Region-wide estimation of landfill volume changes due to waste disposal, using global digital elevation change maps and landfill location datasets

地域広域における埋立容量の変化推定：全球版標高差図と埋立地データセットの活用

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Graduate School of Environmental Science

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Abstract

Keywords: Waste Management, landfill, Remote Sensing, GIS, Global, Open Data

Often countries don't have adequate systems in place to measure and centrally report waste disposal statistics, yet such data are necessary to inform waste policy and government resource allocation, estimate waste-sector carbon emissions, and are used in some indicators for the Sustainable Development Goals. Waste disposal statistics here refers to measures such as the tonnages of waste disposed in landfills, change in available landfill airspace, the proportion of waste diverted from landfills, the proportion of total waste generated that is collected and managed, etc. Satellite remote sensing has been flagged as a potential approach to help address waste sector data shortages, for example by remotely measuring the amount of waste dumped in landfills. The appeal of such a tool would lie in the ability to remotely and centrally collect waste dumping statistics for entire regions of interest where reported data are missing or unreliable – which could be feasible considering the often global coverage of satellite data products. However, previous studies that investigated the measurement of waste dumping by satellite remote sensing data reported large measurement uncertainties, and were only applied to a small number of case-study landfills (e.g., two or three). Past studies generally used synthetic aperture radar data, coupled with repeat-pass radar interferometry to generate elevation models of target landfill sites at different time points, and then calculated landfill volume changes between those time points. However, due to quick surface changes in landfill sites caused by daily waste disposal and redistribution by compactor vehicles, interferometric processing was strongly affected by a phenomenon known as 'temporal decorrelation', leading to low coherence and large elevation uncertainties in produced elevation maps. However, since the completion of prior studies, missions such as the Tandem-X satellite pair have made single-pass synthetic aperture radar interferometry possible, which is not affected by temporal decorrelation during interferometric processing, and also has global coverage. This thus represents an opportunity to revisit the landfill-dumping measurement problem and address issues identified in earlier work. However, even if a measurement technique could successfully be presented, the extent to which it could be scaled up and used as a tool to collect dumping data over large regions depends entirely on the availability of corresponding landfill location datasets, since landfill locations and perimeter needs to be known before volume changes in the landfill can be measured by remote sensing. Yet, the current availability of landfill location across the world, and the characteristics of the data is still unreported, deeming it difficult, at the outset, to even gauge the possible scope of such a method's usability. Therefore, to promote more complete collection of global waste disposal statistics, this study had two primary research aims: firstly, to evaluate the global availability and quality of landfill location data, since landfill locations need to be known before volume changes can be estimated by remote sensing; and secondly to propose and evaluate a new remote sensing approach for estimating dumping in landfills that has potential to be applied globally, and that has higher accuracy than previous work – achieved by using bistastic synthetic aperture radar derived elevation data.

To address the first aim, a global inventory of publicly available landfill location datasets was compiled and assessed in terms of their data formats, facility types included, number of facilities, etc. The compiled datasets and their attributes are presented, along with maps showing their global spatial footprint. Government compiled datasets were available for 64 countries, and some sub-national jurisdictions, yet these were mostly in the "Global North", while many developing countries had no landfill location data, especially in Africa, the Middle east and Southeast Asia. OpenStreetMap has the largest landfill location dataset (exceeding 51,000 landfills), but global coverage was nevertheless low, with 49% of 11,541 cities not

having any reported landfills in a 30 km vicinity. And, by comparing OpenStreetMap to reference landfill location datasets from around the world (7,132 reference landfills in total) it was found that overall, only 37% of reference landfills were represented in the OpenStreetMap data – indicating low data completeness. Further, 50.7% of OpenStreetMap sites don't have any descriptive information – such as the type of facility or its name – making it difficult to use this data in other analyses.

To address the second aim, a landfill volume change measurement method was proposed that relies on elevation change data from the TanDEM-X satellite mission. In short, measured elevation changes are translated to volume change by multiplication with pixel area size, and the time stamp of the elevation data are used to calculate the rate at which volume changes occur. Waste mass disposed in the landfill is then estimated by multiplying volume changes with an estimate of the density of waste in the landfill. The remotely estimated volume changes had high agreement with in-situ measured data from selected case study landfills in Columbia (97% agreement) and Hong Kong (93% agreement[1]). However, scaling the analysis to 100 landfills around the world showed that temporal coverage of the data product varies between regions, and for 24% of considered sites only a single change measurement could be estimated using the proposed approach. Further, it was observed that the length of time between consecutive elevation measurements is inversely proportional to the error in the volume change estimate. This means that if an application requires higher landfill volume change measurement frequency, there will be a more stringent requirement on the vertical accuracy of input elevation data to achieve the same final volume change accuracy. A code module was developed to enable batch processing and calculation of landfill volume change for many landfill sites simultaneously.

A further case study was used to demonstrate how this proposed technique for estimating waste dumping could supplement existing waste reporting infrastructure, and to assess limitations of the method in an operational setting. The proposed method was applied to all the landfills in South Africa's metropolitan municipalities, and municipality level waste disposal to landfill was estimated and compared to government reported statistics. Measured volume changes had $r = 0.86$ correlation with reported waste mass in 7 reference landfills, and estimated annual waste mass going to landfills at the municipality level had high correlation ($r = 0.92$) with government reported statistics.

The thesis's overall contributions were (1) to show that landfill location data is currently unavailable for many regions, restricting the application of remote sensing based landfill monitoring in those areas; and thus indicating that relevant authorities need to prioritise landfill location data collection and promote public sharing in interoperable data formats. (2) A new approach to measuring landfill volume changes by remote sensing was successfully proposed, which can assist collection of landfill dumping data for currently underreported regions. Further, the method's limitations and possible solutions are clearly presented, to guide further work.

[1] Assuming the same waste density as reported for the Columbia landfill, since the Hong Kong landfill statistics report tonnages, and the relation between tonnage and volume change is not mentioned in the official statistics.

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Chapter 1: General introduction

1.1. A word on definitions and terms

This work is primarily concerned with **landfills**, and their measurement at a global scale. However, especially if considering waste management systems of all different countries, there are many related terms used to describe landfills and waste disposal sites. It is thus important to specify at the outset what is being referred to.

In this thesis I refer to the definition according to the Cambridge English dictionary,

Landfill: the process of getting rid of large amounts of rubbish by burying it, or a place where rubbish is buried

This is thus a broad definition, that does not imply any specific waste type or management approach. It is important to highlight, since several works use the term "landfill" synonymously with "sanitary landfill" or "engineered landfill" and will not, for example, consider a "dumpsite" as a landfill. To illustrate, the Solid Waste Emissions Estimation Tool (SWEET) published by the United States Environmental Protection Agency requires users to classify sites as "Dumpsite" "Controlled Dumpsite" or "Landfill"(US EPA, 2023). However, in this thesis, the term landfill refers to both sanitary landfills, open dumpsites, mining waste dumps (e.g., tailings) and other places where rubbish is buried or dumped. A further glossary with terms and definitions is supplied in Section 1.6.

1.2. Importance of waste data and its applications

Waste dumping data collated at the state, country or regional level are a valuable input for waste management policy processes and are necessary to assess impacts of waste production more broadly (Wilson & Velis, 2015). For instance, temporal data on the amount and types of waste disposed of in landfills assist policy makers to assess the effectiveness of implemented waste reduction policies (DEFF South Africa, 2020). Waste data also aid in allocating appropriate national or municipal resources to the waste sector. For example, a municipality may consult data on the amount of waste being sent to landfill and the remaining available airspace in their current landfill to estimate the time that the site can still be used, and appropriately plan for its closure and replacement. Also, certain United Nations Sustainable Development Goals (SDGs) targets require waste data, such as SDG indicator 11.6.1: *"Proportion of municipal solid waste collected and managed in controlled facilities out of total* *municipal waste generated, by cities"* (United Nations, 2020). These data are collected since understanding waste management practices in a settlement is important for assessing the sustainability and quality of life in the city, due to the wide-ranging health & environmental impacts associated with (incorrect) waste disposal (Siddiqua et al., 2022).

In the last few years, waste data from landfills has also become increasingly important due to its relevance to the estimation of waste sector carbon emissions (Cohen, 2017; Lee et al., 2016). The solid waste sector is understood to contribute significantly to global carbon emissions through methane emitted from waste disposal sites and CO_2 released by open waste burning (Hoy et al., 2023; Wiedinmyer et al., 2014). To more accurately understand the contribution of this sector the global carbon contributions, several countries have initiated projects to monitor methane emissions from landfills, such as the US EPA's Landfill Methane Outreach Program (LMOP) (US EPA, 2017), or the Greenhouse Gas Reporting Program in Canada (Government of Canada, 2025). However, globally a large proportion of final disposal sites for waste do not directly measure methane emissions, due to lacking infrastructure. As result, modelling approaches such as the 'Solid Waste Emissions Estimation Tool' (US EPA, 2023) and the IPCCs First Order Decay Model for estimating methane emissions from waste disposal (Lando et al., 2021). These models require as input estimates of the waste disposal rate at sites, the management method of waste in the city (i.e., amount of waste diverted from landfills, method of disposal and management at landfill) and waste compositions (Sweet v 4.0.5 User Manual). Therefore, data about waste amount being disposed of in landfills are important for carbon emissions estimation.

Waste dumping data are also necessary to study trends in waste management and disposal practices over time, and variation between regions or communities. Understanding these patterns help to clarify the drivers of waste management and disposal practices in different communities, which can in turn be used to improve estimation of waste dumping patterns for areas where measured data is not available, and to predict future waste management scenarios. For example, studies have highlighted the relationship between local waste generation and economic growth. Showing that, in general, economic growth and increases in living standards lead to higher waste generation rates per capita (Sjöström & Östblom, 2010). But, that directed policy interventions can successfully 'de-couple' waste generation and disposal from economic growth, as has been in the case in Europe (Haberl et al., 2020; Inglezakis et al., 2012; Mazzanti, 2008). Waste data can also help show how economic growth and waste policy affect waste disposal practices in specific regions (Okumura et al., 2014). Finally, through a better understanding of the different drivers and factors that affect waste management practices, and how specific policies have affected those patterns, governments are empowered to formulate waste management policies that will accelerate common objectives such as reducing the amount of waste going to landfills, and decoupling waste generation from economic growth.

The importance of waste data can be summarised by the following quote from the UN Data Revolution Report, "*Data are the lifeblood of decision-making and the raw material for accountability. Without high-quality data providing the right information on the right things at the right time, designing, monitoring and evaluating effective policies becomes almost impossible*." (Independent Expert Advisory Group on a Data Revolution for Sustainable Development, 2014, p. 2).

1.1. Global state of waste data, trends and initiatives.

Due to the importance of waste sector data, as elaborated in the previous section, there are a variety of initiatives from both government and non-governmental organizations to compile waste sector data. Since this thesis is concerned with methods for collecting waste management data, it is necessary to map out the existing waste data landscape and point out current shortcomings.

National Waste Inventories

Several, especially high and upper-middle income countries have national waste reporting systems in place, where waste disposal facilities need to be licensed, and need to report their annual disposed waste mass. Examples of such systems are SINIR+ (National System of Information on the Management of Solid Waste) in Brazil, or South Africa's 'SAWIC' (South African Waste Information Centre) which serves as a central repository for waste disposal data and site licenses, or the Annual Waste statistics reports for Hong Kong, published by the Hong Kong Environmental Protection Department (Statistics Unit, Environmental Protection Department, 2021).

Non-Governmental International Waste data collation efforts

There have been several initiatives to collate cross-national datasets of waste generation, disposal patterns, and existing trends. The most recent global effort of which is the Global Waste Management Outlook 2024 report (United Nations Environment Programme, 2024), which is an update to the original Global Outlook (Wilson et al., 2015). These reports collated data from all available country sources, to present a global picture of the state of waste management. However, both reports point out that reliable data at the global scale is currently lacking. In the 2024 report: "*Some countries have no official waste data whatsoever, or this data may be incomplete or inaccurate. The use of different methodologies can also make comparisons challenging*" (United Nations Environment Programme, 2024, p. 17). The data issue was so significant that the authors of the first global waste outlook published an accompanying 'calling to action' article, in which it was stated as follows:

"*How much waste is generated around the World? In trying to answer this apparently simple question, the GWMO team rapidly identified one of their key conclusions and recommendations: That availability and reliability of waste and resource data is dire, and urgently needs attention.*" (Wilson & Velis, 2015)

However, despite a decade passing since Wilson & Velis's striking observations, the current statistics of waste dumping around the world are still inadequate, due to issues like non-standardized waste measurement methods and differing definitions, lack of systems to monitor waste dumping (particularly in developing regions), and lack of transparency in reporting (Maalouf & Agamuthu, 2023). As a result, efforts to calculate global waste statistics often need to rely on outdated waste data, or data that are based on estimations instead of measurement. It is telling that the most recent 2024 global report had to use the year 2020 as a base-line year for the report citing that the majority of countries' waste data was dated earlier than 2020. So that in effect, the 2024 global report primarily used the same data sources as the What a Waste 2.0 global World Bank report, which was published 6 years earlier (Kaza et al., 2018). Other challenges faced in terms of waste statistics are discussed in (United Nations Economic Commission for Europe, 2022).

In response to the identified lack of waste statistics, there are several initiatives to improve the state of waste collection data around the world. Frameworks to improve waste reporting and the quality of data are also being developed by individual countries, and internationally (United Nations Economic Commission for Europe, 2022). Internationally there has been a push for standardization of definitions and measurement (Maalouf & Agamuthu, 2023; United Nations Environment Programme, 2024). There are also non-government efforts to facility collection of standardised waste data such as the Waste Wise Cities Tool published by UN Habitat, which is a tool to help city governments to collect meaningful municipal solid waste data (UN-Habitat, 2021). At the time of writing, this project showed participation from 54 cities globally[2], but a

[2] https://unh.rwm.global/Map

number of which have no submitted data, and available data is mostly not more recent than 2021, suggesting that the project has stalled to some extent. Another notable global efforts has been the global 'Waste Atlas' , which used crowd-sourcing and other approaches to gather global level waste data (D-Waste, n.d.). However, the most recent publications from the project were in 2014, and repeated attempts at correspondence with the project from the author (me) failed, suggesting that the Waste Atlas project may also not be currently maintained.

For regional/global waste studies, one approach to side-step the unreliability or unavailability of waste dumping statistics has been to rely on 'Material Flow Accounting'. In this approach, the amount of waste generated is not measured directly, but estimated by modelling the flow of materials from their extraction, to being produced/traded, etc., and finally disposed as waste. By material flow accounting based methods, recent studies have estimated regional and global waste production, and also how waste production has changed historically (Krausmann et al., 2018). Still, this approach does not substitute actual waste production and dumping statistics, and since the flow of materials to waste is not directly tracked, Material Flow Accounting can also not give insights to realized waste dumping dynamics e.g., between different cities, or for landfill sites, but is more appropriate for understanding regional or global waste dynamics.

As introduced earlier, there are also several national and international initiatives to support collection of waste sector carbon emissions, spearheaded by organisation like the Global Methane Initiative (GMI) and the Clean Air Task force, culminating in tools like WasteMAP, short for 'Waste Methane Assessment Platform' (RMI & Clean Air Task Force, 2023), or the waste sector carbon inventory by the 'Climate Trace'(Climate Trace, 2024). Such international efforts are informed again by national projects to monitor waste sector emissions, such as the US EPA's Landfill Methane Outreach Program (LMOP) or the similar GHGRP program in Canada (Government of Canada, 2025). But, such direct measurement programs are the exception, so for the majority of countries a variety of estimation and modelling based approaches are employed to estimate waste sector carbon emissions (Krsna Raniga, 2024).

1.2. Remote Sensing in Waste Management

Considering the existing gap in waste data reporting infrastructure, it is necessary to also consider alternative avenues of data collection, such as satellite radar and imagery data (i.e., remote sensing data). Remote sensing based methods have recently been flagged as a research priority within the waste management sector, thanks to its potential for filling waste data gaps, and assisting with identification of illegal waste disposal sites, and other applications (United

Nations Economic Commission for Europe, 2022).This doctoral study is indeed also one part of the larger effort to let remote sensing and geo-analysis techniques bring value to the waste management sector, and thus it is appropriate to present a brief history and current overview of the field. For further reference, the reader my refer to the review by Papale et al. (2023).

Since the initial years of satellite remote sensing science, the possible applications to the waste sector were recognised. In 1973, data from the Earth Resources Technology Satellite (ERTS-1) was used to assess the effects of ocean-waste dumping by showing how large areas of ocean water was affected, and mapping the distribution of sewage sludge, acids, and suspended waste solids in the New York Bight (Wezernak & Thomson, 1973). Since then, remote sensing has been used in several applications, which are summarised in Table 1-1.

Table 1-1 Summary of the applications of Remote Sensing to landfill monitoring

Application	Source
Satellite imagery help cartographers to outline landfill boundaries in land use maps	(European Environment Agency, 2019)
Identify and map illegal landfills by probability and machine-learning based approaches	(Glanville & Chang, 2015; Karimi et al., 2022; Krtalić et al., 2018; Selani, 2017; Torres & Fraternali, 2021)
Automatic identification of landfills by deep-learning imagery classification	(Kruse et al., 2023; Luong Nguyen & Tram-Anh Pham, 2022; Sun et al., 2023)
Assessment of landfill environmental impacts	(Foody & Embashi, 1995; Splajt et al., 2003; K. Yang et al., 2008)
Landfill subsidence measurement by DInSAR	(Baek et al., 2019; Milillo et al., 2015)
Landfill volumetric changes measurement by drone	(Filkin et al., 2022; Incekara et al., 2019)
Landfill volumetric changes measurement by satellite	(Cadau et al., 2014; Karathanassi et al., 2012; Louw & Avtar, 2025; van Zyl & Celik, 2021)
Describing and monitoring of landfill surface properties	(Gill et al., 2019; Nazari et al., 2020; Pasternak et al., 2023)
Measurement of air pollution and greenhouse gas emissions from landfills	(Cusworth et al., 2020; Duren et al., 2019; Maasakkers et al., 2022; Wiedinmyer et al., 2014)

Although remote sensing has been applied to landfill-related research studies for a number of decades, efforts to use it in an 'operational capacity', i.e., to actively support the activities of local government or environmental non-profits have only recently started to increase, along with the recent growth in remote sensing data quality, quantity, and infrastructure to disseminate and interpret the data (i.e., reliable high-bandwidth internet, increased computing resources, cloud based geo-data processing, and artificial intelligence tools).

The use-cases that appear to have shown most promise for operational applications have historically been to use aerial imagery data to help manually identify landfills and delineation their boundaries. For example the Corine 2018 landcover map of Europe has a ‘dumpsite” landuse class, which was produced by using existing landfill spatial datasets from local authorities, to pointpoint sites, followed by visual interpretation of satellite imagery and manual digitization of landfill boundaries by a GIS team (European Environment Agency, 2019). Further, imagery has been a valuable data source to help locate illegal landfills and small/informal dumpsites (Torres & Fraternali, 2021). For such applications, machine learning and deep learning are increasingly being used. For example, the global plastic watch initiative recently presented a tool that uses deep learning to identify the location and perimeter of plastic dumpsites, as well as the spatial growth of the site over time by using time series satellite imagery (Kruse et al., 2023). The related work by Torres et al. have also led to the publication of large landfill imagery datasets, which are made available and aim to further enable deep-learning based landfill classification models (Torres & Fraternali, 2023).

One of the applications that have received the most attention recently, however, is the monitoring of methane emissions from landfills by satellite. Several high-profile works have used remotely measured methane emissions data to estimate facility level point-source emissions – showing that actual emissions often surpass that reported by facilities (Cusworth et al., 2020; Maasakkers et al., 2022). Due to the large global interest in quantifying carbon budgets (Friedlingstein et al., 2025), but simultaneous lack of facility level emissions measurements for many methane emitting facilities around the world, there has been an increased drive to operationalize the remote sensing based monitoring of carbon emissions, through initiatives like MethaneSAT (Environmental Defense Fund, 2025). However, not being the primary focus of this research, a further elaboration of the topic is omitted here.

We progress then next to applications that are more closely related to the work to be presented in this thesis, namely, the use of remote sensing data to measure surface changes in landfill sites such decrease in the available landfill airspace, or subsidence caused by the natural compression of waste over time. Although historically calculated by surveying, the volume of landfills and the change in available airspace is increasingly being estimated from data obtained from unmanned aerial vehicle photogrammetry (Filkin et al., 2022; Sliusar et al., 2022), or aircraft borne LiDAR data[3]. However, commissioning aerial LiDAR surveys to map landfill volume changes is not feasible for many local waste authorities or landfill operators, who often struggle with limited financial resources. Small scale (cm scale) surface changes in landfills such as subsidence caused by the compression of waste has been measured by SBAS DInSAR (or, Short Baseline Subset Differential SAR Interferometry) (Baek et al., 2019) – a methodology commonly used in the study of small earth surface deformations due to earthquakes or volcano, or peat subsidence (Li et al., 2022). SBAS DInSAR has also been applied once to estimate the rate of waste disposal in landfills (van Zyl & Celik, 2021). This study reported a positive outcome, and is thus directly relevant to the current study. Therefore, the author spent significant effort to replicate the results reported by van Zyl, yet without success. There are relatively large daily changes in landfill sites, which seems to lead to low coherence and inaccurate SBAS results. Further, SBAS processing for even a single landfill requires a dense time-series of SAR images, leading to high requirements on internet bandwidth, storage space and computing resources. These considerations make this approach particularly non-ideal for cases where monitoring need to be scaled to many landfills in different locations. Finally, this leads us to another method proposed to measure volume changes in landfills, namely DEM differencing of DEMs produced for different times by InSAR processing. This approach would only require InSAR processing of 2 SAR pairs at different times, leading to lower computational requirements. The past work on this approach, their shortcomings and its relevance to the current study are introduced in the following "Research Gaps" section, and in more detail in Section 3.1.

1.3. Research gaps

One remote sensing application that has significant operational-use potential in landfills but has not been realised at current is the accurate measurement of waste dumping rates by satellite in a way that is scalable to wide regions. Existing studies demonstrated limited success in measuring volumetric changes in individual landfill sites by subtracting digital elevation models generated at separate time points, and then using the measured elevation change between the time points to calculating the volume changes in the landfill. However, the technique used in prior studies (Repeat-Pass Interferometry) was subject to a phenomena known as temporal-decorrelation which severely affected the measurement accuracy in

[3] Personal communication with representatives of a landfill management company at the International Solid Waste Association World Congress 2024 in Cape Town.

landfills, and finally rendered the approach unsuitable for use (Cadau et al., 2013, 2014; Karathanassi et al., 2012). This is described more thoroughly in Section 3.1

However, a satellite data based approach that is sufficiently accurate to be used for dumping statistics reporting and also scalable to wide regions is very desirable, due to its potential for bridging existing global landfill dumping data gaps, as explained in section 1.1. One research gap addressed by this study is therefore the development and assessment of a new satellite data based approach for remotely measuring landfill dumping volumes. This new approach relies on a type of Synthetic Aperture Radar (SAR) data that is not susceptible to temporal decorrelation during interferometric processing, as was the case in previous related studies. The new SAR data was released after the previous Radar landfill volume studies, and its unique properties warrant a revisit to the issue.

Secondly, during this work it quickly became apparent that, even if a measurement method could be successfully developed, to truly realise 'region wide' monitoring of landfill dumping volume it would be necessary to also know the spatial location and perimeter of all the landfills in that region. This is not only true of the dumping volume measurement application, but also the majority of other remote sensing based landfill monitoring applications. For example, point source measurement of methane emissions from satellite or aircraft also first requires a spatial database of the location of target infrastructures (Duren et al., 2019).

Realising the importance of landfill location spatial data to remote sensing based landfill monitoring, the second research gap addressed by this study then became the assessment of the current state of global landfill location data. Where is landfill location data stored, and what is the global coverage of such datasets? What are the data characteristics, such as available site attributes data, the format of the data (site points, perimeter polygons, table with addresses), and the current trends in data gathering methods, such as crowd sourcing, or landfill classification by deep-learning from satellite images. What government policies or non-governmental activities could promote the accessibility and quality of landfill location data? Historically remote-sensing landfill studies have focused on individual, or a small number of known case-study sites, and demonstrated the applicability of some remote sensing based technique in those sites (Karathanassi et al., 2012; Nazari et al., 2020; van Zyl & Celik, 2021). However, as the focus shifts to the use of remote sensing as a scalable tool to monitor landfill sites across a country or region, the availability and usability of site location data becomes a central issue.

1.4. Objectives of the study

Considering the research gaps explained in the previous section, this study had the following objectives:

Objective 1: Clarify the current state of waste disposal site location data globally, due to the relevance of such data to remote sensing based monitoring of landfills. Here 'the state' includes the spatial coverage and completeness across regions, the format of the data and thus potential for further use. It also includes understanding data sources, and trends of landfill location data collection (such as increased use of machine learning based classification and crowd sourcing). This is achieved by two sub-objectives:

- Systematic compilation of all publicly available landfill location datasets, and assessment of their data formats, included facility types, spatial coverage, etc.
- More detailed assessment of the landfill location data in OpenStreetMap, to determine to what extent it can be used as data source for regional remote sensing based landfill volume change measurement. This assessment needs to clarify the data completeness, global coverage, and availability of descriptive site data for OpenStreetMap landfills.

Objective 2: Present and evaluate a methodology for estimating landfill volume changes that uses Single-Pass InSAR based DEM data, which can be applied globally.

- The **presentation** includes a description of source data structure, mathematical description of the volume change measurement technique, mathematical derivation of appropriate error propagation methods, and finally implementation of the methodology into a software module using the R programming language.
- The **evaluation** includes applying the developed methodology to landfills with known dumping statistics, to allow for accuracy validation; Assessing the temporal coverage and frequency of the volume estimates in landfills around the world; and

Objective 3: Demonstrate how the proposed method may serve as a tool to support existing waste reporting systems by – as case study – applying the developed landfill volume estimation technique to all landfills within a region to estimate overall waste dumping remotely, and then comparing the findings to the existing reported data for the region.

Objective 4: Considering the outcomes of the above objectives, point out important caveats that hinder the application of the method, and highlight the potential of using remote sensing techniques to measure dumping in landfill. Give suggestions that may help steer further research efforts.

Overall, these objectives contribute to the central aim of improving landfill waste disposal data at the global level, which is currently lacking for many regions around the world.

1.5. Outline of the thesis

To address the five stated objectives, the remainder of this thesis is structured as follows, with summary in Figure 1-1:

Chapter 2: Assessment of landfill location datasets globally. This includes a compilation of both government and non-governmental data sources. The chapter aims to show which regions in the world have data on the location of landfills, and what the format of those data are (e.g., tables with site coordinates, web maps, or vector files, etc.). A data table of all the compiled data sources, and accompanying information is also given in Annexure I:. The chapter also further shows the detailed analysis of the OpenStreetMap landfill dataset, to address the second component of objective 1.

Chapter 3: The landfill volume estimation methodology is presented and evaluated, to address objective 2. The method is applied to 100 landfills around the world, and the temporal coverage of the volume estimates in the sites is noted, to determine the time period for which dumping statistics can be estimated using the described methodology and source data. The methodology is also applied to three case study landfills with corresponding in-situ data, acquired from the local authorities used to validate the remote sensing based method. Additional analyses are also presented in Annexure II:.

Chapter 4: To demonstrate the use of the methodology from chapter 3 as a landfill monitoring tool for a country or region, it is applied to all 42 landfill sites in South Africa's 8 metropolitan municipalities. Using a proposed method for determining the relationship between volume changes and actual dumped waste mass, the waste mass in each municipality is estimated and finally compared to officially reported statistics from the South African Waste Information Centre. Through this case study in South Africa, objective 3 is addressed. Several possible considerations and issues that hamper the usability of the method in operational settings are also identified, which are then further elaborated in chapter 5.

Chapter 5: This chapter reflects on the research contributions presented in this study, as perceived by the author. It further highlights several issues with the proposed methodology, which requires further refinement and inclusion of alternative elevation data sources.

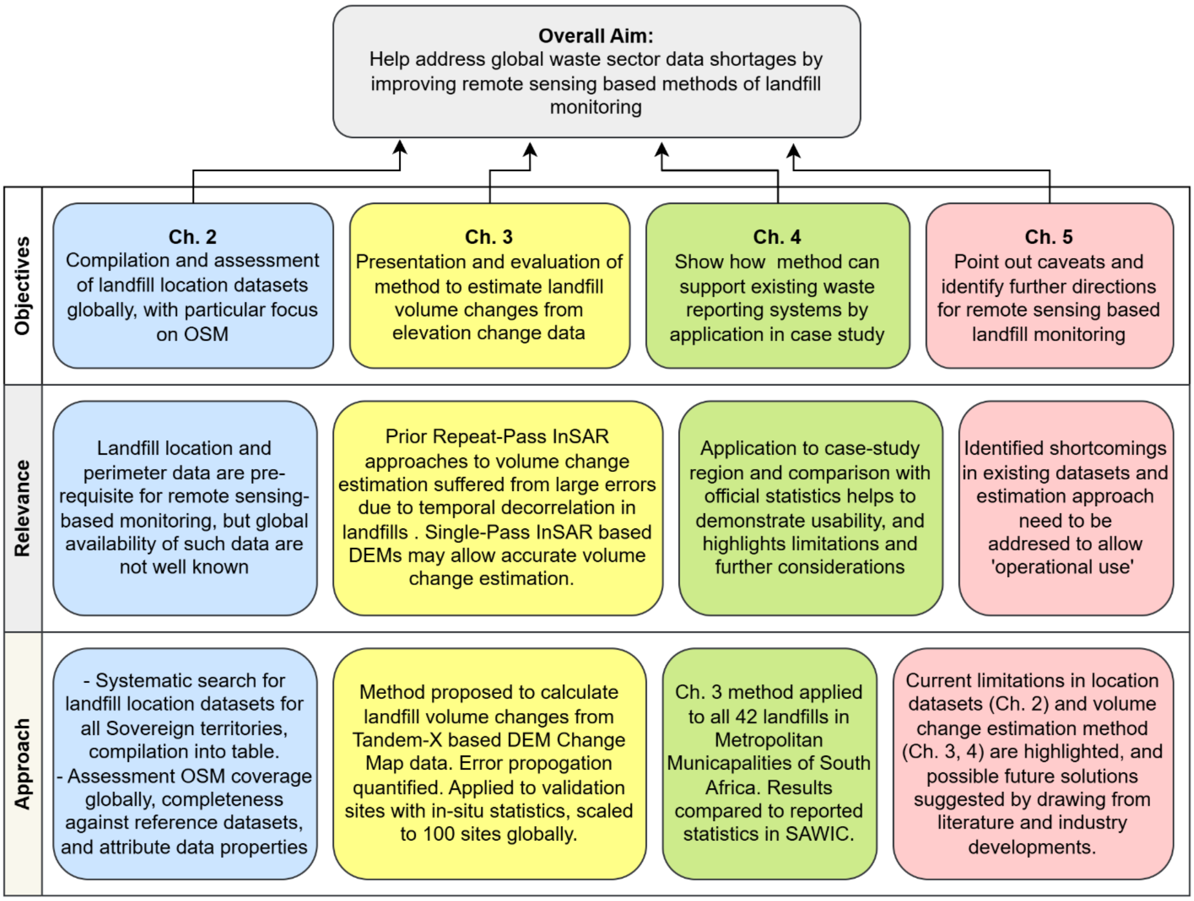

Figure 1-1 Outline of thesis objectives and chapter contents.

1.6. Glossary of terms

Landfill: broadly, a place where rubbish is buried. In this work it refers to both informal waste disposal sites such as open waste dumps, engineered municipal landfill sites, and also waste disposal sites for other waste streams, such as mine tailings facilities, coal combustion residual (CCR) landfills, and nuclear waste sites, etc.

Sanitary landfill: An engineered method of disposing of solid waste on land in a manner that protects the environment, by spreading the waste in thin layers, compacting it to the smallest practical volume and covering it with compacted soil by the end of each working day or at more frequent intervals if necessary.(European Environment Agency, 2021)

(Open) Dumpsite: landfill where solid waste is deposited without planning and consideration for environmental and health standards and are illegal to establish or operate. (Infoscipedia, 2025)

Synthetic Aperture Radar (SAR): "…a type of active data collection where an instrument sends out a pulse of energy and then records the amount of that energy reflected back after it interacts with Earth. Unlike optical imagery, which is a passive data collection technique based on emitted energy, SAR imagery is created from the reaction of an emitted pulse of energy with physical structures (like mountains, forests, and sea ice) and conditions like soil moisture." (Earth Science Data Systems, 2021)

SAR Interferometry: Techniques for mapping ground deformation or topography, which uses multiple SAR images of the same location, but captured from different vantage points.

Chapter 2: A Collation of global landfill location datasets, and further assessment of the completeness and quality of landfill data in OpenStreetMap

2.1. Introduction

Datasets containing the spatial locations and characteristics of landfill and dumping sites can contribute to our understanding of the impacts of waste management practices in different regions and countries (Benedine et al., 2011; Sun et al., 2023). For example, geographic data of landfills for specific regions have been used to evaluate the health impacts of landfills, their impacts on environment, education and property value (Benedine et al., 2011; Elliott et al., 2009; Mahmood et al., 2019; Vrijheid, 2000). Datasets on the location of landfills are also used in studies assessing the drivers of waste dumping patterns (Antczak, 2020; Syafrudin et al., 2023). Studies that use remote sensing data to quantify greenhouse gas emissions from landfill or dumpsites (Cusworth et al., 2020; Maasakkers et al., 2022), or estimate volumes of waste dumped (Louw & Avtar, 2025) also require firstly the spatial location of the relevant sites. It is thus clear that location data of landfills are an important input for several climate, environment and waste management research objectives.

It is known that some countries maintain spatial databases of permitted landfills (Environment Agency, 2024; Geoscience Australia, 2022; US EPA, 2024), whereas other countries report number of landfills for administrative jurisdictions (Rajya Sabha, 2024). There are also non-government organizations (NGOs) that compile landfill site data as in the 'Global Waste Atlas' (D-Waste, n.d.). Recent studies explored machine vision models to automatically detect landfills and illegal dumpsites from high resolution satellite or aerial imagery (Selani, 2017; Sun et al., 2023; Torres & Fraternali, 2021). NGOs such as the "Global Plastic Watch" have also attempted to use machine learning based imagery classification to identify dump sites across the world, although in selected countries (Kruse et al., 2023; Minderoo Foundation, 2024). To the author's knowledge, there is however no assessment of the global state of landfill location data, i.e., who stores data, its format, available site description data in existing datasets, the spatial footprint/global coverage of landfill location datasets.

OpenStreetMap (OSM) may be one valuable source of global landfill location data. OSM is a global geographic dataset that is actively compiled by volunteer contributors. Contributors can annotate roads, buildings, amenities and land use classes. The locations of landfills and other waste management infrastructure can also be explicitly annotated in OSM (OpenStreetMap

Wiki, 2023b). As of February 2025, the OSM dataset contained already 54,000 features tagged as “landfill” (OpenStreetMap Wiki, 2023a). This thus represents a significant possible source of landfill location data. Moreover, since OSM is a volunteer contributed dataset, informal and illegal dumping sites can be captured in the dataset by volunteers who are aware of the sites, while official government-maintained datasets typically only contain data on permitted landfills. Therefore, since OSM contain a large “landfill” database, makes provision for annotation of important site attributes, and can include informal and illegal dumps overlooked by official databases, it may be a promising source of global landfill and dumpsite location data.

However, the completeness and accuracy of data in OSM is often brought under question, since the dataset relies on volunteer contributions (Haklay, 2010). Studies have evaluated the completeness and accuracy of different components of the OSM dataset for specific countries or regions (e.g. road networks (Nasiri et al., 2018), building data (Tian et al., 2019) and broad land-use cover classes (Zhou et al., 2019)). These studies often evaluated OSM data against official reference datasets, considered to be accurate (Dorn et al., 2015; Girres & Touya, 2010). However, since reference datasets are not always obtainable, intrinsic data quality metrics, such as saturation in the number of new contributions over time, have also been proposed (Gröchenig et al., 2014). The regional disparities in OSM data quality, and the socio-economic and other factors that correlate with those disparities have also been investigated (Herfort et al., 2023). But the accuracy, completeness and other attributes of the “landfill” and other waste management related spatial data present in OSM have not specifically been evaluated.

The objectives of this study was:

1. To clarify the current state of waste disposal site location data globally, due to the relevance of such data to remote sensing based monitoring of landfills. Information on all publicly available datasets were compiled (to author’s knowledge).
2. Further evaluate the OSM landfill dataset, being the largest single waste disposal site dataset, by assessing its global distribution and coverage, its completeness for regions where reference datasets where available, and the type of landfills and available descriptive metadata that is provided for sites.

2.2. Methodology

2.2.1. Definitions

During the collation of landfill datasets from different countries, it was found that landfill location data were sometimes part of larger waste management infrastructure datasets that included a range of facility types, not all of which are strictly landfills (for example, transfer stations, or recycling facilities). Where possible, datasets were filtered to include only landfills, according to the definition explained in Section 1.1. Such a broad definition for landfill was considered, partially because of the ambiguity of the meaning of more specific terms in different datasets. For example, I encountered a range of related terms with probably partially overlapping meanings, such as ‘landfill’, ‘engineered landfill’, ‘controlled landfill’, ‘dump’, ‘open dump’, ‘dump site’, ‘waste facility’, ‘extractive waste facility’, and definitions that described waste type received (e.g., inert waste landfill, C&D landfill, MSW landfill, solid waste landfill, ‘tailings’, ‘ash dump’, etc.). To deal with the difficulties of definitions and differences between datasets, I opted to include a broad range of facilities that could be considered landfill sites, according to the dictionary definition. This was also helpful, since the work focused largely on assessing the OpenStreetMap dataset, which has a broad but specific definition for ‘landfill’. So, it was preferable to include a broad ‘landfill’ definition when comparing all the different datasets.

A landfill is described in the OpenStreetMap Wiki as "A site for permanent or long-term storage of waste materials. Also known as a tip, dump, rubbish dump or dumping ground and historically as a midden" (OpenStreetMap Wiki, 2023a). The definition includes active and disused landfill sites, given the landfill feature is still visible on the ground. Both sanitary landfills and open dumpsites, fall under the “Landfill” class. The landfill type (sanitary, or open dump), whether it is an active or closed site, the waste type received by the site (e.g., Municipal Solid Waste, Hazardous waste, nuclear waste, mining ash or sludge, etc.) can further be specified by the contributor, but is not required.

2.2.2. Waste disposal site location data collation

Landfill location datasets were compiled by Google search queries for each country or sovereign state (Administrative level 0) in the Database of Global Administrative Areas (GADM 4.1). I used variations of search terms such as ‘landfill location dataset <country name>’; “the location of dumpsites in <country name>”, etc., for each country, including search terms translated to the local language of the area. If government open data portals where found, these were separately searched for landfill location data. Data sources where the location of landfill sites could be determined where considered, such as, point or polygon vector data formats, or tables (csv or excel file formats) with coordinates or physical addresses of sites. In the case where only site addresses were available, reverse geo-location was used to turn the data into a spatial data format for further analysis. Although most countries had waste sector data available in waste sector reports (pdf format), these were not considered if the location of specific landfills could not be determined. Some countries have platforms to request data from government, which could potentially be used to obtain relevant data that is not publicly available on the internet. However, such services were not made use of, and thus only datasets already findable on the internet were reported on. The datasets, their attributes and where they can be found were compiled in Annexure I:, and their spatial coverage illustrated on a world map.

2.2.3. OpenStreetMap Data access

The complete global dataset of OSM features tagged with land-use as "landfill" was downloaded in October 2024, and again on 14 January 2025 using Overpass Turbo (OpenStreetMap Wiki, 2024), which is a webpage that allows for specifying queries to the OpenStreetMap database through Overpass. The OSM dataset is constantly updated by contributors, but changes are considered small enough to deem the current analysis a meaningful representation of the general condition of the dataset.

2.2.4. Assessment of OSM landfill dataset

One objective of this study was to evaluate the global coverage and data completeness of the OSM landfill dataset. The author further evaluated the use of tags to describe the sites in the dataset.

2.2.4.1. Global Coverage

As indicator of the OSM landfill dataset's global coverage, I calculated the number of OSM landfills within a 30 km radius of the boundary of urban centres (dense large settlements). It is assumed that dense large settlements have waste disposal facilities, so if there are no waste disposal sites reported around a settlement, it indicates a lack of coverage in the OSM dataset. A dense large settlement or 'Urban Centre' is defined as a settlement that consists of contiguous grid cells with a density of at least 1,500 inhabitants per km^2 of permanent land, and has at least 50,000 inhabitants, according to the Degree of Urbanization definition (Eurostat, n.d.). All urban centres were taken from the Global Human Settlement Layer (GHSL) Settlement Model

Grid dataset (GHS-SMOD R2023A) (M. Schiavina et al., 2023) , and totalled 11,541 settlements.

2.2.4.2. Completeness

The described approach for assessing the OSM landfill global coverage does not measure the completeness of the data, since it does not consider the actual number of waste disposal sites in an area. However, the OSM definition for landfill is wide, including mining disposal sites, open dumps, and small informal waste disposal sites. This complicates comparison of OSM data with official waste disposal site datasets, which typically include permitted/licensed waste management facilities such as engineered landfills that are operated by municipalities or contracted companies. However, as indicator of the completeness of the municipal landfill subset of the OSM dataset, I used spatial filtering predicates to determine the proportion of reference landfill sites that were also included in the OSM dataset. To achieve this, reference data on the spatial location of landfills, were collated from eight landfill location datasets from different continents and regions equalling 7132 sites. A spatial intersection was used to calculate the proportion of reference waste disposal sites that were also present in the OSM dataset. However, to account for slight spatial mismatches in the geolocation data, a buffer distance of 1km for point location reference data, and 100 m for polygon reference data were allowed.

2.2.4.3. Accuracy

To quantify the accuracy of the OSM landfill dataset, a global sample of 300 sites were manually classified by a team of annotators as landfill or not, according to the OSM landfill definition. A spatially balanced (Stevens Jr. & Olsen, 2004) sampling approach was used to account for possible spatially dependent factors like within-country spatial income inequalities, and urban-rural differences in population density and number of OSM contributors. The sample was further stratified according to the world bank country income class of the country, since the quality of OSM data may vary by country income and development level(Herfort et al., 2023). This described sampling scheme allows for 5.9% margin of error at 95% confidence interval for population proportion as sample statistic (Berman, n.d.). Here, the target proportion metric was the proportion of sites correctly classified with the land-use tag ‘landfill’, according to the OSM definition. Sampling was implemented using the Generalized Random Tessellation Stratified (GRTS) algorithm from the R package *spsurvey* (Dumelle et al., 2023).

2.2.4.4. Descriptive tag analysis

OSM features are described by combinations of tag:value pairs, such as “landuse:landfill”, “waste_type:construction”, “disused:no”, etc. I extracted the number and types of tags, and analysed their frequencies and values, grouping results by World Bank country income classes.

2.3. Results

2.3.1. Overview of landfill location datasets

A full table with datasets, their coverage, method of compilation, number of included sites is given in Annexure I:. In summary, official (government) compiled sources included landfill location datasets for 64 countries, although several countries without national reported data had landfill location data for sub-national jurisdictions, reported by city or provincial governments. The spatial coverage of these datasets are mapped in Figure 2-1. Countries with publicly available landfill location datasets where often the countries with open data sharing platforms or geo-data portals. The data locations were reported in spatial formats, or tables that include physical addresses column or latitude-longitude columns. However, different countries’ databases had differing facility types included, and often unclear definitions, which complicates comparison and collation of the datasets (further described in Methodology section).

