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Satellite bathymetry for the monitoring of supernatant water volumes within tailings storage facilities

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Abstract

The availability of water plays a fundamental role in the operational continuity associated with mineral and metal extraction operations. As part of this process, it is necessary to recover as much water as possible for reuse and reduce make-up water requirements while trying to maintain a reduced impact on the surrounding environment and natural resources. Specifically related to tailings disposal, the past few decades have seen a shift towards high-density tailings with advances in thickening and filtering technologies, thus improving the water recovery and reducing the volumes of water deposited within a tailings storage facility. However, the vast majority of tailings facilities worldwide still generate a supernatant pond as the tailings naturally consolidate and bleed. These ponds need to be controlled in their size and volume, particularly in larger throughput operations. In some countries, it is a requirement to report volume to the authorities on a routine basis.

This paper presents a study to monitor the growth of supernatant ponds in tailings facilities using remote sensing techniques. Principally, this relates to a multispectral analysis of satellite bands which, by means of various corrections and applications of combinations of these bands through mathematical algorithms, the depths of relatively shallow supernatant ponds can be determined reasonably accurately. The importance of the study is to provide an alternative to current in situ monitoring techniques, such as sonar instrumentation, which is limited to a minimum depth. The added advantage is that satellite monitoring delivers information quickly and cost effectively and, more importantly, avoids the requirement for human presence, thus reducing operational risks.

Keywords: *satellite, spectral band, bathymetry, supernatant water, sonar*

1 Introduction

Water represents one of the most important resources in any mining project, from the early stages of engineering, operation, and later in the closure stage. In mining operations, water is used primarily for minerals processing, dust suppression, slurry transport and employees' needs. Water used in mining is commonly obtained from superficial or underground sources or pumped from a desalination plant or directly from the sea. In many countries, the extraction of water is strictly regulated, and the quantity available for use can be limited.

In recent years, seawater has been incorporated as a source of process water in several projects; however, although this resource seems to be an unlimited and economic alternative, the cost and logistics of its transportation from sea level to a mineral processing operation, particularly to plants at a high geographical elevation, remains prohibitive.

In Chile, the use of water in the mining industry represents only 3% of the country's total supply. However, many mining operations are located in the Atacama Desert, the driest desert in the world, where water scarcity is a limiting factor for development of alternative industries in the region (Chilean Copper

Commission 2018). The quality and quantity of water resources represents a very sensitive issue in any mining project, since water is involved in almost every area of the operation, which can often lead to a conflict with other users of the resource. The demand for water in mining is increasing due to the global demand for metals and the increased number of projects processing lower grade ore at higher throughputs. The focus of modern-day mining is decreased consumption of water and reduced impacts on the surrounding environment through, for example, the development of high-density thickened or filtered tailings disposal.

Satellite technology has developed considerably over the past decade allowing a cost-effective method of monitoring water bodies in mining projects, especially associated with tailings storage. Multispectral high-resolution sensors, as well as radar-based satellites, are providing new methods to monitor the Earth's surface and detect change, often autonomously.

2 Satellite-based remote sensing and spectral signatures

Satellite remote sensing technology is based on a remote data acquisition system, through detectors installed on satellites orbiting the biosphere that can measure specific parameters, most commonly electromagnetic radiation reflected by the Earth's surface. Optical satellites have their own spectral response that can detect a wide variety of wavelengths that can be used to improve detection and data interpretation when combined in a particular sequence.

Different types of surfaces, such as water, bare earth or vegetation, reflect radiation differently when they are detected by the bands of a particular optical satellite. The reflected radiation as a function of the wavelength is called the 'spectral signature' of the surface.

The detectors on a satellite can be cameras, multispectral scanning radiometers (MSS), radars and laser receptors. These detectors generate images that analyse the radiation emitted or reflected by the shapes and objects on the Earth's surface at the wavelengths in which they are sensitive (ultraviolet, visible, near-infrared, technical infrared, hyper-frequencies) to recognise the varied range of shapes and objects. Figure 1 presents the electromagnetic spectrum showing the limited range that is detectable by the human eye (visible light) and the range that can be detected by satellites.

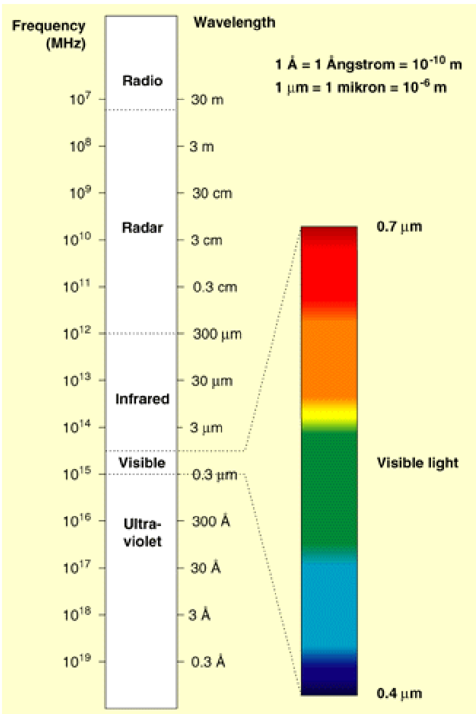

Figure 1 Electromagnetic spectrum – the human eye can see only a limited range of the spectrum, whereas satellites can register visible, infrared and a large range of other wavelengths (European Space Agency (ESA) 2018a)

Figure 2 presents the actual detector bands for NASA's Landsat 7 optical satellite showing how different reflectance detection can be achieved outside the visible light wavelengths.

