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Deliverable 5.6, Mine tailing ponds

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Reference

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Task objective (from DoW)

The objective of the workpackage is to show the applicability of S2 (and possibly of S3) data to locate mine tailing ponds to serve as input for risk analysis studies. Mine tailing or (mine dumps) can produce distinctly coloured waters. Mine tailing represent an external cost of mining, and this is particularly true of mining operations which do not take adequate steps to make tailings areas environmentally safe after closure. Occasionally, the material can be highly toxic. These mine tailing ponds might as appear as exceptional spectra, as known as novelties (Schiller et al., 2007).

Scope of this document

The scope of this document is to show how satellite data, especially GLaSS products, can be used to detect mine tailing ponds in Azerbaijan, Finland and Mongolia.
Abstract

Mine tailing ponds, especially the thousands of abandoned ones, can cause large environmental and social disasters. About yearly, a break of a dam happens somewhere in the world, spilling tons of toxic sludge into surrounding ecosystems and villages. Locating them, in often very remote areas is the first step into monitoring their stability and preventing future disasters.

Tailing ponds can be very distinctive in colour and constituents. By analysing the spectral signature of a mine tailing pond, it is possible to distinguish between other water bodies and mine tailing ponds. In the Global Lakes Sentinel Services (GLaSS) project the objective is to make use of Sentinel data and in preparation for this data Landsat-8 is used as a proxy.

Three different study areas are selected: Azerbaijan, Finland and Mongolia. For these areas all available Landsat-8 images for the year 2014 were acquired from the U.S. Geological Survey. All images are level 1 products. The images were converted to top-of-atmosphere (TOA) reflectances. One initial information for the identification of mine tailing ponds is the L1 snow high probability flags which is provided with the Landsat-8 images. The Landsat-8 snow flag is turned on in small parts of mine tailing ponds. To select only water bodies, several land masks were applied to the TOA reflectance images. One was selected, that did not flag out the mine tailing ponds. In evaluating the images it was found that images with snow were not useable. Consequently the dataset was reduced to only the months with low snow cover potential, the months July through September for the Northern Hemisphere. By applying all masks and restrictions, the remaining data was mostly comprised of mine tailing ponds, other bright unusual coloured water bodies (e.g. salt lakes) and cloud shadow. By evaluating the spectra of the remaining data, several band ratios were applied to reduce the dataset to primarily areas within mine tailing ponds. This final selection was used to select the distinct water bodies they are a part of, this was done using a binary propagation algorithm.

The final results show mine tailing ponds across all three study areas. There are some false positives and false negatives, but the overview provided does allow clear insights in mining tailing ponds locations. With the availability of Sentinel data it is expected that it will be possible to elaborate and expand this method to increase accuracy and reliability.
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1 Introduction

1.1 Mine tailings and tailing ponds

Mining activities are focused on retrieving minerals from the earth's crust, which yield enough economic value on the market. The raw minerals, usually called ore, can differ per mine site and may even change in time. There are varying methods for extracting ore from the host material. As a result of mining, impacts in the environment become apparent, resulting from the different processes involved, which depend on hazardous chemicals and modify the surrounding area and the local groundwater systems. The largest by-products resulting from mining are mine water and rock waste. For a large part the by-products are reused into the processing, because of the remaining metal content; the leftovers are stored and distributed (EPA, 2000).

All the water entering the surface of the mine or the underground area is called mine water. The water can be stopped at the border of the mining area using different methods and the stopped water can be caught and used for varying purposes. After a mine has become abandoned or production has stopped, water will return to its normal path raising the water level underground and in surface shallows. The composition of the waste products depends on the nature of the waste, which processes have been used, and the chemical composition of the soil, the mine water may still hold heavy metals, other dissolved compounds, have a different temperature and altered pH (Salomons, 1995). After exposure to oxygen, pyrites and sulphide minerals react and acidify the water dissolving remaining metals in the mining area. When mine water runs off into downstream groundwater and surface water it is called Acid Mine Drainage (AMD).

The solid remains after mining are named mine dumps or tailings. These tailings are composed of ground rock and effluents leftover from processes in a mining plant. The extraction of the target minerals in done using a combination of mechanical and chemical processes and result in stream of waste called tailings. The extraction process is not perfect, neither is the reclamation of potentially useful substances. The inextricable and undesired materials, composed of metals, chemicals, process water, minerals and organics are released, most often as a sludge, to a designated storage area, also known as the Tailings Management Facility (TMF) or Tailings Storage Facility (TSF). The composition of most of the slurry differs per mine and substrate characteristics.