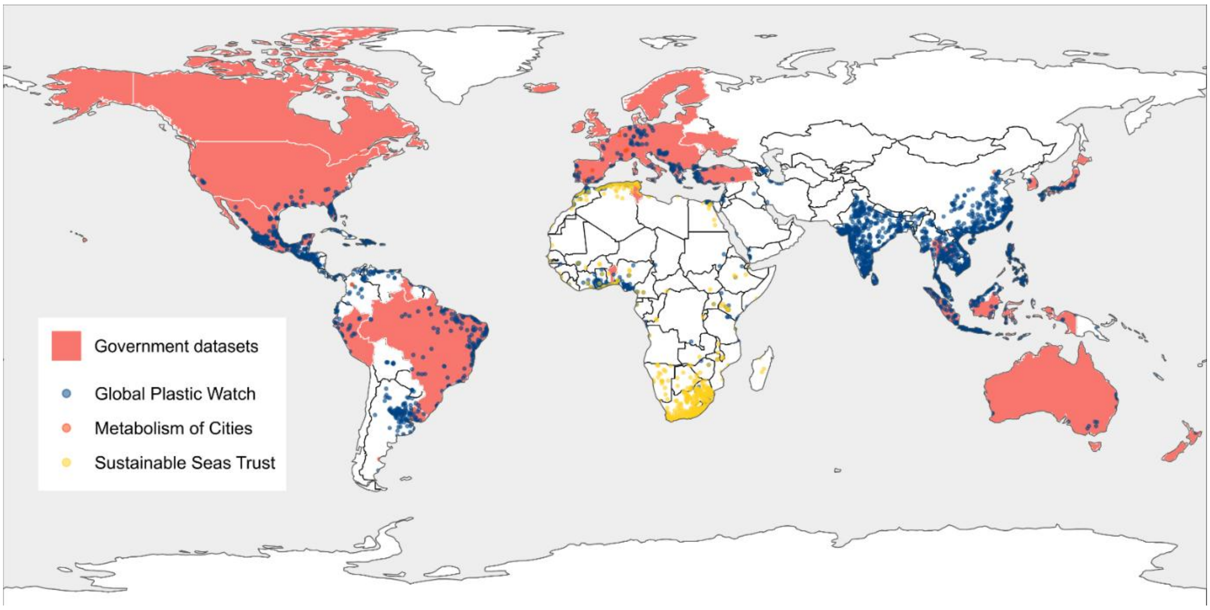

Figure 2-1 Global spatial footprint of landfill location datasets maintained by government (red polygons), and cross-national datasets compiled by non-profit organizations (actual site locations shown as points, with point colour denoting the dataset). Full list of datasets in Annexure I:.

In Africa, although very few governments publish landfill location data, a continent-wide landfill dataset (n = 612) has been compiled by the Sustainable Seas Trust" non-profit organization. However, the sites in this dataset are mostly located in South Africa, with limited coverage in other African countries (yellow points, Figure 1). Another non-profit, the Global Plastic Watch, used deep-learning classification on satellite imagery to identify 4,317 plastic dumpsites globally, but this dataset's coverage is mainly in the Indian sub-continent, China, and some areas in central and South America (blue points on the world map in Figure 1). There are cross-border open data initiatives that facilitate the central sharing of datasets like landfill locations, such as the "Metabolism of Cities" initiative (global, city level)(Metabolism of Cities, n.d.), the Pacific Environmental Data Portal (Pacific Island Countries), OpenAfrica (*openAFRICA*, n.d.), the 'Open Development Mekong' data portal for countries in the Mekong Delta(Open Development Mekong, n.d.), and the INSPIRE Geodata portal in Europe(INSPIRE Geoportal, n.d.). But, despite the sharing infrastructure being available, most countries do not use such platforms to publish landfill datasets. For example, of the six countries contributing to the Mekong data portal, only Thailand published landfill location data, and for the OpenAfrica portal, only Benin listed landfill location data (Annexure I:).

2.3.2. OpenStreetMap global coverage and characteristics

The OSM landfill dataset has a global footprint, but the local availability of data depends on contributions by volunteers, so data coverage may vary by regions. Without reference data, the true coverage and completeness of the landfill dataset cannot be determined. However, the author postulates that all cities have waste disposal sites. And thus, the absence of any waste disposal facilities in the OSM dataset within reasonable vicinity of a city suggest that the dataset is incomplete locally. In an analysis of 11,541 cities ('urban centres', by the degree of Urbanization definition(Eurostat, n.d.)) around the world, 49% had no OSM landfill within 30 km of the settlement's borders (Figure 2-2). These settlements without OSM landfills are mostly in Africa, Central Asia, and some parts of Southeast Asia. On the contrary, in large areas of North America, Europe and Australia, urban centres on average have 4 or more OSM landfills within 30 km of the settlement border.

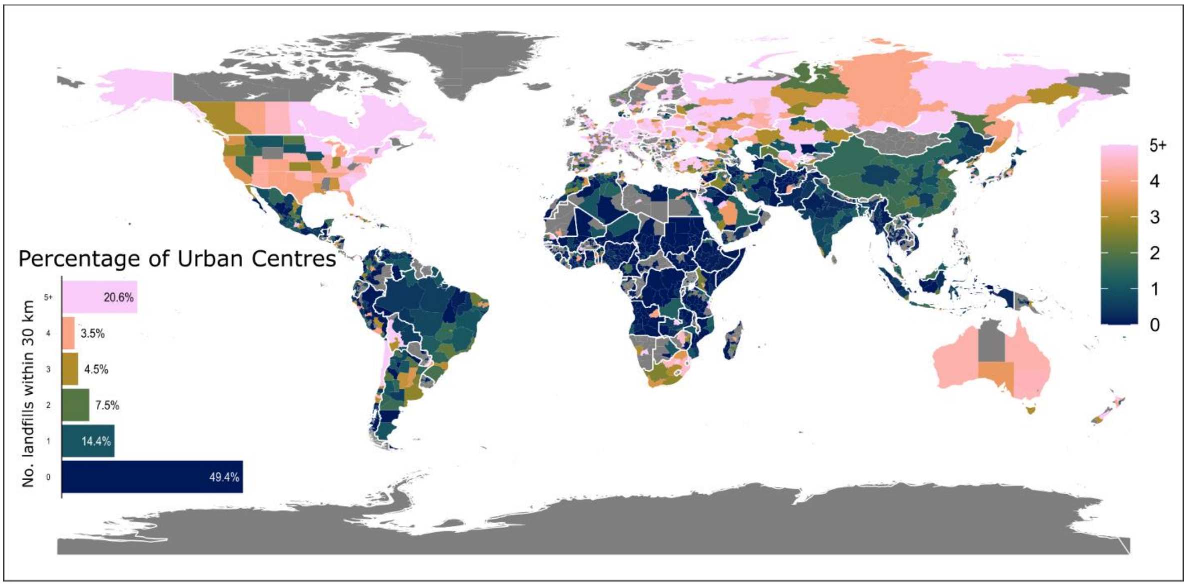

Figure 2-2 Number of landfills in the OpenStreetMap dataset within 30 km of Urban Centres (degree of Urbanization definition, n = 11,541). The world map reports the average aggregated to level 1 administrative units, to avoid overplotting. The inset column chart shows a global summary.

A quick glance at the World map of OSM coverage suggests a general pattern of data shortage in the 'Global South', while the 'Global North' has better OSM coverage (Where Global South refers broadly to more developing, or poorer regions of the world, such as Africa, South and Southeast Asia, the Caribean, etc. For a more detailed discussion on the global south, the reader can refer to Hollington et al. (2015)) . This general pattern can be validated if comparing countries while grouping them by the World Bank's country income classification. A paired Wilcox Rank sum test reports lower landfill sites per capita in lower income groups ($p < 0.05$

four all Income Group combinations except between Lower Middle and Low Income classes, which had p = 0.08). High Income countries have a median number of landfills of 2.18 sites per 100,000 people, whereas low-income countries have a median of only 0.07 landfills per 100,000. When accounting for waste generation instead of population size, a similar pattern is observed (Figure 2-3 b).

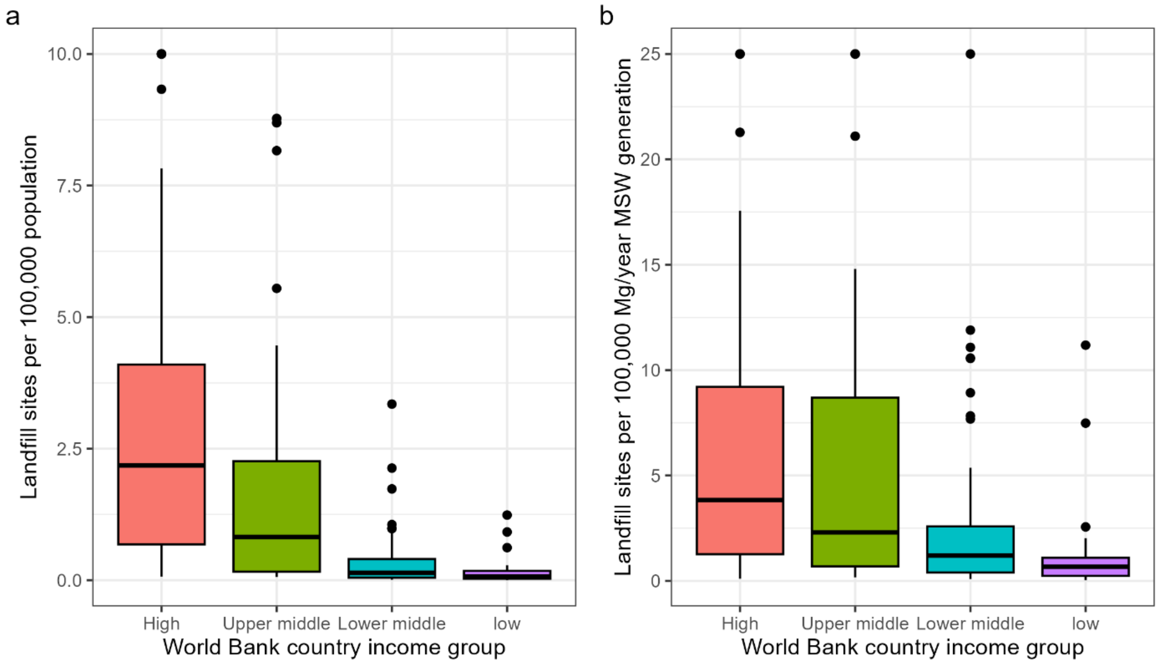

Figure 2-3 Box plots that show the distribution of (a) the number of reported landfills in OSM per 100,000 of country population, and (b) landfill sites per 100,000 Mg waste generation per year, for countries in the 4 World Bank country income classes. Sites not associated with any Income Group are omitted (e.g., dumping sites located in open ocean).

2.3.3. OpenStreetMap completeness in reference regions

Reference datasets of spatial locations of waste disposal sites, published by national or regional authorities or compiled by other organizations, were further used as a reference to evaluate the completeness of the OSM landfill dataset. Here completeness is interpreted as the percentage of waste disposal sites in the reference datasets that are also included in the OSM dataset. Overall, 37 % of the 7132 waste disposal sites in the reference datasets were included in the OSM landfill dataset (Table 2-1). For the reference regions, the OSM dataset however contained more than four times the number of disposal sites as reference datasets, which is partially a result of a broader range of facility types included in the OSM dataset. This may however be a consequence of informal dumping sites being captured in OSM while being overlooked in official datasets, or because of erroneous entries in the OSM dataset that do not correspond to actual landfill sites.

Table 2-1 OpenStreetMap landfill data completeness, defined as percentage of waste disposal sites in reference datasets that are included in the OpenStreetMap dataset.

Reference dataset	Coverage Region	Reference (n)	OSM (n)	Reference sites in OSM (n)	Completeness (%)
Recycling & Waste locations (SST)	Africa	612	4318	154	25.2
Disposal Sites, Australian Waste Management facilities database	Australia	1093	730	309	28.3
Cook Islands Landfill polygons (LiNZ)	Cook Islands	2	3	1	50
Corine2018 "Dump Site" layer	39 European countries and dependencies	1889	20324	1037	54.9
Sanitary landfill locations (SEMAD)	Minas Gerais, Brazil	49	198	11	22.4
New Zealand Landfill polygons (LiNZ)	New Zealand	68	200	66	97.1
Permitted Waste Sites (UK Environment Agency)	United Kingdom	1101	2109	164	14.9
LMOP landfill repository	United States	2318	3112	944	40.7
Overall		7132	30994	2686	37.7

2.3.4. <u>OSM landfill Accuracy Assessment</u>

To evaluate the accuracy of the landfill dataset, a stratified sample of 300 sites were manually classified by a team of annotators as "disposal site" or "not disposal site", according to the OSM landfill definition. Overall, 67% of the samples were annotated correctly, but accuracy was higher in upper middle income countries (81.6%) and lowest in low income countries (57.1%). A few (n = 7) samples were not located in countries classified by the World Bank system (e.g., nuclear waste sites located in the open ocean). 100% Of these sites were classified correctly as waste disposal sites. A map showing the spatial distribution of the sampled sites are given in Figure 2-4. Despite following a spatially balanced sampling approach, the sample locations are, by visual inspection, clustered in certain areas (e.g., Europe). This local clustering is a consequence of the uneven distribution of OSM landfill data around the world.

Table 2-2 Accuracy of Landfill features in the global OSM dataset, based on a n = 300 sample, stratified by World Bank country income classes. Accuracy refers to proportion of 'landfill' features in the OSM dataset correctly classified, according to the OSM wiki's definition of a 'landfill'.

Stratum (Country Income Class)	Accuracy (%)	Sample (n)	Total (n)
High income	63.8	185	33197
Upper middle income	81.6	38	13463
Lower middle income	71.4	35	2878
Low income	57.1	35	1226
not classified	100	7	345
Overall	67	300	51109

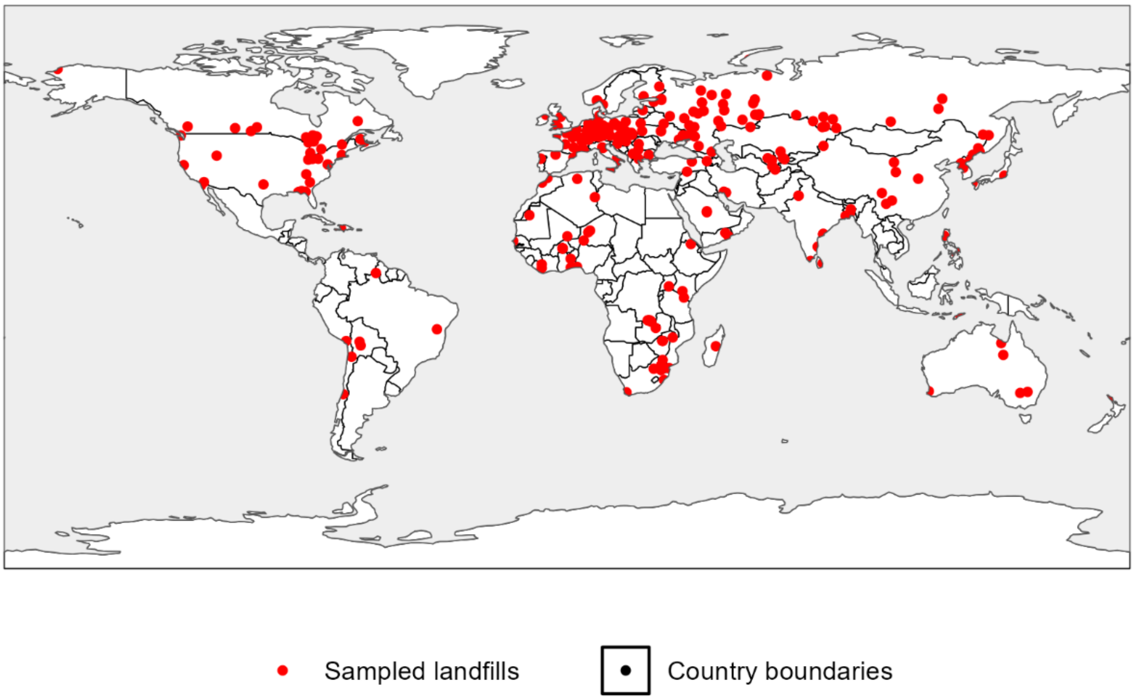

Figure 2-4 Locations of sampled OSM landfills shown as red points on a world map with country borders. Map Coordinate Reference System: WGS84.

2.3.5. Descriptive data of landfill sites in OpenStreetMap

Most "landfill" features in the OSM dataset (50.7%) did not contain additional descriptive site data (Figure 2-5). The proportion of sites without descriptive data was highest in low-income countries. Still, around 25% - 35% of sites had a single tag, and 5 – 15% had 2 tags. The most common tag was "name" (23.7% of sites) followed by the data "source" used by the map annotator (13.3% of sites., Table 2-3). Other notable tags denote whether the site is an officially operated site or informal ("informal", 2.8 % of sites) and whether the site is actively used or closed ("disused"; 3.3%).

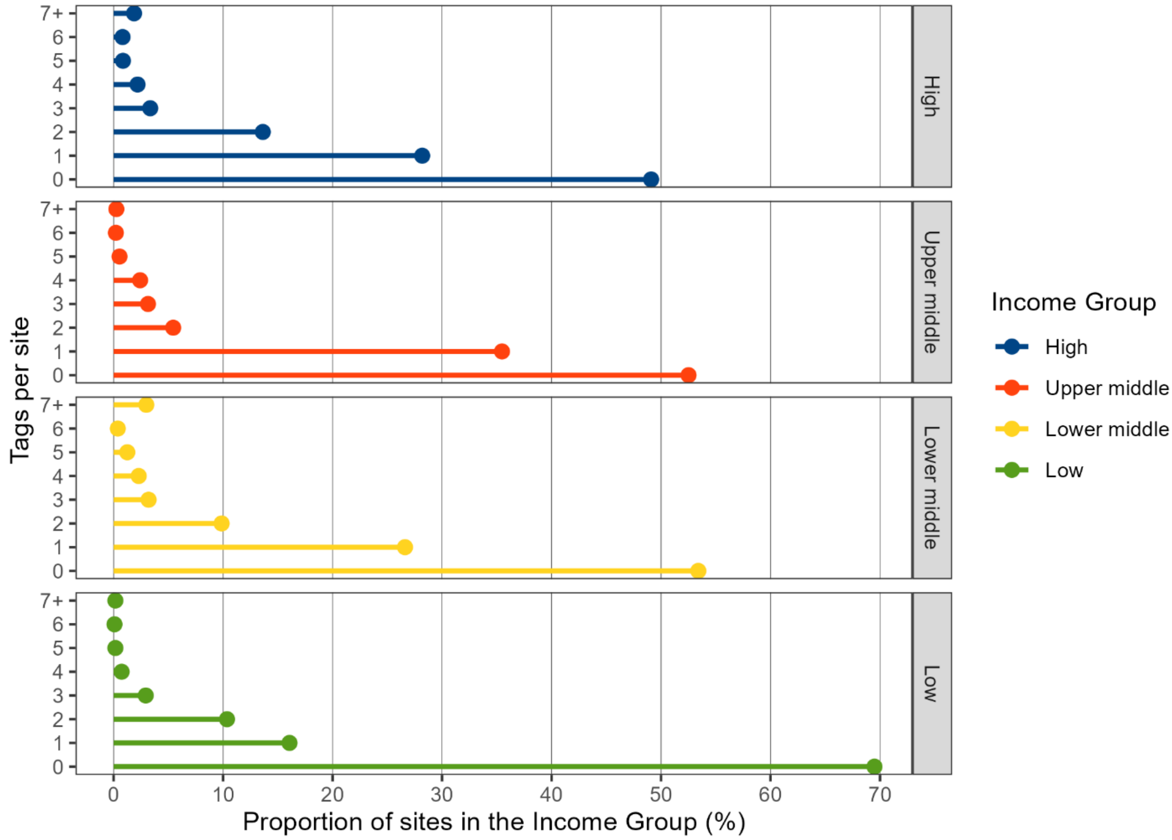

Figure 2-5 Frequency of descriptive tags per site, grouped by World Bank Income Group of the country where the site is located.

Table 2-3 Most common tags used to annotate "landfill" sites in the OSM dataset, with their frequency and example values.

Tag	Proportion of features (%)	Example values
name	23.7	"Basurero Municipal", "Buckeye Street Landfill", "Bauschuttdeponie und Recyclinganlage"
source	13.3	"Yahoo", "Bing", "survey", "local knowledge"
note	5.1	"Closed for rehabilitation", "not official; in the middle of the fields", "excavation material from quarry"
operator	3.9	"Tronox", "Petra Diamonds", "Gemeente Dordrecht"
disused	3.3	"Yes", "no"

Landfill:waste	3	“Tailings”, “nuclear”, “domestic”
man_made	2.9	“spoil_heap”, “tailings_pond”, “environmental_hazard”
informal	2.8	“Yes”, “no”, “probably”
description	2.3	“junkyard”, “mining_dump”, “Illegal dumping area”
Others	2.2	Described in Appendix document.

The waste type received by the site can be specified by “landfill:waste” (3% of sites). The most denoted waste tags in all Income Groups where mining related (e.g., “tailings, “mine_dump”, “ash”) but other waste streams (e.g., domestic waste, nuclear and construction waste) were also reported, although primarily in high income countries (Figure 2-6). But, since 97% of sites did not have waste type reported, this distribution of waste type values may not represent the true frequency of different waste disposal sites in the dataset. Notably, information that could be used to describe the type of waste disposal facility is occasionally reported in other tags such as “note”, “description” or “man_made” (Table 2-3) instead of the tags recommended by the mapping guidelines (OpenStreetMap Wiki, 2023b).

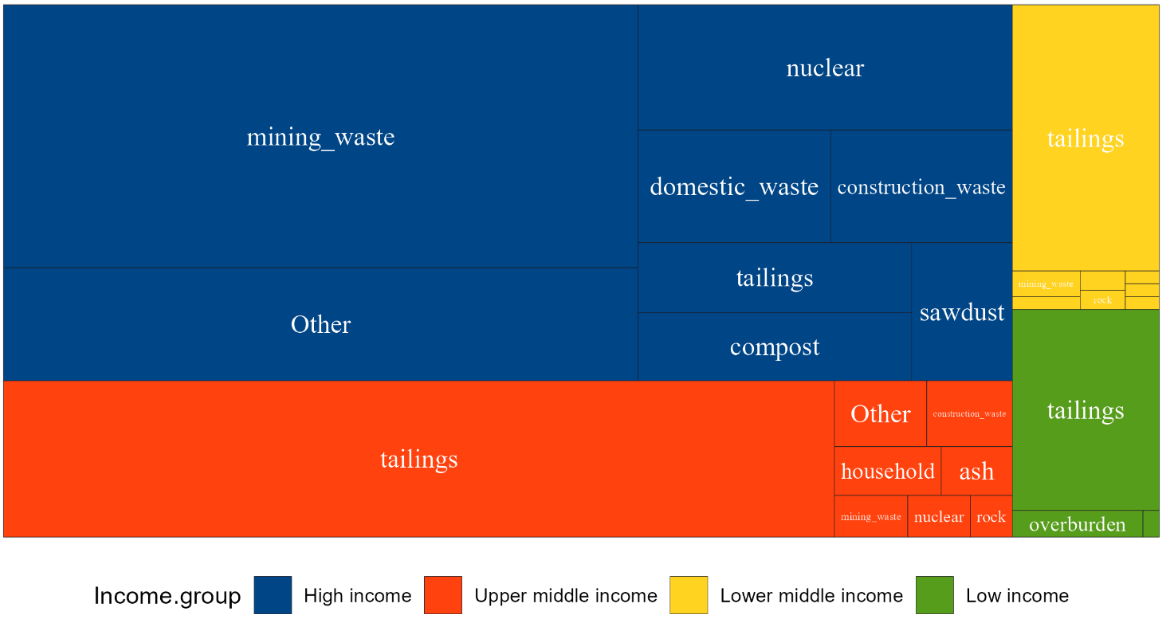

Figure 2-6 Tree diagram showing the frequency of waste types annotated in different World Bank Income Groups. Income Group differentiated by colour.

2.4. Discussion

This analysis showed that many countries, especially in the global south, do not publish landfill location datasets. It was noted that in several cases, although relevant authorities have information of landfill sites mentioned in waste sector reports, location and site attribute information was not published in a usable data format. While for other countries with weak waste management infrastructure, the lack of landfill spatial datasets could possibly be attributed to the widespread use of small-scale and non-centralised waste management approaches such as home waste burning, open-dumping, and the use of informal small dumpsites, which could be infeasible for a local environmental authority to keep track of. Countries with data often had implemented open data sharing policies and maintained data and/or geodata web portals.

Considering these observations, the author recommends that governments further encourage the digitalization and open sharing of data such as waste infrastructure and landfill locations in formats that will enable further analysis and direct use. For example, a list of landfill sites, their location and known attributes, published as a table (csv or excel file) supports not only carbon emissions measurements, as introduced earlier, but also studies that evaluate the health impacts of landfills, their impacts on environment, education and property value (Benedine et al., 2011; Elliott et al., 2009; Mahmood et al., 2019; Vrijheid, 2000). Datasets on the location of landfills are also used in studies assessing the drivers of waste dumping patterns (Antczak, 2020; Syafrudin et al., 2023). By comparison, a pdf report with only a summary of waste sector statistics has limited use. Countries with limited capacity and resources for maintaining spatial data infrastructure can make use of existing cross-national data sharing platforms (INSPIRE Geoportal, n.d.; Metabolism of Cities, n.d.; Open Development Mekong, n.d.; *openAFRICA*, n.d.). Additionally, in countries with widespread use of informal waste management practices, and where authorities have limited capacity to maintain datasets, non-governmental agencies can step in to encourage more image classification based and crowd-sourced mapping of waste disposal sites through platforms such as OpenStreetMap (OpenStreetMap Wiki, 2023a), Openlittermap (Jacquin & Valdivia, 2023), and the Global Plastic Watch (Minderoo Foundation, 2024).

It was observed that different definitions and classification systems for waste disposal sites, as well as insufficient attribute data to describe individual sites complicate comparison between countries, and the further use of the data. For instance, Ireland's 'licensed waste facilities database' contains location of not only landfills but also licensed meat processing facilities and diaries. The LMOP dataset of landfills in the United States implicitly refers to engineered or sanitary landfill sites, while on the other hand the "landfill's in the Sustainable Seas trust dataset for Africa are often in practice dumpsites. This issue is pronounced for the OSM landfill dataset, since the OSM landfill definition is broad, including facility types that are usually not considered together for analysis purposes (such as, large mine tailings facilities, small illicit open dumping sites, and abandoned sanitary landfill that has since been converted to greenspace). Although site attributes can be described by contributors by use of specific tags, over 50% of landfill sites in the OSM dataset had no descriptive information. This stresses the need volunteered mapping efforts to encourage inclusion of site attributes and descriptive tags, which will facilitate further use of the dataset. Government maintained datasets should also include more descriptive information, such as the waste types received, waste amounts received, and other measured data that could inform more accurate estimation of point source carbon emissions.

One objective of this study was to evaluate whether the OSM landfill dataset is currently a representative source of global landfill location data. However, in addition to shortcomings related to the availability of descriptive site data, the global coverage and completeness dataset is currently low. Globally, 49% of cities did not have any OSM landfills in a 30 km radius around, and a comparison with reference landfill datasets, representing 7132 landfills across several continents showed that on average only 37.7% of reference sites were included in the OSM dataset. Yet, several characteristics of the dataset make it a good candidate to become a central repository of global waste disposal site location data. Firstly, since OpenStreetMap is a VGI project, different stakeholders like countries' national waste authorities, humanitarian aid organizations, waste management associations, and local volunteers with knowledge of dumping locations may all contribute, thus creating a rich waste site dataset that could be more comprehensive than possible if compiled by only a single entity (such as a local waste authority). OpenStreetMap can accommodate and describe different types of waste disposal sites (municipal landfills, informal dumps, hazardous waste, mining and industrial disposal sites, etc.) Therefore, it is suitable for a global dataset that needs to accommodate differing waste management practices in different regions. Finally, despite its lacking coverage, the OpenStreetMap landfill dataset already represents the largest repository of global waste disposal site location data and therefore requires less work to improve than coordinating new global waste location data sharing initiatives.

In conclusion then, this analysis shows that for most of the world's countries, data on the location of landfills are currently not sufficiently available. Stronger open data sharing policies and initiatives by governments, and crowd-sourced landfill and waste mapping initiatives are needed to address this data gap. Global landfill location data, coupled with descriptive site information and remote sensing data such as provided by MethaneSat (Environmental Defense Fund, 2025) are needed to facilitate more detailed assessments of global waste sector carbon emissions.

2.4.1. Acknowledgements

The author is grateful to the Sustainable Seas Trust (SST), for allowing the use of their Recycling & Waste locations database for this analysis under a non-disclosure agreement. This analysis also used OpenStreetMap data, which is made available at openstreetmap.org under the Open Database License (ODbL).

Chapter 3: Evaluation of Global elevation change map as source for waste statistics

This chapter is an extended version of the article: Louw, A. S., & Avtar, R. (2025). Methodology for measuring landfill dumping statistics globally using Digital Elevation Change maps. Resources, Conservation and Recycling, 212, 107924. https://doi.org/10.1016/j.resconrec.2024.107924

3.1. Introduction

One of the applications of remote sensing data to waste monitoring is the measurement of volumetric changes in landfill sites over time, and thus estimating the amount of waste dumped. The current study is also aimed at this application. Three general techniques for the estimation of volumetric changes from remote sensing data have been suggested thus far. For context, these methods and their limitations are described below:

3.1.1. Drone photogrammetry and Airborne LiDAR

Firstly, drone imagery and photogrammetry is increasingly being used to calculate volumetric changes of waste in individual landfill sites (Incekara et al., 2019). This approach can be used by landfill managers as an alternative to land surveying to measure changes in the available airspace of individual landfill sites. However this approach is not applicable to remote measurement of landfills across a region, and requires field visits to the landfill.

3.1.2. Short Baseline Subset (SBAS) Differential InSAR

Van Zyl & Celik (2021) measured the velocity of landfill surface change using SBAS Differential InSAR (or, Short Baseline Subset Differential Synthetic Aperture Radar Interferometry) for three case-study landfill sites in different countries. The study focused primarily on estimating relative changes in the rate of waste dumping over time, rather than measurement of waste dumping statistics like waste mass, or waste volumes. Still their methodology could potentially be extended for such applications. However, using this approach to capture volumetric changes in landfills over large regions will require a large amount of data and computing resources, due to the dense time series of radar images needed for SBAS Differential InSAR analysis.

3.1.3. InSAR based DEM generation and differencing

A third, less computationally intensive method has also been proposed, which consists of firstly generating digital elevation models (DEMs) of the landfill site at two different times using

Repeat-pass InSAR, and then using the changes between the two DEMs to calculate the change in volume of waste in the landfill (Cadau et al., 2014; Karathanassi et al., 2012). This approach has an order of magnitude smaller data and computing requirement than the method proposed by van Zyl & Celik. However, the volume change accuracy in these studies were low, in part due to an InSAR phenomenon known as temporal decorrelation, which Repeat-pass InSAR is susceptible to in landfill sites (Ahmed et al., 2011; Ottavianelli et al., 2006).

To understand temporal decorrelation in InSAR processing, its consequences, and how it may be mitigated, it is necessary to first introduce briefly some concepts from InSAR. Therefore we briefly touch on this topic in the following few paragraphs, however for a further and more authoritative introduction to InSAR, the reader can refer to Chapter 2 of The SAR Handbook (Flores-Anderson et al., 2019).

SAR data points (i.e., a pixel value in a SAR image) are complex numbers (a number that has both a real part and imaginary part). The value of the real part represents the amplitude of the received radar signal, while the imaginary part represents the radar phase. Radar signals can be considered to move like waves (or, like a sinusoidal function), where the amplitude is like the height of the wave, and the phase refers to the current position horizontally along the wave (e.g., at its peak, in the trough, or someway midway). In interferometric processing, two or more SAR images captured of the same region are multiplied. These images can either be captured at different times, or simultaneously but by sensors separated from each other at some distance, so that the sensors look at the scene from a slightly different angle. The multiplication of the complex SAR images allows the difference in the phase measurements between the two images to be determined for each pixel. The shifts/differences in measured phase values can be used to infer the distances between the sensor (on the satellite) and the points on the ground. The distance measurements can then be used to generate elevation maps or surface deformation maps.

However, the reliability of the inferred elevation or surface deformation information is strongly affected by the local correlation or similarity of measured phase values between the SAR acquisitions. This similarity is called 'coherence' in SAR terminology and is usually calculated using small moving windows of a predetermined size (e.g., 5 x 5 pixels). If there are large and haphazard changes in the phase values in near or adjacent pixels (and thus low coherence) the technique of using shifts in phase to infer elevation or deformation becomes unreliable, leading to artifacts and erroneous interferometry results.

Low coherence, or decorrelation, occur due to various reasons (Ahmed et al., 2011), but one prominent source of decorrelation between SAR images are due to large changes in the target area's surface scattering properties over time. This is known as temporal decorrelation. When there are dramatic surface changes between one SAR image and the next, for example due to a landslide, the construction or demolition of buildings, or wind that changes the orientation of vegetation in a field, the scattering of the reflected radar signals also change dramatically, leading to low coherence. This is most starkly seen in waterbodies. Since the surface of water in the oceans and rivers change constantly, they can characteristically be seen as dark spots of near zero coherence in coherence images. As mentioned earlier, (active) landfills are also characterized by strong temporal decorrelation (Ottavianelli et al., 2006), since waste is deposited, spread around, and compacted daily, predictably causing dramatic changes to the surface scattering properties in the site. And, due to this phenomenon, past attempts to use Interferometric processing to generate elevation models for landfill sites had limited success (Cadau et al., 2013).

However, temporal decorrelation is only relevant in cases where there is a temporal gap between the acquisition of the SAR images used for the interferometric processing (often called 'Repeat-Pass InSAR', since the same satellite usually captures the SAR images on different orbital passes). If the images used for the interferometric processing can be captured simultaneously by different SAR sensors that are operating together, temporal decorrelation is avoided. This is known as 'Single-Pass InSAR'. A famous example of a SAR system that enabled Single-Pass interferometry was the Shuttle Radar Topography mission (SRTM), in which the Space shuttle Endeavour carried one SAR sensor in its payload bay, and a second SAR sensor extended on a long (60 m) mass, outside the shuttle, as illustrated in Figure 3-1 (Farr et al., 2007). The two sensors collected their SAR images simultaneously, which was then later interferometrically processed into the well-known SRTM DEM. A more recent and ongoing example is the Tandem-X mission, which is also used in this study, and will thus be introduced further in the following section.

Figure 3-1 Illustration of the Space Shuttle Endeavour with secondary SAR Sensor extended from the spacecraft, enabling simultaneous acquisition of two SAR images[Public Domain: (USGS, 2005)]

3.1.4. Proposed Methodology and characteristics

Considering the past challenges experienced during the interferometric processing of landfill sites, as described in the previous section, there is currently still scope for developing satellite remote sensing-based techniques to measure the changes in waste volume that (1) has sufficient accuracy to be useful to stakeholders, and (2) can be applied to larger areas. The methods currently described in literature did not estimate waste dumping reliably enough to be used operationally, and were moreover mostly applied in individual case-study landfill sites. However, if such approaches could be extended to enable remote estimation of landfill statistics for many landfill sites (e.g., all landfill sites in a region or country), it would be a potential solution to providing landfill waste statistics for large regions, including regions where in-situ waste data is not reported.

In 2023 the German Aerospace Center (DLR) released a data product called the "Tandem-X DEM Change Map", which will further be referred to as the DCM (Lachaise & Schweißhelm, 2023). The DCM dataset reports elevation changes over time at a 1 arc-second spatial resolution (approximately 30 m by 30 m per pixel). The elevation changes are between the DLR's EDEM product – which is a global elevation model generated from radar data captured between 2010 and 2015 by the Tandem-X radar satellite mission – and other DEMs that were produced from Tandem-X data captured after 2015. This dataset thus offers a potential source of landfill volume change data. The DCM dataset is particularly promising for this application, since

1. The dataset has global coverage, and therefore could potentially inform statistics on the volume of waste dumped for any landfill with a known location.
2. The DEMs used to generate the elevation change maps are produced from the Tandem-X SAR mission, which is not susceptible to a SAR interferometry phenomenon known as 'temporal decorrelation' (Zink et al., 2021). Temporal decorrelation during InSAR analysis is a challenge in landfill sites, since the surface structure of active landfill sites experience quick changes over time (Ottavianelli et al., 2006). Temporal decorrelation of SAR data often causes elevation errors in DEMs. This issue resulted in large volumetric change errors in previous studies that attempted to use SAR interferometry to calculate waste volume change in landfills (Cadau et al., 2013, 2014; Karathanassi et al., 2012). Therefore, the dataset considered in this study is expected to offer more accurate volume change estimates than prior studies, since the interferometry technique used here is not susceptible to temporal correlation.

This study evaluates the possibility of using the new Tandem-X Global DEM Change Map (DCM) as a data source for estimating the volume of waste dumped in landfills over time. This methodology could hypothetically be applied to different types of landfills (e.g., municipal waste landfills, construction waste, both sanitary and open dumps, etc.) However, the relationship between change in landfill volume and the amount of disposed waste will differ depending on the landfill management, and the composition of waste. Thus, when applying the approach, the target landfill type needs to be taken into consideration. The following specific research questions were investigated:

1. For what temporal interval can waste statistics be extracted from the DCM dataset?
2. What is the expected accuracy and other characteristics of landfill waste statistics estimated from the DCM dataset?
3. Can the proposed methodology be validated for individual landfill sites with known dumping statistics?

The study aims to create a foundation for follow up studies that can apply the proposed methodology to estimate landfill statistics for various regions and so contribute to filling global waste data gaps.

3.2. Methodology

100 landfill sites from around the world were selected as case studies, and the temporal coverage, data availability and estimated data errors were estimated and summarized for the sites. The results for all 100 sites, along with aerial imagery of the sites and descriptive

information obtained from other sources, and reported dumping statistics (if available) are supplied in Annexure III. A number of case-study sites from the original 100 were then considered for more detailed comparison with reference data and high resolution satellite time-series imagery, to evaluate and validate the results of the proposed methodology, described in section 3.2.6. A schematic showing the overall study methodology is given in Figure 3-2.

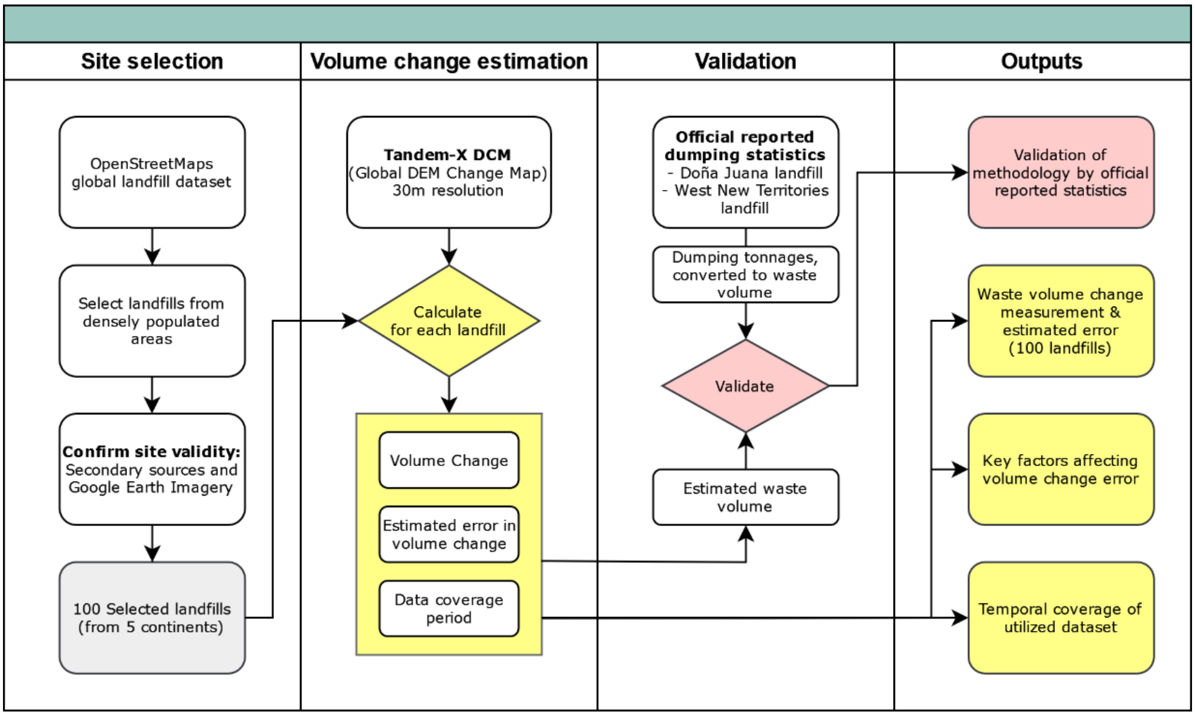

Figure 3-2 Schematic of the study methodology, and target outputs.

3.2.1. Site Selection

For this feasibility study, the primary considerations for choosing case-study sites, were that landfill sites from around the world should be included, to demonstrate the methodology's global applicability. Both sanitary and open dumpsites were included, and large as well as small. To make the selection, landfills were ranked by the human population density of the level 2 administrative unit where the landfills were in, and then the first 100 hundred were selected that could be cross validated as actual landfill sites. Where there were multiple landfills in the same administrative unit, only the largest was selected, to increase the number of landfills from different regions. For this study, spatial location (polygons) of landfill sites from around the world were firstly extracted from the OpenStreetMap database (OpenStreetMap contributors, 2017), by using a query to the OpenStreetMap API for all features with either a tag *landuse = landfill*, or the tag *amenity = waste_disposal*. The author determined the local population densities of the administrative regions the landfills were located in by aggregating the 2020 population estimates from the GHS Multitemporal population grid into the level 2 administrative boundaries reported in the GADM 3.6 dataset (European Commission & Joint Research Centre, 2023; Global Administrative Areas, 2018). A flow chart of the described methodology is given in Figure 3-3.

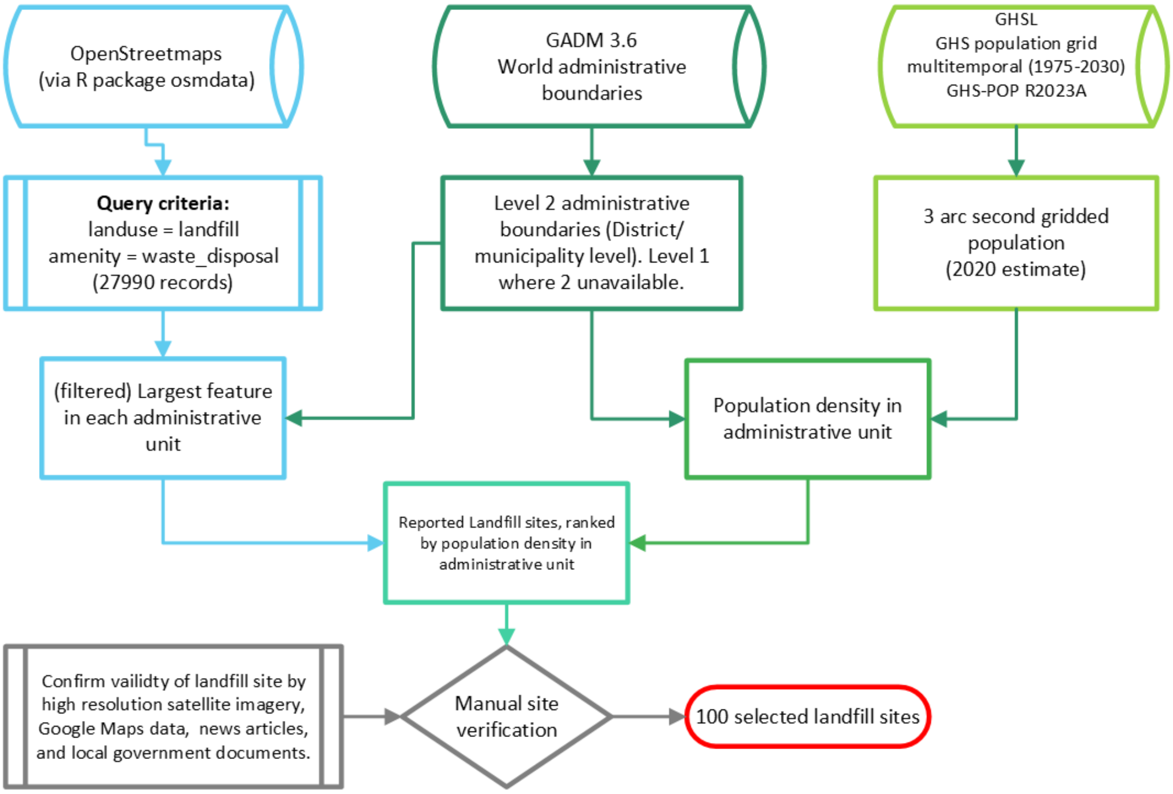

Figure 3-3 Flow chart showing the data sources for landfill sites, administrative boundaries and global population data, as well as selection criteria for the final 100 sites used for the study

For some regions, the lowest administrative subdivision was level 1, so for these areas level 1 was used instead of level 2. The sites were manually confirmed by cross referencing with satellite imagery and location records in Google Earth Pro software, Bing Aerial (high resolution satellite imagery), and by finding local government documents and reports or news articles that mention the landfill sites. A complete description of the 100 sites, with high resolution satellite imagery is shown in Annexure III. The resulting dataset of 100 landfill sites were distributed by continents, as described in Table 3-1, and their locations are shown in the world map in Figure 3-4.