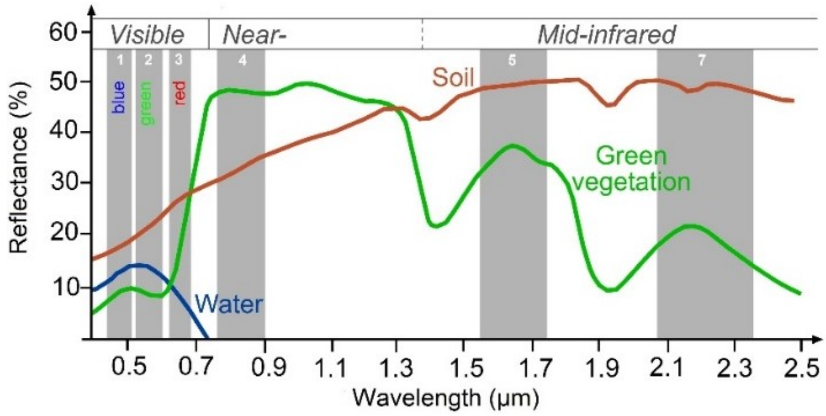

Figure 2 The spectral signatures are processed as digital values in the satellite scanner. This example shows how NASA's Landsat 7 satellite might detect water, green vegetation and bare ground (based on Siegmund & Menz 2005)

Water surfaces are mostly detectable in the visible light range. In the near-infrared range, water surfaces can be differentiated by being delimited as dark areas, which is helpful to confirm the limiting boundaries of water bodies and in improving volumetric calculations. The spectral signature of green plants is characteristic in that the chlorophyll of a growing plant absorbs visible light while near-infrared light is reflected very effectively, thus helping to distinguish areas of vegetation and its health over large swaths of satellite imagery.

2.1 Application of satellite remote detection for monitoring water bodies

The application of satellite bathymetry is used to detect the depth of water and the subsurface profile of water bodies, such as rivers, lakes, oceans and even small bodies of water such as supernatant ponds on tailings facilities. The precision and detail of these measurements are controlled by the detectors of the satellite and their operating resolution; commercial satellites have much higher resolutions compared to the free satellite data available. For this paper, the Sentinel 2 satellite has been used, which is defined as a terrestrial observation mission developed by the European Space Agency within the Copernicus Program. It is composed of two Earth orbital satellites named Sentinel 2A and Sentinel 2B offering a wide range of detection wavelengths. The data is freely available, normally within 24 hours of an acquisition.

The Copernicus Program is jointly run by the ESA and the European Union through the European Environment Agency, which aims to achieve complete, continuous and autonomous ground observation capacity. The general objectives are the conservation of the environment, understanding and mitigating climate change, and ensuring civil security.

Some key features of the Sentinel satellites are as follows:

- Satellites work in opposite orbits.
- Sentinel 2A was launched on 23 June 2015.
- Sentinel 2B was launched on 7 March 2017.
- Multispectral images over 13 bands.
- Special resolution is 10, 20 and 60 m.
- There is a wide field of vision (290 km).
- Revisit times are approximately five days using both satellites (i.e. wait time for new image over a particular location).

Table 1 presents the actual wavelengths of the detectors for both Sentinel satellites for the 13 detection bands.

Table 1 Sentinel 2 sensor features (ESA 2018c)

Sensor	Sentinel 2A		Sentinel 2B	
Bands	**Wavelength (µm)**	**Bandwidth (µm)**	**Wavelength (µm)**	**Bandwidth (µm)**
1 – Aerosol	0.4439	0.027	0.4423	0.045
2 – Blue	0.4966	0.098	0.4921	0.098
3 – Green	0.56	0.045	0.559	0.046
4 – Red	0.6645	0.038	0.665	0.039
5 – NIR (close)	0.7039	0.019	0.7038	0.02
6 – NIR	0.7402	0.018	0.7391	0.018
7 – NIR	0.7825	0.028	0.7797	0.028
8 – NIR	0.8351	0.145	0.833	0.133
8a	0.8648	0.033	0.864	0.032
9 – Water vapour	0.945	0.026	0.9432	0.027
10 – Cirrus	1.3735	0.075	1.3769	0.076
11 – SWIR	1.6137	0.143	1.6104	0.141
12 – SWIR	2.2024	0.242	2.1857	0.238

NIR – Near-infrared, SWIR – Shortwave infrared

For satellite-based bathymetry, different bands are used in combination to extract information relating to the reflectance of the water surface and the depth. Differential absorption of different wavelengths as the depth of water increases can be measured and calibrated together with the measurement of background reflection and dispersion. Figure 3 presents this concept in further detail.

