**POLITECNICO DI MILANO**
**School of Industrial and Information Engineering**
**Department of Electronics, Information and Bioengineering**
**Master of Science in Computer Science Engineering**

# Remote Sensing Identification of Illegal Landfills Using Optical Images

**Supervisor: Piero Fraternali**

**Tesina of:**
**Aishwarya Pabbisetti, 878889**

**Academic Year 2017-2018**

*I dedicate my work to my family and loved ones.*

# Acknowledgements

I would like to take this opportunity to express my profound gratitude and deep regards to my supervisor Prof.Piero Fraternali for the continuous support of my thesis and for his patience and motivation. Also, special thanks to Phd student, Ms.Rocio Nahime Torres for insightful comments and encouragement through out my research period. And I am grateful to our Institution Politecnico di Milano for providing me this opportunity.

Finally, I would like to thank the people who contribute the most to my life, my family. Also, to my friends for their love and support. Without them, none of this work would have been possible.

## Sommario

L'importanza dell'identificazione delle discariche illegali è aumentata rapidamente in tutti i paesi in via di sviluppo e sviluppati. Le informazioni ottenute con il telerilevamento si sono rivelate molto utili ed economiche nell'identificazione delle discariche. In questo studio, spieghiamo vari modi di rilevamento e identificazione delle discariche caratterizzate dalle tecniche utilizzate. Descriviamo il significato delle immagini satellitari ottiche di Google Earth nella comprensione dell'esistenza delle discariche. E abbiamo implementato uno script automatico per scaricare le immagini satellitari di tutte le posizioni sospette che sono ulteriormente filtrate e annotate manualmente per rilevare e identificare discariche illegali e infine ottenere un gran numero di buoni esempi di discariche in modo da utilizzare questa conoscenza ottenuta nell'implementazione di un Deep Algoritmo di apprendimento per rilevare automaticamente discariche illegali.

## Abstract

The importance of identification of illegal landfills has been increasing rapidly in all developing and developed countries. The information obtained by remote sensing has proved to be found very useful and economical in identification of landfills. In this study, we explain various ways of detection and identification of landfills characterized by the techniques utilized. We describe the significance of Google earth optical satellite images in understanding the existence of landfills. And we have implemented an automated script for downloading satellite images of all the suspected locations which are further filtered and annotated manually to detect and identify illegal landfills and finally get large number of good examples of landfills so as to use this obtained knowledge in implementing a Deep Learning algorithm to automatically detect illegal landfills.

# Contents

**Sommario** **i**

**Abstract** **ii**

**1 Introduction** **1**

**2 State of the Art** **3**

2.1 Detection by analysing and drawing inferences from Satellite data . . . . 3

2.2 Detection by application of data classification methods . . . . 7

2.3 Detection by Ground Penetrating Radar surveys . . . . 9

2.4 Detection with Probability and Predictive models . . . . 10

2.5 Detection by implementing Image processing and Image differentiation on Satellite data . . . . 15

**3 Data** **24**

3.1 Earth Observation Data . . . . 24

3.1.1 Background . . . . 24

3.1.2 EO Passive Sensors . . . . 26

3.1.3 Active sensors . . . . 33

3.1.4 Sounders . . . . 37

3.2 Illegal Landfills data sets . . . . 41

**4 Implementation** **44**

4.1 Images downloader . . . . 44

**5 Examples characterization** **47**

**6 Conclusions and Future Work** **54**

**Bibliography** **55**

# List of Figures

3.1 Operation of synthetic aperture radar . . . . . . . . . . . . . . 36

4.1 Screenshot of location with 500m span . . . . . . . . . . . . . 45
4.2 Zoomed version of suspected location . . . . . . . . . . . . . . 45
4.3 Annotation of an image with landfill . . . . . . . . . . . . . . 46

5.1 Construction leftovers in urban area . . . . . . . . . . . . . . . . 48
5.2 Empty land in urban area . . . . . . . . . . . . . . . . . . . . . 49
5.3 Waste dumps in urban area . . . . . . . . . . . . . . . . . . . . 49
5.4 Demolished site in urban area . . . . . . . . . . . . . . . . . . . 50
5.5 Wooden waste in rural area . . . . . . . . . . . . . . . . . . . . 51
5.6 Legal landfill in rural area . . . . . . . . . . . . . . . . . . . . . 51
5.7 Waste dumps in rural area . . . . . . . . . . . . . . . . . . . . . 53
5.8 Industrial waste near water bodies . . . . . . . . . . . . . . . . . 53

# List of Tables

2.1 State of Art Summary . . . . . . . . . . . . . . . . . . . . . . . 23

3.1 EMR Spectral Regions and Atmospheric Windows . . . . . . . 25
3.2 Spectral regions observed by EO sensors . . . . . . . . . . . . 26
3.3 Examples of Satellite Optical Sensors . . . . . . . . . . . . . . . 29
3.4 Commonly Used Thermal Imaging Sensors . . . . . . . . . . . 32
3.5 Radar Frequency Bands . . . . . . . . . . . . . . . . . . . . . . 34
3.7 Sensor Description . . . . . . . . . . . . . . . . . . . . . . . . . 41
3.6 Examples of Active and Future Satellite SAR Sensors . . . . . 42

5.1 Percentage of various landfills identified . . . . . . . . . . . . . 52
5.2 Percentage of different areas that landfills are identified . . . . 52

# Chapter 1

# Introduction

Detection of illegal and uncontrolled dump sites is a central environmental issue in all developed countries including Italy. There are several serious environmental consequences effecting public health and nature like contamination of air, land and water due to this uncontrolled disposal of wastes and inappropriate waste treatment. Remote sensing and GIS played an important role in detecting illegal dumps and monitoring landfill sites, providing feasible and economical solution. This study explicates various techniques and approaches that have been employed till date for detecting illegal landfills and monitoring existing legal landfill sites. Also clearly explained various remote sensing satellite data, sensors and their applications that can be utilized for detecting illegal landfills. We have analysed numerous data points from regions of Lombardia and Campania in Italy using Google earth satellite images to understand the existence of illegal landfills and gained interesting insights which are clearly illustrated. We have also designed an automated script for downloading satellite images of suspected locations. We have then filtered and annotated the images with landfills among all inspected locations, such that this knowledge can be used further to train a Deep learning algorithm to automatically detect illegal landfills.

Based on the objectives of the study the structure of thesis is divided into 5 chapters. Chapter 1 introduces the background of the study, research problem, the objectives, and the structure of the thesis. Chapter 2 discusses state of art, the existing landfill detecting and monitoring methods characterized by techniques and approach. Chapter 3 presents a review of satellite remote sensing sensors and their applications, also describe illegal landfill data sets used in this study. Chapter 4 describes the implementation details of satellite image downloader, filtering and annotation process to characterize good illegal landfill examples. Chapter 5 discusses various concerns in using Google earth satellite images and analysed good examples obtained from inspected illegal landfill data sets.

# Chapter 2

# State of the Art

Several research studies have utilized remote sensing, GIS in detection, identification and monitoring of landfills. Various methods and techniques have been employed in understanding patterns and theory of illegal landfill detection and existing landfill monitoring, which can be clearly characterized and summarized by their approach as follows and Table 2.1 shortly presents summary to this chapter.

## 2.1 Detection by analysing and drawing inferences from Satellite data

In a research study [1] from Italy, Detection and Monitoring of illegal landfills is carried out on areas of Campania region, that historically suffers from illegal waste disposal by analysing vegetation indexes calculated from high resolution optical images.

Vegetation index provide information on health status of plants that in case of soil contamination presents typical stress characteristics. The main cause of soil contamination around a landfill is due to leachate infiltration, which is formed by rain precipitation percolating through waste deposits and starts flowing out of waste material.

The soil contamination due to leachates that was distinguished by analysing the radiometric properties surface vegetation, which presents stress symptoms is detected by RED-VNIR(Red - VisibleNearInfrared) spectral signature and characteristic irregular texture patterns based on RAPIDEYE and SPOT-5 image data. Results show that soil contamination is mainly observed in agricultural areas located very close to well-known landfills.

As uncontrolled landfills do not have a proper methane collecting system and the greenhouse gas leaks causes temperature increase on surface site, several night time ASTER-TIR(ThermalInfraRed) images acquired over the Campania region have been processed to retrieve the LST (Land Surface Temperature) trends and detect potential thermal anomaly on suspected areas. The results show significant LST values compared to the background which would confirm the waste interred illegaly.
This project also involves monitoring of existing and catalogued landfills using optical and SAR(Synthetic Aperture Radar) data. While optical data for 2D monitoring purposes, SAR data for 2D and 3D variations of landfills. The decrease of the coherence between different SAR image pairs is symptomatic of the modification of scattering mechanisms belonging to landfill geometry. Secondly, highly values of coherence have been detected over the disposal sites of RDF(Refused Derived Fuel) and these structures are characterized by regular pyramidal geometry and therefore variations in height can be detected by exploiting phase information of SAR data.

Case study [2] have used Quickbird pansharpened images from Digital Globe to identify an illegal landfill with illicit burning of waste deposits for prosecuting the criminal activity related to illicit waste management and storage in UK, which took place from 2005 to 2006. Also, another case related to keeping of scrap vehicles without having waste management license has been prosecuted using Quickbird images of 0.6 m resolution of that location. They have found that vehicles in the scrap yard are tightly packed into the available space, with no organization or alignment, and there is no room for the vehicles to move in and out of the scrap yard. These differences related to alignment and organization were used to identify illegal scrap yards from regular car parks with help of high resolution imagery.

Case study [3] was carried out in the area of Caserta, Southern Italy, a region famous for Mozzarella cheese, there is a serious concern for illegal buffalo

breeding facilities (BBF), where waste waters and manure is treated inappropriately causing environmental pollution. This study uses remote sensing by exploiting SAR data and optical multi spectral data together with geo-spatial analysis for finding BBFs that are not included in official census, which is their ground truth data.
The adopted approach includes three phases namely detection, recognition and identification:

- Detection: A typical BBF has two distinguishing features: (i) outdoor areas dedicated to the breeding of buffaloes (fences and containments of manure) that are typically covered by animal waste, (ii) the metal roofs of the barns. The goal is to detect areas that have similar spectral characteristics of structures observed in typical buffalo farm. A decision trees classifier which performs multi stage classification, it is possible to locate areas with spectral responses very similar to those ones with metal roofs or with manure. For this purpose, GEOEye-1 multispectral image which has a set of four (blue, red, green, NIR) spectral bands with 2m/pixel of ground resolution and panchromatic band with 0.5m/pixel of resolution has been used.

