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*Review*

# Remote Sensing Analysis Techniques and Sensor Requirements to Support the Mapping of Illegal Domestic Waste Disposal Sites in Queensland, Australia

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**Abstract:** Illegal disposal of waste is a significant management issue for contemporary governments with waste posing an economic, social, and environmental risk. An improved understanding of the distribution of illegal waste disposal sites is critical to enhance the cost-effectiveness and efficiency of waste management efforts. Remotely sensed data has the potential to address this knowledge gap. However, the literature regarding the use of remote sensing to map illegal waste disposal sites is incomplete. This paper aims to analyze existing remote sensing methods and sensors used to monitor and map illegal waste disposal sites. The purpose of this paper is to support the evaluation of existing remote sensing methods for mapping illegal domestic waste sites in Queensland, Australia. Recent advances in technology and the acquisition of very high-resolution remote sensing imagery provide an important opportunity to (1) revisit established analysis techniques for identifying illegal waste disposal sites, (2) examine the applicability of different remote sensors for illegal waste disposal detection, and (3) identify opportunities for future research to increase the accuracy of any illegal waste disposal mapping products.

**Keywords:** waste management; illegal dump sites; domestic waste; remote sensing; image processing methods; Australia

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## 1. Introduction

Remote sensing has been under-utilized in monitoring and mapping illegal waste disposal. Limited research has been published globally over the past 15 years into developing and trialing methods on monitoring and mapping illegal waste disposal [1]. The limited publications identified by the authors focused on study areas in Europe (36.5% of published papers), Japan (23.1%), and the United States of America (15.4%). No relevant published research was identified from Australia. Illegal waste disposal presents a global management problem for contemporary governments [1,2] including Australia, France [3], Ireland [4], Italy [5], Japan [6], the United Kingdom [7], and the United States of America [8,9]. Illegal waste presents governments with a wide range of risks that have prompted demands for cost-effective, efficient monitoring and mapping solutions to support improved management outcomes [10]. Remote sensing has the potential to provide critical information about the location of illegal waste to inform targeted active surveillance operations and cost-effective remediation activities.

This paper aims to critically analyze existing remote sensing methods used to monitor and map illegal waste disposal sites on the surface. The purpose of this analysis is to support the evaluation of existing remote sensing methods for mapping illegal domestic waste sites in Queensland, Australia. In this paper, illegal waste disposal sites are restricted to the unlawful deposit of an amount of domestic waste 200 liters or greater in volume, as defined in Queensland's Litter and Illegal Dumping Action Plan [11]. This definition was chosen to maintain consistency with the relevant Queensland legislation. A short overview of the geography of illegal domestic waste disposal in Queensland (Section 1) is followed by a review of remote sensing methods published over the past 15 years to monitor and/or map illegal waste disposal sites (Section 2). This review of existing analytical methods provides a context to the discussion (Section 3) of the applicability of these methods for use in monitoring and mapping illegal domestic waste disposal in Queensland. The discussion includes the identification of opportunities for future research considering recent advances in technology.

### *1.1. Geography of Illegal Waste Disposal Sites*

Queensland has an estimated population of over 4.7 million people [12] and extends across 1.7 million square kilometers of Australia [13]. Waste management responsibilities are shared between the state government and 77 local governments in partnership with a wide range of non-government organizations, research organizations, businesses, community groups, and land managers [11]. The scale of the illegal domestic waste disposal issue in Queensland is particularly difficult to quantify without a comprehensive state-wide dataset [11]. However, recent reports indicate that it is a widespread problem shared by many, if not all, local governments [11]. It is estimated that up to 20,666 tons of domestic waste are illegally disposed of each year [14] in Queensland. Illegal waste includes items such as asbestos, chemical drums, construction and demolition materials, furniture, garden waste, household rubbish, mattresses, televisions, tires, and whitegoods [11]. This illegal waste is typically deposited on the land surface.

The geography of illegal waste disposal sites is not random [1,3,4,15] but rather a complex pattern influenced by a multitude of economic [6,10], environmental [7,8], and social [8,16] factors. The specific range of factors and their relative level of influence on the distribution of illegal waste disposal sites vary both within and between regions. Factors that have been shown to influence the geography of illegal waste disposal include:

- demographics (e.g., population density, employment rate, and income per capita) [3,8,16,17]
- the availability of waste facilities or services [5,7,8,18]
- the affordability of legal waste facilities or services [5,6,10,16,19]
- the effectiveness of law enforcement [10,16]
- site access (e.g., proximity to roads) [3,8]
- remoteness of illegal waste disposal location [3,8]
- sociocultural acceptability of illegal waste disposal [10]

### *1.2. Threats Posed by Illegal Waste*

Illegal waste represents an economic, environmental, and social risk. Remediation activities targeting illegal waste often incur high costs that consume approximately 30% of some local government budgets in the United States of America [7,8,10]. Reports indicate a similar experience in Queensland with estimated management costs ranging from A$670 to A$1270 per ton of illegal domestic waste [11,14], totaling close to A$17 million in 2013–2014 [14].