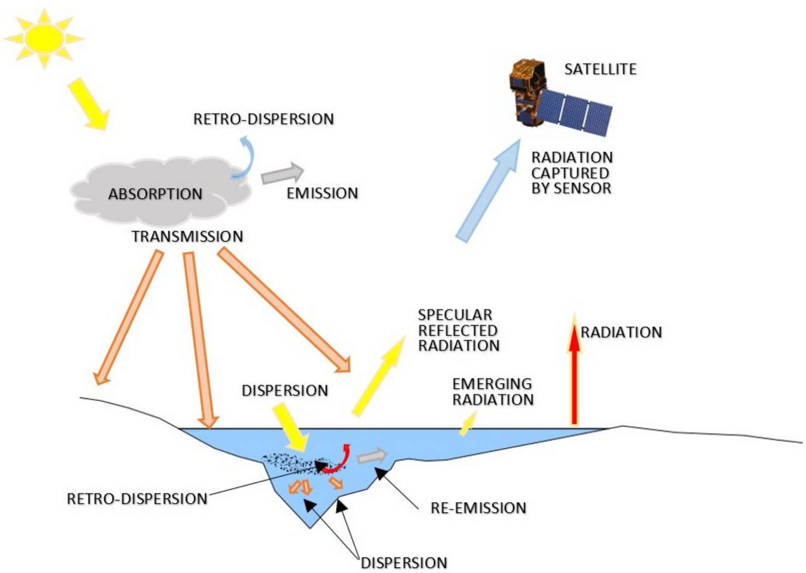

Figure 3 Detection of radiation for satellite-based bathymetry

3 Methodology and case study

As part of this paper, a case study for a tailings facility was developed and compared with measured bathymetry data collected from a conventional sonar-based system. Multispectral images of the Sentinel 2 satellite were obtained, using the Copernicus platform of ESA, and processed using the Sentinel Application Platform (SNAP) software. The architecture of this software is ideal for the processing and analysis of terrestrial satellite images due to its versatility and large number of specific tools for Sentinel and other satellites.

The images obtained correspond to a type of product called Level-1C (L1C), which delivers reflectance values top of atmosphere (TOA). These are then transformed to reflectance values bottom of atmosphere (BOA), and are called Level-2A (L2A). This process is executed using a processing tool called Sen2Cor (ESA 2018b). L2A products are resampled as L1C products with a constant ground sampling distance (GSD) of 10, 20 and 60 m, according to the native resolution of the different spectral bands. Where applicable, L2A products are also provided for each multispectral instrument (MSI) band at a coarser resolution (i.e. 20 and 60 m).

3.1 Post-processing algorithm

The physical principle of the energy received by the satellite can be divided into four basic components, which are outlined in Equation 1 and Figure 4:.

$$L_{TOA} = L_b + L_v + L_s + L_a \quad (1)$$

where:

L_{TOA} = radiance registered by the detector of each band.

L_b = lower radiance.

L_v = subsurface volumetric radiance.

L_s = specular radiance.

L_a = trajectory atmospheric radiance.

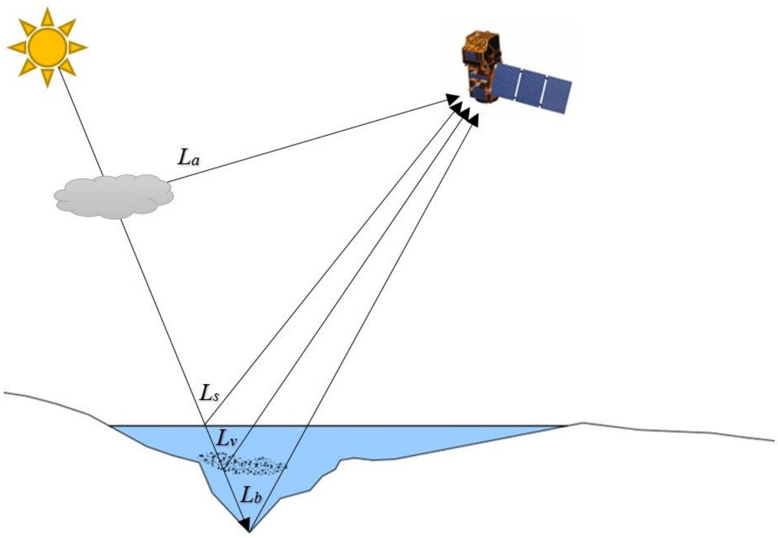

Figure 4 Energies captured by satellite detector and used in post-processing

To obtain the depth of the body of water observed by the satellite, it is necessary to extract the lower radiance and the volumetric luminosity from the total radiance.

There are two fundamental models to obtain the satellite bathymetry eliminating L_b and any specular effects. This is achieved by assuming that the bottom of the water is equal to zero and considering the optically deep reflectance ($L\infty$ o $R\infty$) represents the combined effect of volumetric glare, specular glare and trajectory of atmospheric radiance.

After having made the radiance and atmospheric corrections, the reflectance of shallow water will contain only the subsurface water information. Assuming that the volumetric subsurface and the atmospheric absorption in shallow water are equal in the adjacent deep waters, the radiation of the water detected by the satellite sensors can be used to correct the surface volumetric luminosity and thus minimise errors in the depth estimation. The main limiting factors in this calculation of maximum depth is the turbidity of the water from suspended solids and the wavelength range of the detector on the satellite. Based on satellite bathymetry used in oceans, the blue band has the smallest attenuation and can penetrate up to 30 m under optimal conditions. The other bands used are green with a penetration up to 15 m, red with penetration up to 5 m and NIR with penetration up to 0.5 m (Chybicki 2017; Deidda & Sanna 2012).