  By analysis of proximity between roofs and manure detectors, the areas distant from each other more than 50 m have been deleted. A further filtering of such zones, based on their geographical area (typically lesser than 8,000 $m^2$ for roofs and lesser than 800 $m^2$ for manure), reduces false alarms without compromising the chances of correct detection. An updated map that identifies highly urbanised zones was obtained with SAR data by means the methodology described in [4], based on SAR inter-ferometry. The performance of the automatic detection system was assessed in terms of precision P(25.9%) and recall R(89%).

- Recognition: In this phase, an expert human photo-interpreter can discriminate the buffalo farms among the detected structures. This inspection took place on GeoEye-1 image after pansharpening, which increased spatial resolution to 0.5 m per pixel. This leads to a reduction of 76.69% of the inspected area with a recall of 95.60%.

- Identification: These recognized buffalo farms are compared to the official register, in order to identify the unregistered breeding activities, which is carried out automatically by means of a geo-spatial analysis in a GIS environment. If a recognized farm does not match with any entry in the database, it is marked as unregistered. As a result, the 27% of the recognized BBFs were not registered. Finally a vulnerability map is produced for the area of interest depicting the areas with increasing vulnerability.

Two case studies from [5], In first case study of Trail Road landfill site in City of Ottowa, Canada, analysed multi-temporal remote sensing images to determine the spatial distribution of land surface temperature (LST) due to the emission of landfill gas for monitoring purpose. A preliminary analysis was also conducted to investigate the relationship between amount of methane gas recorded from ground monitoring wells and the LST derived from remote sensing images.

In this case study of Trail Road landfill, 30 Landsat TM images are downloaded from years 2001 to 2009, conducted atmospheric corrections with ATCOR2 model developed by Richter. ATCOR2 model requires weather information like air temperature and visibility, obtained from Governments national climate and water data archive. The calibration parameters for Landsat TM and ETM+ sensor are also required for atmospheric correction. After conducting atmospheric correction, LST was derived from thermal band of the Landsat images. These derived LST were compared with the measurements of methane gas obtained from ground monitoring wells of landfill site(ground truth data) and hence deriving the relationship between methane gas emission and LST is not significant.

Second case study from [5] using multi temporal Landsat satellite images(TM and ETM+ images of 1985-2001) are used to detect suspicious dumping areas within the Ai-Jieeb landfill site in the city of Ai-Farwanyah, Kuwait. In the Ai-Jieeb landfill case study, multitemporal LST images were imported to GIS for further analysis. Temperature contours(polylines) were generated for each of the LST images by using raster to vector conversion tool, then highest temperature of the contours was extracted from the polylines for each of the LST images. The extracted temperature contours were then overlaid in the GIS environment and the location with the high dense overlapping areas was regarded as possible location for waste dumping areas in Ai-Jieeb landfill site. Finally a topographic map was produced by overlaying these temperature contours in the boundary of Ai-Jieeb landfill site and identified five suspicious locations.

## 2.2 Detection by application of data classification methods

Case Study [6] conducted in area around Venice lagoon watershed, North East Italy have used IKONOS multi-spectral pan-sharpened at 1m pixel high-resolution remote sensing imagery to map potential landfills. The pan-sharpening procedure was applied by the data producer Space Imaging, based on IKONOS 1-m resolution panchromatic band, which were then radio metrically calibrated and atmospherically corrected by applying the MODTRAN 4 radio active transfer model (ATCOR software; see Richter 2005). The objective of the remote sensing imagery processing was to locate stressed vegetation associated with dumps.

So, a total of 52 illegal landfill sites from this area were first acquired from local authorities and military agencies. They used 7 of these known illegal landfill sites from this area to calibrate vegetation stress. Then, 45 known illegal sites were used to validate the calibrated vegetation stress levels. The method to identify uncontrolled landfills from large area was divided into 3 steps.

- With help of information from remote sensing imagery, created four vegetation stress classes by using maximum likelihood ML classification

Class 1 (very stressed brown–yellow vegetation);
Class 2 (non-uniformly stressed vegetation cover)
Class 3 (bare soil with very rare vegetation presence);
Class 4 (lightly stressed vegetation).
The classification results were evaluated by considering the known illegal landfills disseminated with validation area. Two validation methods were considered: calculation of confusion matrices to validate the 4 classes and evaluation of percentage of regions classified into above 4 classes. 24 sites out of 45 validation dumps were excluded because water or buildings occupy the entire surface. So, only 21 sites are to be studied for identification of illegal landfills. And the results show that all selected illegal landfills contain stressed vegetation, which are correctly recognized by classification.

- Then visual human interpretation is employed to digitize each candidate site. For this purpose, IKONOS RGB/NIRGB images are used as auxiliary information and identify candidate sites only in areas containing portions of class 1 and 2 areas. The procedure applied to entire study area has produced 2944 possible contaminated sites.

- This information is organized in GIS and areas falling within authorized quarries and landfills were excluded, also other areas with low probability of being contaminated on the basis of following criteria were excluded:

    - Areas not accessible through streets or paths cannot be a disposal site.
    - Sites for which no previous suspect activity could be traced from historical aerial photographs (when available) or from reports of the local authorities were excluded.

It was thus possible to considerably decrease the number of candidate sites obtained from last 2 steps to 1199 which were then reported to local authorities for further investigation.

## 2.3 Detection by Ground Penetrating Radar surveys

A research conducted in England [7] for continuous monitoring of the landfill sites, a conventional method of constructing boreholes and chemical analyses of surface sampling, which found to be very expensive and time consuming is replaced by GPR (Ground Penetrating Radar) surveys to understand the geological structure, define water table points and leachate breakout points. This GPR surveys proved to be a cost-effective solution and helped in modelling for enhancing contaminant migration.

GPR's provide high resolution images of the dielectric properties of the top few tens of meters of the earth which can be used to detect liquid organic contaminants, obtain models of the large-scale architecture of the subsurface and assist in estimating hydro-geological properties such as water content, porosity and permeability. To acquire this GPR's data, a range of antennas (50, 100, 200, 225 and 450 MHz), a 'reflection' mode of operation and a fixed offset profile mode were employed.

To aid the analysis of the GPR survey data, five surface samplings transects were carried out in the study area sampled for chlorophyll, heavy metal concentration in the vegetation, soil, surface water.The GPR data is validated against surface sampling and results show that:

a) In the section affected by leachate contamination, anomalously high concentrations of heavy metals were present in the vegetation, soil and surface water.

b) GPR data set with 450 MHz found to be more useful, helped to clearly identify the structure and dimensions of buried waste due to both the strong reflection from the surface and the distinct contrast in the strength of the strata reflections above and below water table.

c) GPR data set with 50, 100, 200 MHz helped to identify anomalous feature, nothing but leachate break out points. At this anomalous feature the radar signal does not penetrate the soil smoothly but is seen to be absorbed in a distinct vertical strip, which is mainly due to pore water conductivity increasing due to the presence of leachate contaminant from the landfill causing the radar signals to be more strongly absorbed and hence the signal penetration decreases, hence providing the information about leachate formation.

## 2.4 Detection with Probability and Predictive models

A research [8] analysed a sample of 120 possible areas with illegal landfills in Andalusia, Spain using logistic regression in order to obtain a predictive model for occurrence of these landfills based on geographical and behavioural variables jointly, perform an analysis using a multi-scale approach in order to gain an overall understanding of the phenomenon.

This regression model enabled to: (1) Identify the relationship between spatial and behavioural variables (independent variables) and the presence of uncontrolled landfills (dichotomous dependent variable). (2) Measure the magnitude of these relationships by estimating the regression coefficients $\beta$ (3) Establish, using the logistic regression equation, the probability that an uncontrolled landfill will appear according to the spatial and behavioural variables included in the final model.Variables considered are as follows:

a) Geographical characteristics of location and site:

- Topography: Large illegal dumps were more likely to occur in areas with a slope of 3 -10 degrees due to the propensity to use areas with higher inclination for dumping. In areas with an inclination greater than 10 degrees it is physically more difficult to dispose of waste due to the relative inaccessibility.
- Land use: Illegal landfills occur in industrial areas due to the fact that it is easier to dispose of the waste materials from industrial activities there, especially when workers lack environmental awareness. On the

> contrary, illegal landfills are less likely to occur in residential and urban areas because, according to these authors, they are controlled by the authorities and by citizens.