The presence of illegal waste degrades environmental values at the disposal site and in surrounding areas, particularly at those sites where illegal waste disposal is frequent [3,6,8,15,19,20]. The quality of local natural resources in these areas can be degraded by illegal waste [5,8,10,16,20,21] through the addition of abnormal concentrations of heavy metals [20], hydrocarbons, nitrogen [5], and volatile organic compounds (e.g., solvents or gasoline) [2].

Research has shown that the presence of illegal waste also negatively impacts upon human health, particularly where there is prolonged direct or indirect contact with illegal waste [3,6,21]. In some rural areas of the United States of America and neighboring Mexico, research has demonstrated a statistically significant contribution of the presence of illegal waste and the higher recorded levels of kidney and lung damage in those areas [2,8].

### *1.3. The Need for Improved Management of Illegal Waste*

An improved understanding of the distribution of illegal waste disposal can support improvements to the cost-effectiveness and efficiency of waste management efforts [10]. Currently no comprehensive monitoring or mapping of illegal waste is undertaken in Queensland. Monitoring of illegal waste disposal sites largely relies on (1) voluntary reporting of incidents by the public [22] and (2) on-the-ground surveillance of known hotspots [11]. This critical knowledge gap is recognized by waste managers and included as an explicit program in the recent Queensland Littering and Illegal Dumping Action Plan [11]. Relevant action items in this program include "sponsor research projects that build knowledge about the behaviors associated with litter and illegal dumping. These projects will enhance prevention, develop evaluation methodologies and analytical techniques including data mapping; and develop technologies to aid efficiency of service delivery" [11]. Remote sensing has the potential to address this knowledge gap through the use of existing analytical techniques to comprehensively monitor and map illegal waste disposal sites. Illegal waste disposal sites may be identified in remote sensing data either directly (*i.e.*, through spectral signatures) or indirectly (e.g., through temporal changes in spectral signatures). Mapping the distribution of illegal waste disposal sites is the first step to improving the efficiency of waste management efforts, particularly surveillance and clean-up efforts. Regular or continuous surveillance efforts using remote sensing may act as a deterrent against future illegal waste disposal.

## 2. Review of Remote Sensing Based Methods for Mapping Illegal Waste Disposal Sites

Over the past 15 years, remote sensing has been utilized to obtain information on the distribution of illegal waste dumps. From March to May 2014 a series of database searches were conducted to identify articles containing technical information on the monitoring and/or mapping of illegal waste disposal sites. During the database searches, preference was given to peer-reviewed scientific journals. Given the relatively small number of articles available on the subject, the search terms used in the database searches were broad, including "illegal waste", "mapping waste", and "illegal waste management". A wide variety of databases were searched, including databases hosted by EBSCO Publishing, Elsevier, ProQuest, and Taylor and Francis. Each article ($n$ = 52) identified was then evaluated based on the relevance to the research topic with a resulting score of one (lowest relevance) to five (highest relevance). Not all identified articles utilized remote sensing data, and many studies focused entirely on the combination of other spatial data using geographic information system (GIS) analysis techniques. This paper reviews remote sensing analysis methods to monitor and/or map primarily surface deposits of illegal waste disposal published over the past 15 years. This section includes analysis methods that integrate remote sensing data with other spatial data in a GIS. This provides the basis for the discussion, in section three, of the applicability of the existing methods for monitoring and mapping illegal domestic waste disposal. This review also informs the discussion on opportunities for future research, applying existing methods to recent advances in technology and planned earth observation missions. Table 1 provides an overview of the remote sensing sensors utilized to monitor and/or map illegal waste disposal. Table 2 provides an overview of the remote sensing analysis techniques developed and trialed to monitor and/or map illegal waste disposal using data acquired from those satellite sensors.

### *2.1. Overview of Illegal Waste Monitoring and Mapping Methods Utilizing Aerial Photography*

Several studies have trialed visual identification and automated classification techniques to identify and map illegal waste disposal sites using aerial photography including 1:10,000 digital orthophotos [21], images obtained from digital video camera at an altitude of 300 m [19], and other aerial photographic data [2]. Visual identification analysis techniques were primarily used to manually identify potential illegal waste disposal sites for field assessment [2] and to inform the interpretation and validation of remote sensing analysis [21]. In these studies no assessment was made of the suitability of aerial photography for comprehensively mapping illegal waste disposal sites.