Table 3-1 Distribution of chosen 100 landfill sites by continent.

Continent	Number of landfill sites
Africa	21

Asia	50
Europe	9
North America	7
South America	13
Oceania	0

Figure 3-4 : World map showing study landfill locations as red dots (n = 100). Antarctica is excluded from the map.

3.2.2. Data Description: TANDEM-X 30 m DEM Change Maps (DCM)

The DCM dataset (Lachaise et al., 2022; Lachaise & Schweißhelm, 2023) reports elevation changes between the Tandem-X 30 m EDEM digital elevation model – produced from Tandem-X SAR data collected from 2010 to 2014 – and later Tandem-X acquisitions made after the completion of the original DEM mission. The data product reports the elevation change between the EDEM and the DEM produced at a later date, and reports the time stamp of the later acquisition. However, since the EDEM uses aggregated elevation data collected between 2010 and 2014, it is not possible to work out the exact temporal rate of elevation changes that are reported in the DCM map. To account for this temporal ambiguity, the DCM product includes two change maps for every location. The two maps show the change between the EDEM and a DEM produced at some later time t_1 (DCM_1) and also the change between EDEM and a second DEM produced at time 2 (DCM_2). This is shown in graphic in Figure 3-5. Since the acquisition days t_1 and t_2 are known, it is possible to calculate the rate of DEM change for the period between the first change map, and the second change map. However, not all areas have multiple repeated DEM acquisitions, and for these locations the two reported change maps are identical (i.e., $DCM_1 = DCM_2$). The data product also includes an error estimate layer, which is further explained below in the error propagation calculation sub-section.

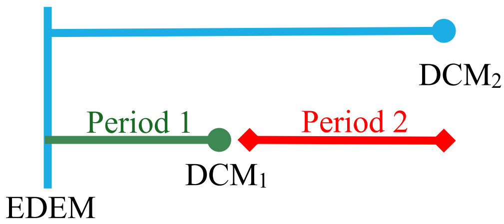

Figure 3-5 Graphic showing the structure of the DCM dataset. Elevation changes can be calculated for the target period (in red) between the DCM1 and DCM2 change maps

3.2.3. <u>Landfill Volumetric Change Estimate</u>

In the study our target measurement was rate of volumetric change inside the landfill area (unit: $m^3 \cdot day^{-1}$). This was calculated separately for *period 1* and *period 2* (Figure 3-5).

Due to the uncertainty of the EDEM data acquisition date for any given location, the Period 1 volume change calculation is not precise. An acquisition date for the EDEM data needs to be assumed, after which the volume change rate during *period 1* can be estimated. Since the Tandem-X data collection period for the EDEM was from 2010 to 2014, I specified the EDEM date to the middle of 2012 (i.e., 2 July 2012), which is the middle of the data collection period. If the true acquisition was made earlier than the assumed date, the actual volume change rate will be slower than estimated, and if the true acquisition date for DCM_1 is later than the assumed date, the actual volume change rate will be higher than estimated. The calculations for estimating volume change rate are described below:

A – Area of a single pixel in the DCM raster map (unit: m^2)

t_{edem}, t_1, t_2 – assumed acquisition date of the EDEM, and acquisition date of DCM_1 and DCM_2 respectively.

Δt_1 – Temporal gap between t_{edem}, and t_1 (unit: days)

Δt_2 – Temporal gap between t_1, and t_2 (unit: days)

h_1, h_2 – height change values reported in the DCM_1 and DCM_2 respectively (reported per pixel in the raster)

Then, the temporal rate of volume change in period 1 ($\Delta Vol_{period1}$) and period 2 ($\Delta Vol_{period2}$) for a single pixel is:

$$\Delta Vol_{period1} = \frac{A}{\Delta t_1}(h_1) \tag{3-1}$$

$$\Delta Vol_{period2} = \frac{A}{\Delta t_2}(h_2 - h_1) \tag{3-2}$$

The total rate of volume change for the landfill is then calculated by summing the values for all the pixels in the area of interest (as demarcated by the polygon vector file of the landfill.) That is, if the landfill site covers *n* pixels, with each pixel's volume change $\Delta Vol_{*_i}, for\ i = 1\ to\ n$, then the total volumetric change is given by:

$$\Delta Vol_{period1_{tot}} = \sum_{i=1}^{n} \Delta Vol_{period1_i} \tag{3-3}$$

$$\Delta Vol_{period2_{tot}} = \sum_{i=1}^{n} \Delta Vol_{period2_i} \tag{3-4}$$

The DCM product reports the dates of the DCM_1 and DCM_2 data acquisitions dates on a per pixel basis. However, in some cases the pixel value in the DCM_1 and DCM_2 were identical (the same data point and acquisition date were reported in both), and for these pixels the Period 2 the volume rate ($\Delta Vol_{period2}$) could not be calculated., since effectively $\Delta t_2 = 0$ days. Therefore, I introduced a pixel level filter that excluded pixels that had $\Delta t_2 = 0$.

3.2.4. Error propagation calculation

The DCM data product includes a data quality layer that reports the Height Accuracy Indication (HAI). According to the data product guidelines, HAI "*approximates the resulting height error of the combination of the Height Error Map values (HEM) of the new DEM data and the reference TanDEM-X 30m EDEM assuming both height errors (HEMs) follow a Gaussian distribution.*" [4]

Error estimates of the volume rate change in landfills were calculated from the HAI layer, using the rule of quadrature (McCormick, 2016). The rule of quadrature says that if measurements

[4] TDM DCM data guide https://geoservice.dlr.de/web/dataguide/tdm30/

are added or subtracted, the associated error/uncertainties add together, and if measurements are multiplied by a constant, their errors are also multiplied by the constant. More generally, for some function *f* of variables x_i for $i = 1 \; to \; n$ with associated errors (δx_i), the total error of the function, is calculated as:

$$\delta f = \pm \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i}\right)^2 (\delta x_i)^2} \tag{3-5}$$

The error of the volumetric change rate for a pixel can thus be derived as follow for the two periods:

$$\begin{aligned} \delta \Delta Vol_{period1} &= \pm \sqrt{\left(\frac{\partial}{\partial h_1}\frac{A}{\Delta t_1}(h_1)\right)^2 (\delta h_1)^2} \\ &= \pm \sqrt{\left(\frac{A}{\Delta t_1}\delta h_1\right)^2} \\ &= \pm \frac{A}{\Delta t_1} \; \delta h_1 \end{aligned} \tag{3-6}$$

$$\begin{aligned} \delta \Delta Vol_{period2} &= \pm \sqrt{\left(\frac{\partial}{\partial h_1}\frac{A}{\Delta t_2}(h_2 - h_1)\right)^2 (\delta h_1)^2 + \left(\frac{\partial}{\partial h_2}\frac{A}{\Delta t_2}(h_2 - h_1)\right)^2 (\delta h_2)^2} \\ &= \pm \sqrt{\left(\frac{A}{\Delta t_2}\delta h_1\right)^2 + \left(\frac{A}{\Delta t_2}\delta h_2\right)^2} \\ &= \pm \frac{A}{\Delta t_2}\sqrt{(\delta h_1)^2 + (\delta h_2)^2} \end{aligned} \tag{3-7}$$

Where $\delta h_1$and δh_2 refer to the HAI value in the corresponding pixels of DCM_1 and DCM_2. Then, if the landfill site contains n pixels with each pixel having associated error ${\delta \Delta Vol_{period1}}_i$ or ${\delta \Delta Vol_{period2}}_i$, (for $i = 1 \; to \; n$) The error estimate for the rate of total volume change in the landfill site becomes, by the rule of quadrature:

$$\delta\Delta Vol_{period1_{tot}} = \sqrt{\sum_{i=1}^{n} \left(\delta\Delta Vol_{period1_{i}}\right)^{2}} \tag{3-8}$$

$$\delta\Delta Vol_{period2_{tot}} = \sqrt{\sum_{i=1}^{n} \left(\delta\Delta Vol_{period2_{i}}\right)^{2}} \tag{3-9}$$

3.2.5. Aggregation of results

To address the questions posed in the introduction, the following analysis was conducted:

Calculating the temporal coverage of the DCM dataset for each landfills site. Here ‘temporal coverage’ refers to the time periods for which elevation change rates could be calculated, i.e., the period between DCM_1 and DCM_2 change maps. The DCM product reports the dates of the DCM_1 and DCM_2 product on a per pixel basis. Although individual landfill sites were generally covered only by one date (all pixels having the same product date), there are cases where inside one landfill’s area, data from two or three dates were used for the DCM map. Therefore, to report the temporal gap for one landfill, the time period that occurred most frequently in the considered area of interest was used. The distribution of time periods among the 100 considered sites was then illustrated with a histogram and by calculating distribution summary statistics.

To evaluate the expected error in the volumetric change estimates for individual landfill sites, $\delta\Delta Vol_{tot}$ for each site, and the 50%, 75%, 90% and 95% quantiles of the estimated error was calculated. The estimated error is expected to be inversely proportional to the temporal gap between the two DCM products (eq. 4). This relationship was investigated by plotting the temporal gap (Δt) against estimated volumetric error ($\delta\Delta Vol_{tot}$).

3.2.6. Individual case studies

For validating the accuracy of the proposed method, two landfills were selected from the 100 sites, and their estimated volumetric changes for the *period* 2 were compared to officially reported waste statistics for the corresponding time. Further, the estimated location of dumping within the landfill (i.e., the landfill’s working face) was verified by high resolution satellite imagery from Google Earth, Bing Aerial Imagery, and data provided by the landfill operators. These two sites were selected based on the availability of in-situ waste disposal statistics reported for the same time window as the *period 2* DCM product in the respective sites. The period 2 results were used for the primary validation, since the period 2 volume change estimate has lower estimation uncertainty (as explained before) and thus offers an assessment of the method in a “best-case scenario”. However, since not all sites have adequate period 2 DCM data, two additional sites with only period 1 DCM data are also explored, and estimated volume changes compared to satellite images and reported statistics.

3.2.6.1. Period 2 validation landfills

The first case-study site was the Doña Juana landfill (Spanish: Relleno Sanitario Doña Juana), located at (4.505° N, 74.1339° W) in Santafé de Bogotá, Colombia. This large sanitary landfill covers a total area of 623 hectares and receives municipal waste from Bogota and surrounding municipalities. The site has separate managed zones for non-hazardous waste deposition, hazardous wastes, and biogas reclamation. Monthly tonnages of final disposed waste, and changes in available landfill airspace are reported for the site (UAESP, 2024). The second case-study was the West New Territories Landfill (WENT) in Hong Kong. WENT is situated at (22.419° N, 113.934° E) and covers an area of 110 hectares. It is the largest landfill site in Hong Kong, and receives municipal solid wastes (MSW), construction waste and special wastes (Statistics Unit, Environmental Protection Department, 2020). Waste is compacted before transportation to the site. Hong Kong’s Environmental Protection Department reports annual waste statistics for the site, including the tonnages, waste types, and breakdown of waste composition (Environmental Protection Department, 2023). A map of the site is shown in the results section. Further detailed information on the two landfill sites is given in Annexure II:.

To compare daily volumetric change from the DCM data with reported statistics, the reported monthly/annual disposed tonnages for the period overlapping with the temporal coverage of the DCM data was aggregated and converted to average daily waste mass. The reported waste mass was converted to volume estimates by dividing the mass by an estimate of the density of waste disposed in the landfill, using a waste density range of $1 - 1.5\, Mg \cdot m^{-3}$ (*Mg*: Megagram, equivalent to 1 metric tonne). This density range was chosen since both sites are managed sanitary landfill sites with routine compaction. In general, waste density reported in literature ranges from approximately 0.4 $Mg \cdot m^{-3}$ for uncompacted waste to 2 $Mg \cdot m^{-3}$ for highly compacted waste (Feng et al., 2017; Owusu-Nimo et al., 2019; Zekkos et al., 2006).

3.2.6.2. Period 1 validation landfills

Since not all landfills had complete period 2 data, it is also important to evaluate the accuracy of volume change estimates calculated using Period 1 DCM data. Sites with insufficient period

2 data (missing, or with a short data capture period) are also valuable for empirically confirming the predicted error in such sites. Two sites were considered:

The North of the Seventh Ring Road landfill in Kuwait (29.192° N, 47.913° E) was chosen. This landfill was in operation between 1986 and 2005, but has been closed since, and therefore is expected not to show volumetric changes in the time period of the DCM data set (Kuwait Environment Public Authority, 2022). This site had a short period two data coverage, of only 22 days.

Secondly, the The Mediouna Landfill in Casablanca, Morocco (French: Décharge de Médiouna) was chosen, since it only had period 1 data available. This 60 hectare landfill suffered from inadequate management and was reported to be a strong nuisance to the surrounding community until its closure in 2021, around which time it is reported to have received around 3800 Mg of waste per day (Kaiss, 2024).

3.3. Results

3.3.1. Temporal coverage of the dataset

Due to the known uncertainty for period 1 volume change estimates (explained in section 3.2.3), the primary focus of this analysis was on the period 2, (the period between DCM_1 and DCM_2 acquisitions, for which precise volume change rates can be calculated). However, according to the data guidelines, not all locations on earth have a 'period 2'. The periods of DCM data coverage of the 100 study sites are illustrated in Figure 3-6a. Most of the sites have period 2 DEM change data for periods between 2018 and 2020, with about 7 sites having data coverage into 2021. Blank lines in the figure represent landfill sites with no temporal gap between DCM observations (n = 24). The distribution of temporal gaps (Δt) between the first and second DEM change maps for the 100 sample landfill sites is shown in the histogram in Figure 3-6b. Of the 100 sites, 24 did not have *period 2* data (i.e., $\Delta t\_2 = 0$). For the remaining 76 sites with *period 2* data, the median gap was 495 days (or, approximately 1.3 years), and the longest gap was 1177 days (3.2 years) (Table 3-2).

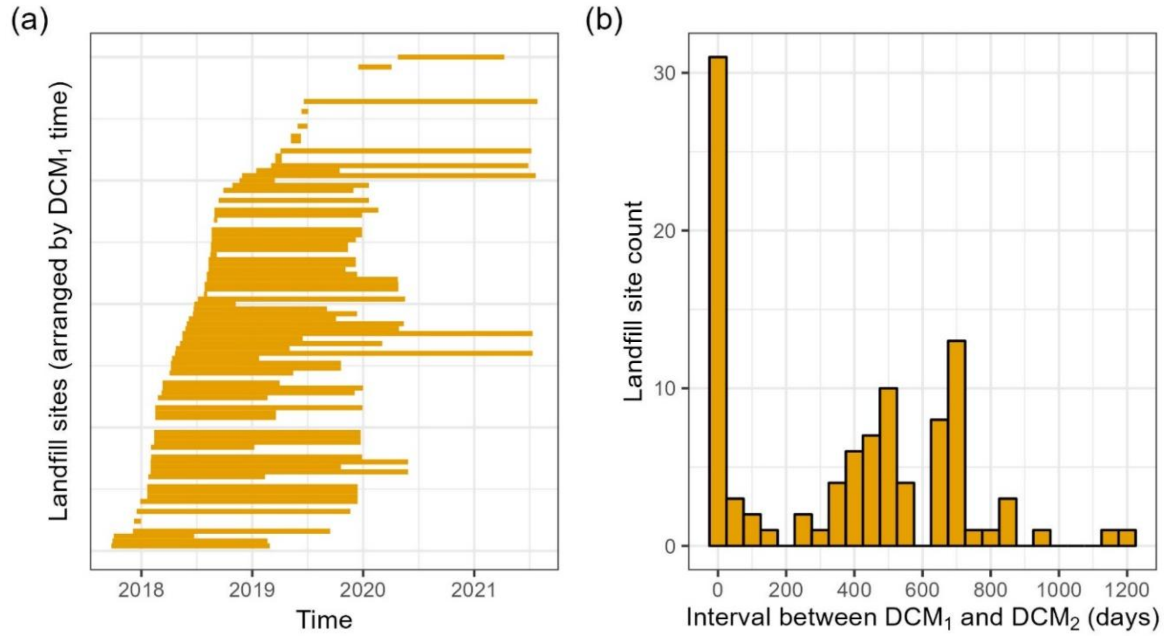

Figure 3-6 (a) Period 2 temporal coverage of the DCM data, shown for each of the 100 landfill study sites. (b) Histogram of time interval (Δt_2) between the DCM_1 and DCM_2 products, measured at the landfill sites (Histogram binwidth = 50 days).

Table 3-2 Percentiles of temporal gap (in days) between first and second DCM maps in the 76 field sample sites, that contained temporal gap.

Percentile	0 %	25 %	50 %	75 %	100 %
Days	11	371.25	495	682	1177

3.3.2. <u>Error estimation</u>

To evaluate the practical usability of the DCM dataset for waste volume change estimation in landfills, it is necessary to quantify errors associated with the method's volume estimates. As shown in equation 3-6 and 3-7, the theoretical error in the estimated rate of waste dumping in a landfill site is inversely proportional to the temporal gap between the first and second DCM change products. In the obtained results there were also noticeably higher estimated errors for landfill sites with short temporal gap between the DCM maps, particularly sites with $\Delta t < 50\ days$ (Figure 3-7a). The distribution of volumetric change errors for landfill sites with $\Delta t > 50\ days$ is shown in Figure 3-7b. If landfill sites with below 50 days temporal gap are excluded, the 95% quantile of volumetric change error reduces from 450.53 $m^3 \cdot day^{-1}$ to 110.85 $m^3 \cdot day^{-1}$, but the median error remains approximately the same, at 14.74 and 15.72 $m^3 \cdot day^{-1}$

respectively (Table 3-3) . The reduction in error can also be seen by the large difference in the axis limits between Figure 3-7 (a) and (b).

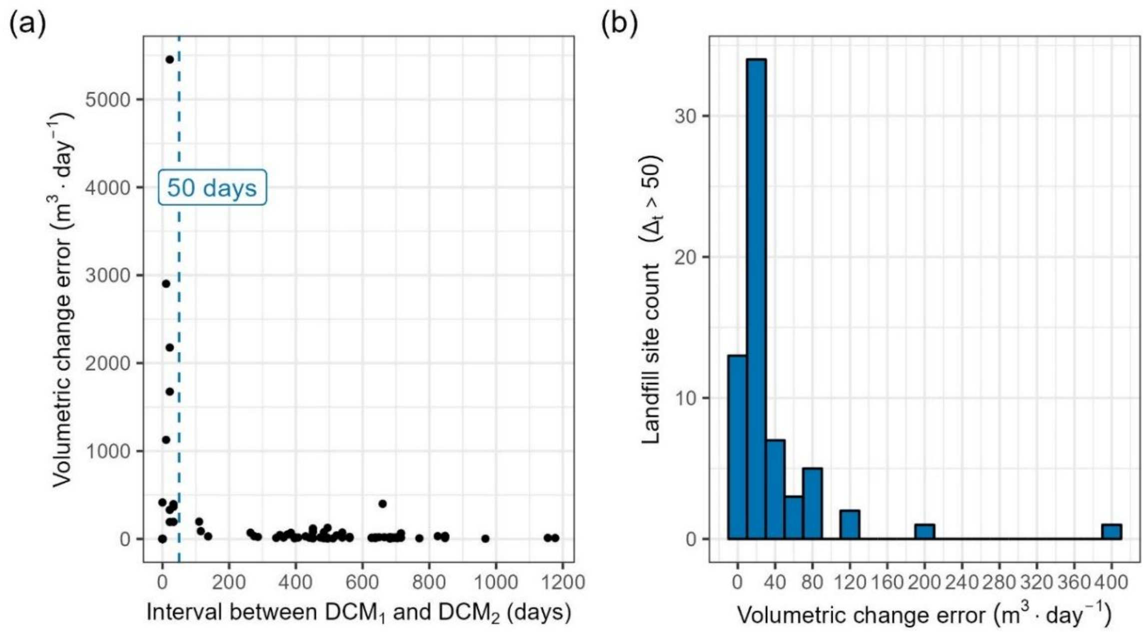

Figure 3-7 (a) Relationship of time interval (Δt) between DCM maps and landfill volumetric change error, for all sites with data coverage (n = 76). Data points to the left of the dashed blue line have $\Delta t < 50\ days$. (b) Histogram of volumetric change errors for landfill sites that have $\Delta t > 50\ days$; (n = 66).

Table 3-3 Distribution (as percentiles) of the estimated error in landfill volumetric change (δ〚ΔVol〛_tot; eq. 5), calculated for all sites with Δt>0 , and for sites with short temporal gap filtered out (Δt>50).

Percentile	50%	75%	90%	95%
Volumetric error (All sites, n = 76) ($m^3 \cdot day^{-1}$)	14.74	41.59	209.68	450.53
Volumetric error ($\Delta t > 50$, n = 66) ($m^3 \cdot day^{-1}$))	15.72	32.25	74.72	110.85

3.3.3. Period 2 validation

To offer a validation of the accuracy of the proposed method, estimated period 2 volumetric changes were compared with reported data for the West New Territories Landfill in Hong Kong, and the Dona Juana landfill in Colombia. The estimated volumetric change from the DCM analysis and the waste statistics found from secondary sources are listed below in Table 3-4. A further description is reported separately for each site in the section below. Estimated volumetric changes for all 100 sites are reported in Annexure III).

Table 3-4 Volumetric changes in two landfill case study sites, as calculated from DCM dataset, and as reported in secondary data (official landfill statistic reports).

	West New Territories Landfill	Doña Juana Landfill
DCM volumetric change (total in site) ($m^3 \cdot day^{-1}$)	5777	2577
Estimated volumetric change error ($m^3 \cdot day^{-1}$)	73	127
DCM volumetric change (in dumping area) ($m^3 \cdot day^{-1}$)	6307	5685
Reported volumetric change* ($m^3 \cdot day^{-1}$)	4966 to 7449	4230 to 6345
Reported final disposal tonnages ($Mg \cdot$ 〚day〛 ^(−1))	7448.7	6345.3
Time period	2018-08-30 to 2020-02-20	2018-09-12 to 2020-01-20

* Conversion from reported tonnages using waste density range 1 $Mg \cdot m^{-3}$ to 1.5 $Mg \cdot m^{-3}$

3.3.3.1. Doña Juana Landfill

In the map in Figure 3-8b, areas with positive volumetric change (red) as well as areas with negative volumetric change (blue pixels) can be seen. High resolution satellite imagery from the study period shows that the areas with high negative volumetric change were being excavated by excavators, and soil removed by trucks (Annexure II:, Figure A3 b,d) while areas with positive changes corresponded to active disposal sites (Annexure II: Figure A3 b,c). Daily volumetric changes in the four dumping areas denoted in Figure 3-8 sum to 5685 $m^3 \cdot day^{-1}$, which corresponds to estimated volumetric changes obtained by converting reported tonnage to volume using a waste density range of 1 to 1.5 $Mg \cdot m^{-3}$ (Table 3-4). If considering a waste density estimate of approximately 1.1 $Mg \cdot m^{-3}$, as used by the site's monthly statistics reports[5], the estimated volume change is in fact within 97% of the in-situ result. However, if the volumetric changes in the entire landfill site area is considered, the daily change is 2577 $m^3 \cdot day^{-1}$, which is below the range of expected values. This is attributed to the

[5] https://www.uaesp.gov.co/content/informes-supervision-disposicion-final

negative volume changes from excavation also being included in the estimate, and large areas having small local change values, potentially due to local errors in the underlying DEM used to produce the change maps. This can be seen from the large area in Figure 3-8b with the slightly pink hued color, which represent a small but negative volume change rate.

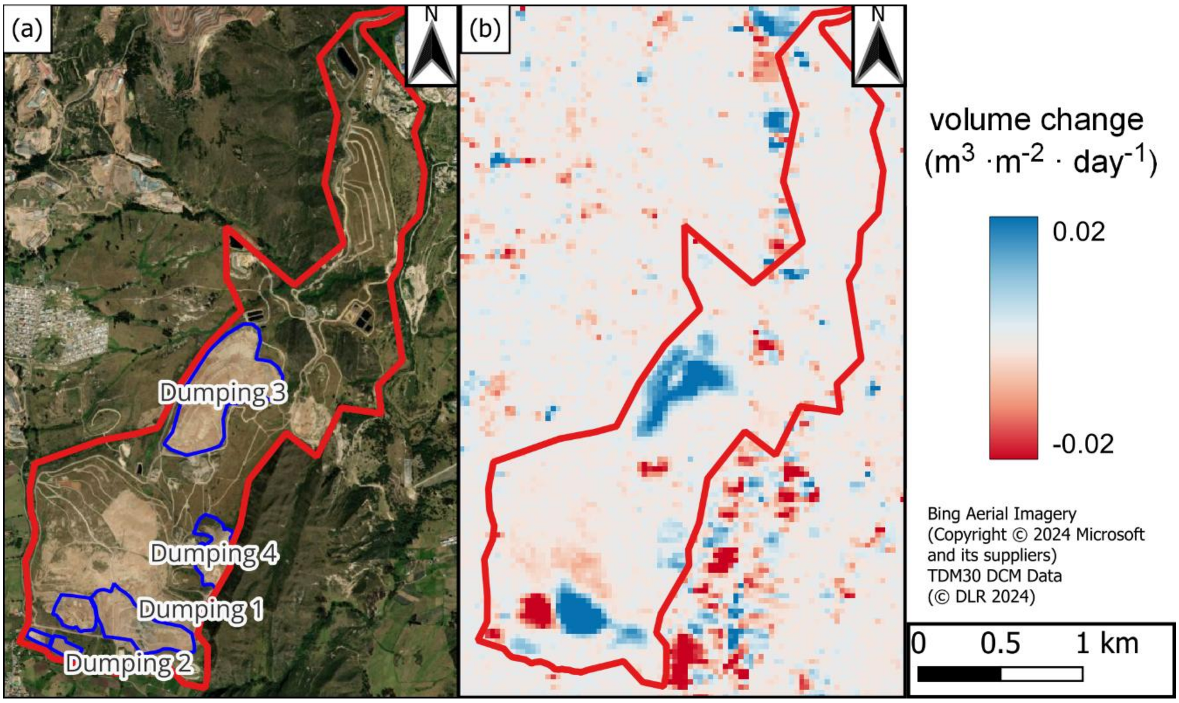

Figure 3-8 Map of the Doña Juana Landfill, showing (a) high resolution Bing Aerial imagery with the active dumping and excavation areas denoted by blue polygons, and (b) the daily volumetric change estimated from DCM data.

3.3.3.2. West New Territories landfill (WENT)

Temporal analysis of high-resolution satellite imagery for WENT (Annexure II: Figure A5-2, Figure A5-3) revealed that the tipping face of the landfill changed over time during the study period, However, three main active dumping areas were identified, and are denoted in Figure 3-9. The daily DCM-estimated volumetric change in these active areas of WENT was 6307 $m^3 \cdot day^{-1}$, and correspond to the volumetric change estimates from the annual waste reports for WENT (Table 3-4).

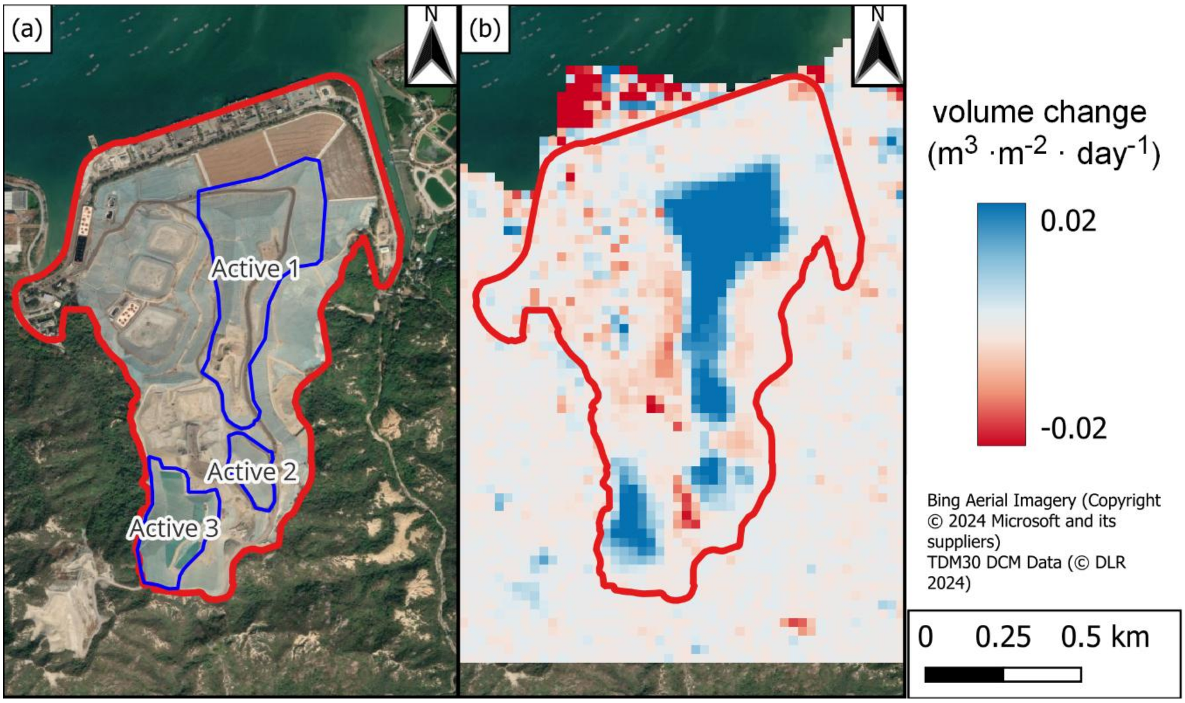

Figure 3-9 Map of the West New Territories landfill in Hong Kong, showing (a) high resolution Bing Aerial Imagery with the active dumping areas denoted by blue polygons, and (b) the daily volumetric change estimated from DCM data.

3.3.4. Period 1 validation

As explained earlier, due to ambiguity in the temporal aspect of the period 1 data, it is not possible to calculate precise volume change rates for period 1. However, a significant portion of locations (24% of considered sites in this study) may not have *period 2* data, or data with a very short time interval, leading to high volume change error (Figure 3-7a). Therefore, if data coverage is a higher requirement than measurement accuracy, it may be preferable to use the *period 1* volume estimate, which is available everywhere. Therefore, in this section results from *period 1* for two landfills that had insufficient *period 2* data are evaluated.

The North of the Seventh Ring Road landfill in Kuwait has been closed since 2005 (Kuwait Environment Public Authority, 2022), and thus volume changes are expected to be negligible in the site. The period 1 volume change shows a constant white/grey color, indicating the expected "no-change" in the closed landfill. Interestingly however, the *period 2* estimated volumetric change rates are clearly erroneous, at 35,626 $m^3 \cdot day^{-1}$. The DCM data coverage for *period 2* was short, at 22 days, between 16 Aug 2018 and 6 September 2018, making it susceptible to volume change errors, as explained earlier. This large and erroneous estimated change is thus in agreement with our expectation (See Figure 3-7; Equation 3-7). The volumetric change map for period 2 also reflects this error, showing a speckled pattern of extreme volumetric increases and decreases in adjacent pixels (Figure 3-10c).

The Mediouna Landfill in Morocco (Décharge de Médiouna) did not have data coverage for *period 2* (Figure 3-10 f). So, only the period 1 volume change estimate is available. The data for period 1 shows clear volume increase inside the landfill area (Figure 3-10 e). The overall volume change rate for the measured period from June 2012 to September 2018 is estimated at 2571 $m^3 \cdot day^{-1}$(Annexure III, p. 95). Literature for the site from 2017 reports that on average 3500 Mg of domestic waste was being delivered to the site daily (Florin & Garret, 2017), and by it 2019 was reported at 3660 Mg per day (Younsi, 2019) , and by its closure in 2021, 3800 Mg per day (Kaiss, 2024). These reported values are higher than estimated from the *period 1* data (i.e., 2571 $m^3 \cdot day^{-1}$), but it should be noted that the reported values show a clear increase in waste disposal over time. If this trend was also present earlier, it would make sense that the period 1 volume changes – which is essentially an average daily change from the period 2012 to 2018 – would be lower than reported values from the end of the study period. However, without in-situ data directly for the earlier period, it is only speculation.

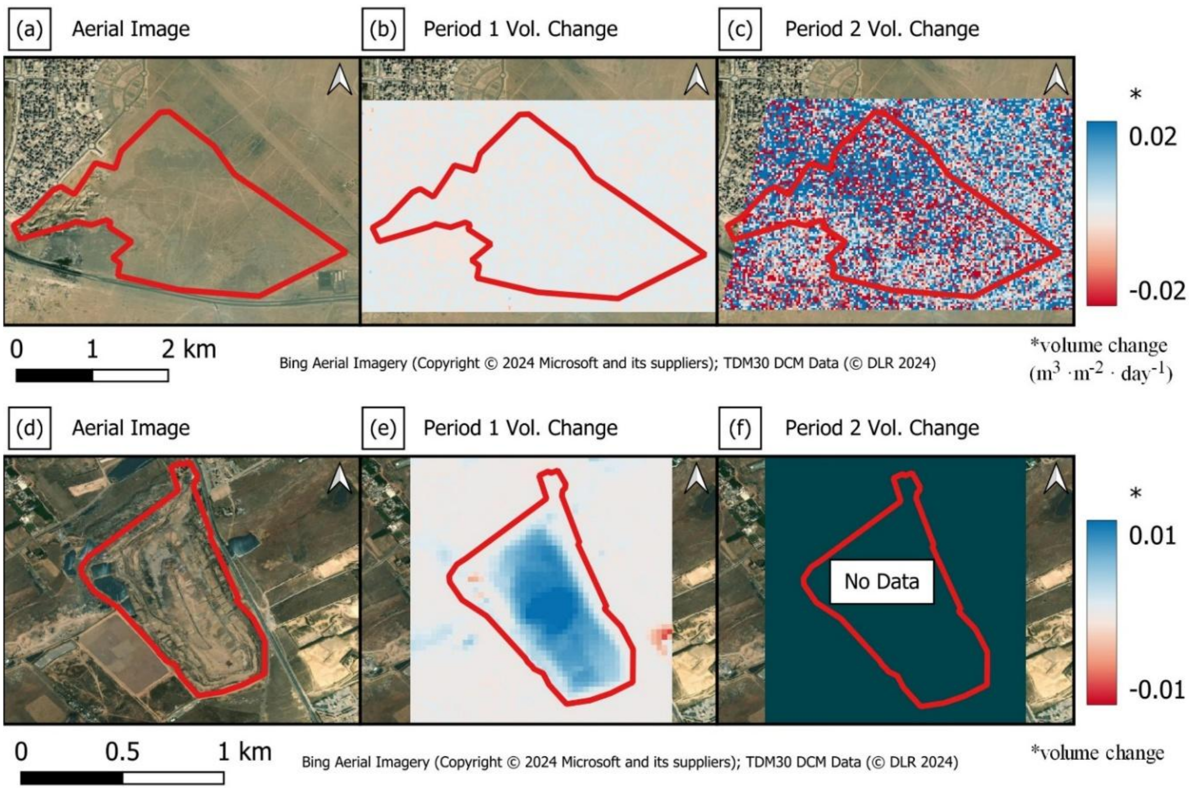

Figure 3-10 Volume change for period 1 and 2 for the closed North of the Seventh Ring Road landfill in Kuwait (a – c), and the Mediouna Landfill in Morocco (Décharge de Médiouna). The period 2 data coverage interval for North of the Seventh Ring Road landfill is 22 days, and Mediouna Landfill is 0 days (i.e., no data).

3.4. Discussion

This study proposed a dataset and methodology that could be used to estimate volume of waste dumped in landfills, without on-site measurements. The methodology could be used to remotely estimate the dumping rate of waste in landfills over large areas/regions, including regions with no officially reported waste dumping data. The method could thus supplement other sources of global waste statistics.

As shown in Figure 3-6, the temporal coverage of the dataset varies among landfill sites but is in a window between 2018 and 2021. This shows that the dataset, although recent, will not be suitable for ongoing/real-time monitoring of landfill dumping, but can only give a global snapshot of waste dumping patterns within the time frame of the dataset. Still, the time frame is more recent than, at the time of writing, the most recently available global waste data products (Kaza et al., 2018; United Nations Environment Programme, 2024). Further, although waste dumping patterns change over time with local population change, consumer behaviour, and new waste management policies, the changes are often steady and can be estimated for specific regions (Chen et al., 2020). Therefore, it may be possible to use the DCM dataset to inform a new “baseline” of landfill dumping patterns across regions/cities, and then extrapolate more recent statistics using estimates of changing dumping patterns over time, as done by Chen et al. (2020), who used the *What a Waste 2* (Kaza et al., 2018) dataset as source material. A time snapshot of global waste dumping patterns – as may be obtained from the proposed methodology – may additionally be valuable for studies that correlate waste dumping patterns to other social and economic indicators, in order to identify factors influencing waste dumping patterns in different regions (Antczak, 2020; Syafrudin et al., 2023). A further point to be noted here is that the Tandem-X mission is still operating nominally and continues to collect DEM data that can realise ongoing monitoring efforts in landfills. The data considered in this study (the DCM product) was collected during the Tandem-X Science Phase between 2016 and 2022. However, since then the mission has entered its ‘4D Phase’, which focuses specifically on collecting DEM change data for monitoring temporal elevation change around the world (Bachmann et al., 2023). Although not yet released as a public dataset like the DCM dataset, the future release of updated Tandem-X elevation change data will enable acquiring newer landfill dumping volume data using the same methodology as in this study.

In addition to the periods of data coverage, the lengths of the data coverage periods also varied significantly among the 100 study sites, with 24 % of sites having no temporal coverage for the desired *period 2*, and more than 30% (n = 33) with the time between the first and second DCM acquisition dates below 50 days (Figure 3-6). There was a sharp increase in estimated error at sites with temporal coverage below 50 days (Figure 3-7, Table 3-3). This spike in measurement error for sites with a short temporal data coverage was also observed empirically in the closed North of the Seventh Ring Road landfill in Kuwait, which had a data coverage period of 22 days for *period 2* (Figure 3-10). This shows that although the data product has global coverage, volumetric changes cannot be accurately estimated for all landfill sites, but rather only landfill sites that have sufficient temporal gap between the first and second DCM maps of the site. The error in volumetric change estimates decreases with increases in temporal gap (Equation 3-7; Figure 3-7). Therefore, future studies using this dataset should pay attention to the temporal gap between the DCM products. In addition to the increase in estimated error, short temporal coverage also means that the derived statistics are representative only of a short temporal window. Possible seasonal/temporal variations in waste dumping patterns can also be better accounted for if the temporal coverage of a site is longer.

Estimated volumetric changes may vary depending on the specific area within the landfill being considered (Figure 3-8). This is because activities other than waste dumping also affect volumetric changes in a landfill area. For example, at times soil is excavated from certain areas in landfill sites to prepare new waste cells, or to be reused for covering soil layers in the working face of the landfill (Yachiyo Engineering Co., Ltd & EX Corporation, 2004) or for other applications (Datta et al., 2021). There are also cases where infrastructure such as gas recovery and waste-to-energy facilities are constructed within an existing landfill (e.g., UNFCCC & CDM Executive Board, 2015). Such infrastructure will result in changes in DEMs produced of the landfill and could erroneously be considered in landfill waste estimates. Therefore, to only extract statistics of volumetric changes resulting from waste disposal, future studies need to pay attention to the selection of appropriate area of interests (AOIs) in individual sites. In this study landfill polygons from the OpenStreetMap database were used, and active dumping areas identified from time-series of high-resolution satellite imagery. However, if landfill statistics for many sites need to be extracted semi-autonomously, further work should establish a method from which the active dumping areas in a landfill site can be automatically determined. InSAR coherence datasets, such published by Kellndorfer et al. (2022), can potentially be used as input for determining specific areas of activity in landfill sites, since quick temporal decorrelation – causing low InSAR coherence – is characteristic of active landfill sites (Ottavianelli, 2007). Such InSAR coherence datasets and optical imagery may be used together as inputs to machine learning models that can classify the active dumping areas in landfill site (Torres & Fraternali, 2021).

Waste dumping metrics are generally reported and used in terms of waste mass (Statistics Unit, Environmental Protection Department, 2020; United Nations, 2020). However, the methodology proposed in this study estimates the change in the volume of landfills. If the density of waste within a landfill is known, the waste mass can be calculated from volume, as was done to validate measurements for the two case-study sites in this study (Table 3-4). However, waste density varies depending on waste composition (moisture content, proportion of organic waste, etc.), landfill type (municipal or construction waste landfills, open dump or sanitary landfill), and management approaches in particular landfills (Zekkos et al., 2006). Therefore, applications that require waste statistics reported in terms of mass need to extend and modify the methodology proposed here to also bring into consideration the conversion of waste volume estimates to mass, which will vary by regions and landfill types.

3.5. Conclusion

To the authors' knowledge, this study is the first to use Single-Pass SAR Interferometry derived Digital Elevation Models to estimate waste volume change in landfills. Validation against officially reported statistics for selected landfills showed higher accuracy than prior studies that used Repeat-Pass or Differential InSAR based approaches. The method proposed here could thus be refined and applied for landfill dumping monitoring, especially in light of increased availability of Single-pass interferometry capable SAR data in future (Bachmann et al., 2023; Deng et al., 2024).

Since the study used and evaluated a publicly available 'analysis ready' dataset with global coverage, the method proposed here can be adopted by national waste authorities or other stakeholders to compile waste dumped statistics for their areas of interest. This work may thus support efforts to improve global waste dumping data availability, and facilitate measurement of waste-dumping related SDG Targets (United Nations, 2020).

Finally, this work showed possible sources of error in the methodology (i.e., higher error with short temporal data coverage, volumetric changes caused by reasons other than waste dumping) and thus offer direction for follow-up research.

Chapter 4: Application Case Study: Remote measurement of landfill dumping volume, to support national waste reporting in South Africa.

This chapter is an extended version of the research titled "Remote measurement of landfill dumping volume, to support waste reporting systems", presented at the International Solid Waste Association World Congress 2024, Cape Town, South Africa 16 – 18 September 2024.

4.1. Background

Developing countries often struggle with inadequate reporting of waste-to-landfill data, which is reflected in the relative scarcity of waste statistics data for these countries (Kaza et al., 2018; Maalouf & Agamuthu, 2023). These data issues arise from insufficient infrastructure at landfill sites, such as weight bridges for incoming trucks, and waste reporting systems that are not managed correctly (Salvia et al., 2021; Srivastava et al., 2015).

Remote Sensing based estimation of waste volume, as described in the previous chapter, could support waste reporting efforts in countries with insufficient in-situ reported statistics, or supply data for areas without any. As a case-study application this chapter demonstrates the scaling of the method described in Chapter 3 to estimate waste disposal in South Africa, and so complement the existing national waste reporting system, known as SAWIC[6] (South African Waste Information Centre).

