USING LIMNOLOGICAL AND OPTICAL KNOWLEDGE TO DETECT DISCHARGES FROM NUCLEAR FACILITIES - POTENTIAL APPLICATION OF SATELLITE IMAGERY FOR INTERNATIONAL SAFEGUARDS

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Abstract

In this paper, we introduce some important hydrological phenomena that govern the biological and physical organization of natural water bodies, and discuss some basic concepts of marine optics that are relevant to the safeguards problem. We then present a preliminary examination of imagery from both satellite multispectral and aircraft hyperspectral sensors, to illustrate extraction of information that could be useful in the detection and verification of declared or undeclared nuclear activities. In the first example, an IKONOS image of the Canadian Bruce Nuclear Generating Facility, simple enhancement techniques failed to find any plume other than a small jet visible in the surface wave field. With a knowledge of limnology and aquatic optics, we have been able to separate and remove the surface reflection, and detect a large plume of slightly less turbid water emanating from the facility. Previous work carried out under the Canadian Safeguards Support Program, has shown that thermal imagery from the American series of Landsat satellites could be used to qualitatively detect the cooling water discharges, and could therefore be used to verify the operational status of nuclear facilities. We show in this paper that it is possible to use the calibration data associated with the digital image data to produce quantitative images of surface temperature in degrees Celsius. We also show that the visible bands of Landsat and IKONOS images often contain additional information, and that the thermal signature of a discharge from a nuclear facility is not the only signal available to describe its operation. Finally, we briefly discuss the use of airborne imagery of phytoplankton concentrations in water bodies in and around a uranium processing facility in northern Canada, as an example of potential application of hyperspectral data products for international safeguards.

1. INTRODUCTION

Most nuclear and thermal-electric plants are located either on the shorelines of lakes or on the connecting channels and lower reaches of major tributaries because of the large volumes of water needed for cooling and condensing steam in the generation of power. About 90% of the water used at a nuclear power plant is for removing excess heat generated in the reactor by condenser cooling. These water discharges provide several potential mechanisms to monitor the activities of these power plants using open-source remote sensing assets.

1.1. Potential hydrologic changes caused by cooling discharges from power plants

There are two main types of cooling systems in use for nuclear (and other) power plants: closed systems in which water is recycled internally, or in which cooling towers are used, and condenser systems in which water is passed through the plant. Operation of condenser cooling systems may produce several kinds of local hydrologic changes in the receiving water bodies, including:

(1) altered thermal structure in the vicinity of the discharge, including reduction of ice,
(2) altered current patterns at intake and discharge structures,
(3) altered surface wave patterns,
(4) alteration of the concentration of suspended inorganic material,
(5) scouring caused by increased flow near intake and discharges,
(6) stimulation of phytoplankton and/or benthic algal growth, and
(7) altered salinity gradients in estuaries.

All of these except salinity gradients are potentially observable at present via available open-source remote sensing assets.

1.1.1. Thermal effects

The density of water decreases with increasing temperature, and calm poorly mixed natural water bodies tend to stratify into two layers, a surface layer that is warm in the summer and cold in the winter, and a deep layer which remains cool throughout the year. Most power plants draw their intake water from this cool, deep water, and discharge it at or near the surface at temperatures from 2 to 10 degrees Celsius above ambient. These heated discharges tend to remain at (or move toward) the surface, intensifying the stratification in the summer and altering it in the winter. Typically the discharges form a plume of warm water that dissipates with distance from the source by releasing heat to the atmosphere or mixing with cooler surrounding waters. These plumes can be detected by remote sensing instruments from the water body's thermal emissions. In rivers and in the ocean, mixing occurs more rapidly than in lakes because of increased turbulence caused by flow in the river or by tides, and thermal plumes in those areas are likely to be smaller than in lakes.

1.1.2. Current patterns

Operation of the cooling system will usually cause changes in water currents in the immediate vicinity of both the intake and the outfall. The extent of these effects depends on the design and siting of the intake and discharge and the nature of the body of water [1]. While no currently available satellite sensor can directly detect water current patterns at this scale, currents may be inferred from thermal, phytoplankton and/or sediment patterns.

