Advanced Mineral Resources Development: MSc Thesis

Investigation into the utilisation and exploitation of abandoned mining areas, with a recommended plan for remediation and subsequent use of the New Mill Site, Roseworthy, Cornwall, UK

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Declaration of Authorship

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet."

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Abstract

The usage of remediated mine sites is common around the World. Such is the ubiquity of these sites that local residents may often be unaware of their proximity to a former mine site. Especially if sufficient time has passed and/or if the remediation process was carried out in a highly effective manner. The process of remediating disused mine sites can be approached in a number of different ways and the methods will vary depending on a number of different factors, chief among which are economical and geographic. As a result, different countries will also vary their methods of remediation to accommodate these different factors. Many countries now have adopted far more sustainable methods of remediation in keeping with GSR principles. Previously China relied primarily on mechanical excavation in order to remediate its former mining areas due to the low cost of the operation. Now however, the country has made more investment into more sustainable methods, including the commonly used technique of combining multiple methods to accommodate the different characteristics of a mine area. This technique has been used in other parts of the World such as Europe and the USA with great success having been introduced in recent decades. This investigation has analysed the differences between different countries remediation methods and the factors that affect these differences as well as the different remediation methods themselves. In addition, the contamination site of Roseworthy, Cornwall, UK has been used as a hypothetical case study to recommend a remediation plan and subsequent reuse of the land. This area has been found to contain highly elevated levels of arsenic in the sub-soil due to the previous use of the site as an As processing facility. There are plumes of contamination in three major spots, upstream and downstream of the calciner in the NE and around the stack in the centre west of the site. This investigation has recommended the more highly contaminated area downstream of the calciner should undergo encapsulation to prevent mobilisation of the concentrated As and the remaining contamination should undergo mechanical excavation and reuse as aggregate material in construction. This investigation then goes on to recommend the subsequent reuse of the Roseworthy site for environmental monitoring undertaken by the nearby Camborne School of Mines (CSM) as an academic asset. Sampling of the area every three months would provide a representative image of how the contamination is spreading through the area in reaction to the remediation efforts. In particular focus on the encapsulated section of contamination as this area is the most potentially harmful to the environment and is proximal to the water system.

Keywords: Abandoned Mining Areas, Remediation, Reutilisation, Legislation, Roseworthy (Cornwall)

Contents

Introduction

Due to the international nature of mine workings and the fluctuating economic nature of the mining industry, there remain large numbers of abandoned or mothballed mine works around the world. Likewise, there are mine works which are no longer profitable and will need to be closed down within the near future. Not only will they pose issues relating to economic degradation but also contamination of the immediate area. The question therefore arises as to what use these former mine areas and soon-to-be former mine areas may have. There exist mine workings in the world which have been able to repurpose themselves as part of another venture, such as in tourism or for academic disciplines. An example of this can be seen in the various mine workings which are now used as academic tools for use in mining universities. This allows students to gain experience within a mine working environment whilst completing their studies, an invaluable asset to an academic organisation. This paper will seek to investigate to what extent former mining areas around the world can be revitalised for uses in a post-mining economy after their use in mining activity has been exhausted. This paper will also investigate the different types of ventures that these former mines can be used for.

It is possible to know when a mine will close down. Thanks to resource evaluation and feasibility studies before and during the mine is under operation. However, this can change when new resources are discovered or the economic status of an industry changes. The investigation will look at the process by which former mining areas are revitalised and converted into areas which benefit the local community and potential investors while also looking at the issues associated with this process. The paper will also look at the differing approaches between different nations in their attempt to complete this revitalisation and the reasons behind these differences. The different types of revitalised mine will also be investigated, as mines can be revitalised to form businesses in the tourism industry, for academic disciplines or others.

An example of a former mine which has been converted to a tourism venture is Geevor Mine in Cornwall, UK. With the mine ceasing operation in 1990, the area has since been designated a UNESCO World Heritage Site and is now open to tourists after having been converted into a museum.

As mentioned before, there are examples of former mines which have been converted for use in academic disciplines such as the example of the former Reiche Zeche silver mine currently owned and used by TU Bergakademie Freiberg, Germany. With the university specialising in the field of mining engineering, this disused silver mine is used by the University for use in educating it's students and providing practical experience of working in a mine during their studies.

These examples show that former mining areas can not only be remediated and made safe but can also be used to produce profit or at least recover the money lost during their decommissioning. Remediation is a question of whether a large enough danger is posed to the immediate environment. However, the question of whether to commence with operating a mine-based business such as an academic or touristic venture is one that is far more complicated. It is subject to the same discretion that any business venture will be subject to. Questions regarding long-term profit, value added to the parent organisation and other issues regarding long-term value and benefit to society. There must be an overlap of contributing positive factors which will result in a post-remediation project to be undertaken. As a result, post-mining operation ventures are rare when compared to the alternative of simply remediating the area.

Research will be conducted to determine the varying degrees of success that projects have had when attempting to tackle the issues surrounding mine revitalisation. The degree of success that these projects have had will vary depending on the approach taken, which will in turn vary between different countries and organisations.

In addition, a UK site containing significant mining related contamination has been selected for hypothetical remediation. The Roseworthy site, Cornwall, is located on a disused arsenic processing facility and as a result the area has been significantly saturated with arsenic compounds within the soil and, to a lesser extent, the nearby water systems. This investigation aims to suggest a remediation plan to deal with the contamination present and suggest uses for the area should it be needed. Using past contamination investigations of similar sites and legislation determining the correct and legal procedures that would provide the most efficient and optimum results, leaving the minimum hazard levels present to pose a danger to human infrastructure and ecological habitats in the area.

1.0 Difference in Remediation Methods

The remediation method employed by an organisation will depend on a number of factors associated with the country in which it is operating. Chief among which are the economic and legal limitations. The legal framework governing the decommission and remediation of former mine sites are set by the local government, such as national or state level. The environmental and safety standards impressed upon organisations will often be directly dependent on the economic standards of the country being operated in. Other reasons such as population density, proposed future use of the land and proximity to human infrastructure or protected wildlife sanctuaries will also come into play and effect the standards required of the remediation process. Depending on the country, remediation may also be carried out by state owned businesses or private businesses, though this in theory will have no effect on the outcome, in practise state owned and private owned businesses can be subject to separate standards.

As well-documented by many publications and investigations, mining has the capability to drastically damage the local ecosphere. The magnitude of which will vary on the type of commodity being mined, the method by which it is carried out and the geological conditions present at the mine site, (Gupta and Nikhil, 2016).

While there are arguable methods of categorisation, Khalid *et al* (2017) identifies 3 separate categories of remediation processes when dealing with heavy metals. This is frequently the most common of mining-related contaminants. Within each section the study further categorises within these categories. It is predominantly the opinion of this paper (Khalid *et al,* 2017) which will be taken into account for this investigation.. These are physical, chemical and biological. Though many large scale remediation operations will use a combination of 2 or more.

1.1 Physical Remediation

By far the most common method of remediation is by physical methods. This process is often the cheapest and most efficient available to the operators. It involves the removal by mechanical means of the contaminant from the site and area. Khalid *et al* (2017) identifies and details four physical methods of remediation. These are, soil replacement; soil isolation; vitrification and electrokinetic remediation.

1.1.1 Soil Replacement

Soil replacement is the process of gradually diluting the contaminants in the soil by adding non-contaminated soil to the area. This eventually reduces the effects of high-grade contamination in the soil and allows biological and/or geological processes to take over and reduce the remaining contaminants naturally. This method is very expensive in labour and transportation of raw materials cost.

1.1.2 Soil Isolation

As its name would suggest, soil isolation is the process of isolating the contaminated soil from the water table and prevent the spread of contaminants. This method is used when a contaminated site's proximity to a water source puts it at greater risk of contaminating further afield when the contaminated soil would be disturbed. As a result, subsurface barriers are erected between the water table and contaminated soil.

1.1.3 Vitrification

Via the application of high temperatures to areas of contaminated soil, the mobility of heavy metals contaminants can be impeded and reduced drastically, (Mallampati *et al*, 2015). This process is known as vitrification. Electrical currents passed through the soil via electrodes and produce heat through resistance in the soil. By its nature, this method requires a degree of moisture in the soil to conduct the electricity which cannot always be found at every mine location. While the process can be carried out in-situ or ex-situ, it is more favourable to carry out in-situ. This reduces costs dramatically and will inevitably produce the same result. Ex-situ is only used when the contaminant poses such a danger that it must be removed immediately and remediated off site. While different heavy metals will undergo the process under different conditions, there are limitations of the vitrification process. Buelt and Thompson (1992) noted that the process works best in wet soil and with a low alkaline content. The moisture in the soil and the low alkaline content conduct electricity most effectively. This process is however, costly and not frequently the best choice for the remediation process.

1.1.4 Electrokinetic Remediation

A recently developed method, ER works under the principle of separating heavy metal contaminants from the soil by the deployment of an electric field gradient over a volume of contaminated material. Yao *et al* (2012) identified the 3 component sources of separation as electrophoresis, electro-seepage and electro-migration. While the processes can take place on simple soil samples, for heavy metals in the sample present as purely metallic forms or with a low conductivity, dissolution of the sample to draw out these contaminants must take place. A key aspect of this technology is that it will leave the soil in a similar state as it was prior to remediation. Albeit, with greatly reduced heavy metal concentrations. This property is widely desirable in regards to remediation. Another factor which must be taken into account is that different metals will require different electrokinetic conditions. For example, Tang *et al* (2018) found that Cd was separated from the soil matrix at a percentage of 41.98% of its original total under saturation in FeCl and $CaCl_2$. However, these conditions will not favour other heavy metals as they will react differently.

1.2 Chemical Remediation

The use of chemical agents to remove contaminants from an area is commonly employed during remediation. Khalid *et al* (2017) identifies 3 different techniques of chemical remediation. Immobilization Techniques; Encapsulation and Soil Washing.

1.2.1 Immobilization Techniques

The reduction of mobility and other factors which allow a spreading of contaminants, including bioavailability and bioaccessibility. This is accomplished by the addition of a chemical agent to the soil which will inhibit the movement of the contaminant. In the case of heavy metals, this process is best carried out by a mixture of organic and inorganic compounds (Shahid *et al*, 2014). Sun *et al* (2016) recommended the addition of cement, clay and phosphates among other compounds.

1.2.2 Encapsulation

It is the view of this paper that encapsulation is a mixture of both physical and chemical remediation, however Khalid *et al* (2017) places it exclusively as a chemical remediation technique. The process involves the removal of a contaminant from soil by the addition of concreting agents which will then immobilise the contaminant and the soil sample is physically removed from the area by mechanical excavation. This can also be achieved by isolating the contaminant by the chemical incision/injection of low permeability barriers to restrict the movement of the contaminant. The difference between this method and soil isolation is the chemical treatment aspect of the technique. With the soil isolation method using exclusively mechanical methods to facilitate the removal of the contaminant and encapsulation using chemical methods. Liu *et al* (2018) notes this technique is used when the area in question is small, at a shallow depth, yet has a high contamination value. While concrete/cement is most commonly used due to its relatively cheap cost and availability, other agents are used. A study by Navarro *et al* (2013) found that cement with a calcium aluminate component was very effective at the immobilization of contaminants within the soil sample. A major disadvantage of the encapsulation method is that large volumes of soil are lost and have to be dumped off site.

1.2.3 Soil Washing

As its name suggests, soil washing involves the removal of contaminants by soaking a soil sample in a solution designed to absorb the contamination directly from it. This technique again requires the mechanical excavation of the soil as it must be washed out of situ. However, it does not require the dumping of the soil samples, and can be carried out on site.

1.3 Biological Remediation

In Khalid *et al* (2017) this is categorised into 2 categories, phytoremediation and microbial-assisted phytoremediation. The same paper further categorises phytoremediation into 5 sub-categories. Though this paper will not detail these for the sake of brevity and because it does not affect the overall categorisation of these methods.

1.3.1 Phytoremediation

This is a natural process by which plants are used to detoxify and remediate an area. While Sabir *et al* (2015) recommend the process only for medium to low heavy metal contamination, the process is known to be energy efficient, cheap, environmentally friendly. Furthermore, unlike many other chemical and physical remediation techniques, it is aesthetically pleasing and will leave the area un-scarred. This technique is best used in conjunction with other remediation techniques which have already reduced the contamination levels of the soil as this technique will take a longer amount of time to remediate an area.

1.3.2 Microbial-Assisted Phytoremediation (MAP)

While Phytoremediation uses plants exclusively as the medium for remediation, MAP seeks to supplement the capacity of phytoremediation by using microbes to act as inducers of heavy metal absorption in soil. This is accomplished by lowering the pH of the soil and the secretion by bacteria of compounds which may act as leachants. The type of bacteria used will vary dramatically depending on the heavy metal profile in the soil being remediated.

2.0 Potential Uses of Former Mining Areas

Examples of remediated mining areas can be found around the World and fulfilling different purposes. Many are basic and passive in use, such as simply for areas of leisure i.e quarries being flooded in order to provide areas for the introduction of local wildlife and the local community to enjoy. Others are more active in nature. These are areas in which the characteristics or even infrastructure of a mine is used/reused for a variety of purposes. These purposes may be commercial, scientific or academic. There is also the possibility of reopening a mine for use after its initially presumed lifetime and recommencing mining operations. This will be most often be due to changing circumstances in the market i.e. the price of a commodity increasing to the point where it becomes profitable to mine it at a cost equal to that of when the mine was initially closed down. In this case, it will also almost always be cheaper to reopen a mining area where infrastructure is present and the commodity is known to exist, than to investigate and invest in new unknown areas.

Disused mines such as Geevor tine mine, Cornwall, UK (as mentioned previously) have been reopened with an emphasis on catering to tourism and using the cultural history of the area as a business asset. Academic institutes with a focus on mining have reopened or developed former mine or mine sites in order to provide academic and scientific knowledge to their students. TU Bergakademie Freiberg, Germany and Camborne School of Mines, UK have both used these sites in the past.

3.0 National Differences between remediation Methods

One framework for a remediation plan that has been implemented globally and more recently in China, is that of Green and Sustainable Remediation (GSR). A 2014 report by the Chinese Ministry of Environmental Protection found that, in a national collection of soil samples, 16.1% of those collected contained material which exceeded the nations soil control standard. Furthermore, 19.4% of farmland was found to be contaminated, an even more alarming figure, (MEP, 2014). The Sino-German Environmental Partnership is currently seeking to implement the framework of the "Soil Pollution Prevention and Control Action Plan". This is part of the overall GSR method and is seeking to introduce large scale remediation plans throughout the country. The GSR movement was first implemented in Europe and has had immense success. As a result, there are many Sustainable Remediation Forums (SuRFs) present in countries around Europe. These organisations adapt the legislation and frameworks for implementing GSR as technology progresses. The GSR methods must be tailored depending on the country in which they are being implemented. For example, SuRF-UK has emphasised an approach with regard to stakeholders of the remediation project (Bardos *et al*, 2010).

When dealing with a proposed remediation plan for a mega-site in southern China, Song *et al* (2018) identifies 3 categories for the determination of sustainability in remediation These categories can be further separated into its constituents. Each one representing a different aspect required to be monitored and taken into consideration when undertaking sustainable remediation.

1. Environmental
    a. Human Health
    b. Ecosystem
    c. Resource
2. Social
    a. Worker Safety
    b. Public Acceptance

        c. Impact to local community
3. Economic
    a. Cost
    b. Benefit

Within each of these sub-categories are further defined "core" and "optional" elements. Obviously with the core elements being deemed more important and given greater priority. For example, within the Human Health sub-category of "Environmental"; "human toxicity" is a core element and "ozone depletion" is an optional element. While both are detrimental to human health, human toxicity is by far the more immediately dangerous. This template was designed by Song *et* al in order to allow prioritization of more important factors affecting the remediation plan.

3.1 Chinese Approach to Remediation

3.1.1 Currently Implemented Governing Legislation

The Chinese government has had major success in implementing large scale improvements in terms of water and air quality in recent decades and is now aiming to tackle the same issues of soil contamination.

At present, the method most commonly employed in Chinese mine remediation operations is that of excavation and land filling, (Song *et al*, 2018). This is due to the ease with which the operation can be applied. It is reliable, cheap and readily available as a remediation method regardless of the assets of the remediation company.

3.1.2 Case Study: "Mega Site" of Former Mining Contamination in Southern China, Song *et al* (2018)

Song *et al* (2018) conducted an investigation into a "mega-site" of heavily contaminated soil in southern China, along with the MEP (Ministry of Environmental Protection). The site had been subject to extensive mining contamination for "over a 50 year period". As a result, this had left a legacy of 16Ha and 520,000m^3 of contaminated soil. Contaminants included heavy metals such as As, Cu, Pb, Zn and Ni.

