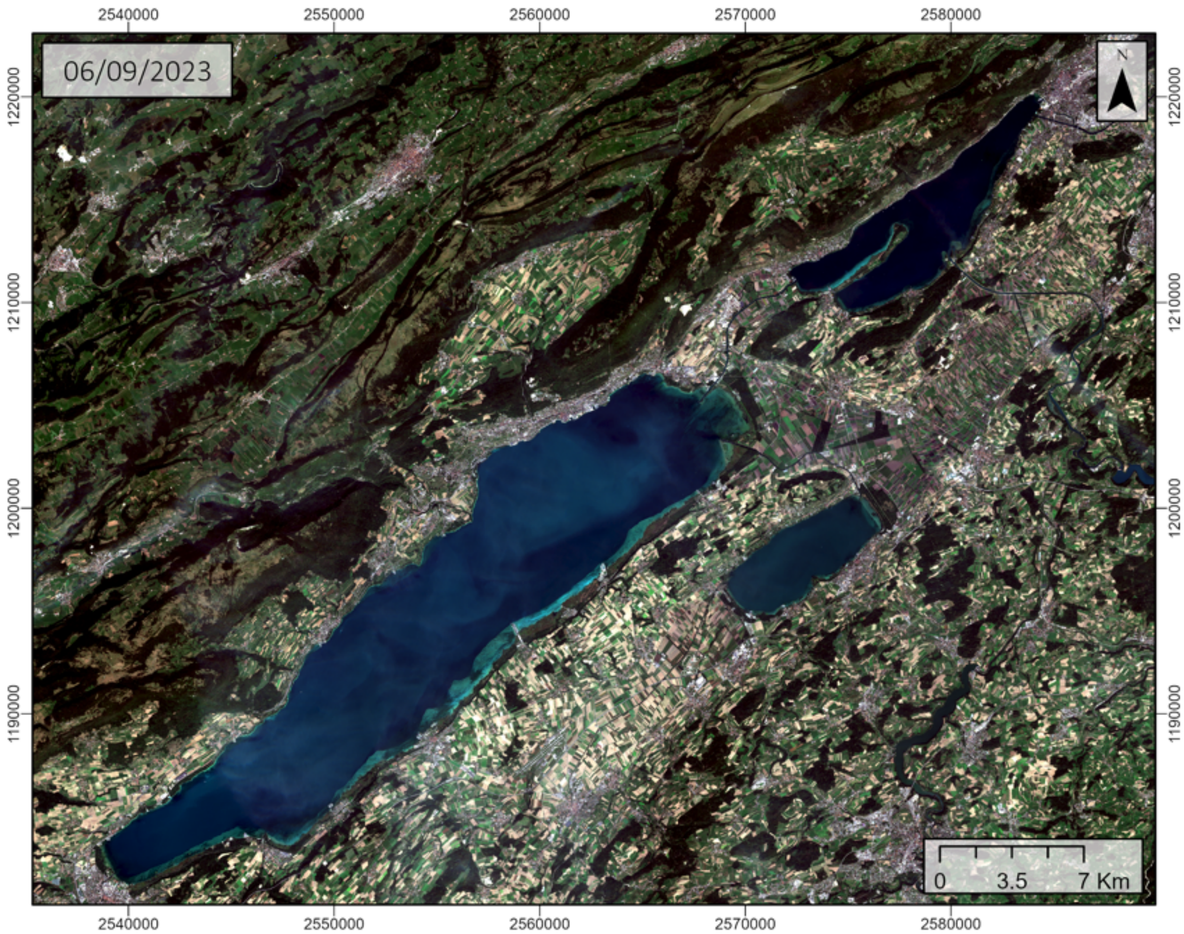


Figure 36: Three Lakes region overview

Sentinel-2 image presenting the natural color band combination red (B4), green (B3), and blue (B2).

→ The biggest lake is Lake Neuchâtel and we can observe that is approximately 28-km long. It is connected to Lake Bienne (second biggest lake of the region) by a human-made channel (Thielle river). The smallest lake is Lake Morat, and we can also see that it is connected to Lake Neuchâtel. The surrounding areas are primarily agricultural, indicating the region's use for cultivation.

4.4.2.4. Lake Geneva

Lake Geneva is located at the border between Switzerland (cantons of Vaud, Geneva and Valais) and France (department of Haute-Savoie). The lake lies on the course of the Rhône, that has its source at the Rhône Glacier, near the Grimsel Pass. With a length of 78 km and a surface area of 580 km2, it is one of the biggest lakes of Western Europe. Between 1960 and 1980, the eutrophication of the lake due to high phosphorus levels was a major issue. Today, water quality is much better thanks to the improvement of wastewater treatments and the ban on the use of phosphate-containing detergents in Switzerland and France [55]. In September 2021, a massive microalgal bloom was observed in Lake Geneva (Switzerland/France). This phenomenon was unprecedented since end-1900s (when phosphorus concentration drastically decreased) and was due to a combination of specific weather conditions together with the subsequent hydrodynamic processes [56].