3.2 Ratio method

The first model was proposed by Stumpf et al. (2003) and is based on Equation 2 (a logarithmic equation):

$$Z = m_1 * \frac{\ln(nR_w(\lambda_i))}{\ln(nR_w(\lambda_j))} - m_0 \tag{2}$$

where:

Z	=	depth.
m_0, m_1 and n	=	constant coefficients for the model.
$R_w(\lambda_i)$ and $R_w(\lambda_j)$	=	observed radiances for the optical bands λ_i and λ_j (after the atmospheric and solar corrections).

For this model, the background depth is estimated based on the attenuation of light and shortwave radiation that varies spectrally.

3.3 Analytical model

The second model is derived directly from Equation 3, the simplified equation for shallow water.

$$L_{TOA} = L_\infty\left[1 - e^{-kz}\right] + A_d e^{-kz} + L_A + L_s \tag{3}$$

where:

A_d	=	spectral radiance directly reflected from depth (before interacting with the superimposed water column).
K	=	attenuation coefficient.
Z	=	depth.

Equation 3 shows the effect of the attenuation resulting from the passage of energy through the column of water of a known depth.

Assuming that the lower reflectance ratio between two spectral bands is constant for all background types and the variability of light attenuation caused by atmospheric effects is negligible for a given area, the estimated depth with the use of the model (Lyzenga 1978, 1985) can be expressed per Equation 4:

$$Z_{est} = \alpha_0 + \sum_{i=1}^{N} \alpha_i \ln[L(\lambda_i) - L_\infty(\lambda_i)] \tag{4}$$

where:

N	=	no. of spectral bands.
α_i $(i=1, 2, ...N)$	=	constant coefficients obtained during the calibration of the model.
$L(\lambda_i)$	=	radiation obtained after the atmospheric and solar corrections (the logarithm makes the expression linear).

From these methods and carrying out tests with known bathymetries as part of this paper, the following new algorithm is shown in Equation 5:

$$z = \alpha * \sum_{i=1}^{n} \left[\left(\ln(\lambda_i) - \ln\infty(\lambda_i) \right) \right] / \left(\nu + \rho \right) \tag{5}$$

where:

z	=	estimated depth for a selected region of interest (ROI).
A	=	coefficient of penetration of luminosity according to studies by Secchi for attenuation in waters with turbidity (Secchi disk n.d.).
$\ln(\lambda_i)$	=	radiation obtained after the atmospheric and solar corrections.
$\ln\infty(\lambda_i)$	=	original band without corrections.
$(\nu) + (\rho)$	=	spectral bands corrected to attenuate surface undulations.

3.4 Summary of work flow

The work flow shown in Figure 5 for satellite bathymetric estimation, and used in the case study presented in this paper, is as follows:

- Identification of the study site (date and geographic location).
- Optimal image selection nearest the proposed date (e.g. neglecting clouds and haze).
- Transformation of TOA-BOA atmospheric correction.
- ROI work area generation (only visible bodies of water).
- Subset of ROI.
- Application of mathematical algorithms in spectral bands.
- Band generation resulting from post-processing.
- Generation of deliverables (contour lines, depth plane, sections).
- Generation of final report.

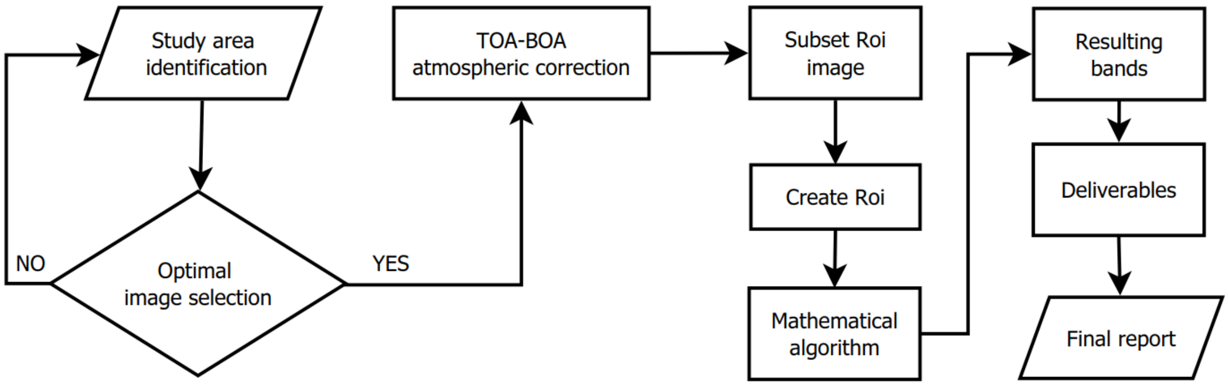

Figure 5 General work flow diagram

The work flow for the TOA-BOA atmospheric correction is presented in Figure 6 for the Sentinel 2A and 2B satellites (Müller-Wilm 2016).