**Table 1.** Overview of the remote sensing satellite sensors utilized in monitoring and/or mapping illegal waste disposal sites over the past 15 years. Further information on the analysis techniques used in monitoring and/or mapping illegal waste disposal sites is contained in Table 2.

| | **Sensor Specifications** | | |
|---|---|---|---|
| **Sensor** | **Spectral Range (Wavelength Width of Different Frequency Bands)** | **Pixel Size** | **Temporal Resolution** |
| Optical sensors (moderate spatial resolution) | | | |
| LANDSAT TM [27] | 0.45–0.52 µm (band 1)<br>0.52–0.60 µm (band 2)<br>0.63–0.69 µm (band 3)<br>0.76–0.90 µm (band 4)<br>1.55–1.75 µm (band 5)<br>10.4–12.5 µm (band 6, thermal)<br>2.08–2.35 µm (band 7) | 30 m<br>120 m (thermal) | 16 days |
| Optical sensors (medium spatial resolution) | | | |
| FORMOSAT-2 [24] | 0.45–0.90 µm (panchromatic)<br>0.45–0.52 µm (blue)<br>0.52–0.60 µm (green)<br>0.63–0.69 µm (red)<br>0.76–0.90 µm (near-infrared) | 2 m (panchromatic)<br>8 m (multispectral) | 1 day |
| ALOS AVNIR-2 [23] | 0.42–0.50 µm (blue)<br>0.52–0.60 µm (green)<br>0.61–0.69 µm (red)<br>0.76–0.89 µm (near-infrared) | 10 m | 46 days |
| Microwave sensors (medium spatial resolution) | | | |
| ALOS PALSAR [23] | 1.3 GHz or 23 cm | 10 m<br>100 m | 46 days |
| Optical sensors (high to very high spatial resolution) | | | |
| ALOS PRISM [23] | 0.52–0.77 µm | 2.5 m | 46 days |
| QUICKBIRD [28] | 0.45–0.90 µm (panchromatic)<br>0.45–0.52 µm (blue)<br>0.52–0.60 µm (green)<br>0.63–0.69 µm (red)<br>0.76–0.90 µm (near-infrared) | 0.65 m (panchromatic)<br>2.62 m (multispectral) | 1–3.5 days |
| IKONOS [25, 26] | 0.45–0.90 µm (panchromatic)<br>0.45–0.52 µm (blue)<br>0.51–0.60 µm (green)<br>0.63–0.70 µm (red)<br>0.76–0.85 µm (near-infrared) | 0.82 m (panchromatic)<br>3.2 m (multispectral) | 3 days |

**Table 2.** Overview of the remote sensing analysis techniques applied to data acquired from remote sensing satellite sensors to monitor and/or map illegal waste disposal sites over the past 15 years.

| **Sensor** | **Remote Sensing Technique** | | | | | | | **Associated GIS Technique and/or Tool** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Infrared thermography | ISODATA Unsupervised Classification | Least-square Linear Mixture | Manual (Visual) Classification | Maximum Likelihood Classification | Pixel Purity Index | Principle Component Transformation | Certainty Factor Model | Spatial Analysis Tools | Weighted Linear Combination |
| ALOS AVNIR-2 | | | | [29] | | | | | | |
| ALOS PALSAR | | | | [29] | | | | | | |
| ALOS PRISM | | | | [29] | | | | | | |
| Digital orthophotography | [31] | | | [2,21] | [18] | | | | | [2] |
| FORMOSAT-2 | | | [20] | | | [20] | | [20] | | |
| IKONOS | | | | [1,3] | [1,3] | | | | [1] | [3] |
| LANDSAT TM | | [21] | | | | | [21] | | | |
| QuickBird | | | | [29] | | | | | | |

Only one study assessed the applicability of using aerial photography for mapping illegal waste disposal. Salleh and Tsudagawa [19] used an automated method to analyze and classify remote sensing data obtained from a digital video camera at an altitude of 300 m. This method used a spatial filter to remove multiple-order energy peaks and clean the signal before applying a maximum likelihood classification [19]. The classification of remote sensing data solely using spectral characteristics (*i.e.*, maximum likelihood classification) resulted in a correctness percentage of 76.72% [19]. When a spatial filter was applied prior to the maximum likelihood classification, the correctness percentage of the resultant mapping increased to 97.36% [19]. However, the exact method used to calculate the correctness percentage was not clear.

There is limited research utilizing aerial photography to identify and/or map illegal waste disposal, particularly considering the availability of this remote sensing data to waste managers. This may be due to a bias towards delivery of waste management services rather than publication of research results. This can be exemplified by the numerous scientific and non-scientific documents identifying aerial photography acquired from unmanned aerial vehicles (UAVs) as being applicable to the identification of illegal waste disposal sites. However, there are very few scientific papers that specifically trial remote sensing analysis techniques on data acquired from UAVs. Pereschino *et al.* [31] conducted infrared thermography to analyze data acquired from UAV to identify illegal waste disposal sites and environmental pollution. Infrared thermography is effective in identifing thermal anomolies including heated biogas produced by bacteria in illegally disposed organic matter [31].