1.1.3. Surface waves

Where the discharge is at or near the surface, there may be some disruption of surface waves. Wind waves are generally visible because of reflection off the wave facets tilted toward the sun. In the region of discharges, the waves are disrupted and there is typically less sunglint.

We have also visually observed a similar phenomenon off the San Onofre, California nuclear power generating facility, where the discharge structure is in deep water. The warm water rises to the surface, and the surface wave field is altered as a result. This is easily visible by eye in the pattern of waves when looking toward the sun, and might therefore be visible in high spatial resolution optical satellite imagery acquired at high tilt angles, provided that the wave field, sun zenith angle and viewing angle are correct.

Surface wave phenomena will also be visible in Synthetic Aperture Radar (SAR) imagery of sufficiently high spatial resolution.

1.1.4. Sediment and scouring effects

Cooling water discharges have the potential for scouring sediments and increasing erosion, especially near high-velocity discharge structures, and for changing patterns of sediment deposition. Changes in sediment composition have been observed near some operating power plants. Erosion and scouring may lead to sorting of the sediments in the vicinity of the plant. Fine-grained materials will tend to become suspended by the discharge plume and be carried away from the plant, while coarser-grained sediments will remain near the discharge. Increases in turbidity of the discharge plume will be remotely detectable.

1.1.5. Alteration of phytoplankton and benthic plant life

Thermal discharges can affect phytoplankton growth because of the effects on water stratification and nutrient supply. Temperature-induced density stratification of oceans, lakes and reservoirs is a principal regulator of phytoplankton growth and distribution. At a very simple level, plant growth (including phytoplankton) is regulated by sunlight and nutrient availability. In a lake, light for photosynthesis is mostly available near the surface, while nutrients are more available in deep water (because of decomposition at depth and phytoplankton uptake near the surface). In a stratified system, phytoplankton growth is typically restricted to the surface layer where it is light, but regulated by the supply of nutrients from the deep layer. If a power plant draws cool, nutrient rich water from the deep layer, heats it, and discharges it into the surface layer, the result is intensified stratification, increased nutrient supply and, therefore, increased phytoplankton growth. This growth can be detected by remote sensing.

Power plant discharges may also alter the benthic plant life near the plant through effects on bottom sediment grain size, thermal and stratification effects, including alteration of the local nutrient regime, and siltation and scouring effects. Plant life may be absent immediately in front of a large discharge because of the strong scouring, but it may be enhanced just outside of the strong discharge. For example, at the Loviisa Nuclear Power Plant in Finland, there has been a clear change in biota specifically caused by warm water. A significant increase in littoral vegetation was observed in the vicinity of the cooling water outlets at both Loviisa and Olkiluoto. The abundance of the vascular plants *Myriophyllum spicatum, Potamogeton perfoliatus* and *Potamogeton pectinatus* has increased strongly and in some places they form together with their epiphytes, filamentous algae (*Cladophora glomerata, Ectocarpus siliculosus* and *Pilayella littoralis*), an almost impenetrable population [2]. Again, such local increase in aquatic plant life is easily detectable using remote sensors.

From a safeguards standpoint, the time scales over which phytoplankton and benthic plants respond are quite different. Because of their rapid growth rates and short life cycles, phytoplankton respond quickly (within days) to environmental change. Therefore remotely detected changes in the phytoplankton regime can be indicative of changes in a power plant's operational status. Benthic plants on the other hand respond more slowly and would reflect longer term changes.

1.2. Remote sensing of water properties

1.2.1. Signal as seen from a remote sensor

In simple terms, the optical signal received by a passive remote sensing instrument originates from the sun, passes through the atmosphere, through the air/water interface, through the water, then reflects off the target and travels back through the equivalent pathway on its way to the sensor. The signal is spectrally moderated by each of these interactions, and information can be gained at each stage (Figure 1).