South Africa relies primarily on landfilling as final disposal method for waste, with only 11% of waste being diverted from landfill . However, government and other initiatives are working to increase diversion of waste from landfills and improve waste management in general, in light of projected shortage of landfill airspace in the near future (3SMedia, 2022; Githathu, n.d.). The National Waste Management Strategy 2020 outlines South Africa's waste management policy to achieve more sustainable long-term management of waste. The document highlights the need for improvement of waste data capture, stating that all private and municipaly-managed landfill sites are required to report annual waste dumping statistics (DEFF South Africa, 2020). However, it is known that many municipalities do not comply with waste management legislation, and some also operate unlicensed, effectively outside the radar of the official waste reporting system (*Status of Waste Management in South Africa*, 2022). This situation thus reduces the reliability of the statistics reported at the national level, since

[6] https://sawic.environment.gov.za/

not all municipalities' landfills are accounted for. It is also understood that in some cases municipalities do not have functional weighbridges at sites, so that reported waste disposal data may be based on guesses of the landfill operating staff[7]. There are also cases where centrally reported data contains errors, resulting from incomplete or wrong data entering by the responsible staff[8]. However, for central government to assign appropriate waste management resources to local municipalities, as well as assess progress toward waste diversion goals it is necessary that waste disposal data be both complete and accurate.

Since South Africa has an existing waste reporting system in place, but with uncertain data quality, a secondary validation source such as satellite remote sensing data could serve to confirm correctness of reported statistics, and flag possibly erroneous data entries (i.e., if reported statistics for a municipality differs largely from remotely estimated dumping amount it could be flagged for review and confirmation of accuracy.) The objective of this research was to use the Tandem-X DEM based DEM Change Map (DCM) product to calculate volume changes in all landfills in South Africa's 8 Metropolitan Municipalities, and then estimate waste disposal tonnages in each municipality by multiplying the measured volume changes with estimated waste density in the sites. Waste density was estimated by comparing measured volume changes with reported tonnage at the landfill level, which was available for the landfills in the *City of Cape Town* and *City of Johannesburg* municipalities.

4.2. Methodology

4.2.1. Study Area

This study focused on the 8 Metropolitan municipalities in South Africa. Metropolitan municipalities are large level 2 administrative jurisdictions in the largest cities in South Africa, including the cities Cape Town, Johannesburg, Pretoria, Durban, Port Elisabeth and Bloemfontein. Apart from Metropolitan Municipalities south Africa also has 44 district municipalities and 205 local municipalities. Together, the Metropolitan Municipalities had in 2022 a population of approximately 24.9 million people, accounting for 40.1% of the South African population (Statistics South Africa, 2023). The Metropolitan municipalities together had 42 landfill sites. A map of South Africa, with Metropolitan municipalities and landfills sites is given in Figure 4-1.

[7] Based on personal communication with landfill manager during phone call interview, 6 September 2023
[8] Confirmed by email conversation with Makhozosazana Baker, City of Johannesburg, 23 April 2024.

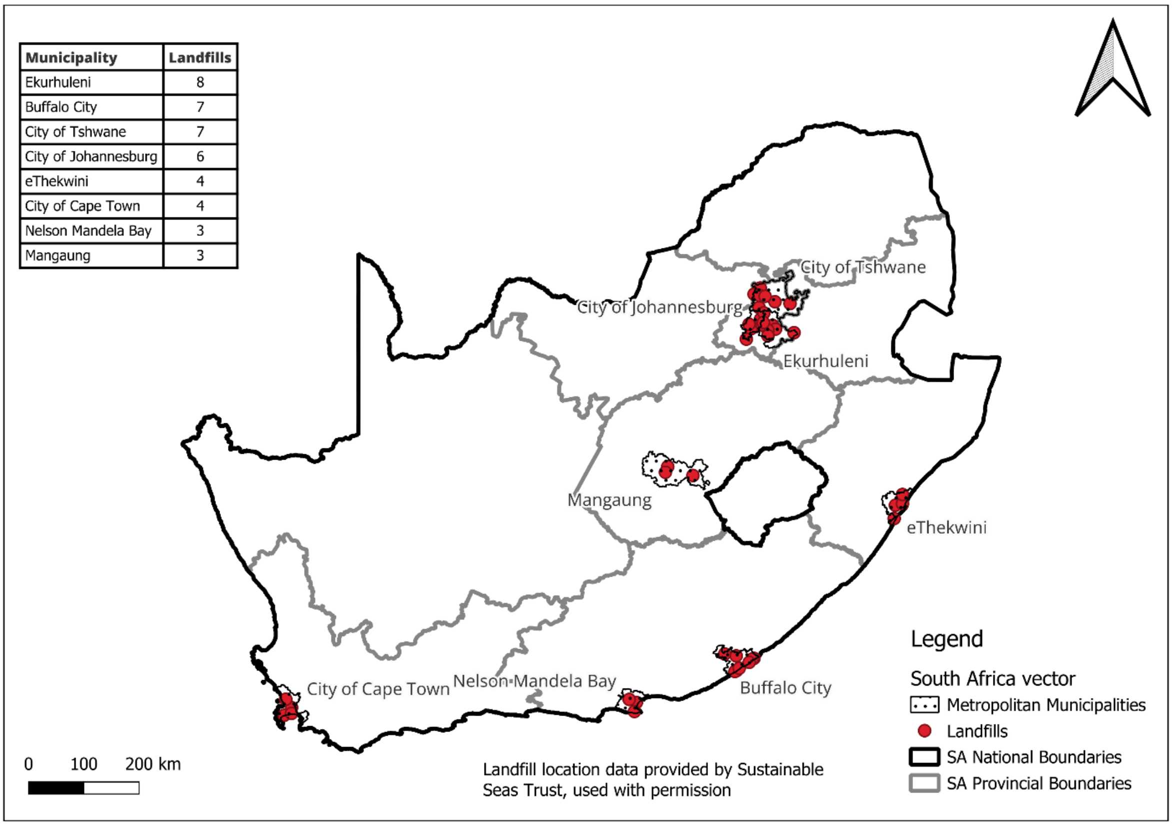

Figure 4-1 Map of South Africa, with Metropolitan Municipalities and landfill sites denoted. The inset table gives the names of the eight municipalities and the number of landfills in each.

For calibrating the waste density estimate used in the analysis, site specific reported statistics were acquired for the landfills in the City of Cape Town and City of Johannesburg municipalities, which is elaborated in section 4.2.2.3 and will be omitted here. The 8 largest municipalities in the country were chosen for this case study, since they represent a large proportion of the country's population, and landfill location data could reliably be gathered for these municipalities. In the hundreds of local municipalities, especially in more rural areas, it is known that the waste management systems are often not well managed, leading to a low waste collection rate, and the location of dumping sites are not documented reliably. Additionally, even if some landfill locations could be verified, the manual digitization of site perimeters for the hundreds of landfills was deemed unfeasible within the availability time. Therefore, the case study focused on the 8 metropolitan municipalities. However, the gathering of site location data for small landfills, and the application of the method to them would be critical in an actual implemented monitoring system and should thus be given priority in follow up work.

4.2.2. Data

4.2.2.1. Landfill location data

For this study, landfill locations were acquired under a non-disclosure agreement from the Sustainable Seas Trust (SST) non-profit organization. The SST has compiled a database of waste management infrastructure in South Africa (Swanepoel, 2020). The data consists of site longitude and latitude (point location) and site attributes such as the name, managing entity, operating hours, waste types received, etc. The sites in Metropolitan municipalities were selected, and then the perimeters of sites were manually digitized into polygon vector files in GIS by overlaying and then visually assessing high resolution satellite imagery from Bing Aerial and Google Satellite. It was found that the Ennerdale landfill in Johannesburg was omitted from the provided SST dataset, so Google Map and Google Street View was used to confirm its location and then digitize its perimeter as in the case of the other sites.

4.2.2.2. DEM Change Map Data

DEM Change data from the Tandem-X DCM product was acquired for each landfill from the EOC Geoservice of the Earth Observation Center (EOC) of the German Aerospace Center (DLR). In this analysis the ability to measure volume changes for all target sites was more important than the measurement accuracy, and therefore the *period 1* DCM data was used exclusively. The *period 1* data was assumed to be captured from mid-2012, as in Chapter 3, and the end date for the data was different between the landfills but is given for each site in Table 4-2.

To enable bulk processing (i.e., across multiple landfill AOIs at the same time) while constraining data download sizes, a custom program was developed in the R-programming language, and using the terra geospatial data analysis library (Hijmans, 2022). The program restricted data download sizes by using the GDAL Virtual File System's (vsicurl and vsizip) functionality to only download the subset of raster data overlapping with landfill AOIs. This allowed for the download of all locations' DCM data to only use a few megabytes of storage, while in the past it was necessary to download 1-arc degree tiles of the data, which was several hundred megabytes each.

4.2.2.3. Reference landfill reported disposal data

In this study, landfills from the City of Cape Town and City of Johannesburg municipalities were used as references from which volume-mass ratio's were calibrated for the landfills in all the municipalities. The landfills and information such as their area and location are listed in Table 4-1.

Reported landfill data for City of Cape Town is available from the city's GIS Authority (City of Cape Town Corporate GIS, 2025). This data currently reports statistics from 2015 to 2024 in monthly intervals. It includes the waste received, disposed and diverted in the city's waste management facilities. During the study period the city had 3 active landfills: Bellville South Landfill, Vissershok landfill and the Coastal Park landfill. The Bellville landfill was however closed since 2022 (City of Cape Town, 2022), and before that (from 2018) only primarily received building rubble and garden waste, which is reported to be reused instead of landfilled. The Vissershok landfill received waste by rail from all the Waste Transfer Stations (RTSs) in the city (i.e., Athlone, Kraaifontein, Bellville and Swartklip RTSs), but the waste is measured at the RTSs and not again at the Vissershok weighbridge, so I was advised[9] to count all the RTS statistics to the Vissershok landfill. Furthermore, the city reuses building rubble for roads and cover material, and also diverts garden waste, so only the general and special waste streams were counted toward landfilled tonnages. The information summarised here were acquired from the city's website (City of Cape Town, 2025b, 2025a), from the metadata of reported statistics (City of Cape Town Corporate GIS, 2025) and direct correspondence with the city's department of Integrated planning. For the City of Johannesburg, the five landfills managed by the city's waste management company Pikitup were considered, since the site level data were reported in the company's annual waste report (Pikitup, 2019). However, the data did not differentiate waste streams and diversion, so just the available values were used.

The reported statistics for the reference landfills did not overlap entirely with the *period 1* of the DCM data used for the estimations. Specifically, the DCM *period 1* is for mid-2012 to end-2018 or beginning-2019 (depending on the landfill, Table 4-2). However, the city of Cape Town data was only available for the period 2015 to 2019, and the City of Johannesburg data was available from their 2014-2015 data year, to the first semester of the 2018-2019 data capture year. To fill in the reported tonnages data gap for the period 2012 to 2014, ARIMA (Autoregressive Integrated Moving Average) models were fitted to the reported data for 2015 to 2019, and then time-series forecasting was used to estimate the missing observations for the period from 2012 to time when reported data began. The ARIMA models were fit using the *auto.arima* function from the R package 'forecast' (Hyndman et al., 2024). The *auto.arima*

[9] Email correspondence with the Management & Geographic Information Services staff of Department: Integrated Planning , City of Cape Town

model consecutively fits different model order combinations and calculates metrics of fit for each. The model with the lowest corrected Akaike Information Criterion (AICc) value is selected as the final model. To evaluate the model fit the model residual plots are evaluated to confirm that the residuals were random (with no clear trend or pattern), approximately normally distributed, and without significant autocorrelation. The Ljung-Box test was finally used to test for autocorrelation in the fitted time-series's residuals. Finally, the forecasted time-series was added to observed time-series (so that it represented data for the entire study period), and the average daily disposal over the entire study period was then estimated for each site. This calculated average daily waste disposal for each site as well parameters of the fitted ARIMA-models for each site are given in Table 4-1.

Table 4-1 Information of landfills considered as reference to estimate waste density, through comparison of measured volume change with reported tonnages. The ARIMA terms are p: Autoregressive order, d: degree of differencing, q: Moving Average order. Ljung-Box test has null-hypothesis of no autocorrelation in model residuals.

Municipality	Landfill Name	Area (ha)	Location (lat., lon.)	Reported disposal ($Mg \cdot day^{-1}$)	ARIMA (p, d, q)	Ljung-Box test p-value
City of Cape Town	Bellville South	61.5	(-33.935, 18.651)	637	(0,1,0)	0.436
	Coastal Park	76.65	(-34.090, 18.501)	1022	(0,1,1)	0.85
	Vissershok	255.27	(-33.766, 18.534)	1610	(0,0,0)	0.155
City of Johannesburg	Robinson Deep	63.30	(-26.233, 28.038)	1577	(0,1,0)	0.151
	Marie Louise	28.82	(-26.190, 27.884)	945	(0,0,0)	0.331
	Goudkoppies	41.79	(-26.281, 27.925)	861	(0,0,0)	0.309
	Ennerdale	15.04	(-26.369, 27.834)	253	(0,0,0)	0.134

4.2.2.4. South African Waste Information Centre (SAWIC) data

SAWIC is the government's central platform to which landfill managers from all municipalities need to submit annual disposal statistics (Department: Forestry, Fisheries and the Environment, 2025). Statistics released to the public are reported annually at the municipality level (provincial or national aggregates can also be requested). It states the number of facilities considered and waste tonnages in different stream (general, hazardous, and total). However, the amounts of waste collected, diverted and sent to landfill are not differentiated. Due to the ambiguity in the SAWIC data, I use SAWIC collected for the metropolitan municipalities not as a strict validation method for estimated results, but merely as a rough reference for comparison. The intention is to show that the proposed method can supply information of a similar nature to the current official reporting system.

4.2.3. Volume Change and Tonnage estimation

In this study the first DCM image (i.e., period 1 data, as described in chapter 3) was used exclusively to calculate volume changes in landfills. The date for the EDEM was fixed to 2 July 2012, which is approximately the centre point of the full data collection period for EDEM. As explained in Chapter 3, this time fixing was necessary since the final EDEM is a merged product of data collected between 2010 and 2014, which means the exact time stamp of the elevation reported at a particular location in EDEM is not known.

The method introduced in Chapter 3 only determines volume changes in the landfill. Thus, to estimate disposed waste mass, it is necessary to determine the relationship between volume change and disposed tonnages. This relationship is denoted as the waste density (measured in Mg per cubic meter). Waste density is known to vary with the composition of waste, the compaction technique used in the site, and the amount of cover material used between waste layers (Feng et al., 2017; Owusu-Nimo et al., 2019; Zekkos et al., 2006). The approach used in this study to estimate waste density for the South African landfills was to calculate waste density Equation 4-1 in the seven reference landfill sites introduced in section 4.2.2.3, and then use the average of these densities as the density for all the other landfill sites. Then, waste disposal tonnages can be estimated for each non-reference site by multiplying the waste density estimate by measured volume changes in the site (Equation 4-2).

$M_{reported}$ – reported average daily waste mass disposed in site (Mg)

$V_{measured}$ – measured average daily volume change in landfill (m^3)

Wdensity –Waste density (Mg m^{-3})

$Wdensity_{av}$ – Average waste density from all reference sites (Mg m^{-3})

$$Wdensity = \frac{M_{reported}}{V_{measured}} \tag{4-1}$$

$$Estimated\ waste\ disposal\ (Mg) = V_{measured} \times Wdensity_{av} \tag{4-2}$$

4.3. Results

4.3.1. Reference landfills and waste density estimation

Among the seven reference landfills, the relationship between measured volume changes and the officially reported statistics was fairly consistent, having a Pearson's correlation coefficient of $r = 0.85$ (Figure 4-2). The relationship between volume change and disposed tonnages was approximately 1-1, since the average ratio between reported tonnages and measured volume changes, i.e. $Wdensity_{av}$, was 1.09. This can also visually be observed by the data points placed around the 1-1 line in Figure 4-2. However, there was also some variation among the sites, with standard deviation of 0.33. In particular, the Vissershok landfill in Cape Town had a notably larger volume change relative to the reported tonnages for the site. Further, if considering the municipality (which is indicated by the point shape in the figure), it becomes clear that City of Johannesburg's points are all above the 1-1 line, while the City of Cape Town's landfills are all below. The possible reasons for this pattern, and its implications are covered in the discussion section. Still, the calculated waste density $Wdensity_{av} = 1.09$ was used in the following step of scaling up measurements to other municipalities.

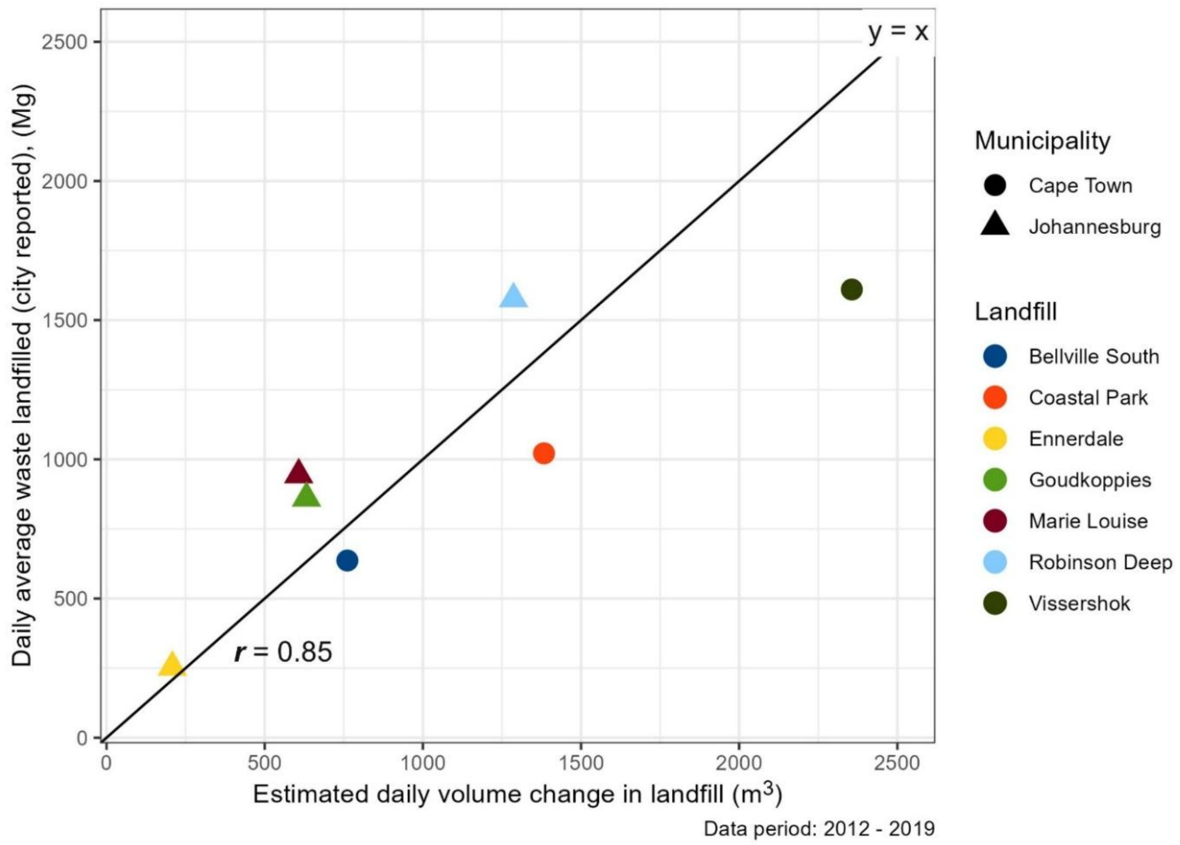

Figure 4-2 Measured volume changes against reported landfilled tonnages in seven landfills. Average daily rates are shown for the measured period approximately 2012 to 2019, although

exact data coverage period differs between landfills. Point colour differentiates landfill, and shape indicates the two municipalities that the landfills belong to.

4.3.2. Waste dumping estimates in Metropolitan Municipalities

The volume change in the 42 landfills in 8 Metropolitan Municipalities were calculated for the period July 2012 to dates in the period 2018/19 (the end of the capture period differs between landfills) (Table 4-2).

Table 4-2 Calculated average daily volume change in the 42 landfills in South Africa's Metropolitan Municipalities. The end of data capture period is also reported.

Municipality	Landfill	Surface Area (ha)	Volume change (m^3 day^{-1})	Data end date (YYYYMMDD)
Buffalo City	Roundhill Landfill Site	24.3	202.40	20190623
	King Williams Town Landfill	26.9	41.95	20190703
	Riegers Landfill Site	6.6	0.91	20190509
	Christmas Rock	1	1.66	20190703
	Kaysers Beach	1.1	-1.05	20190703
	Kidds Beach	4.9	-0.53	20190623
	Beacon Bay	2.3	-12.29	20190509
City of Cape Town	Coastal Park	76.7	1382.84	20190207
	Vissershok	255.3	2356.00	20190207
	Bellville South	61.5	761.30	20190207
	Swartklip	48.3	97.21	20190207
City of Johannesburg	Linbro Park Landfill	71.4	357.36	20190527
	Marie Louise Landfill Site	28.8	607.59	20181211
	Robinson Deep Landfill site	63.3	1286.75	20181211
	Goudkoppies Landfill site	41.8	632.11	20181211
	Palm Springs Landfill	10.6	111.79	20190913
	Ennerdale Landfill	15	208.19	20190913
City of Tshwane	Hatherly Landfill Site	43.2	794.80	20181119
	Bronkhorstspruit landfill site	14	54.88	20170927
	Soshanguve landfill site	32.9	179.95	20190527
	Ga-Rankuwa landfill site	14	130.19	20190527
	Onderstepoort landfill site	22.3	11.74	20190527
	Mooiplaats Landfill	26.2	165.01	20190527
	Bon Accord	9.3	81.40	20181119
Ekurhuleni	Weltevreden landfill	161.3	686.38	20190527
	Rietfontein landfill	44.1	442.40	20181119

	Simmer and Jack Landfill	54.3	647.84	20190527
	Rooikraal landfill	69.6	522.63	20190527
	Devon landfill	1.9	-3.85	20170927
	FG Landfill Site	45.8	951.65	20190527
	Chevron Crushtech	8.5	124.51	20190527
	Platkop Landfill	64.1	309.26	20190527
eThekwini	Bisasar Road Landfill	62.1	942.26	20190611
	Mariannhill Landfill Site	9.9	645.67	20191011
	Buffelsdraai Landfill Site	35	403.36	20190611
	Lovu Landfill Site	38.7	199.32	20191011
Mangaung	Southern landfill site	91.8	321.68	20190703
	Northern landfill site	95.3	-91.55	20190703
	Botshabelo landfill site	36.5	54.99	20190623
Nelson Mandela Bay	Aloes Hazardous	54.8	96.73	20190627
	Arlington	66.1	636.49	20190627
	Koedoeskloof	76.3	369.30	20190627

Using the average waste density determined in the reference landfills, the waste mass (tonnage) was estimated for the 42 sites and then aggregated to the municipality to allow comparison with the SAWIC data, which is reported at the municipality level. The result of this analysis is reported in Figure 4-3. For most of the municipalities the remote sensing estimated waste disposal agreed relatively closely to the SAWIC reported values, with the difference between the reported and estimated (the bias) approximately an order of magnitude smaller than the reported values. However, since the SAWIC data does not differentiate landfilled and diverted waste and is known to be susceptible to data entry errors from municipalities, this comparison is not intended as a validation of the calculated values but as comparison. Indeed, a number of municipalities had larger SAWIC reported tonnages than estimated, especially the City of Tshwane Mangaung.

Figure 4-3 Estimated against reported landfilled tonnages in South Africa's metropolitan municipalites. Points represent annual reported amounts, obtained from SAWI, and the blue line is the average of the reported values. The red line represents the estimated average annual diposal in the study period, obtained by remote sensing. The bias value reported on each subplot is the difference between the average of reported and the remote sensing based estimate.

4.4. Discussion

This case study demonstrates that satellite InSAR derived DEM data can be used to estimate dumping in many landfills 'at-once' and so support government-based data capture. Estimated volume changes in 42 landfill sites for eight municipalities and corresponding waste disposal values corresponded well with reported waste disposal statistics at both individual site and municipality level within the data capture period (Figure 4-2, Figure 4-3). It was also possible to identify municipalities where reported waste disposal differed largely from the remote sensing derived data, such as the City of Tswhane (Figure 4-3). In this municipality the difference between estimated and reported differed by more than 1.6 million Mg per year, on average, and the reported values also fluctuated strongly between years. According to recent publications by the city's waste authority, the city is experiencing problems with waste data collection due to lacking weighbridges at the municipality's landfill sites, which may explain the source of this irregular pattern in the reported data (Dept. Environment and Agriculture

Management & City of Tshwane, 2025). This highlights that a remote sensing based approach as proposed here could possibly serve as a secondary validation tool to help flag possibly erroneous data entries reported to SAWIC. For example, the central waste authority could identify cases where data reported from a municipality differs significantly from the remote sensing estimate, which would allow them to follow up with the municipality and verify that reported statistics were correct.

However, all statistics reported here are only until 2019, due to more recent TanDEM-X DEM change not being available in the DCM data product for the majority of sites. Also, the waste disposal from the DCM data does not have a temporal frequency (e.g., data once per year) but instead corresponds to a single estimate value for the entire data period (2012 – 2019). This precludes the measurement of trends and changes in dumping patterns. Stated otherwise, the low temporal resolution of the elevation change data used in this study hampers the workflow from directly being useful as an operational landfill monitoring tool.

However, the methods developed and presented here could be applied using other satellite data sources for DEM change data. These data sources are required to be un-affected by temporal decorrelation during InSAR processing and have revisit cycles to the target landfill sites frequently enough to match existing data capture systems. For example, if waste data is required to be reported annually, as in the case of South-Africa, then the DEM data will also need to be updated at least annually, so that volume changes calculated using that DEM data can be supplied at the same temporal frequency as required by the existing national legislation. Furthermore, the elevation uncertainty associated to the DEM data needs to be small, especially if higher frequency data is required. This is because as the time between measurements shorten, the magnitude of elevation change in the landfill during that time span will be smaller. And, if the actual elevation change is smaller, the elevation uncertainty in the DEM will represent a larger proportion of the measurement. In other words, if the measure period becomes shorter, the relative error in the change measurement will be larger despite the absolute DEM error being the same. Other considerations for suitable data sources and specific possibilities are further discussed in Chapter 5:.

Next, it is necessary to make some observations on the proposed way of relating volume changes to tonnages. In this case study, a few landfills in the region under study with reported annual tonnages were used as reference from which a waste density was estimated, and this waste density was then multiplied to volume changes in all municipalities. The waste density was thus necessarily assumed constant across sites. However, this would in reality not be the case. In fact, between the two municipalities used for reference sites already a clear distinction was observed, with city of Johannesburg waste densities being constantly higher than those calculated for city of Cape Town (Figure 4-2). This type of discrepancy may arise from differing management practises in different municipalities. For example, in the City of Cape Town only the general and special waste streams were considered as being landfilled, since other waste streams, such as builders rubble, are diverted from landfill to be reused for other purposes (City of Cape Town Corporate GIS, 2025). However, those reuse purposes include being used as cover layers for waste. Thus, while the building rubble is also added to the landfill and contribute to measured landfill volume changes, they are not counted toward tonnages. Of course, engineered landfills in the city of Johannesburg also require cover layers between waste. However, if they do not have the practice of reusing other waste like building rubble as cover layers, they may prioritise using the minimum necessary cover materials to save on cost and landfill airspace. Conversely, in Cape Town, the landfills may use thicker cover layers of the building rubble waste, since the cover material is free of cost and needs to be disposed of in any case. Such differences in management would result in different relations between waste tonnages and changes in landfill airspace. It is further worth noting that the considered reference sites were managed landfills in South Africa's most developed metropolises. In smaller and less well managed landfills in local municipalities the differences in management practises may be even more pronounced, leading to even larger variation in the relationship between waste tonnage and landfill volume. For example, some local municipalities may not have resources to use a compacting vehicle on the site, leading to a lower waste density in the sites. And, in rural landfills the practise of open waste burning is common (Mebratu & Mbandi, 2022), which also affects the relationship between the initial amount of waste going to the landfill, and the final volume change in the site. If a national authority wishes to determine waste tonnage disposal to landfill using the method proposed here, it could help to create a classification system for landfill type (e.g., engineered landfill, controlled dumpsite, open dump with waste burning, etc.), use field studies to determine the average density of waste in each of the landfill types, and then use the type specific relationship to create more accurate tonnage estimates.

Chapter 5: Primary contributions and limitations of the study

In this chapter I reflect on the specific advances and takeaways from the research presented in this thesis. I then highlight the main current shortcomings that will need to be addressed to realize remote sensing-based monitoring of landfill dumping.

5.1. Main findings and advances

This work is the first to show that digital elevation data generated from single-pass SAR interferometry can be used to measure volume changes accurately in landfills, opening the possibility for dumping monitoring applications. For context, there were a series of studies between 2012 and 2014 in Greece and Italy to implement a SAR DEM change based landfill monitoring tool (Cadau et al., 2013, 2014; Karathanassi et al., 2012). But the satellite radar data and interferometry techniques available at the time (Repeat-Pass InSAR) could not supply sufficiently accurate elevation data in landfill sites, which may be why the projects appear to have been abandoned. However, the SAR data made available through the DLR's Tandem-X mission enabled a different type of interferometric processing known as Single-Pass InSAR, which avoids the issues with Repeat-Pass InSAR in landfill sites (Zink et al., 2021). In this work DEM data from Tandem-X mission was successfully used to overcome the challenges in the immediately previous research. Further, some general considerations were identified that may be useful to stakeholders interested in implementing these methods. Namely:

- The accuracy of volume change measurements is strongly affected by the length of time between DEM observations. If the period is too short, estimated volume changes will be susceptible to error due random error in the DEM data used. The implication is that, if some application requires landfill volume change data at a higher temporal frequency, there will be a more stringent requirement on the DEM vertical accuracy, to achieve the same level of accuracy in volume change estimates. This relationship is derived in equation 3-6 and equation 3-7, and shown empirically in Figure 3-7.
- As shown in Figure 3-8, measured volume changes occurring within the perimeter of a landfill may be due to reasons other than waste dumping, such as the construction of new infrastructure, or excavation of old landfill heaps. Not accounting for such changes may lead to erroneous waste dumping estimates. This issue can be avoided by considering as AOI not the entire landfill perimeter, but only the waste dumping area (for example, the active cells in the case of engineered landfills). The implication is that entities responsible for compilation of landfill site boundary spatial datasets should pay

attention to delineate the actual dumping areas where possible. Current landfill spatial polygon datasets generally delineate the entire perimeter of the facility, rather than the specific are where waste is disposed.

Another main contribution of this work was the collation and assessment of global landfill location datasets. Although there are, or have been, a number of initiatives to map the location of landfills at the global or regional scale (see Section 2.1), this work was the first to collate (as far as possible) all publicly available landfill location datasets from national waste authorities, non-profit organisations, and crowd-sourced mapping projects such as OpenStreetMap. This contribution could help stakeholders interested to use landfill location data – such as environmental initiatives, the United Nations, or waste management researchers – to have a reference of the current state of available landfill data and which countries or regions there are available data for. It could also serve as roadmap for initiatives to improve global landfill location data coverage by highlighting the regions where data coverage is still low. Finally, this section also aims to encourage open sharing of landfill location data by governments, and gives some guidelines on maximising the usability of the data, such as the inclusion of descriptive metadata defining facility types and publishing data in spatial vector data formats such as 'geojson' or 'shapefiles' rather than pdf maps and tables, which cannot be easily used by other stakeholders.

Thirdly, the detailed assessment of landfill data in OpenStreetMap (OSM) is a contribution to the large body of literature on Volunteered Geographic Information (VGI). Past VGI research had focused on the quality of OSM land-use data in broad land-use classes (Wang et al., 2020; Zhou et al., 2022), completeness and accuracy of specific map components such as building footprints and road networks (Herfort et al., 2023; Nasiri et al., 2018), or on quality assessment approaches for OSM data: a review of which is given by Senaratne et al. (2017). However, this study provides the first specific assessment of landfill location data. Reference landfill datasets from a number of countries were used to assess the completeness of landfill data in OSM, and a study of attribute tags helped to show the availability or lack of important descriptive data needed for further applications of the dataset. Finally, an assessment of the global landfill dataset's coverage in over 11,000 cities globally, reveal regional patterns of data coverage (Figure 2-2). The observed difference in availability of OSM landfill data between regions reflect those observed in other map components, such as building footprints (Herfort et al., 2023). The findings from this section highlight that the majority of landfill entries in the OSM dataset do not currently have any descriptive information such as the type of facility (e.g., mine tailings facility, engineered landfill, or informal dump), which complicates its use in other research. Also, it highlights that for many developing regions there is very little landfills listed, and thus that the OSM dataset is currently not representative of the ground reality, even though it is the largest single publicly available landfill location dataset, with the widest coverage (i.e., global). The implication of these observations is that stakeholders who wish to use OSM landfill location data need to assess whether the data is representative or reliable for their specific study area. Also, the findings are a motivation for map contributors to increase the amount of descriptive data when annotating facilities, to improve the dataset's usability in research.

Finally, the South Africa case study – which used the developed dumping estimation method and landfill location data to estimate dumping in several large municipalities – was, to the author's knowledge, the first report of using remote sensing data to estimate landfill dumping for specific administrative districts with the objective of complementing official data reporting. This case study highlights that such a remote sensing based landfill monitoring tool could in principle be implemented, and has the potential to overcome current disposal data shortages in developing countries. However, the case-study also points out several caveats and considerations that need to be met before the technology could effectively be applied in an operational setting. These considerations are thus described in the following sub-section.

5.2. Current shortcomings, and data needed for effective implementation

Several challenges to the operational use of remote sensing data for landfill dumping monitoring were identified during this work. Although these are highlighted in the respective chapters, here I summarise them and point out some possible interventions or solutions for the attention of relevant stakeholders.

5.2.1. Elevation change data

The most immediate shortcoming of the proposed workflow is the temporal coverage of the DCM elevation change dataset, which makes it unsuitable for continuous monitoring of landfill volume changes. As explained earlier, the dataset currently only has a maximum of two observations for any location, which is from the collection time of EDEM (around 2012) until the first DCM map – around 2018 – 2019, and then for some locations there is a second change map until around 2020-2021. This temporal coverage is irregular, and already outdated in 2025 (the time of this research), making it unsuitable for routine monitoring applications. Therefore, other sources of elevation data with good elevation accuracy, and which can be captured regularly over time (e.g., yearly) need to be identified. With the rapid expansion of commercial remote sensing data services, including Synthetic Aperture Radar data, there may be an increasing number of data sources that can fulfil the requirements of this application. A summary of which is provided below in Table 5-1. Yet, the majority of the listed data sources represent at the time of writing new and 'leading edge' technologies that are in a developmental or deployment phase. Thus, these recommendations are intended to serve as guideline for future research, rather than data that can immediately substitute the TanDEM-X DCM data used in this study.

Table 5-1 Potential future temporal DEM data sources for landfill volume change measurement.

Potential Data Source	Description	Source
Tandem-X 4D Phase	Since 2022 the Tandem-X mission has entered its 4D phase, which focuses on measurement of temporal change data. This data may thus provide continuity to the current DCM product, which has data coverage only until 2021. A DCM dataset updated with more recent change data will provide an immediate continuation of the data used in this thesis. It will also be publicly available, improving the datasets accessibility. However, the issue of irregular timing of data will persist, and this dataset has also not been made publicly available at the time of writing	(Bachmann et al., 2023)
Commercial Tandem-X DEM data	The Tandem-X mission also provides higher resolution DEM and InSAR data commercially. This mission is ongoing, and provides updated acquisitions routinely, or on demand. This thus satisfies the need for monitoring applications. However, the data is made available at prices starting at $1,093.75 per sq km.	(Airbus Defence and Space, 2025; Apollo Mapping, 2025)
Hongtu-1	Hongtu-1 is a commercial multi-baseline SAR constellation that can act as a single-pass interferometer and is intended for uses such as DEM generation. It can cover the globe at a once-yearly frequency. This thus offers possibility of temporal monitoring of landfill volume changes at an annual rate.	(Deng et al., 2024; Wegmüller et al., 2024)
ICEYE commercial SAR data	ICEYE is a commercial SAR data provider that uses a constellation of satellites to cover the whole word with frequent revisits (even within the same day). Although not a single-pass interferometer like Tandem-X, the short	(ICEYE, 2025; Rankl et al., 2024)

	revisit times may enable InSAR DEM generation in landfill sites without significant error introduced by temporal decorrelation. Further research is required to quantify elevation error in landfill sites using this data product, and cost-performance needs still to be assessed.	
Umbra Bistatic	Umbra Space is a commercial SAR data provider similar to ICEYE. However, they launched a Bistatic SAR satellite pair in 2024, the data from which has potential for DEM generation similar to Tandem-X data (Duque et al., 2010). And, they are scheduled to launch a constellation of 32 such satellites. Umbra also offers a open-data portal through which a limited but large collection of their data products are made available freely, which makes development of DEM generation techniques more accessible for researchers. Yet, DEM generation based on this SAR data is yet unreported in literature. This company is still in the process of deploying and developing their product, so it is difficult to assess its final se potential for landfill monitoring, but may have significant potential.	(Umbra Space, 2023, 2024)
LuTan-1	LuTan is a public Chinese SAR satellite pair, similar to the TanDEM-X system used in this study. It was launched in 2022, and is scheduled to provide updated SAR data until 2030. The satellite uses longer wavelength radar (L-band), than TanDEM-X, which may reduce the effect of decorrelation or error during interferometric processing, and the satellite pair can also capture in Bistatic mode. However, it is unsure what the global coverage and availability of the data will be. This data may thus be useful particularly for landfill volume change monitoring in China. Hongtu-1 is also a	(Deng et al., 2024; Liu et al., 2022; F. Yang et al., 2024)

5.2.2. Landfill location and perimeter data

As shown in Chapter 2:, the location of landfill sites in many countries is not publicly known or not recorded in spatial data formats. Incidentally, the countries without landfill location data are often also countries without adequate waste reporting. This creates a catch-22 situation, since one of the main objectives of remote sensing data to measure landfill dumping is to help fill waste data reporting gaps. However, capturing in GIS the location and boundaries of dumping sites is arguably easier than ‘fixing’ entire waste measurement and reporting infrastructures. Moreover, existing initiatives such as the Humanitarian OpenStreetmap Team (HOT) could help realise such landfill location mapping in areas where government do not have the capacity to do it (Humanitarian OpenStreetmap Team, 2023).

Further, the majority of existing official landfill location datasets found in this study used point locations to locate the site, but did not include a boundary file of the site perimeter (with some exceptions such as the European Corine 2018 dataset, New Zealand official landfill dataset, and OpenStreetMap). Therefore, if countries wish to implement a monitoring system, it will be necessary to digitise the boundary of landfill sites, which will require significant labour hours unless a reliable machine-learning and segmentation or similar method can be developed to automate the delineation of landfill boundaries. This should thus also be a focus of future work.

5.2.3. Practical complications: The effect of variable waste density, landfill size and illegal waste disposal

There are several further complications that affect the reliability of dumping statistics obtained using the proposed methodology, especially when the approach needs to be applied to estimate disposal at a regional or larger scale. Firstly, as discussed in Chapters three and four, the relationship between the amount of waste disposed of in landfills and the corresponding volume changes may depend strongly on the composition of waste and practices at the site (waste burning, compaction, etc.) These practices differ between areas, and therefore needs to be taken into account when doing regional assessments. To address this issue, an approach as followed in Chapter 4 can be used, where a small number of reference landfills with in-situ data are used to 'calibrate' the relationship between volume and disposal in a specific region.

Secondly, the approach used here can only estimate the amount of waste disposed of in landfill sites for which the location and perimeter is known, but in many regions a large proportion of generated waste is not formally handled and disposed of in official landfills, but rather dumped illegally, or in small informal dumpsites (Ferronato & Torretta, 2019). The locations of these sites may be unknown, or if known, the amount of waste disposed of in individual small dumps may be so little that it can not be reliably estimated using satellite SAR data. For such cases, alternatives such as drone surveys or in-situ stock taking will become necessary.

5.3. Significance: This study's findings placed in a broader context

Up to this point in the concluding chapter we have looked primarily at the methodological advances presented in this work, and the current un-addressed caveats. In this section I would like to ‘take a step back’ and reflect on the significance of these findings, by revisiting again the topic of waste management related issues at global and local scales, the role of waste data in addressing those issues and finally how the presented methodology (or derivatives of it) could be valuable in that context.

The recent Global Waste Management Outlook (GWMO) report estimates that 2.126 billion tonnes (Mg) of waste was being produced yearly by 2020 (United Nations Environment Programme, 2024). The report also predicts that this could increase to more than three billion tonnes per year by 2050, due to increases in global population and changing consumer behaviour as countries develop. The large (and increasing) level of waste generation and disposal is a global concern due to its direct role in the ‘triple planetary crisis” i.e., Climate Change, Pollution and Biodiversity loss (United Nations Environment Programme, 2024, p. 12).

- **Climate Change:** The waste management sector is considered a significant contributor to global carbon emissions, due to black carbon released during open-burning of waste (Reyna-Bensusan et al., 2019), and also methane emissions at landfills caused by the decomposition of waste (Lando et al., 2021).
- **Pollution:** Uncontrolled waste disposal on land can lead to long-term pollution of fresh water sources through leakage of hazardous compounds and leachate (polluted water in emitting from landfills) into water sources. During open burning of waste, landfills also contribute to air pollution, which affect local communities’ health, and have broader ecosystem impacts through the release of persistent organic pollutants (“forever chemicals”) that can bioaccumulate in ecosystems (Weber et al., 2011).
- **Biodiversity loss:** The long-term pollution caused by landfills could contribute to diversity loss due to chronic exposure to persistent pollutants that bioaccumulate and biomagnify within ecosystems (Tovar-Sánchez et al., 2018). Mismanaged waste entering oceans is also a large concern for marine species (Tekman et al., 2022).

Apart from the “big picture” issues related to waste management that are mentioned above, waste management also presents a practical challenge to local authorities (Guerrero et al., 2013). Municipalities often have limited resources available for waste management, such as finances to maintain and improve waste management infrastructure, and limited available landfill airspace. The acquisition and development of new waste management facilities are also often a lengthy and expensive process, due limited land availability and stringent compliance requirements (distance from water sources, communities, local topography considerations, etc.) (Sin et al., 2016). When municipalities fail to achieve adequate waste management, it has cascading consequences such as vulnerability of the surrounding communities to vector borne diseases and pollution related health conditions, increased burden on local medical infrastructure, reduction in property value, public dissent, and ecosystem degradation.

Waste data, although not a solution in itself, has often been cited as an important component of efforts to deal with the above mentioned waste-sector challenges (Independent Expert Advisory Group on a Data Revolution for Sustainable Development, 2014) . For example, at the local level data on the amount of waste produced, collected, and disposed of in specific ways can help the local waste authority to evaluate their current system and implement necessary changes to meet their waste management objectives. For example, knowing waste disposal amounts and trends makes it possible to estimate the remaining lifespan of existing facilities more accurately, and thus facilitates better preparation for site closure and replacement). At the national government level, data on waste disposal in municipalities can help inform appropriate distribution of national resources allocated to waste management (i.e., how much money and other resources should be assigned to specific municipalities or cities to meet their respective needs for waste management). Waste data also offers critical feedback needed to evaluate implemented waste management policies. For example, many countries have in recent years implemented policies to reduce the amount of waste going to landfill, through increased waste diversion education campaigns, etc. (DCCEEW Australia, 2024; DEFF South Africa, 2020). However, without rich temporal data showing changes in waste disposal and handling, it is difficult to quantitatively evaluate the effectiveness of such policies.

Regarding the role of waste sector data in addressing climate change: a significant portion of recent research and discourse around addressing climate change has focused on quantifying the contribution of different sectors and regions to the using up of the remaining “Global Carbon Budget” (Which is the amount of carbon that can still be emitted before the resultant global warming reaches 1.5 °C above a pre-determined historical baseline) (Friedlingstein et al., 2025). In line with this trend, the waste sector has also received much attention, with ongoing efforts to quantify the amount of methane emissions from landfills through initiatives such as ‘Climate Trace’ (Climate Trace, 2024) and WasteMAP (RMI & Clean Air Task Force, 2023). Several countries also have government programs to track methane emissions from waste facilities (Environment and Climate Change Canada, 2022; US EPA, 2024). However, it is important to understand that, at a global level, the majority of waste sector carbon emission estimates do not stem from methane emission measurements, but rather from data or estimates of waste disposal. Models such as the Solid Waste Emissions Estimation Tool (SWEET) are used to estimate methane emissions, given some inputs such as the amount of waste disposed, waste composition, disposal methods, etc. (US EPA, 2023). This means that worldwide accurate waste disposal data is very important for accurate estimates of the waste sector's contribution to the global carbon budget.