### *2.2. Overview of Illegal Waste Monitoring and Mapping Methods Utilizing Moderate Resolution Satellite Data*

Remote sensing techniques based on identifying temporal changes have been trialed on data acquired from the LANDSAT Thematic Mapper (TM), a sensor with moderate spatial resolution (*i.e.*, 12–50 meter pixel size) and medium temporal resolution (*i.e.*, 4–16 day revisit time). The technique trialed on LANDSAT TM data aimed to map the visible indirect temporal land changes associated with illegal waste disposal [1,21]. These visible indirect temporal land changes include thermal anomalies and/or vegetation stress [1,21]. Land degraded by the presence of illegal waste is usually noticeable for its spectral signature stability over time in comparison to other features such as urban areas, sea, salt evaporation pools, cultivation systems, *etc.* [21].

Notarnicola *et al.* [21] analyzed LANDSAT TM data using a combination of principal component transformation and unsupervised classification. The principal component transformation reduces the impact of spectral redundancy and enhances spectral differences. Following the principal component transformation an unsupervised classification (ISODATA algorithm) was run to identify radiometric categories. The relatively stable spectral signature of illegal waste disposal sites is used as a key identification characteristic and is most successful in extensive areas with relatively homogenous land cover [21]. The resultant mapping was compared to ground truth land cover mapping and digital orthophotos at a scale of 1:10,000 [21]. In addition, a Student's *t*-test was undertaken to ensure that the spectral signatures identified as illegal dumps were statistically significant in comparison to other features [21]. In areas with complex land cover or external factors influencing temporal change (e.g., drought), it is likely that the accuracy of maps produced using this method will be decreased [21]. The feasibility of this method increases with access to more spectral bands [21] and may have better results using data acquired from higher spectral resolution sensors.

### *2.3. Overview of Illegal Waste Monitoring and Mapping Methods Using Medium Resolution Satellite Data*

Medium spatial resolution (*i.e.*, 4–12 meter pixel size) remote sensing has been used to trial methods to monitor and map illegal waste disposal sites based on their spectral signatures [1,19,20,29]. These trials have used remote sensing data acquired from FORMOSAT-2 [20] and Advanced Land Observing Satellite (ALOS) Advanced Visible and Near Infrared Radiometric type 2 (AVNIR-2) and Phased Array type L-band Synthetic Aperture Radar (PALSAR) sensors [29].

Yonezawa [29] compared the data from the ALOS AVNIR-2 and PALSAR sensors to identify illegal waste disposal sites based on their spectral signature. Remote sensing data from the ALOS AVNIR-2 and PALSAR was visually examined, as both sensors have 10-meter spatial resolution [29]. Remote sensing data acquired from the ALOS AVNIR-2 and PALSAR sensors were unable to support the visual identification of illegal industrial waste disposal sites against known waste disposal sites [29]. Illegal waste disposal sites in the ALOS PALSAR data were obscured by a speckle pattern [29]. In this instance, the use of medium-resolution satellite data was unable to support the identification of illegal waste disposal sites.

Chu *et al.* [20] used the pixel purity index to automate the identification of pure spectra pixels of waste, shade, soil, and vegetation in eight-meter spatial resolution data acquired from the FORMOSAT-2 sensor. Using these pure spectral pixels, it was possible to estimate their relative proportion within each pixel based on a least-square linear mixture analysis [20]. The outputs were validated against a separate set of known waste disposal sites [20]. The outputs of this method were integrated with other spatial data in a GIS to increase the accuracy and efficiency of illegal waste disposal mapping, as discussed further in Section 2.5.

### *2.4. Overview of Illegal Waste Monitoring and Mapping Methods Utilizing High- to Very-High-Resolution Satellite Data*

A large proportion of studies using remote sensing techniques to map illegal waste disposal sites have focused on high (*i.e.*, 1–4 meter pixel size) and very-high (*i.e.*, 0.5–1 meter pixel size) spatial resolution satellite data. Research has focused on mapping illegal waste disposal sites based on direct spectral signatures (*i.e.*, of the waste itself) [29] and indirect spatial signatures (e.g., stressed vegetation associated with waste) [1] using several high and very-high spatial resolution satellite remote sensors.

In addition to trialing the use of medium spatial resolution satellite data, Yonezawa [29] visually examined and compared spectral signatures to known illegal waste disposal sites using the high spatial resolution ALOS Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) and Quickbird sensors. Multispectral remote sensing data acquired from the ALOS PRISM sensor has 2.5-meter spatial resolution and was useful for the visual identification of illegal industrial waste disposal sites [29]. However, pan-sharpened panchromatic ALOS PRISM data improved upon these results, proving to be more useful in the visual identification of surface changes [29].