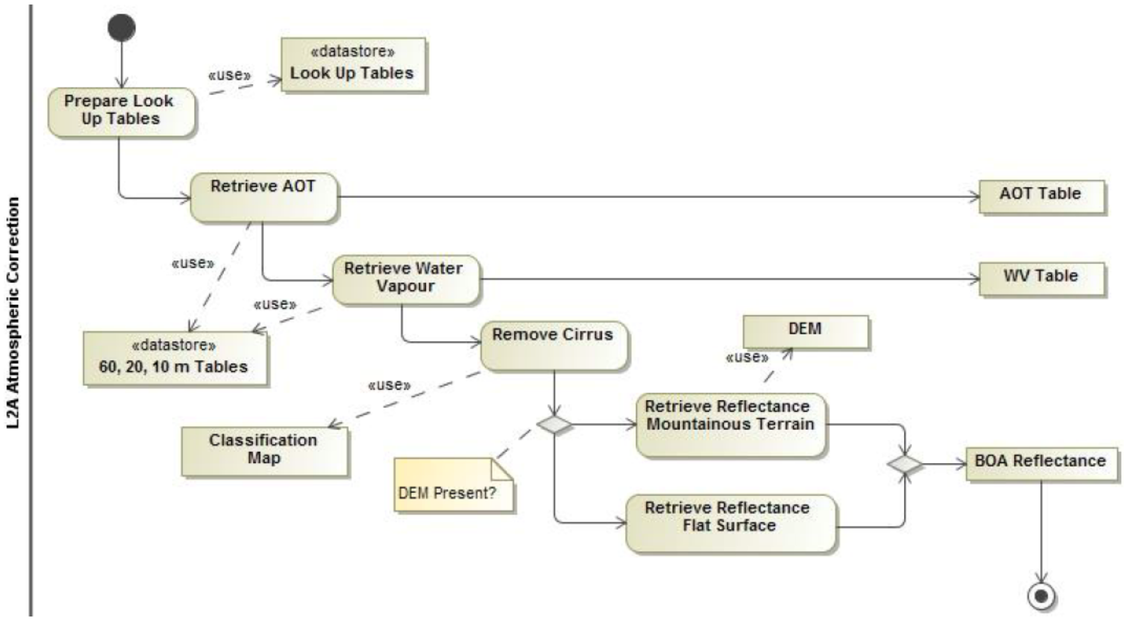

Figure 6 Work flow for atmospheric correction of Sentinel 2A & 2B products (Müller-Wilm 2016)

4 Case study

4.1 Introduction

For this paper, freely available spectral bands of the Sentinel 2A and 2B satellites were used over the Las Tórtolas tailings facility belonging to Anglo American's Los Bronces Mine in Chile. As a check to the methodology of the work presented, bathymetric surveys using sonar equipment were used to compare with the data obtained from satellite imagery processing (Figures 7 and 8). As part of the analysis, all satellite bands were used since each of them presented information of interest, although the first bands (blue, green and red) presented more detailed information relating to the depth of water.

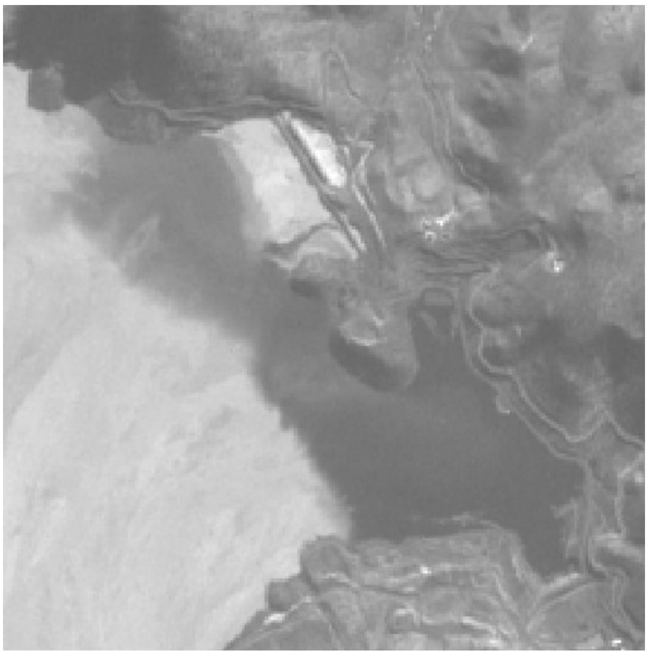

Figure 7 Satellite image of the original band 2 of the L1C Sentinel 2 top of atmosphere

