Inspiring Great British Manufacturing

Report Title: **Problem Definition**

Version Number: 1.0

Project Title: Hyperspectral Imaging for Soils

Prepared For: Electricity North West

Author: Lauren Moore and Bethan Nye

Date: 20 May 2022

MTC Classification: Private - Commercial in Confidence

Executive Summary

The Environmental Agency (EA) Regulatory Position Statement (RPS) 211 applies to businesses that handle excavated waste from unplanned utilities installation and repair works. Under RPS211, small amounts of spoil from unplanned works can be disposed of or recycled as non-hazardous waste. Electricity North West (ENWL) and fellow utility organisations use this exemption to dispose of or recycle spoil which cannot be reused as backfill for thousands of emergency works activities across the UK each year.

RPS211 is currently under review, and is expected to be withdrawn in the near future. Withdrawal of this RPS would require companies such as ENWL to classify all of its waste. Without the ability to classify waste on-site, they will be forced to either dispose of all waste as hazardous, or sort and segregate waste at an off-site location. The Energy Innovation Centre has quoted an average disposal cost of £40 for 10 m^3 of non-hazardous spoil, and £1,200 for 10 m^3 of hazardous spoil, with additional costs depending on the type of waste.

ENWL therefore wishes to explore opportunities for technologies which can classify waste on-site. The MTC has offered Hyperspectral Imaging (HSI) as a potential solution and, working collaboratively with ENWL and an independent laboratory (pending advisement from ENWL), is looking to prove the technology as an option to address the problem statement.

The first phase of work aims to demonstrate a proof of concept in a laboratory environment, establishing key contaminants and required sensitivities, and trial selected HSI hardware in a laboratory environment with standardised contaminant samples. This report constitutes the first deliverable of this package of work, detailing inspection requirements. A brief summary of hyperspectral imaging and a description of the inspection problem are provided for context. Inspection requirements are defined in two subcategories: detection (e.g. sensitivity to each contaminant type) and practical (e.g. size and cost of hardware) criteria.

Contents

1 Introduction

1.1 Background

The Environmental Agency (EA) Regulatory Position Statement 211 (RPS211) applies to businesses that handle excavated waste from unplanned utilities installation and repair works. Under RPS211, small amounts of spoil (≤ 10 m^3, which is approx. 13 tonnes) from unplanned works can be disposed of or recycled as non-hazardous waste. Electricity North West (ENWL) and all fellow utility organisations use this exemption to dispose of or recycle spoil which cannot be reused as backfill for thousands of emergency works activities across the UK each year.

RPS211 is currently under review, and is expected to be withdrawn in the near future, with a phased withdrawal beginning in June 2022. Withdrawal of this RPS would require companies such as ENWL to classify all of its waste. Without the ability to classify waste on site, they will be forced to either dispose of all waste as hazardous, or sort and segregate waste at an offsite location. The Energy Innovation Centre has quoted an average disposal cost of £40 for 10 m^3 of non-hazardous spoil, and £1,200 for 10 m^3 of hazardous spoil, with additional costs depending on the type of waste.

ENWL therefore wishes to explore opportunities for technologies with can classify waste on site. The MTC has offered Hyperspectral Imaging (HSI) as a potential solution and, working collaboratively with ENWL and an independent laboratory such as Enviro-Lab (pending advisement from ENWL), is looking to prove the technology as an option to address the problem statement. Spoils should be tested for contaminants in line with *Technical Guidance WM3* [2].

The first phase of work aims to produce a proof of concept in a laboratory environment, establishing key contaminants, required sensitivities and trialling selected HSI hardware in a laboratory environment with standardised contaminant samples. This deliverable is the first of this package of work, detailing inspection requirements from both performance (e.g. what contaminants must be detected and at what sensitivity) and practical (e.g. size and cost of hardware) perspectives.