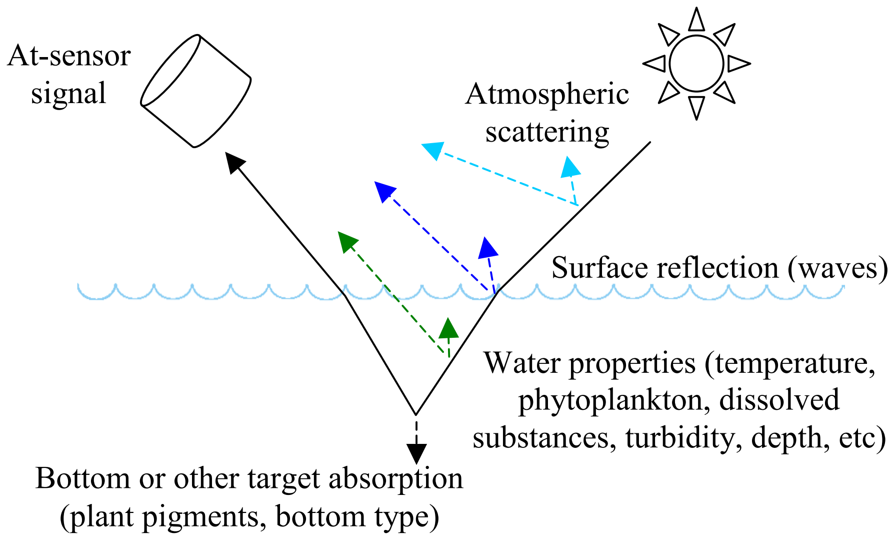

FIG. 1. Pathway of an optical signal received by a passive remote sensor

Table I summarizes the remote sensing tools that can be used to derive information about power plant emissions and their effects. In some cases spectral (colour) data can be used to directly make quantitative measurements of parameters such as phytoplankton chlorophyll or temperature. In other cases such as surface currents, the patterns are inferred from distributions of other measurable parameters.

Table I. Detection of power plant effluents using remote sensing information

Optical component	Remote sensing bands
Thermal plumes	Thermal 10-12μm
Suspended particles	Visible
Phytoplankton	Visible (Blue/green ratio, narrow red fluorescence)
Dissolved Organic Substances	Visible (Blue)
Ice	Visible & IR
Surface wave patterns	Visible (red), Radar
Current patterns	Inferred from plumes (thermal, turbidity, phytoplankton)
Bottom scouring	Inferred from other patterns

The colour of the water in a natural aquatic system (the signal seen by the remote sensor) can be expressed as the sum of several components:

$$a_{\text{total}} = a_{\text{water}} + a_{\text{particles}} + a_{\text{phytoplankton}} + a_{\text{dissolved}},$$

where a is light absorption at a given wavelength. Each component has specific spectral properties that can be used to quantify its contribution to overall absorption. Figure 2 illustrates typical absorption spectra for the major optical components of aquatic systems. By taking advantage of the spectral differences, and using specific spectral bands (or combinations) these components can often be resolved. Much depends on the spectral configuration of the sensor. The number, placement and width of bands determine the information that can be extracted for a given sensor. Figure 2 shows the visible bands for Landsat (IKONOS bands are very similar).

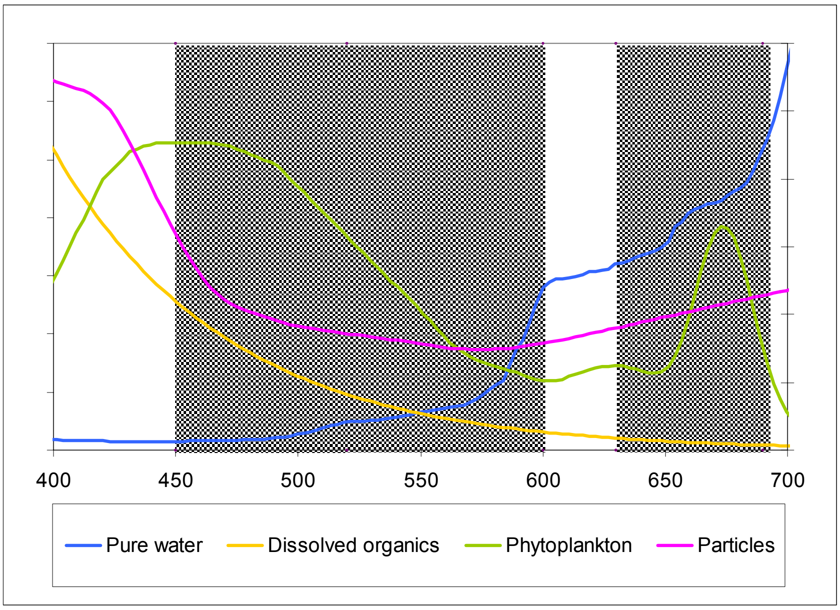

FIG. 2. Modelled absorption spectra of the main colour producing agents in natural aquatic systems. The extents of Landsat bands 1 (blue), 2 (green) and 3 (red) are shown for comparison.