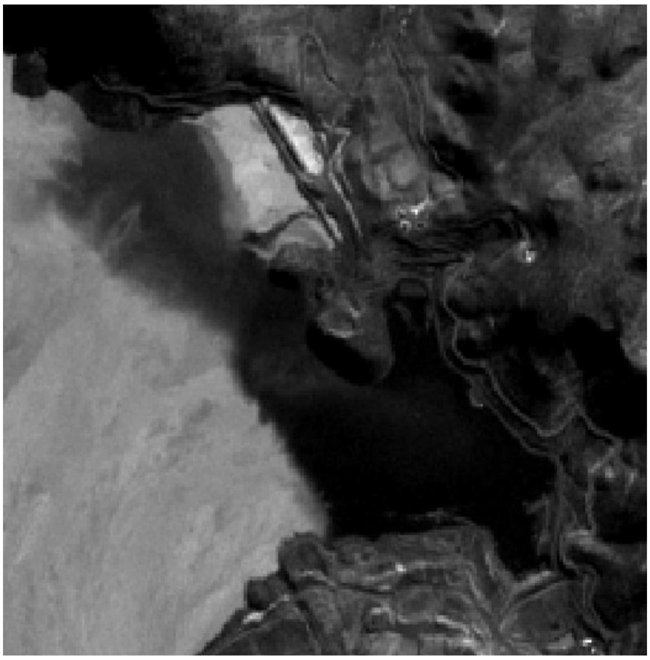

Figure 8 **Satellite image of the processed band 2 of the L2A Sentinel 2 with atmospheric correction and radiance applied with Sen2cor bottom of atmosphere**

4.2 Results

Four Sentinel 2 acquisitions during July 2018 were analysed and processed. The dates selected were those that were the closest to the sonar bathymetric surveys for improved comparison purposes. The bands were analysed with SNAP software and Global Mapper (Blue Marble Geographics 2017) and the results presented for each dataset in Figures 9–12.