Initially, the beginning of the 1900s, tailings were often disposed in local waterways. In some cases the formation of an “upstream tailings dam” was created from the tailings settling on the bank, in a beach-like scene in the stream. After World War II, understanding of processes in the soil improved and dam technology advanced, resulting in more tailing ponds. These ponds were mostly earth-filled or constructed from leftover mining debris. By building an embankment a pond is formed at the start of the mine construction. The pond “walls” are designed to restrain suspended solids. A beach is formed from the tailings, as they are piped in at the crest and the solids are deposited while the water drains away. This beach acts as a buffer between the water in the pond and the dam's wall, these embankments are designed to hold water up till the top. The most dangerous substances are in the water, for example acid, the beach shields the embankment from erosion.

At this time there are methods to store mine tailings on the surface, either in ponds or in piles (dry stacks), or underground in empty mined out areas, usually called backfill. Through storage underground additional support can be provided and ventilation is improved, additionally it can prevent subsidence (EC, 2004). Many parameters should be considered when designing a tailings storage facility. These parameters have a big influence on the
optimal site, storage and dispersal methods (Ritcey, 1989). The most important parameters are the environment and the ground composition, these determine methods for tailing control and lead to the design of the facility, the operation and the closure. The unique play between available methods, desired processing and environment result in a specific design. Different technique are suited best for different purposes, to control oxidation of sulphides sub-aqueous disposal, dry stacking or high density thickened tailings can be employed. Current designs take a lot of additional different variables into account, for example: local rainfall, flooding and earthquake chances, seepage and tailings discharge method and rates.

1.2 Environmental challenges of tailings

Due to acid drainage during the lifetime of a mine tailing, tailings can be seen as a potential environmental hazard, in addition there is the risk of a dam breaking, either can lead to leakage of toxic metals, e.g. arsenic and mercury, into the local surroundings (examples can be found in the next section). Often the most important environmental aspect of a mining operation is the disposal of the tailings (Vick, 1990). The volume of tailings can exceed the mined volume, resulting in justified primary focus. The last 100 years the amount of tailings produced has increased significantly. As the market for metals and minerals increased so does the threshold for suitable sites. In additional to advances in technology more and more ore is mined. Over the last 50 years the production has increased from several 10000 tonnes to several 100000 tonnes (Jakubick, McKenna et al. 2003). There are currently single mines producing over 200000 tonnes of tailings per day. At this moment, there are believed to be around 3500 tailings dams of operational mines worldwide.

The increase in production and technology, also increase the challenges for storage. Lower grade ore is accessible through technological breakthroughs. Resulting in a bigger volume of waste, leading to higher storage demands. In tandem the environmental regulations are keeping pace, more and better controls are required, with extra attention of storage facilities. The increase in workflow and the need to control it properly increase the pressure on mine operators. As can be seen in the recent incidents with mine tailings the largest part is due to poor management, which in turn result in more stringent control.

The main issue with bad management is often seen as the lack of a financial incentive to manage the waste product properly. The most cost effective approach is often chosen to limit expenses, while meeting regulations. As a results surface impoundments, e.g. dams, embankments, are the go-to method for storage and remain a industry staple. To maintain a dam properly, repairs to reclamation systems and tailings pipes are needed, in addition the water levels in the embankments needs to be monitored and the foundation checked for structural deformations. Changes in the sediment movement are often measured using survey pins. With increased production the mine tailing dams are raised every few years. The design engineers plan out the entire life expectance, can be upwards of 20 years, of a mine and raise accordingly. External inflow into the mine tailing ponds is an additional issue. Diversion channels are included in the designs to keep run-off from the surface out, any water flowing in will be contaminated and has to be treated for metals and chemicals.

Despite advances in technology, allowing for better recycling and more reuse of a lot of waste products at mine locations, the largest part of waste that is untreated is stored in storage facilities, and management and remediation of these storage facilities is becoming a increasingly large part of modern mine development and mine closure. Ultimately, no solution for tailings is environmentally friendly, consequently miners try to minimize the amount of water in the decommissioning phase to limit the need to long-term management. By covering dry materials and replanting areas the influence of erosion can be minimized, the final design and land formation will limit maintenance after closure. The design of the dam should be
sufficient to maintain for at least 1000 years, no matter the natural occurrences, e.g. floods and earthquakes. The amount of abandoned mines is several orders of magnitude higher than the estimated 3500 active tailing ponds dams in the world. In response of a recent spill in the Colorado River, an expert in mine waste treatment explained to National Geographic (Howard, 2015) that just in Colorado, there are an estimated 4650 abandoned mine sites currently leaking toxic waste. There are about 500000 abandoned mines in the U.S., according to the Environmental Protection Agency (EPA). A world-wide number could not be found.

