Hyperspectral and Multispectral Remote Sensing at Uranium Processing Facilities

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Summary

Many mines and processing facilities are in remote, difficult to access areas, or are in areas where access is limited or restricted for national reasons. In a joint project with Borstad Associates Ltd. and the Canada Centre for Remote Sensing, the Canadian Safeguards Support Program is investigating utility of multi- and hyperspectral remote sensing for remotely inspecting such site. With a view to eventually using the hyperspectral satellite data now coming available, airborne data over uranium and copper mine tailings and uranium processing facilities in northern Canada were acquired in the year 2000.

The objective of this work is to demonstrate that multispectral and hyperspectral data can provide complementary and supplementary information to high-resolution panchromatic imagery for the following safeguards applications: Inspection aids (up-to-date maps of remote locations), change detection, evaluation of member state declarations, monitoring of reactor, mining and processing facility operations, and detection of undeclared activities through the detection and identification of substances which could be associated with nuclear or chemical operations.

An experienced analyst, in combination with a person knowledgeable of the uranium mining industry can:

- map the buildings, roads, trails, paths, disturbed and vegetated parts of the site with high resolution imagery;
- map the amount and type of terrestrial vegetation on and around the site, variations of which can indicate changes in the local water table;
- map the type of rock, tailings and soils on and around the site;
- ascertain the drainage patterns for the site;
- detect potential leakage from the mine tailings into surrounding water bodies;
- detect increased turbidity of disturbed water bodies due to fine inorganic material running off the active areas of the mine site;
- detect in-filling of water bodies due to deposition of waste materials (reduction of depth);
- map growth of algae or other vegetation along the margins, or suspended in or floating on the surface;
- detect changes in water colour due to dissolved materials;
- detect plumes from point sources (e.g., outfalls and sub aqueous dispersal of fine tailings).

On land, hyperspectral imaging can distinguish the mineral type of exposed rocks and ores. The water bodies on and around a site indicate whether there is activity at the site, exactly where on site it is taking place, and give many hints at the kind of activity occurring. Having such information prior to an on-the-ground inspection is of immense value to national and international inspectors. This paper discusses some examples of these indicators as they pertain to water bodies on a uranium processing facility and potential applications for international safeguards.

Keywords: uranium mines, international safeguards, remote sensing, hyperspectral, water quality.

1. Introduction – description of the Key Lake Uranium milling facility

The Key Lake facility, situated in North Central Saskatchewan 570 kilometres north of Saskatoon and 220 km north of Pinehouse, the nearest village, is on the southern rim of the uranium-rich Athabasca sandstone basin. It is the largest high-grade uranium milling operation in the world, with a production capacity of 18 million pounds U_3O_8 annually. No ore is currently mined at Key Lake, but ore is transported for milling over an 80-kilometre, all-weather road from an active mine at McArthur River.

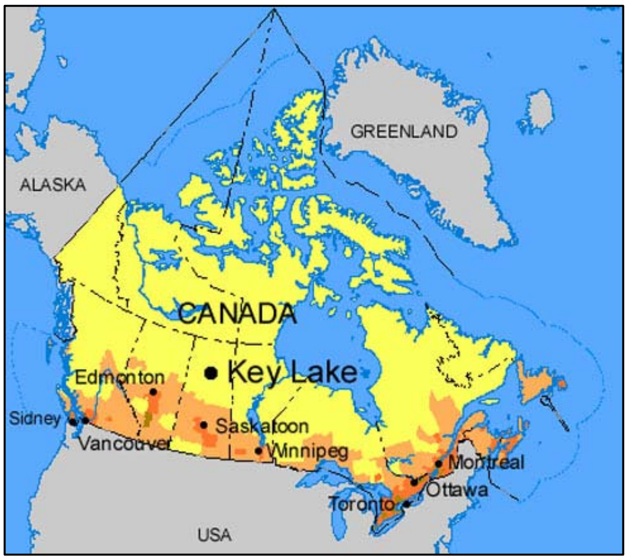

Fig. 1: The Key Lake Facility is located far from Canadian population centres (dark areas show distribution of Canadian population).

There are two mined-out pits on the Key Lake facility (figure 3). The Gaertner ore body was mined out in 1987 and the mining of Deilmann ore body was completed in May of 1997. Beginning in 2000, stock piled ore from Key Lake is blended with the high-grade ore from the McArthur River mine and is being used to feed the mill. The deeper portion of the Deilmann pit are now used for subaqueous dispersal of tailings from the blended McArthur/Key Lake ore.