The results also confirms the above hypothesis that the occurrence of illegal landfills is associated with plains, rural land (not for agricultural use) and industrial areas.

b) Type of waste, accessibility and control:

According to various studies, most illegal dumping takes place in easily accessible areas (at less than 100 metres from tracks), although scarcely visible to the majority of the population. With regard to the type of waste that is deposited in illegal landfills, postulated that it is mainly construction and demolition waste(CDW). Another factor for uncontrolled dumping is the lack of an effective local authority policy of waste inspection and control (supervision). Results shows a negative relationship between CDW landfills and accessibility via the urban area, which means that these uncontrolled landfills are reached by alternative routes like tracks or secondary roads and indicating that these landfills occur in unsupervised areas.

c) Proximity and distance to geographical elements of the surrounding area:

Uncontrolled landfills always originate far from populated areas, in remote areas, thus becoming suitable places for those that intend to dispose of waste illegally. Also having proximity to communication routes especially near tracks, secondary roads, inhabited areas and their limits facilitate the anonymous and furtive disposal of waste. Results show that this hypothesis(c) is fulfilled in relation to the proximity of uncontrolled landfills to tracks, which also reinforces above hypothesis(b) in relation to the type of access.

d) Socio-economic aspects of the municipality:

In peripheral countries and regions, highly urbanised municipalities, with a high income, densely populated and economically dynamic, are those that have the greatest number of illegal landfills. The accelerated process of urbanisation in recent decades, the globalisation process, industrial growth and the modification of the consumption patterns of modern societies have led to shifts in the concentration of population and economic activities (intensive agriculture, industry and services) in the territory becoming key variables in identifying places where illegal landfills occur. Results also affirmed this hypothesis and this seems to indicate that the presence of illegal landfills is more likely to occur in large municipalities (population over 20 thousand inhabitants and percaptia income over 17 thousand euros) where there is substantial construction activity, but which allocate very little of the municipal budget to inspecting illegal dumping.

e) Management system for municipal waste:

The existence of inadequate systems of collection, transport and transfer of municipal waste (bad route planning, insufficient infrastructure) or a lack of information about collection times tend to increase the dumping of rubbish and other types of waste. The implementation of waste management systems, facilities and municipal policies reduces the occurrence of illegal landfills and results also confirm this hypothesis.

f) Environmental sensitisation and awareness of households:

It included variables on: (1) waste separation in households and businesses at the municipal level (plastic, paper, metal, glass, organic materials, building materials, electrical and electronic equipment, etc.); (2) characteristics of collection systems (structured and organised collection of solid waste, available recycling centres, etc.) and (3) environmental awareness and recycling campaigns. The population's lack of environmental awareness has a significant influence on the occurrence of illegal landfills and results align with this hypothesis.

The coefficients $\beta$ enable the importance of the independent variables used as predictors of the dependent variables to be assessed. This value is measured by the odds ratio or increase in probability (in%).The results

confirm that the variables that most influence the occurrence of illegal landfills are spatial (Industrial Land, Plains and Rural Land); whilst the variables that most reduce the likelihood of illegal landfills are those related to certain characteristics of the municipal waste management system and environmental awareness, such as Availability of Recycling Facilities, Punitive Policies, Supervision and Awareness-raising Campaigns. Hence, probability model for the occurrence of an illegal landfill in Andalusia is created from the estimated regression coefficients $\beta$.
Lastly, since it is a predictive model, the appropriateness of the final model has also been assessed by using a classification table, correctly identifying 92.9% of the areas that were not illegal landfills and 93.5% of those that were. Thus, the overall result reached was that 93.1% of the cases analysed were well classified in the final step of the prediction.

Case Study from [9] also used factor analysis, constructed a geo-statistical model to calculate spatial patterns and integrated into GIS to determine the high probability areas of the presence of illegal landfills in the study area of Andalusia, Spain and results show that 63.6% of uncontrolled landfills fall in these high probability areas.

Case study [1] proved that vegetation presence and stress is a reliable indicator of the presence of former uncontrolled landfills and can be successfully used to detect possibly contaminated sites over large study areas. In fact, the number of sites resulting from remote sensing data processing may be very large, because vegetation stress may be due to not only to soil contamination but also to a number of other factors. So, to establish a priority list for further investigations, another study [4] uses GIS combined with multi-criteria and multi-factor evaluation (MCE and MFE) to assess the probability of occurrence of illegal landfills. Criteria are those rules that prohibit a landfill from being placed within a certain area, while factors are the attributes used to evaluate the suitability of a specific site. This experiment is conducted in Venice, North East Italy.

A ground truth data about landfills is obtained from local authorities and the study area was divided into two sub-areas, one for the calibration of the method (with an area of 546 km2), and one used for the validation of results (with an area of 1491km2). The training area contains 20 known illegal and 26 authorized landfills, while 19 additional illegal sites and 28 authorized ones fall in the validation area, along with 182 former or still active quarries.

Based on the observations from training area, following conclusions are made for each factors and criteria.

Siting factors:

- Former Quarries(Q): all the quarries (active and abandoned) were considered as having an extremely high probability of contamination, hence conditional probability is assumed to be equal to 1 for areas with in quarries.
- Proximity to authorized landfills (L): The probability of an illicit landfill being located within 6 km from an authorized landfill is nearly 0.9 and at a distance of 6 km - 8 km is 0.1, estimated using GIS tools by calculating euclidean distance between landfills.
- Industrial sites (I): waste materials coming from industrial activities may be easily disposed of in areas adjacent to industries and factories. Hence illicit dumps are considered to be typically present in agricultural or natural areas and within industrial zones, with a probability equal to 0.9 and the probability of finding an illegal dump near towns is very low (less than 0.1),

Siting criteria:

- Road network accessibility (R): (i) Areas not accessible through streets or paths cannot be a disposal site. (ii) Sites for which no previous suspect activity could be traced from historical aerial photographs (when available) or from reports of the local authorities were excluded.
- Population density (D): We found that 90% of illegal dumps are located in areas with a very low population density. The probability is set to 0.9 in areas with less than 105 inhabitants per $km^2$, and to 0.1 in the rest of the territory).

- Land cover classes (C): residential and urban areas are controlled by authorities and citizens, and the creation of illicit landfills would not be unnoticed.

A suitability map is created for each of these criterias and factors except R criteria for the entire study area and combined all to create a final suitability map. Then R criteria is used to exclude numerous candidate sites. A Maximum Likelihood classification was applied to locate stressed vegetation associated with dumps, using multispectral pan-sharpened IKONOS data, radiometrically calibrated and atmospherically corrected. Candidate contaminated sites obtained from remote sensing analyses were finally overlaid on the final suitability map. This allowed the assignment of a suitability value to each of the candidate sites. The suitability value associated to each candidate can now be used to establish a priority list for field investigations. The last step of the method was based on the analysis of auxiliary spatially distributed information organized within a GIS step-by-step exclusion of areas with a very low probability of being contaminated on the basis R criteria, considerably reduced the number of candidate sites from 2944 to 1199 which were then classified into low(43/1199), medium(418/1199) and high probability(738/1199) areas. To validate the results, 19 illegal landfills from validation area were considered and found that 84 percent of these sites fall in high probability(greater than 0.67) areas according to suitability maps, while only 5 percent of the validation illegal dumps fall within areas with low probability (0 to 0.33).

## 2.5 Detection by implementing Image processing and Image differentiation on Satellite data

A study from Hurghada, Egypt [10], two Landsat Thematic Mapper (TM) images acquired on 21 August 1984 and 18 July 1997, geometrically corrected were used for analysis, identification and transformation of different constructions like landfills, recreation buildings, marinas, artificial lagoons and pools by scene to scene re-sampling over 13year period. Using this multi temporal, multi spectral satellite data, three change detection analysis techniques namely Image subtraction, Image rationing and post classification change have been applied to the study area.

Image subtraction is a technique where by changes in brightness values between two or more data-sets are determined by cell by cell subtraction of co-registered image data-sets. The result calculated to be landfill areas of 2.3 million $m^2$.

Image rationing considered to be a relatively rapid means of identifying areas of change by acquiring two images in one or more bands and are ratioed band by band, compare data on pixel to pixel basis. The resulting of image ratio gives landfill areas which are shown to be 2 million $m^2$ over 13 year period.

A supervised classification was performed using the Maximum Likelihood Classifier to the two sets of satellite images independently, which involved training over representative areas for each land use/land cover category to create a signature files for each date. These signatures were given input to an MLC. These training areas were selected based on ground data acquired during field inspection. The resulting signatures were tested using the SIGCOMP module (IDRISI 1995). This method of evaluation was performed to assess spectral signature accuracy. Two different land-use/land-cover thematic layers were formed. A post classification filtering, using median function, 3×3pixel size, was performed to reduce the noise. Then, a comparison between the two classification maps was carried out on a pixel-by-pixel basis. Two main classes are observed namely urban sector, which represents all coastal villages, shopping centres, sports fields etc has increased by 12 times. Other is agriculture sector which represents all Greenland areas and coral reefs area has decreased owing to landfill operations along coastline.

A study [11] conducted in Naples and Caserta, region of Campania has several environmental illegal activities like illegal sanitary sewer, storm drain connections. Illicit water discharges are detected using novel approach of Thermal Patterns and Thermal tracking by identifying different phenomena

and several pollutants, also introducing a finger print paradigm for environmental police investigations defining several specific signatures that permit the identification of illicit activity. Also establish a procedure to use this information to find the co relation between the crime and the culprit or the source and the target.
Various platforms which are segmented by air, land and water like satellite, airplane, drones, off road vehicles, cars, boats are used to obtain several images. Devices like Multispectral/hyperspectral sensors, CCD TV + IR, IR-radio metric sensor, DSLR camera, air pollution real time sensors, air sampler, magnetometer, Geiger counter, spectrophotometer tool have been used in their study. Focal points of this research are the definition of Thermal pattern and Thermal tracking as methods to link specific phenomena/anomalies to an IR dataset.

An IR thermal sensor detects radiant energy from a surface target, heated through radiation, convection and conduction. The principle of IR thermography is that all objects at a temperature above absolute zero emit IR radiation. The intensity of radiation emitted by an object, as a function of wavelength and surface temperature is a characteristic of that object and can be used to identify and quantify it using aerial infrared thermography combined with data collected at different altitudes.By analysing different shots of the same typology of phenomena, we can discover a composite of traits or features characteristic of the same geometric perceptual structure; if the examined pictures are the rendering of IR data (grabbed with an IR Camera), our new concept is termed a Thermal Pattern. In order to detect a problem in a complex scenario, it is important to define several standard thermal patterns related to known phenomenology.
Thresholding and edge detection are two image processing techniques which can be used to distinguish image regions and find sudden changes in image intensity. Combining edge detection and pattern recognition/tracking ideas is termed as Thermal Tracking. Using thermal tracking, pictures/matrices that are the rendering of an IR dataset (grabbed with an IR camera with radiometric output) can be analysed, links between two or more objects in the same scene can be found, and a source/path/target correlation can be

defined.

The effectiveness of the use of the proposed integrated system were tested and validated during environmental police investigations directed by Italian Government Bodies. For example, One of the investigation is able to discover a link (illegal discharge) between an industry and a river by acquiring thermal images over the river and noticed a spot anomaly. By post-processing the acquired IR data set (thermal tracking approach), discovered the link/pollutant path. Another example is an investigation of a site with two adjacent landfills: the one is legal and the other is the illegal one. In this case, key role of the combination of the IR radiometric output and a 3-day textured polygonal model is obtained. Using this approach, it is possible to relate thermal data with the morphology of the land, thus avoiding mistakes coming from a wrong interpretation of the thermal gradient/gap.