There were two remediation plans proposed to remediate the mega-site area, known as Alternative 1 (A1) and Alternative 2 (A2). A1 used soil washing, thermal desorption and stabilization, in that order, to treat a total of 520,000m^3 of contaminated soil. While soil washing, the soil was tier sorted through <0.075mm sieves. This was to remove larger particle sized sands, silts and gravels, which would then be reused as backfill on site. Upon removal, this left 100,000m^3 of <0.075mm particles left. These were treated through thermal desorption to immobilize the heavy metal contaminants remaining in the sample. This soil was not permitted to be used as backfill. Post thermal desorption, the finer soil was subject to immobilization using MgO as a binder to prevent leakage of the heavy metal contaminants within.

A2 had much more mechanical approach to the remediation project. It was predominantly dominated by mechanical excavation and land filling. As mentioned before, this practise is common in China, owing to the natural availability of resources to deal with large-scale mechanical excavation practises. Mechanical excavation and land filling is also deemed reliable as a method to deal with large volumes of heavy metal contamination., (Suer and Sköld, 2011). However, the sheer volume of the contaminated soil was deemed necessary to be subject to immobilization, as seen in A1, using MgO as a binder. This was in accordance with legislation dictated by the Ministry of Environmental Protection, (MEP, 2007). This would be much easier to accomplish were the contaminated soil isolated using the methods seen in Alternative 1. As a result, A1 was the method chosen.

While Song *et al* (2018) produces a very in depth analysis of the GSR remediation plan for China that has been laid out in recent years, it lacks specific details in key areas. The mega site that has been subject to investigation as part of the operation to improve the GSR legislation, is not described in any capacity. Other than the information that the area is in the south of China, there is no information available. It is not clearly stated why this is. This investigation will assume that legal issues surrounding the site prevent its clear identification. The document concludes with well described and clear recommendations drawn from the data produced by the investigation. When pursuing a Green Sustainable Remediation plan Song *et al* found that emphasis should be given towards techniques such as soil washing, thermal desorption and stabilization/solidification over techniques such as mechanical excavation and landfill. These techniques produce far less in the way of carbon emissions. They also provide greater benefits in areas such as greater worker safety, less waste generation and lower impacts on the local communities and area which lead to greater benefits in the local environmental and social domains. It also corroborates the view of the EPA Abandoned Mine Site Characterisation and Cleanup Handbook (2000), discussed later in this investigation, that treatment trains are most often able to produce the most green and sustainable remediation processes overall. A combination of multiple remediation strategies that, in tandem, will reduce the effect from the operation on local infrastructure and the environment.

3.1.3 Case Study: Yunnan Province remediation operation to remediate former mining sites due to As contamination, Lindern *et al* (2009)

From 2008 through to 2009 the Blacksmith Institute, now known as Pure Earth, a non-profit organisation aimed at providing research and remediation strategies for contaminated land in developing countries, was contacted by the Yunnan Environmental Protection Bureau for assistance in developing strategies to deal with large amounts of arsenic contamination in the province. Lindern *et al* (2009) detailed the operation and conclusions. The operation was a two stage operation. Stage 1 was the identification of the source of the contamination. Stage 2 was the planning and implementation of a remediation strategy to deal with the existing contamination and to pre-emptively deal with any more that might occur. There were three villages that were the subject of the investigation, with each being located in a different county. These were in Huaning County, Nan Hua County and Wenshan County. These were chosen as they were representative of the whole area. The sources of the contamination were former mining facilities, such as mine works, tailings ponds and tailings heaps. The vast majority of these facilities were unstable and causing the leakage of heavy metals into the local water supply and surrounding soil. The location of these facilities, uphill in the mountains, meant the gradient caused the contamination to run directly into the areas surrounding these counties. The Blacksmith Institute estimates that the heavy metal contamination has directly affected 8,600 people and indirectly affected 3,200,000 people, (Pure Earth, 2009). Lindern *et al* utilised the guidelines produced by the United States Environmental Protection Agency (USEPA) in order to propose and plan a remediation strategy. This investigation will use the same legislation, in conjunction with other sources, to propose a remediation plan for the Roseworthy site.

The three stage approach to the remediation of these sites was as follows, (Lindern *et al*, 2009):

1. Evaluate the three sites to assess feasibility of implementing a pilot project to reduce contamination
    a. Assess contamination levels, site conditions etc
    b. Estimate a prognosis for the continued exposure to the contamination and prognosis for the effects of remediation
    c. Feasibility study for the implementation of remedial activities
    d. Conduct an assessment of the local authorities capabilities in terms of infrastructure which could aid remediation work
2. Propose and establish remediation objectives for each site
3. Evaluate the proposed objectives for each site
4. Estimate the costs of the remediation plan

This investigation chose the three separate counties to investigate; Huaning, Nan Hua and Wenshan, in order to establish remediation plans for a selection of different sources of remediation and infrastructure.

3.1.3.1 Huaning County

Located at Huaning county was a smelting waste recovery and recycling facility. While the site had previously been officially closed, there was evidence at the site indicating recent activity such as warm kilns and new equipment. Surrounding the area were large deposits of slag and ash which were tested for their heavy metal content. While a number of heavy metals and metalloids were tested for, this report will only focus on arsenic, as this is the metal present at the Roseworthy site which is the subject of this investigation. At Huaning, two areas were tested, the large slag pile and slag pond area immediately next to the facilities. When looking at bulk samples using XRF data the As values of the pile and pond were 16mg/kg and 260mg/kg respectively. However, when analyses were conducted on the fine sediments (<150µm) upon sieving, the As values increased. The results were 171mg/kg on the slag pile and 413mg/kg in the slag pond area.

This area is located adjacent to agricultural land with no access restriction to prevent trespassing and in addition, water transport of contamination from the deposits of slag and ash was present flowing into the agricultural area. The report also highlighted the possibility of a catastrophic failing of the holding pond which had been implemented at some unknown point in the past. This would release large amounts of heavily contaminated water in the ponds into lower drainage areas and eventually the nearby infrastructure and agricultural land.

To remediate the Huaning area, Lindern *et al* (2009) proposed six objectives to target the contamination and prevent harm to the local area and population:

1. Prevent migration of contamination in the area.
2. Minimize leaching of contamination into ground water.
3. Minimize exposures to remediation workers through on site controls.
4. Investigate the possibility of using the ash pile for secondary uses in aggregates.
5. Create adequate disposal facilities for the ash pile.
6. Determine degree of off-site contamination within the area and contamination profile.

3.1.3.2 Nan Hua County Arsenic Mining and Smelting Plant

A former smelting site and mine with approximately 50,000 tons of As residue and 500 tons of waste rock on site. This residue and waste rock covers an area of approximately 53,000m^2. This area is also 5km upstream of a local village, with no restrictions, (Linder *et al*, 2009). This allows contamination to flow unhindered downriver and contaminate the local area. As at Huaning, XRF on the bulk and on <150µm fine samples was conducted. The results can be seen in the table below:

Sample Location	**XRF <150µm sieved samples As values (mg/kg)**	**XRF Bulk samples (mg/kg)**
Residue/smelter bottom ash S1	71,100	89,000
Residue/smelter bottom ash S2	85,500	95,000
Reject ore dump	86,000	150,000
Hoist area soil	227,000	220,000
Crusher area soil	191,000	200,000
Parking area soil	171,000	100,000
Factory entrance soil	48,500	30,000

Table 1: Lindern *et al* (2009) As XRF values at Nan Hua arsenic mining and smelting plant

In addition to the high level of contamination at the site, Lindern *et al* found a water As value of 73mg/L, a hazardous level of As contamination. This sample was taken from the lower drainage area. There have been attempts to prevent the spread of contamination at the area around the site. There has been an attempt to dam the contaminants, however this is in danger of failure and has reached the end of its useful life and capacity.

To remediate the Nan Hua area, Lindern *et al* (2009) proposed four objectives to target the contamination and prevent harm to the local area and population:

1. Stabilize on site wastes to allow later removal of contaminants in waste.
2. Develop a strategy and methodology to minimize leaching of As to surface and groundwater. i.e. cap waste piles etc.
3. Establish institutional controls to prevent salvaging and scavenging of the infrastructure, which could lead to the influx of contaminants to local water and soil spheres due to destruction of the contamination safety equipment.
4. Determine degree and extent of contamination in the area and hazard to local populations.

3.1.3.3 Wenshan Arsenic Refinery Complex

The Wenshan area consists of 4 As processing facilities spaced a short distance of kilometres apart. The facilities operated from 1958 to 2004 and the dumpsite in the area is estimated to contain about 60,000 tonnes of waste residue. A retaining dam was constructed by local authorities shortly after

2002 when a tailings pond failed and released large amounts of contaminants into the local area, which consists largely of terraced rice ponds. The initial incident which led to the implementation of a retaining dam resulted in the deaths of 27 water buffalo in the local agricultural areas. Initial testing of the water supplies in the area showed As values of 1.0mg/L, (Lindern *et al*, 2009). This was of particular concern as rice is known to accumulate As contaminants and was providing a large bulk of food for the region. Seven areas were sampled using the same XRF method on both fine (<150µm) samples and bulk samples, the results are displayed in table 2 below:

Sample Location	**XRF <150µm sieved samples As values (mg/kg)**	**XRF Bulk samples (mg/kg)**
Composite furnace material S1	384,000	<35%
Composite furnace material S2	131,000	160,000
Surface composite small pond	2680	1800
Surface composite large pond	2330	1800
Surface composite below dam	2180	2600
Lower road soil composite	4860	3700
Rubble composite soil	10,200	83,000

Table 2: Lindern *et al* (2009) Wenshan County As processing facility XRF analysis results

To remediate the Wenshan area, Lindern *et al* (2009) proposed five objectives to target the contamination and prevent harm to the local area and population:

1. Stabilize the waste present at the site to prevent further migration.
2. Minimize contaminant leaching into groundwater.
3. Minimize exposure during operation.
4. Create adequate disposal facilities to allow removal of ash waste from the area.
5. Determine the degree of off-site contamination.

3.1.3.4 Summary and Remediation of Area

The XRF of fine and bulk samples show a clear and definite high degree of contamination around all sites. The Huaning county is significantly less contaminated than both the Nan Hua and Wenshan areas however.

When determining remediation methods, Lindern *et al* (2009) used three general criteria to determine the most effective method. These were, long term effectiveness/permanence, implementability and cost. Lindern *et al* considered a number of different remediation strategies for each area. These were as following, no action, institutional controls, excavation and removal, disposal, barriers and site controls, surface water controls and reprocessing. At each site, prevention of catastrophic failure of the retaining dam or other already implemented restraining infrastructure was considered the top priority of the remediation operation. The secondary priority for each site was the stabilization of the already present contamination, such as ash, waste tailings, contaminated pond waste etc.

The Wenshan site was deemed necessary for immediate remediation. Lindern *et al* (2009) details the construction of remediation measures as follows. Wenshan site 1 had the greatest chance of catastrophic collapse of the tailings dam, as the same event had happened before in the past. In order to prevent this 3 approaches were developed. At sites 2 and 4 fugitive dust minimization was prioritized with sediment containment and soil barriers along with salvage/demolition of the existing structures facilitating the contamination. The remediation steps involved the construction of a retaining wall, this allowed the stabilization of the tailings storage area and encompassing this was an impermeable tailings liner to prevent mobilization of the contaminants. Arsenic waste and residue was then moved to this tailing from other areas of the Wenshan site and the surface of the area was re-vegetated using local species so as not to disturb the local ecosphere and allow further stabilization of the tailings area. The use of local species to avoid the introduction of potentially damaging species to the area is in direct correlation with practises described the Green Sustainable Remediation (GSR) objectives as seen in Song *et al* (2018). In order to divert water flows from the tailing area drainage ditches were constructed in order to divert meteoric rainwater and other sources from causing damage to the area and/or absorb and transport As contaminants. This was in direct corroboration with objective 1 of the Wenshan site, which was to stabilize the contamination present. The testing of As contamination in the tailings ponds post remediation showed a notable decrease in the contamination from 1.07mg/L to 0.048mg/L. Further testing is planned by the EPB in later seasons as monitoring of the area to see how different seasons affect As discharge from the tailings. The initial prognosis of the costs was estimated to be $470,000, however, the final budget for the area exceeded this estimate due to the remoteness of the site, leading to issues with infrastructure. The Wenshan County government did provide higher than initially agreed funding in order to buffer the exceeded costs, though the project still ran over budget. The project has been deemed a success by Linder *et al* (2009) and by the local Wenshan government. However, there are still other areas within the county which need remediation attention. There are five former arsenic smelters in the county and an estimated 1,000,000 tonnes of waste material which requires recovery or stabilization.

At present Wenshan is the only one of the 3 sites to have had the remediation objectives implemented. Further remediation of the area is planned.

3.2 UK Approach to Remediation

3.2.1 Currently Implemented Governing Legislation

According to the UK Environmental Agency Report by Johnston *et al* (2008) on abandoned mines and the water environment, an estimated 9% of rivers in England and Wales, while a further 2% of rivers in Scotland are at risk of failing to meet the targets of the Water Framework Directive. These frameworks attempt to reduce the levels of heavy toxic metals within the water supply, such as Cd, Fe, Cu and Zn. Furthermore, Jarvis and Younger (2000) have postulated that 700km of waterways in the UK are "detrimentally affected" by contamination from mining activity. Though the definition of "detrimentally affected" is not made clear. However, from later context in the paper it is possible to conclude that this occurs when biological processes are severely constricted in their capacities. The phrase "highly impoverished" is later used to describe these waterways, with this impoverishment having drastic effects on the flora and fauna of the river and also possibly nearby human habitation.

3.2.1.1 Sustainable Remediation: the SuRF-UK Framework for Applying sustainable development principles to Contaminated Land Management SuRF-UK 2010

In 2010 SuRF-UK introduced framework to assess the sustainability of current UK-based soil and water contamination methods. "Sustainable Remediation: the SuRF-UK Framework for Applying sustainable development principles to Contaminated Land Management" argues that sustainability in this field is not as guaranteed as once assumed. The legislation dictates that the assessment of whether a remediation plan falls under the definition of sustainable remediation depends on its adherence to a rule. If the practise adheres to the rule that sustainable remediation must have a greater social, economic and environmental benefits than negative impact on the area being remediated, (Bardos *et al*, 2010). Its aim is to implement the sustainable remediation strategy that best "maximises the benefits, while limiting the impacts of undertaking remediation." (Bardos *et al*, 2010).

This legislation, while attempting to improve upon and supplement formerly implemented legislation, such as that seen in *2.2.1.2,* appears lacking in specific details regarding remediation. It is designed to work in conjunction with former remediation legislation. Therefore, it does not alter existing legislation and offers little in terms of new legislation.

Ellis and Hadley (2009) state the objectives of SuRF as follows:

1. Minimise or eliminate energy consumption or the consumption of other natural resources
2. Reduce or eliminate releases to the environment, especially to the air

3. Harness or mimic a natural process
4. Result in the reuse or recycling of land or otherwise undesirable materials; and/or
5. Encourage the use of remedial technologies that permanently destroy contaminants

No. 3 is not described, in exact terms, in other legislation or documentation associated with SuRF. This document is not describing the objectives of SuRF UK specifically, though it is describing SuRF as an international body. Therefore the wording cannot be expected to be exactly the same, but similar, as well as the objectives. The methods described by SuRF UK will differ from those described by SuRF as an international standard, due to the unique nature of remediation processes necessary in the UK, and indeed in individual countries. SuRF UK does not recommend the specific use of "harnessing" or "mimicking" a natural process as Ellis and Hadley (2009) does. This can be assumed to be the difference between the methods of SuRF as encompassing legislation and that of SuRF UK.

3.2.1.2 Model Procedures for the Management of Land Contamination: Environmental Agency 2004

This new framework has been introduced to supplement the current outdated framework used, known as "Model Procedures for the Management of Land Contamination" introduced by the Environmental Agency. These two models are designed to work in tandem. Model Procedures for the Management of Land Contamination is designed with a 3 stage assessment and action stage that the new legislation (Sustainable Remediation: the SuRF-UK Framework for Applying sustainable development principles to Contaminated Land Management) builds upon. The stages are:

1. Risk Assessment
2. Options Appraisal
3. Implementation of the Remediation Strategy

(Environmental Agency, 2004)

Risk assessment is the process by which the nature of the problem and any potential issues associated with it are identified. When defining the nature of the problem, the objectives will have also been set and so any problems which may affect the result will be identified. The risk assessment process will take into account not just risks to personnel on site, but also financial and ecological risks. The risk level will be quantified and the decision of if the risk poses a significant enough threat that steps should be taken will be asked and answered. As a general rule, risk is characterised by a combination of 2 factors:

1. The severity of the outcome
2. The overall chance of the outcome occurring

The factor governing all decisions made in regard to risk assessment is the degree of confidence (DOC). The degree of confidence indicates the validity of the risk and how reliable the actual value of risk assigned to it is. It is determined by making an informed assessment on the quality of information used to provide the risk value. Depending on the type of risk, different degrees of confidence will be desired. For example, when dealing with risks to personnel, a high degree of confidence will be desirable. Some uncertainties can be quantified and therefore a DOC with a value may be represented. However, others will be qualitative in nature and therefore will have DOC's represented as "low", "medium, "high" etc, (Environmental Agency, 2004).