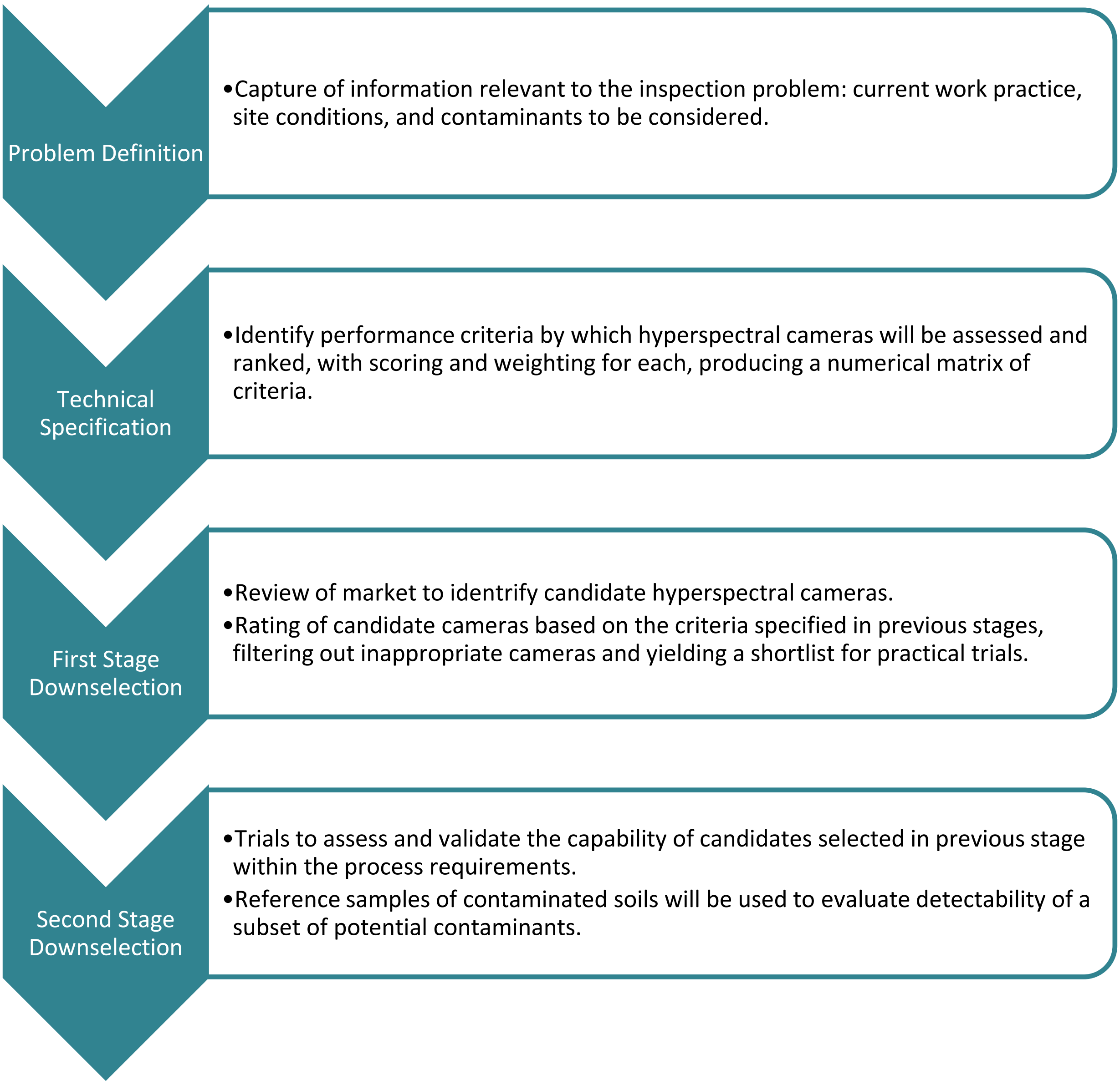
1.2 Objectives

Objectives of this report are:

- To summarise work site conditions as they pertain to contaminant detection.
- To define criteria for hardware downselection relating to:
    - Detection performance, e.g. various contaminant types and required sensitivities;
    - Practical aspects, e.g. cost, space requirements on site, ease of inspection.
- To list said criteria with scoring metrics and weighting, determined in collaboration with ENWL.

2 Downselection Process

The downselection process is used to quantify the suitability of candidate inspection systems for a specific inspection task, scoring each candidate against a number of technical requirements. Figure 1 outlines this process for this project – quantifying the suitability of hyperspectral cameras for detecting contaminants in spoil. This report concerns the first two stages, problem definition and technical specification. The first and second downselection stages will be undertaken in the second and third deliverables, respectively.



- Capture of information relevant to the inspection problem: current work practice, site conditions, and contaminants to be considered.

- Identify performance criteria by which hyperspectral cameras will be assessed and ranked, with scoring and weighting for each, producing a numerical matrix of criteria.

- Review of market to identrify candidate hyperspectral cameras.
- Rating of candidate cameras based on the criteria specified in previous stages, filtering out inappropriate cameras and yielding a shortlist for practical trials.

- Trials to assess and validate the capability of candidates selected in previous stage within the process requirements.
- Reference samples of contaminated soils will be used to evaluate detectability of a subset of potential contaminants.

Figure 1. Flowchart showing the downselection process undertaken during this project.

3 Hyperspectral Imaging

Conventional digital photography captures light in overlapping red-, green-, and blue-centred channels, as shown in Figure 2. While these channels are most sensitive to red, green, and blue light respectively, the full range of wavelengths (the “waveband”) each is sensitive to overlap significantly. This emulates the function of photoreceptors in the human eye and hence conventional digital images are similar to what can be perceived by humans.

Hyperspectral cameras, in comparison, capture light in many narrow wavebands with minimal overlap. Depending on the camera, c. 200–300 wavebands may be captured over a range 600–800 nm wide (for example, 300 wavebands in the range 400–1000 nm.) Hyperspectral cameras typically operate in visible (400–700 nm) and infrared (700 nm – 1 mm) ranges. Infrared imaging may be subdivided into short-wave (SWIR, or near-infrared), medium-wave (MWIR), or long-wave (LWIR, or far-infrared), though the boundaries between these divisions are not strictly defined.

