The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-1/W1-2023
12th International Symposium on Mobile Mapping Technology (MMT 2023), 24–26 May 2023, Padua, Italy

CONCEPTUALIZATION OF A SATELLITE, UAS AND UGV DOWNSCALING APPROACH FOR ABANDONED WASTE DETECTION AND WASTE TO ENERGY PROSPECTS

A. Mei[1*], V. Baiocchi[2], S. Mattei[3], E. Zampetti[1], HJ. Pai[4], P. Tratzi[1], A. V. Ragazzo[1], A. Cuzzucoli[1], A. Mancuso[1], A. Bearzotti[1], G. Fontinovo[1], M. Grosso[3], CY. Chu[4], D. Bianconi[1]

[1] Institute of Atmospheric Pollution Research, National Research Council of Italy, 00015 Monterotondo, Italy - (alessandro.mei, emiliano.zampetti, patrizio.tratzi, alfonso.ragazzo, alice.cuzzucoli, aurora.mancuso, andrea.bearzotti, giuliano.fontinovo,daniele.bianconi)@iia.cnr.it
[2] Department of Civil, Constructional and Environmental Engineering (DICEA), Sapienza University of Rome, 00184 Rome, Italy - valerio.baiocchi@uniroma1.it
[3] Department of Civil and Environmental Engineering, Politecnico di Milano, piazza Leonardo da Vinci 32, 20133, Milano, Italy - sara.mattei@mail.polimi.it; mario.grosso@polimi.it

[4]Green Energy Development Center, Feng Chia University, Taichung, Taiwan - cychu@mail.fcu.edu.tw; paihaojen@gmail.com

KEY WORDS: abandoned waste, remote sensing, UAS, UGV, waste to energy, circular economy.

ABSTRACT:

The aim of this research is to develop a multiparametric downscaling analysis for the detection of abandoned waste in the environment. This methodology, using a multi-technological approach, involves the adoption VHR satellite images, Unmanned Aircraft System (UAS) and Unmanned Ground Vehicles (UGV). The identified Warning Areas (WA) will be investigated through an in-situ analysis with air quality measurement devices based on advanced sensors mounted on drones. The creation of a Cadastre Accumulation of Abandoned Materials (CAMA) and the related APP will allow the administrations to monitor the phenomenon. Finally, the waste product analysis, retrieved by means of UAS dataset computation, allows to retrieve some interesting prospects regarding Waste to Energy framework. Here, preliminary results obtained by the on-going INTESA Project are presented.

1. INTRODUCTION

1.1 Framework overview

The illegal dumping of waste, still taking place in many areas, requires the application of a multi-disciplinary system for the environmental characterization and the recognition of polluted sites (Muraoka et al. 2012; Kaza et al. 2018). The innovative objective of this research is to develop a semi-automatic downscaling system capable of identifying sites which are potentially contaminated by abandoned and buried waste. This will be achieved by a multi-parametric approach that considers remote sensing imagery and air pollution characterization. Satellite, Unmanned Aircraft Systems (UAS) and Unmanned Ground Vehicle (UGV) are combined to attain such purpose.
Traditionally, polluted sites can be detected by the chemical description of soil or by evaluation of microelements, regarding soil nutrients availability (Lu et al. 2012, Qaswar et al. 2020). An alternative detection method relies on the assessment of vegetation stress condition (Sellers, 1985) or even the measurement of temperature differences on the ground (Baiocchi et al. 2018). The critical issue in pollution studies, for both inorganic and organic substances, is to define their natural background level. Finally, the analysis of gases mixing is a crucial task to evaluate and to characterize the emission fluxes in the potentially contaminated sites (Cusworth et al. 2020).
As compared to remote sensing techniques, the complete characterisation of the contamination by laboratory chemical analyses is less sustainable in terms of costs and time. Nowadays, remote sensing studies are considered as alternative tools, even if currently they are mostly limited to qualitative assessments of the site contamination without a multidisciplinary approach (Glanville and Chang, 2015, Torres and Fraternali, 2023).

In the framework of abandoned waste detection, remote sensing techniques provide a site-specific analysis without in-situ sampling and analytical analysis, connected with parameters that are useful for environmental quality assessment. In this research, a downscaling approach has been established to determine sites' spatial features variability by integration of classified remote sensing images and GIS data. According to this, the application of the proposed downscaling approach is based on the use of evaluation / validation training sets, which are useful for the environmental quality management at the local, regional, and even global scales.
Concerning waste detection by remote sensing data, the Unmanned Aircraft Systems (UAS) is used to acquire and manage very high-resolution RGB imagery and to distinguish spectral features (multispectral and/or thermal) from the surface. The new Very High Resolution (VHR) satellite constellation and the development of robust algorithms for data processing, can lead scientific research to interesting new results. Indeed, decision support processing systems are designed to detect and characterize contaminated sites by integrating different data (Youme et al. 2021). Thus, the satellite and UAS sensors can improve the quality of environmental analysis at the regional and local scales.
Furthermore, the UAS platform is widely used in many research fields, focusing on environment analysis at the local scale and becoming pioneers in abandoned waste detection contexts (Torres and Fraternali, 2023). The UAS becomes a final step of a downscaling system, reducing costs and time-consuming activities for the analysis of this kind of study areas. The collection of these measurements occurs through the use of thermal cameras and a multispectral device that can register, at very high spatial resolution, emitted and reflected energy from the surface (Baiocchi et al. 2018, Cusworth et al. 2020, Torres and Fraternali, 2023).