If risks are found to be at unacceptably high levels or with a very low degree of confidence then an options appraisal will be carried out. The options appraisal is designed to determine which measures should be carried out to reduce the risks posed by the operation. This may be one or a combination of measures. According to the Environmental Agency (2004) legislation used in the UK, the options appraisal is carried out in 3 stages:

1. Identify feasible remediation options for each relevant pollutant linkage.
2. Carrying out a detailed evaluation of feasible remediation options to identify the most appropriate option for any particular linkage.
3. Producing a remediation strategy that addresses all relevant pollutant linkages, where appropriate by combining remediation options.

The risk assessment and options appraisal allow for the decision to be made as to what action to take. The first step is to implement a plan to deal with the issue of remediation and to closely monitor that plan, (Environmental Agency, 2004), it's effectiveness and ways in which it may be improved. The verification plan will also be used to foresee any issues which are likely to present themselves during the operation. This will in turn allow the remediation plan to be altered to accommodate new unforeseen issues presented.

This document is an incredibly in-depth analysis of the modern state of the UK's attempts at land remediation. When dealing with land contamination, this document provides an excellent guideline on how to accommodate a remediation plan. In addition to this, it lists all the relevant preliminary risk assessment documentation one would need when undertaking a remediation operation, as well as providing a brief summary of each.

3.2.2 Case Study: Wheal Jane Mine, Cornwall UK

The Wheal Jane mine in Cornwall, UK is a former copper mine that was mined extensively from the 1800's until it's closure in 1992. The same year of its closure saw 45 million litres of contaminated mine water discharged into the local Fal river due to a collapsed drainage tunnel, (Morris, 2014). This incident was highly publicized and drew widespread demand for an investigation and subsequent solution to the issue of contamination from the mine drainage.

A study by Bowen *et al* (1998) found that, weather dependent, the Wheal Jane had an approximate daily discharge of between $5,000m^3$ and $40,000m^3$. This was calculated by catchment water balance in the local hydrosphere. While underground contamination values of the Wheal Jane are difficult to know exactly, Wells (2016) measured surface sediment samples, using ICP analysis, to have an As value 4743.6ppm, Pb were 92.4ppm and Cu were 1181.0ppm. Sims *et al* (1990) found that the Clarke value of As to be approximately 5.1±.01ppm. Therefore, surface levels of As at the Wheal Jane site are approximately 930 times greater than average.

To prevent further leakage of acid mine drainage (AMD) into the local hydrosphere, a large scale remediation plan was implemented. A pilot plant, designed to modify the pH of the minewater was set up. This pilot plant works in 3 stages:

1. Construction of aerobic reed beds to remove Fe and As from the water
2. Anaerobic cells to reduce sulphide content and remove sulphide compounds
3. Aerobic rock filters which encourage algal growth and the removal of manganese

(Whitehead and Prior, 2005)

The desired pH of the out flowing mine water is 5. This is accomplished by the introduction of calcium carbonate solutions at points in the pilot plant structure to raise the pH. By 2002 this project was estimated to have cost the local community £20 million, (Younger, 2002).

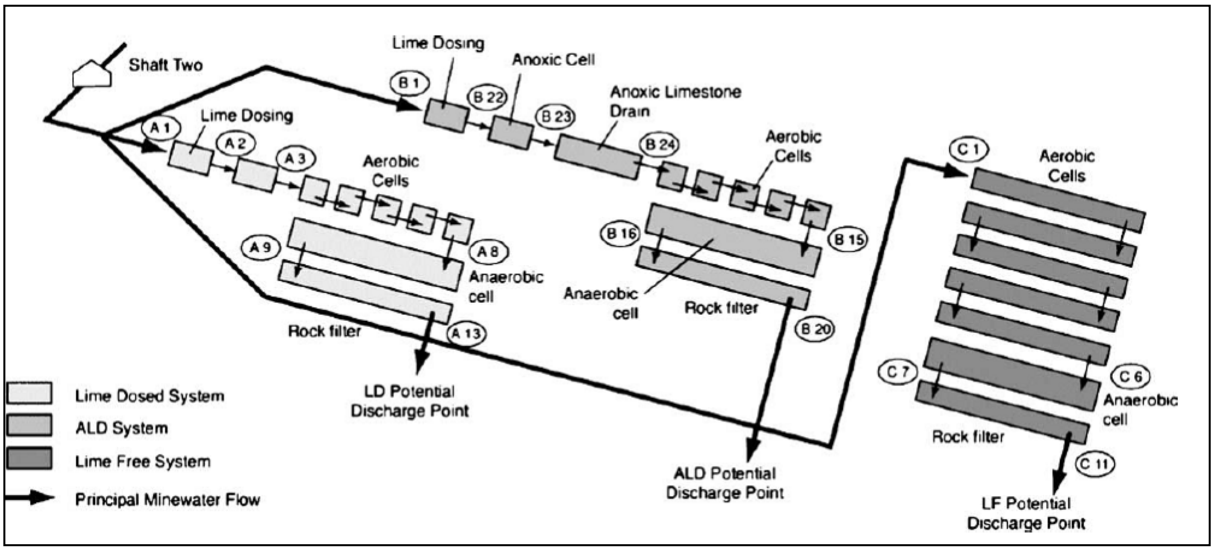

Figure 1: Wheal Jane Pilot Plant Schematic (Whitehead and Prior, 2005)

All three stages can be observed in the schematic of the pilot plant (fig.1). As discharged water from the Wheal Jane flows through the plant it is also measured for its physiochemical quality.

These include the pH, dissolved O2, redox potential, alkalinity, dissolved metals and anions. The sites measured are A1-3, A8-9, A13, B1, B11, B15-16, B21-24, C1, C6-7 and C11.

Mass influxes of AMD from the Wheal Jane have ceased in recent years indicating that the situation is stable and that the remediation operations, while expensive, have been largely successful.

3.3 USA Approach to Remediation

The Environmental Protection Agency (EPA) is the organisation responsible for determining the safest and most efficient remediation practises. It is a federal agency and therefore works across-state boundaries in order to enforce these remediation practises, along with the other duties it is tasked with.

3.3.1 Currently Implemented Governing Legislation

The EPA's Technology Innovation and Field Services Division has released a large number of Best Remediation Practises (BMP) Factsheets to cover and instruct the implementation of green and sustainable techniques in the modern remediation industry. These factsheets each deal with a specific situation or aspect of a remediation project. This investigation has discussed 5 of these factsheets, however there are many more available that are not discussed here, including soil vapour extraction and air sparging technologies; in-situ thermal technologies and leaking underground storage tank systems. This list of factsheets is an in-depth analysis of free to access open source publications developed by the EPA to aid companies and individuals with the techniques, technology and logistics of remediation processes.

3.3.1.1 EPA Green Remediation Best Management Practises: An Overview

The EPA overview of green remediation best management practises (2015) defines green remediation as the process of actively attempting to reduce the environmental footprint of a remediation project. This definition is not in direct conjunction with that given by Song *et al* (2018), which defines green remediation in a more vague manner as simply sustainable management of contamination in an area. However, since the EPA is using definitions in relation to legislation, it is expected that it is more specific in its use of language.

This factsheet encompasses definitions and topics which will go on to be expanded upon in later legislation, also examined in this publication. For example, EPA site investigation and environmental modelling (2016) factsheet also discusses the possibility of minimizing total energy use and installing a focus on renewable energy sources when discussing remediation techniques.

The main focus of the overview BMP (2015) is the instruction of how best to utilize these factsheets in the series, of which there are more than just discusses in this publication. The factsheet also identifies the stages of a remediation project and advises the use of these factsheets with every step of the project. Further advising that the use of these factsheets will help to reduce costs in the long term and reduce the environmental footprint of the project. The stages are as follows:

1. Site Investigation
2. Remedy Design
3. Remedy Construction
4. Remedy Operation and Maintenance
5. Long-Term Monitoring

3.3.1.2 EPA Abandoned Mine Site Characterisation and Cleanup Handbook

Documentation outlining the basic legal obligations of a remediating organisation can be found within the "EPA Abandoned Mine Site Characterisation and Cleanup Handbook". However, for further reading, the EPA has published Best Managing Practises (BMP) factsheets. These factsheets allow a more tailored approach to specific situations, such as bioremediation and environmental monitoring.

The EPA Abandoned Mine Site Characterisation and Cleanup Handbook (2000) identifies 6 categories of negative impact due to mining operations. It is important to note, these categories are defined by their impact on the environment, not their chemical constituents, which is the far more common method of categorisation. These are:

1. Acid (Mine) Drainage
2. Metal contamination of ground/surface water and sediments
3. Sedimentation
4. Cyanide
5. Air Emissions and Deposition
6. Physical Impacts

After outlining the environmental effects of mining, the handbook provides information on measurement of contamination and risk assessments associated with it. However, this publication is focused on the analysis of the post-mining remediation process. The handbook also addresses this in chapter 10, "Remediation and Cleanup Operations". The options listed for remediation of mine-site contamination here are similar in nature to those listed by Khalid *et al* (2017). Albeit they often have a different name, which can be attributed to regional differences in the language used. Song *et al* (2018) also lists similar remediation strategies, for example, thermal desorption appears in both publications. However, there are also many further techniques recommended here for more specific situations of remediation and this handbook is a practical guide to their implementation. Therefore, the detail given here is much greater than in Song *et al* and Khalid *et* al. The handbook separates between 3 types of remediation technology, depending on their working principles. This is similar to Khalid *et al* (2017) differentiating between remediation based on chemical, biological and physical methods. However in this case, the handbook differentiates between technology used to accomplish the means. Therefore, it categorises between "Conventional Technologies", "Innovative/Emerging Technologies" and "Institutional Controls".

Conventional Technologies include three sub-categories and are characterised as techniques currently used commonly in mining remediation on a large scale due to their proven track record of successes. They have frequently been used for a long period of time, depending on the technology, and are heavily implemented in mining remediation sites today. The three sub-categories are, treatment technologies, defined by the handbook as those processes that are used to break down the contaminant into less harmful components or to limit the contaminants mobility if this is not possible. This includes processes such as chemical treatment, thermal desorption and soil washing. Collection, diversion and containment technologies, which as the name suggests, involve preventing the escape or general mobilization of contaminants into the environment more than they already have. This often involves limiting the escape of further contaminants and damage control. This sub-category includes cut-off walls, pumping groundwater and capping. The third sub-category is reuse, recycle, reclaim, again with the methodologies often obvious from the name of the sub-category. There are only two remediation strategies linked to this sub-category, sale of usable materials and re-mining/reprocessing.

Innovative and emerging technologies are technologies which are still in developmental phases. While some are used with success in the field, either individually or more commonly in conjunction with other conventional technologies, there are still questions as to their effectiveness or conditions for best use. The technologies listed here include bioremediation, phytoremediation and vitrification. All three are described previously (1.0: Difference in Remediation Methods) by Khalid *et al* (2017). Though it is interesting to note that Khalid *et al* categorises phytoremediation as a sub-category of bioremediation and not its own technique entirely. However, the definitions of both techniques remain the same, meaning this is simply a choice of convenience for the authors and depends on how one categorises the techniques.

Institutional Controls (IC) are techniques which aim to restrict human or ecological access to contaminants rather than deal with contaminants directly. Primarily, IC deals with risk management, the stage just prior to remediation taking place. However, these methods will also be used in conjunction with other remediation technologies listed prior during remediation in order to reduce the risk of contamination to humans or the local ecology. Access restriction, zoning and limited future developments are examples of institutional controls.

The handbook clearly states that it does not identify itself as policy or official guidelines for the remediation of a landsite. However, it does provide access and information on the factsheets derived from this legislation that will go on to be detailed further in this section. The handbook is a detailed account of almost all aspects of a remediation operation. However, it does not go into any details about costs of an operation. While this is understandable, given the highly variable nature of costs to a mining operation, it is entirely possible to approximate costs given information already available to the EPA. Sources such as EPA: *Cost of remediating mine sites* (1997) provide case studies and approximations of process costs associated with a remediation operation. This document will be used later in this investigation.

3.3.1.3 EPA Bioremediation (BMP Factsheet)

The EPA Bioremediation Best Mining Practises Factsheet (2010) defines bioremediation in a similar manner as Khalid *et al* (2017). In that it is a manner of remediation that utilises naturally occurring biological processes to break down contaminants in the soil. However, where Khalid *et al* separates the bioremediation process into two categories, phytoremediation and microbial-assisted bioremediation, the EPA Bioremediation handbook separates the category into four separate techniques. These four techniques are as follows:

1. Biostimulation: motivation of in-situ indigenous microbial cultures to degrade contaminants in the area. e.g. through O_2 injection producing aerobic conditions
2. Bioaugmentation: the introduction of non-native microbial cultures to degrade contaminants
3. Land-Based Systems: removal and treatment of contaminated soils from the area or in-situ, through mixing of non-contaminated material to allow bio-remediative processes to occur

4. Bioreactors: Treatment of contaminated material through biological processes out of situ in controlled environments to optimize conditions for degradation of contaminants

The BMP goes on to recommend techniques for designing, constructing, maintaining and monitoring bioremediation systems.

3.3.1.4 EPA Site Investigation and Environmental Modelling (BMP Factsheet)

Prior to any remediation operation, a site investigation is necessary, or at least an in-depth understanding of the situation present at the site. The EPA Site Investigation and Environmental Modelling (2016) BMP factsheet identifies the goals of a site investigation as confirming the presence of contaminants, delineating the nature of contamination, identifying contaminant sources, providing data for assessing risk to humans or the environment, gathering data to determine the optimum method of contaminant removal and identifying site characteristics.

The BMP factsheet has subsections on project planning, field activities, materials and waste management and the subsequent laboratory report.

The project planning section recommends activities such as scheduling of activities, selection of service providers and identifying locations for the delivery/processing of hazardous wastes among others.

In keeping with green remediation practises, field activity recommendations in this BMP factsheet are kept sustainable. Such as techniques with sustainable power sources such as solar powered telemetry systems to monitor remediation progress. Materials and waste management is approached in the same method of sustainability. Such as ignoring petroleum based products for waste management due to their tendency to leave behind further contamination. The section also emphasises a reliance on more sustainably sourced waste management products, with less synthetic components. Reuse and recycling is another technique frequently recommended to reduce the imprint of the waste management, for example, minimizing the use of disposable equipment when carrying out field activities.

With regard to laboratory support, the EPA recommends against the use of on-site techniques due to their tendency to produce a significantly larger environmental footprint. The factsheet recommends carrying out laboratory work by the removal of samples from the area and utilising laboratories away-from-site. If this means the use of more expensive 3rd party laboratories, then this can be deemed a necessary expense. The factsheet also lists the recommended attributes of a "high performing" laboratory, though the exact definition of this is not explained. These attributes include optimized ventilation rates for reducing pollutants in the atmosphere and implementing technologies such as energy consumption control in regard to thermostats and insulation.

3.3.1.5 EPA Excavation and Surface Restoration (BMP Factsheet)

The Excavation and Surface Restoration factsheet (2008) seeks to address the reasons for this process to occur at the mine site and to assess the factors which affect the implementation of the process. The potential reasons to carry out this process are as follows, to address the immediate risk to human health/environment, preparing the implementation of bioremediation technology and address areas where other remediation processes will be deemed necessary due to different conditions. The factsheet provides information on green and sustainable development options for the excavation process. Such as the implementation of low energy demanding equipment for use in the excavation process. The factsheet also discusses the use of air and water monitoring equipment when carrying out excavation, as the process is liable to cause some disturbance to these parameters.

All factsheets used here provide references for the information in them, linking to EPA cited documentation, meeting notes and amendments to former legislations to ensure a comprehensive and encompassing summary of the issues they deal with. As a result, they are reliable and accurate with regard to their subjects and would allow an organisation to be informed when undertaking a remediation operation if they were to use these factsheets as part of a desk study prior to planning the operation.