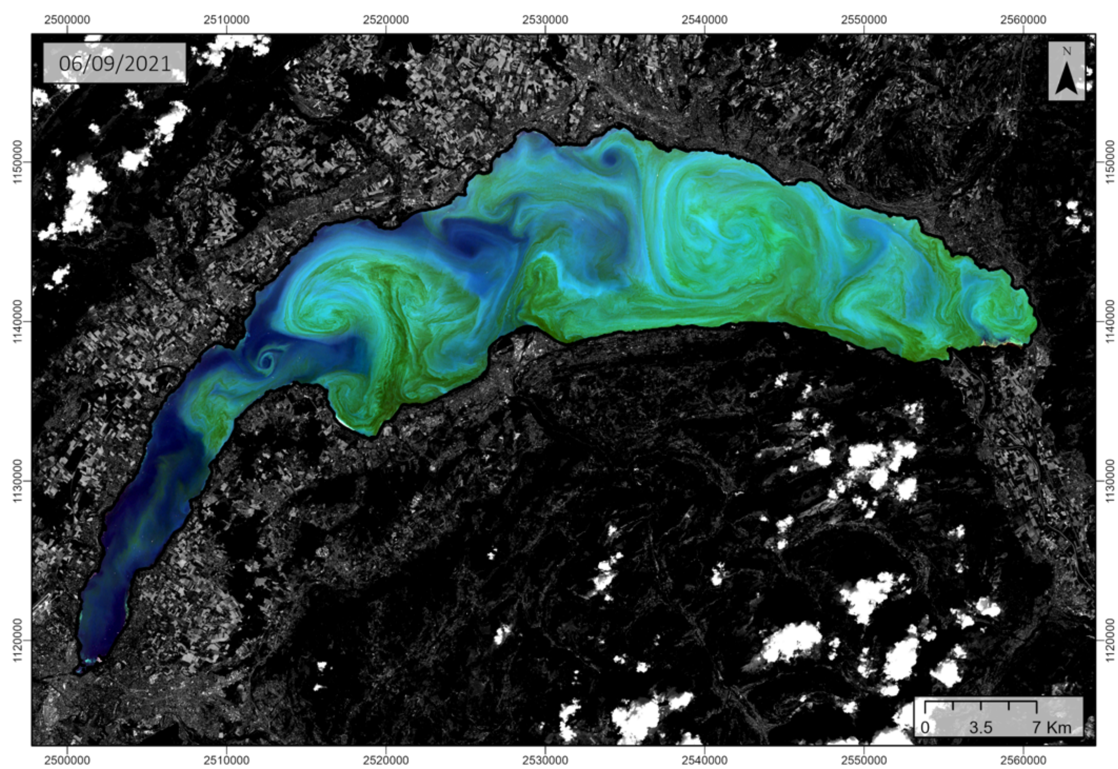


Figure 37: Microalgal bloom in Lake Geneva

Superposition of two Sentinel-2 images captured on September 6, 2021: A black and white image corresponding to the red band (B4) and a superposed clip of Lake Geneva with the natural color band combination (B4), green (B3), and blue (B2). To create this clip, a vector file of the shape of Lake Geneva was download from the SITG database.

→ We can easily detect the presence of microalgae in the water. There distribution show the characteristic surface rotational currents of Lake Geneva surface water.

4.4.2.5. Rhine falls

Rhine falls are the Europe's biggest waterfalls. Located on the border between the cantons of Schaffhausen and Zürich, in northern Switzerland, these falls are 150 meters wide and 23 meters high. They were formed in the last ice age, approximately 14,000 to 17,000 years ago, by erosion-resistant rocks narrowing the riverbed. Today they are one of the most touristic attractions in the country.

Figure 38: Rhine falls

Sentinel-2 image presenting the natural color band combination red (B4), green (B3), and blue (B2).

→ The Rhine falls can be easily observed in this satellite image. They are marked with the yellow arrow.

4.4.3. Protected natural areas

Protected areas of national importance cover around 24% of Switzerland's territory [57]. Indeed, the Federal Office for the Environment (FOEN) indicates that: “The implementation of conservation measures to promote biodiversity has a long tradition in Switzerland. The Swiss hunting reserves were the first protected areas to have their status enshrined in law in 1875. Over the past 100 years, Switzerland has designated a range other protected area, starting with the National Park (1914) and including areas as diverse as amphibian spawning areas (2001) and dry meadows and pastures (2010)” [58].