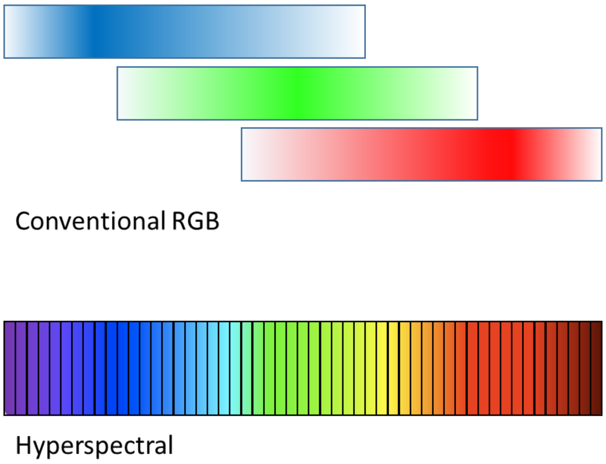


Figure 2: Illustration comparing light-sensitive channels in conventional RGB (top) and hyperspectral (bottom) cameras.

Capturing many narrow wavebands and sensitivity to infrared wavelengths allow hyperspectral cameras to capture information unavailable to conventional digital cameras (and hence conventional machine vision) and to the human eye. In particular, hyperspectral imaging can measure the subject’s *reflectance spectrum*, the proportion of incident light reflected with respect to wavelength. Beyond what colours are visible to the human eye, these spectra contain characteristic features that correspond to the subject’s chemical composition.

This capability is what makes hyperspectral imaging a promising technique for this application; providing a rapid, non-contact method to identify materials. Hyperspectral imaging has already found applications in a range of fields that exploit this capability including in the food and drink sector, agriculture and mining, and recycling.

The reflectance spectrum of a material is dependent on its chemical and structural composition, with photos being scattered and absorbed at the material’s surface (or even penetrating it). For a mixture of two or more materials (e.g. soil and a contaminant), the mixture’s reflectance spectrum will be a combination of the reflectance spectra of each component. The most significant factor in this combination is surface area [2]. This is proportionate to each material's relative abundance by weight/volume, but also dependent on the grain size (or equivalent) of each material. As grain size increases, the surface area for a given volume of material decreases, and hence it has less contribution to the mixture's reflectance spectrum. An example of this relationship is illustrated in Figure 3. The spectrum of a pure material is also affected by grain size, affecting the relative size of different absorption features [3].

Estimation of a contaminant's abundance is therefore non-trivial. The relationship between relative abundance and overall reflectance can however be determined empirically from measurements of mixtures of known composition. From these observations, it is possible to predict material abundances while compensating for grain size [4].

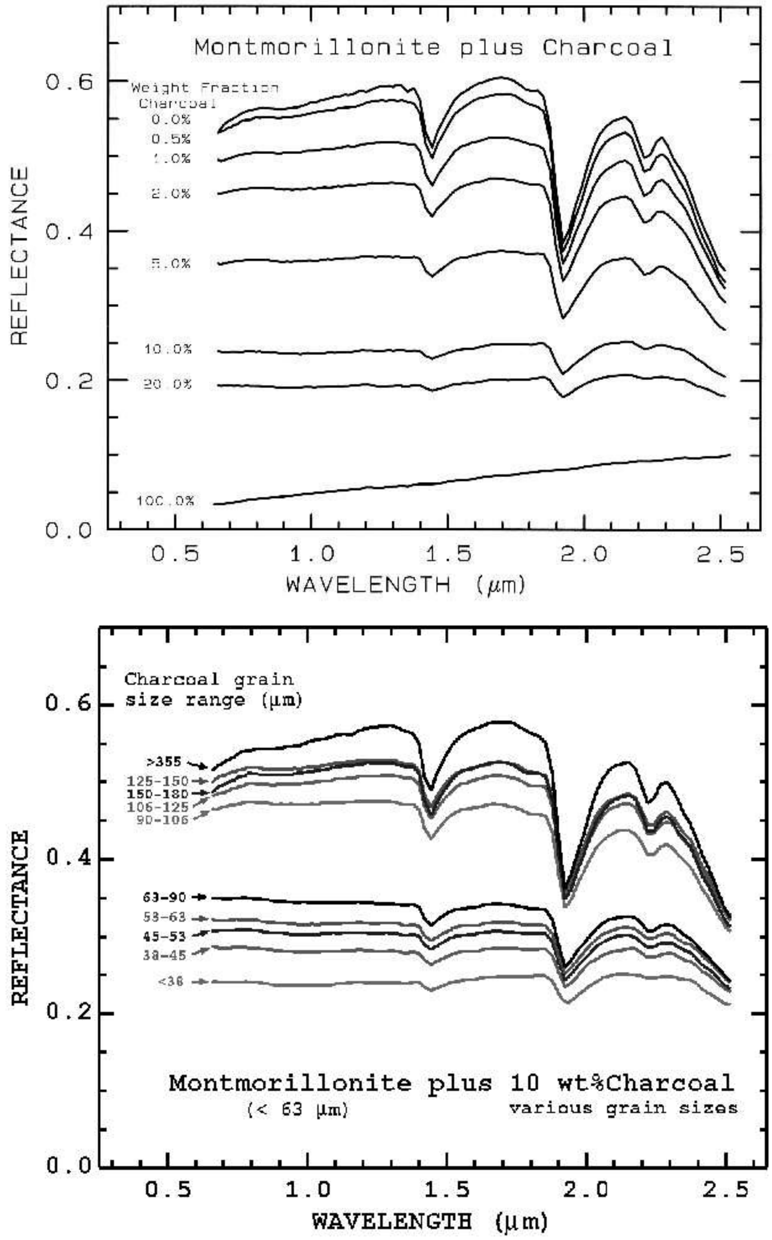


Figure 3: Reflectance spectra of mixtures of montmorillonite clay and charcoal, for differing abundance of charcoal with fixed grain size (top) and fixed abundance and differing grain size (bottom). From [2].