3.3.2 Case Study: State of remediation in the Tri-State Mining District of Kansas, Missouri and Oklahoma, Johnson *et al* (2016)

By 1970 mining operations had completely ceased in the tri-state area of Kansas, Missouri and Oklahoma. Formerly one of the largest producers of zinc and lead in the world, this left a legacy of disused shafts and waste piles in large quantities and covering large areas of the tri-state. Despite remediation work taking place in the 1980's much of these areas still retain heavy metal concentrations far in excess of the EPA recommended limits for safe use of land. Johnson *et al* (2016) produced an in depth analysis of contamination patterns and degree of contamination and presents it in this 2016 paper. The investigation analysed the contamination profile of three sites, each from one of the three mining districts. These were, Cherokee County Superfund site, Kansas; Oronogo Duenweg Mining Belt Superfund site, Missouri and Tar Creek Superfund Site, Oklahoma.

3.3.2.1 Cherokee County, Kansas

Covering an area of 298km^2 this area was sub-divided into 7 categories. The main threat posed with Cherokee County was the closure of mines had caused flooding of the former mine sites. The formation which had been mined previously was the Boone Formation, a known aquifer. This meteoric pore water then reacted with the sulphide minerals present in the mines and caused the formation of large amounts of Acid Mine Drainage (AMD) a common problem in former mining areas. This overflowed from the mine into the local Tar Creek and prompted immediate plans for remediation, (USEPA, 1994). According to USEPA (1994) remediation plans involved the prioritization of preventing the downward migration of acid drainage. This was accomplished by stopping abandoned wells to prevent water influx and hindering recharge of the aquifer by other sources in the former mining areas.

3.3.2.2 Oronogo Duenweg Mining Belt Superfund site, Missouri

Covering an area of 498km^2 and within the vicinity of the three towns of Joplin, Webb City and Carterville, the Oronogo Duenweng Mining Belt was primarily affected by mine wastes and a smelting plant which ceased operation in 1970, (Gibson, 1972). By 2002, such was the issue of mine waste and contamination, that 2600 homes had needed the removal of soil contaminated with heavy metal contaminants. In addition, 6.06km^2 of milling waste was remediated and some water supply systems were also remediated, (USEPA, 2012). After severe weather in 2011, funding was secured for future remediation projects in the area over concerns about large volumes of mobilized soil containing contaminants.

3.3.2.3 Tar Creek Superfund Site, Oklahoma

This was the most productive area of the tri-state district. Areas requiring remediation included large 60m tailings piles and former flotation ponds containing large amounts of sediments. Between 1984 and 1986 the EPA conducted remediation measures to prevent further spread of contamination and as cleanup for already present contamination. The measures included constructing dikes and stopping wells to divert water meteoric pore water and groundwater around the abandoned mine shafts and mine works. However, Johnson *et al* (2016) described these measures as "only partially affected". From 1995 to 2003 further remediation was carried out, on discovery by the EPA that 30% of children in the county had elevated Pb levels. In 2003 the Tar Creek plan that was implemented involved the implementation of large scale green remediation processes to treat the contaminated water and soil/tailings. However, this was scrapped after just a short period as it was discovered that the subsidence and contamination profile was in fact more complicated than initially presumed and that a different approach would be necessary to deal with the contamination situation.

3.3.2.4 Remediation Action Recommendations

Johnson *et al* (2016) identifies three categories under which all mine waste operations can be grouped into:

1. Removal of material from the immediate area and safe disposal in a controlled, monitored and safe area.
2. Encapsulation of contaminated material to prevent its uncontrolled or total movement into the environment through exposure pathways.
3. Reactive neutralization of the material, in situ or ex situ.

Johnson *et al* also notes the possibility of cost factors on the operation, and the large degree to which they place in policy suggestion. In addition the paper also acknowledges that profit can be obtained from remediation actions via the recovery of materials at the site which may pose some economic benefit. This can mean infrastructure and machinery i.e. the salvaging of material, though this is only relevant in recently decommissioned mining areas or waste material which may be remediated and profitable minerals extracted. Rock material may also be used as a construction material and it is common practise to utilise waste rock for this purpose. Johnson *et al* (2016) also suggests the ideas of sequentially constructed wetlands. A similar process is observed in Whitehead and Prior (2005) when constructing the pilot plant at the Wheal Jane, Cornwall, UK. The alternating of aerobic reed beds and anaerobic cells uses the same principle. Phytoremediation and bioremediation are also investigated as processes to remediate the areas of the tri-state mining district. The bioaccumulation of metals has been implemented with great success in other areas in need of mining remediation. Adding to the viability of this process is that phytoremediation and bioremediation takes a comparatively longer time than other methods to remediate an area, due to the processes involved. This is ideal for the tri-state mining district as the area does not need to be reused and there are currently no plans to reopen the area for mining or other industry.

However, other than cost and other physical factors, Johnson *et al* (2016) identifies one major factor which may cause issues associated with the remediation of the minewater. The area of the tri-state district is prone to large scale karst development, (Brockie *et al*, 1968). This means that heavy metals present in the stratigraphy or soil are more mobile and likely to enter water systems much faster than anticipated.

In 2004, a comprehensive plan to remediate the tri-state mining district was created which would take into account all the issues associated with the complex hydrology (karsts) of the area. It was deemed that the tri-state mining district was similar enough in its homogeneity of stratigraphy that this plan could be implemented across all three states with little change between policy. The plan possessed four stages, Johnson *et al* (2016) details the process as follows:

1. Construction of passive remediation systems that allow sequestering and filtering of heavy metals, i.e. phytoremediation and bioremediation.
2. Paving or repaving the remaining chat graded roads, followed by the revegetation of chat piles and millponds to reduce lead dust exposure.
3. Sealing of mine works by infilling of chat to remove the threat of mine waste mobilizing and damaging the immediate environment.
4. Reclaim unproductive land and re-vegetate/re-contour the areas around the mine works to encourage productive use of the areas.

This plan has been implemented in areas of the tri-state mining district with great success since 2004, although in 2006 fund reallocation meant the ceasing of a small amount of the process. It is the opinion of Johnson *et al* (2016) that the area of the tri-state mining district requires more remediation work and funding. The investigation also recommends the implementation of different methods of remediation in collaboration with each other, so called "treatment trains".

3.4 Summary of National Differences Between Remediation Methods

From this analysis of the three example countries' approaches to remediation, there are conclusions which can be drawn. In recent decades there has been a concerted effort to implement sustainable remediation goals when it comes to remediating mining-related contamination. After high profile events such as the flooding of Fal Estuary in the UK in 1992 and recent assessments of contaminated areas such as that of the Yunnan province, China by Lindern *et al* (2009) and the assessment of the tri-state mining district, USA by Johnson *et al* (2016) the industry has seen the use of GSR methods to remediate areas. Shown by the use of treatment trains in all areas. For example, at Wheal Jane there have been mixtures of anaerobic, aerobic reed beds and lime dosing in order to lower the pH of the out flowing water. Notice this is not used in conjunction with mechanical excavation as there have been attempts to preserve the natural qualities of the land. In Yunnan and the tri-state area both areas have recommended and implemented the use of treatment trains.

However, the differences in the methods used in areas are apparent. Chinese remediation projects frequently utilise mechanical excavation as a way to remediate mining contamination as the method is cheap and areas for dumping are easily available. While there is an attempt to reduce the use of this method, it is obvious that in many areas this will still be the most common and efficient method of remediation. This is due to the large area of China. European countries were among the first to adopt GSR methods and the reason for this is most likely due to the rising need to preserve the limited natural resources of the countries. In Johnson *et al* (2009) there is no direct recommendation of mechanical excavation, however in the EPA Abandoned Mine Site Characterisation and Cleanup Handbook (2000) there is the recommendation of collection (excavation) as one of the most reliable options available. However, the handbook then goes on to suggest methods to remediate the contamination upon excavation. This highlights a difference between international remediation methods, the strong advice to neutralise contamination, regardless of its final destination. This is something not seen in Chinese sources until more recently with the implementation of GSR. Concluding from this, this investigation determines that the two greatest factors in remediation operations between countries is that of economic resources and geographic characteristics. However, in recent decades the differences between national methods have been decreased dramatically due to the sharing and collaboration of information and legislation.

4.0 Case Study and Recommendation of Remediation Plan: New Mill Site, Roseworthy, Cornwall, UK

This section will seek to analyse the degree of contamination at the site of the New Mill, a former calciner stack and refinery of iron ore, located in Cornwall, UK. The area was extensively investigated for contamination by Camm *et al* (2004) with high levels of arsenic being found in the surrounding area. Located next to the parish of Roseworthy, the area is near to Camborne, UK and is roughly equidistant (approx. 2-3 miles) between the nearby small town of Hayle and Camborne.

4.1 Background and Former Activity

The county of Cornwall has a long history of mining activity, dating back to Bronze age Britain. Copper and tin mining was always the largest mining industry in the county. This has left tailings dumps and former mining areas heavily saturated with large amounts of heavy metals and varying toxic compounds at many locations around the county. Many of these have been heavily sampled and investigated to build up an accurate county wide image of the extent of mining contamination. One example is the Wheal Jane and surrounding area, investigated by Wells (2016).

The copper and tin ore present in the underlying geology often contains large quantities of arsenic, most often as arsenopyrite. In order to remove this, initially as a by-product, though later as a product in and of itself, calcination was carried out on the ore. The calciner stack located at the site of investigation was used to remove arsenic compounds from sulphidic ore types as more conveniently processed placer and gossan deposits began to reduce in availability. It achieved this by heating the ore to a high enough temperature as to achieve thermal decomposition. As a result, the sediment around the calciner stack became saturated in arsenic compounds. This rise in saturation was reduced by legislation aiming to create safer working conditions, limiting the legal value of airborne arsenious oxide to 2.9g/m^3 in the late 1800's (Camm *et al,* 2004). The calciner stack at Roseworthy was constructed in 1889 and ceased operation in 1923, and was constructed on the west bank of the River Reens, a tributary of the Red River. It was responsible for processing ore from the various mines in the vicinity for the duration of this period though production data is not available, (Camm *et al,* 2004) and over its years of use, the calciner stack slowly saturated the area with arsenic compounds.

The area had been known to be contaminated not only from local knowledge but also from previous studies of the area. The site at Roseworthy was chosen for initial investigation by Camm *et al* (2004) because it has only one source of arsenic contamination, that of the calciner stack. While there are many sources of arsenic compounds, the only source at this location is that of the calciner. There are no nearby mine works or tailings that would produce arsenic leachates or further contaminants or natural weathering from parent arsenic bearing rocks and Camm *et al* (2004) aimed to study the effects of strictly calciner contamination with no other influences. However, there are four reasons this investigation has chosen to use the Roseworthy site to recommend a remediation and utilisation plan.

1. The site has not currently undergone any remediation work and the original contamination is still present.
2. There are currently no future plans to remediate the area despite the contamination.
3. The area has been mapped extensively and as a result, there is a highly detailed knowledge of the underlying geology, sedimentology and contamination patterns, information vital for thorough remediation plans.
4. There are currently no attempts or plans to construct any infrastructure on top of the area.

In order to produce a remediation and utilisation plan for a site, this investigation required one which could be recommended for, as opposed to simply providing a different approach to a remediation plan that had already been put in place in another area.

4.2 Geography and Underlying Geology

Cornish geology is predominantly composed of granitic material related to the Cornubian batholith, a large igneous intrusion dating to the Variscan Orogeny occurring approximately 380-280mya. Surrounding this intrusion is an aureole of mostly Devonian era slate formations, mudstones and fine grained sandstones that have undergone metamorphism due to the effect of the intruding batholith. These are known as the Mylor slate formation.

The bedrock geology of Roseworthy as mapped by the British Geological Survey (2017), is shown to overlay Mylor slate formations of varying age. The Mylor formation is noted for fine silt laminae and metabasites interbedded within the slate formation, (Goode and Taylor, 1988). However, the area is sectioned by a large fault system running in a northerly direction. To the south east, lies the Cornubian batholith, and resulting aureole of metamorphosed rock. It is this batholith and aureole that provides Cornwall with its rich reserves of copper, tin and other metal ores. The vast majority of the land is arable pasture, with small areas of natural, un-worked scrub. The Red River has been heavily augmented by the years of its association with the mining community, with artificial adjustment of its flow and banks, no part of the river can be said to be truly in its original natural state. The same can be assumed for the surrounding areas, including the supposed "natural" scrub and the majority of sediment in the area has been enriched with artificial fertiliser, (Camm *et al*, 2004). According to a study conducted of the entire Hayle area by Staines (1979) the soil around Roseworthy is comprised of loam soil with a large clay component in the upper valley, and alluvium in the bottom section of the valley. Soils with high quantities of aluminosilicates, such as clays, are noted for their ability to retain heavy metal contaminants within their structure, as opposed to more coarse grained sediments.

Figures 2 and 3 below show the location of the study area of Camm *et al*'s (2004) investigation.

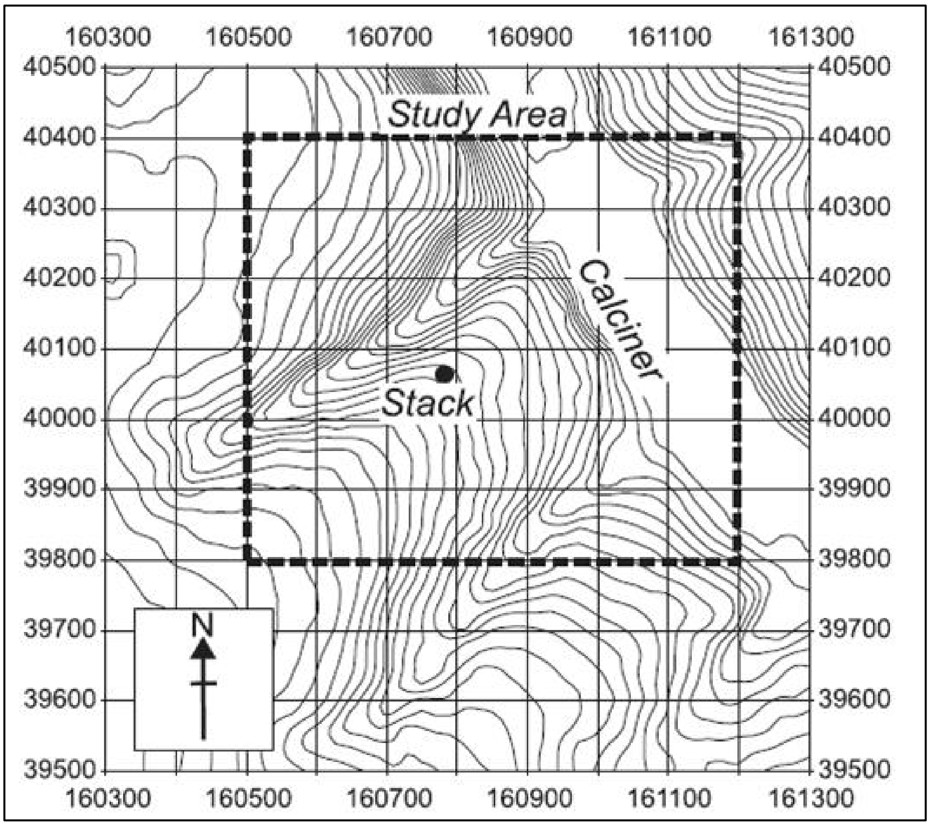

Figure 2: Camm *et al* (2004) 2D topography map showing, within the study area, the location of the river valley, calciner and stack

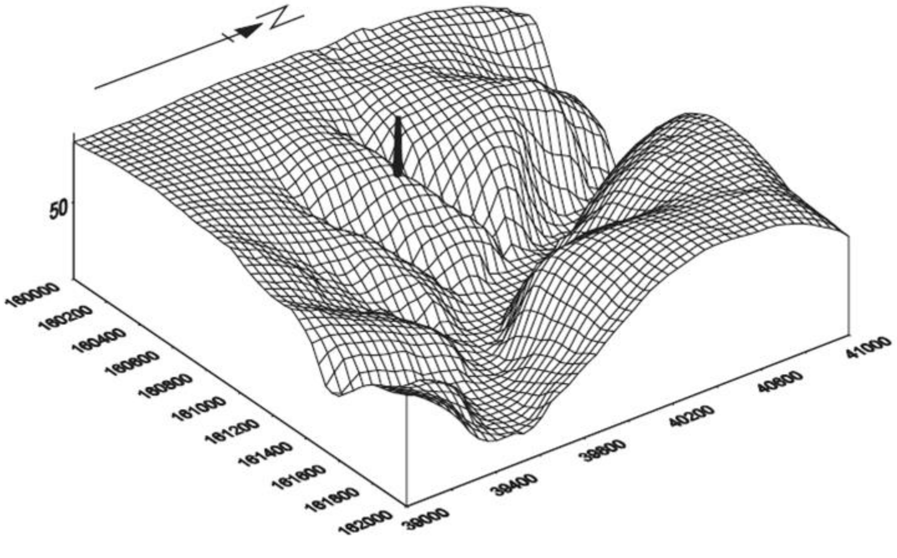

Figure 3: Camm *et al* (2004) 3D topography map showing the location of the calciner in relation to the study area

4.3 Previous Investigations and Camm *et al* (2004) contamination investigation and findings

4.3.1 Previous Investigations of the area

The investigation by Camm *et al* (2004) built upon work done by previous studies of the area. For example, Abrahams and Thornton (1987) had found that of the 58 samples taken of the area, 51 had elevated arsenic levels in excess of 110mg/kg, the threshold for moderate contamination. The same study found levels of soil arsenic to be between 600mg/kg and 2200mg/kg when taken from the immediate vicinity of the calciner stack and valley floor respectively. This increase towards the valley floor from the stack can be attributed to sediment flow down the gravity gradient over time. An investigation by Li and Thornton (1993) focused more closely on the immediate area around the calciner stack, with three sediment cores taken from a depth of 0cm to 45cm, taking an account of the topsoil and subsoil. This investigation found arsenic values ranged from 210-925mg/kg in the topsoil (0-15cm), 257-962mg/kg in the subsoil (15-30cm) and 190-236mg/kg in the deeper subsoil (30-45cm). The final study by Frizzel (1993) found that As values averaged 800mg/kg around the calciner site. These previous investigations all corroborated the others findings, that the area immediately around the calciner stack was heavily contaminated with As.