Once critical areas are detected by means of superficial anomalies from remote imagery, an on-site confirmation of warning areas will be obtained by a UGV. The UGV will recognize the presence of potential contamination sources by using an integrated measurement system, equipped specifically with different devices such as electrochemical, optical and photoionization sensors (Zampetti et al. 2020). The navigation system, which is waypoints based, and the semi-automatic navigation will allow access to every area at different times, granting acquisitions of a large amount of information on a wider area. At the same time, several sensors applied on UGV will analyse the atmospheric concentrations of PM_x, CO, CO_2, H_2S and NH_3.

Usually, different kinds of materials (such as paper, plastics and the organic fraction) are not re-usable or recyclable when they are indiscriminately dumped or abandoned. As a second-best option, Waste-to-Energy (WtE) can play a key role in transforming non-recyclable wasted materials into resources. In fact, modern technologies, such as anaerobic digestion, pyrolysis, and gasification, ensure high-efficiency energy conversion. WtE can be a keystone for three different policies: waste management, energy and environmental (climate change) policy, also enabling the Member States to meet their targets of the EU policy (European Commission communication, 2011).

In 2021, the Italian operating incinerator plants were 37 and they have processed 6.066.180 t of total waste (89% of Municipal Solid Waste - MSW). In that year, the total energy recovered by WtE plants was 4,53 million MWh of electrical energy and 2,34 million MWh of thermal energy. Moreover, at the end of the process, the metals recovered from the bottom ashes, were directed to authorized plants for recovery and recycling (ISPRA report, 2022).

As seen, environmental protection agencies and institutions could benefit from this semi-automatic downscaling system, to identify and recognize polluted sites (buried an unburied) and to produce remediation priority maps and policies. In this short-paper, preliminary results are presented which are related to the model conceptualization for the detection and analysis of abandoned wastes by means of VHR satellite data UGV and UAS platforms. In addition, the potential opportunities to reintroduce these abandoned materials in a WtE framework is evaluated.

1.2 Papers related to the topic.

The main useful topic able to determine the characteristics of uncontrolled landfills or illegal waste areas is the acquisition of information by UAS or satellite techniques. Based on this topic and on Web of Science resources, the issue-related papers associated to different keywords (illegal landfill, uncontrolled waste disposal, and remote sensing) show that this matter is not extensively studied despite being interesting. The details are indicated in Figure 1.

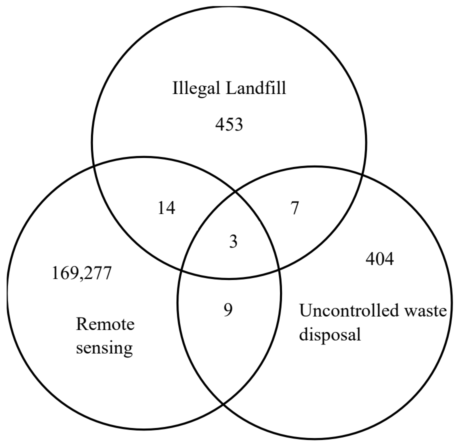

Figure 1. Number of issued-related papers.

According to the bibliographical search, Geographic Information System (GIS) and Remote Sensing (RS) are the main techniques used for studying landfill expansion and for dump sites identification by using specific spectral indices.

1.3 Global abandoned wastes drawback

In literature, the main references related to abandoned wastes are associated to illegal dumpsites. Waste dumping is a worldwide problem which generally affects the developing countries. One of the principal causes, according to Ichinose and Yamamoto, 2011, is a shortage of proper waste treatment facilities, which induces illegal dumping. As is well-known, improper solid waste treatment contributing to a substantial emission of atmospheric pollutants of different kinds, including methane, a powerful greenhouse gas (GHG). The quantification of such emissions from landfills is still a complex matter, because of site-specific factors (Cusworth et al. 2020). Nevertheless, it is observed that the waste sector is the third methane emitter after the agricultural and energy sectors (Yusuf et al. 2012).