2. Methods

2.1. Instrumentation

On August 5 and 6, 2000, airborne multispectral and hyperspectral data were acquired over the Cameco uranium processing facility at Key Lake, Saskatchewan with the Borstad Associates Compact Airborne Spectrographic Imager (CASI) and the Borstad Associates Short wave infrared Full Spectrum Imager (SFSI-2). These are both relatively small portable imaging devices that were in this case flown on a small single engine float plane chartered a few hundred km away from the site. More details concerning both instruments are available at www.borstad.com.

Fig. 2. This mapping was done from a small single engine float-plane chartered in northern Canada.

The SFSI produces 230 channels in the Short Wave Infra-Red between 1230 and 2380 nm. Many clay minerals and other rocks and soils exhibit narrow absorption features in this spectral region, and the SWIR can be used to map exposed minerals and tailings on a site. SFSI data from this flight were discussed by Neville et al., 2000 and will not be presented here.

We acquired both hyperspectral and multispectral CASI data over the Key Lake facility. The Borstad CASI produces up to 288 channels in 'Spectral Mode', but in this mode does not produce a detailed image. In 'Spatial Mode', the instrument produces up to 15 channels of multispectral imagery, but the spectral position and width of the bands is under operator control, and we placed the bands to best capture the information content of water, based on long experience in marine and aquatic remote sensing. The instrument operates in the visible and near infra-red parts of the spectrum, between 403 and 913 nm. This spectral range is one most utilised by plant life, and is most useful for detecting and mapping land vegetation. Because of the properties of water, the range 400 to 750nm is the most useful for detecting suspended and dissolved materials and living microscopic and rooted plants.

3. The Data

At the 8,500' altitude flown here, the multispectral image maps produced by the CASI are strips of imagery 1.5 km wide, by 10 to 20 km long, and with spatial resolution of 3 m. In post processing, the individual files are radiometrically calibrated, corrected for aircraft attitude (roll, pitch and yaw), mapped north-up and mosaicked to produce image maps as in Figure 3.

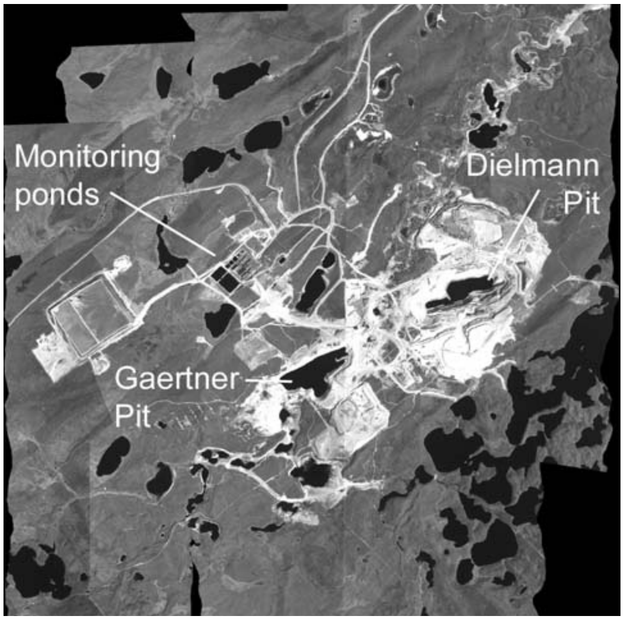

Fig. 3: Airborne image map of the Key Lake facility.

The image in figure 3 is a mapped mosaic of several separate files acquired on parallel flight lines over the mine. The latitude and longitude grid has been left off for clarity. It is but one of 10 bands acquired here in the visible and near infra-red part of the spectrum. At every location in the image, we therefore have a spectrum (figure 4) that allows one to make very precise measurements of the reflected colour of the surface.

The hyperspectral data (for example figure 5) contain a detailed description of the water colour on the Key Lake facility, but do not provide detailed imagery. Since the following discussion concentrates on the areal distribution of water quality on and around the facitliy, we will therefore focus on the 'Spatial Mode' data.

Note that in the black and white version of this paper printed in the proceedings the colour figures will not reproduce well. Please contact the primary author for color copies.

3.1. The vegetated parts of the site

It would be possible to map out the different types of land vegetation on and around the facility based on its pigmentation, but this discussion is aimed primarily at the water portions of the data. We did however, produce an image of vegetative biomass. One distinguishing feature of land plants is a strong increase in reflectance in the near infrared above 700 nm ('land plants' in figure 5). Healthy plant growth on land appears very bright in wavelengths above about 700nm, almost reflecting 100% of the solar illumination.