Yet, despite the various use cases described above, in many regions around the world waste sector data is not being collected, or not reported adequately (Maalouf & Agamuthu, 2023). It is telling that the most recent and authoritative global waste report – the GWMO 2024 – was required to consider 2020 as a baseline for the global analysis, since a large proportion of countries' most recent statistics were older than that. The report also states that, "Some countries have no official waste data whatsoever, or this data may be incomplete or inaccurate." (United Nations Environment Programme, 2024, p. 17). We thus see that, ideally, comprehensive waste disposal data and estimated emissions data should be available to inform waste policy, guide waste sector planning, and guide our response to climate change. But in practice, outdated and incomplete data are out of necessity still being relied on for these important applications.

It is in this context that we can better understand the potential future value of a remote sensing based tool that can gather waste disposal statistics at a regional or global scale. The methodology proposed in this study (Chapter 3) showed that it was possible to estimate waste disposal in landfills over time using only satellite data, and that under some conditions the estimated values correlated closely to in-situ measured data (Section 3.3.3). This approach could feasibly be used by a national waste authority to supplement their waste data collection efforts. For example, remotely sensed dumping volume estimate could serve as a secondary validation for in-situ data reported by landfill operators, or can, if necessary, be a primary data source for dumpsites that have no in-situ waste measurement. In this way a remote sensing tool could help track progress toward waste management targets and allow authorities to understand differences in disposal practices between cities or municipalities.

This type of tool could also be adopted by non-governmental entities like UNEP or UN Habitat, who are interested in cross-national data (UN-Habitat, 2010). A remote sensing based methodology could be especially helpful in such regional or global analysis, since it can facilitate data collection for unreported regions, and can also allow for getting data for a desired time period, and with a standardised methodology. It is worth noting that apart from missing or outdated data, recent global analyses also faced significant challenges because reported data from different countries have differing reporting periods, differing reporting standards and methodologies, and differing reporting formats (i.e., different table formats, document formats, different languages, etc.). The work of firstly collecting such diverse data and then harmonising it into a single comparable format places a large burden on the project team, and also introduces uncertainty. If waste disposal could be 'centrally' collected using a remote sensing approach as described in this work, it would significantly streamline the work of initiatives like the GWMO, and also allow for more standardised and transparent data collection. Other attempts to improve data collection and standardized reporting between countries are also underway, such as the UN Habitat's Waste Wise Cities Tool (WaCT), which collects data using a standardised survey format, that cities can participate in (UN-Habitat, 2021). A remote sensing based tool as proposed here, could be used in conjunction with other initiatives like WaCT.

Returning to the topic of waste sector challenges and the role of data in addressing them, I would like to focus next on the specific role of spatial data, and consequently the possible significance of the findings presented in this work. It is well understood that pollution related impacts of landfills on surrounding communities, and ecosystems depend on the proximity of the landfill to the surrounding affected areas (Siddiqua et al., 2022; Singh et al., 2021; Vrijheid, 2000). Therefore, if city authorities have spatial datasets of the locations of waste facilities, it can help inform future town planning that minimizes the effects of the landfills on surrounding communities. If landfill location datasets are available at a national level it can help government to assess the current potential impacts of landfills on communities across the country and can help assess whether landfills comply with environmental legislation. Research studies that assess the proximity based impact of landfills on community health generally also rely on landfill location GIS datasets (Tomita et al., 2020). The outcomes of such studies can help guide future waste management regulation. We can thus see that landfill location data can contribute to reduce the impacts of landfills on the environment and communities. However, this study showed only 64 out of 263 considered sovereign territories had landfill location datasets available (publicly accessible). And, coverage of non-governmental datasets like OpenStreetMap and Global Plastic Watch is currently also still incomprehensive, with many cities around the world not having any landfills listed in those datasets (Figures 2-1; 2-2). This study will hopefully be a call to motivate better collection and open sharing of landfill location datasets by governments, and non-governmental initiatives.

Another topic that received significant attention in literature recently is the mapping of illegal or informal landfill sites (Glanville & Chang, 2015; Syafrudin et al., 2023; Torres & Fraternali, 2021). Informal landfills have disproportionate impacts on the environment because they are generally not managed properly. The waste disposed of at these sites are also not captured in official waste disposal statistics. Most past work on this topic focused on the use of remote sensing data to identify illegal landfills. However, in this work's analysis of landfill location datasets it was observed that the large volunteer contributed landfill dataset in OpenStreetMap contains the location of many possibly informal or illegal landfill sites. The OpenStreetMap landfills can have additional information provided by the annotator that includes information about the site's status, such as: "note: not official; in the middle of the fields", or "informal: yes" (see Table 2-3). In several regions where the OpenStreetMap landfills were compared to reference landfill location datasets, the OpenStreetMap had notably more landfill entries than reference datasets (Table 2-1). This difference in number of entries may partially be due informal landfills being annotated by volunteers who notice their presence on the ground, while such landfills are generally not included in official datasets of registered facilities. Therefore, OpenStreetMap or similar initiative could be especially helpful in regions where informal landfills represent a large proportion of the waste management 'infrastructure'. In Africa, for example, the number of landfill entries in OpenStreetMap are already six times as many as the largest other reference dataset (Table 2-1). This study thus highlights the possible role of volunteered landfill location data to aid mapping of landfills not captured by official datasets. If such sites can be successfully mapped, it will facilitate quicker intervention by waste authorities to close informal sites, so mitigating their environmental impacts. If their location can be mapped, it also opens the possibility of monitoring the amount of waste dumped in the sites by remote sensing, which will be valuable since informal landfills generally have no weighbridges, and the amount of waste entering them are not tracked adequately by authorities, and are thus not included in official statistics. Especially in countries with relatively weak waste management systems, the waste disposed of informally may contribute a significant proportion of the overall waste management, and this has implications for global waste assessments, such as the GWMO. Therefore, a dual approach of mapping the location of informal waste sites by crowd-sourcing (or other method), and then estimating waste disposal in such sites by remote sensing could help improve waste statistics at the global level.

5.4. Conclusion

In conclusion, this study aimed to promote more complete collection and reporting of waste disposal data in landfills globally by furthering our understanding of how satellite data may be used to measure landfill dumping remotely. The study highlighted the current availability and state of landfill location data around the world showing that considerable efforts will be required to improve the quality of such data before true "region wide" measuring by remote sensing can be achieved. Further, the study proposed and assessed a new technique for measuring volume changes in landfills which relies on single-pass InSAR based elevation data. This method achieved higher accuracy that prior work that relied on repeat-pass InSAR to generate elevation data in landfill sites. Yet, the temporal coverage of the considered input data (Tandem-X DEM Change Map data) was low (no data more recent than 2021) and irregular between locations. Thus, to realize a more operational monitoring tool, future work could extend this approach by attempting InSAR processing of new commercial SAR satellite constellations, some of which also have a bistatic mode – enabling single-pass InSAR – and which should have more frequent and updated data coverage.

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Annexure I: Collation of Landfill location datasets from all regions and countries

Dataset	Coverage	Features (n)	Facility types included (self-reported)	Source or method of compilation	Data format	Further notes	Source(s)
OpenStreetMap Landfills	Global	53758	Any site intended for permanent storage of waste. (e.g., Municipal landfills, open dumps, ilegal dumping, nuclear and hazardous waste, mining waste and tailings, coal ash)	Volunteer contributed	vector polygon of site outline or site point locations	This dataset is constantly being updated, the listed number of sites is for January 2025. Landfills were features with the tag "landuse = landfill"	https://wiki.openstreetmap.org/wiki/Tag:landuse=landfill
Global Waste Atlas	Global	2643	Dumpsites, Sanitary landfill, MBTs, WtE facilities	Industry and academic collaboration, crowd sourcing	Point locations on interactive map, spatial data not directly accesible.	Compiled by D-Waste, includes engineered landfills, dumpsites, mechanical biological treatment plants, waste to energy plants. Appears to be updated last in 2014	http://www.atlas.d-waste.com/
GPW Plastic Waste	Global (112 countries)	4137	Plastic waste dumpsites	Deep learning based classification	vector of point locations, or contours of boundaries in different years.	Contains sites as small as 25 m sq., and informal and formal sites. But the model is trained to identify plastic waste sites. Identified sites far less that actual number, if comparing reference datasets. Accessible by API after obtaining access credentials	https://globalplasticwatch.org/
Corine 2018	39 European countries & foreign territories	1889	"dump site" as landuse class	classified by professional annotators, with aid from other national datasets and remote sensing imagery	spatial vector (polygon)	The dump site landclass is Corine_18 ID "132". But there is no site information (e.g., names, facility type, etc.)	https://land.copernicus.eu/en/products/corine-land-cover/clc2018#download
Sustainable Seas Trust (SST) Landfill dataset	Africa, primarily South Africa	612	municipal landfill sites	internally compiled by NGO, with public participation	point locations	Point dataset of municipal solid waste landfill sites, compiled by the Sustainable Seas Trust (NGO). Available on webmap, spatial data obtained by written agreement and NGO	https://sstafrica.org.za/my_map/index_waste_recycle.html
Australian Waste Management Facilities Database (Disposal sites)	Australia	1093	Waste disposal sites (inert and putrescible landfills)	Government	point locations	We are reporting the Waste disposal sites (n=1093). But the dataset also contains other waste management infrastructure (drop off stations, recycling facilities, etc., totalling 6240 entries)	https://doi.org/10.26186/147594
Permitted Waste sites, UK	United Kingdom	1101	"Permitted Waste Sites - Authorised Landfill Site Boundaries"	Government	site polygons	The Permitted Waste Sites - Authorised Landfill Site Boundaries is a polygon dataset that contains	https://www.data.gov.uk/dataset/ad695596-d71d-

						the boundaries of landfill sites that are currently authorised by the Environment Agency under Environmental Permitting Regulations. Landfill permits are authorised by a Waste Management Licence, a PPC Permit or an EPR Permit, and are recorded within the Regulatory Information System (Regis).	4cbb-8e32-99108371c0ee/permitted-waste-sites-authorised-landfill-site-boundaries
Ireland (official)	Ireland	21	"Waste facilities (including licensed, applied, surrendered, rejected etc.)"	Government	point locations	Landfill sites are 21, which is a subset of the full waste facility dataset with 703 entries. By observation, the definition of waste facility in this dataset is broad, including entries for sawmills, meat processing facilities, entries under pharmaceutical company names, farms, etc. However, a query for licenses including the word "landfill" returns 21 sites.	https://data.gov.ie/dataset/licensed-waste-facilities
LMOP landfill repository	United states	2318	municipal solid waste landfills	Government	point locations (coordinates or street address)	The LMOP Landfill and Landfill Gas Energy Project Database (LMOP Database) with location and other information (name, opening and closing year, capacity, etc.).	https://www.epa.gov/lmop/landfill-technical-data
Cayman Islands Gov.	Cayman Islands	3	landfill	Cayman Islands Government	site addresses	not spatial data format, but site location and address described clearly on gov website.	https://www.gov.ky/deh/waste-management/waste-disposal.html
Land Information New Zealand (LINZ) Landfill Polygons	New Zealand, Cook Islands, Niue, Tokelau	73	landfills	Government; Land Information New Zealand (LINZ)	site polygons	Description: "A portion of land on which refuse, solid or semi-solid waste, is dumped and then covered with earth." Data Dictionary for landfill_poly: https://docs.topo.linz.govt.nz/data-dictionary/tdd-class-landfill_poly.html	https://data.linz.govt.nz/layer/50294-nz-landfill-polygons-topo-150k/
SINIR+ (Solid Waste Management Plus National Information System)	Brazil	2678	Final disposal sites (Controlled landfills, C&D landfills, Dump, Other)	Government	Point locations on interactive map, spatial data not directly accesible.	The SINIR+ platform includes a variety of waste management statistics and data for Brazil. Rich data with disposal site type and other meta-data included for each site entry. Underlying data may be aquirable at request.	https://www.sinir.gov.br/mapas/gestao-residuos-solidos/ data access: https://www.gov.br/acessoainformacao/pt-br

sanitary landfill locations in Menas Gerais	Minas Gerais, Brazil	49	sanitary landfill sites	Government	point locations	Official Landfill locations for the state of Minas Gerais in Brazil, as compiled by SEMAD (State Secretariat for Environment and Sustainable Development)	https://idesisema.meioambiente.mg.gov.br/geonetwork/srv/por/catalog.search#/metadata/500132b1-8474-411e-bf9c-a4a22f3dbc20
4A Sanitary Landfills as of April 2024 (Environmental Management Bureau, Calabarzon region)	Calabarzon Region, Philipines	59	sanitary landfill sites	Government	point locations (lat-long coordinates in table)		list of landfills and locations for calabarzon: https://calabarzon.emb.gov.ph/wp-content/uploads/2024/05/R4A-SLF-2024.pdf statistics:https://app.powerbi.com/view?r=eyJrIjoiZjdhNDE3YzMtZGIxNi00MjZhLTlhNmItNTQ4YWUyYTIzMDYzIiwidCI6ImY2ZjRhNjkyLTQzYjMtNDMzYi05MmIyLTY1YzRlNmNjZDkyMCIsImMiOjEwfQ%3D%3D
INEGI Waste Disposal sites database	Mexico	2319	Municipal Waste landfills	Government	point locations	Currently I am referencing Climate trace"s record of the dataset, since INEGI version doesn't show spatial info	https://climatetrace.org/data https://www.inegi.org.mx/rnm/index.php/catalog/997/data-dictionary/F10?file_name=sdfn_cngmd2023
Ontario Landfills	Ontario (Province of Canada)	2459	"approved landfills"	Government	addresses	open: 641, closed: 1816 Official description: This is a listing of approved landfills in Ontario. Here you will find basic information on Ontario's landfills including: * Environmental Compliance Approval (ECA) number * Ministry of the Environment, 641 open sites and Conservation (MECP) region * MECP district * client name * site name * site address * site municipality * operation status (open/closed).	https://data.ontario.ca/dataset/ontario-landfills
Saskatchewan Solid Waste Management	Saskatchewan (Province	993	landfills, industrial landfills, transfer stations, industrial landfarms and unauthorized sites	Government	point locations	Provincial inventory of regulated and monitored Solid Waste sites. Includes information on current Status – closed/open/proposed, Permit Expiry Date,	https://open.canada.ca/data/en/dataset/a4ec4fdb-

	of Canada)					Permit Number, Recent Inspection Date , Site Name, Site Type – industrial landfarm/industrial landfill/landfill/transfer station/unauthorized.	1fea-8c2e-cd17-acf777439f1f
Canada GHGRP	Canada	144	Waste Treatment and Disposal facilities	Greenhouse Gas Reporting Program (Canada government)	point location	Sites in Canada's GHGRP database, which includes facilities that emit 10 kilotonnes or more of GHGs, in carbon dioxide (CO_2) equivalent (eq.) units, per year, in the industry category "Waste Treatment and Disposal"	https://open.canada.ca/data/en/dataset/a8ba14b7-7f23-462a-bdbb-83b0ef629823
Dump Sites In Guyana (ArcGIS Story)	Guyana	6	Dump Sites	student compiled	point locations (Web Map)	Compiled as part of a student project, as comprehensive as data is available, in 2022. But, not official data.	actual map: https://cdn.arcgis.com/home/webmap/viewer.html?webmap=64b5c93bd7d94cdbb7ea8f6a0a4f6bae https://cdn.arcgis.com/home/item.html?id=64b5c93bd7d94cdbb7ea8f6a0a4f6bae
SIPSN	Indonesia	1477	TPA/TPST	Government	point location (web map); facility database		https://sipsn.menlhk.go.id/sipsn/public/home/peta database: https://sipsn.menlhk.go.id/sipsn/public/home/fasilitas/tpa-tpst
National Land Numerical Information Waste Treatment Facility Data (Japan)	Japan	14320 (final disposal sites = 965)	classes of facility types: # 1 Incineration facilities # 2 Bulky waste disposal facilities # 3 Facilities for recycling, etc. # 4 Waste-to-fuel facilities # 5 Other Facilities # 6 Storage Facilities # 7 Final disposal site # 8 Human waste treatment facilities # 9 Community Plants #10 Reuse & Repair Facilities ## Industrial waste treatment facilities (intermediate and final)	Government	point locations	in Japanese. Updated as of 2012. description translation: "Representative locations of general waste treatment facilities and industrial waste treatment facilities nationwide were acquired, attributes were assigned, and they were prepared as GIS data."	National Land Numerical Information | Waste Treatment Facility Data

전국폐기물처리업소표준데이터 (National waste disposal facility standard data)	South Korea	7890		Government	point locations	updated 2025-02-04	national: Location of landfill sites nationwide – Kukdong E&C as data: https://www.data.go.kr/data/15114147/standard.do
Mapa Nacional de Infraestructura de disposición final (Peru)	Peru		Sanitary Landfill, Mixed Sanitary Landfill, Security Landfill, Transitional Cell	Government	pdf map with site point locations	updated 2021. Map and sites list	https://cdn.www.gob.pe/uploads/document/file/2002072/Mapa%20Nacional%20de%20Infraestructura%20de%20disposici%C3%B3n%20final_191021.pdf.pdf?v=1652317381
Landfill Web map by SNIAmb (Sistema de Nacional Informacao de Ambiente)	Portugal	not listed	Landfills	Government	site polygons (web map)	The data is available in web map, but not clear how to download data. Maybe by contacting the agency?	https://sniamb.apambiente.pt/content/aterros?language=pt-pt
Rellenos sanitarios del país (Landfills in El Salvador)	El Salvador	16	Sanitary landfills	Government	site addresses (description)	The sites locations are described, but will need manual geolocation before use. Dated 2018	https://www.transparencia.gob.sv/institutions/marn/documents/245428/download
landfills register of the Slovac Republic	Slovakia	not listed	landfills	Government	point locations (Web Map)	Registered landfills are characterized by the following attributes: topographic situation, relation to the biosphere, geological data, hydrogeological parameters, technical data, and composition of the waste. It keeps the data on a site operator, proposal for further use of landfill, landfill status, regional importance and method of operation. All these items are part of the presented application, which allows database SQL search by a variety of search criteria selected. Individual data are regularly updated (e.g.	https://www.geology.sk/maps-and-data/mapovy-portal/geofond-registries/landfills/?lang=en map: http://apl.geology.sk/skladky/

						extension of the landfill surface, changes in its volume, setting up a monitoring system, landfill closure, etc.). The update takes place annually on the basis of reports by workers of Environmental Municipal Administration.	
Statistical table of coastal public landfills (Taiwan)	Taiwan	29	coastal public landfills	Government	point locations (csv with coordinate columns)	updated 2024	Coastal Public Landfill Statistical Table | Environmental Data Open Platform of the Ministry of Environment
Statistical table of landfill capacity of public landfills in operation	Taiwan	107	public landfills (operational)	Government	point locations (csv with coordinate columns)	updated 2025	https://data.moenv.gov.tw/dataset/detail/FAC_P_02
Ukraine Open Data Portal	Ukraine	not collated	waste disposal sites', 'waste management facilities'	Government	site addresses	Ukrainian datasets are reported by individual city councils and regions, and kept on the government open data portal. But, I couldn't find a national dataset thay has all local data collated.	all: https://data.gov.ua/dataset?tags=%D0%B2%D1%96%D0%B4%D1%85%D0%BE%D0%B4%D0%B8 https://data.gov.ua/dataset/8aed281e-5415-41cb-a771-c6dd6cd085c2
Uruguay Ministry of Environment Final disposal site web map	Uruguay	187 (including transfer stations)	landfill and transfer stations	government	point locations (Web Map)	difficult to download the dataset, viewavle as interactive web map	https://www.ambiente.gub.uy/oan/visualizador-de-sitios-de-disposicion-final/
Trinidad & Tobago's landfills Map	Trinidad & Tobago	4	landills	government	point locations on country map		https://swmcol.co.tt/Landfills/Landfill-Management
Landfill Sites in Thailand	Thailand	3,129	Open dump, Sanitary landfill, Others	Government	point locations	updated 2021. Published by Open Development Thailand. rich metadata, downloadable as shp or geojson, etc.	https://data.opendevelopmentmekong.net/en/dataset/waste-dumping-sites

Metabolism of cities waste data	21 cities or regions globally	The Metabolism of cities Data hub contains publicly contributed datasets on cities, on date of access [2025-01-23] 110 waste sector datasets, of which 24 are spatial datasets (e.g., locations of landfills or other waste management infrastructure). These datasets cover the following 21 cities: Buenos Aires, Madrid, Beijing, Montreal, Singapore, Cape Town, Barranquilla, Medellín, The Hague, Comodoro Rivadavia, Brussels, Geneva, Metro Vancouver Regional District, Sevilla, Rosario, Anadia, Barcelona, Lausanne, Johannesburg, Bello Medellín, La Plata	https://data.metabolismofcities.org/layers/infrastructure/894/
INSPIRE Geodata (Waste)	Europe	The INSPIRE geodata portal for Europe contains spatial location datasets for European national and subnational jursidictions, including at time of access [2025-01-23], waste landfill sites for for Austria, Sweden, Germany, Latvia, Lithuania, Luxembourg, and "Extractive waste facilities" for Belgium, Bulgaria, Germany, Hungary, Italy, Poland, Slovakia, Spain, Sweden.	https://inspire-geoportal.ec.europa.eu/srv/eng/catalog.search#/overview?view=priorityOverview&envdomain=location-of-landfill-of-waste-sites

End of section

Annexure II: Additional Materials for Chapter 3

Doña Juana Landfill, Colombia

The Doña Juana landfill site is a large complex (623 ha) that receives municipal waste from Bogota District, and the surrounding municipalities of Cáqueza, Choachí, Chipaque, Fosca and Gutiérrez, Ubaque, Une. The site receives approximately 684 truckloads of waste per day, which on average add up to $6{,}368\ Mg \cdot day^{-1}$. According to the site management the landfill receives waste and distributes the waste to several final disposal zones, depending on the waste type. The site includes a hazardous waste disposal area, and a biogas reclamation facility. A diagram of the facility layout is given on the landfill site's website (UAESP, n.d.). Figure A3 also shows a 3D rendering of some of the dumping zones. The site also has active leachate management and a biogas waste-to-energy facility. In the period overlapping the study, the facility captured gas captured at the facility varied approximately around 7000 – 8000 Nm^3/hr (UAESP, 2020). A breakdown of waste composition is not given, but the landfill management reports the relationship between remaining airspace in the site and the expected waste mass that can be dumped. This allows for calculation of the estimated density of disposed waste in the landfill, which is $1.11\ Mg \cdot m^{-3}$.

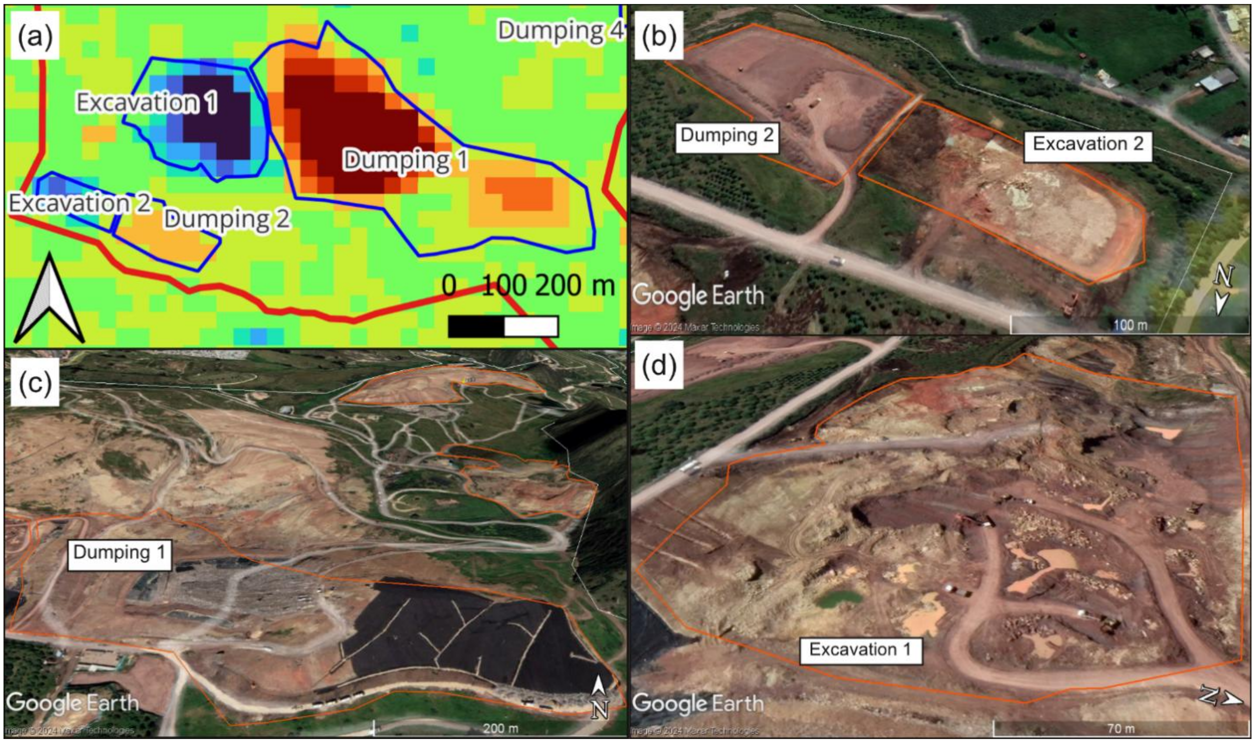


Figure A5-1 Google Earth Pro 3D perspective rendering of the Doña Juana landfill site, using high resolution satellite imagery acquired 9 December 2019. (a) Shows a zoomed image of figure 6 b, with active dumping areas showing positive (red) volumetric changes, and areas with excavations showing negative volumetric changes (blue). Sub-figure (b) Shows adjacent "Dumping 2" and "Excavation 2" areas. Sub-figure (c) shows the landfill site's primary active dumping area ("Dumping 1"), and (d) shows ongoing excavation with trucks receiving soil from excavators.

West New Territories Landfill (WENT)

The WENT Landfill in Hong Kong is the largest landfill serving the city, and is one of the 3 strategic landfills for Hong Kong, alongside the South New Territories and North New Territories landfills. Waste is received directly from the city or transported from waste transfer stations after compaction. A breakdown of waste types received at the facility for the years overlapping with this study is shown in Table A5-2. The composition of MSW in the city is approximately Food waste (30%), Paper (24%), Plastics (21%), Other (20), glass (2%), Metals (2%). And, 'Others' include textiles, wood, yard waste, household hazardous wastes, bulky items and miscellaneous waste materials. The site covers an area of approximately 110 hectares,

Table A5-2 Waste disposed at WENT, broken down into categories for Municipal Solid Waste (MSW), Construction waste, and Special Wastes. Reported in $Mg \cdot day^{-1}$. Special waste consist *mostly of Incineration ash and stabilised residue, dewatered waterworks sludge, livestock waste, and others.*

	Waste Category ($Mg \cdot ⟦day)^(-1)$)		
Year	MSW	Construction	Special
2014	5813	874	568
2015	6170	956	459
2016	7406	1020	389
2017	7616	747	363
2018	7940	624	345
2019	7521	524	346
2020	5921	194	260

Source: HK Environment Protection Department annual reports, 2014 – 2020.

Figure A5-2 Google Earth Pro 3D perspective rendering of the West New Territories landfill site in Hong Kong. (a) Active site 1, dumping area throughout the study period. (b) Perspective view of active dumping area are denoted as "Active 2, and Active 3 in the background.

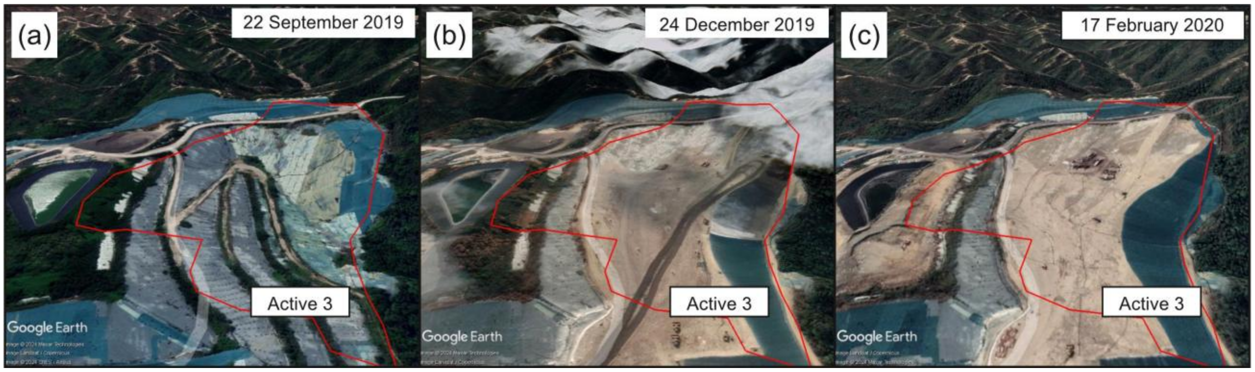


Figure A5-3 Time series of "Active 3" area in the WENT landfill site, showing imagery from (a) 22 Sept. 2019; (b) 24 Dec. 2019; (c) 17 Feb. 2020. The site was opened for dumping between September and December 2019, and remained open to the end of the study period.

Annexure III: 100 landfill sites volume change estimates and accompanying information

Albertus Stephanus Louw

This appendix shows a short summary of the results as well as accompanying information for each of the 100 study landfill sites considered in Chapter 3. The study sites are separated into (1) active landfill sites, (2) Closed landfill sites, and (3) sites for which data was deemed inadequate to allow for calculation of volumetric changes in period 2, i.e., sites with no data coverage (n = 24) and sites with coverage, but the period of coverage was below 50 days (n = 10). Since different landfill types including informal and illegal dump sites, and sites from different countries are considered, the available information differ among the landfills. However, as far as possible the waste types, landfill types, and other information that could be obtained for the sites are reported here, along with references.

For each site three figures are shown, namely:

(a) Bing Aerial imagery,
(b) Period 1 Volume changes ($m^3 \cdot m^{-2} \cdot day^{-1}$), as calculated from the TDM30 DEM Change Map data, for the period from EDEM creation (mid 2012) to the DCM_1 date, which is reported for each site.
(c) Period 2 Volume changes ($m^3 \cdot m^{-2} \cdot day^{-1}$), as calculated from the TDM30 DEM Change Map data, for the period from date of DCM_1 to that of DCM_2, which is also reported for each site. For some large landfill sites the aerial imagery does not cover the entire site.

Sites where the DCM_1 and DCM_2 products were identical (n = 24), i.e., when the temporal gap Δt between the DEM observations was zero, the volumetric change could not be calculated for period 2. In such cases no data is shown in the volumetric change map.

Active landfill sites

Study Site: AOI_002

Country: Nigeria

Administrative area: Agege

Location (Lon, Lat): 3.302125 6.639392

Name: Abule Egba Landfill

Description: Municipal Waste; Open Dump

Additional site information: Opejin, A., Pijawka, K., 2016. Regenerating Waste to Energy: A Scenario-Based Assessment of Lagos, Nigeria. Environmental Management and Sustainable Development 5, 183. https://doi.org/10.5296/emsd.v5i2.9822

Area: 11.2 ha

Period 1 Date (yyyymmdd): 20180119

Period 2 Date (yyyymmdd): 20191213

Period 1 Volume Change: 15.06177 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 91.30684 $(m \quad \cdot day \quad)$

Estimated Period 2 error: 3.432767 $(m^3 \cdot day^{-1})$

Figure 1: Aerial Image

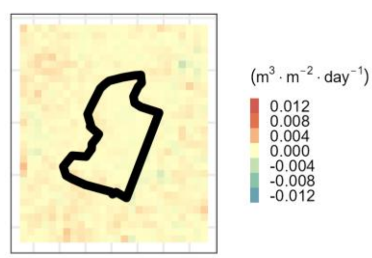


Figure 2: Period 1 changes

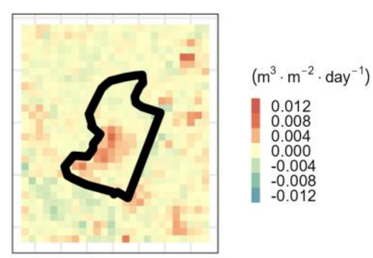


Figure 3: Period 2 changes

Study Site: AOI_003

Country: Nigeria

Administrative area: Shomolu

Location (Lon, Lat): 3.372515 6.556174

Name: Unnamed Landfill site

Description: Municipal Waste (assumed); Open Dump

Additional site information: Open dump in Araromi (Lagos).

Area: 1.1 ha

Period 1 Date (yyyymmdd): 20180211

Period 2 Date (yyyymmdd): 20191223

Period 1 Volume Change: -0.19685 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -3.906575 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 0.9350516 ($m^3 \cdot day^{-1}$)

Figure 4: Aerial Image

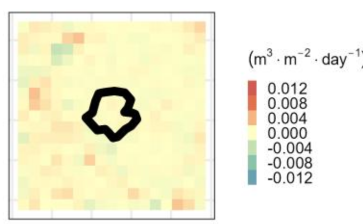


Figure 5: Period 1 changes

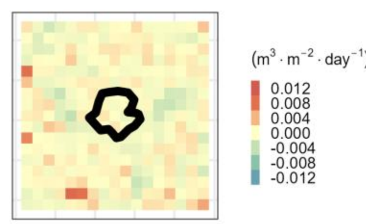


Figure 6: Period 2 changes

Study Site: AOI_004

Country: India

Administrative area: Mumbai Suburban

Location (Lon, Lat): 72.95089 19.12415

Name: Kanjur Landfill

Description: Municipal Waste; Bioreactor & Material Receiving and Segragation Facility. Processes 6000Mg waste per day

Additional site information: Primary Landfill serving the Bombay Municipal Corporation. kanjurmarg dumping ground Feature Photo Kanjur landfill… [WWW Document], n.d. . Times Of India. URL https://timescontent.timesgroup.com/photo/feature/kanjurmarg-dumping-ground/627824 (accessed 3.19.24).

Area: 142.4 ha

Period 1 Date (yyyymmdd): 20190403

Period 2 Date (yyyymmdd): 20210707

Period 1 Volume Change: 2829.819 ($m \cdot day$)

Period 2 Volume Change: 2914.923 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 5.479234 ($m^3 \cdot day^{-1}$)

Figure 7: Aerial Image

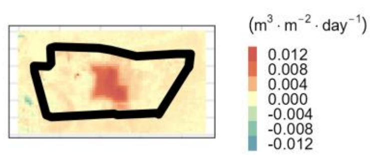


Figure 8: Period 1 changes

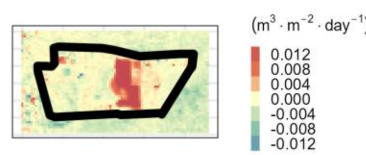


Figure 9: Period 2 changes

Study Site: AOI_005

Country: India

Administrative area:Chennai

Location (Lon, Lat): 80.22624 12.95466

Name: Perungudi dump yard

Description: Municipal Waste; Open Dimp

Additional site information: Kumar, A., 2023. How Perungudi dump yard has made life difficult for residents in Chennai’s IT corridor [WWW Document]. Citizen Matters. URL https://citizenmatters.in/perungudi-dumpyard-mashland-pallikaranai-fire-pollution-biomining/ (accessed 3.19.24).

Area: 88.8 ha

Period 1 Date (yyyymmdd): 20190303

Period 2 Date (yyyymmdd): 20210627

Period 1 Volume Change: 1587.127 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 1140.687 $(m \ \cdot day \ )$

Estimated Period 2 error: 4.822507 $(m^3 \cdot day^{-1})$

Figure 10: Aerial Image

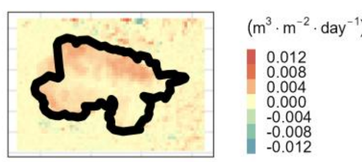


Figure 11: Period 1 changes

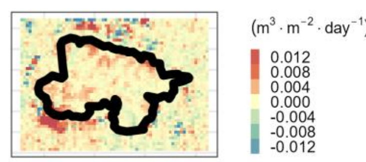


Figure 12: Period 2 changes

Study Site: AOI_008

Country: Philippines

Administrative area: Las Piñas

Location (Lon, Lat): 120.972 14.47447

Name: Las Pinas Dump Site

Description: Waste type unknown; Open Dump; Possibly illegal

Additional site information: Landfill not documented by Local Environmental agency [https://calabarzon.emb.gov.ph/services/eswm-map/]
But site documented in OpenStreetMaps, and online. Satellite imagery confirm presence of landfill site. Possibly illegal. Las Piñas Dump Site, Province of Rizal, Calabarzon, Philippines [WWW Document], n.d. URL https://ph.geoview.info/las_pinas_dump_site,166119627w (accessed 3.19.24).

Area: 2.9 ha

Period 1 Date (yyyymmdd): 20180809

Period 2 Date (yyyymmdd): 20191207

Period 1 Volume Change: 17.38175 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -3.453583 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 1.269658 ($m^3 \cdot day^{-1}$)

Figure 13: Aerial Image

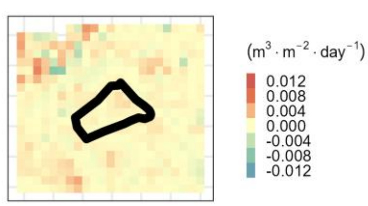


Figure 14: Period 1 changes

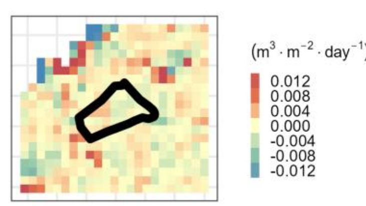


Figure 15: Period 2 changes

Study Site: AOI_010

Country: Thailand

Administrative area: Yannawa

Location (Lon, Lat): 100.5508 13.70491

Name: Small Open dumpsite in Chong Nonsi

Description: Open Dump; Municipal Waste

Additional site information: Chong Nonsi, Yan Nawa, Bangkok 10120, Thailand

Area: 1.8 ha

Period 1 Date (yyyymmdd): 20180525

Period 2 Date (yyyymmdd): 20200427

Period 1 Volume Change: 37.17032 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: -48.98287 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.715068 $(m^3 \cdot day^{-1})$

Figure 16: Aerial Image

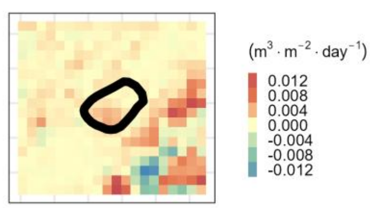


Figure 17: Period 1 changes

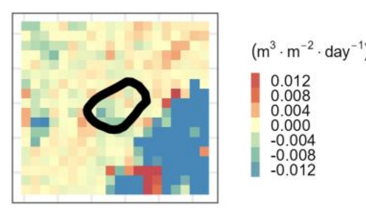


Figure 18: Period 2 changes

Study Site: AOI_011

Country: Philippines

Administrative area: San Pedro

Location (Lon, Lat): 121.0128 14.33514

Name: Pilotage Trading and Construction landfill

Description: Construction waste; Managed Landfill

Additional site information: Pilotage Trading and Construction [WWW Document], n.d. URL http://pilotage.ph/ (accessed 3.19.24).

Area: 11.7 ha

Period 1 Date (yyyymmdd): 20180819

Period 2 Date (yyyymmdd): 20191207

Period 1 Volume Change: 180.2831 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -84.5305 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 2.814065 ($m^3 \cdot day^{-1}$)

Figure 19: Aerial Image

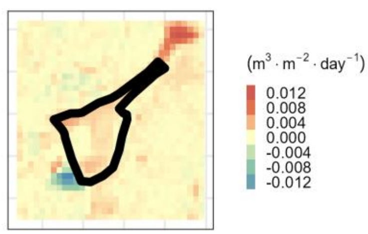


Figure 20: Period 1 changes

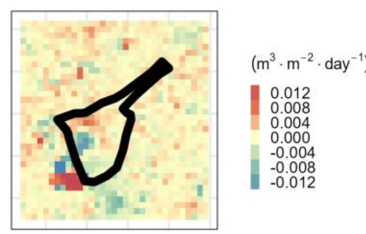


Figure 21: Period 2 changes

Study Site: AOI_013

Country: Indonesia

Administrative area: Kota Bekasi

Location (Lon, Lat): 106.998 -6.348867

Name: TPA Bantar Gebang

Description: Municipal Waste; Integrated Waste Management Faciltiy

Additional site information: DKI Jakarta Provincial Environmental Service, 2020. Data-Data TPST Bantargebang [WWW Document]. Official Portal of the Integrated Waste Management Unit. URL https://upstdlh.id/tpst/data (accessed 2.27.24).

Area: 129.8 ha

Period 1 Date (yyyymmdd): 20180131

Period 2 Date (yyyymmdd): 20200527

Period 1 Volume Change: 3033.94 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 3463.302 ($m \cdot day$)

Estimated Period 2 error: 10.08871 ($m^3 \cdot day^{-1}$)

Figure 22: Aerial Image

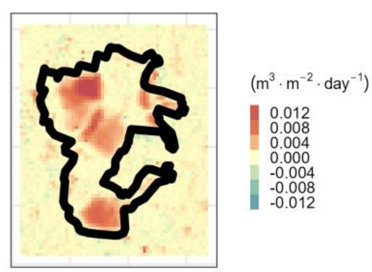


Figure 23: Period 1 changes

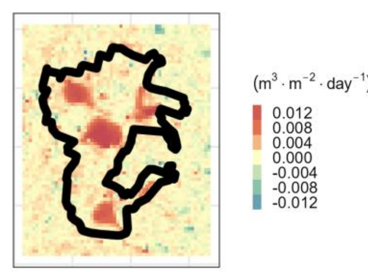


Figure 24: Period 2 changes

Study Site: AOI_015

Country: Indonesia

Administrative area: Depok

Location (Lon, Lat): 106.7878 -6.421536

Name: TPA Cipayung

Description: Municipal Solid waste (63.59% Organic waste, 26.7% Recycables, 9.7% Inorganic Non-recycables); 850 ton per day

Additional site information: TPA Cipayung Bakal Miliki Fasilitas Pengolahan Sampah Ramah Lingkungan Tahun Depan, Ardan: Tahun 2025 Mulai Beroperasi [WWW Document], 2021. . Portal Berita Resmi Pemerintah Kota Depok. URL https://berita.depok.go.id/tpa-cipayung-bakal-miliki-fasilitas-pengolahan-sampah-ramah-lingkungan-tahun-depan-ardan-tahun-2025-mulai-beroperasi (accessed 3.19.24). additional: https://doi.org/10.5614/jtl.2011.17.1.6 https://ereport.ipb.ac.id/id/eprint/9602/1/J3M219183-01-Qonitat-Cover.pdf

Area: 12.4 ha

Period 1 Date (yyyymmdd): 20180131

Period 2 Date (yyyymmdd): 20191019

Period 1 Volume Change: 199.2281 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: -5.018931 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 3.494683 $(m^3 \cdot day^{-1})$

Figure 25: Aerial Image

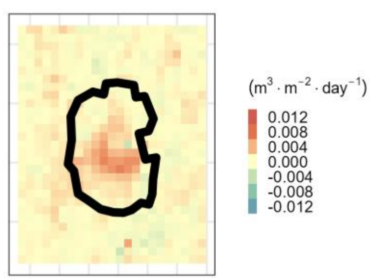


Figure 26: Period 1 changes

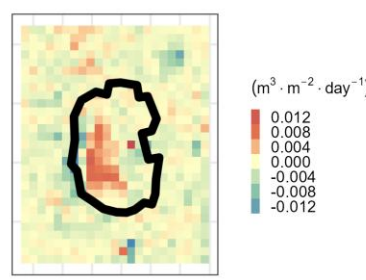


Figure 27: Period 2 changes

Study Site: AOI_016

Country: Ghana

Administrative area: Kumasi

Location (Lon, Lat): -1.592014 6.62511

Name: Dompoase Landfill and Fecal Sludge Treatment Plant

Description: Waste water treatment; Municipal Solid Wase

Additional site information: Osei-Tutu, E., 2020. Waste Recycling Plant In Kumasi, Very Timely And Progressive [WWW Document]. Modern Ghana. URL https://www.modernghana.com/news/1033849/waste-recycling-plant-in-kumasi-very-timely-and.html (accessed 3.19.24).