2. CASE STUDY: BRUCE NUCLEAR GENERATING FACILITY

We use IKONOS and Landsat imagery of the Bruce Nuclear Generating Facility on the shore of Lake Huron, Ontario, Canada to illustrate some of the phenomena referred to above.

2.1. Surface waves

The IKONOS image in Figure 3 was acquired on November 11, 1999. Sun reflection off the wave facets indicate that this was a windy day, with wind from the north-northeast. With a simple 'true colour' image, using 3 channels to represent natural colours seen by eye, the single most overpowering factor in the appearance of the water is sunglint and sky reflection off the waves. The pattern of the waves is very clear, and the modification of the wave patterns near rocks and headlands can also be seen as the waves enter shallow water and begin to feel the bottom. This classical phenomenon is well known and can be exploited to derive maps of water depth.

2.2. Currents, scouring & turbidity

Near the Bruce A discharge at the north end of the site, the slight alteration of the wave field suggests that the darker blue, linear feature is a dredged channel. At the Bruce B discharge, a vigorous jet about 875 m long and 285 m wide is made visible via its disruption of the pattern of the waves and the reflection. The size and shape of this jet may give us information about the velocity of the discharge.

Without further processing, no colour differences are evident near the plant. However, after mathematical removal of the surface reflection, a very large plume of water with slightly lower turbidity (particle content) can be seen extending more than 7 km south of the plant. The direction of this plume is consistent with the direction of the wind, and can even be seen curling into the small bays.