4 Problem Definition

4.1 Site Conditions

Work conditions vary, with works conducted on both footways and carriageways themselves. Figure 4, shows photos of example works, with one approximately 5 × 2 m in area, though some works are much smaller. The area is cordoned off with barriers, but the spoil is left unsheltered, meaning that the testing area and the water saturation of the soil will vary depending on the recent weather conditions. The cordoned-off area usually does not have much extra space within the boundary itself, meaning that the available area for set up and testing is likely to be small. When excavating the site, the surface asphalt is removed first and set aside, and the soil is then dug out. It is probable that some asphalt will be collected in the soil during this excavation, and other foreign materials such as rock, brick, and litter may also be mixed in with the soil. In addition, the soil composition can vary, based on location [1].

Figure 4: Photos of example ENWL roadside work sites. One (left) has an excavation across most of the footpath with spoil deposited on one lane of the road. The other (right) is constrained to half the width of the footpath. Both are exposed to the elements, with minimal space between barriers, excavation, and spoil.

The standard work light available is the battery-powered Milwaukee M18 SAL LED Stand Light, which has a maximum light output of 2000 Lumens. At this output, the maximum run time on the battery is 4 hours. At the lowest output of 850 Lumens, the run time on the battery is 10 hours. It is not a definite that a work van will be available at every dig site, but if there is, then a 240V power supply is able to be used.

4.2 Contaminants

ENWL have identified total petroleum hydrocarbons (TPH), coal tar, asbestos, and heavy metals as contaminants of interest, with guidance for assessment of spoil with said contaminants given in *Technical Guidance WM3* [2] and *Excavation Arisings Sampling Plan* [3]. Of heavy metals, arsenic, cadmium, chromium, copper, lead, mercury, selenium, and zinc are to be considered. While not all of these contaminants may be suitable for trials later in this project, all are to be considered for selection of candidate technologies.

4.3 Non-Contaminant Materials

In addition to contaminants (see above), the system should be able to distinguish materials that are neither contaminant nor soil, in particular asphalt (from the road surface) and litter (for example, plastic bottles). It may also be desirable for the system to be able to identify soil types (e.g. soil texture and organic material) and the level of water content, which will affect the spectra of both contaminated and non-contaminated spoil. If these variations cannot be accounted for, false results (false positives or negatives) may be produced.

5 Technical Specification

The criteria for downselection are grouped into two categories, detection performance and practical considerations, described in sub-sections below. In downselection, scoring and weighting are defined for each criterion, with each candidate technology/system scored accordingly. Scores will be reported separately for each category; weighting is not assigned to each category as a whole.

In first-stage downselection (Deliverable 2), candidates will be scored according to manufacturer's materials (e.g. technical specifications). These will therefore reflect what each is capable of detecting (based on reference spectra and literature), but do not confirm that the contaminant is detectable within spoil, nor evaluate the sensitivity of such detection. Concentration and distribution of the contaminant, along with other materials in the sample, will affect practical performance. A number of these factors will be evaluated in laboratory trials during Deliverable 3.

5.1 Detection

Detection criteria concern the (nominal) suitability of the camera to detect and distinguish potential contaminants, other foreign bodies, and soil type. These are listed in Table 1. The scoring is identical for each criterion, on the principle that each material (or group of materials) will be identifiable from one or more spectral features in the visible–infrared range. To identify these materials, these spectral features must lie within the range that the hyperspectral camera is sensitive to.

Multiple, resolvable, characteristic features within a camera's range are preferable for greater sensitivity and confidence in classification, and cameras will be scored higher where this is a case. Generally, cameras are less sensitive to wavelengths at the extremes of their range, in which case they will be scored lower for a given material.

Which features are resolvable (in ideal conditions) depends on the camera's spectral resolution. While a camera with (for example) 300 channels in the spectral range of 400–1000 nm may have a spectral sampling of 2 nm per channel, channels typically have some sensitivity to wavelengths outside of their nominal width, e.g. a spectral resolution of 4 nm. Finer resolution is preferable, but is not included as a separate criterion. Generally, cameras have greater spectral sampling and resolution at longer wavelengths. Spectral sampling and resolution will be considered in whether cameras are able to resolve characteristic features for each contaminant.

Table 1: Summary of detection downselection criteria.

Criterion	Summary	Scoring	Weight
TPH	Ability to detect total petroleum hydrocarbons (TPH).	5 – Multiple characteristic spectral features resolvable in camera's spectral range. 4 – As (5), but one or more in less-sensitive range. 3 – Single resolvable characteristic feature in range. 2 – As (3), but feature in less-sensitive range. 0 – No resolvable characteristic features in range.	9
Coal Tar	Ability to detect coal tar.		9
Asbestos	Ability to detect asbestos.		9
Arsenic	For each heavy metal: ability to detect heavy metal and/or its compounds.		1
Cadmium			1
Chromium			1
Copper			1
Lead			1
Mercury			1
Nickel			1
Selenium			1
Zinc			1
Asphalt	Ability to detect asphalt.		3
Litter	Ability to detect litter (e.g. plastics).		3
Water	Ability to infer water content, if it may affect contaminant detection.		6
Soil Types	Ability to distinguish soil textures (proportion of sand, clay, loam).		9

Weighting

ENWL reported that all contaminant types are an equal priority, and so they have each been given equal weighting within the detection category. The weighting for heavy metals has been divided amongst the nine specific elements considered. As soil type may influence the detectability of specific contaminants, it has been given the same weighting.