4.4.3.1. Creux-du-Van

The Creux-du-Van is a giant natural rock arena that have been formed due to water and ice erosion. It is located at the border between the canton of Neuchâtel and the canton of Vaud. Cliffs are 160 meters high and surround a valley floor that is four kilometers long and one kilometer wide. Urgent measures have recently been taken to restore the flora in this area, which has deteriorated due to the influx of mountaineers. These measures involve closing off about half of the cliff path to allow restoration of the flora, which is suffering from foot trampling [59].

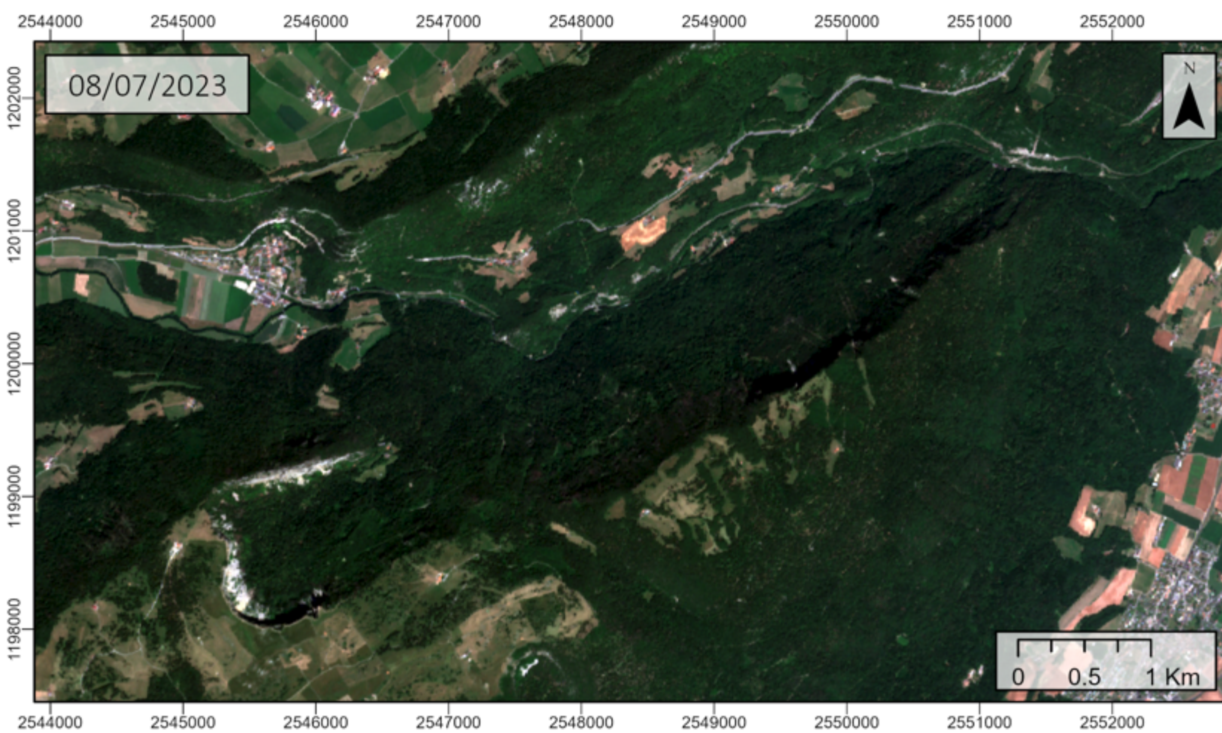


Figure 39: Creux-du-Van overview

Sentinel-2 image presenting the natural color band combination red (B4), green (B3), and blue (B2).

→ The Creux-du-Van can be observed as a depression.

4.4.3.2. Swiss National Park

The Swiss National Park is located in the Engadine Valley (canton of Grisons). It was created in 1909 on the basis of private initiatives. However, it was officially created on August 1, 1914, when it was ceded to the Swiss Confederation, being the oldest National Park of the Alps. The park territory was extended several times between 1918 and 2000. According to the International Union for Conservation of Nature (IUCN), it is a category 1a reserve (highest protection class, strict nature reserve) [60].