The analysis of abandoned waste materials can help in detailing the problem, to focus on the causes and on how to prevent them. Generally, household waste, plastics, construction and demolition and industrial wastes are the most common materials that can be found in illegal dumps. Moreover, this dumping is frequently linked to illegal activities. An investigation in Thailand discovered that 181 recycling facilities over 762 tend to illegally dump hazardous recyclable waste. This was categorized as: oil, solvent, and petrochemical waste (25.64%); slag, fly ash, coal waste, and sulfide waste (10.26%); automobile parts, printed circuit boards (PCB), and electronic waste (17.95%); pesticides, chemicals, and metal precipitates (21.79%); and asbestos and construction waste (6.41%), while the remainder of the waste (17.95%) was mixed and unidentifiable (Otwong et al. 2021).

In Italy, the main factors leading to illegal dumping are criminal activities associated with inadequate industrial waste management. In the Campania region, for example, two independent investigations led by ARPA and Legambiente have documented 39 dumpsites, half of which probably holding hazardous materials (Mazza et al. 2015). Another example is related to the Calabria region, where a study led by the World Health Organization (WHO), analyzed the Italian “environmental high-risk sites” and an epidemiologic analysis and monitoring of the population around the contaminated sites have been done through the specific project. In the whole region, the survey has resulted in 696 dumpsites potentially contaminated by waste, where only 354 of them are authorized. The non-authorized sites are divided in 73 at marginal risk; 262

at low risk; 261 at middle risk; 40 at high risk (Comba and Pitimada, 2016).

1.4 Environmental and health implications

The WHO defines a contaminated site as a site which hosts, or hosted in the past, an anthropic activity which contaminated or could contaminate soil, superficial or ground water, air, or the food chain, as each of these can impact human health (WHO report, 2013). During the past decades, the illegal practice of dumping industrial toxic waste and solid urban waste occurred mainly in Southern Italy areas, such as the Campania region Alberti, 2022). Tons of waste have been either dumped in agricultural areas or illegally burned releasing dangerous chemicals, including dioxins, a large family of chlorinate compounds, some of which have been recently classified as carcinogenic in both animals and humans by the International Agency for Research on Cancer (IARC) (Steenland et al. 1997). High levels of chemical contaminants (e.g. dioxins and polychlorinated biphenyls) have been reported in air, soil, water and humans. These results underline the possible long-term role of waste and its positive correlation with outcomes such as liver and lung cancer and mortality in humans, in addition to a short-term (less than one year) waste-related effects, confirmed by the association with congenital malformation already documented (Triassi et al. 2015, Bertolini et al. 1997).
Moreover, industrial activities can have significant environmental and health implications. The magnitude of contamination sites in the European continent is largely unknown. In each European country there are contaminated sites because of uncontrolled and mis-managed industrial activities in post-war decades.

2. MATERIALS AND METHODS

2.1 Model concept

Traditionally, the identification of abandoned waste sites and its categorization require extensive field investigations and laboratory analysis, while remote sensing technology can provide an alternative approach to determining the characteristics of such kinds of areas.
Different remote sensing techniques can help in detecting and analysing flagged sites also to provide suitable information about uncontrolled waste.
The approach is organized as a downscaling system, defined by multisource remote sensing analysis (satellite), Unmanned Aircraft Systems (UAS) and Unmanned Ground Vehicles (UGV). Field investigations are used for the validation of satellite data and commodity studies from UAS data computing. Information about the commodity class of waste is finally used to set up an LCA study focused on waste-to-energy policies and circular economy perspectives.
Finally, a DataBase Management System (DBMS) is set up with all the geographical, environmental and commodity class information. These phases are organized in a series of packages which will be described in the following paragraphs.

2.2 Regional and local analysis

The first step of the aforementioned model will collect, process and extract indexes via remotely sensed data at VHR spatial resolution in order to identify, at regional scale, some parameters which describe the study area and the temporal changes.
A pre-processing step will spectrally/spatially co-register satellite images and these will be classified for land use analysis. Additionally, satellite data are used to retrieve areas which can be considered sensitive to waste abandonment.
In these areas, we will focus on image-differencing analysis of spectral indices, highlighting all local anomalies in comparison to the natural background.
For what concerns data within visible and near-infrared domains, widely adopted spectral indexes descriptive of vegetation and soil which will be used, such as Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI), Soil Adjusted Vegetation Index (SAVI) or Modified Soil Adjusted Vegetation Index (MSAVI). These indexes are widely adopted because they can monitor land changes globally. In fact, as reported by Mahamood et al. 2018 MSAVI is used to retrieve a relation between waste heaps and hazardous areas.
The false positives resulting from the regional analysis could be reduced by using geoprocessing with the ancillary data such as geo-environmental factors and the historical aerial photographs. As reported in Manzo et al. 2017, spatial filtering allows to generating maps of hazardous waste sites, which will be compared with ground truth-based maps of known contamination areas.