5.1.1 Total Petroleum Hydrocarbons

Petroleum hydrocarbons are hydrocarbons (compounds containing only carbon and hydrogen) found in crude oil. Total petroleum hydrocarbons (TPH) refers to any mixture of these between C_6 and C_{40} (petroleum hydrocarbons with between 6 and 40 carbon atoms per molecule). Detection of TPHs is potentially challenging, given spectral similarity to benign materials such as mineral substrates in soil [4], though detection has been found possible with spectral features in the 1200–2400 nm range.

5.1.2 Coal Tar

Coal tar is a mixture of hydrocarbons produced from pyrolysis of coal, containing thousands of chemicals and with specific composition depending on the coal it is produced from. Many constituent compounds are carcinogenic, and benzo[a]pyrene (BaP) is used as a marker for carcinogenicity of the whole, relative to the total concentration of coal tar in spoil [2]. In the worst case, BaP concentration above 50 ppm indicates a hazardous concentration of coal tar.

For some works, coal tar may be removable alongside asphalt layers above, with coal tar materials being used within binder course layers.

Due to its complex composition, coal tar is likely to challenging to detect as a whole mixture. It is expected that detection of coal tar is best achieved through the detection of marker chemicals such as BaP for which the reflectance spectra are known (see **Error! Reference source not found.**, below) [5].

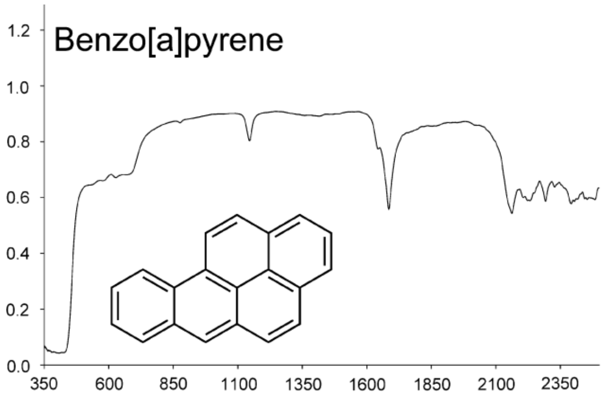


Figure 5: Reflectance spectra of benzo[a]pyrene with chemical structure inset. *x*-axis: wavelength (nm); *y*-axis: absolute reflectance (dimensionless). From [5].

5.1.3 Asbestos

Classification of asbestos-containing waste as hazardous considers both the presence and form of asbestos, i.e. whether is free fibres of asbestos-containing material. Fibres are typically on the order of 3 µm or less in diameter, and hence hyperspectral imaging may not be able to distinguish between the two. Waste classification does not distinguish between forms of asbestos [2, p. 19], but asbestos may be one of six different materials. While these vary in chemical composition, shown in Table 2, the amphibole minerals have an inosilicate $Si_8O_{22}(OH)_2$ group, though this is shared by some non-asbestos materials. Chrysotile as a characteristic feature at 1383 nm, and amphiboles a similar feature at 1393 nm [6].

Table 2: Chemical formulae of asbestos minerals.

Mineral	Chemical Formula	Group
Chrysotile	$Mg_3Si_2O_5(OH)_4$	serpentine
Actinolite	$Ca_2(Mg,Fe^{2+})_5Si_8O_{22}(OH)_2$	amphibole
Amosite	$(Mg,Fe^{2+})_7Si_8O_{22}(OH)_2$	amphibole
Anthophyllite	$(Mg,Fe2+)_7Si_8O_{22}(OH)_2$	amphibole
Crocidolite	$Na_2(Fe^{2+}{}_3Fe^{3+}{}_2)\ Si_8O_{22}(OH)_2$	amphibole

Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$	amphibole

5.1.4 Heavy Metals

With respect to waste classification, heavy metals are antimony, arsenic, cadmium, chromium (VI), copper, lead, mercury, nickel, selenium, tellurium, thallium, and tin, in either compounds or metallic form. Not all were stated as contaminants of interest by ENWL, who also requested zinc and its compounds be considered. While reflectance spectra depend on both metal element and specific compounds, common spectral features have been identified for some in the region 1000–2400 nm (SWIR) [7].

5.1.5 Asphalt

While asphalt is generally separated from soil during excavation, it is anticipated that some quantity will be deposited in spoil. The presence of asphalt may detection of TPH and coal tar, having similar composition (potentially including detectable quantities of each).

5.1.6 Litter

Litter may be blown into piles of spoil or dropped by passers-by. It is unlikely to be practical to detect specific materials (e.g. PET bottles) due to the large variety (though hyperspectral imaging is used in recycling to discriminate types of plastic, etc.) but it may be necessary for the inspection system to identify and flag foreign objects not identifiable as any other material of interest.