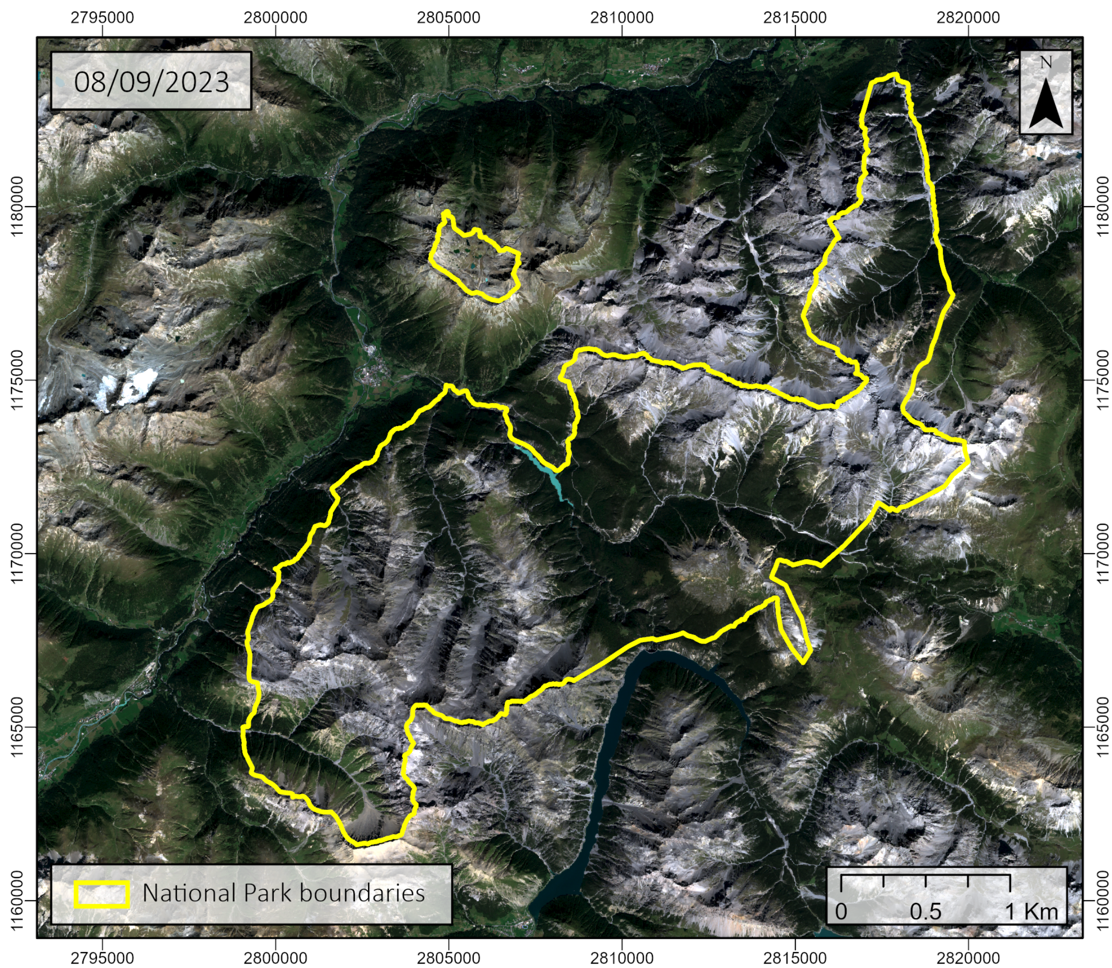


Figure 40: Swiss National Park overview

Sentinel-2 image with the natural color band combination red (B4), green (B3), and blue (B2). The Swiss National Park boundaries have been added from a vector file that was downloaded from swisstopo database and added to the image using ArcGis Pro.

→ The National Park covers an area of 170 km^2, dominated by mountainous landscapes.

4.4.3.3. UNESCO Biosphere Entlebuch

Located between Lucerne, Berne, and Interlaken, Entlebuch was designated by UNESCO in 2001 as a biosphere reserve. It represents pre-Alpine moorland and karst landscape [61].