4.3.2 Camm *et al* (2004) Investigation and Findings

4.3.2.1 Sampling Methods

In the investigation by Camm *et al* (2004) 78 soil samples were taken in a $700 \times 600m$ grid. Each sample consisted of a 30cm deep trench of 8cm width and the soil type and consistency was recorded. Each soil sample taken weighed approximately 250g. Seven water samples were also taken at the Reens River and the two minor streams flowing in the area into the river, coded NM1 to NM7. The locations of all the samples (water and soil) can be seen in figure 4 below.

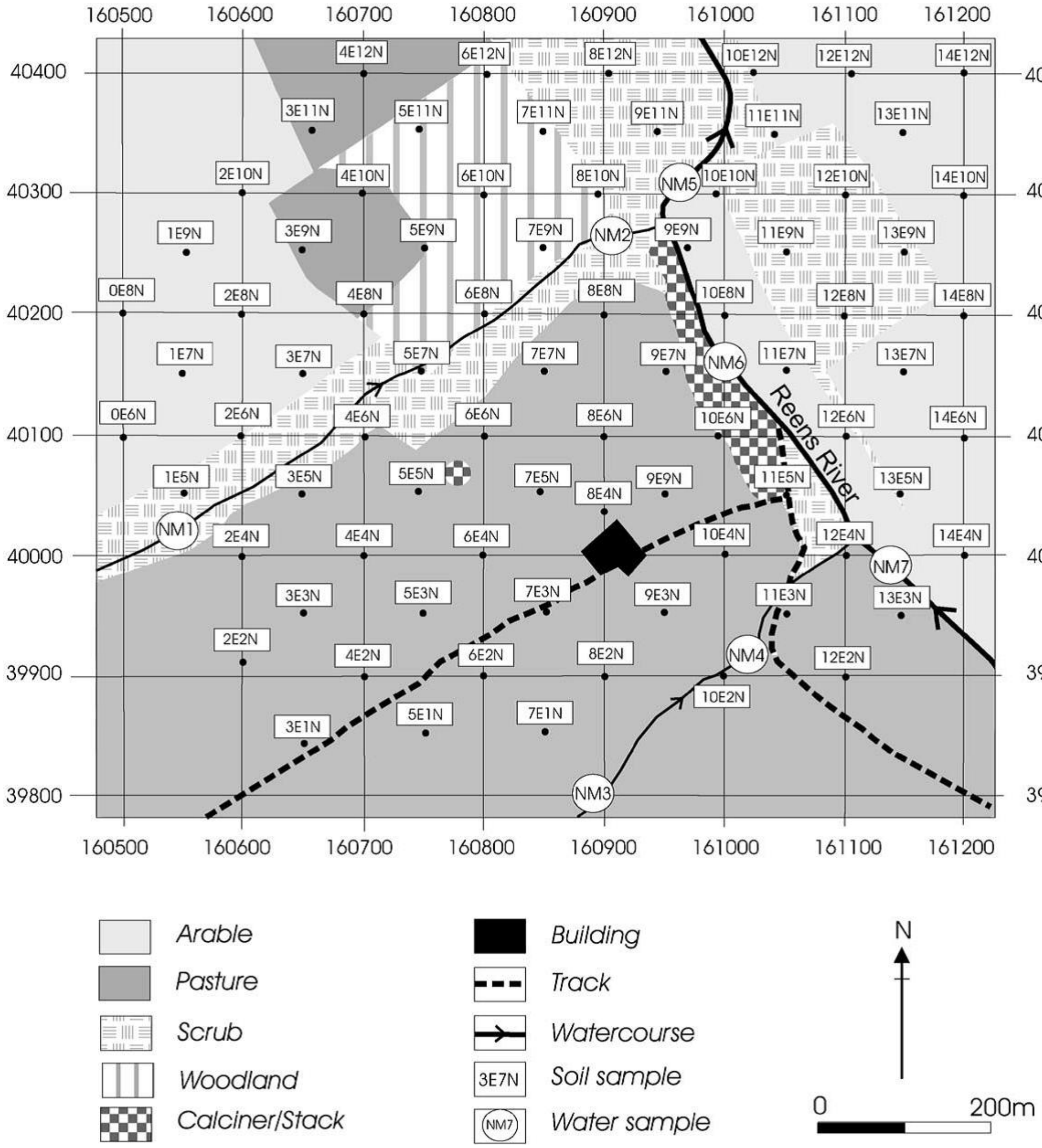

Figure 4: Camm *et al* (2004) Sample map w/ legend

4.3.2.2 Laboratory Methods during Analysis

When measuring As levels in the samples taken, soil samples were outsourced to ACME Laboratories in Vancouver, Canada for ICP-MS (Inductively Coupled Plasma Mass Spectrometry) analysis. The model of ICP-MS used by the company is a Perkin Elmer Elan 6000 ICP Mass Spectrometer. Prior to this, they were submerged and leached in 95°C aqua regia as well as digested in a 2:2:2 ratio mixture of HCl, concentrated HNO_3 and demineralised water. This method produces results accurate to a 0.5mg/kg limit of detection.

Water samples were tested using HPLC-HG-AFS (High Performance Liquid Chromatography-Hydride Generation-Atomic Fluorescence Spectrometry), also outsourced by to South West Water. This procedure produced results in the same format as the soil samples (mg/kg) however, they are expressed in µg/L due to the more diluted nature of the samples.

4.3.2.3 Results of Investigation

XRD analysis of samples 5E5N adjacent to the stack and 9E9N of the valley floor showed a soil mineralogy predominantly dominated by quartz, chlorite and mica. With the samples clay mineralogy being primarily composed of illite and kaolinite. A Quantitative Evaluation of Minerals by Scanning electron microscopy (QEMSCAN) revealed that the vast majority of soil samples contained arsenic bearing minerals. The most common of which were arsenic-oxide and iron-arsenic-oxide. Webster (1999) quantifies the background sedimentary value of As as approximately between 5mg/kg and 10mg/kg. This is in corroboration with Sims *et al* (1990) who puts the Clarke value of As as 5.1ppm(mg/kg). However, these values encompass all areas, regardless of mineralogy. Elghali (1994) places a range of sedimentary values of As in uncontaminated areas of Cornwall as between 26mg/kg and 67mg/kg. With this as a background value, an assessment of the contamination levels of the site can be conducted. The spatial distribution map produced as part of Camm *et al*'s investigation can be seen below in Fig. 5.

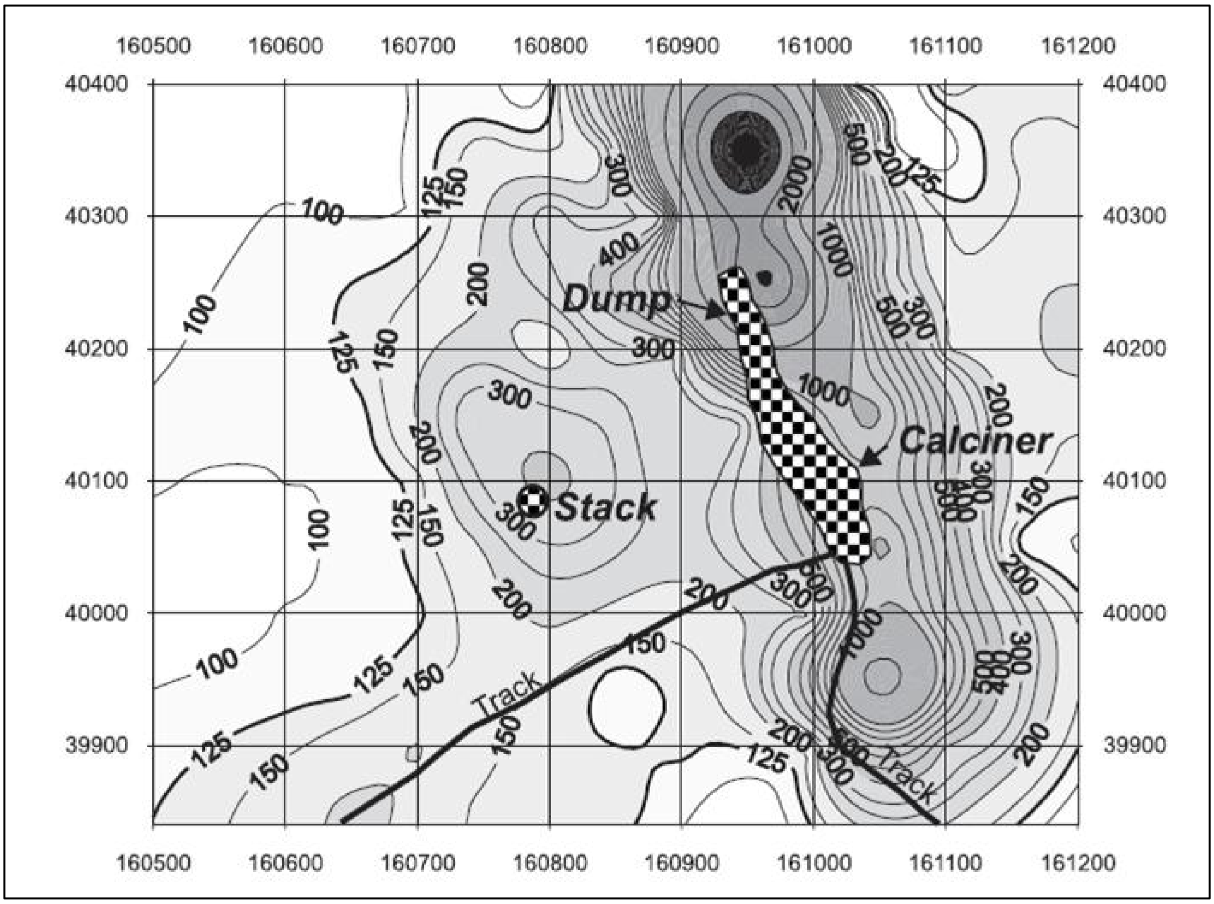

Figure 5: Camm *et al* (2004) Spatial distribution of As contamination, with darker areas representing greater levels of As contamination

The contamination plume observed in the NE corner of the map shows a spike in the levels of As. This occurs downstream and downwind of and directly around the stack and was measured as having a peak of 4466mg/kg. The secondary plume seen NE and downwind of the stack peaked at a value of 456mg/kg. The SE plume, upstream of the stack peaks at 1830mg/kg. The final plume in the SW of the map area, though it is debatable to what degree this denotes a "plume", peaks at 218mg/kg. The peaks close to the valley and stack are clearly related to the sources of contamination found there. The valley is located next to the calciner dump, where much waste product would have been stored and leached into the surrounding soil. The plume occurring downstream of the dump is the result of the water flow transporting the arsenic contamination. In the case of the calciner plume, this is due to this being the location where calcination was taking place, leaching these contaminants into the soil. The other two plumes are not related to any source of contamination. Camm *et al* (2004) associates these with either raw material that has been spilled upon transport or a line source of either raw material or finished product. The majority source ore of the calciner at Roseworthy was identified by Camm *et al* as that mined at the nearby Camborne-

Redruth polymetallic ore complex. This was due to the elevated concentrations of tungsten, antimony, tungsten, uranium, lead and copper found in the ICP-MS analysis of samples from the calciner dump residue. As well as these trace metals, the same samples produced values of 15% arsenic, a unique geochemical signature which was then matched with the known geochemical values of the aforementioned ore complex.

The core samples taken to a depth of 45cm were sectioned into three cores of 10cm to a depth of 30cm. The tests of arsenic distribution between the depth samples revealed that there was no change in concentration in depth. As values in the calciner stack sample 5E5N increased from 228mg/kg at the surface to 252mg/kg at 30cm. As values in sample 9E9N downstream of the waste dump range from 2844mg/kg at the surface to 3029mg/kg at 30cm depth. In both cases there is only a small increase. While Camm *et al* does not provide an explanation for this, they do acknowledge that these values are in corroboration with the values found by Li and Thornton (1993). The explanation for the stable values of As in the surface and sub-soil is most likely that limited ground disturbance has taken place since the use of the area. There is little arable land, except that in the north of the area, and there is very little anthropogenic disturbance to the ground. This has allowed the contamination to slowly leach into the soil at a constant rate and saturate the area in a homogenous distribution. Though the distribution is not entirely homogenous in its pattern. Camm *et al* notes that while most plume patterns tend to form ellipse shapes, as noted by Davies (1983), the pattern at the New Mill stack forms a more dispersed pattern of contamination.

When measured, all seven of the water samples taken produced results below 50µg/L, the recommended WHO threshold for arsenic contamination. NM1 registered as 1.3 µg/L, NM2 as 7.9 µg/L and NM4 registered between 2.2-5.9 µg/L. In the Reens river, upon the banks of which the contaminated stack was located, arsenic values were higher, though still below the WHO recommendation. Being located upstream of the stack, NM7 registered 11 µg/L. NM6, directly adjacent to the stack registered 18 µg/L and NM5, downstream of the stack, registered 21 µg/L. Overall, water sample arsenic measurements were far lower than those of the soil samples. This is simply due to the nature of the medium. Constant water flow will remove contaminants from the area, whereas soil will retain its contaminants for longer periods.

4.3.2.4 Corroboration with previous investigations

All previous investigations corroborate with the patterns of contamination observed in the area by Camm *et al* (2004). The investigation of Roseworthy by Camm *et al* (2004) corroborates what was already known about the levels of contamination in the area and furthermore the contamination profile of Cornwall as a county. The investigation of the area by Li and Thornton (1993) produced lower results, albeit similar, than Camm *et al* (2004) when investigating the calciner stack.

However, the investigation by Abrahams and Thornton (1987) differed in its assessment of the contamination values. This investigation, as mentioned before, assessed the area to have a much smaller range of contamination values than Camm *et al* (2004). Abrahams and Thornton (1987) found a maximum value of 600mg/kg surface As contamination at the calciner, as opposed to 456mg/kg found by Camm *et al* (2004). And at the stack Abrahams and Thornton found a maximum value of 2200mg/kg compared to Camm *et al*'s 4466mg/kg. This means that Abrahams and Thornton found the range of maximum contamination between the 2 areas of highest contamination to be 1600mg/kg, whereas Camm *et al* found this value to be much higher at 4010mg/kg.

The study on the Wheal Jane by Wells (2016) is an excellent comparison to make as it allows a comparison between Roseworthy and an area which is known to be heavily contaminated and action has been taken to prevent this contamination spreading and harming the local area. While Camm *et al* (2004) measured surface As values 4466mg/kg (ppm), the Wells (2016) sampling of the Wheal Jane mine to be 4743.6ppm, an almost exact match. While the sample taken by Camm *et al* was in the most heavily contaminated part of the mapping area, this is comparable with the surface sediment As value taken by Wells, which came from one of the many mine tailing dumps at the Wheal Jane. Therefore, it can be concluded that the area at Roseworthy is at least contaminated in some areas to the same extent as the Wheal Jane, an area designated by the government as a hazard to human health and local infrastructure and therefore deemed to require large scale remediation work. The only difference is the scale of contamination. The Wheal Jane covers a much greater area and greater volume of contamination and threatens a much larger waterway than the Roseworthy New Mill site. However, it should be noted that the Roseworthy site also threatens to leach arsenic contamination into a major waterway, as the River Reens is a tributary of the Red River.