5.1.7 Water

Water broadly absorbs visible and infrared light, and hence wetter materials have suppressed reflectance [8]. This suppression may be inferred from hyperspectral images (as it is consistent with the absorption spectrum of water), or determined from independent measurements of water content in spoil. As water suppresses reflectance, it has a negative impact on inspection sensitivity (reducing signal to noise).

5.1.8 Soil Type

The reflectance spectra of uncontaminated soil will vary based on its own composition. A common classification of soil types is soil *texture*, determined by relative quantities of sand, clay, and loam (see Figure 6) [9]. Soil types vary further based on factors such as organic matter, pH, and drainage. Soil types may be referenced from regional maps (for example, see [1] for England and Wales), though infill under roads and pavements may not be the same as typical local soil. Characteristic features for organic matter detection and soil texture classification have been found in the visible–SWIR range [10, 11, 12].

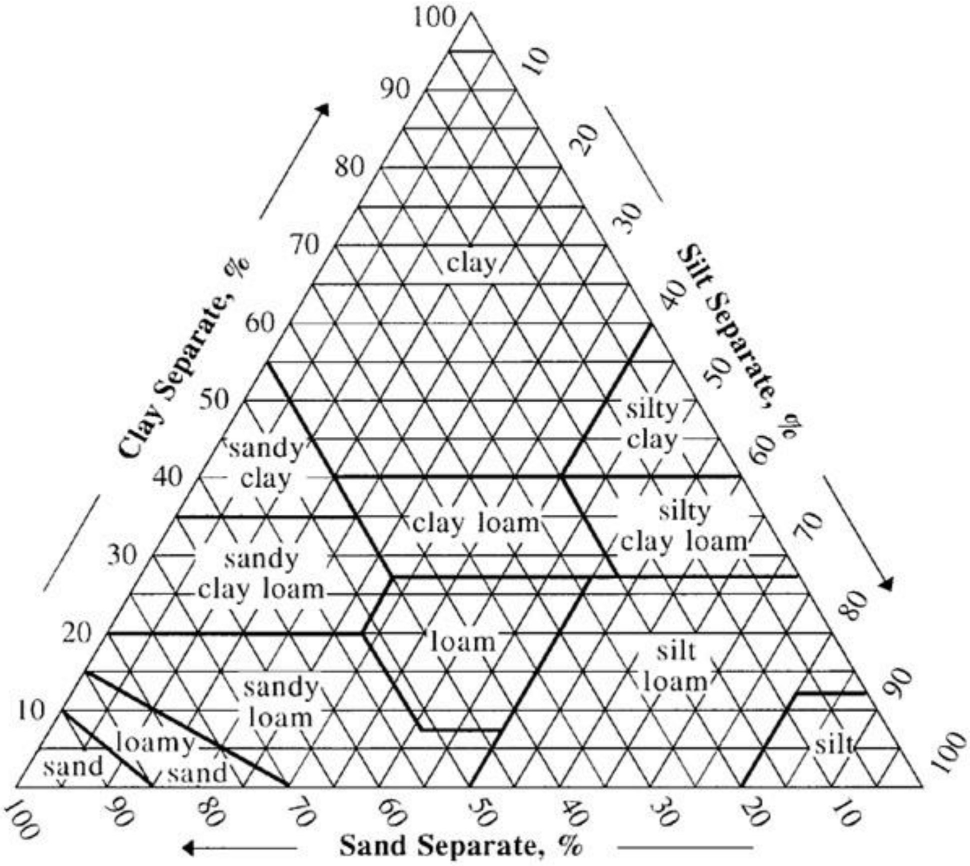


Figure 6: Diagram of soil textures, dependent on clay, silt, and sand proportions. From [9].

5.2 Practical

Practical criteria are summarised in Table 3 and detailed below. These criteria are those not directly related to the hyperspectral camera's sensitivity to various materials but relate to practicality of the camera system for inspection at ENWL's work sites.

Table 3: Summary of practical downselection criteria.

Criterion	Summary	Scoring	Weight
Cost	Cost to acquire camera (not including peripheral hardware).	5 - <£200 3 - £200–2,000 1 - £2,001–3,000 0 - >£3,000	5
Bulk	Size and weight of camera (with respect to portability and handling).	5 - Smaller than work light. 4 - Similar size to light. 3 - Larger, but can be carrier by one person. 2 - Requires two people to carry. 1 - Requires entire van to transport. 0 - Exceeds van's capacity.	7
Weatherproofing	Protection from elements (i.e. dust and rain).	5 - Camera has rating of IP55 or higher. 4 - Optional housing, rated IP55 or higher. 1 - Unsuited to outdoor use.	7
Durability	Protection from physical impact (e.g. from system being dropped.	5 - Can withstand drops of ≥2 m. 4 - Durable housing available. 3 - Can withstand drops of 1–2 m. 2 - Bespoke housing required. 1 - No protection.	7
Power	Power supply required to operate camera. Van *may* be on site with 240 V supply, generators not on site as standard.	5 - Battery, single required for full shift, 50% duty cycle. 4 - Battery, multiple required for shift. 2 - 240 V supply from van.	7