Area: 31.3 ha

Period 1 Date (yyyymmdd): 20171215

Period 2 Date (yyyymmdd): 20191119

Period 1 Volume Change: 323.5095 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 527.3667 ($m \cdot day$)

Estimated Period 2 error: 5.207732 ($m^3 \cdot day^{-1}$)

Figure 28: Aerial Image

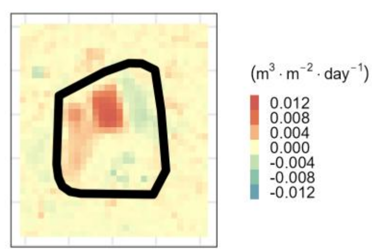


Figure 29: Period 1 changes

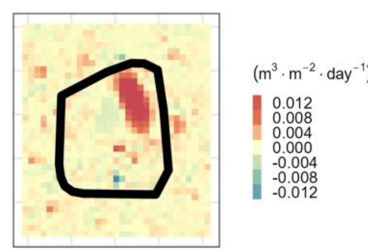


Figure 30: Period 2 changes

Study Site: AOI_017

Country: Indonesia

Administrative area: Jakarta Utara

Location (Lon, Lat): 106.9418 -6.122723

Name: TPA Cilincing

Description: MSW

Additional site information: MINISTRY OF ENVIRONMENT AND FORESTRY, 2018. Perpustakaan Kementerian Lingkungan Hidup [WWW Document]. URL http://perpustakaan.menlhk.go.id/pustak (accessed 3.19.24).
https://www.datatempo.co/foto/detail/P0901200400002/tpa-cilincing

Area: 3.4 ha

Period 1 Date (yyyymmdd): 20180131

Period 2 Date (yyyymmdd): 20200527

Period 1 Volume Change: 68.14147 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -20.48746 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 3.170973 ($m^3 \cdot day^{-1}$)

Figure 31: Aerial Image

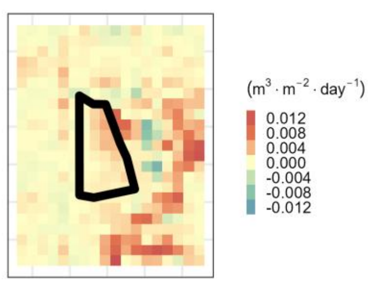


Figure 32: Period 1 changes

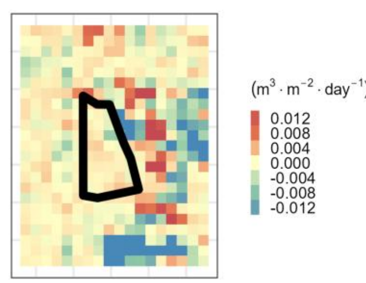


Figure 33: Period 2 changes

Study Site: AOI_018

Country: Cameroon

Administrative area: Mfoundi

Location (Lon, Lat): 11.57033 3.928547

Name: Nkolfoulou Waste Treatment Centre

Description: MSW; Landfill gas recovery; Managed site

Additional site information: HYSACAM, n.d. Nkolfoulou Waste Treatment Centre: an example of controlled discharge - Hysacam [WWW Document]. URL https://www.hysacam-proprete.com/fr/node/23 (accessed 3.19.24).

Area: 36.8 ha

Period 1 Date (yyyymmdd): 20180201

Period 2 Date (yyyymmdd): 20191227

Period 1 Volume Change: 418.4933 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 414.365 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 3.287016 ($m^3 \cdot day^{-1}$)

Figure 34: Aerial Image

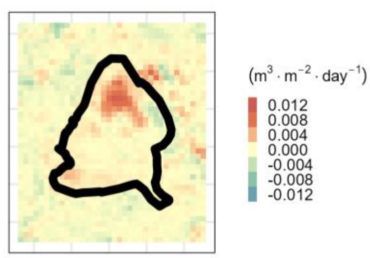


Figure 35: Period 1 changes

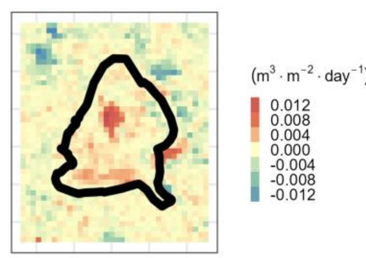


Figure 36: Period 2 changes

Study Site: AOI_019

Country: Russia

Administrative area: South-Eastern

Location (Lon, Lat): 37.82016 55.622

Name: -22

Description: Ash dump

Additional site information: -22 - [WWW Document], n.d. URL http://wikimapia.org/110306/ru/%D0%97%D0%BE%D0%BB%D0%BE%D0%BE%D1%82%D0%B2%D0%B0 %D0%A2%D0%AD%D0%A6-22 (accessed 3.19.24).

Area: 46.2 ha

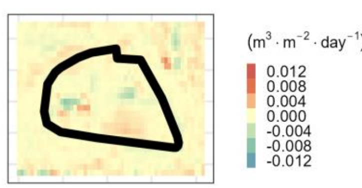
Period 1 Date (yyyymmdd): 20180725

Period 2 Date (yyyymmdd): 20180805

Period 1 Volume Change: -1.179628 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 17942.72 $(m \cdot day)$

Estimated Period 2 error: 9.879528 $(m^3 \cdot day^{-1})$



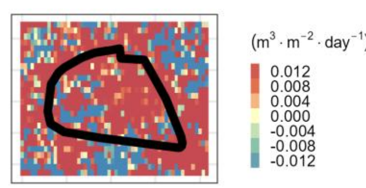


Figure 37: Aerial Image Figure 38: Period 1 changes Figure 39: Period 2 changes

Study Site: AOI_020

Country: Indonesia

Administrative area: Kota Tangerang

Location (Lon, Lat): 106.6183 -6.137207

Name: TPA Rawa Kucing

Description: MSW (60 - 70% Organic waste); Sanitary landfill

Additional site information: JATI, R.P., 2023. TPA Rawa Kucing di Tangerang Kembali Buruk Rupa [WWW Document]. kompas.id. URL https://www.kompas.id/baca/metro/2023/10/24/tpa-rawa-kucing-kembali-buruk-rupa (accessed 3.19.24). Additional info: https://tangerang.tribunnews.com/2022/0 lebih-dekat-tpa-rawa-kucing-tampung-1400-ton-sampah-warga-kota-tangerang-setiap-harinya

Area: 28 ha

Period 1 Date (yyyymmdd): 20180407

Period 2 Date (yyyymmdd): 20191019

Period 1 Volume Change: 490.8421 ($m \cdot day$)

Period 2 Volume Change: 231.0054 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 5.306783 ($m^3 \cdot day^{-1}$)

Figure 40: Aerial Image

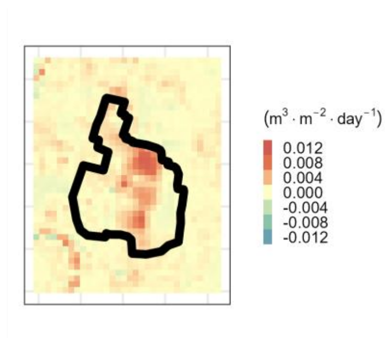


Figure 41: Period 1 changes

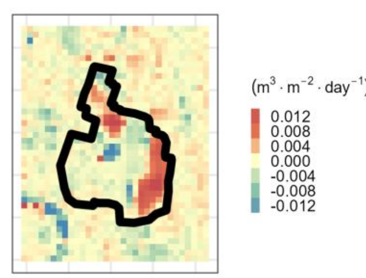


Figure 42: Period 2 changes

Study Site: AOI_021

Country: Nigeria

Administrative area: Alimosho

Location (Lon, Lat): 3.252888 6.564192

Name: landfill at Ajibowo Street

Description: Open Dump; Municipal Waste

Additional site information: Sesan, 2017. Our roads and water very bad, the air we breathe poisonous –Residents living around Lagos dumpsites. Punch Newspapers. URL https://punchng.com/our-roads-and-water-very-bad-the-air-we-breathe-poisonous-residents-living-around-lagos-dumpsites/ (accessed 3.19.24).

Area: 9.7 ha

Period 1 Date (yyyymmdd): 20180119

Period 2 Date (yyyymmdd): 20191213

Period 1 Volume Change: 515.9488 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 81.36752 $(m \ \cdot day \ )$

Estimated Period 2 error: 2.214477 $(m^3 \cdot day^{-1})$

Figure 43: Aerial Image

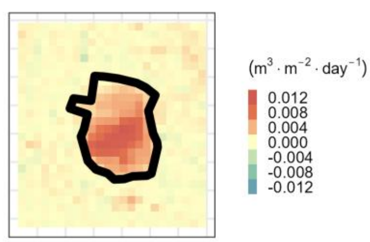


Figure 44: Period 1 changes

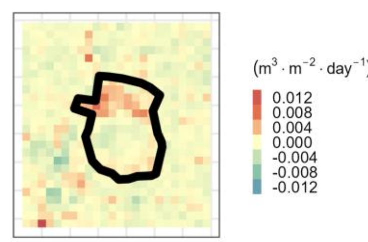


Figure 45: Period 2 changes

Study Site: AOI_022

Country: Nigeria

Administrative area: Kosofe

Location (Lon, Lat): 3.376964 6.594767

Name: Olushosun Landfill

Description: MSW; E-Waste; Construction & Demolition waste

Additional site information: Largest landfill site in Nigeria. Gbadebo, A.M., Alabi, O.A., Alimba, C.G., Bakare, A.A., 2022. Metal Bioaccumulation, Cytogenetic and Clinico-Biochemical Alterations in Rattus norvegicus Exposed In Situ to a Municipal Solid Waste Landfill in Lagos, Nigeria. Biol Trace Elem Res 200, 1287–1302. https://doi.org/10.1007/s12011-021-02758-3

Area: 48.7 ha

Period 1 Date (yyyymmdd): 20180211

Period 2 Date (yyyymmdd): 20191223

Period 1 Volume Change: 1142.427 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 268.3883 $(m \cdot day)$

Estimated Period 2 error: 4.685005 $(m^3 \cdot day^{-1})$

Figure 46: Aerial Image

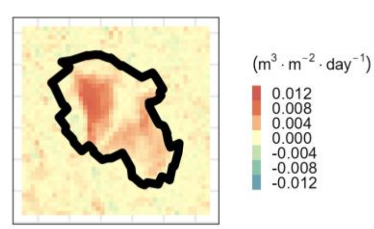


Figure 47: Period 1 changes

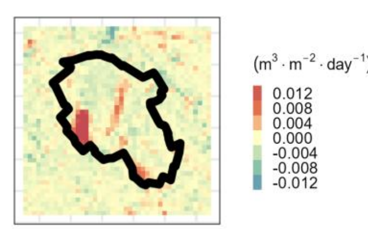


Figure 48: Period 2 changes

Study Site: AOI_023

Country: Egypt

Administrative area: Helwan

Location (Lon, Lat): 31.31694 29.81462

Name: Landfill in Helwan

Description: Not Available

Additional site information: Further information unavailable. Site confirmed by satellite imagery.

Area: 15.7 ha

Period 1 Date (yyyymmdd): 20181027

Period 2 Date (yyyymmdd): 20200119

Period 1 Volume Change: 6.147286 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 127.188 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.817972 $(m^3 \cdot day^{-1})$

Figure 49: Aerial Image

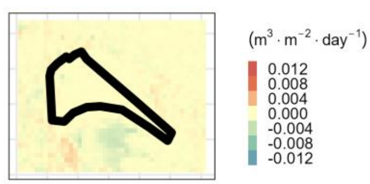


Figure 50: Period 1 changes

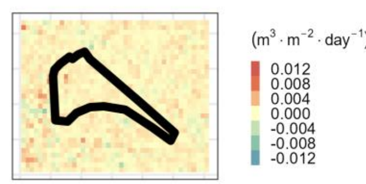


Figure 51: Period 2 changes

Study Site: AOI_024

Country: Bangladesh

Administrative area: Dhaka

Location (Lon, Lat): 90.45071 23.71976

Name: Matuail Sanitary Landfill

Description: MSW landfill for Dhaka. Sanitary Landfill, but management constraints leads to Open Dump like management at times.

Additional site information: , 1970. [WWW Document]. dhakapost.com. URL https://www.dhakapost.com/national/197619 (accessed 3.19.24).

Area: 37.3 ha

Period 1 Date (yyyymmdd): 20191215

Period 2 Date (yyyymmdd): 20200403

Period 1 Volume Change: 575.9572 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 3276.9 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 4.907932 $(m^3 \cdot day^{-1})$

Figure 52: Aerial Image

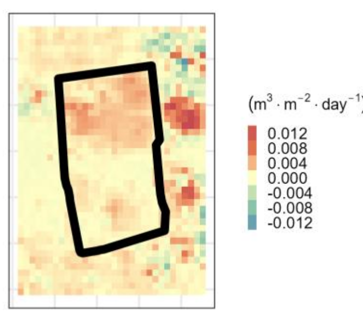


Figure 53: Period 1 changes

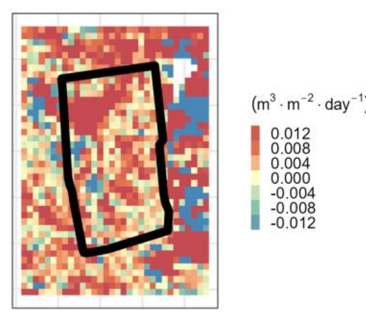


Figure 54: Period 2 changes

Study Site: AOI_028

Country: Indonesia

Administrative area: Tangerang Selatan

Location (Lon, Lat): 106.6606 -6.325544

Name: TPA Cipeucang

Description: Open Dump; MSW

Additional site information: This landfill receives approximately 400 tonnes of waste per day. Media, A.R.S., Ivany Atina Arbi, 2022. Cipeucang, Nasibmu Kini: Ratusan Ton Sampah Masuk Setiap Hari hingga Menggunung… Halaman all [WWW Document]. KOMPAS.com. URL https://megapolitan.kompas.com/read/2022/09/15/08160191/cipeucang-nasibmu-kini-ratusan-ton-sampah-masuk-setiap-hari-hingga (accessed 3.21.24).

Area: 8 ha

Period 1 Date (yyyymmdd): 20180407

Period 2 Date (yyyymmdd): 20191019

Period 1 Volume Change: 128.6933 ($m \cdot day$)

Period 2 Volume Change: 102.4727 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 2.220208 ($m^3 \cdot day^{-1}$)

Figure 55: Aerial Image

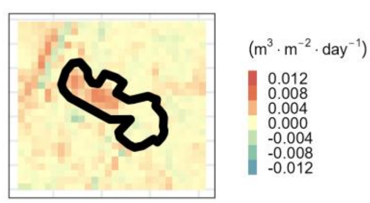


Figure 56: Period 1 changes

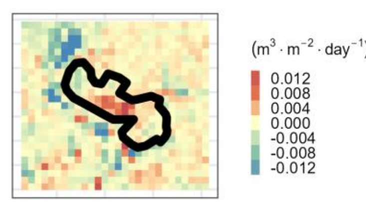


Figure 57: Period 2 changes

Study Site: AOI_034

Country: Ukraine

Administrative area: Solomians'kyi

Location (Lon, Lat): 30.46401 50.40966

Name: Kyiv Landfill site

Description: MSW

Additional site information: Small landfill site, unnamed in Solom'yans'kyi district, Kyiv, Ukraine, 02000

Area: 3.8 ha

Period 1 Date (yyyymmdd): 20190619

Period 2 Date (yyyymmdd): 20210727

Period 1 Volume Change: 41.12003 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 111.6845 $(m \cdot day)$

Estimated Period 2 error: 1.471856 $(m^3 \cdot day^{-1})$

Figure 58: Aerial Image

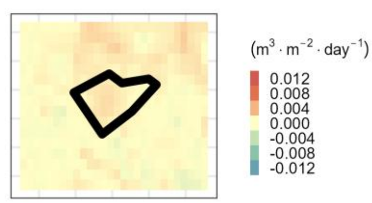


Figure 59: Period 1 changes

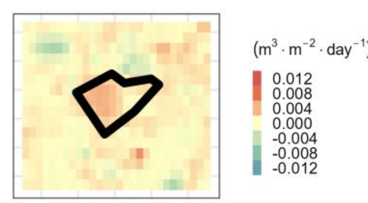


Figure 60: Period 2 changes

Study Site: AOI_035

Country: Indonesia

Administrative area: Kota Medan

Location (Lon, Lat): 98.64953 3.718969

Name: TPA Terjun

Description: MSW;

Additional site information: Climate & Clean Air Coalition, 2020. Assessment for the closure of TPA Terjun waste disposal site in Indonesia [WWW Document]. URL https://www.ccacoalition.org/projects/assessment-closure-tpa-terjun-waste-disposal-site-indonesia (accessed 3.22.24). https://repositori.usu.ac.id/handle/123456789/1348

Area: 12.1 ha

Period 1 Date (yyyymmdd): 20180515

Period 2 Date (yyyymmdd): 20190615

Period 1 Volume Change: 183.9942 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 290.6497 $(m \;\; \cdot day \;\;)$

Estimated Period 2 error: 2.414113 $(m^3 \cdot day^{-1})$

Figure 61: Aerial Image

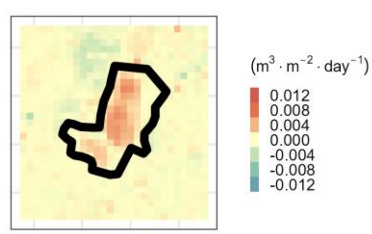


Figure 62: Period 1 changes

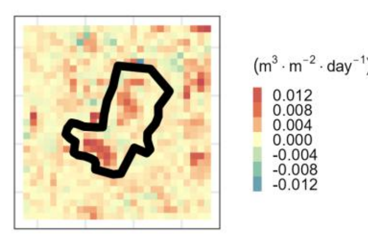


Figure 63: Period 2 changes

Study Site: AOI_036

Country: Indonesia

Administrative area: Surabaya

Location (Lon, Lat): 112.6301 -7.219379

Name: TPA Benowo

Description: Big Open Dump; MSW

Additional site information: This landfill is reported to receive average 1500 tonnes of waste per day, of which 1000 tonnes is redirected to electricity generation by waste gasification. Admin-1, W., 2023. TPA Benowo Surabaya. Yayasan Bina Bhakti Lingkungan. URL https://www.yayasanbinabhaktilingkungan.or.id/tpa-benowo-surabaya/ (accessed 3.22.24).

Area: 44.9 ha

Period 1 Date (yyyymmdd): 20180313

Period 2 Date (yyyymmdd): 20190401

Period 1 Volume Change: 742.9329 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 162.6432 $(m \;\cdot day\;\;)$

Estimated Period 2 error: 11.06264 $(m^3 \cdot day^{-1})$

Figure 64: Aerial Image

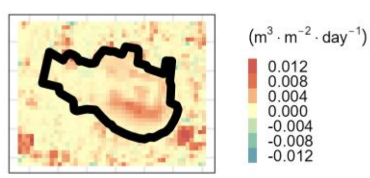


Figure 65: Period 1 changes

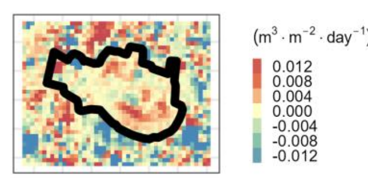


Figure 66: Period 2 changes

Study Site: AOI_037

Country: Israel

Administrative area: Gaza

Location (Lon, Lat): 34.45374 31.45655

Name:

Description: Gaza Landfill information not available

Additional site information: Landfill site in Juhor ad Dik, Gaza. Asharq Al-Awsat, 2023. [translated] A fire has been burning for days in a garbage dump in Gaza… and officials are asking for help to extinguish it [WWW Document]. URL https://aawsat.com/node/4526481 (accessed 3.22.24).

Area: 27.5 ha

Period 1 Date (yyyymmdd): 20180215

Period 2 Date (yyyymmdd): 20190319

Period 1 Volume Change: 482.2728 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 219.6471 $(m \cdot day)$

Estimated Period 2 error: 2.877697 $(m^3 \cdot day^{-1})$

Figure 67: Aerial Image

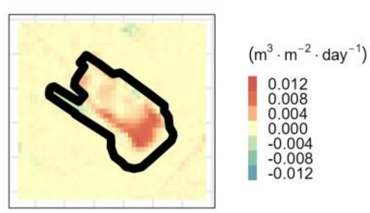


Figure 68: Period 1 changes

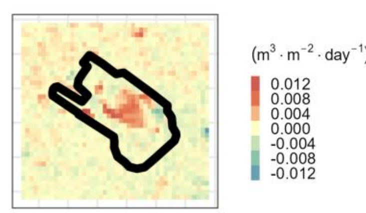


Figure 69: Period 2 changes

Study Site: AOI_038

Country: Indonesia

Administrative area: Makassar

Location (Lon, Lat): 119.4905 -5.176454

Name: Tempat Pembuangan Akhir Tamangapa

Description: Open Dump; 2,871.84 m3/day MSW (Mostly Residential; Commercial and Industrial)

Additional site information: Tamangapa Open dumping landfill site. Juhaidah, S., Usman, F., Subagiyo, A., 2019. PENGELOLAAN SAMPAH TPA TAMANGAPA KOTA MAKASSAR. Planning for Urban Region and Environment Journal (PURE) 8, 133–142. https://purejournal.ub.ac.id/index.php/pure/article/download/329/262

Area: 25.6 ha

Period 1 Date (yyyymmdd): 20180123

Period 2 Date (yyyymmdd): 20190211

Period 1 Volume Change: 139.6522 $(m \cdot day)$

Period 2 Volume Change: 1849.228 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 7.335252 $(m^3 \cdot day^{-1})$

Figure 70: Aerial Image

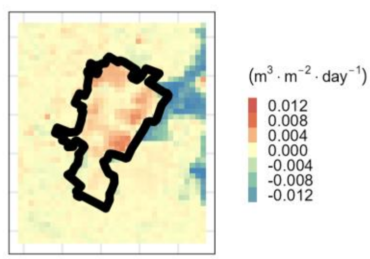


Figure 71: Period 1 changes

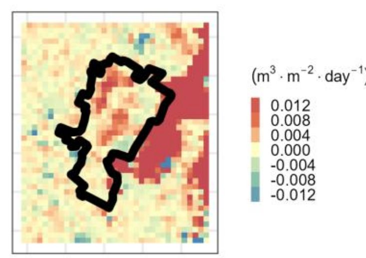


Figure 72: Period 2 changes

Study Site: AOI_039

Country: Japan

Administrative area: Amagasaki

Location (Lon, Lat): 135.3863 34.6816

Name:

Description: Managed landfill; Mainly Industrial Waste, but also MSW and Hazardous waste

Additional site information: Amagasaki Sea-surface waste disposal site in Osaka bay. Ministry of Land, Infrastructure, Transport and Tourism Kinki Regional Development Bureau Port and Airport Department, 2005. Osaka Bay Phoenix Plan [WWW Document]. URL https://www-pa-kkr-mlit-go-jp.translate.goog/general/measures/kinki/main/environment/phoenix_project/index.h (accessed 3.22.24).

Area: 94.5 ha

Period 1 Date (yyyymmdd): 20180817

Period 2 Date (yyyymmdd): 20191111

Period 1 Volume Change: -88.82514 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 3961.172 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 12.75032 $(m^3 \cdot day^{-1})$

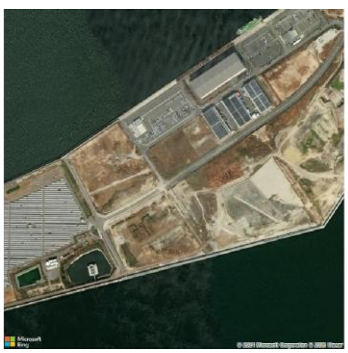


Figure 73: Aerial Image

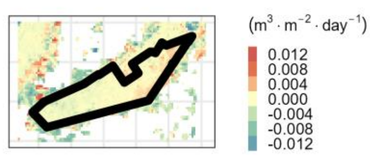


Figure 74: Period 1 changes

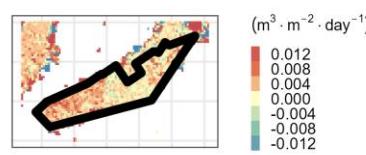


Figure 75: Period 2 changes

Study Site: AOI_040

Country: Spain

Administrative area: Melilla

Location (Lon, Lat): -2.938087 35.30092

Name: Centro de Residuos Sólidos Urbanos

Description: MSW from Melilla city (30,000 Mg per year)

Additional site information: Melilla Comprehensive Waste Treatment Centre (REMESA) emgrisa, 2024. Centro de tratamiento integral de residuos de Melilla S.A. (REMESA) [WWW Document]. Gestión de residuos, tratamiento de suelos y aguas - Emgrisa. URL https://www.emgrisa.es/instalaciones/centro-de-tratamiento-integral-de-residuos-de-melilla-s- a-remesa/ (accessed 3.22.24).

Area: 5.3 ha

Period 1 Date (yyyymmdd): 20180403

Period 2 Date (yyyymmdd): 20190515

Period 1 Volume Change: 202.842 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 100.2718 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 2.081217 $(m^3 \cdot day^{-1})$

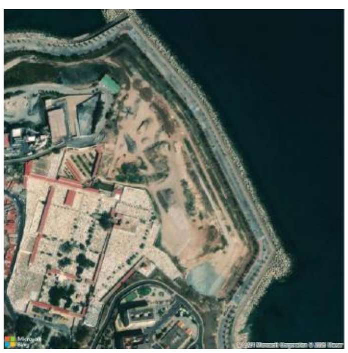


Figure 76: Aerial Image

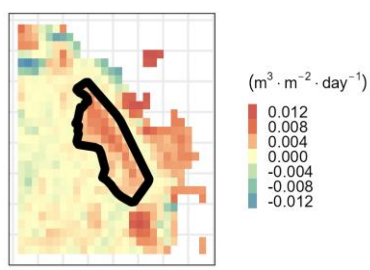


Figure 77: Period 1 changes

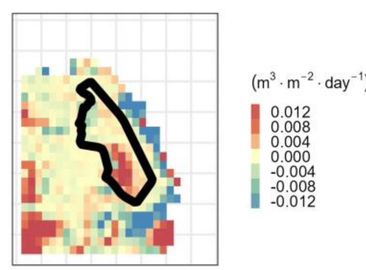


Figure 78: Period 2 changes

Study Site: AOI_042

Country: Nigeria

Administrative area: Apapa

Location (Lon, Lat): 3.349278 6.478206

Name: Open Dump

Description: Informal; unnamed; Open dump

Additional site information: Informal Dumping site on 42Kenneth, Uzoma Dike Ave, Lagos, Nigeria.

Area: 1.5 ha

Period 1 Date (yyyymmdd): 20180211

Period 2 Date (yyyymmdd): 20191223

Period 1 Volume Change: 2.412624 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 20.95361 $(m \ \cdot day \ )$

Estimated Period 2 error: 1.147496 $(m^3 \cdot day^{-1})$

Figure 79: Aerial Image

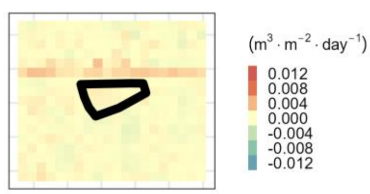


Figure 80: Period 1 changes

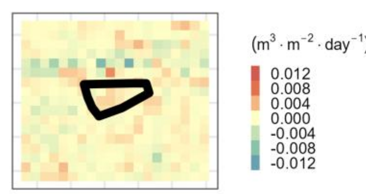


Figure 81: Period 2 changes

Study Site: AOI_044

Country: Indonesia

Administrative area: Surakarta

Location (Lon, Lat): 110.8561 -7.535914

Name: TPA Putri Cempo

Description: MSW; Open Dump

Additional site information: Landfill site reported to receive 300 tonnes of waste per day from Surakarta city, Java. Agnia Primasasti, 2023. TPA Putri Cempo Solo: Largest Waste Disposal Site in Solo – Surakarta City Government. URL https://surakarta.go.id/?p=29845 (accessed 3.22.24).

Area: 12.2 ha

Period 1 Date (yyyymmdd): 20180223

Period 2 Date (yyyymmdd): 20190219

Period 1 Volume Change: 153.74 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 159.0926 $(m \ \cdot day \ )$

Estimated Period 2 error: 2.148776 $(m^3 \cdot day^{-1})$

Figure 82: Aerial Image

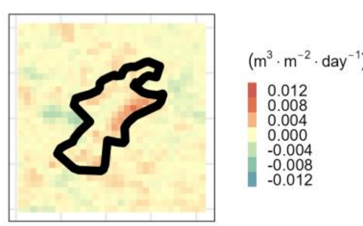


Figure 83: Period 1 changes

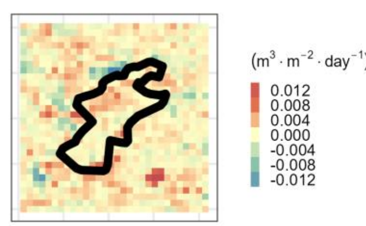


Figure 84: Period 2 changes

Study Site: AOI_048

Country: Mexico

Administrative area: La Paz

Location (Lon, Lat): -98.86466 19.28477

Name: Informal waste dumping site

Description: Open Dump;

Additional site information: Small waste dumping site in Chalco municipality, Mexico.

Area: 5.3 ha

Period 1 Date (yyyymmdd): 20180529

Period 2 Date (yyyymmdd): 20200513

Period 1 Volume Change: 81.84112 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 22.19513 ($m \cdot day$)

Estimated Period 2 error: 2.021098 ($m^3 \cdot day^{-1}$)

Figure 85: Aerial Image

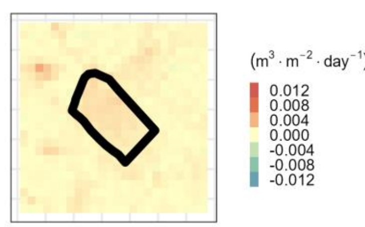


Figure 86: Period 1 changes

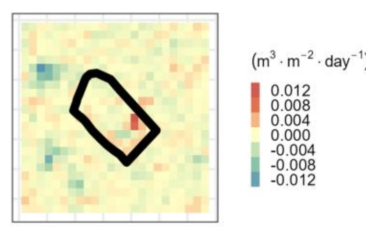


Figure 87: Period 2 changes

Study Site: AOI_049

Country: Romania

Administrative area: Municipiul Bucuresti

Location (Lon, Lat): 25.98406 44.47728

Name: IRIDEX - Chiajna

Description: MSW; Integrated waste management facility

Additional site information: Landfill site closed for operations in 2023. Alina Oprea, n.d. Chiajna landfill closes permanently [WWW Document]. Green Forum. URL https://www.green-forum.eu/environment/20231113/chiajna-landfill-is-permanently-closed-707 (accessed 3.22.24).

Area: 24.6 ha

Period 1 Date (yyyymmdd): 20180619

Period 2 Date (yyyymmdd): 20191211

Period 1 Volume Change: 710.6077 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 864.2488 ($m \cdot day$)

Estimated Period 2 error: 2.479004 ($m^3 \cdot day^{-1}$)

Figure 88: Aerial Image

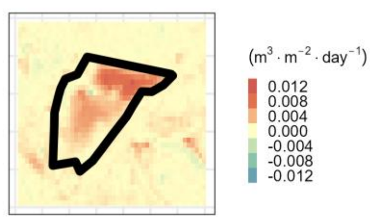


Figure 89: Period 1 changes

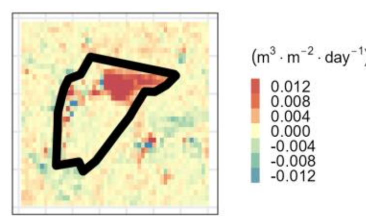


Figure 90: Period 2 changes

Study Site: AOI_051

Country: Indonesia

Administrative area: Denpasar

Location (Lon, Lat): 115.2208 -8.722052

Name: Tempat Pembuangan Akhir Suwung

Description: MSW; Open dump

Additional site information: Arbain -, Mardana, N.K., Sudana, I.B., 2008. ECOTROPHIC : Jurnal Ilmu Lingkungan (Journal of Environmental Science) 3. https://ojs.unud.ac.id/index.php/ECOTROPHI https://www.detik.com/bali/berita/d-6384653/tpa-suwung-akan-ditutup-badung-maksimalkan-2-tpst-pengganti

Area: 30.8 ha

Period 1 Date (yyyymmdd): 20180307

Period 2 Date (yyyymmdd): 20191203

Period 1 Volume Change: 821.6516 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 507.3555 ($m \quad \cdot day \quad$)

Estimated Period 2 error: 3.597354 ($m^3 \cdot day^{-1}$)

Figure 91: Aerial Image

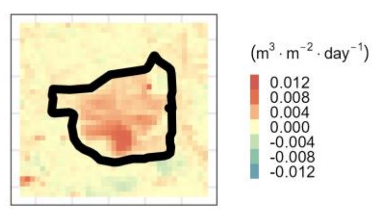


Figure 92: Period 1 changes

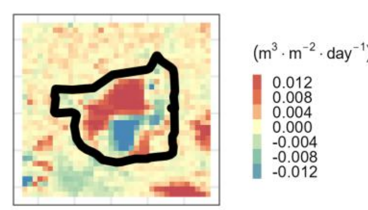


Figure 93: Period 2 changes

Study Site: AOI_053

Country: Iraq

Administrative area: Adhamiya

Location (Lon, Lat): 44.54255 33.41701

Name:

Description: Open Dump; Unmanaged

Additional site information: Unsanitary landfill site in Baghdad

Area: 42.8 ha

Period 1 Date (yyyymmdd): 20180927

Period 2 Date (yyyymmdd): 20191129

Period 1 Volume Change: 226.8226 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -17.85458 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 4.0226 ($m^3 \cdot day^{-1}$)

Figure 94: Aerial Image

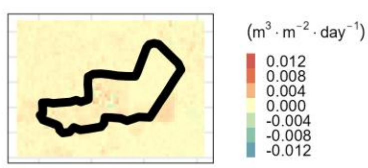


Figure 95: Period 1 changes

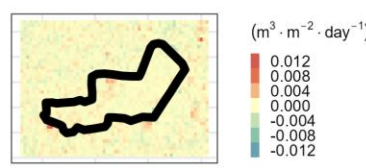


Figure 96: Period 2 changes

Study Site: AOI_054

Country: Denmark

Administrative area: København

Location (Lon, Lat): 12.53213 55.6257

Name: RGS Nordic Selinevej Waste facility

Description: Soil & Construction waste

Additional site information: Soil and construction waste treatment facility. RGS Nordic, 2022. København, Selinevej [WWW Document]. RGS Nordic. URL https://rgsnordic.com/anlaeg/selinevej/ (accessed 3.22.24).

Area: 59.5 ha

Period 1 Date (yyyymmdd): 20171001

Period 2 Date (yyyymmdd): 20180623

Period 1 Volume Change: 202.2952 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 1434.404 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 6.60624 $(m^3 \cdot day^{-1})$

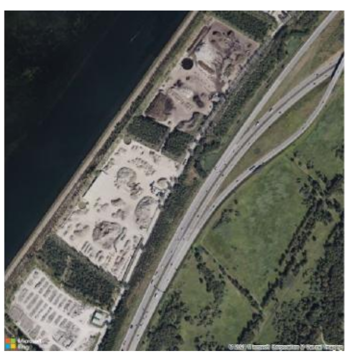


Figure 97: Aerial Image

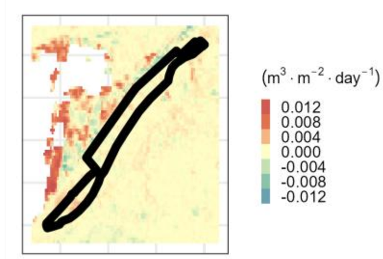


Figure 98: Period 1 changes

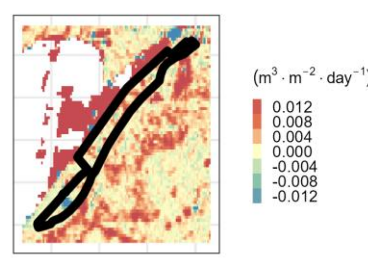


Figure 99: Period 2 changes

Study Site: AOI_056

Country: South Korea

Administrative area: Seongnam

Location (Lon, Lat): 127.0965 37.35473

Name:

Description: MSW; hazardous waste; household and other types

Additional site information: Seongnam City waste landfill Gyeonggi-do, Seongnam-si, Bundang-gu,at South Korea.

Area: 7.9 ha

Period 1 Date (yyyymmdd): 20200423

Period 2 Date (yyyymmdd): 20210409

Period 1 Volume Change: 68.96174 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 48.1665 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 3.489559 $(m^3 \cdot day^{-1})$

Figure 100: Aerial Image

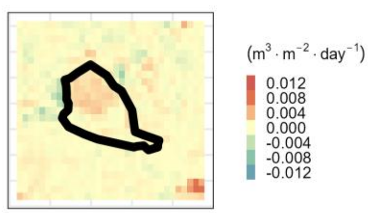


Figure 101: Period 1 changes

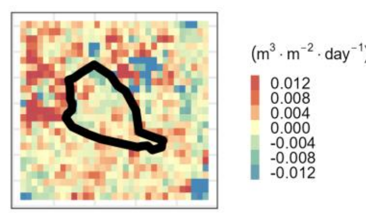


Figure 102: Period 2 changes

Study Site: AOI_057

Country: Portugal

Administrative area: Lisboa

Location (Lon, Lat): -9.17832 38.77772

Name: Valorsul - Centro de Triagem e Ecocentro do Lumiar

Description: Waste separation and recycling facility and sanitary landfill

Additional site information: Valorsul, 2024. Centro de Triagem do Lumiar [WWW Document]. URL https://www.valorsul.pt/pt/areas-de-negocio/tratamento-e-valorizacao-de-residuos-urbanos/triagem-de-materiais-reciclaveis/triagem-de-materiais-reciclaveis/centro-de-triagem-do-lumiar/ (accessed 3.22.24).

Area: 21.8 ha

Period 1 Date (yyyymmdd): 20181119

Period 2 Date (yyyymmdd): 20190315

Period 1 Volume Change: 34.27173 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -619.1815 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 3.073428 ($m^3 \cdot day^{-1}$)

Figure 103: Aerial Image

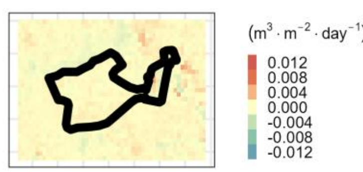


Figure 104: Period 1 changes

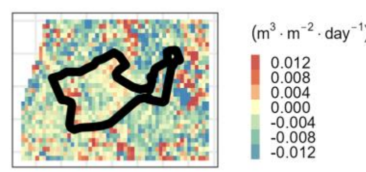


Figure 105: Period 2 changes

Study Site: AOI_058

Country: Japan

Administrative area: Machida

Location (Lon, Lat): 139.4081 35.58738

Name:

Description: Waste type not reported by authority

Additional site information: Machida City General Waste Final Disposal Site. City, M., 2022. [WWW Document]. URL https://www.city.machida.tokyo.jp/kurashi/kankyo/gomi/shiryo/shisetu/m (accessed 3.22.24).
Area: 3.5 ha

Period 1 Date (yyyymmdd): 20180705

Period 2 Date (yyyymmdd): 20200517

Period 1 Volume Change: 39.78341 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: -312.6976 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 2.513944 $(m^3 \cdot day^{-1})$

Figure 106: Aerial Image

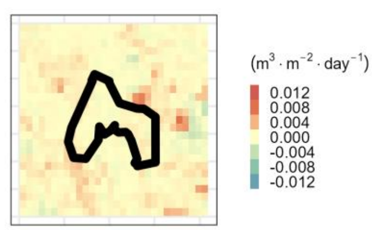


Figure 107: Period 1 changes

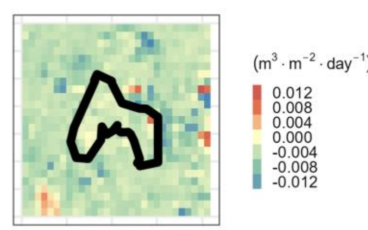


Figure 108: Period 2 changes

Study Site: AOI_060

Country: Palestine

Administrative area: Gaza ash Shamaliyah

Location (Lon, Lat): 34.51645 31.54913

Name: Small Landfill in Levant, Gaza

Description: NA

Additional site information: Further information unavailable.

Area: 1.5 ha

Period 1 Date (yyyymmdd): 20180215

Period 2 Date (yyyymmdd): 20190319

Period 1 Volume Change: 1.23692 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -0.2894845 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 0.9996993 ($m^3 \cdot day^{-1}$)

Figure 109: Aerial Image

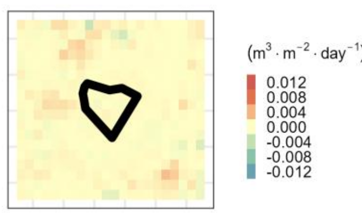


Figure 110: Period 1 changes

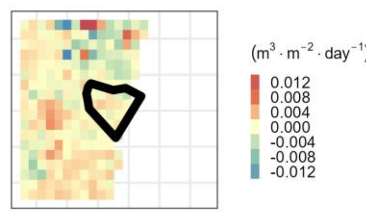


Figure 111: Period 2 changes

Study Site: AOI_061

Country: Guatemala

Administrative area: ZONA 3

Location (Lon, Lat): -90.53284 14.62903

Name: Basurero Zona 3

Description: Big Open Dump; MSW

Additional site information: https://concriterio.gt/un-alivio-para-vecinos-de-la-zona- 3-los-olores-fetidos-del-basurero-desaparecen/ Youtube video: https://youtu.be/D3lI-JriVjE?si=AmJy59YWzrRWnl_A

Area: 17 ha

Period 1 Date (yyyymmdd): 20171227

Period 2 Date (yyyymmdd): 20191213

Period 1 Volume Change: 1083.353 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 635.0899 $(m \cdot day)$

Estimated Period 2 error: 16.99046 $(m^3 \cdot day^{-1})$

Figure 112: Aerial Image

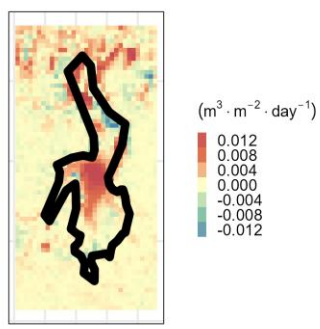


Figure 113: Period 1 changes

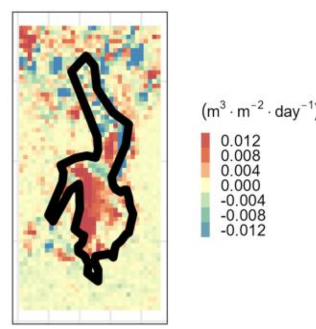


Figure 114: Period 2 changes

Study Site: AOI_064

Country: Togo

Administrative area: Golfe (incl Lomé)

Location (Lon, Lat): 1.21444 6.23864

Name: Ancienne décharge de Lomé

Description: Open Dump receiving MSW from Lome

Additional site information: Open Dump site in Lome. Morgane Le Cam, 2017. « Lomé la poubelle », bientôt de l'histoire ancienne ? Le Monde.fr.