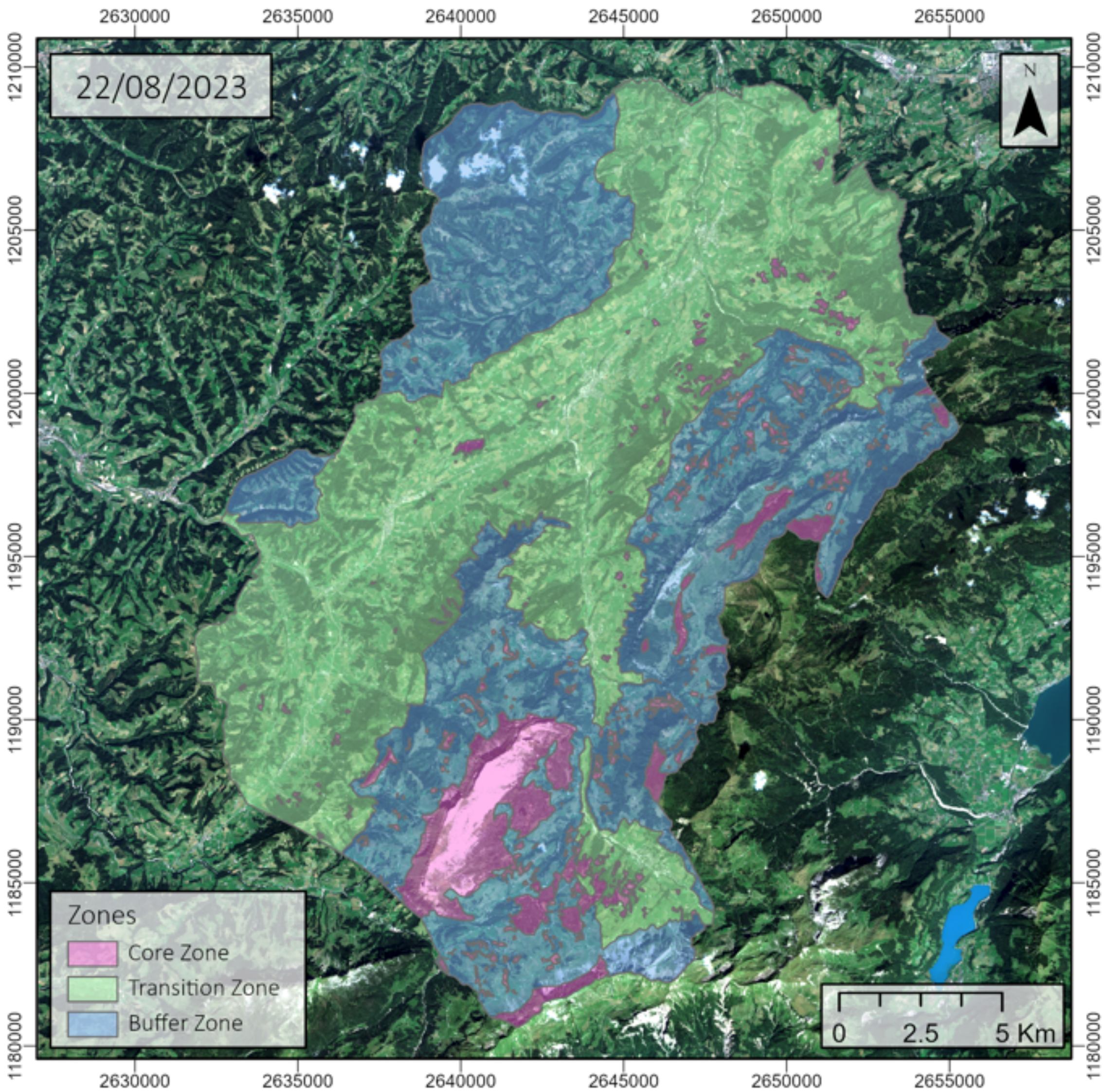


Figure 41: UNESCO Biosphere Entlebuch overview

Sentinel-2 image with the natural color band combination red (B4), green (B3), and blue (B2). Zone boundaries have been added from a vector file that was downloaded from swisstopo database and added to the image using ArcGis Pro.

→ The UNESCO Biosphere Entlebuch covers an area of almost 400 km^2. The core zone corresponds to the Schratteflue mountain, the most striking karst mountain in the biosphere.

5. Discussion - remote sensing strengths and limitations

Through the creation of this atlas, we have been able to discover the strengths and limitations of remote sensing.

We have seen that remote sensing is an extremely useful tool to obtain a global perspective of vast regions of Switzerland, which would not be possible from the ground. This allows us to monitor large-scale phenomena, such as glacier retreat, deforestation, forest fires progression, and more. Additionally, because the images are taken at regular time intervals, we can conduct temporal analysis to observe the evolution of certain landscapes over time. In our case, this has been extremely useful for showing the before and after of different places in the country, where the landscape has changed significantly due to specific events (landslide, flood, fire, human activity) or the gradual effect of climate change (drought, glacier retreat).

Another positive aspect of remote sensing is that it allows to obtain images of remote locations that are difficult to access by land (such as the Matterhorn or Dufourspitze) or are restricted, such as the highly protected areas of the National Park or the UNESCO Biosphere Entlebuch. Finally, multispectral images have provided extremely useful information about the state of vegetation, or the presence of water or snow.

On the other hand, it is important to highlight the three main limitations encountered during the creation of this atlas. The first is the resolution of the images, which in some cases is not sufficient to detect small-scale changes, especially when the images come from Landsat satellites. In our case, this was a problem when we wanted to show the renaturation process of the Aire River basin, even after applying pan-sharpening.

Another limitation to note is the difficulty of obtaining high-quality images when clouds are present. This was especially problematic when we wanted to show the 2005 floods, as most of the country was covered by clouds at that time.

Finally, although we found a solution (and there are likely other more sophisticated techniques), we also found that it is sometimes very difficult to differentiate between water and snow, especially in shaded areas (this happened with the images of Lake Vogorno).

Despite these limitations, the potential of remote sensing is immense, and it is a key tool for a better understanding of the dynamics of our planet and the impact of climate change. Indeed, thanks to this atlas, we have been able to demonstrate that Switzerland's natural landscapes are not exempt from the effects of climate change.