2.3 UAS

Daytime and night-time thermal UAS images will detect superficial thermal anomalies which will be registered as warning data.
Once distinguished warning areas by VHR remote sensed UAS are used, the drone will recognize the presence of potential contamination sources by using an integrated measurement system specifically equipped with different devices (optical and thermal cameras). The navigation system is based on waypoints; the semi-automatic navigation allows to access every area at different times and the acquisition of a larger series of information on wider areas.
In order to be able to distinguish sensitive areas through such collection of images, Deep Learning architectures are often considered successful approaches. Several studies on Deep Learning have proven that these architectures can solve visual tasks with human-level capability. Usually, they are used where remote sensing image analysis is involved, including object detection on images, scene classification, segmentation, and object-based image analysis. Convolutional Neural Networks (CNN), in particular, have been widely known as a powerful tool for massive photo processing, as they are able to recognize and classify landfill targets. In fact, given a substantial dataset which can act for training and testing, we are able to build predictive models which can account for both quantitative and qualitative aspects of classification and detection even in a landfill identification context. CNNs are especially functional for distinguishing several heterogeneous areas, which can uncover a wide variety of waste objects and disposal areas. Consequently, such approaches are also suitable for uncontrolled waste dumping issues, that cause serious problems for environmental, economic, and ecological backgrounds. According to Youme et al. 2021, for example, remote sensing is combined with a CNN structure aiming at building a model which can detect uncontrolled waste dumping with satisfactory results for uncovered areas through high spatial resolution UAV images.
The detection of waste disposal using UAS allows to manage remarkably high spatial resolution images (Youme et al. 2021) also by using a range of innovative applications of thermography to detect several illegal activities: illegal sanitary sewer and

storm-drain connections, illicit wastewater discharges, and other anomalies on surface waters can be easily identified using their thermal infrared signatures. It can also be used to detect illegal solid/liquid waste dumps or illicit air discharges Lega et al. 2014).

Following this approach, an NT8 – NEUTECH-AIRVISION® 9kg UAS is setup, combining different sensors (Figure 2). On the drone's gimbal, an RGB camera (GoPro Hero 7), a multispectral camera (Green, Red, NIR bands) (Tetracam ADC Lite) and a sensor platform consisting of electrochemical sensors (CO, NH_3 and H_2S) are combined. The electrochemical sensors' box is a reduced version of the UGV platform described below. Such sensor combination led to an optimal performance for UAS investigations. A thermal camera will be added to complete the drone setup to acquire a multiparametric data-frame with a single flight.

The RGB dataset will be used for photogrammetric purposes and volumetric computations but also to classify images related to waste classification of wastes.

Thermal imagery can be also suitable to aid such kind of analysis by considering differences in materials emissivity. Additionally, thermal, and multispectral images will be used to evaluate environmental issues of surrounding areas.

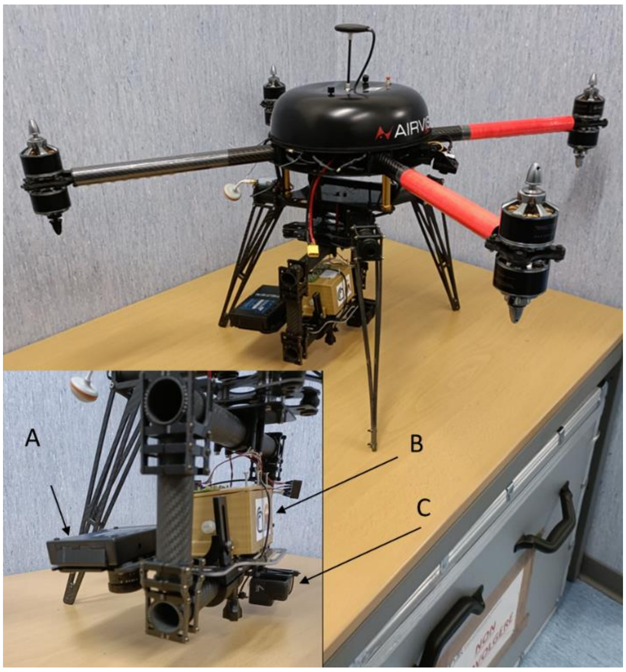

Figure 2. UAS setup: A) Multispectral camera, B) electrochemical sensor platform, C) GoPro Hero 7