Area: 13.3 ha

Period 1 Date (yyyymmdd): 20180215

Period 2 Date (yyyymmdd): 20191229

Period 1 Volume Change: 281.6119 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 3.811108 ($m \cdot day$)

Estimated Period 2 error: 3.084087 ($m^3 \cdot day^{-1}$)

Figure 115: Aerial Image

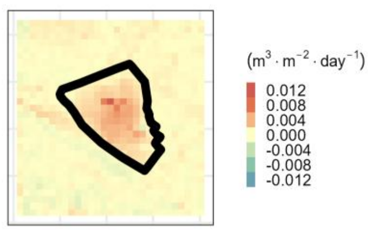


Figure 116: Period 1 changes

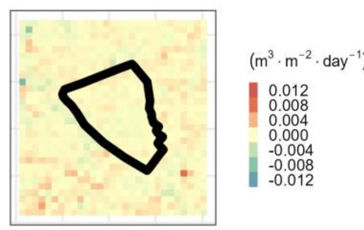


Figure 117: Period 2 changes

Study Site: AOI_069

Country: People's Republic of China

Administrative area: Shenzhen

Location (Lon, Lat): 114.0812 22.59485

Name:

Description: MSW; sanitary landfill
Additional site information: Shenzhen Xiaping Solid Waste Landfill. Additional info: https://baike.baidu.com/item/%E6%B7%B1%E5%9C%B3%E5%B8%82%E4%B8%8B%E5%9D%AA%E5%9B http://www.szlh.gov.cn/attachment/0/227/227124/4517551.pdf
Area: 92.8 ha

Period 1 Date (yyyymmdd): 20180829

Period 2 Date (yyyymmdd): 20191227

Period 1 Volume Change: 2546.855 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 2476.474 $(m \;\; \cdot day \;\;\;)$

Estimated Period 2 error: 11.80393 $(m^3 \cdot day^{-1})$

Figure 118: Aerial Image

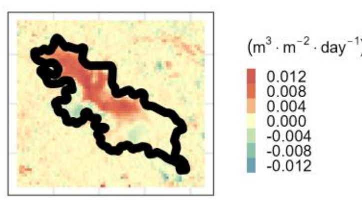


Figure 119: Period 1 changes

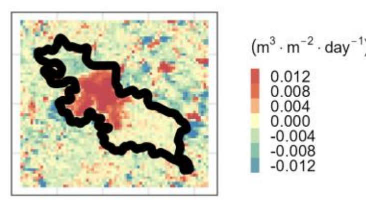


Figure 120: Period 2 changes

Study Site: AOI_071

Country: Colombia

Administrative area: Medellín

Location (Lon, Lat): -75.63347 6.263967

Name: Escombrera municipal

Description: Waste types:rubble; soil; garden; animal excreta
Additional site information: Municipal landfill in Antiquoa.
https://radatilly.gob.ar/medioambiente/escombrera municipal/

Area: 20.8 ha

Period 1 Date (yyyymmdd): 20180421

Period 2 Date (yyyymmdd): 20210711

Period 1 Volume Change: -15.08474 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -135.5032 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 3.649387 ($m^3 \cdot day^{-1}$)

Figure 121: Aerial Image

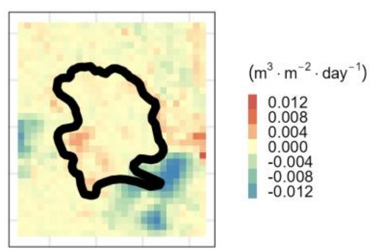


Figure 122: Period 1 changes

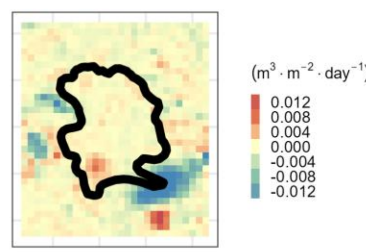


Figure 123: Period 2 changes

Study Site: AOI_072

Country: Philippines

Administrative area: Binangonan

Location (Lon, Lat): 121.2071 14.45797

Name: Lunsad Dumpsite

Description: Open Dumpsite

Additional site information: Small landfill in Rizal, Philipines

Area: 1.4 ha

Period 1 Date (yyyymmdd): 20180819

Period 2 Date (yyyymmdd): 20191227

Period 1 Volume Change: 9.700735 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: -3.444557 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 0.8369518 $(m^3 \cdot day^{-1})$

Figure 124: Aerial Image

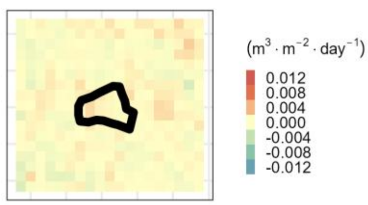


Figure 125: Period 1 changes

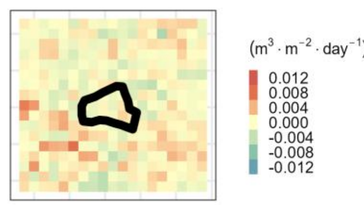


Figure 126: Period 2 changes

Study Site: AOI_074

Country: Philippines

Administrative area: Iloilo City

Location (Lon, Lat): 122.5233 10.70933

Name: Iloilo City Landfill

Description: Sanitary landfill; MSW

Additional site information: Gail Momblan, 2019. First sanitary landfill in Iloilo starts operation in August [WWW Document]. URL https://www.pna.gov.ph/articles/1073875 (accessed 3.22.24).

Area: 4.4 ha

Period 1 Date (yyyymmdd): 20180803

Period 2 Date (yyyymmdd): 20200423

Period 1 Volume Change: 160.6994 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 244.6761 ($m \cdot day$)

Estimated Period 2 error: 2.584515 ($m^3 \cdot day^{-1}$)

Figure 127: Aerial Image

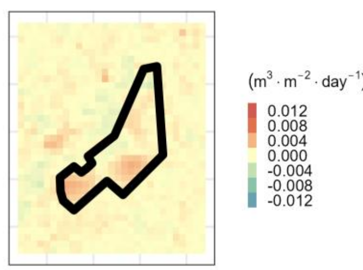


Figure 128: Period 1 changes

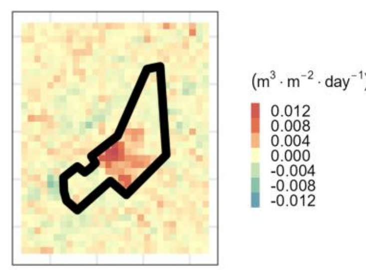


Figure 129: Period 2 changes

Study Site: AOI_075

Country: Indonesia

Administrative area: Palembang

Location (Lon, Lat): 104.7492 -2.912154

Name: TPA Sukawinatan

Description: Open dump; MSW

Additional site information: Puspita, H.I., 2023. TPA Sukawinatan Tetap Beroperasi [WWW Document]. Bisnis.com. URL https://sumatra.bisnis.com/read/20231003/533/1700543/tpa-sukawinatan-tetap-beroperasi (accessed 3.25.24).

Area: 27.7 ha

Period 1 Date (yyyymmdd): 20180515

Period 2 Date (yyyymmdd): 20210711

Period 1 Volume Change: 254.3719 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 305.3257 ($m \cdot day$)

Estimated Period 2 error: 3.778353 ($m^3 \cdot day^{-1}$)

Figure 130: Aerial Image

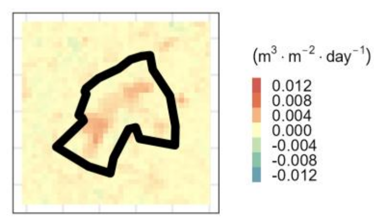


Figure 131: Period 1 changes

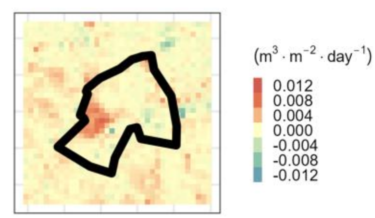


Figure 132: Period 2 changes

Study Site: AOI_077

Country: United Kingdom

Administrative area: Greater London

Location (Lon, Lat): 0.1939516 51.49439

Name: Rainham Landfill

Description: MSW; sanitary landfill; Material recovery facility

Additional site information: Landfill site in Greater London, average reported increase in landfill volume is 1292 cubic meter per day (2019 - 2020). WikiWaste, 2023. Rainham Landfill - [WWW Document]. URL https://wiki.monksleigh.com/Rainham_Landfill (accessed 3.25.24). https://www.veolia.co.uk/veolia-united-kingdom-landfill-sites

Area: 157.6 ha

Period 1 Date (yyyymmdd): 20170923

Period 2 Date (yyyymmdd): 20190227

Period 1 Volume Change: 982.1432 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 1886.082 $(m \ \cdot day \ \ )$

Estimated Period 2 error: 6.929092 $(m^3 \cdot day^{-1})$

Figure 133: Aerial Image

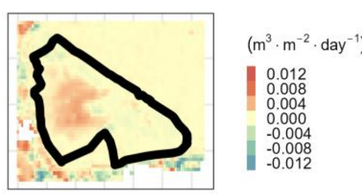


Figure 134: Period 1 changes

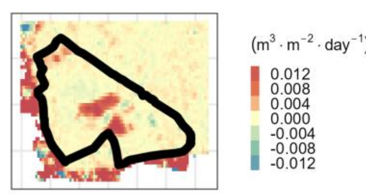


Figure 135: Period 2 changes

Study Site: AOI_078

Country: Indonesia

Administrative area: Kota Madiun

Location (Lon, Lat): 111.5025 -7.613769

Name: TPA Winongo

Description: MSW

Additional site information: Landfill of Madiun city, reported to receive approximately 100 tonnes of waste per day. Sofyan Arif Candra Sakti, 2021. TPA Winongo Kota Madiun Over Kapasitas, Wali Kota Maidi : Manfaatkan Residu Sampah [WWW Document]. Surya.co.id. URL https://surabaya.tribunnews.com/2021/10/21/tpa-winongo-kota-madiun-over-kapasitas-wali-kota-maidi-manfaatkan-residu-sampah (accessed 3.25.24).

Area: 6.4 ha

Period 1 Date (yyyymmdd): 20180201

Period 2 Date (yyyymmdd): 20190109

Period 1 Volume Change: 68.98146 ($m \cdot day$)

Period 2 Volume Change: 43.72723 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 1.607902 ($m^3 \cdot day^{-1}$)

Figure 136: Aerial Image

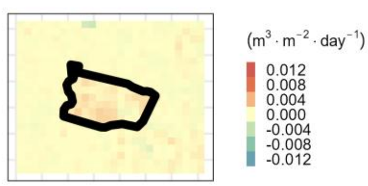


Figure 137: Period 1 changes

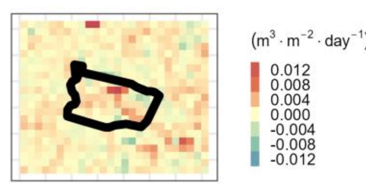


Figure 138: Period 2 changes

Study Site: AOI_079

Country: Philippines

Administrative area: Talisay City

Location (Lon, Lat): 123.8097 10.28513

Name: Talisay Sanitary Landfill

Description: Sanitary landfill; MSW

Additional site information: Small landfill site in Cebu, Philipines.

Area: 3.8 ha

Period 1 Date (yyyymmdd): 20180605

Period 2 Date (yyyymmdd): 20191003

Period 1 Volume Change: 24.61186 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 67.02888 $(m \quad \cdot day \quad)$

Estimated Period 2 error: 2.350158 $(m^3 \cdot day^{-1}\ )$

Figure 139: Aerial Image

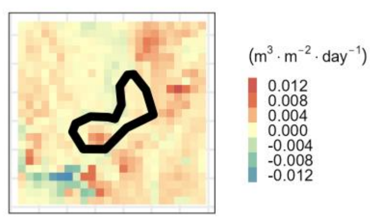


Figure 140: Period 1 changes

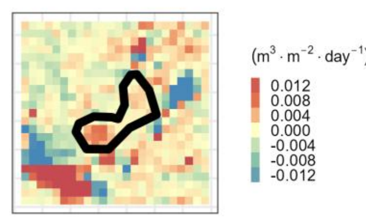


Figure 141: Period 2 changes

Study Site: AOI_081

Country: Colombia

Administrative area: Santafé de Bogotá

Location (Lon, Lat): -74.13632 4.503818

Name: Relleno Sanitario Doña Juana

Description: MSW; Sanitary landfill complex with biogas recovery; Hazardous waste and non-hazardous waste disposal areas

Additional site information: Large Sanitary Waste Management Complex, receiving approximately 6000 tonnes of waste per day. Especiales UAESP: Relleno Doña Juana [WWW Document], 2024. URL https://www.uaesp.gov.co/especiales/relleno/ (accessed 3.22.24).

Area: 355 ha

Period 1 Date (yyyymmdd): 20180911

Period 2 Date (yyyymmdd): 20200119

Period 1 Volume Change: 2890.242 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 2569.348 ($m \cdot day$)

Estimated Period 2 error: 20.21523 ($m^3 \cdot day^{-1}$)

Figure 142: Aerial Image

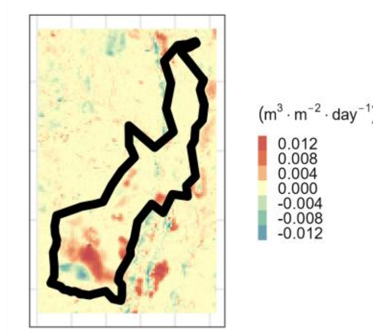


Figure 143: Period 1 changes

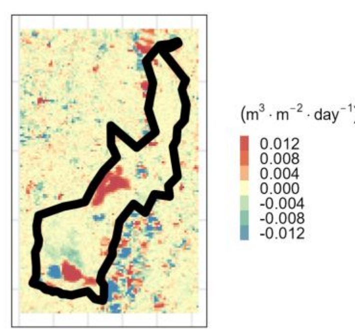


Figure 144: Period 2 changes

Study Site: AOI_084

Country: Japan

Administrative area: Saitama

Location (Lon, Lat): 139.7202 35.88385

Name:

Description: Sanitary landfill; MSW

Additional site information: Saitama city final disposal city. Saitama City, 2022. [WWW Document]. . URL https://www.city.saitama.lg.jp/001/006/011/004/p010372.html (accessed 3.22.24). Additional info: https://www.city.saitama.lg.jp/001/006/010/003/p051434.html

Area: 4.3 ha
Period 1 Date (yyyymmdd): 20180727

Period 2 Date (yyyymmdd): 20200425

Period 1 Volume Change: 28.01776 ($m^3 \cdot day^{-1}$)
Period 2 Volume Change: 43.63274 ($m \cdot day$)

Estimated Period 2 error: 1.848057 ($m^3 \cdot day^{-1}$)

Figure 145: Aerial Image

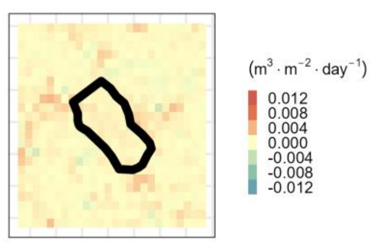


Figure 146: Period 1 changes

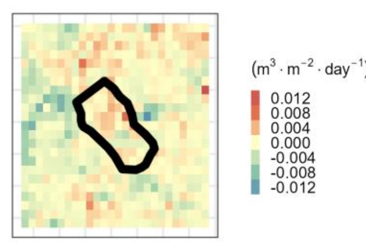


Figure 147: Period 2 changes

Study Site: AOI_085

Country: Hong Kong

Administrative area: Tuen Mun

Location (Lon, Lat): 113.9335 22.41924

Name: West New Territories Landfill

Description: MSW; Construction and Demolition Waste; Special Wastes; Sanitary landfill

Additional site information: Largest Landfill site in Hong Kong. Statistics Unit, Environmental Protection Department, 2020. Monitoring of Solid Waste in Hong Kong: Waste Statistics for 2019, Monitoring of Solid Waste in Hong Kong. Environmental Protection Department, Hong Kong.

Area: 120.7 ha

Period 1 Date (yyyymmdd): 20180829

Period 2 Date (yyyymmdd): 20200219

Period 1 Volume Change: 4863.185 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 5793.753 ($m \cdot day$)

Estimated Period 2 error: 10.01835 ($m^3 \cdot day^{-1}$)

Figure 148: Aerial Image

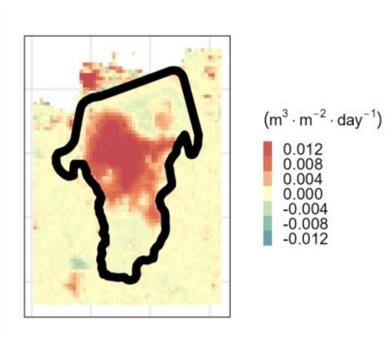


Figure 149: Period 1 changes

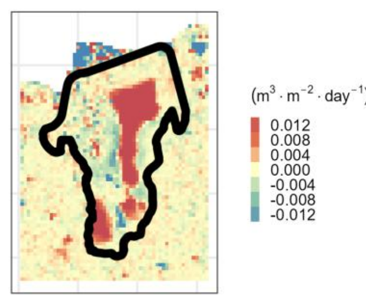


Figure 150: Period 2 changes

Study Site: AOI_087

Country: Japan

Administrative area: Izumiōtsu

Location (Lon, Lat): 135.3761 34.52138

Name:

Description: Waste types: Industrial waste, land surplus, dredged soil, general waste, sewerage slude
Additional site information: Izumiotsuoki Offshore Landfill Site.
https://www.env.go.jp/council/former2013/11s hearing03b/mat03_2.pdf https://www.osakawan-center.or.jp/index.php/business-summary/final-
disposal-site

Area: 158.9 ha

Period 1 Date (yyyymmdd): 20180817

Period 2 Date (yyyymmdd): 20191111

Period 1 Volume Change: 709.3227 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 1761.378 ($m \quad \cdot day \quad$)

Estimated Period 2 error: 10.307 67 ($m^3 \cdot day^{-1}$)

Figure 151: Aerial Image

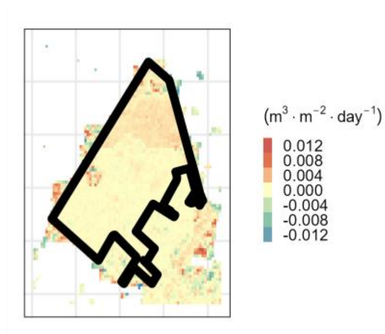


Figure 152: Period 1 changes

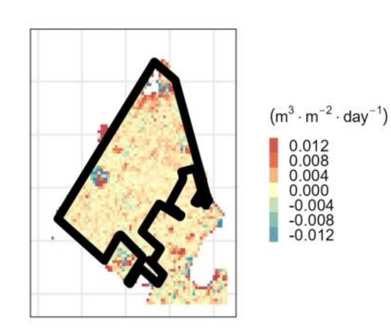


Figure 153: Period 2 changes

Study Site: AOI_089

Country: Indonesia

Administrative area: Kota Semarang

Location (Lon, Lat): 110.3592 -7.02442

Name: TPA Jatibarang

Description: MSW (62% organic 38% inorganic); Waste enter facility: 800 - 900 Mg/day (ref from 2017); open dump

Additional site information: Harjanti, I.M., Anggraini, P., 2020. Pengelolaan Sampah Di Tempat Pembuangan Akhir (TPA) Jatibarang, Kota Semarang. Jurnal Planologi 17, 185–197. https://doi.org/10.30659/jpsa.v17i2.9943 A. H. Pratiwi, B. Budiyono, and N. A. Y. Dewanti, "Identification Types of the Marine Debris and Factors Related them in Semarang City," Jurnal Presipitasi : Media Komunikasi dan Pengembangan Teknik Lingkungan, vol. 18, no. 1, pp. 64-72, Mar. 2021.http://dx.doi.org/10.14710/presipitasi.v18i1.64-72

Area: 34.4 ha

Period 1 Date (yyyymmdd): 20180423

Period 2 Date (yyyymmdd): 20190503

Period 1 Volume Change: 322.528 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 301.2006 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 6.499668 ($m^3 \cdot day^{-1}$)

Figure 154: Aerial Image

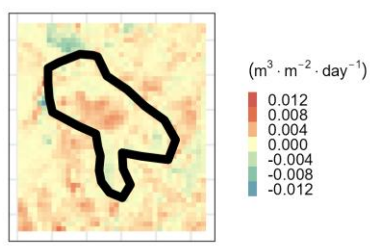


Figure 155: Period 1 changes

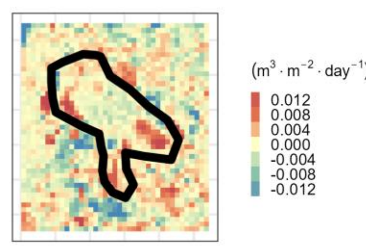


Figure 156: Period 2 changes

Study Site: AOI_093

Country: Tanzania

Administrative area: Kinondoni

Location (Lon, Lat): 39.26241 -6.80247

Name: Small open dumpsite in Magomeni Kondoa

Description: Open Dump; Unofficial; Waste type not reported

Additional site information: The only official dumpsite in Dar E Salaaam is Pugu landfill site. However, 75% of the city's waste is dumped in informal waste dumps or burnt. Envirowise. (2018). What a Waste: Summary of Waste Management Practices in Dar es Salaam. https://www.envirowise.co.tz/what-a-waste-summary-of-waste-management-practices-in-dar-es-salaam/ World Bank. (2019). Zero Waste Event Planning A Guide for Dar es Salaam. https://documents1.worldbank.org/curated/ar/564711578675164791/pdf/Zero-Waste-Event-Planning-A-Guide-for-Dar-es-Salaam.pdf

Area: 2.5 ha

Period 1 Date (yyyymmdd): 20180623

Period 2 Date (yyyymmdd): 20181107

Period 1 Volume Change: -17.88236 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 51.27074 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.232815 $(m^3 \cdot day^{-1})$

Figure 157: Aerial Image

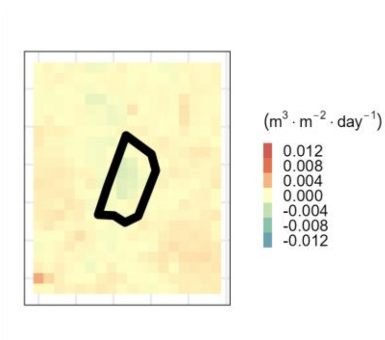


Figure 158: Period 1 changes

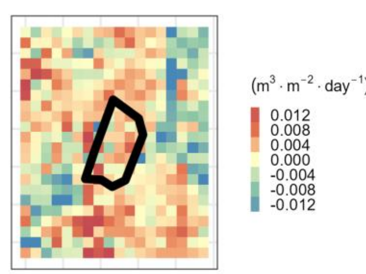


Figure 159: Period 2 changes

Study Site: AOI_094

Country: Indonesia

Administrative area: Jambi

Location (Lon, Lat): 103.6188 -1.690332

Name: TPA Talang Gulo

Description: Sanitary landfill; MSW

Additional site information: This landfill was managed as an open dump until 2021, after which it has been converted to Santitary landfill. Talang Gulo Landfill. MC JAMBI CITY, 2023. InfoPublik - TPA ERIC Talang Gulo Resmi Diserahkan kepada Pemkot Jambi [WWW Document]. URL https://infopublik-id.translate.goog/kategori/nusantara/792900/index.html?_x_tr_sl=id&_x_tr (accessed 3.22.24). Adriansyah, E., Agustina, T. E., & Rachman, S. (2019). Leachate Treatment of TPA Talang Gulo, Jambi City by Fenton Method and Adsorption. Indonesian Journal of Fundamental and Applied Chemistry, 4, 20–24. https://doi.org/10.24845/ijfac.v4.i1.20

Area: 11.1 ha

Period 1 Date (yyyymmdd): 20180411

Period 2 Date (yyyymmdd): 20190123

Period 1 Volume Change: 223.2324 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: -3402.799 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 2.520781 $(m^3 \cdot day^{-1})$

Figure 160: Aerial Image

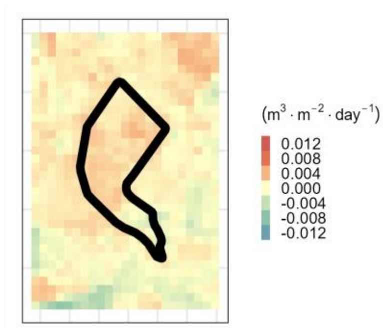


Figure 161: Period 1 changes

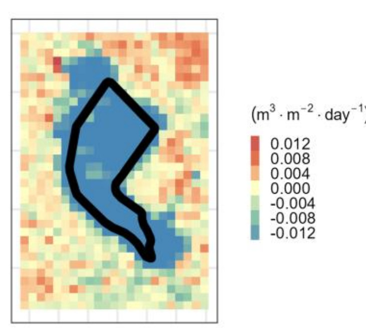


Figure 162: Period 2 changes

Study Site: AOI_098

Country: Guatemala

Administrative area: ZONA 18

Location (Lon, Lat): -90.47868 14.6621

Name: Clandestine dump

Description: Open dump

Additional site information: Illegal dump site in Zone 18 Guatamala city.

Area: 1.9 ha

Period 1 Date (yyyymmdd): 20180119

Period 2 Date (yyyymmdd): 20191213

Period 1 Volume Change: 89.23573 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 35.99126 ($m \;\; \cdot day \;\;$)

Estimated Period 2 error: 3.404426 ($m^3 \cdot day^{-1}$)

Figure 163: Aerial Image

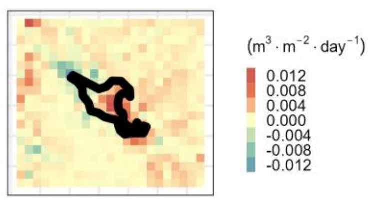


Figure 164: Period 1 changes

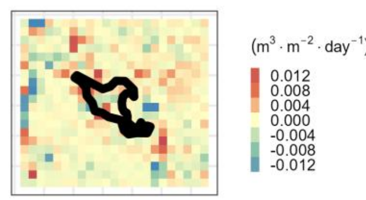


Figure 165: Period 2 changes

Study Site: AOI_099

Country: Ukraine

Administrative area: Kharkivs'ka

Location (Lon, Lat): 36.38039 49.96787

Name: Kharkiv-Eko Co., Ltd.

Description: Managed landfill; treatment of hazardous waste, medical waste; dangerous waste, used tyres, polymer waste

Additional site information: Landfill in Industrialnyi District, Kharkiv, Kharkiv Oblast, Ukraine, 61000. Management company website: http://kharkov-eco.com.ua/service

Area: 6.6 ha

Period 1 Date (yyyymmdd): 20170927

Period 2 Date (yyyymmdd): 20190219

Period 1 Volume Change: 183.0507 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: -147.3468 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.193354 $(m^3 \cdot day^{-1})$

Figure 166: Aerial Image

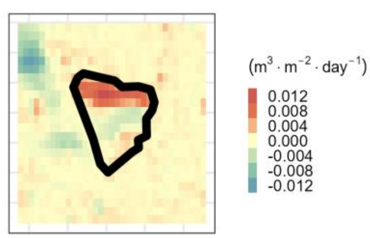


Figure 167: Period 1 changes

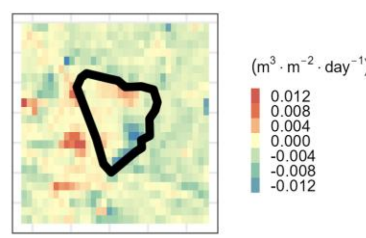


Figure 168: Period 2 changes

Study Site: AOI_100

Country: Indonesia

Administrative area: Kota Pasuruan

Location (Lon, Lat): 112.94 -7.654294

Name: TPA Blandongan

Description: Sanitary landfill; MSW

Additional site information: POLRESTA PASURUAN, 2023. Polres Pasuruan Kota Laksanakan Kegiatan Bakti Sosial di TPA Blandongan Kota Pasuruan - DIVISI HUMAS POLRI [WWW Document]. URL https://humas.polri.go.id/2023/08/01/polres-pasuruan-kota-laksanakan-kegiatan-bakti-sosial-di-tpa-blandongan-kota-pasuruan/ (accessed 3.22.24). Suprayitno, H., & Tangahu, B. V. (2018). Formulating a Policy for Developing Regional Solid Waste Final Disposal Installation in East Java Province. Jurnal Manajemen Aset Infrastruktur & Fasilitas, 2(0), Article 0. https://doi.org/10.12962/j26151847.v2i0.4232 Youtube video showing aerial view: https://youtu.be/at-y4ViqwBU?si=e_PQjkzn5GIUIgO7

Area: 28.4 ha

Period 1 Date (yyyymmdd): 20180313

Period 2 Date (yyyymmdd): 20200101

Period 1 Volume Change: 111.9578 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: -67.32934 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 16.48714 $(m^3 \cdot day^{-1})$

Figure 169: Aerial Image

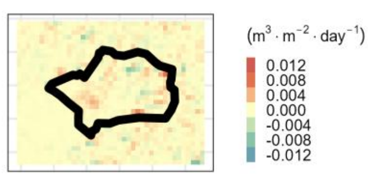


Figure 170: Period 1 changes

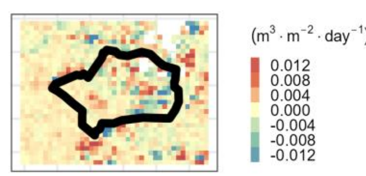


Figure 171: Period 2 changes

Inactive Landfill sites

Study Site: AOI_029

Country: Turkey

Administrative area: Kartal

Location (Lon, Lat): 29.21543 40.93767

Name: Eski Yakacık Çöplüğü Deponi Gaz Yakma Tesisleri

Description: Closed landfill

Additional site information: Old Yakacık Landfill Gas Combustion Facilities [Permanently closed]

Area: 5 ha

Period 1 Date (yyyymmdd): 20180621

Period 2 Date (yyyymmdd): 20190903

Period 1 Volume Change: -8.215135 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 82.92264 ($m \cdot day$)

Estimated Period 2 error: 2.144892 ($m^3 \cdot day^{-1}$)

Figure 172: Aerial Image

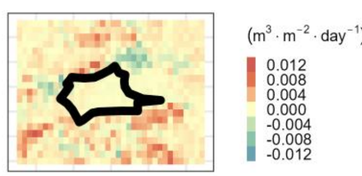


Figure 173: Period 1 changes

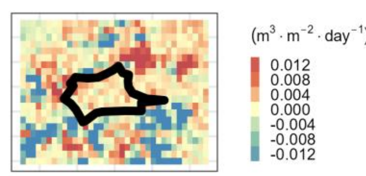


Figure 174: Period 2 changes

Study Site: AOI_033

Country: Japan

Administrative area: Yokohama

Location (Lon, Lat): 139.5576 35.43939

Name:

Description: Waste type: Sludge, ash, wood waste, asbestos et. (industrial waste); Closed facility; 910,000 cubic meter of waste
Additional site information: Closed Shinanomachi landfill in Yokohama. Yokohama C., 2023. [WWW Document]. URL https://www.city.yokohama.lg.jp/business/bunyabetsu/gomi-recycle/sangyo/sonota/shinano/shina1.html (accessed 3.21.24). Additional: https://www.city.yokohama.lg.jp/b
recycle/sangyo/sonota/shinano/gijutsu.files/0036_20180906.pdf
Area: 3 ha

Period 1 Date (yyyymmdd): 20180727

Period 2 Date (yyyymmdd): 20200425

Period 1 Volume Change: 28.75325 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -7.096727 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 2.30728 ($m^3 \cdot day^{-1}$)

Figure 175: Aerial Image

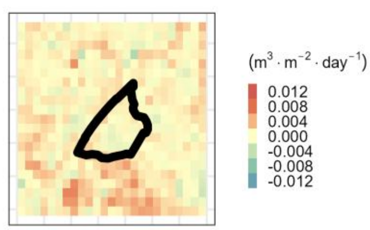


Figure 176: Period 1 changes

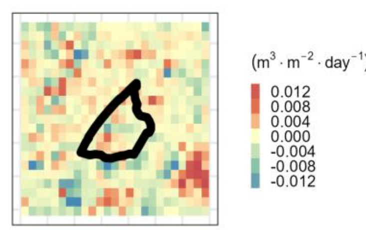


Figure 177: Period 2 changes

Study Site: AOI_045

Country: Sri Lanka

Administrative area: Kolonnawa

Location (Lon, Lat): 79.8906 6.93841

Name: Meethotamulla Garbage Dump

Description: Open Dump; MSW; closed

Additional site information: This landfill site collapsed in 2018, claiming the lives of 32 people. After which dumping at the landfill was abandoned. Jayaweera, M., Gunawardana, B., Gunawardana, M., Karunawardena, A., Dias, V., Premasiri, S., Dissanayake, J., Manatunge, J., Wijeratne, N., Karunarathne, D., Thilakasiri, S., 2019. Management of municipal solid waste open dumps immediately after the collapse: An integrated approach from Meethotamulla open dump, Sri Lanka. Waste Management 95, 227–240. https://doi.org/10.1016/j.wasman.2019.06.019

Area: 6.6 ha

Period 1 Date (yyyymmdd): 20190113

Period 2 Date (yyyymmdd): 20191015

Period 1 Volume Change: 170.8077 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: -625.6948 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.592345 $(m^3 \cdot day^{-1})$

Figure 178: Aerial Image

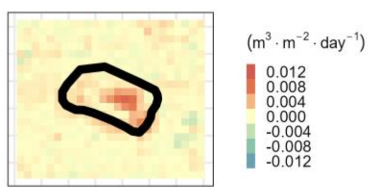


Figure 179: Period 1 changes

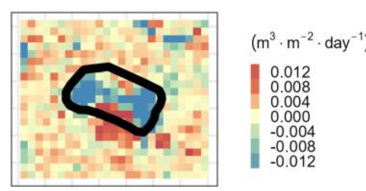


Figure 180: Period 2 changes

Study Site: AOI_050

Country: North Korea

Administrative area: Ch'ŏngnam

Location (Lon, Lat): 125.4448 39.48339

Name: Small landfill in South Pyongan

Description: Information unavailable

Additional site information: Landfill site confirmed by satellite imagery, further information unavailable.

Area: 1.7 ha

Period 1 Date (yyyymmdd): 20180809

Period 2 Date (yyyymmdd): 20191103

Period 1 Volume Change: 5.231366 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: -46.72531 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 0.8350745 $(m^3 \cdot day^{-1})$

Figure 181: Aerial Image

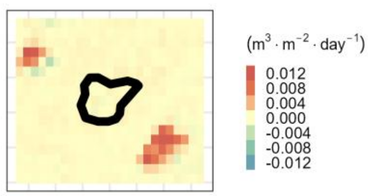


Figure 182: Period 1 changes

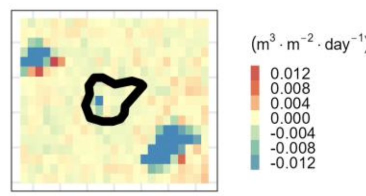


Figure 183: Period 2 changes

Study Site: AOI_052

Country: Philippines

Administrative area: Meycauayan City

Location (Lon, Lat): 120.972 14.72125

Name: Lingunan Dumpsite

Description: MSW; Closed landfill

Additional site information: Municipal landfill closed in 2011. Valenzuela City [@valenzuelacity], 2019. https://t.co/PsaVGMxm31. Twitter. Asian Development Bank, 2004. The Garbage Book: Solid Waste Management in Metro Manila.

Area: 12.2 ha

Period 1 Date (yyyymmdd): 20180809

Period 2 Date (yyyymmdd): 20191207

Period 1 Volume Change: 37.42824 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 21.40492 $(m \quad \cdot day \quad)$

Estimated Period 2 error: 2.606626 $(m^3 \cdot day^{-1})$

Figure 184: Aerial Image

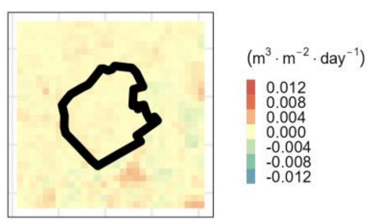


Figure 185: Period 1 changes

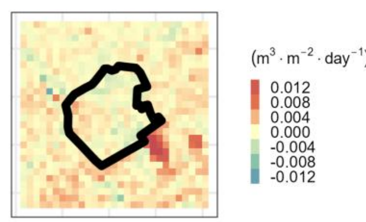


Figure 186: Period 2 changes

Study Site: AOI_063

Country: Uzbekistan

Administrative area: Tashkent City

Location (Lon, Lat): 69.3106 41.30549

Name: Small waste disposal site, Tashkent

Description: Waste type unknown

Additional site information: Construction and excavation visible in site during the study period. [Google earth pro time series]

Area: 1.3 ha

Period 1 Date (yyyymmdd): 20181127

Period 2 Date (yyyymmdd): 20210721

Period 1 Volume Change: -0.7197366 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -7.042735 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 0.7356626 ($m^3 \cdot day^{-1}$)

Figure 187: Aerial Image

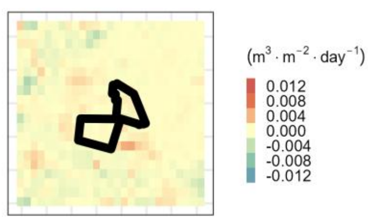


Figure 188: Period 1 changes

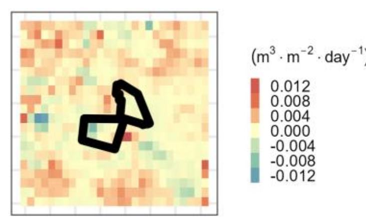


Figure 189: Period 2 changes

Study Site: AOI_065

Country: Philippines

Administrative area: Angono

Location (Lon, Lat): 121.1394 14.53546

Name: Taytay Controlled Dump

Description: NA

Additional site information: This landfill was closed and converted to a sport facility by Taytay local government in 2011,and was not receiving waste during the study period.Mangunay, K.F., 2011. Taytay gov't shuts down 13-hectare dump [WWW Document]. INQUIRER.net. URL https://newsinfo.inquirer.net/79019/taytay-govt-shuts-down-13-hectare-dump (accessed 3.22.24).

Area: 8.7 ha

Period 1 Date (yyyymmdd): 20180819

Period 2 Date (yyyymmdd): 20191227

Period 1 Volume Change: 106.4056 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: -124.6068 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.706197 $(m^3 \cdot day^{-1})$

Figure 190: Aerial Image

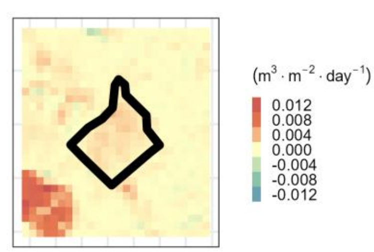


Figure 191: Period 1 changes

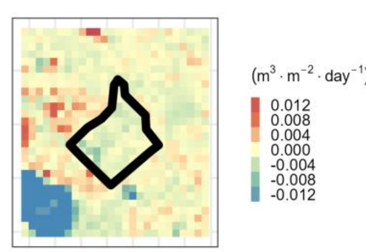


Figure 192: Period 2 changes

Study Site: AOI_076

Country: Mexico

Administrative area: Cuautitlán

Location (Lon, Lat): -99.15084 19.59206

Name: Closed landfill Mexico City

Description: Further information unvailable

Additional site information: NA

Area: 14.7 ha

Period 1 Date (yyyymmdd): 20180507

Period 2 Date (yyyymmdd): 20200303

Period 1 Volume Change: 56.97035 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: -18.35285 $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 5.128108 $(m^3 \cdot day^{-1})$

Figure 193: Aerial Image

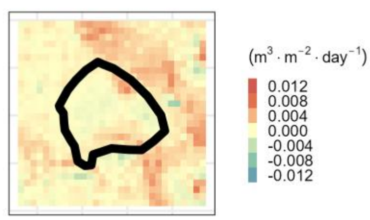


Figure 194: Period 1 changes

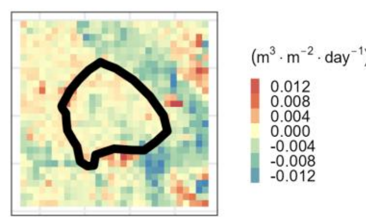


Figure 195: Period 2 changes

Study Site: AOI_080

Country: Brazil

Administrative area: Rio de Janeiro

Location (Lon, Lat): -43.47542 -22.84302

Name: Antigo aterro sanitário de Gericinó

Description: Open Dump; MSW from Rio de Jenerio

Additional site information: Gericino landfill closed in 2014. Emanuel Alencar, 2013. Aterro de Gericinó tem fechamento marcado para março de 2014 [WWW Document]. O Globo. URL https://oglobo.globo.com/rio/aterro-de-gericino-tem-fechamento-marcado-para-marco- de-2014-10196605 (accessed 3.22.24).

Area: 29.3 ha

Period 1 Date (yyyymmdd): 20171203

Period 2 Date (yyyymmdd): 20190913

Period 1 Volume Change: 520.6827 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 238.3631 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 3.2779 ($m^3 \cdot day^{-1}$)

Figure 196: Aerial Image

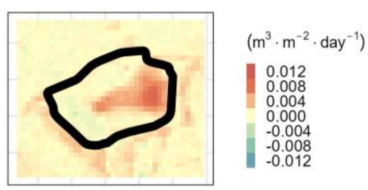


Figure 197: Period 1 changes

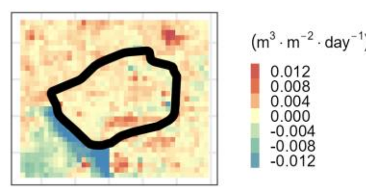


Figure 198: Period 2 changes

Study Site: AOI_092

Country: Mexico

Administrative area: Ocoyucan

Location (Lon, Lat): -98.24278 19.00313

Name: Car Waste Yard

Description: Car Scrap metal site

Additional site information: This car waste yard received and had cars removed repeatedly until 2018, after which the site was cleared until 2023 [Google Earth Pro time series imagery]

Area: 1.4 ha

Period 1 Date (yyyymmdd): 20180803

Period 2 Date (yyyymmdd): 20191211

Period 1 Volume Change: 10.28708 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 49.28531 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 0.7188794 ($m^3 \cdot day^{-1}$)

Figure 199: Aerial Image

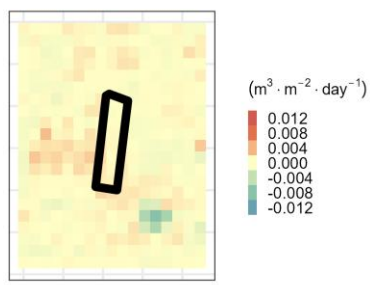


Figure 200: Period 1 changes

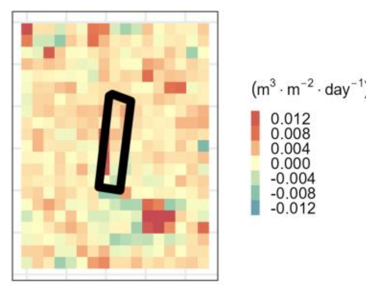


Figure 201: Period 2 changes

Sites with no period 2 data coverage

Study Site: AOI_001

Country: Kenya

Administrative area: Embakasi North

Location (Lon, Lat): 36.89742 -1.248232

Name: Dandora dumpsite

Description: Municipal Waste; Open Dump

Additional site information: A Large landfill in Nairobi, receiving approximately 850 tonnes of waste per day. Global Atlas of Environmental Justice, 2021. Dandora Landfill in Nairobi, Kenya [WWW Document]. Global Atlas of Environmental Justice. URL https://ejatlas.org/conflict/dandora-landfill-in-nairobi-kenya#:~:text=Dandora%20dumpsite%20is%20the%20d (accessed 3.19.24).