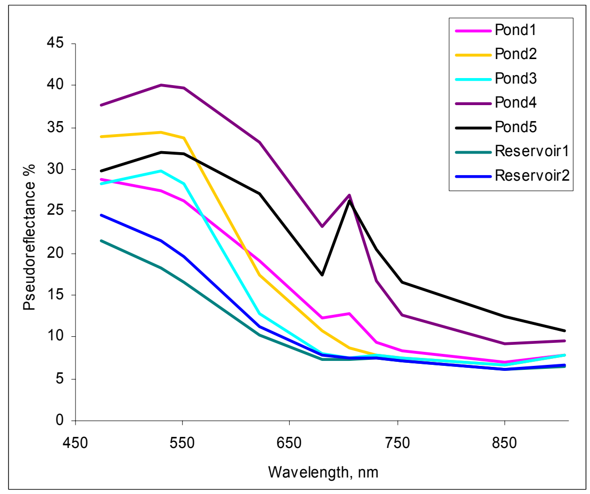

Fig. 4: Spectral variation of water bodies on and around the Key Lake facility as captured by the multispectral imagery shown here.

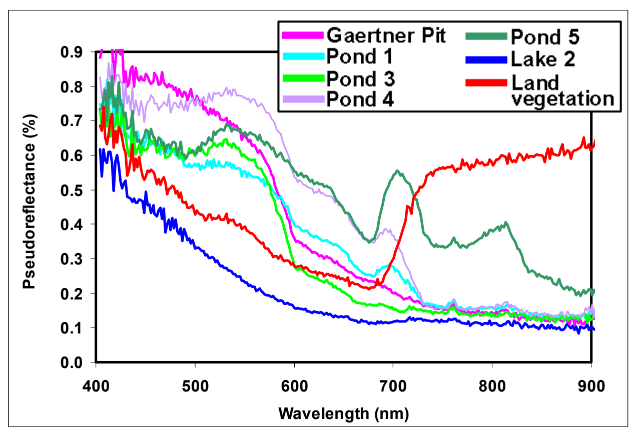

Fig. 5:. Spectral variation of water bodies on and around the Key Lake facility as seen in hyperspectral data acquired at the same time.

We used a Normalized Difference Vegetation Index (NDVI) to provide a simple measure of green biomass on and around the mine site, with the intention of looking for connections between the land vegetation and water quality. NDVI measures the height of the red edge (the strong increase in Radiance above 700nm in figure 4) according to the formula (Radiance at 681nm - Radiance at

850nm)/(Radiance at 681nm + Radiance at 850nm). In figure 6, the highest (red) values in the image represent areas of greatest green vegetative biomass. Low (dark blue) values represent bare areas or water.

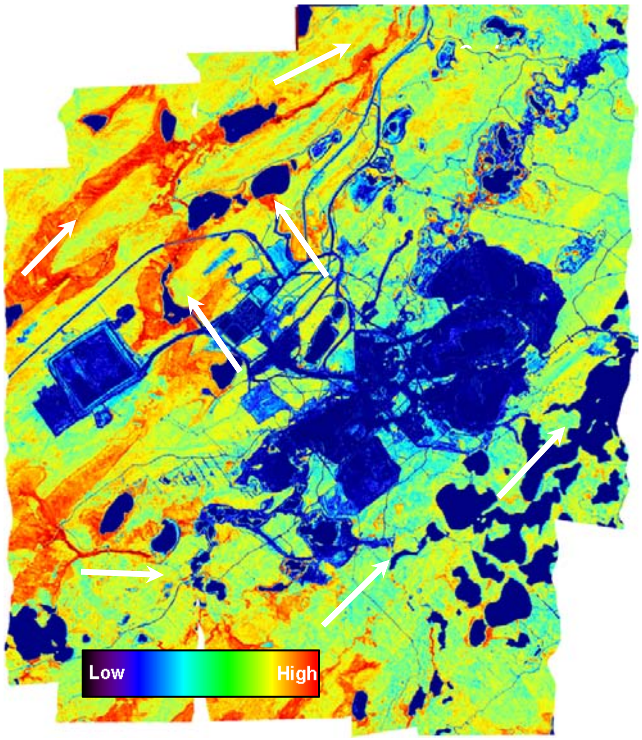

Fig. 6:. NDVI image showing the abundance of green vegetation on and around the Key Lake Facility. Arrows indicate direction of flow.