2.4 UGV settings

In recent years low-cost sensors are used in various fields, increasing the generation of data for example in the field of environmental monitoring (Zampetti et al. 2020, Kulig et al. 2021). Among low-cost sensors, electrochemical sensors offer various peculiar characteristics such as: simplicity of use (with simple consumer electronics it is possible to obtain good performance), specificity, low cross- sensitivity with respect to humidity, good durability, wide range operativity (from a few ppb to tens of ppm) and low energy consumption, as they generate current when exposed to the compound (Li et al. 2023, Privett et al. 2010). The same trend of use and growth in demand on the sensor market has been seen by NDIR sensors for CO_2 measurement. This type of sensor is based on the classic atomic absorption of the CO_2 molecule in the infrared range. In fact, even if this technique has become well-known only in the last few years, there are very small sensors on the market capable of measuring CO_2 with good performance in terms of sensitivity and cross-sensitivity while retaining a low cost (Dinh et al. 2016). Finally, in the field of atmospheric monitoring of pollutants, the use of low-cost sensors for measuring suspended particulate matter (PMx) is increasingly widespread (Zampetti et al. 2017). For this task, the sensors that are used to equip the UGV are based on optical scattering and are known as optical particle counters (OPC) (Alfano et al. 2020). Although, OPCs are available on the consumer market at a very low cost, offering performances comparable to more expensive systems, because they do not directly measure the mass of the particulate, they show, in certain circumstances, a deviation from the values measured by conventional systems based on gravimetric methods. However, the information on dimension is increasingly used, at the expense of mass in the study of the correlation between human health and PM_x. For these reasons, we have developed a monitoring system on board the UGV based on these technologies and the block diagram is shown in Figure 3.

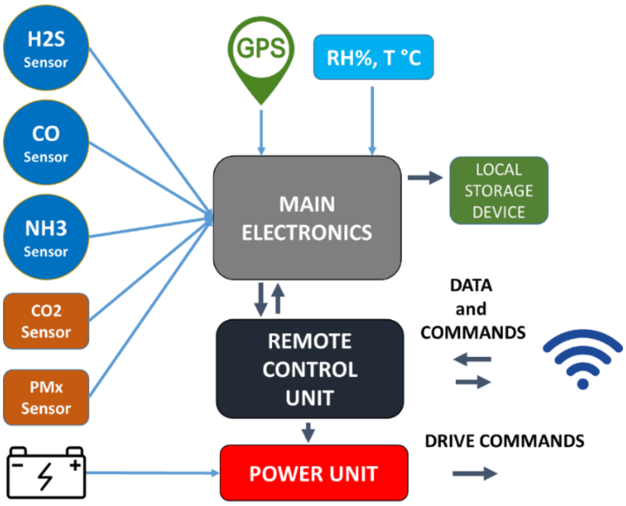

Figure 3. Blocks diagram of the developed sensors platform installed on UGV.

To monitor CO, NH_3 and H_2S, electrochemical sensors (by Alphasense) were used, an OPC (SDS011 by NOVA PM) was used to measure PMx and an NDIR sensor is used to measure CO_2 (COZIR). Suitable main electronics acquired the signal from the sensors and stored the data locally and adding the GPS position. The UGV was equipped with a remote control and a power unit to control the vehicle movements by following simple path patterns to the point of interest with a fixed velocity.

3. WASTE TO ENERGY IMPLICATIONS

Conceptually, circular economy aims to provide new life to something considered no more usable. In fact some NGOs, such as Zero Waste Europe (ZWE), affirm that "WtE does not have a place in the circular economy as the material loops are closed when 'there is nothing left to burn' " (Zero Waste Europe report 2016). For this reason, the European Commission clarifies the role of WtE in the circular economy, expressed that: "Waste-to-energy processes can play a role in the transition to a circular economy, provided that the EU waste hierarchy is used as a guiding principle and that choices made do not prevent higher

levels of prevention, reuse and recycling." (European Commission communication, 2017).
For the EU' objectives, separate collection and recycling capacity should be the priority and WtE must be applied when no more options except landfill are available.
From a waste management point of view, the European Commission stated that a great amount of secondary raw materials could be recovered from European waste streams: only the 43% of municipal waste is recycled, the rest landfilled (31%) or incinerated (26%) (European Commission proposal, 2015). Consequently, recycling and energy recovery must be increased. For illegally dumped or abandoned materials, WtE could be an interesting solution, since usually such kind of materials are mixed, degraded and not efficiently separable, so a very small fraction could be effectively recycled. Considering an average calorific value of 10 MJ/kg, the recoverable energy could be significant (Malinauskaite et al. 2017).
In recent years, several new technologies are in the process of being deployed to recover energy from waste streams. These technologies may be divided into three main groups based on the conversion process used: thermochemical, physicochemical (transesterification), and biochemical (fermentation, anaerobic digestion). Modern technologies of thermochemical conversion include high-efficiency combustion, pyrolysis (Czajczyńska et al. 2017, Chen et al. 2014) or gasification (Lombardi et al. 2015).
To sum up, WtE promotes a synergy of three EU policies: waste management, energy union, and environmental (climate change) policy. The connection of these policies helps the Member States to meet the EU targets especially in the context of resources and energy efficiency (Malinauskaite et al. 2017). The adoption of remote sensing technologies will improve the capacity to detect abandoned wastes and to retrieve effective information about quantities and a generalized waste commodity analysis to be used to evaluate WtE potentials.