6. Conclusion

With the creation of this atlas, we have been able to showcase, with remote sensing, the most significant changes in the Swiss landscape, whether due to climate change, direct human action, or simply the natural evolution of certain environments. Additionally, we have shown some of the main landmarks, from cities to lakes, rivers, and mountains. This work has allowed us to explore the potential of remote sensing but also to discover its limitations. This technology has proven to be an invaluable asset for gaining a comprehensive perspective of vast and often inaccessible regions of Switzerland. It has enabled us to monitor large-scale environmental changes, such as glacier retreat, deforestation, and natural disasters, and to perform temporal analyses that reveal the evolution of landscapes over time. However, the process has also highlighted challenges, including the limitations of image resolution, the impact of cloud cover on image quality, and the difficulty of distinguishing between water and snow in certain conditions.

7. Bibliography

1. Jeremy T Kerr and Marsha Ostrovsky, From space to species: ecological applications for remote sensing. Trends in ecology & evolution, 2003. 18(6): p. 299-305.
2. Ranganath R Navalgund, V Jayaraman, and PS Roy, Remote sensing applications: An overview. current science, 2007: p. 1747-1766.
3. Kazuya Kaku, Satellite remote sensing for disaster management support: A holistic and staged approach based on case studies in Sentinel Asia. International Journal of Disaster Risk Reduction, 2019. 33: p. 417-432.
4. Floyd F Sabins Jr and James M Ellis, Remote sensing: Principles, interpretation, and applications. 2020: Waveland Press.
5. Alex M Lechner, Giles M Foody, and Doreen S Boyd, Applications in remote sensing to forest ecology and management. One Earth, 2020. 2(5): p. 405-412.
6. Ingrid Maria Weiss, et al., Mollusc larval shell formation: amorphous calcium carbonate is a precursor phase for aragonite. J. Exp. Zool., 2002. 293(5): p. 478-491.
7. Alexander Siegmund and G Menz, Fernes nah gebracht–Satelliten-und Luftbildeinsatz zur Analyse von Umweltveränderungen im Geographieunterricht. Geographie und Schule, 2005. 154(4): p. 2-10.
8. Jun Yang, et al., The role of satellite remote sensing in climate change studies. Nature climate change, 2013. 3(10): p. 875-883.
9. Imtiaz Rangwala and James R Miller, Climate change in mountains: a review of elevation-dependent warming and its possible causes. Climatic change, 2012. 114: p. 527-547.
10. Pascal Vittoz, et al., Climate change impacts on biodiversity in Switzerland: A review. Journal for Nature Conservation, 2013. 21(3): p. 154-162.
11. M Bavay, T Grünewald, and M Lehning, Response of snow cover and runoff to climate change in high Alpine catchments of Eastern Switzerland. Advances in water resources, 2013. 55: p. 4-16.
12. Alexander Peringer, et al., Past and future landscape dynamics in pasture-woodlands of the Swiss Jura Mountains under climate change. Ecology and Society, 2013. 18(3).
13. United Nations Environment Programme, et al., One Planet, Many People: Atlas of Our Changing Environment. 2005: UNEP.
14. GIS Geography. Composite Bands: Black and White to Color Imagery. 2024 [cited 2024 May 15]; Available from: https://gisgeography.com/arcgis-composite-bands/.
15. Federal Office of Topography swisstopo. National Survey LV95. 2024 [cited 2024 May 15]; Available from: https://www.swisstopo.admin.ch/en/national-survey-lv95.
16. Confédération Suisse. About Switzerland: Nature. 2023 [cited 2025 May 15]; Available from: https://www.eda.admin.ch/aboutswitzerland/en/home/umwelt/natur.html.
17. Alvaro Ayala, et al., Glaciers: Hydro-CH2018 synthesis report chapters: “future changes in hydrology“. Hydro-CH2018 Project. Commissioned by the Federal Office for the Environment (FOEN), Bern, Switzerland., 2020.
18. Johannes Oerlemans, Glaciers and climate change. 2001: CRC Press.
19. Andrew Kos, et al., Contemporary glacier retreat triggers a rapid landslide response, Great Aletsch Glacier, Switzerland. Geophysical Research Letters, 2016. 43(24): p. 12,466-12,474.
20. Regine Hock and Matthias Huss, Glaciers and climate change, in Climate change. 2021, Elsevier. p. 157-176.
21. Christian Sommer, et al., Rapid glacier retreat and downwasting throughout the European Alps in the early 21st century. Nature communications, 2020. 11(1): p. 3209.
22. RTS. Recouvrir les glaciers pour diminuer leur fonte est efficace, mais trop cher. 2021 [cited 2024 May 15]; Available from: https://www.rts.ch/info/sciences-tech/12090490-recouvrir-