4.4 Proposed Remediation Plan for Roseworthy New Mill Site

4.4.1 Background Parameters

The Roseworthy site has been proven to be as contaminated as the Wheal Jane, an area undergoing large scale remediation work, in at least one area. Both also border on major waterways with significant human infrastructure and ecological habitats surrounding them, though the New Mill occurs on a much smaller scale. The Roseworthy Site is not currently undergoing remediation work as there are no plans to utilise the area or former calciner and stack site for any industrial or other use. However, this investigation is posing the hypothetical situation that the site is in need of remediation, in order to merit the discussion of what processes would be required if the remediation operation were to go ahead. A comprehensive approximation of costs of the operation is seen later in this investigation.

The site should be noted as it does not possess a homogenous topographic profile, uniform sedimentary characteristics or constant contamination pattern. There are differing areas of elevation in the area, the sediment changes slightly from one part of the mapping area to the other and the arsenic contamination plumes depending on its proximity to a source. This makes it difficult to recommend a single process to remove the contamination from the area, as the different characteristics require a number of different approaches. This investigation has prioritized two areas for remediation. The first is the area immediately around the calciner. The second is the area downstream of the dump, within the valley floor. Despite the overall much higher than average contamination profile, the majority of the area is not excessive in its As contamination.

There are parameters of the remediation profile that are known to the investigation that allows a more informed choice of remediation process to be made. The contamination profile remains constant (roughly) with depth. The river water is not dangerous, though the nearby high levels of contamination could be mobilised within the water and make their way into the water table, an outcome that must be avoided at all costs. The area being remediated is comparatively small against other mining areas, such as that of Wheal Jane, and the location doesn't pose a threat to human infrastructure. This therefore could be used as an opportunity to experiment with lesser used remediation methods and improve their performance by providing valuable feedback on their implementation in the field.

4.4.2 Remediation Plan

It is the opinion of this investigation that a mixture of methods is required to fully remediate this area. The differing nature of the topography, inhomogeneous contamination profile and varying environmental factors require process to adapt to each of these parameters. This assessment will use the methods detailed by Khalid *et al* (2017) and assess their viability for this process, while also drawing on other sources for information on remediation processes. This is to produce as informed a remediation plan as possible. Both chemical and physical methods are used in this assessment, but not biological, as these take too long and the area is needed as soon as possible in this hypothetical scenario.

Of the three physical remediation methods listed by Khalid *et al* (2017), soil replacement, soil isolation and vitrification, only the first two have been deemed viable to work. Vitrification is a process which will work most effectively under low alkaline conditions. The average pH of the Roseworthy site is unknown. However, since arsenic becomes more mobile under alkaline and oxygen-rich conditions, and the arsenic in this area is not mobile, it is possible to conclude that the area is low in alkaline. Despite this conclusion, it is the opinion of this investigation that there is not enough known about the pH conditions of the area to merit undertaking vitrification to remediate the area. This investigation recommends soil replacement of the areas of lower (comparatively) arsenic concentrations, this encompasses all areas that are not the valley floor and calciner stack plumes. Soil replacement involves the systematic replacement of the contaminated soil in the area with uncontaminated soil, and the removal of the contaminated soil to an area where it can be processed or simply dumped. Soil isolation could be used on the valley floor, as this has the effect of preventing arsenic contamination flowing into the water system. However, this is not recommended by this investigation as this process is expensive and there are more effective methods of containing the arsenic contamination.

This report recommends a form of chemical remediation as the method by which the areas of higher contamination are to be remediated. There are three chemical remediation methods recommended by Khalid *et al* (2017). Immobilization, Encapsulation and Soil Washing. This investigation recommends encapsulation as the process by which the areas of higher contamination must be remediated. Concreting or cementing the areas of high contamination near the valley floor and the calciner stack and then removing them by mechanical excavation to areas off site would allow the safe removal of the contaminants and pose no risk of releasing the contamination into the water supply by mobilisation. The EPA Abandoned Mine Site Characterisation and Cleanup Handbook (2000) categorises this as one of a number of chemical treatment technologies. The handbook defines any chemical treatment technology as one that changes/alters the composition of the contaminant to render it less dangerous than its original composition. Corroborating the view of this investigation, the EPA recommends and notes that chemical remediation of an area is most often used in conjunction with other remediation techniques. In the case of the EPA Abandoned Mine Site Characterisation and Cleanup Handbook (2000) and Song *et al* (2018) they refer to this situation as a "treatment train" and both corroborate the use of this technique in reducing the effect on the local environment and infrastructure, from the remediation operation. Encapsulation has been proven to be effective under conditions requiring the removal of heavy concentration of contaminants from a shallow, small area, (Liu *et al,* 2018). This is precisely the conditions present at the Roseworthy site. Surface and shallow sub-surface contamination is known to be high and not change in relation to depth. However, the exact extent of the contamination to depth is unknown. Encapsulation will involve the addition of cementing agents, such as concrete into the heavily contaminated soil around the NE of the mapping area and the covering of the soil with a semi-permeable covering in order to limit environmental damage and further prevent the mobilisation of contaminants into the nearby water system.

Further recommendation of this technique comes from an investigation by Johnson *et al* (2016) when recommending a remediation plan regarding the cleanup of an area in the tri-state mining district, USA. However, the same paper also recommends any other chemical or physical remediation technique by which the contamination would be removed from the area.

A map detailing the areas covered can be seen in figure 5 below. This map area shows the areas to undergo encapsulation (blue) and the areas to undergo mechanical excavation (orange).

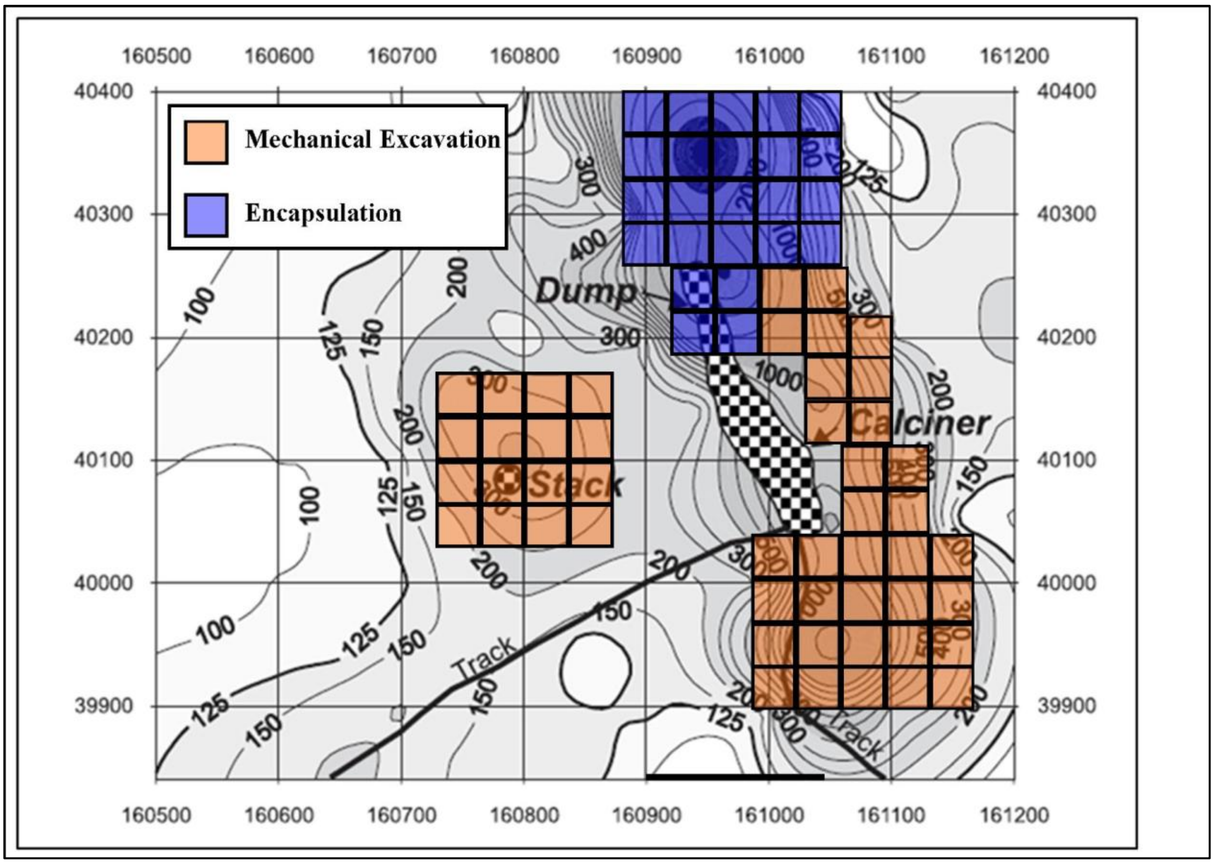

Figure 6: Proposed Encapsulation (blue) and Mechanical Excavation (orange) areas in the Roseworthy area, original map from Camm *et al* (2004)

Each block represents an area of 2500m^2 and has dimensions of 50m by 50m. This block method was used as it allowed an assessment of the excavated/encapsulated total area to be carried out. In addition, encapsulation is often carried out in blocks (Ucaroglu and Talinli, 2012), as this allows the easier implementation of the method.

Immobilization runs the risk of introducing chemical agents to the nearby river, so is recommended to be avoided. Soil washing has no risk associated with it, but is simply deemed to be more expensive and is more suitable for when there is an immediate need to replace the removed soil in the area. The investigation by Song *et al* (2018) of a mega site in southern China was able to utilise immobilization during the remediation process. The reason for this is the difference between the two areas being remediated. While this investigation has a nearby water source, it is concluded from the description of the area in the Song *et al* publication that it does not have a water source. Though this is unclear from the description. Therefore the risk of contamination to the water table is minimised. It is also possible to theorise that the area is not within the catchment of a human settlement and so any contamination would not affect any human populations. This is possibly reflective of a policy difference between China and other countries. To conclude this more thoroughly, a more in depth knowledge of the mega site is needed. Song *et al* released no more information regarding the details of the area, except for the area size (16Ha) and the volume of contaminated soil (520,000m^3). The investigations main focus was on legislation and the implementation of remediation strategies. Since soil washing and encapsulation are similar in their approaches, but soil washing is more expensive, this investigation recommends using encapsulation to remove the heavily contaminated soil, in the interests of reducing the overall cost of the operation.

4.4.3 Summary of Remediation Plan

The remediation of the Roseworthy area will consist of two methods and be contained to two areas. The heavily contaminated area NE and downstream of the calciner will undergo encapsulation to prevent mobilisation of the contamination present in the area into the water system. This will cover an area of approximately 60,000m^2. This process will involve the injection of immobilising agents, in this case, concrete, into the heavily contaminated soil (Khalid *et al,* 2017), thus preventing the mobilisation of As into the water system of the River Reens. This method will produce an area that is safe for future use of the Roseworthy area. In addition, the investigation has recommended the covering of the encapsulated area with a semi-permeable covering in order to prevent rain degradation to the cementitious heavily contaminated soil, and to prevent its subsequent runoff into the nearby river.

Mechanical excavation will also take place on the area around the stack and areas upstream of the calciner as seen in fig. 6. This will involve the large scale removal of all areas highlighted and subsequent dumping of the contaminated material, equating to approximately 55,125m^3 of material. There is also the possibility of remediating this material at a later date off site, though this investigation has not investigated this possibility as it is primarily concerned with the area only. There is also the likelihood that this material will not need to be remediated for its use in aggregates. It will still need to be removed from the area as the plumes will contain As values in excess of government regulations. Assuming the average rate of a $0.5m^3$ hydraulic excavator is $28.6m^3/hr$ (Methvin, 2012), this investigation estimates that the mechanical excavation section will take approximately 241 working days. This is however, assuming that there are no major setbacks to the operation. Similar encapsulation case studies such as those examined by the Environmental Protection Agency (1997), show similar encapsulation operations working with similar soil volumes as taking under a year. Therefore, the mechanical excavation component of the process will be the longest. In total, this investigation will estimate the entire remediation process will take a year upon commencing of work to be completed.

4.5 Cost Estimation of Remediating the Roseworthy Site

An exact calculation will not be possible without an in-depth analysis of the Roseworthy Site, even in excess of the data currently known to this investigation. However, there are methods to estimate, to varying degrees of accuracy, the cost of the remediation operation. Known to this investigation are the contamination levels; the contamination profile; the current infrastructure of the area; the legislation governing the implementation of the operation and a remediation plan has been proposed. Using this, it is possible to estimate an approximate cost of the operation.

This investigation will use the guidelines outlined by the engineering consultancy WSP Global as detailed by Booth (2011). Though this document is designed primarily with uranium mining remediation in mind, the principle remains the same. The first step to estimating the cost of a remediation operation is to have an optimization process that produces the most effective remediation method for the situation. Booth (2011) defines this as follows.

1. Definition of remediation objectives.
2. Identification of remediation technologies.
3. Estimating the costs of each option.
4. Optimization Procedure (ALARA)

Of these steps, this investigation has completed the first and second. This section deals with estimating the cost of the remediation options (stage 3) laid out in the previous sections.

During the cost estimation for each option Booth (2011) has outlined a further 6 steps which aim to reduce the degree of uncertainty in regard to the cost and effectiveness of each step. These are as follows:

1. Site reconnaissance, walkover survey, engineering judgement.
2. Experience, sometimes quotations from vendors and contractors.
3. Design-based cost estimate, tenders, bids.

4. Contracting and implementation.
5. Claims, variations, "value engineering“.
6. Review of costs after completion.

It is important to note that an estimate of operation cost, no matter how accurate, will always be wrong and never perfectly match the final cost of the remediation operation. Despite the small area of the Roseworthy Site and the in depth knowledge this investigation has of it, there are still many unknowns of this area which could lead to changes in policy and costs.

The EPA (1997) also provides information allowing the approximation of remediation costs. The guidelines list the separate factors that will influence the costs of different aspects of the operation. For example, when considering costs of the site operations of the project, the EPA lists several factors that one should consider when approximating costs. These are the effect on production, time to achieve remediation goals, total ore and waste rock tonnage, extent of site impacts, earthwork requirements, labour and imported materials.

4.5.1 Estimating Mechanical Excavation Costs

When estimating the cost of the remediation operation for the Roseworthy Site, case studies of similar areas are an excellent indicator to utilise. Since this remediation operation can be separated into two stages, mechanical excavation and encapsulation, this investigation will approximate the costs of both stages individually. Case studies which have comparable factors such as similar remediation methods, similar areas sizes and similar environmental factors can be used to estimate costs of the Roseworthy remediation operation. However, the majority of the case studies described here are dealing with large scale water issues relating to the regulation of contamination within large bodies of water. This is not as issue that will be need to be addressed in the Roseworthy Site as this investigation has proposed prioritizing preventing the leaching of contaminants into the water supply via encapsulation. Of the 23 case studies described in the document, 7 contain details which can be used to approximate the costs of the remediation operation at Roseworthy, though there are often many factors preventing a totally accurate comparison between both.

Case study no. 2, involving Acid Rock Drainage (ARD) from a waste rock pile involved the removal of 2.7 million tonnes of acidic waste rock. This is significantly higher in volume than the waste that will be generated by the removal of the arsenic saturated soil at the remediation site. According to PHE: Public Health England (2016), the governmentally required maximum levels of arsenic contamination in soil for commercial uses is 640mg/kg. This is significantly higher than both allotment soil and residential soil requirements, 43mg/kg and 32mg/kg respectively. This investigation has chosen to use the maximum arsenic value for commercial use, as the use for the area has not been established. Using the spatial arsenic contamination map shown earlier of the area, produced by Camm *et al* (2004), this investigation has determined that the Roseworthy site has approximately 122,500m^2 of topsoil which has levels exceeding that of the governmental guidelines and can be excavated safely. Note that this does not include the values around the NW of the area, with the highest levels as this area has been deemed too much of a risk for mechanical excavation, lest there be large volumes of arsenic contamination released into the River Reens. The areas this value has been calculated comes from are confined to just 2 plumes, the stack in the centre of the mapping area and the area upstream of the calciner dump site in the SW of the mapping area. This investigation also used the investigation by Li and Thornton (1993) to come to this conclusion. The reason for this is due to the fact that Li and Thornton (1993) found levels of As contamination reached a maximum of 962mg/kg in the subsoil around the stack that Camm *et al* (2004) did not register. This investigation advises caution when dealing with As contamination and advises using the higher value of 962mg/kg. This also then dictates the depth to which excavation should occur. Since 45cm is the deepest any investigation of the area has investigated (Li and Thornton, 1993), this investigation takes this as the maximum depth that should be excavated to, as it would be unreasonable to advise excavating deeper. However, it also acknowledges the probability that contamination continues deeper than 45cm into the subsoil, though there is no way of proving this with the evidence immediately at hand, further investigation is required. When accounting for this and including the 45cm of topsoil into the excavation volume, the value becomes 55,125m^3 of contaminated soil to be removed.