4. RESULTS AND DISCUSSION

This research aims at presenting preliminary results of the on-going INTESA project which aim is to build a downscaling approach to identify areas with evidence of abandoned wastes and those sensitives to abandonment of wastes. The potential application of the downscaling system is mainly to set up a technological system to recognize abandoned waste sites with low cost and prompt procedures but also studying WtE potentials. Figure 4 presents the hierarchical scheme setup for abandoned waste identification and analysis in the framework of environment and circular economy.
The general output of this research is to create a semi-automatized procedure based on the integrated use of remote satellite and UAS/UGV dataset for the identification of areas concerned with environmental issues related to abandoned wastes.
Therefore, the general outputs can be summarized as follows:
1) Analytical procedure able to identify abandoned materials.
2) Development of an innovative sampling and monitoring system for pollutants emitted by the accumulations of materials which will be installed on a UGV and UAS. The devices will be used for short-range inspection in suspicious areas or areas indicated by the air/satellite system.
3) Creation of a register of the areas identified by the presence of abandoned material accumulation.
4) Creation of an app for smartphones that allows individual citizens to report the presence of abandoned waste.

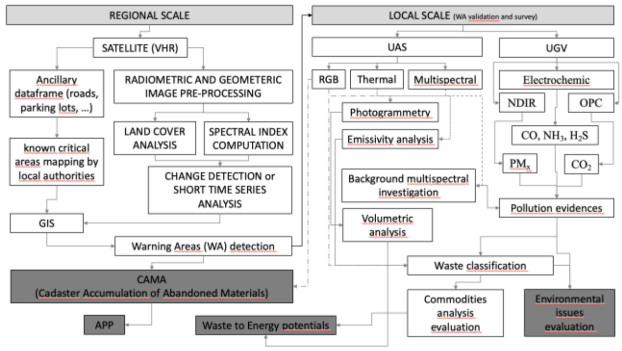

Figure 4. Downscaling procedure for INTESA Project

The assistance of a ground system that can monitor polluting compounds near the point of interest is of great relevance. This is usually done with portable or fixed systems, such as samplers or gas sniffer devices, necessitating to the employ of trained personnel (Daugela et al. 2015, Daugela et al. 2021). To reduce costs and any obstacle to inspection due to hazard, in this work we show the use of a terrestrial drone (UGV) equipped with an ad-hoc monitoring system for compounds emitted in landfills. The monitoring system uses low-cost sensors to measure and transmit data to a remote elaboration platform.
After the design and development phase of the monitoring system, several laboratory tests were performed to calibrate the sensors. In Figure 5 we report an example of the output of the H_2S sensor after the calibration activities.

https://doi.org/10.5194/isprs-archives-XLVIII-1-W1-2023-287-2023 | © Author(s) 2023. CC BY 4.0 License.

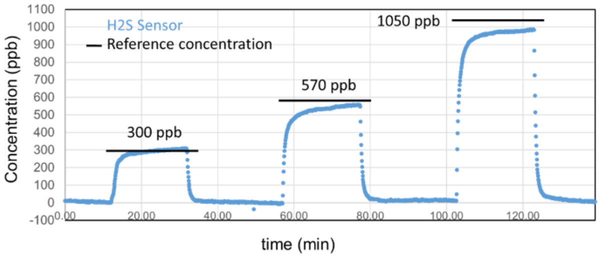

Figure 5. UGV and CO and H_2S sensors calibration

This procedure can provide both local and regional information which can help policy maker with determining the best way to manage the territory.

As reported by Li et al. 2020, the use of remote sensing technologies has different positive traits which can be used to improve the knowledge of the environment and to support institutions and policy makers. In this framework, the scientific impact of this research is linked to an innovative method to detect and describe environmental potential risks related to pollution. It is important to underline that currently there is no methodology capable of integrating multi-platform remote sensing data and chemical-environmental information that can be applied in a smart way.

However, even by using advanced technology we may still encounter some difficulties related to the lack of high-quality training images or the dependency of the training model on a specific geographical location. Nevertheless, the use of a multidisciplinary approach can improve the automation procedure for waste detection and the knowledge of the environmental conditions. Finally, the use of drones for environmental monitoring and waste classification can be considered a pioneering approach to support local authorities and to set new WtE market.

Funding: This Research is developed as a part of the "INtegrazione di sistemi di TElerilevamento e Sensoristica per l'individuazione di accumulo di materiali in Abbandono" – INTESA Project funded by the POR FESR-FSE CALABRIA 2014-2020 Program of Italy.

REFERENCES

Alberti, P. (2022). The 'land of fires': epidemiological research and public health policy during the waste crisis in Campania, Italy. *Heliyon*, e12331.

Alfano, B., Barretta, L., Del Giudice, A., De Vito, S., Di Francia, G., Esposito, E., ... & Polichetti, T. (2020). A review of low-cost particulate matter sensors from the developers' perspectives. *Sensors*, *20*(23), 6819.