Another study [12] examined illegal activities occur most often in areas which have been heavily modified and considered degraded, mainly quarry areas and landfills, Brindisi in Southern Italy, area of 32 $km^2$, developed a fast detection procedure which is applicable to Landsat images, basically change detection in the images.

A ground truth map has been realized by comparison and visual census of available images in the Water Research Institute of the Italian National Research Council archives and referred to years 2000, 2005, 2006, 2010, 2011, and 2013 with different resolutions from 1 m for the year 2000 to 18 cm for the year 2013. Overall, n. 235 sites have been mapped in relation to these time intervals. Their typology partition suggests mainly changes to surface handling lands (n. 107), creation of new excavation (n. 50), buildings construction (n. 38), restoration (n. 17), naturalization (n. 9), installing solar panels (n. 7), dismantling facilities (n. 2), not attributable (n. 5). Areas that change for each time interval have been mapped and transformed into a vector because they deemed suspicious from photo-interpretation and visual census. Then, the vector file with all polygons has been rasterised. This information level is the ground truth map.

For this purpose, two Landsat images are chosen from the same time of the year for reducing the intensity change caused by the Sun angle difference and vegetation. Then these images are processed by importing in GRASS GIS software, set the computational region and convert the digital numbers (DNs) to at-sensor reflections. Two methods have been applied.

1. Image classification with unsupervised method followed by pixel-based comparison:

Landsat bands $1, 2, 3, 4, 5, 7$of ETM and $2, 3, 4, 5, 6, 7$ OLI-TIRS were grouped to run analysis on any combination of the raster map. It created a text file containing n. 5 sets of pixels with similar spectral signatures with the ‘migrating means’ algorithm that is a modification of the k-means clustering algorithm. Thereafter, the cells spectral reflections has been classified based on the spectral signature information generated with a maximum-likelihood discriminant analysis classifier.
Finally, a post-comparison pixel based between the different maps has been made and a raster with pixels whose values only ranged between the considered images has been created.

2. Using Tasselled Cap-Transformation:

This technique especially used for studies on vegetation, to improve the quality of the spectral information contained in Landsat images. Three dimensions are calculated namely brightness (B), greenness vegetation index (GVI), and wetness (W), which are resulting from reflectance different combination of the six bands of Land sat images. These 3 new derived bands are used to identify most changed areas by calculating Greenness normalisation empirical index and Greenness wetness delta ratio with site specific parameters. Then, the tasselled cap transformation brightness parameters and relative soil line have been derived with the differences between the dry (fallows fields close to landfill bedrock) and the wet (irrigated) soil points also using Coordination of Information on the Environment land cover 1999 and 2011 classification at third level for that area and aerial photographic

image interpretation. After that, with the orthogonal to the soil line applying the Gram–Schmidt process, the tasselled cap transformation greenness parameters have been derived with the differences between the dense green vegetation (urban forests) and the dry soil points.
Finally, the tasselled cap transformation wetness parameters have been derived with the differences between the dense green vegetation and the water-body points (water from an irrigation channel). A mask is applied in order to eliminate other irrelevant features such as urban areas, buildings, and other structures like greenhouses, but to contain other useful aspects such as small vegetated areas, to each pixel of the raster, a new value is assigned applying a neighbourhood filter size of 3 around it to Greenness normalization empirical index raster.

Method1 is quicker, although $\kappa$ (kappa analysis coefficient) may seem low, it should not be overlooked in these procedures because the purpose, with only two Landsat images used in a very short time, is to identify certain type of changes relatable to illegal waste disposal. Method 2 is comparatively complex and slower, with k value higher, but not so much, could be applied in huge environmental complex situations where there is need to investigate wide areas in a short time, even gives an accurate reading of what areas need to be further investigated with filed surveys and, possibly, with direct surveys such as soil sampling and probing. Method 2 noticeably reduced the range of soil sample and monitoring activities from 25,402 to only 4600 pixels.
The procedure, therefore, is effective for an initial screening aimed to detect suspicious areas.

| Paper | Area | Ground Truth | Input Data/Features | Technique |
|---|---|---|---|---|
| [1] | Naples, Campania region | Naples municipality | RED-VNIR(Visible and Near Infrared) spectral signature for understanding surface vegetation, night time ASTER-TIR images for LST(Land Surface Temperature), SAR(Synthetic Aperture Radar) data for 3D monitoring of existing landfills | calculating vegetation index and LST |
| [2] | UK | local police, Criminal case against environmental pollution | Quickbird pansharpened images of 0.6m resolution | by drawing inferences from pictures of that location |
| [3] | Caserta, South Italy | official register of province of caserta | SAR data to extract urbanized zones, GEOEye-1 optical multi spectral images for detecting similar spectral features of interested structures, GIS for calculating distances | calculating spectral features and using GIS |
| [4] | Venice, North East Italy | data bout legal and illegal landfills obtained from local authorities | multispectral pansharpened IKONOS data to locate stressed vegetation | GIS + multi criteria and multi factor evaluation |
| [5] | City of Ottowa, Canada | measurements calculated from Landfill sites | Landsat TM images of landfill sites from 2001-2009 | calculating LST from Thermal images and using GIS |

Continued on next page

Table 2.1 – continued from previous page

| **Paper** | **Area** | **Ground Truth** | **Input Data/Features** | **Technique** |
|---|---|---|---|---|
| [6] | Venice, North East Italy | list of position and shape of known illegal landfills from local authorities and military agencies | IKONOS multispectral 1m resolution panchromatic band to locate stressed vegetation sites, IKONOS RGB/NIRGB for identification of land cover like agriculture or buildings or bare lands, GIS | data classification based on vegetation stress levels |
| [7] | England | surface samplings from landfill sites | GPR(Grond Penetrating Radar) data of 50, 100,200,225,450MHz of landfill sites | Analysed GPR data of various frequencies |
| [8] | Andalusia, Spain | aerial photography of previously detected illegal landfills provided by company ambisat, official statistics | created a theoretical model of hypothesis for various factors for the presence of an illegal landfill and used GIS for integration of geographical and spatial variables | calculated probabilities and logistic regression on various factors |
| [10] | Hurghada, Egypt | field survey-site descriptions of more than 30 locations and exact positions were recorded using GARMIN GPS | Landsat TM images of 1984, 1997 | Image differentiation, Image rationing and supervised classification for each land use/land cover |
| [11] | Naples and Caserta, South Italy | field operations directed by various Italian government bodies | aerial infrared thermography | Image processing techniques-Thresholding, edge detection and pattern recognition |

Continued on next page

Table 2.1 – continued from previous page

| **Paper** | **Area** | **Ground Truth** | **Input Data/Features** | **Technique** |
|---|---|---|---|---|
| [12] | Brindisi, South Italy | field surveys and visual sensus of landsat images obtained from Water Research Insitute of Italian National Research Council, overall details of 235sites has been collected | Landsat_7 ETM and Landsat_8 OLITIRS images | method 1 by pixel based comparison of two images and method 2 by taselled cap transformation to obtain spectral information of landsat images and obtain greenness, wetness and brightness by different combination of 6 bands |

Table 2.1: State of Art Summary

# Chapter 3

# Data

## 3.1 Earth Observation Data

EO sensors basically detect energy from Earth, which may be either reflected from another source or intrinsic to our own planet. Remote sensing devices have been designed to detect various types of energy, including electromagnetic radiation (EMR), radioactivity, magnetism, gravity, and sound and seismic waves. Three broad groups of platforms are used to carry EO sensors:

- Space-borne—satellites,shuttles, or space stations.
- Air-borne—manned aircraft, unmanned aerial vehicles, balloons.
- Ground-based—in situ, mobile devices, or animals(including humans).

### 3.1.1 Background

The electromagnetic(EM) spectrum consisting of range of frequencies of Electromagnetic radiation(EMR), respective wavelengths and photon energies. Certain regions of the EM spectrum are completely absorbed by the various gases that make up the atmosphere (particularly $O_3$, $CO_2$, $H_2O$, so that wavelengths in these regions cannot be used for remote sensing of the Earth's surface. The regions of the EM spectrum where radiation is not affected by

| Energy Source | Spectral Region | | Wavelength of Spectral Region | Wavelength of Atmospheric Window |
|---|---|---|---|---|
| Reflected Solar Radiation(+radiation form active optical sensors) | Optical | Visible | $0.38-0.78\mu m$ | $0.38-0.7\mu m$ |
| | | Near-Infrared | $0.7-1.1\mu m$ | $0.77-0.91\mu m$ |
| | | Short wave infrared | $1.1-3.0\mu m$ | $1.55-1.75\mu m$ |
| | | | | $2.05-2.40\mu m$ |
| Reflected and Emitted Radiation by Earth's Surface | Middle-Infrared | | $3.0-8.0\mu m$ | $3.0-5.0\mu m$ |
| Emitted By earth's Surface | Thermal Infrared | | $> 8.0-15\mu m$ | $8.0-9.2\mu m$ |
| | | | | $10.2-12.4\mu m$ |
| Emitted By Earths Surface or Radar | Microwave | | $> 1mm-1m$ | $7.5-11.5mm$ |
| | | | | $> 20mm$ |

Table 3.1: EMR Spectral Regions and Atmospheric Windows

the Earth's atmosphere are called 'atmospheric windows'. Remote sensing data of the Earth's surface can only be obtained from systems operating within these regions of the EM spectrum. These windows allow detection of reflected solar energy from the Earth's surface in the visible and infrared wavelengths, Earth's emitted energy in the thermal infrared and passive microwave wavelengths, plus microwaves emitted by active sensors. Middle infrared wavelengths can originate from both reflected solar radiation and emitted EMR from the Earth's surface (see Table 3.1).

Within these atmospheric windows, atmospheric conditions such as haze, fog and clouds can still affect remote sensing of features on the Earth's surface through scattering of the EM waves by particles in the atmosphere.

