# Scientific Limitations of Remote Sensing for Environmental Pollution Detection

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Remote sensing provides essential synoptic coverage for environmental assessment, but its scientific and technical constraints must be clearly acknowledged when interpreting pollution signals. These limitations affect the reliability of detecting damage to industrial facilities, waste sites, water bodies, and urban environments.

## 1. Resolution Constraints and Mixed Pixels

Satellite sensors must balance spatial, spectral, temporal, and radiometric resolution according to the requirements of a particular application (Jensen, 2007). These characteristics influence the ability to detect and characterize small or spatially heterogeneous environmental features, potentially limiting the detection of fine-scale pollution.

Limited spatial resolution can constrain the detection of small or localized contamination sources and environmental events, such as oil leaks or ruptured pipelines, narrow wastewater discharges, localized soil contamination, small fires, and localized chemical releases. In water-pollution monitoring, limitations in the spatial and temporal resolution of satellite sensors can restrict the detection and characterization of pollution (Kaplan et al., 2024).

Mixed pixels can further obscure pollution signals. A single pixel may contain multiple surface types, meaning that its recorded signal represents a mixture of these different components. If contamination covers only part of a pixel, its signal can be diluted by the surrounding uncontaminated area, making it difficult to identify (Foody & Cox, 1994).

**Implication**: Fine-scale pollution or localized environmental events may remain undetected or uncertain in medium-resolution satellite imagery. Targeted field sampling will therefore be needed to confirm suspected pollution and assess its actual extent and severity (Kaplan et al., 2024).

## 2. Atmospheric Interference, Cloud Cover, and Retrieval Uncertainty

Optical satellite sensors are sensitive to atmospheric conditions. Dust, smoke, aerosols, haze, humidity, and clouds can alter the signal received by the sensor and complicate atmospheric correction. As a result, atmospheric effects can introduce uncertainty into the surface reflectance and pollution indicators derived from satellite imagery (Schaepman-Strub et al., 2006).

These uncertainties can also affect the retrieval of specific pollutants. For example, satellite measurements of atmospheric $NO_2$ can be influenced by retrieval assumptions, atmospheric conditions, and differences between satellite observations and conditions at the ground level (Cifuentes et al., 2026).

**Implication**: Pollution indicators derived from satellite observations should therefore be interpreted together with appropriate uncertainty estimates and, where possible, validated against ground-based measurements to reduce the risk of over- or underestimating pollution levels.

## 3. Limited Sensitivity to Subsurface and Many Chemical Pollutants

Satellite remote sensing primarily measures signals from the Earth's surface or, for atmospheric observations, properties of the atmospheric column. Consequently, many pollutants located below the surface, including groundwater contamination, hydrocarbons infiltrated into soil, PFAS, and subsurface heavy metals, generally cannot be directly detected from space. Some soil contaminants, such as certain heavy metals, can be estimated using imaging spectroscopy, but these methods rely on indirect relationships between contaminant concentrations and changes in soil reflectance (Ben-Dor et al., 2009).

Subsurface contamination may therefore be inferred from indirect indicators such as vegetation stress, changes in soil properties, or surface discoloration. However, these indicators are not unique to contamination and can also result from drought, salinity, nutrient deficiencies, or land degradation. This makes it difficult to distinguish pollution from other environmental processes using satellite observations alone. The challenges of sensing and characterizing subsurface soil and groundwater contamination are well documented, particularly when contaminants occur below the surface or at low concentrations (Davis et al., 2023).

**Implication:** Remote sensing alone generally cannot confirm the presence, concentration, or composition of subsurface pollutants. Field sampling and laboratory analysis remain essential for confirming contamination and determining its concentration and chemical characteristics.

## 4. Passive Optical Limitations: Darkness, Cloud, and Event Timing

Passive optical sensors cannot operate at night or through dense smoke or cloud. Many pollution events—industrial accidents, explosions, chemical releases—occur outside the observation window of optical missions.

Thermal sensors (e.g., VIIRS) can detect large fires and flaring (Elvidge et al., 2013), but spatial resolution remains coarse, limiting detection of smaller industrial releases.

**Implication:** Short-lived pollution events may be entirely missed by satellites; on-site inspections and rapid sampling are required to capture transient contamination.

## 5. Indirect Indicators and Ambiguous Causality

For many pollutants, satellite observations capture proxies rather than the pollutant itself:

- turbidity indicators as signals of possible water-quality changes
- vegetation stress indicators as signs of potential soil or water stress
- thermal anomalies as indicators of fires, industrial heat sources, or other abnormal heat signatures (Kuenzer et al., 2013)
- spectral changes as potential indicators of surface contamination

These proxies are non-unique. For example, turbidity increases may result from natural sediment resuspension rather than contamination, while vegetation stress may reflect drought, salinity, nutrient deficiencies, or other environmental factors rather than chemical exposure. As a result, proxy-based interpretations require careful contextual analysis and cannot confirm contamination on their own.

Urban and industrial environments add further complexity. Buildings, shadows, roads, rubble, vegetation, and other mixed surface materials can create highly heterogeneous reflectance patterns, making it difficult to distinguish pollution-related changes from normal background variability (Herold et al., 2004).

For atmospheric pollution, overlapping emission sources and variable meteorological conditions can make it challenging to link an observed atmospheric signal to a specific source. Satellite observations can constrain pollutant distributions, but additional modelling and contextual information are typically required to attribute pollution to specific sources and relate column measurements to surface concentrations (Martin, 2008).

**Implication:** Remote sensing can identify potential pollution anomalies and hotspots, but satellite observations alone generally cannot establish the causal attribution or responsibility for an observed pollution event. Field verification and supporting contextual information are therefore essential to avoid misinterpretation.

## 6. Sensor Drift, Cross-Mission Differences, and Trend Reliability

Long-term monitoring of pollution requires stable and comparable time series. Sensor degradation, calibration changes, processing updates, and differences between satellite missions can introduce artifacts that mimic or obscure real environmental trends.

Cross-sensor differences are particularly important when combining observations from multiple missions such as Landsat 7, 8, and 9 or Sentinel-2A and 2B. Studies show that differences in sensor characteristics and atmospheric correction can produce systematic differences in surface reflectance, potentially introducing artificial trends if the data are not properly harmonized. For example, a recent global evaluation of Landsat surface reflectance over inland waters found substantial cross-sensor inconsistencies and demonstrated that these can bias downstream water-quality products **(**Yang et al., 2026**).**

**Implication:** Long-term pollution trend analysis should include appropriate cross-sensor harmonization, calibration and validation, and uncertainty assessment. Periodic comparison with field measurements provides an essential independent check that observed trends reflect genuine environmental change rather than changes in satellite data or processing methods.

## 7. Central Scientific Point: Remote Sensing Cannot Replace Ground-Truthing

Across these limitations, one conclusion is consistent:

**Remote sensing is a powerful screening and monitoring tool, but it generally cannot independently confirm the presence, concentration, composition, or source of environmental contamination.**

Field validation, including field sampling, laboratory analysis, and, where appropriate, geophysical surveys, is therefore essential for confirming suspected pollution and assessing its environmental impact.

This applies particularly to:

- soil contamination
- groundwater pollution
- surface-water quality
- air-pollutant concentrations
- industrial chemical releases
- hazardous-waste dispersion

**Remote sensing should therefore be used as a first-layer assessment tool, helping identify potential pollution hotspots and guide where field teams should investigate and sample, rather than as a standalone method for determining the presence or extent of environmental damage.**

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