les-glaciers-pour-diminuer-leur-fonte-est-efficace-mais-trop-cher.html#:~:text=C'est%20le%20cas%20par,la%20grotte%20de%20glace%20artificielle.
23. Saeideh Gharehchahi, et al., Glacier Ice Thickness Estimation and Future Lake Formation in Swiss Southwestern Alps—The Upper Rhône Catchment: A VOLTA Application. Remote Sensing, 2020. 12(20): p. 3443.
24. Jonathan Bussard and Emmanuel Reynard, Conservation of world heritage glacial landscapes in a changing climate: The Swiss Alps Jungfrau-Aletsch case. International Journal of Geoheritage and Parks, 2023. 11(4): p. 535-552.
25. Hanspeter Holzhauser, The Aletsch region with the majestic Grosser Aletschgletscher. Landscapes and landforms of Switzerland, 2021: p. 201-216.
26. Virginia; Molnar Ruiz-Villanueva, Peter (Editors), Past, current, and future changes in floods in Switzerland. Hydro-CH2018 Project. Commissioned by the Federal Office for the Environment (FOEN), Bern, Switzerland., 2020.
27. des transports Département fédéral de l'environnement, de l'énergie et de la communication DETEC, Crues de 2005. 2008.
28. Nadine Hilker, Alexandre Badoux, and Christoph Hegg, The Swiss flood and landslide damage database 1972–2007. Natural Hazards and Earth System Sciences, 2009. 9(3): p. 913-925.
29. Olivier Lateltin, et al., Landslide risk management in Switzerland. Landslides, 2005. 2(4): p. 313-320.
30. RTS. Il y a 30 ans, un spectaculaire éboulement s'abattait près de Randa (VS). 2021 [cited 2024 May 15]; Available from: https://www.rts.ch/info/regions/valais/12130421-il-y-a-30-ans-un-spectaculaire-eboulement-sabattait-pres-de-randa-vs.html.
31. swissinfo.ch. Bondo, cinq ans après l'éboulement, sur la voie de la normalité. 2022 [cited 2024 May 15]; Available from: https://www.swissinfo.ch/fre/bondo-cinq-ans-apr%C3%A8s-l-%C3%A9boulement-sur-la-voie-de-la-normalit%C3%A9/47846434.
32. Office fédéral de la météorologie et de la climatologie MétéoSuisse. Indices de sécheresse. Available from: https://www.meteosuisse.admin.ch/climat/changement-climatique/chaleur-canicule-secheresse-froid-et-neige/indicateurs-climatiques/indices-de-secheresse.html.
33. Office fédéral de l'environnement OFEV. La canicule et la sécheresse de l'été 2022. 2023 [cited 2024 May 15]; Available from: https://www.bafu.admin.ch/bafu/fr/home/themes/climat/dossiers/la-canicule-et-la-secheresse-de-l-ete-2022.html.
34. swissinfo.ch. Le lac des Brenets (NE) à nouveau victime d'un assèchement rapide. 2022 [cited 2024 May 15]; Available from: https://www.swissinfo.ch/fre/le-lac-des-brenets-ne-%C3%A0-nouveau-victime-d-un-ass%C3%A8chement-rapide/47694390.
35. RTS. L'agriculture suisse au défi de la chaleur et de la sécheresse estivales. 2023 [cited 2014 May 15]; Available from: https://www.rts.ch/info/suisse/14287057-lagriculture-suisse-au-defi-de-la-chaleur-et-de-la-secheresse-estivales.html.
36. swissinfo.ch. Incendie de Loèche: du jamais vu depuis 30 ans. 2003 [cited 2024 May 15]; Available from: https://www.swissinfo.ch/fre/science/incendie-de-lo%C3%A8che-du-jamais-vu-depuis-30-ans/3460038.
37. Le Nouvelliste. Incendie de forêt à Bitsch: de nouveaux dégagements de fumée nécessitent l'intervention d'hélicoptères. 2023 [cited 2024 May 15]; Available from: https://www.lenouvelliste.ch/valais/haut-valais/incendie-de-foret-a-bitsch-de-nouveaux-degagements-de-fumee-necessitent-l-intervention-d-helicopteres-1313433.
38. RTS. Les barrages suisses, une histoire humaine. 2021; Available from: https://www.rts.ch/play/tv/histoire-vivante/video/les-barrages-suisses-une-histoire-humaine?urn=urn:rts:video:12654535.