When looking at instances of mechanical excavation, the cost of which has been financially detailed, there are five potential case studies this investigation can use to approximate the costs of the Roseworthy remediation operation. Case study 2 details the mechanical excavation of 2.7 million tonnes of acidic rock, the result of Acid Rock Drainage (ARD), as part of the remediation of an area of South Dakota in 1992 called Richmond Hill. The EPA details this mechanical excavation as having cost approximately $2,500,000 ($2.5 million). This volume of material to be moved is significantly higher than that present at Roseworthy. This case study does not allow an accurate comparison between the two sites and to allow en estimate for mechanical excavation costs. Case study no. 8 describes the attempts to remediate a cyanide leakage from Gilt Edge Mine in South Dakota. The financial declaration shows that 165,000 tonnes of waste ore was mechanically excavated at a price of $451,000. Case study no. 9 is more similar to the Roseworthy site in its volume of waste that needed to be excavated. In Colorado in 1993, 7,000 tonnes of tailings and 2,500 tonnes of pyrite were excavated from the Clear Creek County as part of a remediation operation, however the cost of this operation is not detailed. Case study 13 had a similar premise and issue, with the excavation and transport of 15 million tonnes of waste in Golden Sunlight Mine, Montana in 1992. However, again, this cost is not detailed. Case study no.18 is the most applicable and comparable to the Roseworthy Site. This study details the remediation between 1988 and 1989 of an open pit copper mine in Arizona called Cyprus Miami Operations. In this operation, a total of 70,000yds^3 of the waste dump at the site was required to be mechanically excavated. 70,000yds^3 equates to 53,517m^3 when converted, with Roseworthy needing to excavate 55,125m^3. Therefore, this case study is the closest comparison between the two areas. Case study 18 does not detail individual operation costs. Instead it compares in phases of the operation. With many different operations and processes taking place in the same phase. The cost is then totalled up for the whole phase and individual operations are amalgamated. Mechanical excavation of these 70,000yds^3 is detailed in phase 3 along with haul road excavation; waste dump excavation; excavate key; excavate spillway; place clay and filter and pump and control panel. In this case, haul road excavation is the excavation of the 70,000yds^3 of material. The total cost of phase 3 was $229,800 for all the operations. In the same document, the EPA (1997) states that the average cost of a "collect and treat" operation is $0.49/yd^3. According to this figure, the cost of remediating an area of 70,000yds^3 would be $34,300. The final cost of phase 3 given in the document is clearly much larger than this number by $195,500, so the judgement must be made as to how much of the remaining cost is taken up by additional costs to the mechanical excavation not taken into account by the general guidelines of the EPA or by the remainder of the operations. In order to approximate the costs of mechanical excavation of the Roseworthy Site, the final step is to convert 1989 US dollars ($) to 2018 GBP(£) and make a comparison between the two costs. $34,300 in 1989 equates to approximately $69,000, (Coin News Media Group, 2008-2015, accessed: 03/05/2018). This value equates to approximately £53,650 in today's GBP value, (Bank of America, 2018, accessed: 03/05/2018). To summarise, when assuming a cost value of $0.49/yd^3 to mechanically excavate waste, (EPA, 1997), the modern cost in GBP of mechanically excavating the 55,125m^3 of Roseworthy As waste would be approximately £55,277 (Bank of America, 2018, accessed: 03/05/2018). For clarification, the summary can be seen in table 1, below.

Area	Description	1989 Dollar Value	2018 Pound Value
Cyprus Miami Operations, USA	Mechanical excavation of 70,000yds^3/53,517m^3 waste	$34,300 (\$0.49/yd^3)	£53,650
Roseworthy, UK	Mechanical excavation of 72,103yds^3/55,125m^3 waste	$35,330 (\$0.49/yd^3)	£55,277

Table 3: : Summary of Case Study 19 Cyprus Miami Operations, USA and Roseworthy, UK Sites mechanical excavation costs w/ conversion from 1989 US dollars to 2018 GBP

However, this final calculated value does not take into account further costs that may be incurred during the operation. With the EPA (1997) case study no. 18 giving a figure of $229,800 (in 1989), equating to a modern GBP value of £359,543 (Bank of America, 2018, accessed: 03/05/2018), this investigation will take this value as the upper limit of what the mechanical excavation of the Roseworthy As waste will cost. In conclusion, this investigation estimates the mechanical excavation of the Roseworthy site will cost between £55,277 and £359,543.

4.5.2 Estimating Encapsulation Costs

This investigation has recommended the encapsulation of the NE plume downriver from the waste stack at the Roseworthy Site. In the EPA (1997) document which details a selection of case studies of remediation, as seen before, there are records of encapsulation taking place. Case study no. 9 has a brief description of a tailings pile around which an "earthen berm" was constructed in order to confine these materials at a site in Gilt Edge Mine, South Dakota. This is clearly a form of isolation remediation, however it makes no mention of any chemical remediation of the area, and that this is simply a form of mechanical isolation. In addition to this, the document makes no mention of the price of this process.

Case study no. 11 gives the most accurate assessment of an encapsulation remediation operation. However there are issues that make this comparison less than ideal. In 1986, at a site in Grey Eagle Mine, California, USA a tailings impoundment required a remediation plan to prevent the leakage of further contamination into the local water system. This process resulted in the instalment of an impermeable barrier around the tailings dump with a clay liner, the area also required re-vegetation. The costs were given by the EPA as being $131,000 (1986 US dollars) for every acre of space covered by the impermeable barrier. While this cost will not be exactly the same as encapsulation as it excludes chemical treatment, it is the closest comparison available. This investigation has recommended that the NE plume be subject to encapsulation with an impermeable barrier, this equates to an area of approximately 60,000m^2, a significantly smaller space than the mechanical excavation had to accommodate, though this is to be expected. Since the impermeable barrier only goes on the surface and down to a minor depth, this investigation will treat this as a value of m^2 for the sake of approximation. The barrier is designed to prevent runoff due to surface water flow (Hortonian Flow). 60,000m^2 equates to 14.83 (to 2dp) acres. Therefore the EPA guidelines estimate this as costing $1,942,730 (1986 dollars). When accounting for inflation and taking into account inflation and converting this into modern day GBP, this will equate to approximately £3,447,245. This figure is highly inflated as this is also taking into account the other operations which case study 11 is including as part of the costs, such as re-vegetation. However, it is also the most accurate assessment of costs this investigation can produce and will suffice for an approximation of costs.

4.5.3 Total Costs

After having estimated the costs of mechanical excavation and encapsulation using Booth (2011) and the EPA (1997) it is the opinion of this investigation that the total combined cost of both operations will be between £3,500,000 and £3,850,000.

However, this final figure has only taken into the account the two stages of mechanical excavation and encapsulation. While it is attempted to be as accurate and reliable as possible, any operation seeking to remediate the Roseworthy area must accommodate for the likely possibility that the real cost will be higher. By what degree/value is unknown. Further operations outside of mechanical excavation and encapsulation such as infrastructure construction or licensing/land right acquirements are not taken into account. Furthermore, the costs given by the EPA fail to state which factors are taken into consideration. For example, the value of $0.49/$yd^3$ for "collect and treat" operations does not state which factors were included when estimating this value. Therefore, is this investigation to assume that this includes the worker's salaries involved in the operation is a question of paramount importance. The result of these lack of known variables when estimating the cost of the operation is the large variation in overall costs of the operation.

5.0 Recommendation of Possible Uses for the Roseworthy Site, post-remediation

The area around the Roseworthy site will not be reopened for further use in mineral processing. Aside from the obvious legislation that would prevent the use of the equipment today, regardless of its renovation status, there is no demand for arsenic and no amounts of arsenic being mined in Cornwall.

However, Roseworthy is located in an area that has access to many benefits. The parish sits on one of the main roads through Cornwall, the A30, providing excellent access to the site and other areas around Cornwall. Cornwall itself has many attractions and places of interest that has given rise to a booming tourism industry in recent decades. In 2014 an investigation by the South West Research Company LTD (2016) on behalf of Cornwall County Council conducted a survey of tourism in the county and found that the country attracted 14.7 million day visitors and 4.3 million staying visitors. This supported an industry of 53,000 tourism related jobs throughout the county. In 1997 this figure was stated to be 3 million visitors a year (Andrew, 1997). This significant increase shows how the tourism industry has grown exponentially in recent years, potentially replacing the mining industry that once dominated the economy. This means that there is a market to exploit regarding tourism, if a business venture wished to do so. As well as tourism related uses there is the potential to reuse the Roseworthy site, post, pre or during remediation work for scientific or academic purposes, as well as the possibility of its use in other industrial practises.

There are many examples of mine sites being used for projects such as gas storage. However, given the lack of mine tunnels and adits at the Roseworthy site, this is ultimately impossible at this site.

5.1 Investigation of Roseworthy for Historical and Mining-related Tourism

There is the possibility of taking advantage of this infrastructure and industry by investing in renovation and remediation of the area and utilising it for purposes such as tourism. Examples of sites doing the same thing exist in Cornwall, for example, Geevor Tin Mine. This is a mine site that has been able to reinvent itself after undergoing liquidation in 1990 after continuous economic decline in the latter 20th century. Since shortly after its closure, the mine has been able to use its cultural heritage, significant remaining infrastructure and former workers with hands-on knowledge of the workings to cater and appeal to tourists looking for historical entertainment in the area. Geevor is a mine site that was shut down very recently. The infrastructure is mostly intact and the area's history is well documented. The number of former workers at the mine now working as part of the attraction as tour guides and experts add to the cultural significance of the site. The area was also designated a UNESCO world heritage site in 2006.

However, there are a number of significant differences between Geevor and Roseworthy that will make the same change for Roseworthy untenable. Roseworthy, does not possess the same cultural heritage of Geevor, being used a much longer time ago and having had a recent and significant effect on the local history, economy and culture. When taking this into account and looking at the Roseworthy site subjectively it becomes more clear that the Roseworthy site will not produce the same level of tourism as Geevor. Further exacerbating the issue is that any organization looking to remediate the area for touristic financial gain would have to invest significantly in remediation efforts prior to any attraction opening. This would be in addition to the costs of infrastructure needed to set up any kind of attraction. Compare this to Geevor which, upon closure was legally required to remediate the area and prevent it posing a threat to the local ecosphere and human infrastructure. The site had financial backing that allowed the owners to fund this and carry this remediation work out. Whereas Roseworthy has no such financial backing.

The question needed to be answered in regards to this project is that of cost benefit, as all business projects need to undergo this analysis. From even a brief look at the project, it becomes clear that Roseworthy would not provide the same levels of appeal that other tourism projects in the area, such as Geevor, provide and would not be able to compete in this market. Therefore, it is the opinion of this investigation not to invest in a venture of this nature.

5.2 Investigation of Roseworthy for other types of Tourism

While the use of the Roseworthy site for culture/history related tourism is unlikely due to the costs involved, the area does have other assets besides that of the mine site. Cornwall has a booming tourist industry, as already shown by Andrews (1997) and The South West Research Company (2016). With the area lying along the A30 road, providing excellent connections to the infrastructure and attractions of Cornwall such as areas the Lizard Complex, just a short drive to the south.

The use of the Roseworthy area would therefore be dependent on the tourism infrastructure present in the area, i.e. hotels/accommodation options for the area. As of present this is limited, however the Roseworthy site presents an opportunity. The area is of low land value in comparison to the majority of the UK and has the potential to be constructed upon, with the areas around Plymouth having an average land value of £200,000/acre, (Colliers Intl, 2017). However, another issue is present, in that if there is to be infrastructure constructed within the area, then businesses would most likely find it easier and less expensive to construct on areas not in need of remediation prior to construction.

Further compounding the issue is the fact that, even with the large number of tourists that Cornwall receives on a yearly basis, there is no evidence to suggest that there is a lack of infrastructure to support them. Therefore, there is currently no requirement for more accommodation. In future, there may be the requirement and possibility to invest in new tourism related services.

5.3 Investigation of Roseworthy for Academic Uses

As mentioned before, Roseworthy sits on the A30 road, a significant connection which functions as one of the most important road links through Cornwall. As part of this, it lies close to the Camborne School of Mines, located at Penryn Campus, South East. Part of the University of Exeter, Camborne School of Mines has been an academic institution specializing in the fields of mining and geosciences.

In 2017 CSM lost the use of its field station which enabled the university to provide hands-on experience of working in a mine setting, this was a valuable asset to the institution. TU Bergakademie, Freiberg, Germany still uses a similar asset, a formerly active mine based in the town of Freiberg, the same town the university is based in. The facility is now used to train students in safety procedures when working in a mine and has proven to be an extremely valuable asset to the university. There is the possibility of using the Roseworthy area for academic purposes. The site is located close to the campus and would replace the field station of a similar nature in regards to an academic asset. There is no opportunity to open the area for mining-industry related purposes. Partly due to the lack of infrastructure present and also a complete lack of mining industry in modern day Cornwall to provide a reason for re-opening a processing facility.

However, the area could be used for remediation testing practise as part of the academic services of Camborne School of Mines (CSM). There are three possibilities, remediating the area entirely, which will require large amounts of investment and capital (approximately £3.5 million to £3.85 million); investigating the extent of remediation and instructing students on how to investigate areas of high contamination; and the monitoring of the remediation site after remediation has taken place.

Of these three possible options, the third, monitoring of the remediation site is the most likely as it is the cheapest option. Entering into a university run monitoring operation would allow students to gain firsthand experience of the processes and operations required. Funding could possibly be provided by governmental sources.

By taking measurements of the area and ensuring continuous monitoring of the area, CSM would be able to ensure that the site remains safe and poses no danger to the local ecosystem, agricultural infrastructure or human infrastructure. In addition, the school would provide it's students with valuable expertise. Possibly the greatest threat to the distribution of the Roseworthy contamination over time would be the possibility of erosion caused by water flows mobilizing large amounts of the arsenic compounds present in the calciner stack. Large amounts of rainfall has the potential to destabilize the tailings at the calciner stack by forming Hortonian flow over the surface. This occurs when the soil becomes too saturated with water and the remaining water flows freely over the surface of the soil and can cause runoff of the surface contamination. In the case of Roseworthy, this would cause the arsenic compounds to become oxidised, which they already partly are, and flow into the nearby river Reens and further into the much more commercialised and industrialised Red River, an area already known for its historically high levels of heavy metal contamination. As a result, CSM, or any other organisation wishing to undertake the monitoring operation, may want to factor in rainwater levels and water saturation of the soil into their considerations when monitoring the area. This is in order to predict, and make plans for any possible large influxes of contamination into the local river system. Taking this into consideration, the fact that the area has remained relatively undisturbed since arsenic processing ceased in 1923 and has not had any major contamination breaches should provide reassurance that the area is stable for the time being. Monitoring operations are common around former mine sites or other areas of contamination which have not been successfully remediated previously and require observation to determine whether they will pose a danger in the future. In addition, these operations may also be seen in areas which have undergone remediation and the success of which will be observed over time.

When investigating the Rimac district in Peru, Butler *et al* (2017) were able to conduct an analysis of heavy metal contamination, from upstream mines, flowing into the area over time. The investigation determined how the Fe, Cd, Pb, Cr, Cu, Zn and Mn compounds were distributed over time as well as their contamination patterns. In order to do this, 29 points on the Rimac river basin, which provides fresh water to the capital of Peru, Lima, were tested twice a month over a period of seven years. In addition, historical water quality data from the area was also used to extend the timeline of known contamination change over time. This approach could be mimicked at the Roseworthy site, with constant and consistent analysis of water and soil quality over time, though it should be noted that Butler *et al* only conducted analyses on water quality and none on soil quality.

In addition, the structural integrity of the calciner stack should also be investigated for the same reason. The calciner stack is the result of large amounts of tailings being deposited over a long period of time and is not a planned structure. This suggests that there is the chance of structural destabilization of the area over time, possibly in the immediate future. Combining this with rainwater data would provide an indication as to if or when the tailings would be at risk from partial or total collapse. As discussed previously however, the fact that there have been no major contamination breaches since the use of the site also suggests the tailings are stable. This operation would provide CSM students with experience in structural geology and structural sedimentology planning and monitoring.