Baiocchi, V., Napoleoni, Q., Tesei, M., Costantino, D., Andria, G., & Adamo, F. (2018, June). First tests of the altimetric and thermal accuracy of an UAV landfill survey. In *2018 5th IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)* (pp. 403-406). IEEE.

Bertollini, R., Faberi, M., Di Tanno, N., & World Health Organization. (1997). Ambiente e salute in Italia/a cura di Roberto Bertollini, Michele Faberi, Nicoletta Di Tanno. In *Ambiente e salute in Italia/a cura di Roberto Bertollini, Michele Faberi, Nicoletta Di Tanno*.

Chen, D., Yin, L., Wang, H., & He, P. (2014). Pyrolysis technologies for municipal solid waste: a review. Waste management, 34(12), 2466-2486.

Comba, P., & Pitimada, M. (2016). Studio epidemiologico dei siti contaminati della Calabria: obiettivi, metodologia, fattibilità. *Roma: Istituto Superiore di Sanità*.

Cusworth, D. H., Duren, R. M., Thorpe, A. K., Tseng, E., Thompson, D., Guha, A., ... & Miller, C. E. (2020). Using remote sensing to detect, validate, and quantify methane emissions from California solid waste operations. *Environmental Research Letters*, *15*(5), 054012.

Cusworth, D. H., Duren, R. M., Thorpe, A. K., Tseng, E., Thompson, D., Guha, A., ... & Miller, C. E. (2020). Using remote sensing to detect, validate, and quantify methane emissions from California solid waste operations. *Environmental Research Letters*, *15*(5), 054012.

Czajczyńska, D., Anguilano, L., Ghazal, H., Krzyżyńska, R., Reynolds, A. J., Spencer, N., & Jouhara, H. (2017). Potential of pyrolysis processes in the waste management sector. Thermal science and engineering progress, 3, 171-197.

Daugela, I., Suziedelyte Visockiene, J., Kumpiene, J., & Suzdalev, I. (2021). Measurements of flammable gas concentration in landfill areas with a low-cost sensor. Energies, 14(13), 3967.

Dinh, T. V., Choi, I. Y., Son, Y. S., & Kim, J. C. (2016). A review on non-dispersive infrared gas sensors: Improvement of sensor detection limit and interference correction. *Sensors and Actuators B: Chemical*, *231*, 529-538.

Europe, Zero Waste (2016). Harmful subsidies to waste-to-energy incineration. *Renew Energy Dir Bioenergy Sustain Policy*, 1-16.

European Commission. (2011). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Youth Opportunities Initiative. Brussels, Belgium: European Commission.

EUROPEAN COMMISSION. COM (2017). The role of waste-to-energy in the circular economy 34 final communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.26.1.2017.Brussels.

European Commission. Proposal for a directive of the European parliament and the council amending directive 2008/98/EC on waste, vol. 275; 2015.

Fay, C., Doherty, A. R., Beirne, S., Collins, F., Foley, C., Healy, J., ... & Diamond, D. (2011). Remote real-time monitoring of subsurface landfill gas migration. Sensors, 11(7), 6603-6628.

Glanville, K., & Chang, H. C. (2015). Remote sensing analysis techniques and sensor requirements to support the mapping of illegal domestic waste disposal sites in Queensland, Australia. *Remote Sensing*, *7*(10), 13053-13069. https://www.zerowasteeurope.eu/wp-content/uploads/2016/10/REcasestudy_final8.pdf

Ichinose, D., & Yamamoto, M. (2011). On the relationship between the provision of waste management service and illegal dumping. *Resource and energy economics*, *33*(1), 79-93.

ISPRA – Istituto Superiore per la Protezione e la Ricerca Ambientale. 2022. Rapporto rifiuti urbani. ISPRA Report 380/2022.

Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). *What a waste 2.0: a global snapshot of solid waste management to 2050*. World Bank Publications.

Kulig, A., Szyłak-Szydłowski, M., & Wiśniewska, M. (2021). Application of chemical sensors and olfactometry method in ecological audits of degraded areas. *Sensors*, *21*(18), 6190.

Lega, M., Ferrara, C., Persechino, G., & Bishop, P. (2014). Remote sensing in environmental police investigations: aerial platforms and an innovative application of thermography to detect several illegal activities. *Environmental monitoring and assessment*, *186*, 8291-8301.

Li, D., Sun, Y., Shi, Y., Wang, Z., Okeke, S., Yang, L., ... & Xiao, L. (2023). Structure evolution of air cathodes and their application in electrochemical sensor development and wastewater treatment. Science of The Total Environment, 161689.

Li, J., Pei, Y., Zhao, S., Xiao, R., Sang, X., & Zhang, C. (2020). A review of remote sensing for environmental monitoring in China. *Remote Sensing*, *12*(7), 1130.