EO sensors can be divided into 3 broad types in terms of instrument

| Spectral Region | Wavelength | EO Sensor | |
|---|---|---|---|
| | | Passive | Active |
| Visible | $0.38 - 0.7\mu m$ | Passive Radiometers | LIDAR |
| Near Infra-Red | $0.7 - 1.1\mu m$ | Passive Spectro-Radiometers | |
| | | Passive Imaging Spectrometers | |
| Short-Wave IR | $1.1 - 3.0\mu m$ | Polarimeters | – |
| Middle IR | $3 - 8.0\mu m$ | Passive Radiometers | – |
| Thermal IR | $8 - 15.0\mu m$ | | |
| Microwave | $1mm - 1m$ | Microwave<br>Radiometers<br>Spectrometers | Radar<br>Polarimeters<br>Scatterometers |
| Radio | $> 10cm$ | Passive Radiometers<br>Sounders | Imaging Radar<br>Altimeters<br>Sounders |

Table 3.2: Spectral regions observed by EO sensors

type and function: Passive Sensors, Active Sensors and Sounders. Table 3.2 lists various EO sensors by instrument type, that are used to detect various spectral regions in atmospheric windows of EMR.

### 3.1.2 EO Passive Sensors

Passive sensors detect the intensity of incoming solar energy that is reflected in the visible, near infrared and middle infrared regions, emitted in the middle infrared, thermal infrared and microwave wavelengths by terrestrial materials into the field of view of the sensor. The most fundamental types of passive EMR remote sensing instruments are radiometers, spectroradiometers and spectrometers.

- Radiometers measure EMR from a target in defined wavelength bands.

- Spectroradiometers are advanced radiometers that measure target radiance for multiple, narrowly defined, wavelength channels.
- Spectrometers are precise instruments designed to measure spectra, acquires imagery in numerous, narrow contiguous spectral channels such that a spectrum for imaged targets can be derived.
- Polarimeters are designed to measure a range of polarisation information in optical and thermal wavelengths.

The following are passive sensors that are commonly used in EO divided into 3 categories as: Optical, Thermal Infrared and Microwave

### Optical

Optical sensors detect and record radiance in visible, near infrared and short-wave infrared wavelengths for panchromatic, multispectral and hyperspectral type of information. Optical scanners are available in different spatial resolutions like low($>$80 m),medium(10m–80m), high($<$ 10m) and very high resolution($<$ 1 m). The most commonly used satellite sensors acquiring low, medium and high resolution imagery are listed in Table 3.3

| Spatial Resolution | Instrument | Mission(s) | Agency |
|---|---|---|---|
| Low | Meris | Envsat | ESA |
| | IMAGER | MTSAT-2 | JMA |
| | GOCI | KAMS | KARI |
| | MCOS | Aqus | NASA |
| | MCOS | Terra | NASA |
| | AVHRR/3 | NOAA-15, 16, 17, 18, 19 | NOAA |
| | VYRR | FY-3A,3B,3C | NRSCC(CAST) |
| | VIRS | NPP | NASA |
| | SeeWIFS | ORBVIEW-2 | Orbimage |

Continued on next page

Table 3.3 – continued from previous page

| Spatial Resolution | Instrument | Mission(s) | Agency |
|---|---|---|---|
| Medium | HRVIR | SPOT-4 | CNUS/Astrium |
| | MSS | Beijing-1 | DMCii |
| | SSTL, MSS-3 band | DMC Demos-1 | DMCii |
| | LISS-II | PROBA-1 | ESA,BNSC |
| | AWIFS | RESOURCESAT-2 | ISRO |
| | LSI-ll | RESOURCESAT-2 | ISRO |
| | ALI | NMP EO-1 | NASA |
| | Hyperlon | NMP EO-1 | NASA |
| | OLI | LDCM | NASA |
| | NigeriaSat Mod Res | Nigeria SAT 1-X | NASRDA |
| | NigeriaSat Mod Res | Nigeria SAT 1-X | NASRDA |
| | TM | Landsat-5 | USGS(NASA) |
| | ETM-+ | Landsat-7 | USGS(NASA) |
| High | MSS/PAN | SPOT-6, 7 | Astrium |
| | HiRi | Pielades-HR 1, HR 2 | CNUS/Astrium |
| | HRG/HRS | SPOT- 6 | CNUS/Astrium |
| | Quickbird-II | Quickbird-II | Digital Globe |
| | WV60 | WORLDVIEW-1 | Digital Globe |
| | WY110 | WORLDVIEW-2 | Digital Globe |
| | Multispectral | WORLDVIEW-3 | Digital Globe |
| | MSI | Rapid Eye | DLR |
| | PAN | Beijing-1 | DMCii |
| | GIS | GeoEye-1 | GeoEye |
| | GeoEye-2 | GeoEye-2 | GeoEye |
| | IKONOS-2 | IKONOS-2 | GeoEye |
| | LISS-IV | RESOURCESAT-2 | ISRO |
| | TESPAN | TES | ISRO |
| | NigeriaSat | NigeriaSat-2 | NASRDA |
| | PAN | BJ-1 | NRSCC(CAST) |

Continued on next page

Table 3.3 – continued from previous page

| Spatial Resolution | Instrument | Mission(s) | Agency |
|---|---|---|---|
| | RSI | FORMOSAT 5, 2 | NSPO/Astrium |
| | MSI | Sentinal-2 | ESA |

Table 3.3: Examples of Satellite Optical Sensors

- **Panchromatic** scanners are imaging radiometers that record EMR in a single band, typically including all wavelengths spanning from the visible to infrared region. Panchromatic data is typically displayed as a grey-scale image, in which pixels with lower image values appear dark and those with higher values appear bright and generally deliver higher spatial resolution imagery than multi-spectral scanners. For optical imagery, panchromatic channels typically record low values for water and dense vegetation and high values for urban and bare areas. As such, engineering works such as roads, mines and urban infrastructure clearly contrast with vegetation, and boundaries of water bodies can be delineated.

  Interpretation of panchromatic imagery relies on spatial rather than spectral analysis of features. Various image processing techniques, such as re-scaling, can be used to change image contrast to enhance specific features. Transitions between adjacent pixels can be highlighted using algorithms that enhance edges or texture. Pseudo-colouring can also be applied to panchromatic images, which maps image values to selected colours. High spatial resolution panchromatic images can visually sharpen edges in multi-spectral imagery to create high resolution colour images.

- **Multispectral** scanners are radiometers and spectroradiometers, that senses radiation in multiple, defined wavelength regions of the visible and infrared parts of the EMR spectrum. The principle of this mode of operation is comparable to using filters on a camera to photograph limited parts of the visible spectrum. For example, when using an appropriate filter to photograph only blue light, a purely red object would appear black since only blue radiation will pass through the filter to expose the film. Thus, different information is obtained by recording the reflectance in different wavelength regions.

Landsat 1 to 5 satellites sensed four bands of the EM spectrum for each image pixel (green: 0.5–0.6 $\mu m$; red: 0.6–0.7 $\mu m$; near infrared: 0.7–0.8 $\mu m$; and near infrared:0.8–1.1 $\mu m$), the more recent Landsat sensors, TM, ETM+ and OLI, were designed to record additional image channels like Visible blue(for coastal water mapping), Visible green(vegetation), Visible red(Chlorophyll absorption for vegetation differentiation), Near IR (Biomass surveys and delineation of water bodies), Thermal IR(Vegetation and soil moisture; snow versus cloud), Middle IR(Thermal mapping, soil moisture, plant heat stress).

- **Hyperspectral** scanners, or imaging spectrometers, collect image data for hundreds of narrow spectral channels in optical wavelengths. This type of imaging allows detailed spectra for individual pixels and/or target features to be compiled. In EO, it is especially valuable for identifying geological features, mapping surface mineral deposits and distinguishing between plant species. In particular, the narrow spectral channels of hyperspectral imagers allow the spectral feature known as the ‘red-edge’ (transition from low reflectance to high NIR reflectance) to be located precisely. This feature is considered as a significant indicator of plant biochemistry, which is indicative of plant condition.

### Thermal Infrared

Thermal sensors are radiometers that record few broad channels in middle and thermal infrared wavelengths.Atmospheric gas absorption restricts thermal remote sensing for EO to two spectral windows in the thermal infrared region:3 -5 $\mu m$, and 8–14 $\mu m$.To allow for the weaker energy levels associated with longer EM wavelengths, thermal sensors require larger Instantaneous Field Of View (IFOV) and thus thermal imagery is generally only available with larger pixel sizes than optical imagery and need to have lower spatial resolution to achieve high radiometric resolution. Given the inverse-square law (that is, the intensity of detected radiation is stronger when the sensor is closer to the target) and to ensure that the detected signal is stronger than sensor noise, these restrictions are most significant for satellite sensors.Some commonly used thermal imaging sensors for EO are listed in Table 3.4.

| Instrument | Mission(s) | Agency | No. of thermal bands in $3-5$ $\mu m$ | No. of thermal bands in $8-14$ $\mu m$ | Ground Resolution($m$) |
|---|---|---|---|---|---|
| HCVR (Heat Capacity Mapping Radiometer) | HCMM (Heat Capacity Mapping Mission) | NASA | 0 | 1 (10.5-12.5) | 600 |
| TIMS (Thermal Infrared Multispectral scanner) | Airborne | NASA/JPL Deaoldus | 0 | 6 (8.2-12.2) | 10(at 20,000m) |
| ATLAS (Advanced Thermal and Land Applications Sensor) | Airborne | NASA/JPL Deaoldus | 0 | 6 (8.2-12.2) | 10(at 20,000m) |
| Daedalus AMS(3607DS) | Airborne | Deaoldus | 1(3.0-5.4) | 1 (8.5-12.2) | Selectable |
| TM (Thematic Mapper) | Landsat-4, Landsat-6 | NASA USGS | 0 | 1 (10.4-12.5) | 120 |
| TM (Thematic Mapper) | Landsat-4, Landsat-6 | NASA USGS | 0 | 1 (10.4-12.5) | 120 |
| ETM+(Enhanced Thematic Mapper Plus) | Landsat-7 | NASA USGS | 0 | 1 (10.4-12.5) | 60 |
| TIRS (Thermal Infrared Sersor) | Landsat-8 | NASA USGS | 0 | 2 (10.6-11.2), 11.5-12.5 | 100 |