		0 - 240 V supply insufficient.	
Frame Rate	Higher frame rates allow greater throughput/faster inspection and/or greater spatial resolution in one axis (for 1D cameras).	Relative to best/worst among candidates.	3
Angular Resolution	Spatial resolution in second axis dependent on angular resolution, field of view, and standoff distance. May be specified in one or two axes, depending on camera type.	Relative to best/worst among candidates.	3
Ease of Use (Software)	Ease of use of system by operator, including set up, from perspective of inspection system software (data acquisition, processing, and interpretation).	5 - Intuitive interface. 3 - Some background knowledge required. 1 - Specialist knowledge/training required.	7
Ease of Use (Hardware)	Ease of use of system by operator, including set up, from perspective of hardware (e.g. manual handling), and considering PPE (e.g. gloves).	5 - Requires single operator, no hindrance from PPE. 3 - Requires multiple operators OR difficult with PPE. 1 - Multiple operators AND difficult with PPE.	7
Time for Set-Up	Time required to set up system on site before use, and time to take down after. Potentially includes time to reposition.	5 - <15 minutes 3 - < 1 hour 0 - > 1 day	5
Lighting	Whether camera requires specialist lighting, or may be used with sunlight and/or standard work lights.	5 - Suitable for standard work lights. 3 - Specialist lighting OR sunlight. 0 - Specialist lighting only.	7
Spectral Range	Range of wavelengths detected. Most relevant to detectability of various contaminants, and so reflected in scoring of those criteria.	n/a - Reflected in scoring of Detection criteria.	0
Number of Bands /Spectral Spacing	Number of bands (channels) within spectral range, and resultant spectral spacing.		
Spectral Resolution	Range of wavelengths each band is sensitive to.		

5.2.1 Cost

ENWL anticipates a large number of cameras being purchased, with an ideal cost of £200 per unit, and a maximum of £3,000. It is anticipated that some camera costs may be higher, however.

5.2.2 Bulk

As the camera will be transported via car or work van, alongside existing equipment, and must be set up by hand, there are practical constraints on the size and weight of the camera system. The standard work lights (Milwaukee M18 SAL LED stand lights) have been nominated as an acceptable size and weight. These lights have an integrated telescopic stand and are 1100 × 240 × 230 mm while stowed, with a weight of 7.7 kg. Lighting and computer for processing results (e.g. a generic laptop) are not included in this criterion unless specific hardware is required and/or integrated with the camera.

5.2.3 Weatherproofing

Due to the variation in weather expected in the UK, it is recommended that equipment have an *Ingress Protection* rating of IP55 or higher. The first ‘5’ indicates protection from dust, and the second ‘5’ indicates protection from low-pressure water jets [10]. This rating should be sufficient for the worst reasonable case, though imaging should not be undertaken during rain. Where a camera is not intrinsically weatherproofed, the potential for additional protection (whether from the manufacturer or a third party) is considered.

5.2.4 Durability

The camera should be able to withstand physical damage on the work site, including drops from height onto hard and uneven ground. This includes damage which, while not preventing damage from functioning, may affect the calibration and hence performance of the camera (which may not be apparent to the operator).

5.2.5 Power

Potential power sources for the camera could be from a battery, a mains power supply, or an industrial power supply. Due to the nature of ENWL’s works, hand tools are generally used and hence generators are not present on site. Work vans have a mains-equivalent power supply. While work vans are not always present on site, this may be an acceptable power requirement given work vans are already anticipated to be required in transporting cameras (and peripheral equipment) to each site. However, even where present, work vans may not be adjacent to works. As such, battery-operated cameras are preferable for independent operation, though battery life and charging time may be a limiting factor.

Power requirements of dedicated lighting (if required) are not considered in this criterion.

5.2.6 Frame Rate and Angular Resolution

Frame rate and angular resolution are separate criteria, but both have a similar impact on inspection. All else being equal, a higher frame rate allows more spoil to be imaged in a given time and/or for a given amount of spoil to be imaged with finer spatial resolution. Similarly, a higher angular resolution allows a greater amount of spoil to be imaged at once, or for a given amount of spoil to be imaged with finer spatial resolution. It is not expected that any candidate hyperspectral cameras will have inappropriate frame rate or angular resolution, and hence candidates will be scored according to best and worst among candidates, and with low weighting.

The frame rate criterion anticipates a line-scan camera, which is common for industrial and research hyperspectral imaging. Such a camera images a single spatial axis at a time, with the other spatial axis created by the relative motion of camera and subject. Other hyperspectral cameras capture a 2D scene similar to a conventional digital camera (either capturing different wavelengths over time, or scanning across a fixed field of view) with both camera and subject stationary. Dividing the size of the second axis (e.g. 640 pixels) by acquisition time (e.g. 100 seconds) gives a “frame rate” equivalent to line-scan cameras (e.g. 6.4 fps).

Acquisition time – and hence frame rate – is dependent on lighting intensity. Nominal maximum frame rates (i.e. with maximal lighting) will be reported based on manufacturer’s specifications; practical frame rates may be lower. Some cameras support higher frame rates with fewer (not necessarily consecutive) wavebands being captured. This will be noted in the downselection matrix but does not affect scoring.

5.2.7 Ease of Use

The hyperspectral imaging system may be operated by various ENWL personnel, and so should be accessible to a user without specialised training. Intuitive systems preferred for data acquisition, processing, and presentation/interpretation of results should not require expert knowledge. Presence or absence of contaminants should be clear to the user, though this consideration may depend on software implemented rather than the camera itself.