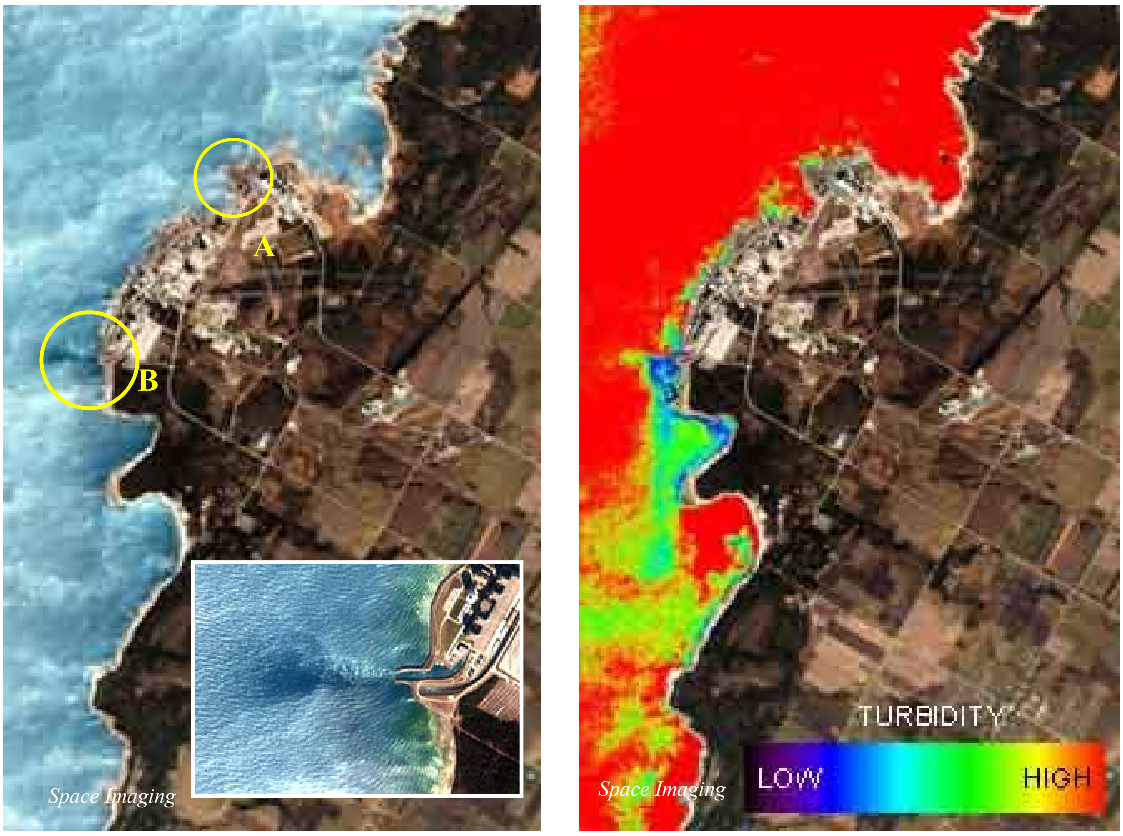

FIG. 3 Left: natural colour image of the Bruce Nuclear Generating Facility, acquired by IKONOS on November 11, 1999. The inset shows an enlargement of the discharge jet visible in the surface wave field at Bruce B. Right: Calculated image of turbidity after removing the surface reflection.

Without further information about the specific limnology of this portion of Lake Huron or the Bruce facility, we suppose that the plant is drawing water from the cold waters of the hypoliminion (below the thermocline), and that these waters have less suspended particles than the surface layers.

Our results are similar to those of Harold Hough [3] who analyzed the red band of a multispectral image acquired by the French SPOT satellite. His analysis showed an effluent plume coming from an artificial island located in a hydroelectric reservoir in the Taechon area (North Korea) which was identified as the site of an underground plutonium production facility. It should be noted that the analysis of multispectral satellite imagery by itself does not provide conclusive evidence that clandestine activities are taking place. However, it may provide important indications for further investigation using higher resolution imagery or other evidence to arrive at the conclusion.

2.3. Water temperature

Previous work [4] has shown that the operational status of a power plant can be detected from imagery with a thermal infrared band such as that from the Landsat 5 and 7 satellites. At that time a quantitative estimate of the cooling water temperature around the facility was not carried out. In this paper we show a quantitative image of water temperature using calibration data provided with the digital data.

Figure 4 (left) shows a Landsat 5 thermal image of the Bruce power plant area from August 2, 1988, calibrated to water temperature in degrees Celsius. Land areas are shown as near true colour for reference. On that day the imagery shows that Bruce A discharges were near 22ºC in the immediate vicinity of the outfall, 3-4ºC warmer than elsewhere along the shore; off Bruce B water temperatures were about 20ºC. A plume from Bruce A appears to be heating the small bay to the east, whereas the heat from Bruce B is dissipated in the lake. Current patterns that day were southwest to northeast.