Remote sensing data acquired from the Quickbird sensor significantly improved the outcome of mapping illegal industrial waste disposal sites compared to the results obtained using ALOS sensors including PRISM [29]. This improved outcome is likely due to Quickbird's higher spatial resolution of 0.61 m (panchromatic) and 2.44 m (multispectral). Using pan-sharpened panchromatic Quickbird data, visual identification was able to map the presence of illegal industrial waste disposal sites larger than two square meters [29]. These illegal industrial waste disposal sites were composed of scrap concrete, tires, and other garbage surrounded by vegetation [29]. The use of pan-sharpened panchromatic Quickbird data was less successful in mapping similarly sized illegal industrial waste disposal sites composed of scrap iron and plastic [29]. This limitation was particularly relevant where these illegal industrial waste disposal sites were located on bare soil, as they have similar spectral characteristics [29]. Multispectral Quickbird data enabled researchers to visually discriminate between waste types including concrete, paper, scrap iron, and plastic based on their different spectral signatures [29]. However, only illegal industrial waste disposal sites greater than 6 × 4 meters in size were able to be identified and characterized due to the lower spatial resolution of Quickbird multispectral data in comparison to panchromatic data [29]

The use of Quickbird remote sensing data in the monitoring and mapping of illegal waste disposal presented several advantages in comparison to ALOS sensors. It was possible to identify illegal waste disposal sites greater than two square meters in size and also to comprehensively characterize those sites greater than 6 × 4 meters in size based on the types of waste. The ability to identify the type of waste at a site is important to inform the selection of appropriate remediation activities and improve the delivery efficiency of waste management services.

Remote sensing analysis methods using visual identification techniques have limited applicability in monitoring and mapping illegal waste disposal over large areas due to their processing requirements. Silvestri and Omri [1] developed a method to map buried illegal waste disposal sites based on the spectral signature of stressed vegetation associated with the presence of illegal waste. This method utilized both high (multispectral) and very high (panchromatic) spatial resolution data acquired from the IKONOS sensor. This method created a spectral library with accompanying statistics that define the spectral characteristics of seven training illegal waste disposal sites [1,3]. The spectral library created was then used as the basis for a maximum likelihood classification to distinguish illegal waste disposal sites using a threshold of 0.98–0.995 [1]. The resultant map was validated using a confusion matrix with the map having an overall accuracy of 60–74% depending on the scan line assessed [1]. Vegetation stress was shown to be a suitable indicator of possible buried illegal waste disposal sites in this study [1]. However, the mapping overestimates illegal waste disposal sites by identifying locations of vegetation stressed for reasons unrelated to waste (e.g., trampling). Approximately 12% of the identified sites actually had illegally dumped hazardous waste [3].

### *2.5. Overview of Illegal Waste Monitoring and Mapping Methods Incorporating Remote Sensing Analysis and other Spatial Data in a Geographic Information System*

GIS analysis techniques and tools have primarily been incorporated into illegal waste disposal monitoring and mapping methods to improve the accuracy and efficiency of mapping outputs. In these mixed-method approaches, remote sensing analysis outputs are often integrated with other spatial data known or expected to influence the location of illegal waste disposal sites within the study area (e.g., site accessibility).

Chu *et al.* [20] utilized a certainty factor model to combine spatial data including information on distance to different land uses and FORMOSAT-2 data (analyzed as discussed in Section 2.3). The mixed-method approach, in comparison to a GIS approach, was shown to improve the accuracy of the resultant mapping by an area under the curve of up to 0.2539 when compared to a separate validation set of known waste disposal sites [20]. No comparison was undertaken quantifying the improvement in mapping between a remote sensing and a mixed-method approach.

The incorporation of GIS analysis techniques was employed to improve the accuracy of mapping obtained using remote sensing analysis techniques by Silvestri and Omri [1] and Biotto *et al.* [3]. Silvestri and Omri [1] used spatial data on road network accessibility (*i.e.*, the distance of sites from roads and paths) to refine the remote sensing analysis output. The use of spatial data in addition to remote sensing analysis removed over half of the candidate illegal waste disposal sites as false positives. The use of this additional spatial data was deemed essential to address the overestimation inherent to the remote sensing analysis method [1]. Biotto *et al.* [3] expanded upon this mixed-method approach using a weighted linear combination GIS analysis method to combine several additional spatial data sets including the location of former quarries, proximity to authorized landfills, location of industrial sites (which are potential sources of hazardous waste), road network accessibility, population density, and land cover. Based on this mixed-method approach, 84.2% of illegal waste disposal sites in the validation area and 61.6% of sites identified from the remote sensing analysis were located in high-probability locations [3]. The inclusion of GIS analysis techniques was shown to be valuable in narrowing illegal waste disposal sites and improving the accuracy of resultant mapping [3].