1.3 Incidents with mine tailing ponds

One large incident with a mine tailings dam occurs every year, according to a study by the International Commission of Large Dams and the United Nations Environmental Program (UNEP, 2000). In recent years the frequency of occurrences has doubled. Davies (2002) found the increase in incidents by examining the statistics gathered from earlier periods only matched in the early to mid-1930s.

The main cause for failure is lack of understanding the specifics of the dam technicalities, resulting in issues with the construction of amount of water. Some incidents can be attributes to large natural events, though current designs should take these into account. The largest contributor to mine tailing dam failure is excessive rainfall, where the retention capacity is flooded.

Some examples of accidents:

- **Stava, Italy:** In 1985, tailings dams built to store waste from fluorite mining failed due to poor design and extreme water pressure. Two hundred thousand cubic meters of tailings flowed more than 4 km downstream at a speed of up to 90 km per hour. The incident killed 269 people and destroyed more than 60 buildings.

- **Los Frailes, Spain:** Poor design led to a failure in 1998, a 50-meter section of the dam’s wall collapsed, sending acidic water containing sulphur, zinc, copper, iron and lead into the Rio Agrio and adjacent farmland.

- **Baia Mare, Romania:** In 2000, a cyanide spill occurred due to a dam failure. The waste leaked into a local river which discharged into the large Danube River, causing a large environmental disaster.

- **Kolontár, Hungary:** In 2010, a tailings dam storing waste from bauxite mining collapsed due to heavy rain. The red toxic sludge from the dam spread over eight square km, flooding nearby towns. Ten people were killed, and about 120 were injured. The CEO of Magyar Aluminium ZRt, the company in charge of the dam, was briefly arrested and released after the incident.

- **Talvivaara, Finland.** Since November 4, 2012 leaked from the gypsum waste pond at the Talvivaara mine in Kainuu to the surrounding rivers and lakes. Only during the first day of the disaster, over 220,000 cubic meters of waste water, containing uranium, sulphate and heavy metals such as nickel and cadmium have leaked away for at least ten days. It is estimated that over 10,000 kilos of nickel and unknown amounts of uranium escaped the mine. A new spill started April 8, 2013 releasing some 350,000 cubic meters of waste waters only within the first day. Talvivaara experienced another leakage releasing some 7,000 cubic meters of waster waters per hour - in total some 350,000 cubic meters are said to have leaked out during the first day. Another new spill started April 7th, 2013. At least 100 hectares of marshland, streams, lakes and ponds have been polluted by the discharges of waste waters. Through heavy application of lime up to a thousand kg of liquid uranium has accumulated as sediment in the grounds and vegetation of the area. At least 20,000 cubic meters of the spill entered in the northern Oulujoki-waterway. The
major leak to the south through lake Ylä-Lumijärvi in the major East Finland Vuoksi-waterway included at least 200,000 cubic meters of waste water.

- Mount Polley copper and gold mine in B.C., Canada. The breach of a tailings pond started August 4, and by August 8 the complete mine tailing pond of 4 km diameter was empty. It released five million cubic metres of mining wastewater into local waterways.
- Colorado River, USA. In August 2015 a large spill happened at the Gold King Mine, from which the hazardous material ended up in the Colorado river.
- Brazil, 5 November 2015. The Samarco iron mine dam collapsed and buried the nearby town of Bento Rodrigues with 62 million cubic meters of toxic sludge and killed at least 9 (19 still missing). Next 400 miles of the Rio Doce River was killed before the waste reached the Brazilian coast. By the time of writing this report, tides are expected to spread the substances along a 5.5-mile stretch of coastline, threatening a nature reserve.