People that will be undertaking the testing will be wearing appropriate PPE, so all related devices should be able to be set up and used while someone is wearing PPE (gloves in particular). Ideally the system should require only a single operator for both set-up and use.

5.2.8 Time for Set-Up

Given the impromptu nature and large number of works, the hyperspectral camera system should require minimal time to set up and take down before and after each inspection. Depending on how the system is used, it may need to be set up and taken down multiple times at a given work site, but scoring will be based only on a single incidence.

Note that whether set-up requires multiple personnel is covered in Ease of Use (Hardware).

5.2.9 Lighting

The quality of hyperspectral imagine is dependent on both camera and lighting. A blackbody (such as the sun) is ideal, though a relatively-uniform emission of light over the spectral range of the camera is generally sufficient. While inspection is to take place outdoors, it is not safe to assume natural sunlight will always be sufficient. If artificial lighting is required, the standard LED work lights are preferred to dedicated lighting for the hyperspectral camera. While white LEDs have a reasonably broad emission spectrum in visible light, they have little emission in infrared – advantageous for humans and energy consumption, but unsuitable for infrared hyperspectral imaging. As such, cameras operating in the infrared region are likely to require dedicated lighting (such as halogen lamps). The power requirements of such lighting are not considered in this downselection.

5.2.10 Spectral Range, Sampling, and Resolution

Spectral range, sampling, and resolution all affect the characteristic features of materials that the camera is able to capture and resolve, and hence is reflected in detection criteria (see §0 –

Detection). These will be captured in the downselection matrix for reference only.

Spectral range is the range of wavelengths to which the camera is sensitive, spectral sampling is the nominal width of each channel within that range, and spectral resolution is the range of wavelengths to which each channel is sensitive.

For example, a camera may have a spectral range of 400 – 1000 nm, 300 bands and hence a spectral sampling of 2 nm, and a spectral resolution of 4 nm.

6 Following Work

This problem definition informs the downselection matrix (see Table 1 and Table 3) than will be used to quantify the suitability of candidate hyperspectral cameras in the next deliverable of this project, D2 – *First Stage Downselection*, and revised following trials in D3 – *Second Stage Downselection*. Nominal scoring and criterion weighting have been decided in conversation with ENWL, but may be revised if additional considerations are identified in reviewing available hyperspectral cameras or in trials (again in agreement with ENWL).

The weighting of contaminant detection criteria will also be used to inform selection of reference soil materials for practical trials in D3. Other considerations are anticipated detectability and similarity of characteristic features to other contaminants, to get a broad view of contaminant detection with a finite number of reference materials. Health and safety will also be considered, which may have additional requirements for, or prohibit, use of some contaminants.

7 References

[1] Cranfield Soil and Agrifood Institute, “Soilscapes Map,” [Online]. Available: http://www.landis.org.uk/soilscapes/. [Accessed May 2022].

[2] Natural Resources Wales, Scottish Environment Protection Agency, Environment Agency, “Guidance on the Classification and Assessment of Waste,” 1st Edition v1.2.GB, Technical Guidance WM3, 2021.

[3] Street Works UK, “Excavation Arisings Sampling Plan”.

[4] R. D. M. Scafutto, C. R. d. S. Filho and W. J. de Oliveira, “Hyperspectral Remote Sensing Detection of Petroleum Hydrocarbons in Mixtures with Mineral Substrates: Implications for Onshore Exploration and Monitoring,” *ISPRS Journal of Photogrammetry and Remote Sensing,* vol. 128, pp. 146-157, 2017.

[5] M. R. M. Izawa, D. M. Applin, L. Norman and E. A. Cloutis, “Reflectance Spectroscopy (350-2500 nm) of solid-state polycyclic aromatic hydrocrabons (PAHs),” *Icarus,* vol. 237, pp. 159-181, 2014.

[6] R. Clark, T. Hoefen, G. Swayze, K. E. Livo, G. Meeker, S. Sutley, S. Wilson, I. Brownfield and J. S. Vance, “Reflectance Spectroscopy as a Rapid Assessment Tool for the Detection of Amphiboles from the Libby, Montana Region,” U.S. Department of the Interior, U.S. Geological Survey, Open-File Report 03-218, 2003.

[7] Y. Jeong, J. Yu, L. Wang and K.-J. Lee, “Bulk Scanning Method of a Heavy Metal Concentration in Tailings of a Gold Mine using SWIR Hyperspectral Imaging System,” *International Journal of Applied Earth Observations and Geoinformation,* vol. 102, no. 102382, 2021.

[8] J. Levy, A. Nolin, A. Fountain and J. Head, “Hyperspectral Measurements of Wet, Dry, and Saline Soils from the McMurdo Dry Valleys: Soil Moisture Properties from Remote Sensing,” *Antarctic Science,* vol. 26, no. 5, pp. 565-572, 2014.

[9] United States Department of Agriculture, “Soil Taxonomy - a Basic System of Soil Classification for Making and Interpreting Soil Surveys,” Natural Resources Conservation Service, 1999.

[10] IEC, “IP Ratings,” [Online]. Available: https://www.iec.ch/ip-ratings. [Accessed 3 May 2022].