## 3. Discussion

Limited studies have been conducted over the past 15 years into techniques to analyze remote sensing data to monitor and map illegal waste disposal. Furthermore, no remote sensor category (e.g., moderate-resolution sensors) has been comprehensively assessed with regard to its potential to support established analysis techniques. Given the porosity of knowledge in this area, it is not possible to provide a comprehensive assessment of the applicability of existing methods for monitoring and mapping illegal domestic waste disposal in Australia. However, existing studies do provide some insight into the future opportunities likely afforded by different remote sensors and methods, which are considered sequentially in this discussion.

### *3.1. Applicability of Existing Remote Sensors for Monitoring and Mapping Illegal Domestic Waste Disposal*

It is evident from the review of previous research that moderate and medium spatial resolution remote sensors are unlikely to be useful in mapping illegal domestic waste disposal. This includes LANDSAT, ALOS AVNIR-2, ALOS PALSAR, and FORMOSAT-2. This is primarily because these studies had limited success in analyzing data acquired from these remote sensors to identify larger illegal industrial disposal sites. Illegal domestic waste disposal sites are often significantly smaller than industrial sites and therefore the 4–50 m spatial resolution of these remote sensors is a key limitation in their use.

High-resolution data proved more useful with methods able to identify 6 × 4 m and 2 square meter illegal waste disposal sites from QuickBird data and ALOS PRISM panchromatic, respectively [29]. The use of QuickBird data for our purposes is likely to be similarly constrained by the relatively small size of domestic waste disposal sites in comparison to industrial sites. Panchromatic data obtained from ALOS PRISM may be applicable, particularly in the monitoring and mapping of frequent illegal domestic waste disposal sites.

The very-high-resolution panchromatic data from the IKONOS remote sensor and similar resolution aerial photography are the most likely of the trialed remote sensors to be of use in monitoring and mapping illegal domestic waste. Therefore, the spatial resolution of the remote sensor is particularly important for any future mapping of illegal waste disposal sites. Based on previous research, a minimum of very high resolution will likely be required.

### *3.2. Applicability of Existing Remote Sensing Analysis Methods for Monitoring and Mapping Illegal Domestic Waste Disposal*

Key considerations in assessing the applicability of existing methods in mapping illegal domestic waste disposal sites in Queensland are effectiveness and efficiency. Visual identification, used in several existing methods, appears to be relatively effective, although there is limited quantification of the accuracy of the resultant mapping. However, visual identification methods are not efficient; they require significant time and human expertise. Given that the intention is to develop a method to regularly monitor and map illegal domestic waste disposal, visual identification will be ill suited for this purpose due to the large resource requirements.

The use of principle component transformation alongside ISODATA unsupervised classification had limited success in identifying illegal waste disposal using data acquired from moderate-resolution remote sensors where land cover was relatively heterogeneous [21]. This does not necessarily preclude this method from being useful for monitoring and mapping illegal domestic waste disposal. The use of a pixel purity index alongside least-square linear mixture to analyze moderate-resolution remote sensing data was not assessed independently from its incorporation into a mixed-method approach. However, based on improvements to the accuracy of the final product, this method should be trialed with higher resolution remote sensing data.

Maximum likelihood classification has been used successful to analyze both digital orthophotos [19] and very high-resolution IKONOS imagery [1] to map illegal waste disposal sites and illegally buried hazardous waste, respectively. It may be possible to apply this method to analyze suitable very high or extremely high resolution data available.

The integration of GIS analysis methods with remote sensing has been demonstrated to improve the accuracy of the resultant maps. Efforts should be made to use a mixed-method approach where additional spatial data is identified as relevant to illegal waste disposal distribution. Improvements in product accuracy will have a significant impact on the usefulness of the final mapping product.

### *3.3. Applicability of New or Upcoming Remote Sensors for Monitoring and Mapping Illegal Domestic Waste Disposal*

Monitoring and/or mapping illegal domestic waste disposal likely requires the interpretation of very high or extremely high spatial resolution data. To date only very high spatial resolution panchromatic data acquired by IKONOS has been trialed for this purpose. There is certainly more remote sensing data of suitable spatial resolution that has yet to be exploited. The higher resolution data is likely to be captured in the future satellite observation missions. The sequential acquisitions of extremely high spatial resolution (*i.e.*, 0.1 meter pixel size) panchromatic and multispectral digital orthophotos provide a prime opportunity to revisit existing methods. The use of very high-resolution data acquired from these satellite sensors could potentially see improvements to the outcomes of existing analysis methods or form the basis of new methodological developments to map illegal domestic waste disposal sites.

The current spaceborne sensors that are capable of acquiring very high spatial resolution data are listed in Table 3. Several sensors are able to provide data with sub-one meter spatial resolutions at several spectral wavelengths [30]. Very high-resolution panchromatic, multispectral, and near-infrared data is currently captured by remote sensors on satellites (e.g., ALOS-2, Cartography Satellite (CARTOSAT) series, COSMO-SkyMed 1-4, Korea Multi-Purpose Satellite (KOMPSAT)-2, 3, and 5, Pleiades 1A and 1B, *etc.*) [30].