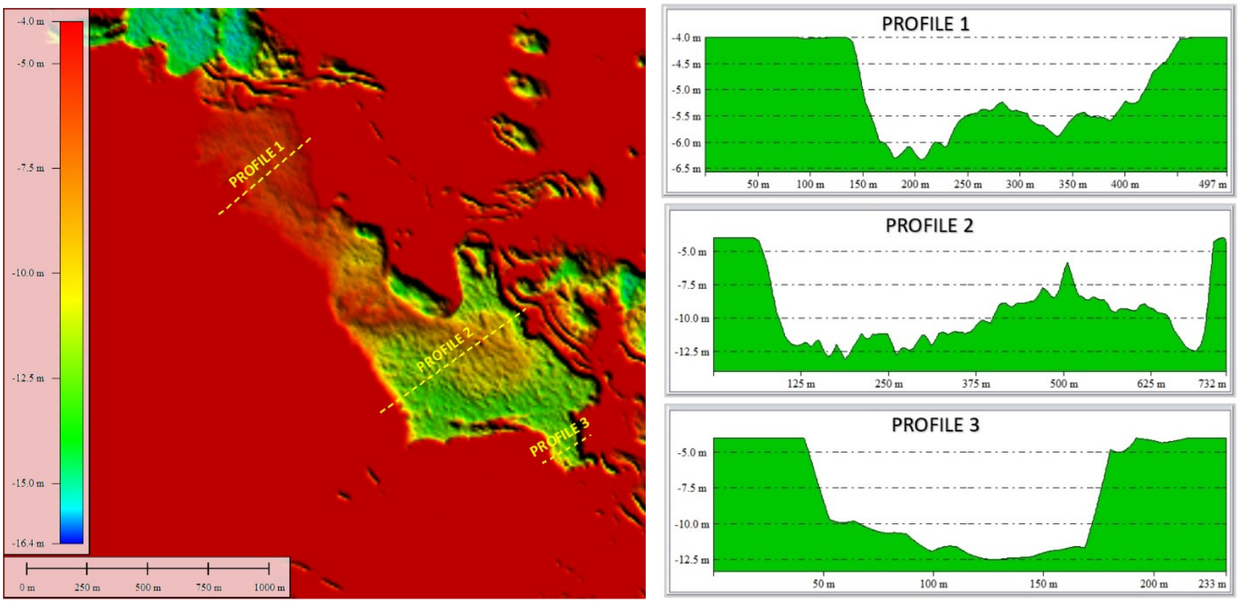

Figure 9 **Depth map and bathymetry profiles 8 July 2018**

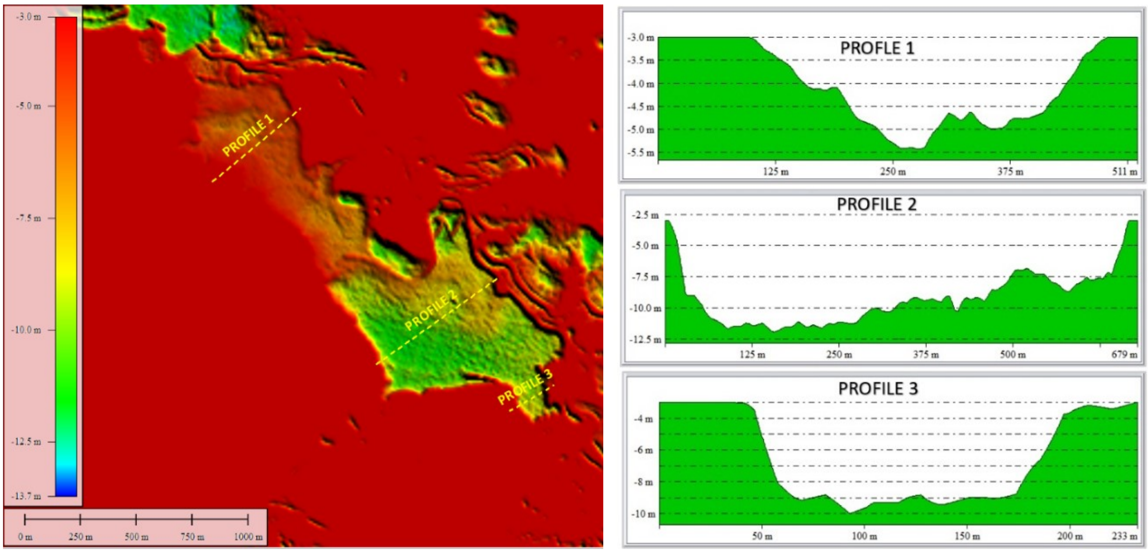

Figure 10 Depth map and bathymetry profiles 13 July 2018

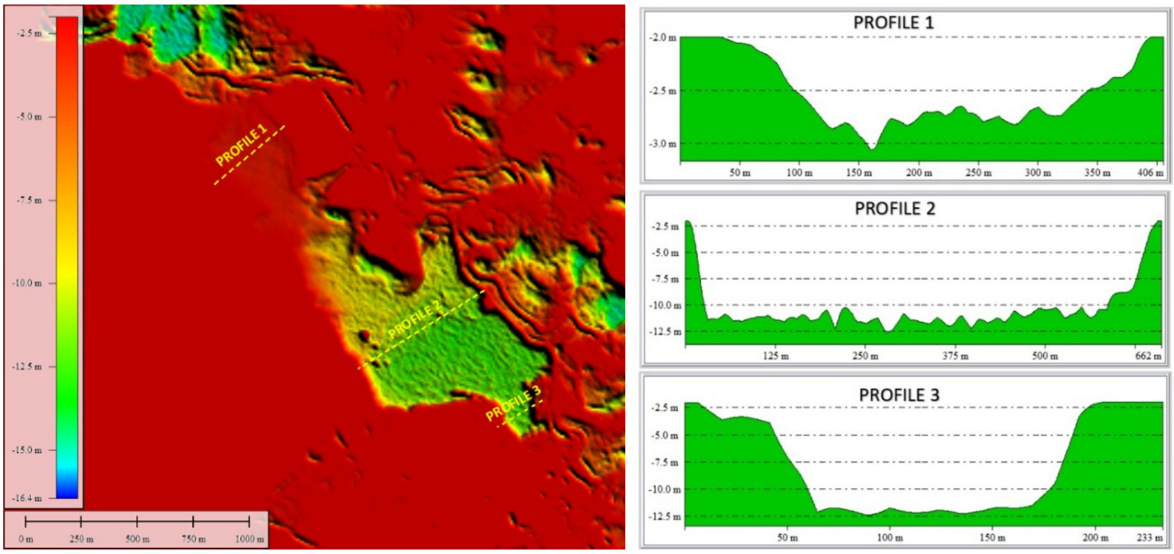

Figure 11 Depth map and bathymetry profiles 23 July 2018

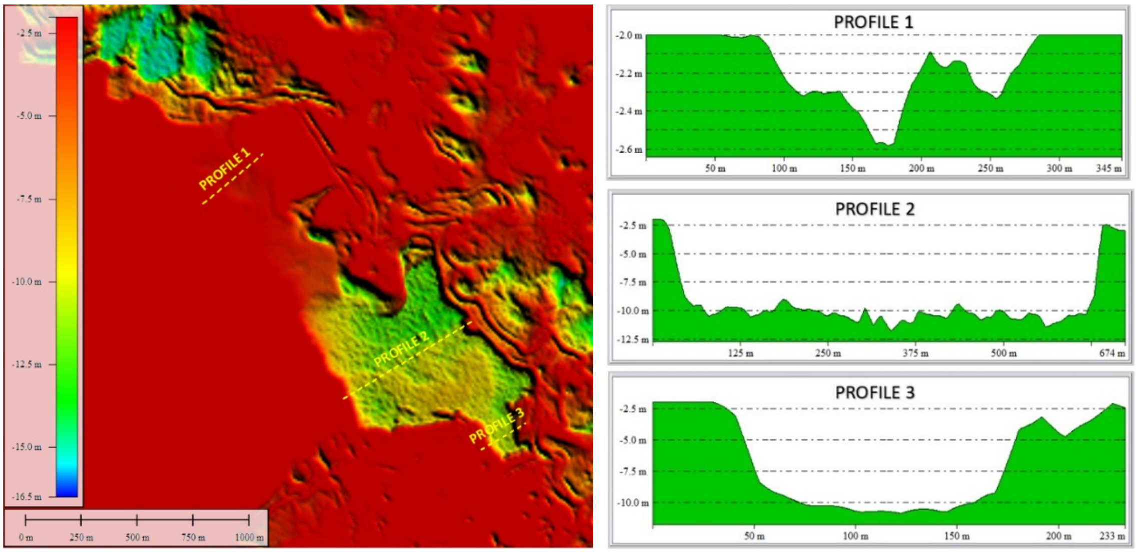

Figure 12 Depth map and bathymetry profiles 28 July 2018

Table 2 and Figure 13 present a comparison between the supernatant pond volumes measured using the satellite bathymetry method and the sonar data provided by Anglo American. An analysis of these results is presented in the following section of the paper.