Lombardi, L., Carnevale, E., & Corti, A. (2015). A review of technologies and performances of thermal treatment systems for energy recovery from waste. *Waste management*, *37*, 26-44.

Lu, A., Wang, J., Qin, X., Wang, K., Han, P., & Zhang, S. (2012). Multivariate and geostatistical analyses of the spatial distribution and origin of heavy metals in the agricultural soils in Shunyi, Beijing, China. *Science of the total environment*, *425*, 66-74.

Mahmood, K., Ul-Haq, Z., Faizi, F., & Batol, S. A. (2019). A comparison of satellite-based indices for hazard assessment of MSW open dumps using spatial analysis. *Waste Management & Research*, *37*(3), 219-236.

Malinauskaite, J., Jouhara, H., Czajczyńska, D., Stanchev, P., Katsou, E., Rostkowski, P., ... & Spencer, N. (2017). Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe. Energy, 141, 2013-2044.

Manzo, C., Mei, A., Zampetti, E., Bassani, C., Paciucci, L., & Manetti, P. (2017). Top-down approach from satellite to terrestrial rover application for environmental monitoring of landfills. Science of the Total Environment, 584, 1333-1348.

Mazza, A., Piscitelli, P., Neglia, C., Rosa, G. D., & Iannuzzi, L. (2015). Illegal dumping of toxic waste and its effect on human health in Campania, Italy. *International journal of environmental research and public health*, *12*(6), 6818-6831.

Muraoka, H., Ishii, R., Nagai, S., Suzuki, R., Motohka, T., Noda, H. M., ... & Muramatsu, K. (2012). Linking Remote Sensing and In Situ Ecosystem/Biodiversity Observations by "Satellite Ecology" In Situ/Remote Sensing Integration Working Group of J-BON. *The Biodiversity Observation Network in the Asia-Pacific region: Toward further development of monitoring*, 277-308.

Otwong, A., Jongmeewasin, S., & Phenrat, T. (2021). Legal obstacles for the circular economy in Thailand: Illegal dumping of recyclable hazardous industrial waste. *Journal of Cleaner Production*, *302*, 126969.

Privett, B. J., Shin, J. H., & Schoenfisch, M. H. (2010). Electrochemical sensors. *Analytical Chemistry*, *82*(12), 4723-4741.

Qaswar, M., Yiren, L., Jing, H., Kaillou, L., Mudasir, M., Zhenzhen, L., ... & Huimin, Z. (2020). Soil nutrients and heavy metal availability under long-term combined application of swine manure and synthetic fertilizers in acidic paddy soil. *Journal of Soils and Sediments*, *20*, 2093-2106.

Sellers, P. J. (1985). Canopy reflectance, photosynthesis and transpiration. *International journal of remote sensing*, *6*(8), 1335-1372.

Steenland, K., Bertazzi, P., Baccarelli, A., & Kogevinas, M. (2004). Dioxin revisited: developments since the 1997 IARC classification of dioxin as a human carcinogen. *Environmental health perspectives*, *112*(13), 1265-1268.

Torres, R. N., & Fraternali, P. (2023). AerialWaste dataset for landfill discovery in aerial and satellite images. *Scientific Data*, *10*(1), 63.

Triassi, M., Alfano, R., Illario, M., Nardone, A., Caporale, O., & Montuori, P. (2015). Environmental pollution from illegal waste disposal and health effects: A review on the "Triangle of Death". *International journal of environmental research and public health*, *12*(2), 1216-1236.

World Health Organization. (2013). Contaminated sites and health: Report of two WHO workshops: Syracuse, Italy, 18 November 2011 & Catania, Italy, 21-22 June 2012.- http://www.euro.who.int/__data/assets/pdf_file/0003/186240/e96843e.pdf?ua=1;

Youme, O., Bayet, T., Dembele, J. M., & Cambier, C. (2021). Deep learning and remote sensing: detection of dumping waste using UAV. *Procedia Computer Science*, *185*, 361-369.

Yusuf, R. O., Noor, Z. Z., Abba, A. H., Hassan, M. A. A., & Din, M. F. M. (2012). Methane emission by sectors: a comprehensive review of emission sources and mitigation methods. *Renewable and Sustainable Energy Reviews*, *16*(7), 5059-5070.

Zampetti, E., Macagnano, A., Papa, P., Bearzotti, A., Petracchini, F., Paciucci, L., & Pirrone, N. (2017). Exploitation of an integrated microheater on QCM sensor in particulate matter measurements. *Sensors and Actuators A: Physical*, *264*, 205-211.

Zampetti, E., Papa, P., Avossa, J., Bearzotti, A., Balducci, C., Tranfo, G., & Macagnano, A. (2020). Low-cost benzene toluene xylene measurement gas system based on the mini chromatographic cartridge. *Sensors*, *21*(1), 125.