**Table 3.** Overview of current spaceborne sensors providing very high spatial resolution data [30].

| | **Sensor Specifications** | | |
|---|---|---|---|
| **Satellite and Sensor** | **Spectral Range (Wavelength Width of Different Frequency Bands)** | **Pixel Size** | **Swatch Width** |
| CARTOSAT-2E Panchromatic Camera (PAN) | 0.5–0.75 μm (panchromatic) | 0.65 m | 9 km |
| Pleiades 1A High-Resolution Imager (HiRI) | 0.47–0.84 μm (panchromatic)<br>0.44–0.54 μm (blue)<br>0.50–0.60 μm (green)<br>0.61–0.71 μm (red)<br>0.77–0.91 μm (near-infrared) | 0.7 m | 20 km |
| Pleiades 1B High-Resolution Imager (HiRI) | 0.47–0.84 μm (panchromatic)<br>0.44–0.54 μm (blue)<br>0.50–0.60 μm (green)<br>0.61–0.71 μm (red)<br>0.77–0.91 μm (near-infrared) | 0.7 m | 20 km |
| KOMPSAT-3 Advanced Electronic Image Scanning System (AEISS) | 0.50–0.90 μm (panchromatic)<br>0.45–0.52 μm (blue)<br>0.52–0.60 μm (green)<br>0.63–0.69 μm (red)<br>0.76–0.90 μm (near-infrared) | 0.8 m (panchromatic)<br>4 m (multispectral) | 15 km |
| Environmental Satellite Resurs: P N1 DK 1 Geoton-L1 | 0.58–0.8 μm (panchromatic)<br>0.45–0.52 μm (blue)<br>0.52–0.60 μm (green)<br>0.61–0.68 μm (red)<br>0.72–0.80 μm (near-infrared)<br>0.80–0.90 μm (near-infrared) | 1 m<br>3 m | |
| Environmental Satellite Resurs: P N2 DK 1 Geoton-L1 | 0.58–0.8 μm (panchromatic)<br>0.45–0.52 μm (blue)<br>0.52–0.60 μm (green)<br>0.61–0.68 μm (red)<br>0.72–0.80 μm (near-infrared)<br>0.80–0.90 μm (near-infrared) | 1 m<br>3 m | |
| Environmental Satellite Resurs: P N3 DK 1 Geoton-L1 | 0.58–0.8 μm (panchromatic)<br>0.45–0.52 μm (blue)<br>0.52–0.60 μm (green)<br>0.61–0.68 μm (red)<br>0.72–0.80 μm (near-infrared)<br>0.80–0.90 μm (near-infrared) | 1 m<br>3 m | |
| KOMPSAT-2 Multi-Spectral Camera (MSC) | 0.50–0.90 μm (panchromatic)<br>0.45–0.52 μm (blue)<br>0.52–0.60 μm (green)<br>0.63–0.69 μm (red)<br>0.76–0.90 μm (near-infrared) | 1 m (panchromatic)<br>4 m (multispectral) | 15 km |

**Table 3.** *Cont.*

| | **Sensor Specifications** | | |
|---|---|---|---|
| **Satellite and Sensor** | **Spectral Range (Wavelength Width of Different Frequency Bands)** | **Pixel Size** | **Swatch Width** |
| CARTOSAT-2 Panchromatic Camera (PAN) | 0.5–0.75 µm (panchromatic) | 1 m | 10 km |
| CARTOSAT-2A Panchromatic Camera (PAN) | 0.5–0.75 µm (panchromatic) | 1 m | 10 km |
| CARTOSAT-2B Panchromatic Camera (PAN) | 0.5–0.75 µm (panchromatic) | 1 m | 10 km |
| ALOS-2 PALSAR-2 | 1270 MHz or 24 cm | 1 m (in spotlight mode) | 25 km (in spotlight mode) |
| COSMO-SkyMed 1-4 Synthetic Aperture Radar (SAR) | 9.6 GHz or 3 cm | 1 m (in spotlight mode) | 10 km (in spotlight mode) |
| KOMPSAT-5 Corea Synthetic Aperture Radar (COSI) | Microwave | 1 m | 100 km |

While current spaceborne remote sensors are unable to rival the spatial resolution of digital aerial orthophotos, advances in technology (whether under development or in planning) mean this technological gap is likely to be narrowed significantly. There are three remote sensors under development (Table 4) that will be able to provide extremely high resolution and very high resolution data when they become operational. The CARTOSAT-3 satellite, planned to be launched in 2018, is expected to capture 0.3-meter spatial resolution panchromatic data [30]. Further extremely high-resolution data may become available depending on the inclusion of planned remote sensors (Table 5) on future earth observation missions. Potential spatial resolutions of up to 0.25 m (microwave X-Band) and 0.5 m (panchromatic) may be possible [30].