The NDVI provides a very clear delineation of the roads and even small foot paths on the site, even though they are below the resolution of the sensors. It also shows lower green biomass to the north-east of the site, consistent with a lower water table in that area, resulting from pumping at Dielmann Pit.

3.2. The colour of water bodies on and around the facility

3.2.1. High phytoplankton concentrations and benthic algal growth

Phytoplankton are microscopic floating algae common in all natural water bodies. They also contain chlorophyll as their solar energy gathering pigment. In clear water, phytoplankton chlorophyll can be measured *in vivo* via its solar stimulated fluorescence (Neville and Gower, 1977) that occurs at 685 nm. However in this case, the turbidity of the water interferes with the measurement and we have used a band near 706 nm.

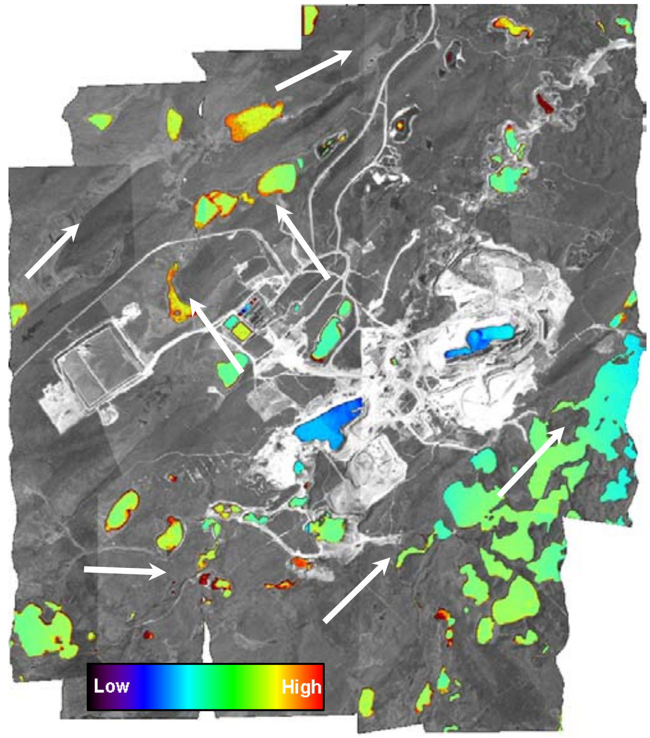

Fig. 7: Phytoplankton and macro algal growth in the water bodies on and around the Key Lake Facility.

In water with concentrations of phytoplankton greater than about 5 mg chlorophyll/L, most of light above 700 nm reflected from the pigment is absorbed by the water, and only a 'remnant red edge' can be observed near 700nm. We used the height of band 6 (706 nm) above a baseline of bands 5 (681nm) and 7 (730nm) to measure this remnant red edge.

If floating or rooted bottom vegetation is present and completely fills the pixel, the signal is more similar to that of land plants. However, if the surface is only partially covered, the signal from the water and from the land will mix, and the 'red edge' will be transformed to a remnant and show up as a elevated signal at 706 nm. The red areas around the edges of the lakes to the north west of the site are probably benthic rooted water plants. It is clear from figure 7, that the water bodies on the site have much lower phytoplankton concentrations than the surrounding lakes.

3.2.2. Turbidity

We used band 5 (680 nm) as a simple index of water turbidity and depth. Clear water absorbs red light and therefore appears dark in this band. However particles (including a bright sandy bottom) reflect all visible and near infrared wavelengths, so turbid or shallow water over a bright bottom appears lighter. The more turbid and/or shallower the water the stronger the signal in band 5 is. Turbid water is differentiated from shallow water chiefly from context. In figure 8, all of the water bodies on the site are shown to have high turbidity, and the undisturbed lakes off site have low turbidity. The known discharges from the site all are in lakes with slightly elevated turbidity. While not shown here in the overview images, detailed imagery shows evidence of the discharges