![Figure 1. Landsat-8 satellite on August 5, 2014, a day after the accident of the Mount Polley mine in Canada. Hazeltine Creek Creek was originally about 1.2 meters wide and after the incident 150 meters](image)

1.4 Factors that influence the characteristics of tailing ponds

The ore composition and means of extraction, both physical and chemical, determine the characteristics of mine tailings. By examining the processing steps an increased understanding can be gained, allowing for better insight into storage challenges. Ritcey (1989) reported that even though the same processes are applied to the ore, the composition will be different and the resulting characteristics will be different as well, both physically and chemically. To understand the processes that will take place in storage, both short term and long term, a thorough understanding of the tailings characteristics is needed to minimize liabilities and environmental impact. From initial laboratory samples and test sites an estimate can be made predict characteristics, full insight will not be obtained. These initial
tests can however limit environmental impact and increase optimal performance.

The first impact on the mined ore is the exposure to the surface, with will increase the speed of weathering and subsequent mobilisation, for example sulphuric bearing hard rock ore. In this example, the physical process increases the relative surface area exposed, increasing the weathering through water and air. Through weathering and subsequent erosion acids are generated and metals are mobilized. These can then find their way into the surrounding area through seepage or runoff. The described problem is a well known phenomenon at mining sites and is often referred to Acid Mine Drainage (AMD) or Acid Rock Drainage (ARD) (Garcia, Ballester, et al. 2005; Ritcey, 2005). Through the addition of more reagents in the chemical process the characteristics may change, resulting in different needs for storage and tailings (EC, 2004).

Each extraction method brings about its own influence on the type of tailings storage. Basic examination of the mineralogy can yield the most efficient method for extraction. In addition to the best extraction method, additional minerals of interest can be identified with the subsequent reagents and quantities thereof to separate the valuable from the detritus. In turn this leads to a better understanding of the needed storage facilities (Ritcey, 1989). With a test site the best grind level can be determined, which chemicals are need and what tailings are produced. Being a test site, it is but a sample of the total mine area, and differences with the full production can occur. Consequently, assumptions and designs should be evaluated as production has started (Blight, 1998).

The separation of the ore through crushing, grinding and chemistry into product and waste is called concentration, the waste is called tailings. This first step is often accomplished through froth flotation, where the first chemicals are introduced (Vick, 1990). If the desired product is easily separated through the use of gravity or magnetism, then these methods make good first steps. In gold mining gravity separation is often used to separate out large parts and chemicals for finer parts (EC, 2004). Pressure oxidation, roasting and bioleaching are often used on refractory ores before proceeding to leaching techniques. These ultra fine processing steps are often done chemical steps and are commonly associated with low in-situ density and slow settling properties.

By reusing water the costs for the water balance of a mining project can be reduced, consequently the design for discharge and return pumping are very important. These possibilities for liberation is tied in with the physical characteristics of the tailings, an estimation for this can be done in a laboratory using different concentrations of solids. In addition this information can determine the best method for storage, to prevent discharge to a mine tailing pond, reduce loss though evaporation and limit potential seepage.

The level of thickening of tailings and the means of deposition of tailings influence the construction parameters. While investigating characteristics of tailings it is critical that the physical parameters and material characteristics that can results from different processes are identified (SANS, 1998). This hold especially true for very thick tailing dispersal and is highly correlated with deposition and transportation questions. The tailings composition of most metal mines is comparable in texture and size as sand, in the process of grinding and separating of waste from value a lot of water is used, the waste is usually stored in mine tailing ponds. The size of the mine tailing ponds can vary greatly, some are enormous with dams of up to 300 meters tall and kilometres long.
1.5 This study: use of Earth Observation to locate mine tailing ponds

The combination of hazardous waste which can erode its protective dams, the tension between the environmentally storage methods versus the costs, the increasing number of tailing ponds and especially the list of incidents and their effects indicates the importance of regularly monitoring tailing ponds, especially those that remain 'abandoned' after closure of the mines, where management might be lacking.

The conclusion of the characteristics of mine tailing ponds is that they can largely vary in (chemical) content and therefore colour, even for cases where the same ores are mined. Also the structure of the dam(s) and the thickness of the tailings might vary greatly. However, they all contain a combination of water and chemicals. Especially for the abandoned ones the chemicals will be concentrated and therefore show the most pronounced colours. Therefore, Earth Observation, using high resolution optical satellites might be a feasible method to locate the thousands of abandoned mine tailing ponds, to allow checking these for safety reasons.