Area: 43.8 ha

Period 1 Date (yyyymmdd): 20190707

Period 2 Date (yyyymmdd): 20190707

Period 1 Volume Change: 360.7257 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 3.229376 $(m^3 \cdot day^{-1})$

Figure 202: Aerial Image

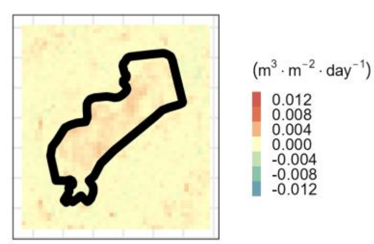


Figure 203: Period 1 changes

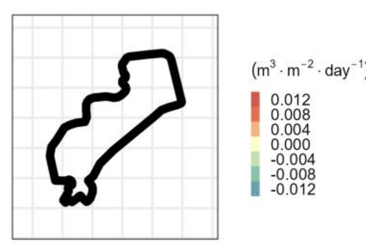


Figure 204: Period 2 changes

Study Site: AOI_006

Country: Angola

Administrative area: Kilamba Kiaxi

Location (Lon, Lat): 13.23753 -8.894554

Name: Aterro Sanitário do Golfe

Description: Closed

Additional site information: Inactive Landfill site [confirmed by time series satellite imagery]

Area: 13.8 ha

Period 1 Date (yyyymmdd): 20190529

Period 2 Date (yyyymmdd): 20190701

Period 1 Volume Change: -21.0236 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 2238.063 ($m \cdot day$)

Estimated Period 2 error: 2.999878 ($m^3 \cdot day^{-1}$)

Figure 205: Aerial Image

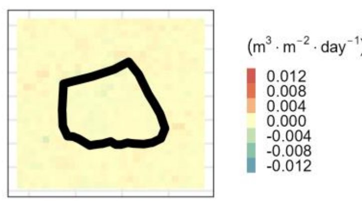


Figure 206: Period 1 changes

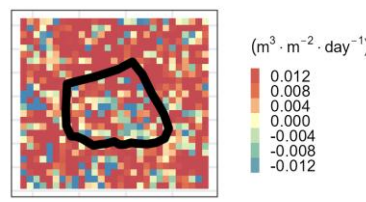


Figure 207: Period 2 changes

Study Site: AOI_007

Country: Kenya

Administrative area: Makadara

Location (Lon, Lat): 36.88419 -1.298421

Name: Mutindwa Lane Illegal landfill

Description: Municipal Waste; Open Dump; Illegal

Additional site information: Illegal dump Documented by Nairobi government. Estimated 150 Mg waste disposed. Designated Illegal site no. 6 in Figure E.6.1 of JICA. (2010). Final Report Volume 3 Supporting Report Section E (Preparatory Survey for Integrated Solid Waste Management in Nairobi City, Republic of Kenya). https://openjicareport.jica.go.jp/pdf/12005468_07.pdf

Area: 9 ha

Period 1 Date (yyyymmdd): 20190707

Period 2 Date (yyyymmdd): 20190707

Period 1 Volume Change: 37.3772 8 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 2.12272 $(m^3 \cdot day^{-1})$

Figure 208: Aerial Image

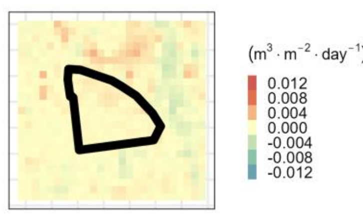


Figure 209: Period 1 changes

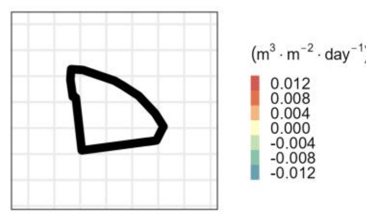


Figure 210: Period 2 changes

Study Site: AOI_009

Country: Senegal

Administrative area: Pikine

Location (Lon, Lat): -17.31463 14.80235

Name: Décharge de Mbeubeuss

Description: Municipal Waste; Open Dump; 2000 Mg per day

Additional site information: Large Landfill that receives about 2000 Mg of MSW per day . Africa, L. rédaction d'Allo D. (2022, May 13). La décharge dakaroise de Mbeubeuss, un tombeau à ciel ouvert. AlloDocteursAFRICA. https://www.allodocteurs.africa/la-decharge-dakaroise-de-mbeubeuss-un-tombeau-a-ciel-ouvert-7410.html

Area: 88.7 ha

Period 1 Date (yyyymmdd): 20180827

Period 2 Date (yyyymmdd): 20180907

Period 1 Volume Change: 1139.921 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 17160.54 $(m \cdot day)$

Estimated Period 2 error: 3.406991 $(m^3 \cdot day^{-1})$

Figure 211: Aerial Image

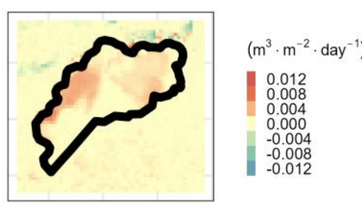


Figure 212: Period 1 changes

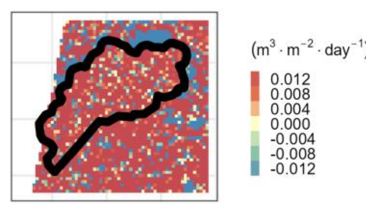


Figure 213: Period 2 changes

Study Site: AOI_012

Country: Senegal

Administrative area: Guédiawaye

Location (Lon, Lat): -17.383 14.7878

Name: Unnamed

Description: Waste type unknown; Open Dump; Possibly illegal

Additional site information: Landfill on VDN extension 3 Golf-Tivaouane Peulh

Area: 4.2 ha

Period 1 Date (yyyymmdd): 20180827

Period 2 Date (yyyymmdd): 20180827

Period 1 Volume Change: -117.9234 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.377055 $(m^3 \cdot day^{-1})$

Figure 214: Aerial Image

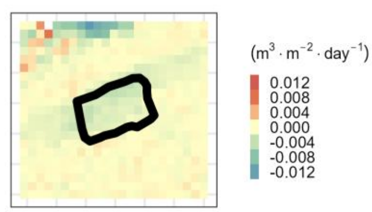


Figure 215: Period 1 changes

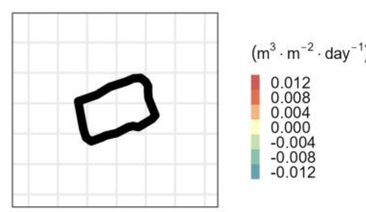


Figure 216: Period 2 changes

Study Site: AOI_014

Country: Sierra Leone

Administrative area: Western Urban

Location (Lon, Lat): -13.24895 8.486359

Name: Kingtom landfill

Description: Mixed waste (eneral and domestic, hospital, industrial and hazardous waste); Unmanaged

Additional site information: Frazer-Williams, R.A.D., 2015. Risk Assessment of The Kingtom And Granville Brook Dumpsites In Freetown, Sierra Leone. Nigerian Journal of Pharmaceutical and Applied Science Research 4, 10–19.

Area: 10.9 ha

Period 1 Date (yyyymmdd): 20191117

Period 2 Date (yyyymmdd): 20191117

Period 1 Volume Change: 43.02782 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.687866 $(m^3 \cdot day^{-1})$

Figure 217: Aerial Image

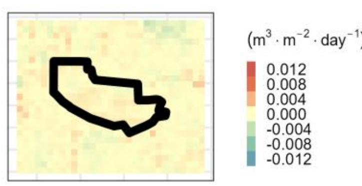


Figure 218: Period 1 changes

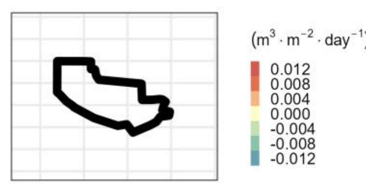


Figure 219: Period 2 changes

Study Site: AOI_025

Country: Ghana

Administrative area: Accra

Location (Lon, Lat): -0.09994488 5.610732

Name: AMA Garbage Recycling Center

Description: Recycling

Additional site information: Accra Metropolitan Assembly, 2024. AMA - Waste Management Services [WWW Document]. URL https://ama.gov.gh/waste-management-services.php (accessed 3.19.24).

Area: 8.3 ha

Period 1 Date (yyyymmdd): 20190921

Period 2 Date (yyyymmdd): 20190921

Period 1 Volume Change: 3.829482 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.767978 $(m^3 \cdot day^{-1})$

Figure 220: Aerial Image

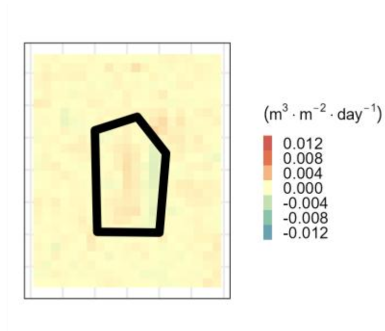


Figure 221: Period 1 changes

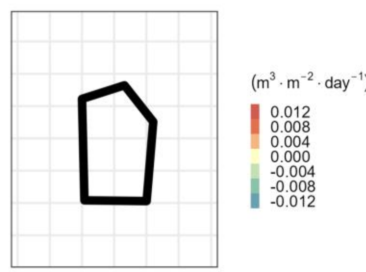


Figure 222: Period 2 changes

Study Site: AOI_026

Country: Brazil

Administrative area: Osasco

Location (Lon, Lat): -46.79727 -23.48267

Name: Aterro Sanitário de Osasco

Description: Sanitary Landfill; MSW (Mainly residential waste, no hospital waste)

Additional site information: Large sanitary landfill receiving approximately 900 tonnes of waste per day. Juliana Oliveira, 2021. Aterro sanitário de Osasco recebe 900 toneladas de resíduos por dia. Prefeitura de Osasco. URL https://osasco.sp.gov.br/aterro-sanitario-de-osasco-recebe-900-toneladas-de-residuos-por-dia/ (accessed 3.21.24).

Area: 21 ha

Period 1 Date (yyyymmdd): 20180121

Period 2 Date (yyyymmdd): 20180121

Period 1 Volume Change: 507.317 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 4.955843 $(m^3 \cdot day^{-1})$

Figure 223: Aerial Image

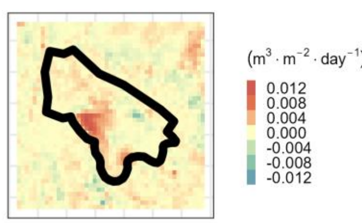


Figure 224: Period 1 changes

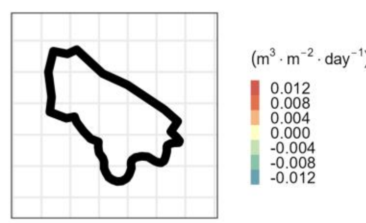


Figure 225: Period 2 changes

Study Site: AOI_027

Country: Brazil

Administrative area: Olinda

Location (Lon, Lat): -34.87889 -7.998976

Name: Aterro Sanitário de Aguazinha

Description: MSW; Closed landfill

Additional site information: This landfill has been closed since August 2017. Diario de Pernambuco, 2017. Aterro Sanitário de Aguazinha será desativado a partir desta quarta-feira [WWW Document]. URL https://www.diariodepernambuco.com.br/noticia/vidaurbana/2017/08/aterro-de-aguazinha-sera-desativado-nesta-quarta-feira.html (accessed 3.21.24).

Area: 8.9 ha

Period 1 Date (yyyymmdd): 20190507

Period 2 Date (yyyymmdd): 20190609

Period 1 Volume Change: 14.69123 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -389.2363 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 1.714979 ($m^3 \cdot day^{-1}$)

Figure 226: Aerial Image

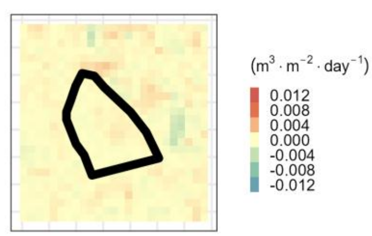


Figure 227: Period 1 changes

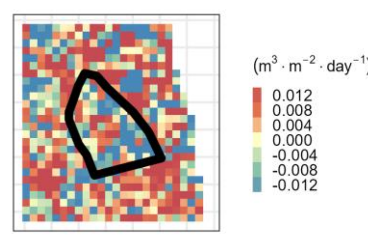


Figure 228: Period 2 changes

Study Site: AOI_030

Country: Turkey

Administrative area: Konak

Location (Lon, Lat): 27.13426 38.36106

Name: Kurşun Fabrikası Atık Bölgesi

Description: Lead Factory Waste [Closed]

Additional site information: Old Lead Factory Waste Zone in Emrez, Gaziemir/İzmir. Not receiving waste. Independent Türkçe, 2021. İzmir'in Gaziemir ilçesindeki eski fabrika arazisinde radyasyon değeri normalin 7 bin 291 katı çıktı [WWW Document]. Independent Türkçe. URL https://www.indyturk.com/node/373596/haber/i%CC%87zmirin-gaziemir-il%C3%A7esindeki-eski-fabrika-arazisinde-radyasyon-de%C4%9Feri-normalin-7 (accessed 3.21.24).

Area: 6 ha

Period 1 Date (yyyymmdd): 20190317

Period 2 Date (yyyymmdd): 20190407

Period 1 Volume Change: -7.711304 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 491.8479 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 1.344411 ($m^3 \cdot day^{-1}$)

Figure 229: Aerial Image

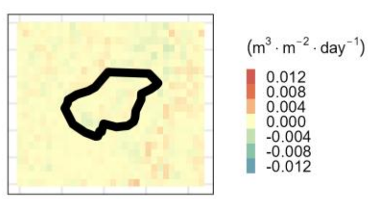


Figure 230: Period 1 changes

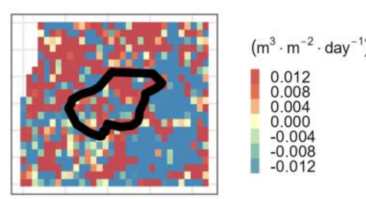


Figure 231: Period 2 changes

Study Site: AOI_031

Country: Turkey

Administrative area: Etimesgut

Location (Lon, Lat): 32.61748 39.91348

Name: Large Waste Disposal area Etimesgut

Description: Managed landfill [confirmed by satellite imagery]

Additional site information: NA

Area: 4.6 ha

Period 1 Date (yyyymmdd): 20190507

Period 2 Date (yyyymmdd): 20190609

Period 1 Volume Change: -300.9193 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -1925.986 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 2.444899 ($m^3 \cdot day^{-1}$)

Figure 232: Aerial Image

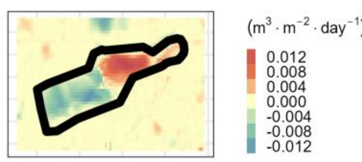


Figure 233: Period 1 changes

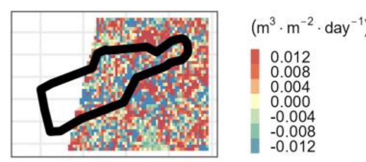


Figure 234: Period 2 changes

Study Site: AOI_032

Country: Brazil

Administrative area: Salvador

Location (Lon, Lat): -38.37071 -12.85789

Name: Aterro Metropolitano Centro

Description: Sanitary Landfill; MSW ; 3000 Mg per day

Additional site information: Large Sanitary landfill in Salvador. Garcia, J.P.R., 2020. ANÁLISE DE ÍNDICES FÍSICOS E PROPRIEDADES GEOTÉCNICAS DE ATERROS SANITÁRIOS DA REGIÃO NORDESTE DO BRASIL. https://repositorio.ufc.br/bitstream/riufc/72059/3/202 additional: https://offset.climateneutralnow.org/salvador-da-bahia-landfill-gas-management-project-52-

Area: 56.5 ha

Period 1 Date (yyyymmdd): 20171205

Period 2 Date (yyyymmdd): 20171205

Period 1 Volume Change: 2987.62 2 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 9.592234 $(m^3 \cdot day^{-1})$

Figure 235: Aerial Image

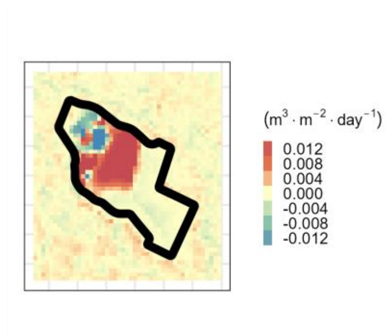


Figure 236: Period 1 changes

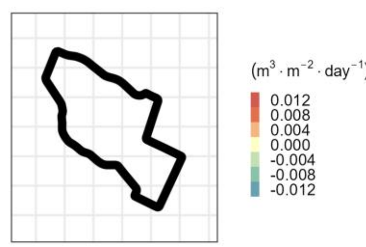


Figure 237: Period 2 changes

Study Site: AOI_041

Country: Brazil

Administrative area: Recife

Location (Lon, Lat): -34.97264 -8.026786

Name: Ciclo Ambiental - Camaragibe

Description: Open dump;

Additional site information: Open dumping Landfill site closed in 2020, which received approximately 190 tonnes of waste per day before it was shut down. Cavalcanti, M., 2020. Último do Grande Recife, lixão de Camaragibe é fechado após quase 30 anos de funcionamento [WWW Document]. JC. URL https://jc.ne10.uol.com.br/pernambuco/2020/09/11979571-ultimo- do-grande-recife–lixao-de-camaragibe-e-fechado-apos-quase-30-anos-de-funcionamento.html (accessed 3.22.24).

Area: 7.4 ha

Period 1 Date (yyyymmdd): 20190609

Period 2 Date (yyyymmdd): 20190609

Period 1 Volume Change: 110.914 5 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.909928 $(m^3 \cdot day^{-1})$

Figure 238: Aerial Image

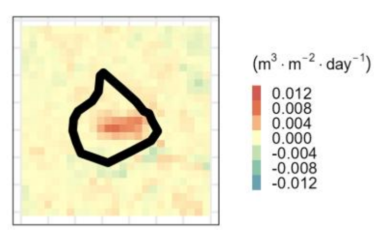


Figure 239: Period 1 changes

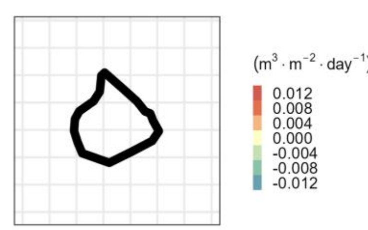


Figure 240: Period 2 changes

Study Site: AOI_043

Country: Argentina

Administrative area: General San Martín

Location (Lon, Lat): -58.61709 -34.53022

Name: CEAMSE Norte 3

Description: Waste Management facility;

Additional site information: Large waste management complex that receives approximately 436,325 t/month. CEAMSE, 2024. Complejo Ambiental Norte III [WWW Document]. URL https://www.ceamse.gov.ar/area-de-cobertura/norte-iii/ (accessed 3.22.24).

Area: 71.4 ha

Period 1 Date (yyyymmdd): 20190613

Period 2 Date (yyyymmdd): 20190613

Period 1 Volume Change: 10311.22 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 10.78116 $(m^3 \cdot day^{-1})$

Figure 241: Aerial Image

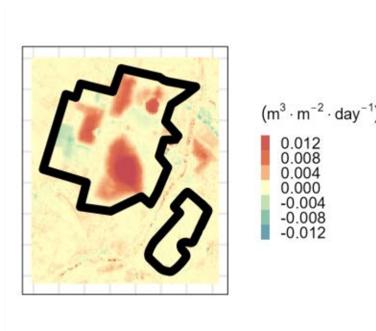


Figure 242: Period 1 changes

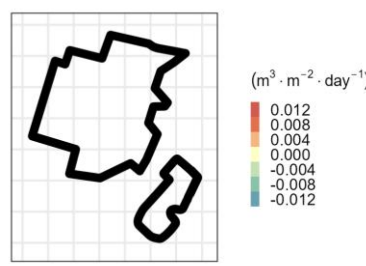


Figure 243: Period 2 changes

Study Site: AOI_046

Country: Brazil

Administrative area: Belo Horizonte

Location (Lon, Lat): -44.01364 -19.91415

Name: Aterro Sanitário

Description: Oldclosed

Additional site information: Landfill site closed since 2007. Prefeitura Belo Horizante, 2018. Central de tratamento de resíduos sólidos [WWW Document]. Prefeitura de Belo Horizonte. URL https://prefeitura.pbh.gov.br/slu/informacoes/coleta-seletiva/central-de-tratamento (accessed 3.22.24).

Area: 65.9 ha

Period 1 Date (yyyymmdd): 20180213

Period 2 Date (yyyymmdd): 20180213

Period 1 Volume Change: 60.91329 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 5.599252 $(m^3 \cdot day^{-1})$

Figure 244: Aerial Image

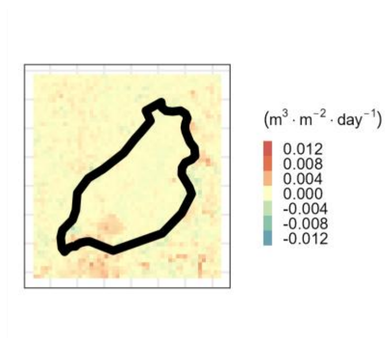


Figure 245: Period 1 changes

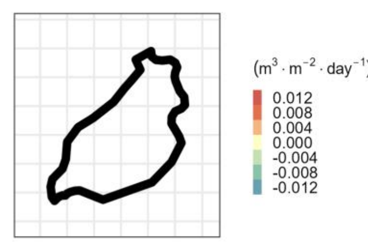


Figure 246: Period 2 changes

Study Site: AOI_047

Country: Brazil

Administrative area: São Paulo

Location (Lon, Lat): -46.42308 -23.635

Name: Aterro Sanitário Sitio São João

Description: Sanitary landfill; MSW and Industrial waste

Additional site information: St. John Sanitary Landfill ; https://saepro.ufv.br/wp-content/uploads/2015/06/2010.10.pdf

Area: 132.1 ha

Period 1 Date (yyyymmdd): 20171207

Period 2 Date (yyyymmdd): 20171231

Period 1 Volume Change: 3542.52 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: 9737.056 ($m \ \cdot day$)

Estimated Period 2 error: 13.37223 ($m^3 \cdot day^{-1}$)

Figure 247: Aerial Image

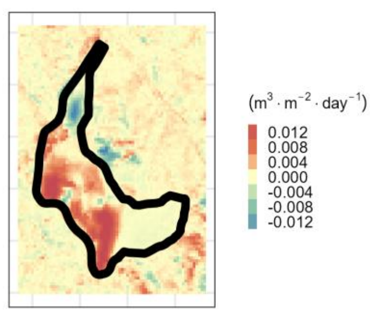


Figure 248: Period 1 changes

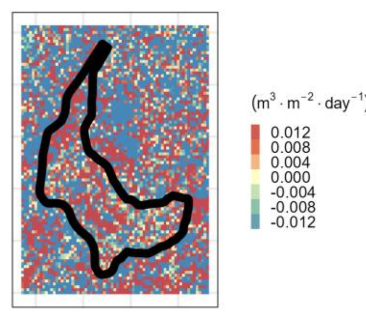


Figure 249: Period 2 changes

Study Site: AOI_055

Country: Turkey

Administrative area: Karşıyaka

Location (Lon, Lat): 27.1617 38.47904

Name: Name not found

Description: NA

Additional site information: Dumping site behind Dr. Ekrem Akurgal Yaşam Parkı, Izmir.

Area: 10.9 ha

Period 1 Date (yyyymmdd): 20190317

Period 2 Date (yyyymmdd): 20190407

Period 1 Volume Change: 19.26796 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -55.87405 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 2.077027 ($m^3 \cdot day^{-1}$)

Figure 250: Aerial Image

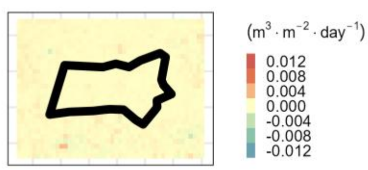


Figure 251: Period 1 changes

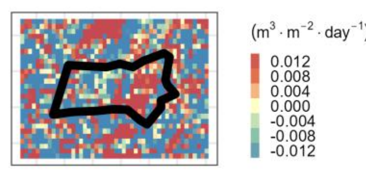


Figure 252: Period 2 changes

Study Site: AOI_059

Country: Cuba

Administrative area: Playa

Location (Lon, Lat): -82.41096 23.06234

Name: Basurero de la Calle 100

Description: Open Dump

Additional site information: 100th Street Dump in Havana, Cuba. El polémico basurero de la calle 100 en La Habana visto desde las alturas [WWW Document], 2020. . CiberCuba. URL https://www.cibercuba.com/noticias/2020-03-11-u185759-e185759-s27061-polemico-basurero-calle-100-habana-visto-alturas (accessed 3.22.24).

Area: 80.9 ha

Period 1 Date (yyyymmdd): 20190911

Period 2 Date (yyyymmdd): 20190911

Period 1 Volume Change: 959.7643 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 3.627466 $(m^3 \cdot day^{-1})$

Figure 253: Aerial Image

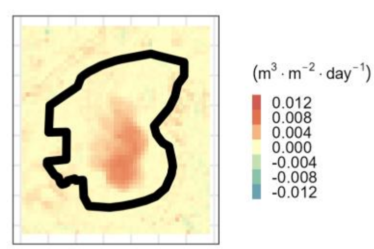


Figure 254: Period 1 changes

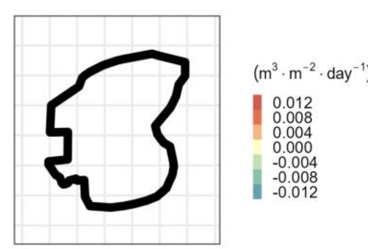


Figure 255: Period 2 changes

Study Site: AOI_062

Country: The Gambia

Administrative area: Kanifing

Location (Lon, Lat): -16.69698 13.4392

Name: Bakoteh Municipal Dump

Description: Open Dump (MSW)

Additional site information: Largest landfill site in Gambia. Child Aid Gambia, n.d. BAKOTEH RUBBISH DUMP [WWW Document]. URL https://childaidgambia.org/bakoteh-rubbish-dump/ (accessed 3.22.24).

Area: 18.5 ha

Period 1 Date (yyyymmdd): 20180205

Period 2 Date (yyyymmdd): 20180205

Period 1 Volume Change: 79.05052 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 2.085907 $(m^3 \cdot day^{-1})$

Figure 256: Aerial Image

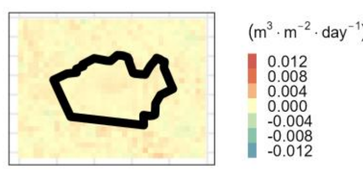


Figure 257: Period 1 changes

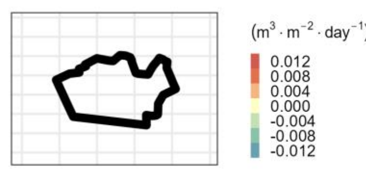


Figure 258: Period 2 changes

Study Site: AOI_066

Country: Democratic Republic of the Congo

Administrative area: Kipushi (ville)

Location (Lon, Lat): 27.26294 -11.77559

Name: Kipushi Tailings

Description: Mine Waste

Additional site information: Mine waste site, for the Kipushi mine in DRC.

Area: 213.2 ha

Period 1 Date (yyyymmdd): 20190611

Period 2 Date (yyyymmdd): 20190703

Period 1 Volume Change: -242.9161 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 49766.47 $(m \ \cdot day \ \ )$

Estimated Period 2 error: 31.25772 $(m^3 \cdot day^{-1})$

Figure 259: Aerial Image

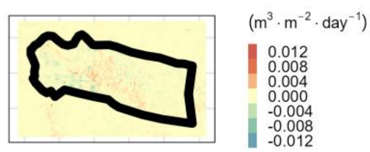


Figure 260: Period 1 changes

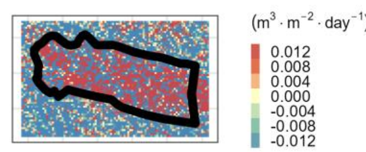


Figure 261: Period 2 changes

Study Site: AOI_067

Country: Brazil

Administrative area: Ferraz de Vascon

Location (Lon, Lat): -46.37645 -23.60867

Name: small landfill Ferraz de Vasconcelos

Description: Unnamed landfill; Waste type unknown

Additional site information: NA

Area: 11 ha

Period 1 Date (yyyymmdd): 20171207

Period 2 Date (yyyymmdd): 20171207

Period 1 Volume Change: 139.8589 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 3.051841 $(m^3 \cdot day^{-1})$

Figure 262: Aerial Image

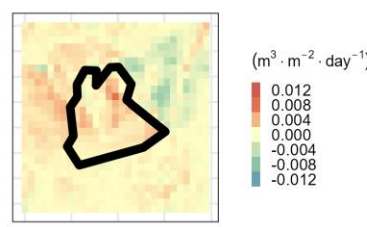


Figure 263: Period 1 changes

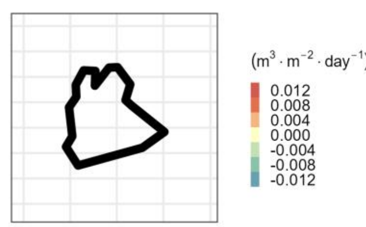


Figure 264: Period 2 changes

Study Site: AOI_068

Country: India

Administrative area: Bangalore

Location (Lon, Lat): 77.7274 13.08107

Name: Mandur Garbage Dump Yard

Description: Open dump; closed; Landfill mining

Additional site information: Closed dumping site in Bengaluru. Bharadwaj, K.V.A., 2023. Legacy waste at four Bengaluru landfills to be cleared in two years. The Hindu.

Area: 32.9 ha

Period 1 Date (yyyymmdd): 20171223

Period 2 Date (yyyymmdd): 20171223

Period 1 Volume Change: 389.404 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 3.582567 $(m^3 \cdot day^{-1})$

Figure 265: Aerial Image

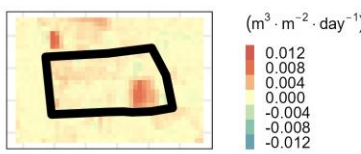


Figure 266: Period 1 changes

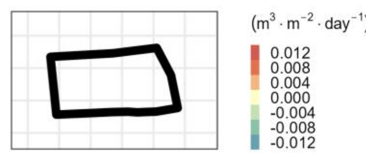


Figure 267: Period 2 changes

Study Site: AOI_070

Country: Kuwait

Administrative area: Al Farwaniyah

Location (Lon, Lat): 47.91049 29.19338

Name: North of the seventh ring road landfill

Description: Closed landfill

Additional site information: Kuwait Landfill site closed in 2005. Kuwait Environment Public Authority, 2022. Waste Management Atlas of Kuwait. Kuwait Environment Public Authority.

Area: 575.7 ha

Period 1 Date (yyyymmdd): 20180815

Period 2 Date (yyyymmdd): 20180905

Period 1 Volume Change: 364.9679 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: 37339.67 $(m \cdot day)$

Estimated Period 2 error: 13.74402 $(m^3 \cdot day^{-1})$

Figure 268: Aerial Image

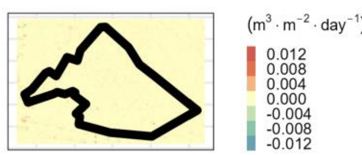


Figure 269: Period 1 changes

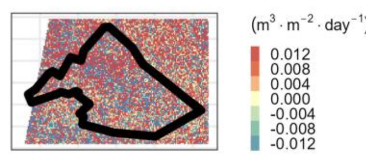


Figure 270: Period 2 changes

Study Site: AOI_073

Country: Kuwait

Administrative area: Mubarak Al-Kabeer

Location (Lon, Lat): 48.03277 29.21429

Name:

Description: Household waste; Construction & Demoliution waste; backfilled soil.

Additional site information: Subhan Military Base Landfill site in Kuwait. Closed since 1991. Kuwait Environment Public Authority, 2022. Waste Management Atlas of Kuwait. Kuwait Environment Public Authority.

Area: 200.9 ha

Period 1 Date (yyyymmdd): 20180905

Period 2 Date (yyyymmdd): 20180905

Period 1 Volume Change: 98.49796 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 6.025646 $(m^3 \cdot day^{-1})$

Figure 271: Aerial Image

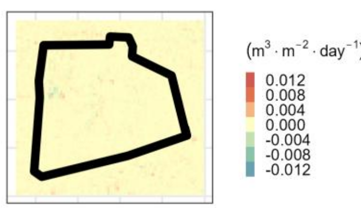


Figure 272: Period 1 changes

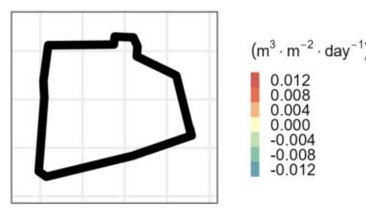


Figure 273: Period 2 changes

Study Site: AOI_082

Country: Brazil

Administrative area: Natal

Location (Lon, Lat): -35.25099 -5.837823

Name: Coopcicla recycling cooperative

Description: Recycling facility

Additional site information: This waste site is appears to be used primarily for recycling activites, while the landfill mound is overgrown and undisturbed during the study period, suggesting no active dumping. [confirmed by temporal satellite imagery in Google Earth Pro]

Area: 8.1 ha

Period 1 Date (yyyymmdd): 20190507

Period 2 Date (yyyymmdd): 20190507

Period 1 Volume Change: 118.7583 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.229123 $(m^3 \cdot day^{-1})$

Figure 274: Aerial Image

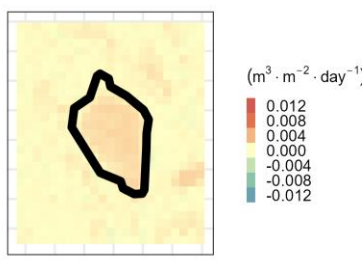


Figure 275: Period 1 changes

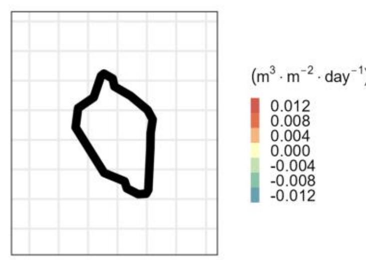


Figure 276: Period 2 changes

Study Site: AOI_083

Country: Costa Rica

Administrative area: Tibás

Location (Lon, Lat): -84.09173 9.965774

Name: Botadero de Santo Domingo

Description: Specific waste type not reported

Additional site information: Santa Domingo landfill site.

Area: 3 ha

Period 1 Date (yyyymmdd): 20180311

Period 2 Date (yyyymmdd): 20180311

Period 1 Volume Change: -39.79184 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 2.809675 $(m^3 \cdot day^{-1})$

Figure 277: Aerial Image

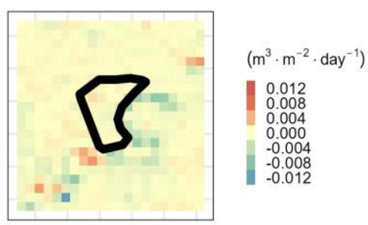


Figure 278: Period 1 changes

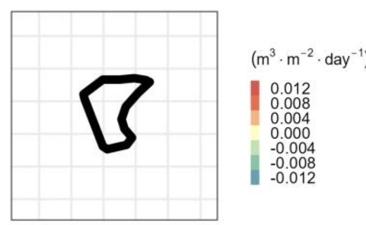


Figure 279: Period 2 changes

Study Site: AOI_086

Country: Venezuela

Administrative area: Libertador

Location (Lon, Lat): -66.98191 10.53482

Name: Relleno Sanitario de Ojo de Agua

Description: Open Dump;

Additional site information: Open Dumping site in Caracas 1030, Distrito Capital, Venezuela

Area: 25.8 ha

Period 1 Date (yyyymmdd): 20180211

Period 2 Date (yyyymmdd): 20180211

Period 1 Volume Change: -16.9223 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 4.197367 $(m^3 \cdot day^{-1})$

Figure 280: Aerial Image

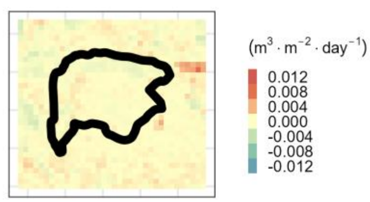


Figure 281: Period 1 changes

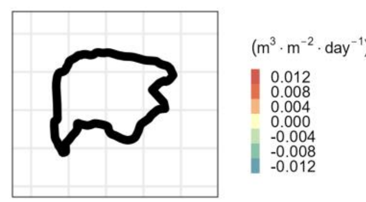


Figure 282: Period 2 changes

Study Site: AOI_088

Country: Mozambique

Administrative area: Maputo

Location (Lon, Lat): 32.59723 -25.90068

Name: Lixeira de Hulene

Description: Open Dump; MSW

Additional site information: Hulene Open Landfill site in Maputo, Mozambique. MZNews, 2022. Lixeira de Hulene vai continuar a funcionar até um futuro distante. MZNews. URL https://mznews.co.mz/lixeira-de-hulene-vai-continuar-a-funcionar-ate-um-futuro-distante/ (accessed 3.22.24).

Area: 16.3 ha

Period 1 Date (yyyymmdd): 20190505

Period 2 Date (yyyymmdd): 20190505

Period 1 Volume Change: 350.3959 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: NA ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 1.439035 ($m^3 \cdot day^{-1}$)

Figure 283: Aerial Image

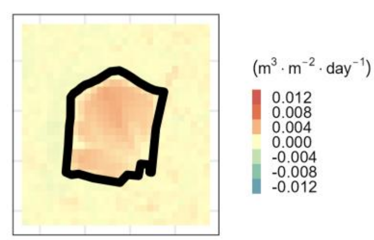


Figure 284: Period 1 changes

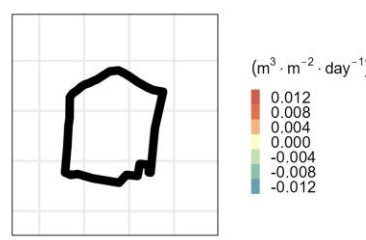


Figure 285: Period 2 changes

Study Site: AOI_090

Country: Germany

Administrative area: M nchen (Kreisfreie Stadt)

Location (Lon, Lat): 11.62672 48.22525

Name: Deponie München Nord-West

Description: non-recyclable construction waste; road sweeping; industrial waste; Asbestos until 2003; Sanitary landfill

Additional site information: Munich North-West landfill. This landfill site was operational from 1987 to 2020. However, Changes to waste management policy lead to large reduction in waste disposal during the 1990s.

Area: 10.8 ha

Period 1 Date (yyyymmdd): 20200401

Period 2 Date (yyyymmdd): 20200401

Period 1 Volume Change: 26.26442 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.940497 $(m^3 \cdot day^{-1})$

Figure 286: Aerial Image

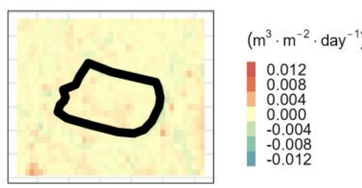


Figure 287: Period 1 changes

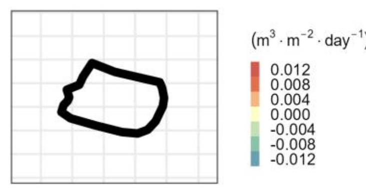


Figure 288: Period 2 changes

Study Site: AOI_091

Country: Morocco

Administrative area: Casablanca

Location (Lon, Lat): -7.537794 33.4833

Name: Décharge de Médiouna

Description: Open Dump; MSW

Additional site information: Mediouna controlled landfill Morocco. Casablanca - Décharge de Médiouna : Une bombe écologique presque désamorcée [WWW Document], 2022. . Agora Francophone. URL https://www.agora-francophone.org/casablanca-decharge-de-mediouna-une-bombe-ecologique-presque-desamorcee (accessed 3.22.24).

Area: 60.9 ha

Period 1 Date (yyyymmdd): 20180925

Period 2 Date (yyyymmdd): 20180925

Period 1 Volume Change: 2571.258 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 4.110209 $(m^3 \cdot day^{-1})$

Figure 289: Aerial Image

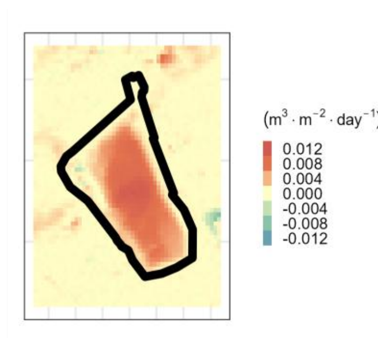


Figure 290: Period 1 changes

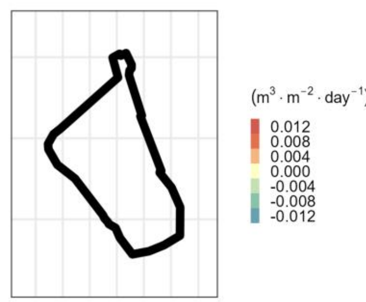


Figure 291: Period 2 changes

Study Site: AOI_095

Country: Iran

Administrative area: Theran

Location (Lon, Lat): 51.66743 35.74989

Name: /

Description: Construction waste

Additional site information: Abali processing and disposal complex / Tehran construction and construction waste disposal center. https://dolat.ir/detail/430191

Area: 214.3 ha

Period 1 Date (yyyymmdd): 20190903

Period 2 Date (yyyymmdd): 20190903

Period 1 Volume Change: 20394.44 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: NA ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 11.66753 ($m^3 \cdot day^{-1}$)

Figure 292: Aerial Image

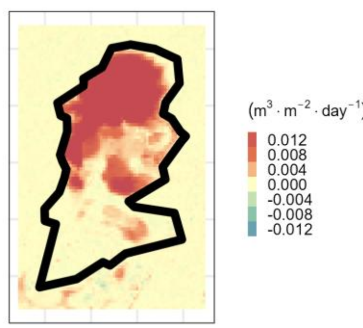


Figure 293: Period 1 changes

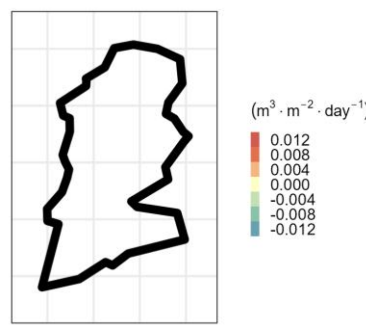


Figure 294: Period 2 changes

Study Site: AOI_096

Country: Israel

Administrative area: Deir Al-Balah

Location (Lon, Lat): 34.38194 31.39251

Name: Unnamed

Description: Open dump; additional info unavailable

Additional site information: Small open dump in Levant, Gaza

Area: 6.7 ha

Period 1 Date (yyyymmdd): 20180215

Period 2 Date (yyyymmdd): 20180215

Period 1 Volume Change: 190.2039 $(m^3 \cdot day^{-1})$

Period 2 Volume Change: NA $(m^3 \cdot day^{-1})$

Estimated Period 2 error: 1.017563 $(m^3 \cdot day^{-1})$

Figure 295: Aerial Image

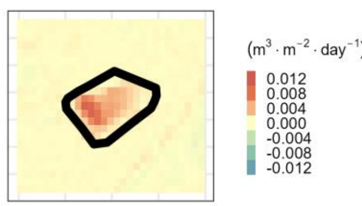


Figure 296: Period 1 changes

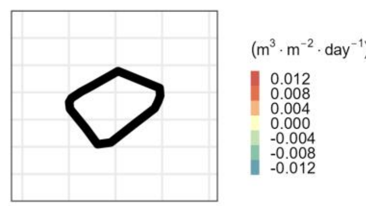


Figure 297: Period 2 changes

Study Site: AOI_097

Country: Turkey

Administrative area: Çankaya

Location (Lon, Lat): 32.93056 39.87744

Name: Mamak Çöplüğü

Description: Sanitary landfill; gas recovery facility; vegetable growing facilities

Additional site information: Managed landfill site in Ankara, receiving 1500 tonnes of waste per day, which is also redirected to energy production. https://www.itcturkiye.com/tr/tesislerimiz/ankara-mamak

Area: 146.6 ha

Period 1 Date (yyyymmdd): 20190609

Period 2 Date (yyyymmdd): 20190609

Period 1 Volume Change: 1346.99 ($m^3 \cdot day^{-1}$)

Period 2 Volume Change: -1025.647 ($m^3 \cdot day^{-1}$)

Estimated Period 2 error: 5.256651 ($m^3 \cdot day^{-1}$)

Figure 298: Aerial Image

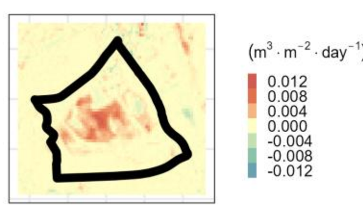


Figure 299: Period 1 changes

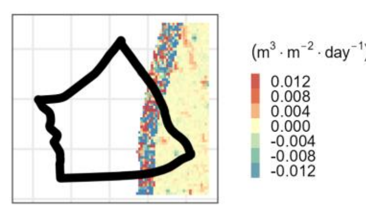


Figure 300: Period 2 changes