Continued on next page

Table 3.4 – continued from previous page

| Instrument | Mission(s) | Agency | No. of thermal bands in $3-5$ $\mu m$ | No. of thermal bands in $8-14$ $\mu m$ | Ground Resolution($m$) |
|---|---|---|---|---|---|
| ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) | Terra | NASA<br>USGS | 0 | 5 (8.125-11.625) | 90 |
| MODIS (Moderate Resolution Imaging Spectroradiometer) | Terra | NASA<br>USGS | 0 | 5 (8.125-11.625) | 90 |
| Imager | GOES | NOAA | 1 (3.8-4.0) | 2 (10.2-11.2) | 4000, 8000 |
| AVHRR(Advanced Very High Resolution Radiometer) | TIROS-N to NOAA | NOAA | 1 (3.55-3.93) | 2 (10.3-11.3, 11.5-12.5) | 1100(LAC),<br>4000 (GAC) |

Table 3.4: Commonly Used Thermal Imaging Sensors

### Passive microwave

Passive microwave are radiometers detecting the emissions of few broad channels of thermal radiation in the in microwave wavelengths (1 to 300 mm) that corresponds to the very low energy end of the Earth's energy spectrum.The intensity of passive microwave radiation depends on an object's temperature and incident radiation plus the emittance, reflectance and transmittance properties of the object. Because these sensors are detecting low energy levels, their imagery is relatively 'noisy', has lower spatial resolution and usually requires more complex interpretation. Although a large volume of knowledge has already been obtained, the acquisition, processing and interpretation of microwave data are still largely experimental.

### 3.1.3 Active sensors

Active sensors generate their own energy source, which is radiated towards a target, and can detect range to the target using phase information of the energy backscattered from the target. Active remote sensing systems operate in the visible and microwave parts of the EM spectrum. The major categories of active satellite-borne EO sensors are lidar and radar sensors that generate their own energy source then detect its echo.

#### Lidar

Light Detection and Ranging (Lidar) is a technique that uses a transmitted laser pulse to detect the presence of a target, operating in the wavelength range from ultraviolet to near infrared. Lidar is only effective in clear atmospheric conditions and such devices are generally aircraft-borne or land-based. No satellite-based scanning lidar systems are currently in operation. Lidar systems with different wavelengths of light can be used: Blue-green wavelength (532 nm) are used for bathymetric measurements in shallow coastal waters and NIR lidar are used to provide topographic data, characterise vegetation canopies and map urban environments. Ground-based lidar provides valuable verification of vegetation structure and density.

#### Radar

Radio Detection And Ranging (Radar) are devices that direct pulses of microwave (a type of radio wave with wavelengths from approximately 1 cm to 100 cm) energy at an object then record the strength, direction and sometimes polarisation of the reflected energy to detect objects and determine their position or ‘range. Radar signals may be transmitted at a range of wavelengths/frequencies. The standard wavelengths used and their standard radar frequency letter codes are given in Table 3.5. In general, atmospheric precipitation has minimal effect on radar signals with frequency $<$10 GHz, which provides a distinct advantage over passive and active optical sensors for EO when cloud cover is present.Heavy precipitation will cause a strong

| Band | Wavelength (mm $= 10^3 \mu m$) | Frequency ($Ghz = 10^9 Hz$) |
|---|---|---|
| W | 2.7 – 4.0 | 75.0 – 110.0 |
| V | 4.0 – 7.5 | 40.0 – 75.0 |
| Q | 6.0 – 9.0 | 33.0 – 50.0 |
| K | 7.5 – 25.0 | 12.0 – 40.0 |
| X | 25.0 – 37.5 | 8.0 – 12.0 |
| C | 37.5 – 75.5 | 4.0 – 8.0 |
| S | 75.0 – 150.0 | 2.0 – 4.0 |
| L | 150.0 – 300.0 | 1.0 – 2.0 |
| P | 300.0 – 1000.0 | 0.3 – 1.0 |

Table 3.5: Radar Frequency Bands

radar echo at wavelengths of 10 mm or less (this principle being used in both ground and aircraft mounted weather detection radar systems). X, C and L bands are most commonly used for EO.

The interaction between these wavelengths and features on the Earth's surface is partly a function of the scale of the surface 'texture' and its dielectric properties (electrical reflectivity and conductivity). Scattered signal amplitude and polarization provides information about scattering properties and structure. Phase measurements of the return pulse are used in interferometry to reconstruct 3D topography, vegetation height and reflectivity profiles use tomographic techniques. For vegetation canopies, the interactions depend on the size, density and orientation of elements. For example, X-band radar with wavelengths of around 3 cm is scattered strongly by foliage; while L-band with wavelengths of 27 cm is scattered more strongly by tree branches and P-bands (wavelengths around 70 cm) is predominantly scattered by tree trunks. Polarimetric radar detection systems can measure backscatter amplitude and phase in up to four specific polarisation modes(HH, VV, HV,VH). More recently, circular polarisation (the tip of the electric field vector is rotating in a circle as it propagates) is also used, where a circularly polarised wave is transmitted and H and V signals are received.

Two types of radar-based systems are commonly used for microwave imaging on aircraft and satellite platforms:

- **SLAR (Side-Looking Airborne Radar) or RAR (Real Aperture Radar)** A radar pulse is transmitted off-nadir by an antenna fixed below an aircraft. This is used to image large ground areas adjacent to the flight line. The echoes are processed to produce an amplitude/time electrical signal that is then recorded as an image line, with 'brighter' pixels indicating higher scattering intensities. The oblique look angle used to acquire radar imagery results in characteristic geometric distortions such as radar shadows, foreshortening and layover effects. While these effects are more pronounced in aircraft radar images, they also occur in satellite imagery, and are more pronounced in mountainous terrain.Systems that utilise the actual antenna size, such as the SLAR systems described, are called real aperture radars (RAR). Because of the physical limitation of antenna size on aircraft, such systems are restricted to short range and low altitudes (which limit the extent of coverage) and relatively short wavelengths (which experience greater atmospheric attenuation and scattering).

- **SAR(Synthetic Aperture Radar)** The physical antenna length may be effectively lengthened using the flight path of the radar platform by processing return signals according to their Doppler shifts (that is, a change in wave frequency as a function of the relative velocities of transmitter and receiver). This basic principle is used in Synthetic Aperture Radar (or SAR) as shown in Figure 3.1. This processing requires that both amplitude and phase information be recorded from objects throughout the time period in which they are within the beam of the moving antenna and gives higher spatial resolution imagery that is constant in the along-track (azimuth) and across-track (range) directions.

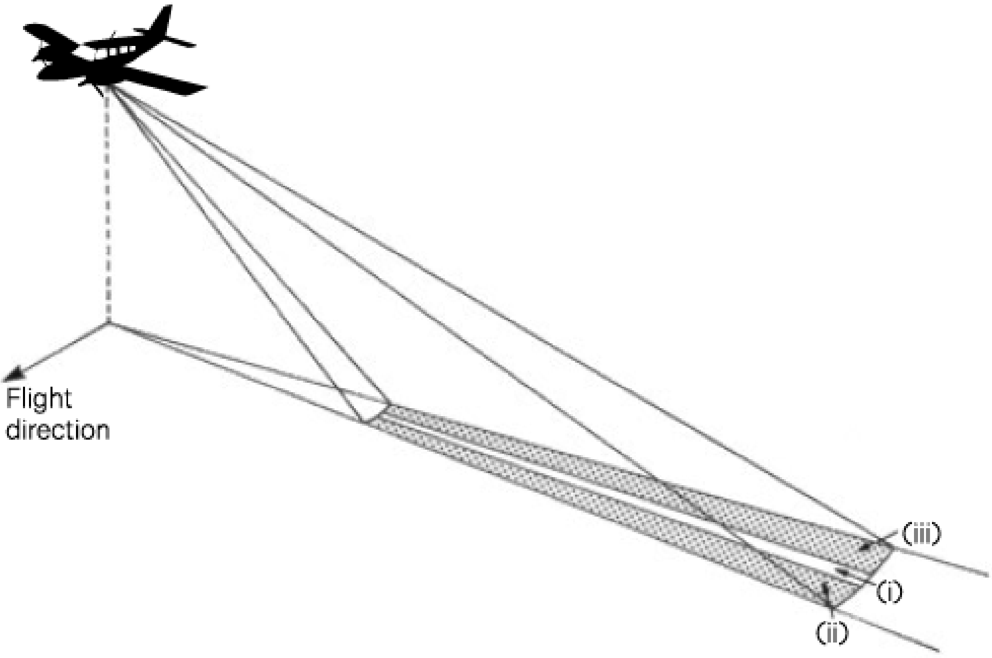

Figure 3.1: Operation of synthetic aperture radar

Recording the frequency as well as the amplitude of echoes allows the surface illuminated by the radar beam to be subdivided into three regions, where the frequency of the return signal from an object will change (due to Doppler shift), which allows the position of the ground object to be more precisely located and thus greatly improves the azimuth or cross-range resolution: (i) a narrow strip perpendicular to the flight line where the echo frequency matches the transmitted frequency, (ii) a region ahead of the aircraft where echoes are up-shifted in frequency, and (iii) a region behind the aircraft where echoes are down-shifted in frequency.