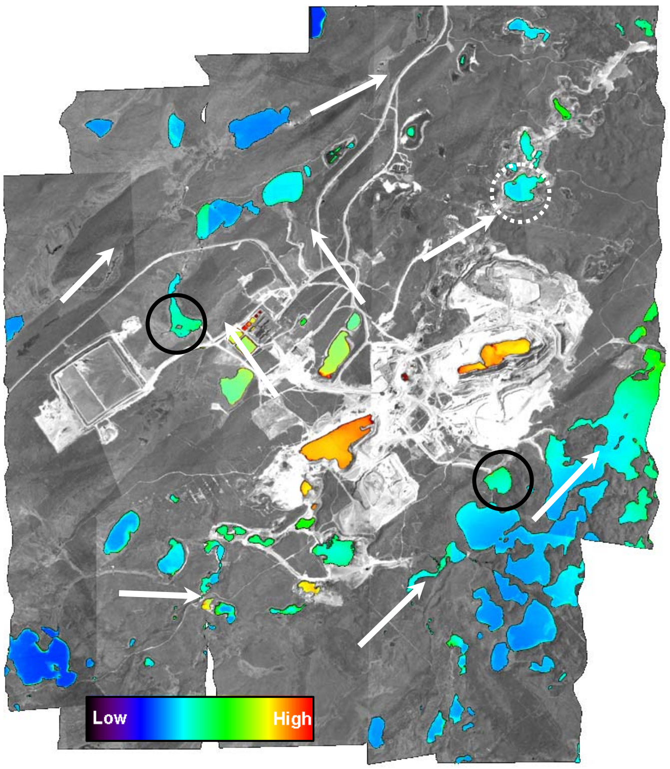

Fig. 8: Turbidity of the water bodies on and around the Key Lake Facility. Arrows mark the direction of flow. Black circles indicate known water drainage from the site. White circle indicates a suspected release point.

3.2.3. Green/Blue ratio - a measure of 'greeness'

Several dissolved and suspended materials can alter the colour of a natural water body. Dissolved organic material (DOM) originating from decomposing vegetation (sometimes referred to as "yellow matter" or Gelbstoffe) strongly absorbs blue light and causes a yellow discolouration of the water (and in high concentrations a brown color in northern muskeg lakes). Therefore a ratio of a green spectral band to a blue one provides a simple index of DOM. In figure 9, we show a band 3/band 1 ratio (Radiance at 550 nm/Radiance at 474 nm)]. Chlorophyll also causes an elevation of this ratio, but can be separated on the basis of the band 6 peak calculated above in figure 7.

Other coloured materials including ores, waste products or agents used in or produced as a result of processing will also be present at a mining processing facility. At the Key Lake facility, nickel compounds used in processing are found in solution in the Gaertner and Deilmann Pits and in the Tailings Management Facility (TMF) ponding waters. These are known to create a blue/green colour similar to Glacier fed streams and lakes. (Glen White, pers. comm.).

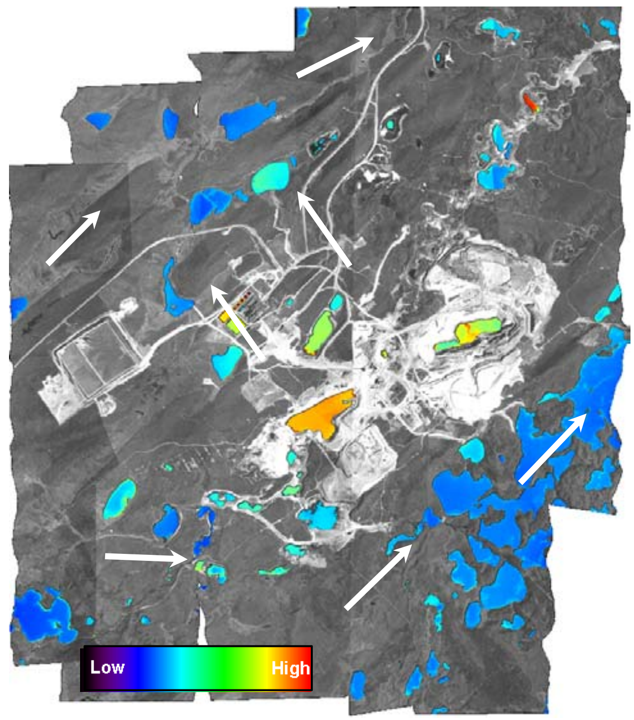

Fig. 9: The 'Green/Blue Ratio' of water bodies on and around the Key Lake Facility – as a measure of dissolved organic material and/or dissolved nickel.

Figure 9 shows that all of the water bodies on the site are strongly coloured with high G/B ratios. The undisturbed lakes off the site all have low ratios, and those surrounding lakes receiving water from the facility exhibit intermediate G/B. This is further indirect evidence that the facility is active.