To access the impact of mining some work has already been done using EO data. Traditionally the impact of mining is done using ground surveys in chemical, physical and hydrological fields. In research using remote sensing as an aid some progress has been made and successes have reached (e.g., Fenstermaker and Miller, 1994; King et al., 1995). With the appearance of high resolution airborne imaging spectrometry data, such as HYDICE (Rickard et al., 1993), more possibilities become available to assess mine tailing activities pertaining to the environment. AVIRIS data has been used to demonstrate the possibilities to map and monitor the changes in a major silver mining area and base metals mining area. Using a technique called constrained energy minimization the spread of mine tailings on the environment was mapped, as shown by Harsanyi (1993) and Farrand and Harsanyi (1994a). In the study area, the Coeur d'Alene River (CDA) valley in northern Idaho, mining has been active for decades. The sediments in the river and the nearby lake, Coenr d'Alene, have high concentrations of Ag, Cu, Pb, Zn, Cd, Hg, As, and Sb (e.g., Horowitz et al., 1992). The freely available iron oxide binds the trace elements and forms oxy-hydroxide minerals and/or mineraloids. Both adsorption and direct incorporation occur (Schwertmann and Taylor, 1977). Iron oxides, goethite and hematite, associated with acid mine drainage environments according to Ferris et al. (1989), but most common is the metastable mineral ibrrhydrite. The mentioned minerals have characteristic spectra in the VNIR range (0.4-1.3 micrometer), resulting in the potential for mapping using spectrometry data.
Figure 2, photos of the Colorado spill incident (2015), showing the typical colour of mine tailing water. The river is the Animas River, which discharges in the Colorado. The images on the right bottom show the also affected Doce River, before and after the accident seen by Landsat-8. This image is from remotepixel.ca.

One of the first studies in which EO data was used to locate mine tailing ponds, was performed by Sol, Peters and Aiking (1999), carried out for the World Wildlife Fund. The purpose of that study was to get a first impression of the environmental risk of toxic waste storage in mine tailings ponds in Europe. When it was found that no central database of active or abandoned mines, or relevant international and national legislation existed, a case study using a Landsat Thematic Mapper (TM) image of the south of Spain was carried out to test the option of remote sensing. A combination of high reflectance in the green and in the red band was used to distinguish mine tailing ponds from other waters (that are either darker or at least darker in the red band). This spectral signatures can be explained by the reddish yellow/orange colour tones resulting from acid mine drainage that can also be seen in the photos of the Colorado River accident (Figure 2). Its conclusions that located tailing ponds with earth observation instead of by completing a country-by-country approach towards all stake holders could greatly speed up an inventory was the starting point for the current study.
Meanwhile, more remote sensing techniques have been applied on mine tailings. Kopačková and Hladíková (2014) applied spectral unmixing of hyperspectral data to map the relative abundances of mine water components iron, dissolved organic carbon and undissolved particles. While interesting, such hyperspectral imagery cannot currently be obtained from a complete continent to located tailing ponds.

Tote et al (2010) present a very detailed report on the environmental impact of mining and the limitations and potentials of EO data to monitor these. They consider the following variables:

The following direct variables are considered by Tote et al (2010):

- Minerals
- Acid mine drainage and ferruginous materials
- Atmospheric pollution and windblown particles
- Temperature increment due to (underground) coal fires

The following indirect variables are considered:

- Land use and land cover change
- Vegetation stress
- Contaminated surface waters: sediment load and metal contamination
- Changes in soil moisture and groundwater environment
- Subsidence

Some of these are interesting for our current goal: locating potential harmful (abandoned) mine tailing ponds. Tote et al list EO as widely used to trace minerals at the surface. With regard to acid mine drainage, based on the results of Swyze et al. (2000) who used an airborne scanner, theoretically Landsat and – in particular ASTER could be used to discriminate between different acid mining drainage minerals based on their reflectance spectra. For contamination of surface waters, Tote et all mainly focuses on suspended particles in mine water, while for contaminating substances they mention the too low spectral and spatial resolution. Higher resolution imagery such as QuickBird and IKONOS are listed as potential sensors for this subject.

In this study we will focus on deriving a practical method that can be applied world-wide, to locate (abandoned) mine tailing ponds.