Stripmap, spotlight and scan are different SAR acquisitions modes used for different applications. Scan mode involves moving the antenna in a scan pattern, and is used to capture larger areas (e.g. for flood mapping) but at the cost of lower spatial resolution. Spotlight is used to capture data over small target areas at high spatial resolution. Stripmap is the standard acquisition mode (fixed beam direction, no scanning) and corresponds with the SLAR. Satellite SAR sensors that are currently used or planned are listed in Table 3.6

### 3.1.4 Sounders

Sounders are used to observe properties of the atmosphere at particular altitudes to derive information about air composition, temperature and movement; or water bodies at specified depths, to determine profiles of water depth, colour and temperature.
Table 3.7 clearly describes various sensors characterized by instrument type, spectral region of EMR it detects, function, uses and their applications.

| Instrument Type | Design Purpose | EM Wavelengths | Radiation Source | Detection System | Applications |
|---|---|---|---|---|---|
| Atmospheric Chemistry Measurements | Carious Techniques to different parts of the EM spectrum to measure atmospheric composition | UV, Optical, Thermal Infrared, microwave | Passive | Non-Imaging Sounding | Atmospheric Studies |
| Atmospheric Temperatures and humidity sounders | Measure distribution of IR or microwave radiation emitted by the atmosphere to deliver vertical profiles of the temperature and humidity through atmosphere | Thermal Infrared, Microwave | Passive (Active) | Sounding | Atmospheric Studies |
| Cloud Profile and Rain radars | Rains at cm wavelength for rainfall as well as very short wavelength($mm$) radar and lidar to detect scattering from non-precipitating cloud droplets or ice particles, to deliver data on cloud characteristics such as moisture content and base height | Microwave | Active | Sounding | Weather Prediction, Climate Studies |

Continued on next page

Table 3.7 – continued from previous page

| Instrument Type | Design Purpose | EM Wavelengths | Radiation Source | Detection System | Applications |
|---|---|---|---|---|---|
| Earth Radiation Budget Radiometers | Measure the radiation balance between the incoming radiation from the Sun and the outgoing reflected and scattered solar radiation, plus the thermal infrared emission to space | Optical, Thermal Infrared, Microwave | passive | Imaging, Sounding | Climate studies |
| Gravity, MF, Geo-dynamic Instruments | Instruments and supporting systems used to derive information on the Earth's gravity field, magnetic field or geodynamic activity | Non EM | Passive | Imaging(Non-EM) | Geo-id Monitoring, ice studies, Hydrology |
| High Resolution Optical Imagers | Measure detailed optical radiance from the Earth's surface; generally nadir-viewing panchromatic and multispectral instruments with a horizontal spatial resolution up to 100 m and swath widths around 100 kilometres | Optical | Passive | Imaging | Land cover mapping and monitoring, geological mapping and cartography |
| Hyperspectral Imagers (or imaging spectroscopy) | Measure optical reflectance from Earth's surface in many (usually 100 or more), narrow, contiguous, spectral bands | Optical | Passive | Imaging | Characterising spectral properties, especially for minerals, vegetation and coastal studies |

Continued on next page

Table 3.7 – continued from previous page

| Instrument Type | Design Purpose | EM Wavelengths | Radiation Source | Detection System | Applications |
|---|---|---|---|---|---|
| Imaging multi-spectral radiometers (visible/infrared) | Measure optical and thermal infrared reflectance from the Earth's surface and atmosphere, generally with spatial resolution from 100 m to several kilometres, for broad ground swaths (thousands of km) | Optical, Thermal Infrared | Passive | Imaging, Sounding | Global and regional studies of vegetation, snow, ice and surface temperature, especially to identify and monitor biosphere and ocean processes |
| Imaging multi-spectral radiometers (passive microwave) | Measure microwave emission (1-40 GHz and 80-100 GHz) from the Earth's surface at low spatial resolutions | Optical, Microwave | Passive | Imaging | Snow and ice mapping and monitoring soil moisture, vegetation health and ocean salinity |
| Imaging microwave radars (X-Band, C-Band, and L-band) | Measure back-scattered signals from transmissions in the range 1-10 GHz at spatial resolutions between 10 m and 100 m, with a swath width of 100-500 km, Includes both synthetic aperture radars (SARs) and real aperture side-looking imaging radar systems. | Microwave | Active | Imaging (after processing) | Ocean waves and pollution, vegetation structure especially in tropical areas, snow and ice sheet measurements, flood monitoring, subsidence studies. |
| Lidars | Measure radiation reflected from the Earth's surface or atmosphere when illuminated by a laser source | Optical | Active | Imaging (after processing) | Surface topography, vegetation height, atmospheric studies |

Continued on next page

Table 3.7 – continued from previous page

| Instrument Type | Design Purpose | EM Wavelengths | Radiation Source | Detection System | Applications |
|---|---|---|---|---|---|
| Lightning Instruments | Optical sensors (-777nm) with high-speed cameras, focused on cloud tops, detect lightning | Optical | Passive | Imaging (after processing) | Weather prediction, climate studies |
| Multiple direction/ polarisation SAR instruments (or polarimeters) | Custom-built radar instruments for observing the direction/polarisation characteristics of the target's signature to derive geophysical information | Microwave | Active | Imaging (after processing), Sounding | Surface temperature, aerosol modelling for improved Radiative transfer models and biomass estimates, soil moisture and ocean salinity estimates |
| Ocean colour instruments | Measure radiance from marine waters in visible and near infrared wavelengths (400-800nm), typically with high spectral resolution and low spatial resolution | Optical | Passive | Imaging | Shallow water mapping, chlorophyll content, suspended sediment, water dynamics, marine pollution |
| Radar altimeters | Use the ranging capability of radar to measure the topographic profile of the Earth's surface (land and ocean) along the satellite track | Microwave | Active | Non-Imaging | Topography of water surface and substratum (seafloor), sea Ice, ocean wind speeds, wave height |

Continued on next page

Table 3.7 – continued from previous page

| Instrument Type | Design Purpose | EM Wavelengths | Radiation Source | Detection System | Applications |
|---|---|---|---|---|---|
| Scatterometers | Transmit radar pulses and receives backscattered energy, the intensity of which depends on the roughness and dielectric properties of a particular target | Microwave | Active | Non-Imaging | Sea surface wind speed and direction, weather and wave prediction, soil moisture, snow levels |

Table 3.7: Sensor Description

All the figures, tables and information in this section 3.1 is obtained from the source: Earth Observation: Data, Processing and Applications [1].

## 3.2 Illegal Landfills data sets

Accidental events, spills and illegal dumping of waste in the ground is observed to be the main cause of major pollution cases detected, which affects all environmental matrices air, soil, subsoil, groundwater and surface. In this study, four data sets from different sources have been manually scrutinised at every data point to understand various patterns of landfills and their geographical, spatial characteristics.

**Campania region**, a region notorious for illegal activities, especially illegal landfills due to their history of mafia [1]. So, it is a suitable place to look for good examples.
A Regional Environmental Protection Agency Campania (ARPAC) has provided an open data set, which is freely available online[2]. The Registry data set contains total of 244 sites, divided in the following categories: 117 landfills, 44 production activities, 41 Fuel, 3 Waste treatment plants, 1 quarry,

---

[1] http://www.crcsi.com.au/history-2/earth-observation-series-2/

[2] http://www.arpacampania.it/web/guest/1408

| Frequency Band | Launch Year | Mission(s) | Agency(Country) |
|---|---|---|---|
| C-Band | 2007 | RADARSAT-2 | CSA/MDA(CANADA) |
| C-Band | 2014<br>2016 | Sentinel-1A<br>Sentinel-1B | EC/MSA(EUROPE) |
| X-Band | 2007<br>2007<br>2008<br>2010 | COSMO-SkyMED-1<br>COSMO-SkyMED-2<br>COSMO-SkyMED-3<br>COSMO-SkyMED-4 | ASI(Italy) |
| X-Band | 2007 | TerraSAR-X | DLR/Airbus DS(Germany) |
| X-Band | 2010 | TanDEM-X | DLR/Airbus DS(Germany) |
| X-Band | 2009 | RISAT-2 | ISRO(INDIA) |
| X-Band | 2015<br>2017<br>2022 | HY-3A WSAR<br>Hy-3B WSAR<br>Hy-3C WSAR | NSOAS/CAST(China) |
| L-Band | 2014 | ALOS-2, POLSAR-2 | JAXA(JAPAN) |
| L-Band | 2020 | NISAR | NASA/ISRO |
| L-Band | 2017<br>2018 | SAOCOM-1A<br>SAOCOM-1B | CONAE(Argentina) |
| P-Band | 2017 | BIOMASS SAR | EC/ECA(Europe) |

Table 3.6: Examples of Active and Future Satellite SAR Sensors

11 Waste (Abandoned waste, Temporary storage sites), 27 Other (areas contaminated with dioxin, sandy and seabed, ports, etc.). Basically, all these data points are registered considering the presence of pollutants like metals, inorganic compounds, hydrocarbons and soil contamination spotted in that area.

Each data entry has attributes namely, identification code, name, location (Municipality and Province of belonging), whether or not belonging to Sites of National Interest (SIN), contaminated matrices, type of contaminants, coordinates (UTM33N WGS84).

**Region of Lombardia** Other three data sets are from Region of Lombardia, North Italy are obtained from organisation called SCIAM labs that hosts and maintains open data hub of Italy, largest Italian data catalogue, also provides modern big data solutions and AI. These three data sets[3] [4] [5] belong to different years, 2014, 2016, 2018.

All the data points from these data sets are considered to be sites with contamination of soil and water table, sites with contamination or only soil or groundwater, sites with groundwater contamination and land reclamation ended. Each data entry has 7 attributes: Province, Commune, Name of the site, Local address, street number, classification of waste.

---

[3] https://www.dati.lombardia.it/Ambiente/MI-Giambellino-129/kcu8-8c3y

[4] https://www.dati.lombardia.it/Ambiente/Aree-Contaminate-Milano/x774-7qxt

[5] https://www.dati.lombardia.it/Ambiente/Elenco-dei-siti-bonificati-sul-territorio-lombardo/4pzs-yf3y/data

# Chapter 4

# Implementation

## 4.1 Images downloader

We have implemented an automated script to download pictures of all suspected locations from Google Earth Pro Application. This automated script, given a set of addresses or set of latitude and longitude of the locations in a .csv format as input, extract the addresses from that file and uses PyAutoGUI library to automate all the tasks like to set the desired time of the year that we would like to capture the image, search for an address, take a screenshot of the location with desired size, zoom the location and get another screenshot with a zoomed version of that location, save the screenshots in a desired format. The Script scans the locations and extract set of pictures as output and giving a .csv file as an input, mentioning which rows to extract to make a valid address to search for and time of the year the image required. For example, below are the two screenshots, one with 500m around as in Figure 4.1 and other is zoomed version as in Figure 4.2. In the next step, among all the images obtained from Image downloader, images with landfills are filtered and annotated as in 4.3.