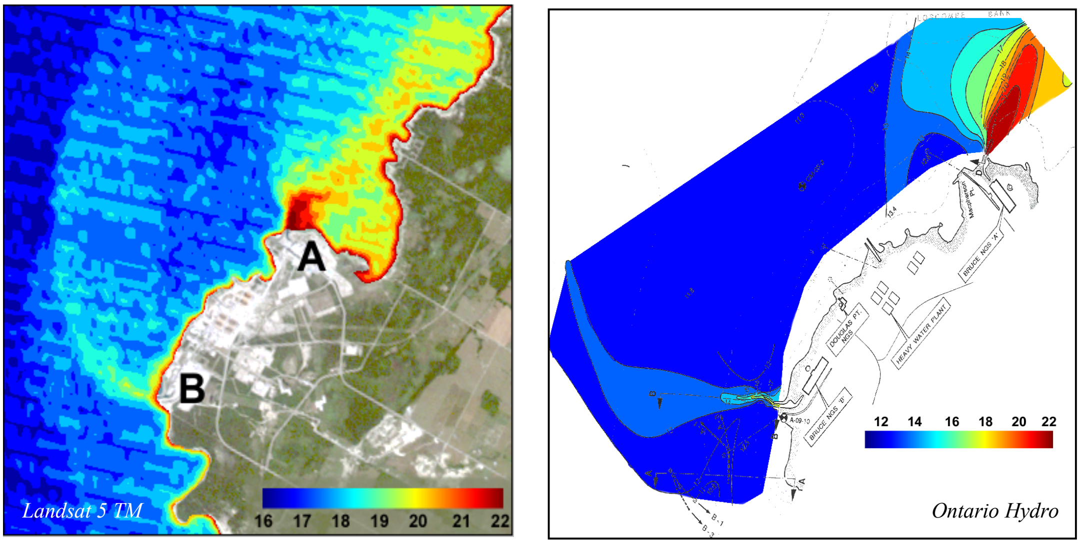

FIG. 4. Left: Thermal imagery of the Bruce A and B Nuclear Generating Facilities, acquired by Landsat 5 on August 2, 1988, and calibrated to degrees Celsius. The linear striping is due to instrument noise. Right: In situ measurements of water temperature made by Ontario Hydro June 28, 1988.

No *in situ* temperature data are available for the day of the image. Figure 4 (right) shows *in situ* temperatures measured a little over a month earlier on June 28, 1988 by Ontario Hydro [5]. Although the ambient temperature of the lake is lower, the thermal patterns are similar to those in the August Landsat image.

3. OTHER EXAMPLES

3.1. Hyperspectral mapping at a uranium processing facility

We have been conducting remote sensing studies of a processing site for high grade uranium ore at Key Lake, Saskatchewan, Canada using the airborne hyperspectral sensors, Compact Airborne Spectrographic Imager (*casi*) and SWIR (Short-Wave Infra-Red) Full Spectrum Imager (SFSI). Early results with an emphasis on SFSI sensor calibration and mineral identification have been presented [6,7]. The Key Lake area has many small lakes, and preliminary studies show large variations in water quality related to processing activities. Using the rich spectral data available from these airborne sensors, detailed maps of phytoplankton chlorophyll, turbidity (particles) and dissolved substances have been made in and around the site.

4. CONCLUDING REMARKS AND RECOMMENDATIONS

This work demonstrates that with a knowledge of limnology and aquatic optics, additional information can be extracted from commercially available imagery. Together with other evidence, this additional information can be used for international safeguards applications such as the detection of clandestine facilities. In addition, the water temperature around a nuclear facility has been quantitatively estimated using the data embedded in Landsat imagery. The discharge water temperature along with other information such as cooling flow rates would allow an estimate of the thermal power output of the plant.

Further analysis of IKONOS, Landsat imagery and the airborne hyperspectral survey data for various nuclear sites continues and additional results will become available in the near future.

REFERENCES

[1] COUTANT, C. C., A Critical Review of Aquatic Ecological Effects of Power Plant Cooling, U.S. Department of Energy, Office of Health and Environmental Research, Washington, D.C., 1981.

[2] ILUS, E., ILAHEIMONEN, T. K., KLEMOLA, S., Nuclear power and environment in Finland – with special emphasis on the marine environment. Finnish Centre for Radiation and Nuclear Safety. Helsinki, Finland, http://www.gr.is/nsfs/ilus.htm, 2001.

[3] HOUGH, H., Jane's Intelligence Review, 1999.

[4] CANTY, M., JASANI, B., TRUONG, Q.S. Bob., Remote Sensing and Change Detection for Nuclear Safeguards: The Bruce Nuclear Power Development Site. Juelich Report Jul-3843, Forschungszentrum Juelich, Germany, ISSN 0944-2952, 2001.

[5] BURCHAT, W.L., A study of the combined thermal plume from Bruce NPD 1987-1989. Report no 91225, Ontario Hydro Design and Development Division, 1991.

[6] LEVESQUE, J., NEVILLE, R. A., STAENZ, K., TRUONG, Q.S. Bob., Preliminary Results on the Investigation of Hyperspectral Remote Sensing for the Identification of Uranium Mine Tailings. Paper presented at the International Symposium on Spectral Sensing Research (ISSSR), Quebec City, Canada, 2001.

[7] NEVILLE, R.A., LEVESQUE, J., STAENZ, K., NADEAU, C., TRUONG, Q.S. Bob, BORSTAD, G.A., Uranium Mine Detection Using an Airborne Imaging Spectrometer. Proceedings of the Fifth International Airborne Remote Sensing Conference and Exhibition, San Francisco, 2001.