### 1.6 Study areas

The development focus in this project is on a globally applicable algorithm for detecting mine tailing ponds. As study area Finland was selected because of the potential for early Sentinel-2 data access. The second study areas is Azerbaijan, where in situ reflectance measurements of ‘strange’ coloured water bodies are available (a pink salt lake and a lake contaminated with oil), that are located close to known mines. The third study area is Mongolia, for which there is an interested party (the German ecological institute IGB). In Mongolia there are abandoned mine tailing ponds with unknown locations, but also very new technically mines that are designed to work with zero discharge (e.g. Inam, 2011).
Study areas:

Figure 3, known mines in Azerbaijan

Figure 4, known mines in Finland
Figure 5, known mines in Mongolia
2 Methodology

To work on the mine tailing ponds a dataset had been acquired. The goal was to use Sentinel-2 data, but due to delays in launch, a proxy sensor was selected. The proxy sensor was Landsat-8 and the available images for 2014 of the study areas were downloaded from the USGS website:

- Azerbaijan ~ 300
- Finland ~ 1000
- Mongolia ~ 2000

2.1 Initial approach

The initial approach to map mine tailing ponds, as seen in figure 6.1, was atmospheric correction followed by a Gaussian gradient algorithm and ending with the use of watershed segmentation to be able to classify tailing ponds using supervised classification through machine learning. First, a Landsat-8 image with relative low cloud cover of a known mining area in Finland was used and converted to top-of-atmosphere reflectance. As a follow-up step an atmospheric correction was required. While investigating different possibilities for atmospheric correction, the reliability of the results and the amount of data after flagging was not high enough.

After some initial tests it was decided to use the top-of-atmosphere reflectance as a start. From the image set the SWIR_1 band was processed with a Gaussian gradient algorithm which should yield the potential water bodies as individual objects. Unfortunately the segmentation did not prove to be adequate enough to perform a classification using machine learning. Therefore a more simple and feasible follow-up approach was explored.

2.2 Follow-up approach:

In the follow-up approach, as illustrated by figure 6.2, the idea was to use the available masks in the original Landsat-8 product. Screening for clouds using the cirrus and cloud masks in the quality assessment (QA) seemed a prudent step to reduce further computations and storage space. After the cloud screening, using the water masks in the QA band could constrict the selection of relevant data even more. A binary erosion algorithm should then reduce the improper detected water bodies by excluding mixed-pixels from the selection. The final selection of water pixels should be atmospherically corrected using a dark object subtraction (DOS) atmospheric correction. The data would then be investigated in feature space plots. From these plots, classes would be defined leading to mine tailing pond specific parameters. In implementing these steps it was found that the cirrus masks provided with the Landsat-8 QA band did not provide a good basis to distinguish between relevant and irrelevant data. The cirrus masks where therefore not used. In evaluating the cloud masks in the QA band only the high, 65%-100%, confidence mask allowed for reasonable selections. The selection of completely cloud-free images (based on the cloud masks statistics for whole images) resulted in a substantial reduction in available data. From the original dataset only a fraction remained:

- Azerbaijan ~ 2
- Finland ~ 15
- Mongolia ~ 30

In the remaining images, whole image statistics indicated an abundance of cirrus or other
artefacts that made them not suitable for further analysis. In trying to increase the selection of suitable data, the cloud mask was applied on equal-sized parts of the images as a whole. The images were divided in 3 subdivisions of 4, 16 and 64 equal sized parts per image. The subsections were then evaluated for 0%, 1% and 10% cloud cover. The end result was an abundance of selections for each image, with promising numbers of suitable images. In the images with known mine tailing ponds it was found that the mine tailing ponds were mostly flagged out as containing too many clouds. Upon further evaluation it seemed that mine tailing ponds very often have an area in it that is flagged as cloud with high confidence irrelevant of the presence of clouds in the area. This resulted in the need to include all clouded images and rethink the follow-up approach.

Figure 6.1: flow chart of initial approach

Figure 6.2: Follow-up approach

Figure 6.3: Final approach
2.3 Final approach:

The final approach, as seen in figure 6.3, was designed to use all images and not correct for the atmosphere. The extent of the study areas and availability of needed atmospheric data across the extent leave only a DOS atmospheric correction as an option. In a DOS atmospheric correction the darkest pixel is assumed to be black and have no information but the atmospheric data. On land the darkest pixels are often bodies of water. Since we are interested in the data of water and the subset of mine tailing ponds, the darkest pixels probably contain interesting data. As a result it was decided to skip the atmospheric correction and work with the top-of-atmosphere reflectance.

On all the images a land mask had to be applied first. The water masks in the Landsat-8 QA band upon themselves did not provide a suitable basis to distinguish inland water with high confidence. Therefore we applied 3 separate land masks:

1) any of the 3 water masks in the QA band

2) (((NIR - RED) / (NIR + RED)) > 0.1) AND (0 < SWIR_1 < 5)

3) (AERO < NIR) AND (NIR > 0.15)

From these 3 land masks, the 2nd mask gave the best result for including mine tailing ponds. Upon evaluation of the masked data it was seen that most mine tailing ponds had a small area that was flagged as ‘snow/ice 65%-100% confidence’, in the QA band, even in the heart of summer, see figure 7.