Figure 4.1: Screenshot of location with 500m span

Figure 4.2: Zoomed version of suspected location

Figure 4.3: Annotation of an image with landfill

# Chapter 5

# Examples characterization

Several locations have been examined based on the address and their year of entry of illegal landfill data point available from data sets. Google Earth provides optical satellite images from various years and accordingly, all data points are examined for landfills. In general, periodical satellite images are available at Google Earth for every year and their frequency of obtaining in various time periods depends on habitation and accessibility of that area. For example, based on type of location, if areas are well accessible by roads, street views of that location are available, along with satellite images(top view of land cover, usually 10-50m resolution).

Besides having advantage of availability of various temporal optical images from Google Earth which served the purpose of understanding data sets, there are some complications in determining if there is a landfill at a given data point. For example,

- if data point exists somewhere in between agricultural areas or near to forest areas, where street views are not possible, then it is difficult to determine if there is a landfill just from a top view of satellite image due to their poor resolution at that local point.
- if there is no recent snapshot of satellite image available from Google earth, close to the date of reporting data entry, there is a possibility that it has been cleared or some action has been taken, so we cannot find anything suspicious like illegal landfill.

Illegal dumping is defined as discarding waste in an improper or illegal manner, where it does not belong and/or where environmental damage is likely. But, data sets examined in this study are data points/locations indicating soil contamination that can be due to various reasons. Major number of data points are found to be petrol bunks, on going construction sites(understood from observing images of that location from various years), industries, factories, empty barren lands, demolished sites, small dumps of wood, tires, iron or other metals thrown out, hence not serving our purpose which is a huge drawback. Despite these drawbacks in data sets and limitations in availability of image sources from Google Earth, 80 good examples of illegal landfills are found, which serves our purpose.
So by observing these few interesting data points it is understood that few uncertainties can be a reason for creation of illegal landfills like

- People might have started to throw things in an incomplete construction site or there are some construction left overs after construction like in Figure 5.1

Figure 5.1: Construction leftovers in urban area

- empty/abandoned lands is filled with waste water causing soil contamination and eventually environmental damage like in Figure 5.2

Figure 5.2: Empty land in urban area

- empty sites filled with some waste dumps and its not being taken care of anymore like in Figure 5.3

Figure 5.3: Waste dumps in urban area

- demolished sites eventually might have turned into an illegal landfill or the waste could be under-ground like in Figure 5.4.

Figure 5.4: Demolished site in urban area

- Others are small scale industries manage their extra material/waste like tires, wood, metals or other materials with less care like in Figure 5.5
- Some legal landfills are also found like in Figure 5.6.

H

Figure 5.5: Wooden waste in rural area

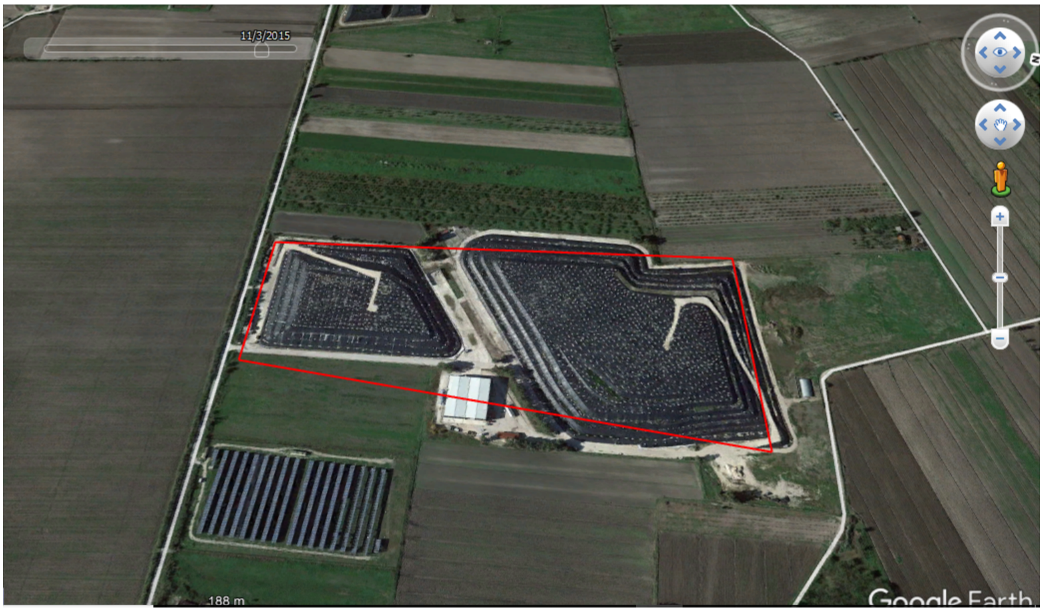

Figure 5.6: Legal landfill in rural area

To understand type of waste/landfills found, Table 5.1 describes percentage of different types of landfills found in our study.

| **Identified Type of landfills** | **Percentage of examples** |
|---|---|
| waste dumps | 47.5%, 14/80 |
| Construction left overs | 47.5%, 34/80 |
| Industrial left overs(tires, wood and other metals) | 2.5%, 16/80 |
| Empty barren lands(filled with waste water/small dumps) | 2.5%, 15/80 |
| legal landfills | 2.5%, 15/80 |

Table 5.1: Percentage of various landfills identified

| **Identified pattern** | **Percentage of examples** |
|---|---|
| Urban(residential or industrial) | 47.5%, 38/80 |
| Rural(crop lands or city outskirts) | 47.5%, 38/80 |
| Near water bodies | 2.5%, 2/80 |
| Miscellaneous | 2.5%, 2/80 |

Table 5.2: Percentage of different areas that landfills are identified

Based on study of these few good examples, it is observed that, In case of Campania region, most of the illegal landfills are present in areas that are not generally noticed like somewhere in between of crop lands or agriculture areas but there is an easy accessibility by roads like in the outskirts of the city like in Figure 5.7 or non-residential areas. Where as in case of Milan and other parts of Lombardia region, that concludes 75% of our study(3/4 data sets belong to Lombardia) many landfills are found in Urban areas. Also in areas of less habitation with few small scale industries and dumps are managed irresponsibly or not given enough care. Others are incomplete construction sites or found near small water bodies like in Figure 5.8. Table 5.2 clearly describes percentage of different areas that various types of landfills found in case of both Campania and Lombardia region.

Figure 5.7: Waste dumps in rural area

Figure 5.8: Industrial waste near water bodies

# Chapter 6

# Conclusions and Future Work

In this study, we have clearly summarized the remote sensing data and all the methods and techniques that are employed till date to detect illegal landfills using this remote sensing data and most of them are found to be economical. We have used high resolution optical images to analyse geo-spatial variables, understand the existence of landfills and characterized them. We have successfully implemented an automated script to download optical satellite images of all suspected locations given in csv format. We have then filtered those images containing illegal landfills among all the downloaded satellite images. In the next step, all these filtered images containing landfills are annotated to identify landfills in that image. And finally obtain a set of good examples of illegal landfills, which can be used in further research. In future, all these good example of images and knowledge gained can be fed to a Deep neural network to develop a Deep learning algorithm which can automatically detect and identify illegal landfills in the images, which could be a very efficient and effective solution.

# Bibliography

[1] Enrico Giuseppe Cadau et al. «SIMDEO: An integrated system for landfill detection and monitoring using EO data». In: *2013 IEEE International Geoscience and Remote Sensing Symposium-IGARSS*. IEEE. 2013, pp. 3305–3308.

[2] Ray Purdy. «Using Earth observation technologies for better regulatory compliance and enforcement of environmental laws». In: *Journal of Environmental Law* 22.1 (2009), pp. 59–87.

[3] FRANCESCO GARGIULO et al. «Remote sensing in the fight against environmental crimes: The case study of the cattle-breeding facilities in Southern Italy». In: *International Journal of Sustainable Development and Planning* 11.5 (2016), pp. 663–671.

[4] Giancarlo Biotto et al. «GIS, multi-criteria and multi-factor spatial analysis for the probability assessment of the existence of illegal landfills». In: *International Journal of Geographical Information Science* 23.10 (2009), pp. 1233–1244.

[5] K Faisal. «Environmental monitoring of landfill sites using multitemporal remote sensing images». In: *Ryerson University* (2011), pp. 1–78.

[6] S Silvestri and M Omri. «A method for the remote sensing identification of uncontrolled landfills: formulation and validation». In: *International Journal of Remote Sensing* 29.4 (2008), pp. 975–989.

[7] T Splajt, G Ferrier, and LE Frostick. «Application of ground penetrating radar in mapping and monitoring landfill sites». In: *Environmental Geology* 44.8 (2003), pp. 963–967.

[8] Angel Luis Lucendo-Monedero, Rosa Jorda-Borrell, and Francisca Ruiz-Rodriguez. «Predictive model for areas with illegal landfills using logistic regression». In: *Journal of Environmental Planning and Management* 58.7 (2015), pp. 1309–1326.

[9] Rosa Jord-Borrell, Francisca Ruiz-Rodrguez, and Angel Lus Lucendo-Monedero. «Factor analysis and geographic information system for determining probability areas of presence of illegal landfills». In: *Ecological indicators* 37 (2014), pp. 151–160.

[10] Kh M Dewidar. «Landfill detection in Hurghada, North Red Sea, Egypt, using thematic mapper images». In: *International Journal of Remote Sensing* 23.5 (2002), pp. 939–948.

[11] M Lega et al. «Remote sensing in environmental police investigations: aerial platforms and an innovative application of thermography to detect several illegal activities». In: *Environmental monitoring and assessment* 186.12 (2014), pp. 8291–8301.

[12] Carmine Massarelli. «Fast detection of significantly transformed areas due to illegal waste burial with a procedure applicable to Landsat images». In: *International Journal of Remote Sensing* 39.3 (2018), pp. 754–769.