**Table 4.** Overview of spaceborne remote sensors under development that would provide high spatial resolution data [30].

| | **Sensor Specifications** | | | |
|---|---|---|---|---|
| **Satellite and Sensor** | **Spectral Range (Wavelength Width of Different Frequency Bands)** | **Pixel Size** | **Swatch Width** | **Launch Date** |
| CARTOSAT-3 Panchromatic Sensor | 0.5–0.75 µm (panchromatic) | 0.3 m | 15 km | 2018 |
| KOMPSAT-3A Advanced Electronic Image Scanning System-A (AEISS-A) | 0.5–0.9 µm (panchromatic)<br>0.45–0.52 µm (blue)<br>0.52–0.60 µm (green)<br>0.63–0.69 µm (red)<br>0.76–0.90 µm (near-infrared) | 0.8 m (panchromatic)<br>4 m (multispectral)<br>5.5 m (near-infrared) | 15 km | December 2014 |
| PAZ X Band Synthetic Aperture Radar (SAR-X) | 9.65 GHz or 3 cm | $<1 \times 1$ m | 5 km | March 2015 |
| Meteor-M Oceanographical Satellite N3 Synthetic Aperture Radar X Band | X-Band | 1 m | 10 km | December 2016 |

**Table 5.** Overview of planned spaceborne remote sensors that would provide high spatial resolution data [30].

| | **Sensor Specifications** | | | |
|---|---|---|---|---|
| **Satellite and Sensor** | **Spectral Range (Wavelength Width of Different Frequency Bands)** | **Pixel Size** | **Swatch Width** | **Launch Date** |
| TerraSAR Next Generation (TSX-NG) X Band Synthetic Aperture Radar | 9.65 GHz–1200 MHz or 3 cm–25 cm | 0.25 m (HR Spotlight mode) | 5 × 10 km (HR Spotlight mode) | 2018 |
| OPtical System for Imagery and Surveillance (OPSIS) Very High Resolution Panchromatic Camera | 0.45–0.90 µm (panchromatic)<br>0.45–0.52 µm (blue)<br>0.52–0.60 µm (green)<br>0.63–0.69 µm (red)<br>0.76–0.90 µm (near-infrared) | 0.5 m (panchromatic)<br>2 m (multispectral) | 10 km | 2017 |
| High Resolution Wide Swath (HRWS) X-Band Digital Beamforming Synthetic Aperture Radar | 9.65 GHz–1200 MHz or 3 cm–25 cm | 0.25 × 0.5 m (VHR mode);<br>0.5 m (HR Stripmap mode)<br>1 m (Stripmap mode) | 10 km (VHR Mode)<br>20 km (HR Stripmap mode)<br>70 km (Stripmap mode) | 2022 |
| Cartography Satellite-2E (CARTOSAT-2E) High Resolution Multi Spectral (HRMX) | VIR and NIR | 0.65 m<br>2 m | 10 km | 2016 |
| HY-3A Synthetic Aperture Radar (WSAR) | 8–12 GHz or 2.5–3.7 cm | 1 m | 40 km | 2015 |
| HY-3B Synthetic Aperture Radar (WSAR) | 8–12 GHz or 2.5–3.7 cm | 1 m | 40 km | 2017 |
| HY-3C Synthetic Aperture Radar (WSAR) | 8–12 GHz or 2.5–3.7 cm | 1 m | 40 km | 2022 |

The most appropriate remote sensor as a data source for the purposes of monitoring and mapping illegal domestic waste disposal will depend on several considerations including balancing spatial resolution, spectral resolution, and temporal resolution requirements. The considerations for selecting an appropriate remote sensor should be driven by waste management needs. Another important consideration will be the cost of data acquisition, which can vary greatly between these options.

## 4. Conclusion

The literature regarding the use of remotely sensed data and data analysis techniques to monitor and map illegal waste disposal sites is currently incomplete. Given the porosity of knowledge and application of this type of work in Australia, the authors reiterate the recommendation of Notarnicola *et al.* [21] that further methodological developments in this space would be beneficial. This is particularly relevant considering the opportunities provided by recent advances in technology and data acquisition. Queensland is well placed to capitalize on the acquisitions of extremely high spatial resolution digital orthophotography for extensive urban areas. This research would represent an important first step in addressing a critical gap in the detection of illegal waste disposal sites and enhance the cost-effectiveness and efficiency of waste management efforts.

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## Author Contributions

Katharine Glanville and Hsing-Chung Chang conceived and designed the review; Katharine Glanville performed the review; Katharine Glanville and Hsing-Chung Chang wrote the paper.

## Conflicts of Interest

The authors declare no conflict of interest.

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