Figure 7: July 11 2014: Example of Vuonos mine in Finland

The question if there is any logic behind the snow/ice flag being raised in a mining area can be answered by a combination of checking if the reflectance spectra of the flagged pixels and the theory of the snow/ice flag.

Figure 8 shows an extract of some pixels of the area of in Figure 7. This explains why the snow/ice flag can be found in many of the mining locations. The NIR part of the reflectance spectrum is really low, as can be expected from a pixel containing water. However, the visible part of the spectrum is much higher than that of the surrounding water, which makes sense from the perspective that mine tailing ponds often contain brightly coloured water.
Figure 8, reflectance spectra extracted from the L8 image of the area presented in Figure 7. Note that the ‘snow’ spectrum is not real snow, but from one of the pixels flagged as snow.

Theory confirms this. The snow/ice flag in the Landsat-8 product is derived from a combination of filters and algorithms. The basics for the detection of ice is currently:

- RED > 0.08
- (GREEN - SWIR_1) / (GREEN + SWIR_1) > 0.8

This value with 4 other values from different algorithms (as found at: https://landsat.usgs.gov/l8handbook_section4.php) are combined using weights found at: http://landsat.usgs.gov/cpfbpf.php. From this combination the final masks are selected. In the future the plan from the USGS is to use CFmask (https://github.com/usgs-eros/espa-cloud-masking). In this new approach the following steps determine snow/ice:

- NDSI > 0.15
- Brightness temperature > 283 K
- NIR > 0.11
- Green > 0.1

Information on this approach can be found in Zhu (2012) and Scaramuzza (2012).

By limiting the images to only the months with the lowest chance of snow cover, for the northern hemisphere the months July, August and September see figure 9, the snow/ice flag can be used in the procedure to select potential mine tailing ponds.
The selection of data, after applying the temporal mask, land mask and snow mask, contained mostly mine tailing ponds, clouds and cloud shadows. By evaluating the feature space of the remaining data new masks were added of adjusted. Resulting in the one final additional mask: (AERO < 0.3) AND ((AERO < 0.18) OR (BLUE > AERO)). The final selection mostly represents parts within a mine tailing pond. By employing a binary propagation algorithm the small part can be “grown” back to the original body of water it was a part off. The final step is reducing the body of water to eliminate mixed pixels at the edges; this is accomplished using a binary erosion algorithm.

Figure 9: Extent of Northern Hemisphere Snow Cover (copied from National Snow and Ice Data Center)
3 Results

3.1 General results

With increased cloud cover the reliability of the detection algorithm is reduced, as can be seen in figure 10. The algorithm can still detect mines under partial cloud cover, if the right part of the mine is visible, as seen in figure 11.

![Figure 10. Left: RGB of Finnish area with cloud cover. Middle: detected potential mine tailing ponds (in white), without additional cloud mask. Right: detected potential mine tailing ponds (in white), with additional cloud mask.](image)

Figure 11. Siilinjärvi mine as detected (red) under partial cloud cover
3.2 Results for Azerbaijan

In the analysis of Azerbaijan, seemingly bare soil or rock (probably with specific mineral composition) leads to misclassification of land as water (Figure 12). Therefore, the algorithm leads to false positives for mine tailing ponds. Also, some other brighter coloured water bodies show up as potential mine tailing pond (Figure 13).

![Figure 12 Left: RGB of Azerbaijani area. Right: land mask (in black). As can be seen, a lot of the land is masked as water.](image)

![Figure 13. Area with detected potential mine tailing ponds (in red), which are actually a river and fish ponds (Azerbaijan)](image)

Some tests show that adjusting the water mask removes most of the false positives, after which no real mines are found in the area.
3.3 Results for Finland

The results of Finland show good matches with known mines, as can be seen in the Figure 14.

![Figure 14. Detected potential mine tailing ponds (in red), validated from other sources. Top left is the Vuonos mine. Top right is the Boliden Kylylahti processing plant. Bottom left is the Nunnanlahti mine. Bottom right is the Siilinjärvi mine with clouds classified as mine tailing ponds.](image)

The availability of data on mines in Finland makes validation easy and reliable: the available data allows to check also for false-negatives in the same image (Figure 15).