39. KWO Grimselstrom. Remplacement du barrage de Spitallamm. 2019 [cited 2024 May 15]; Available from: https://www.grimselstrom.ch/ausbauvorhaben/zukunft/dossier-remplacement-du-barrage-de-spitallamm/.
40. L'illustré. L'année de la grande vidange du barrage du val Verzasca. 2022; Available from: https://www.illustre.ch/magazine/lannee-de-la-grande-vidange-du-barrage-du-val-verzasca.
41. RTS. Au Tessin, les vestiges engloutis du Val Verzasca refont surface. 2022 2024]; May 15]. Available from: https://www.rts.ch/info/suisse/13177993-au-tessin-les-vestiges-engloutis-du-val-verzasca-refont-surface.html.
42. Confédération Suisse. About Switzerland: Biodiversité. 2023 [cited 2024 May 15]; Available from: https://www.eda.admin.ch/aboutswitzerland/fr/home/umwelt/natur/biodiversitaet.html.
43. Federal Office for the Environment FOEN. The Aire renaturation project wins the Landscape Award of the Council of Europe. 2019 [cited 2024 May 15]; Available from: https://www.bafu.admin.ch/bafu/en/home/topics/landscape/dossiers/landscape-award.html.
44. ge.ch. EAU - Vidéo sur la renaturation des rives du Léman. 2020; Available from: https://www.ge.ch/document/eau-video-renaturation-rives-du-leman.
45. Office féréral de la statistique OFS, L'utilisation du sol en Suisse. Résultats de la statistique de la superficie 2018. 2021, Confédération Suisse.
46. Office fédéral du développement territorial ARE. Développement de l'urbanisation vers l'intérieur. [cited 2024 May 15]; Available from: https://www.are.admin.ch/are/fr/home/agglomerations-espaces-ruraux/strategie-et-planification/developpement-de-l-urbanisation-vers-l-interieur.html.
47. Confédération Suisse. About Switzerland: Urban and spatial development. 2023; Available from: https://www.eda.admin.ch/aboutswitzerland/en/home/umwelt/geografie/staedtebau-und-raumentwicklung.html.
48. Patrimoine Suisse. Sous la pression de la croissance. 2023; Available from: https://www.patrimoinesuisse.ch/details-actuels/sous-la-pression-de-la-croissance.
49. RTS. Crise du logement: Le canton de Genève mise sur la construction d'au moins 30'000 nouveaux appartements d'ici 2030. 2022 [cited 2024 May 15]; Available from: https://www.rts.ch/play/tv/19h30/video/crise-du-logement-le-canton-de-geneve-mise-sur-la-construction-dau-moins-30000-nouveaux-appartements-dici-2030?urn=urn:rts:video:13276601.
50. Federal Statistical Office. Portraits of the cantons. [cited 2024 May 15]; Available from: https://www.bfs.admin.ch/bfs/en/home/statistics/regional-statistics/regional-portraits-key-figures/cantons.html.
51. 20 minutes. Voici les chiffres de la croissance de l'agglomération. 2023 [cited 2024 May 15]; Available from: https://www.20min.ch/fr/story/les-chiffres-de-la-croissance-de-lagglomeration-911021525004.
52. Zermatt Tourismus. Matterhorn. 2024 [cited 2024 May 15]; Available from: https://www.zermatt.ch/en/matterhorn.
53. Hans Stadler. Lac des Quatre-Cantons. Dictionnaire historique de la Suisse (DHS). 2013; Available from: https://hls-dhs-dss.ch/fr/articles/008666/2013-02-27/.
54. Heinrich Bührer and Heinz Ambühl, Lake Lucerne, Switzerland, a long term study of 1961-1992. Aquatic sciences, 2001. 63: p. 432-456.
55. INTERNATIONAL COMMISSION FOR THE PROTECTION OF THE WATERS OF LAKE GENEVA Cipel. Phosphorus and eutrophication. 2020 [cited 2024 May 15]; Available from: https://www.cipel.org/en/le-leman/presentation-du-

leman/#:~:text=Phosphorus%20and%20eutrophication&text=The%20eutrophication%20of%20Lake%20Geneva,89.5%20%C2%B5g%2FL%20in%201979.
56. Abolfazl Irani Rahaghi, et al., Combined Earth observations reveal the sequence of conditions leading to a large algal bloom in Lake Geneva. Communications Earth & Environment, 2024. 5(1): p. 229.
57. Confédération suisse. About Switzerland. Nature – Facts and Figures. 2023 [cited 2024 May 15]; Available from: https://www.eda.admin.ch/aboutswitzerland/en/home/umwelt/natur/natur---fakten-und-zahlen.html.
58. Federal Office for the Environment FOEN. Biodiversity: In brief. 2024 [cited 2024 May 15]; Available from: https://www.bafu.admin.ch/bafu/en/home/topics/biodiversity/in-brief.html#1126723157.
59. République et Canton de Neuchâtel. PROTECTION DU HAUT PLATEAU DU CREUX DU VAN: MISE EN ŒUVRE DES MESURES URGENTES. 2020 [cited 2024 May 15]; Available from: https://www.ne.ch/medias/Pages/20200701-creux-du-van-zones-interdites.aspx.
60. Parc National Suisse. Fondements et impressions. [cited 2024 May 15]; Available from: https://nationalpark.ch/fr/about/parc-national/.
61. UNESCO Biosphere Entlebuch. Nature and landscapes. Available from: https://www.biosphaere.ch/en/unesco-biosphere-a-z/nature-and-landscapes/.