Table 2 Comparison of supernatant pond volumes between the sonar data and satellite bathymetry

Date	**09-07-18**	**17-07-18**	**24-07-18**	**30-07-18**
*Sonar	3,126,000	3,037,000	2,836,000	2,787,000
Date	**08-07-18**	**13-07-18**	**23-07-18**	**28-07-18**
Satellite	3,577,000	3,340,000	3,019,000	2,828,000
% error	-14.4%	-10.0%	-6.5%	-1.5%

*Sonar data provided by Anglo American

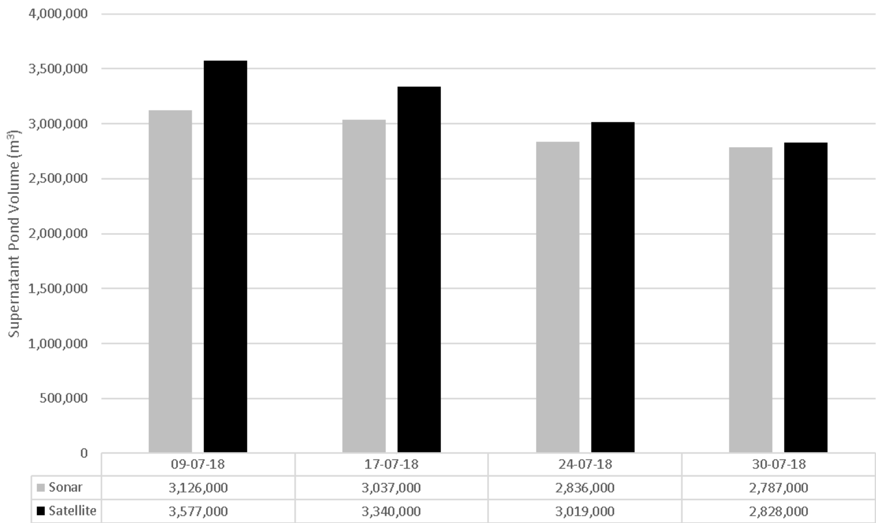

Figure 13 Comparative graph of sonar versus satellite bathymetry measurements (dates presented are for the sonar survey)

4.3 Analysis

As the results of the analyses show, the calculated bathymetry volumes are greater for each particular date compared to the sonar collected data. Although these values are within the expected errors to be obtained, the following features are important to consider:

- The pixel resolution of the Sentinel 2 satellites is 10 m, which reduces the accuracy of the defining the edge of the water body to be analysed compared to higher resolution satellite data.
- For the sonar measurements, the boat can only navigate in depths greater than 0.75 m. The non-navigable area was estimated in their analyses.
- The scale factor used for the attenuation of luminosity by penetration in the body of water (Sechhi disk) can vary between a range of 1.7 to 2.5 or more. For these cases, it was estimated to use a factor of 2.5 (an average for waters with suspended sediments or high turbidity).
- Climate conditions on the day of capture by the satellites can affect the spectral bands and the process of atmospheric correction.
- There is a minor difference in the dates between both compared survey methodologies.

5 Conclusion

This paper has presented bathymetry measurements for supernatant pond volumetric analysis using freely available satellite data. A case study that compares two independent methods for calculating the volume of a supernatant pond of an actual tailings storage facility has been presented with reasonable accuracy being achieved via satellite bathymetry when compared to a conventional sonar measurement obtained using a boat.

The methodology presented can provide a guide to assessing the volume of a supernatant pond, without the need to intervene or access the pond using manual techniques. There are important limitations to the use of satellite bathymetry, such as the turbidity of the supernatant water in a tailings facility that can impact the accuracy and interpretation of the true pond depth and is a factor to assess for a particular facility prior to evaluating the use of satellite bathymetry compared to conventional methods. Based on the case study presented, having reasonably clear supernatant water, measurements of more than 12 m could not be detected. Another important limitation is the local climate for a particular tailings facility location, where frequent cloud cover can prevent acquisition of images. In this case, commercial satellite services would be required to repeat shots daily until a clear acquisition is made (there are no costs associated for failed acquisition attempts).

Based on the case study presented, an average error of less than 10% was achieved between the satellite and sonar-based surveys. According to the studies reviewed as part of this paper, satellite monitoring is the next step to conventional bathymetry processing and accuracy is likely to improve as the resolution and technology develops further.

As part of the continued development of this paper, the following future work is proposed:

- Analysis using commercial satellites having a better resolution compared to Sentinel 2 and other free data sources. Funding is currently being acquired to use the WorldView-2 Satellite or higher, having eight high-resolution satellite bands. WorldView-2 offers a panchromatic band of 0.46 m and multispectral resolutions of 1.8 m (DigitalGlobe 2018).
- According to studies relating to light attenuation in turbid waters, the constant used predominantly appears in a range between 1.7 and 2.5 and is commonly derived for open water bodies not related to mining. For supernatant ponds of tailings facilities, this light attenuation factor requires a more customised approach and is specific to a particular tailings facility (depending on the turbidity and colour of the supernatant water). The use of Secchi disks in the field can assist in the determination of this attenuation factor.
- A more in-depth study of the SNAP software (and alternatives) is required in order to improve and automate post-processing as well as the classification of the images and final bathymetry result.

Acknowledgement

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