The mine that is not found by the algorithm has a tailing pond, however, this pond has a natural water colour. Therefore, it would not even theoretically be possible to locate this pond by optical remote sensing. Interestingly, one of the mines that was located properly does not have a tailing pond. The excavation site still shows as a combination of water (according to the mask) and snow/ice (according to the flag).
3.4 Results for Mongolia

Mongolia has a few lakes which seem to resemble mine tailing ponds, as seen in Figure 16. For the most part structures resembling mine tailing ponds are identified, though the verification of the potential mines is limited due to limited information. Enough verification can be achieved to be optimistic about mine tailing detection in Mongolia.
A few lakes were also classified as a mine tailing pond, two example seen in Figure 17. The lake on the left appears to be a salt lake, and also the one on the right has a distinct bright colour. This makes sense as the reason for the detection as a mine tailing pond.
Figure 17. Natural lakes that are located by the algorithm as potential mine tailing ponds. Left: Lake Shariin Tsagaan classified as a potential mine tailing pond. Right: another example of a natural lake with a distinct colour (image from Google Earth).

In a complete L8 image of this area many mines (as in Finland, also some without a pond) were located in this remote area, showing the advantage of using remote sensing to trace mine tailing ponds (Figures 18 and 19).

Figure 18, Landsat 8 image of Mongolia with red pins for all areas that are located by the algorithm.
(including false positives). Blue pins are false negatives. Lables describe their confirmed actual status. Figure 19 shows the area within the red circle.
4 Conclusion and recommendations

From this work it can concluded, that it is possible to trace mine tailing ponds based on Landsat-8 satellite data, however, the method developed can be improved and expanded upon.

The initial issues to trace mine tailing ponds worldwide were automating the download and the size of the dataset: high resolution satellite data of a complete continent makes downloading, processing and subsequent testing a slow process. To reduce the size of the dataset to expedite the process of finding mine tailing ponds, land and clouds were to be removed first. Because the standard flags to remove unwanted pixels tend to remove the main tailing ponds as well, a clever combination of selection criteria was needed. In a next step, areas with spectral shapes similar to snow and water could be identified. Often these did not cover the complete pond, but with a combination of binary propagation and binary erosion the total ponds were located.

After extensive testing on large datasets in three continents with known tailing locations, a final method was set up which works without atmospheric correction and can be applied on various areas around the globe. This makes it rather robust.

However, the selected method still comes with false positives and false negatives. Therefore, it is recommended to use a larger set of images, to create overlays in time. Where it can be assumed, that the tailing ponds will remain consistent, while the false positives to be artefacts of for example cloud shadow. An overlay in time showing a persistent potential tailing pond will most likely be a real tailing pond, while artefacts will be removed. By using more imagery, chances for false negatives might also be reduced, although there will still be mine tailing ponds with a colour that is so similar to natural water that it cannot be traced as tailing pond based on optical satellite data.

Another major improvement is expected to be possible by using Sentinel-2 data, instead of Landsat-8. The band settings allow for a more precise selection of spectral signatures, allowing for more differentiation potential between types of mine tailing ponds amongst themselves and artefacts (the presence of specific metals). Distinct spectral features might be more observable with increased spectral resolution, enabling the removal of more false negatives. The spatial resolution of 10 metres in most of the visible spectrum (instead of the 30 metres of Landsat-8) is expected to improve the discriminating potential of the method, as some tailing ponds can be only a hundred metres across. A higher spatial resolution will allow the detection of these smaller ponds.

Atmospheric correction has not been applied in this study, because it is generally time consuming, and – more important – atmospheric correction methods either needs atmospheric parameters at the time of image acquisition (which are not available in the needed spatial extent and temporal resolution for areas of this size) or are not applicable to distinct water types such as mine tailing ponds (e.g. methods which are trained on a dataset without these waters will not lead to results out of their training range). However, by the time generic atmospheric correction methods become available, selecting mine tailing ponds based on surface reflection might further improve the possibilities.

The algorithm itself can also be improved, by improving the water mask (which fails in e.g. Azerbaijan) and most logically by the development of a dedicated mask that looks for bright waters, instead of using the snow/ice mask.
Separate of the potential improvements on the current method, it is an important achievement to be able to trace mine tailing ponds based on EO data. As an independent data source, it can help governmental agencies or nature conservation organisations to locate them in remote environments. Allowing for directed visits and checks for safety. This is important, as especially older abandoned tailing ponds, which can be very badly maintained, can lead to large environmental and societal problems.
References