3.3. Direct evidence of operation of the facility

Subaqueous dispersal into Deilmann Pit is used to control the fine radioactive dust from the milling of the tailings. The high concentration of suspended solids in the slurry dumped into the pit can be seen clearly in the chlorophyll, tubidity and G/B ratios of the Pit, and is direct evidence of processing (figure 10)

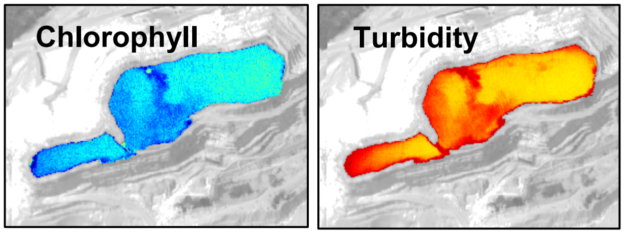

Fig. 10: Plume of low chlorophyll, turbid green waters into Deilmann Pit showing underwater tailings dispersal.

During the processing of uranium ore, water moves through the monitoring ponds at the facility, and variation of the colour, turbidity and phytoplankton concentration in these ponds is a function of how long the water remains in the ponds. It is another direct indication of processing activity that can be detected remotely.

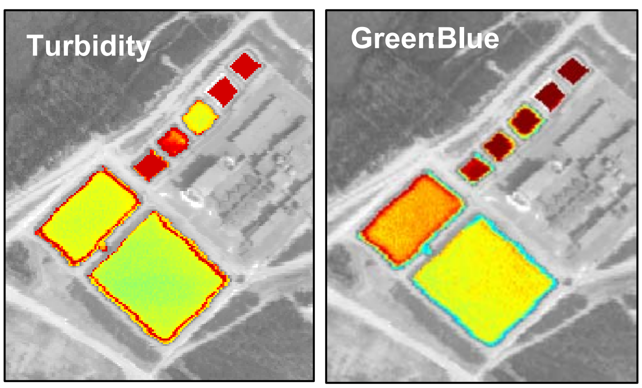

Fig. 11:. Variations of the colour, turbidity and chlorophyll concentration of the monitoring ponds are indication of processing activity.

4. Conclusions

This work was done as an exploration of the potential application of very high spectral resolution that will eventually be available on hyperspectral satellite sensors, such as from the American research satellite HYPERION and a Canadian hyperspectral satellite sensor now in the planning stages. The airborne system also mimics the high spatial resolution (but low spectral resolution and only 4 bands) currently available from operational commerical satellites such as IKONOS and QUICKBIRD.

While HYPERION has many narrow bands, it has much lower spatial resolution (30m), and much of the detail shown here would be lost. All four of the indices used here would be available from HYPERION, and all but phytoplankton fluorescence would also be available from the high resolution IKONOS and QUICKBIRD sensors.

Such image maps can provide safeguards inspectors with valuable supplemental information both in advance of an inspection, and between inspections. Environmental managers will also be interested in the spatial variability of water quality and land vegetation around a site. For sites that are remote or difficult to access for what-ever reason, the imagery can provide clues as to operations that are difficult to hide. They can provide an up-to-date map of buildings, roads, trails and paths on and around the site that can be used to check declarations. Knowledge of the vegetation on and around a site, can provide clues as to the level of the water table, the position of fences, power lines and other disturbances – such as the presence of buried material.

As we have discussed here, the water bodies on a site provide both direct and indirect evidence of the operation of a processing facility and its affect on the surrounding environment. The fine inorganic silt particles that run off a gravel or dirt surface experiencing truck traffic, can be seen in the water bodies on and around the site as elevated turbidity. The subaqueous tailings dispersal is also easily seen and difficult to hide. Both of these signals would not be present after a site was unused for several years.

The strong green colouration due to the presence of nickel compounds may be a suggestion that a site is processing uranium ore, but this signal is not conclusive since other materials can produce this colour effect. We know however that the high G/B ratio is not caused by phytoplankton because of the lack of a fluorescence signal, and a strongly disturbed unvegetated site like this is unlikely to be introducing high concentrations of dissolved organic compounds.

The phytoplankton fluorescence signal is not a direct indication of processing activity, but since these micro-plants require nitrate and phosphate compounds, and light for growth, their presence in variable amounts in the shallow monitoring ponds suggests that the water has been in each pond a different length of time. That is, the water passes through the ponds at different rates. If the facility were not in use, one would expect the ponds to exhibit much more similar characteristics.

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