5.4 Investigation of Roseworthy for Waste Material Recycling and Reuse

As noted in previous investigations, such as that of Johnson *et al* (2016), waste materials can be used for recycled purposes in other ventures. Frequently, waste materials from remediation sites have been used in construction or in other ventures as the material is easy to acquire for the companies requiring it. Since the material is being removed by necessity, in the case of mechanical excavation, companies may acquire it much cheaper than if they were to mine it directly. However, the drawback is that these areas, for obvious reasons, may contain much larger concentrations of dangerous contaminants and will require removal of these in many cases. Depending on the proposed use of the materials however, this may not be necessary. The reuse of materials can be separated into two categories, reuse of infrastructure and reuse of materials.

5.4.1 Infrastructure Recycling

Infrastructure recycling is the use of formerly used mining related infrastructure in other areas. For example, the re-commissioning of decommissioned mining equipment and subsequent selling and reuse in other areas of the industry. While this is a useful benefit to have, it isn't practical in terms of the Roseworthy site. When Johnson *et al* (2016) investigated parts of the tri-state area for the same intention of infrastructure recycling, the investigation was conducted in an area where mining work and processing work had officially been carried out until as late as 1970 and evidence suggested processing had continued at some of the facilities even recently. As a result, large amounts of the infrastructure could be used. Equipment was relatively modern and had seen limited use, with little to no damage due to age. In comparison, the Roseworthy site ceased operations in 1923 and had been effectively abandoned since. No real infrastructure remains except the calciner stack, a construct of no recyclable benefit. Due to this, it is the opinion of this investigation that no recycling of infrastructure will be possible from the Roseworthy site, and no cost benefit can be expected.

5.4.2 Waste Materials Recycling

While recycling of waste tailings is possible in some cases of mining remediation, owing to the large values of economically viable elements or minerals within the tailings, this is not possible in the case of the Roseworthy site. There is no significant concentrations of As and no significant demand for arsenic as a product.

However, there is the possibility of using recycled materials from the Roseworthy site that have been reused from the mechanical excavation operation of the remediation process. As stated by the remediation plan proposed by this investigation, the volume of soil to be mechanically excavated is approximately 55,125m^3. Public Health England (2016) cites allotment soil and residential soil requirements as 43mg/kg and 32mg/kg respectively. There are no areas of the Roseworthy Site that are below this, and so none of the soil may be used for these purposes. However, for commercial use the value cited is 640mg/kg. So therefore, all soil under this As concentration value has the potential to be reused for another purpose. While this investigation has recommended removing soil with an As value greater than 640mg/kg, the vast majority of the soil removed will in fact have an As value lower than 640mg/kg. Owing to the fact that it is impossible to be precise during the excavation as the areas targeted have been the plumes of contamination, with the exception of the NW corner by the stack. This investigation has opted for a more cautious approach and has resulted in increasing the volume of soil recommended for excavation. As a result, the soil value will be much lower than 640mg/kg of As contamination. This investigation estimates that the average value of As contamination will be between 300mg/kg to 400mg/kg in concentration. This will place it well within the concentration values for commercial use. Aside from the usage of soil for various purposes in construction, Johnson *et al* (2016) provides the example of using the lower As contaminated soil as overbearing on the more contaminated soil. In the case of the Roseworthy site, this could involve using the less contaminated soil taken from elsewhere in the site to contain the encapsulated soil adjacent to the calciner stack. This would solve the problem of what material to overlay the encapsulated soil with and reduce costs from the operation, as instead of spending money to transport and dump/remediate the soil, the less contaminated soil could simply be recycled.

If the waste present at Roseworthy is in need of reprocessing to remove the arsenic contamination, or at least reduce them to acceptable levels, Gunning *et al* (2011) published findings indicating that the use of accelerated carbonation is able to transform waste materials into viable building constructions. This process has been tested on many different forms of waste, including mine waste such as bauxite waste, metal dust and coal fired power station waste. The soil contamination at Roseworthy would fall under "metal dust" as a category. Tripathi (2017) has used this data to suggest the implementation of programmes using agricultural and mine waste in construction projects in India. During the last few decades, authorities and companies within India have had difficulty supplementing the massive demand for construction materials and have frequently looked to other sources. Tripathi notes that, citing Gunning *et al* (2011) the process of accelerated carbonation produces materials that "meet European specifications for lightweight aggregates", this is significant as, as of 2018, the UK also complies with these regulations. Lightweight aggregate is material used in concrete or other cementitious products. Though it should be noted that there is no current international industry standard or definitions encompassing its characteristics.

5.5 Implementation of Recommended Plan for Reuse of the Area

The remediation plan proposed here encompasses two sections, that of the monitoring set up and the mechanical excavation and subsequent remediation of the contaminated soil. These stages will be able to be carried out simultaneously, with monitoring of the area taking place as excavation is carried out. Since the area is council owned there is no need to buy the land, simply apply for permission to examine the land.

When monitoring for contamination change over time, the distribution of points to measure must be established as this will need to be kept constant over time. In order to establish a representative image of the contamination over time, this investigation has recommended the following sites (figure 7, below) to be measured every 4 times a year, once every 3 months. Butler *et al* (2017) tested for contamination twice a month, however this investigation was dealing with water contamination, which is more prone to rapid changes, unlike soil contamination which is more stable. In addition, a 3 month/4 times a year cycle will allow the contamination to be mapped with changing seasons.

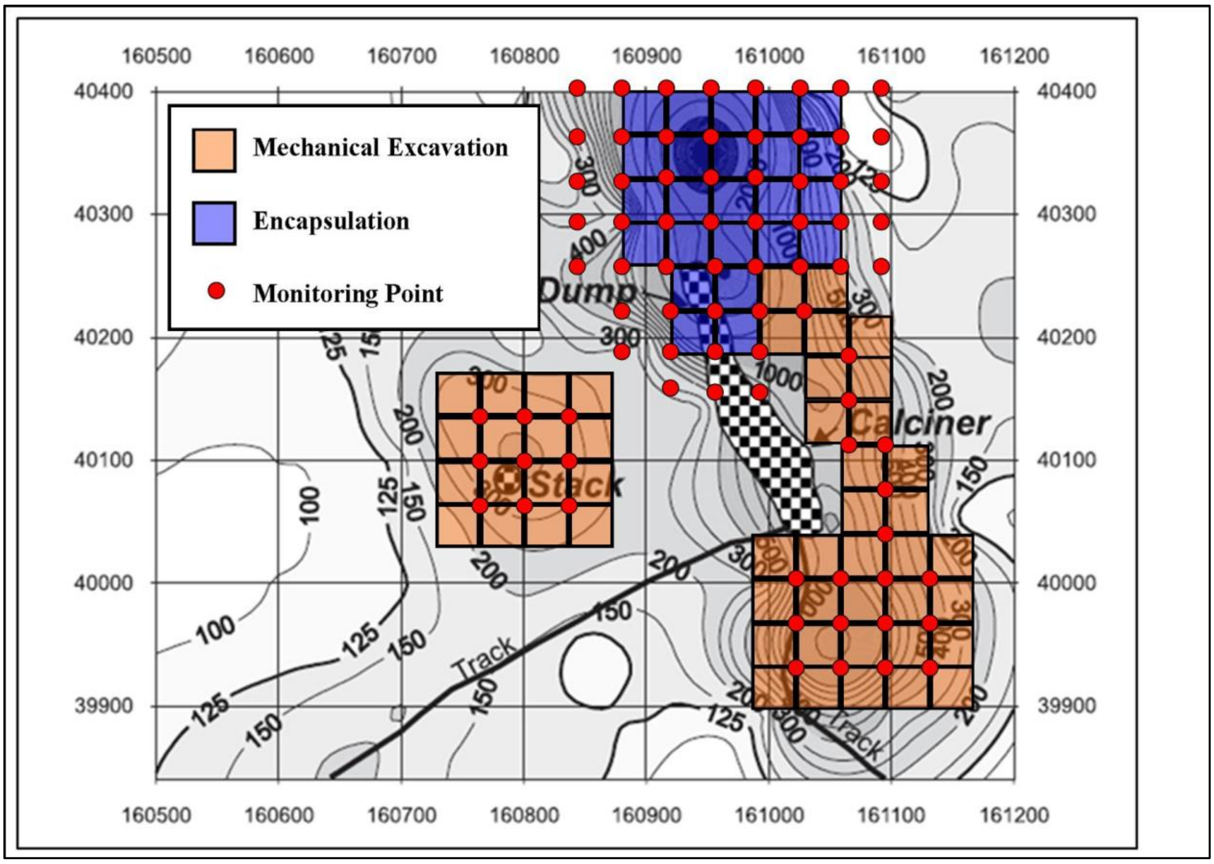

Figure 7: Map showing monitoring sites, in which samples for later analysis will be taken, also with areas of mechanical excavation and encapsulation. Original map from Camm *et al* (2004)

This investigation recommends using ICP-MS for a more accurate reading of results. PXRF was considered, but this investigation requires an in depth knowledge of the arsenic concentrations and ICP-MS will provide this more accurate reading. In addition, the aim of the monitoring project is to provide students with an insight to contamination from a geographic perspective and can also provide laboratory experience via the use of ICP-MS. These sampling/monitoring sites provide an even distribution around the areas of encapsulation and excavation. It was also considered taking samples of the surrounding area to determine if there is any change in the surrounding sediment, but since there is no drastic work being carried out in these areas this was deemed unnecessary. This investigation wishes to investigate how contamination distribution will be affected after the instalment of the encapsulation infrastructure and after mechanical excavation. As can be observed in figure 7, the area around the encapsulation area is to be sampled, whereas the area around the mechanical excavation areas are not. This is because this investigation wishes to ascertain if the contamination will be mobilised during encapsulation and if so, how will the encapsulation affect the distribution over time. Obviously, it is expected that the encapsulation would immobilise the contaminants. In addition to the use of soil sampling methods, this investigation recommends the use of water samples taken at regular intervals downstream of the Roseworthy area to determine if the encapsulation has disturbed contaminants to the degree where they are mobilised into the river. This cannot be shown on figure 7 as the mapping area does not show the river. But regular water samples every 100m of the river and taken every 3 months would provide a comprehensive view of the contamination levels.

Mechanical excavation of the areas shown in fig. 7 will take place prior to the sampling of the area. This will be carried out with the use of heavy excavating machinery as the infrastructure is already present to allow large machinery to access the area. However, the terrain immediately surrounding the area could pose issues to regular machinery, with the difference in height being 35m between the stack and calciner in the valley floor of the Reens River. Therefore this investigation recommends a tracked excavator for the task of excavation, as this will be able to deal with the steep inclines and uneven terrain. The excavation of 55,125m^3 will take approximately 241 working days, with the total time of the operation taking approximately 1 year to factor in setbacks.

6.0 Summary

6.1 Types of Remediation

This investigation has analysed the policies and methods of three countries when it comes to the task of mining remediation. This investigation has shown that the task of remediating a mine site, or mining related requires a multi-faceted approach to the problem, including a plan to utilise the area after the remediation process has been successfully implemented. The variation between sites is so great that there can be no general approach, however there is legislation, guidelines in place and environmental studies to enforce or recommend the implementation of safe and green practises. As well as practises which will produce the most effective result in the environment.

The categorisation by Khalid *et al* (2017) of remediation practises appears to be the most widely accepted within the industry, including by the EPA in the USA. By categorising remediation practises by their basic type of process, physical, chemical and biological, one can more easily vary the type of approach to a remediation project and allows the implementation of "treatment trains" which are becoming far more common in the industry, especially as this process allows the implementation of GSR practises.

6.2 National Differences between Remediation Methods

Remediation methods vary by country, frequently determined by their geology/geography or economic capabilities. China has in the past focused heavily on mechanical excavation as its main method of remediation, followed by dumping. Very rarely has processing been used as a means to deal with the tailings and contamination. The reason for this is most likely due to the low cost of the excavation and the availability of large areas of land, the same method would not be as effective in a geographically much smaller country. However in recent years there has been a push by governmental organisations to emphasise a much more green approach to remediation, as the vast majority of mining contamination originates from the time before well-enforced green remediation practises. This has been accomplished by implementing Green Sustainable remediation goals, such as those documented by Song *et al* (2018). At the same time, outside organisations have been contracted to fulfil these new environmental requirements such as Lindern *et al* (2009). In the case of Lindern *et al,* the three areas were remediated to remove their sources of contamination. However, there is currently little demand to re-use former mining areas, beyond simply reusing the areas for purposes that only require the minimum standard of contamination remediation. This is possibly due to the large availability of land in China. China appears to be following in the direction of the UK and USA, and implementing "treatment train" policies instead of simply following mechanical excavation, in response to these calls for more environmentally friendly policies.

The state of contamination within the UK is better understood than many other countries, with approximately 700km of waterways "detrimentally affected" by mine pollution Jarvis and Younger (2000) and with 9% of rivers in England/Wales and 2% in Scotland affected by mine pollution

(Johnston *et al,* 2008). Like in many European countries, there has been an interest in promoting GSR in relation to mining operations. In the case of the UK this is promoted via organisations such as SuRF-UK (Sustainable Remediation Forum - UK). As stated by Ellis and Hadley (2009) the objectives of SuRF are as follows:

1. Minimise or eliminate energy consumption or the consumption of other natural resources.
2. Reduce or eliminate releases to the environment, especially to the air.
3. Harness or mimic a natural process.
4. Result in the reuse or recycling of land or otherwise undesirable materials; and/or
5. Encourage the use of remedial technologies that permanently destroy contaminants.

The implementation of these guidelines into legislation governing the remediation of mine waste appears to have a had a beneficial effect, promoting the use of more sustainable methods and the use of "treatment trains".

The implementation of legislation regarding environmental factors is governed in the USA by the EPA (Environmental Protection Agency). This means that the responsibility of dictating policy and implementing environmental considerations comes under the jurisdiction of the EPA, making it very simple when it comes to implementing environmental sensitive remediation processes and goals. By publishing the series of guidelines titled Best Management Practises Factsheets, the agency has provided streamlined and concise guidelines which can be tailored to a specific situation depending on the requirements of the remediation operation. Examples such as the factsheets on bioremediation and excavation and surface restoration provide guidelines on how to carry out these practises, often with sustainable development goals as guiding principles. This selection of guidelines has allowed operators to implement treatment trains with great success by combining multiple remediation technologies such as those seen in the investigation of the Tri-State Mining District of Kansas, Missouri and Oklahoma by Johnson *et al* (2016).

6.3 Roseworthy Site: Remediation and Reuse options

Previous investigations of the Roseworthy area have shown it to be heavily contaminated due to its past history of arsenic processing. There are two identifiable structures which give proof of the past industrial nature of the area, the stack and calciner. Both of these are sources of As contamination. Abrahams and Thornton (1987) had found that of the 58 samples taken of the area, 51 had elevated arsenic levels in excess of 110mg/kg. Camm *et al* (2004) identified plumes of contamination within the site, around the stack, downstream of the calciner and upstream of the calciner. The largest was downstream of the calciner with 2844mg/kg at the surface to 3029mg/kg at 30cm depth.

This investigation has recommended a treatment train approach to the area, due to the varied nature of the geography and inhomogeneous distribution of the contamination. Encapsulation of the heavily contaminated area downstream of the calciner stack, to avoid mobilisation of the large areas of contaminants, equating to an area approx. 60,000m^2. As well as, mechanical excavation and dumping of 55,125m^3 of remaining contaminated material. In total this operation is estimated to cost between £3,500,000 and £3,850,000, based off of previous similar operations and guidelines from the EPA. However, this estimated value does not take into account unknown values such as worker costs, infrastructure, material dumping costs etc.

Possible uses of the Roseworthy area include using the site for tourist, academic and recycling of materials related purposes. Regarding tourism, the only tenable use of the area would be in relation to natural tourism related industries, utilising the beneficial location of Roseworthy within the county of Cornwall, providing the area with excellent connections to local attractions. Academic use of the area is more likely and this is the method recommended by this investigation. The nearby Camborne School of Mines may be able to use the area as a remediation project as an academic asset to the school. Providing valuable experience for the students at the school in the industry of remediation. Also as part of the operation, the mechanical excavation of the area will produce a large quantity of reusable material, approximately 55,125m^3 of soil. This material will most likely, though testing will be required to confirm, contain levels of As lower than the governmental limits for commercial use in aggregate construction. As a result, this can be sold to alleviate the costs of the operation.

7.0 Conclusion

When analysing the differences between remediation methods it becomes clear that there are two dominant factors which determine the standard and method of remediation of a contaminated site. These are economic and geographical. Of these two, economic is by far the more important. This factor determines the standard of remediation more than any other factor, with geographic factors only having a marginal effect. However, in smaller countries with more limited resources and space, geographic factors will have an increased effect. This is most obvious when comparing the UK and China. The UK, along with many countries in Europe, has focused heavily on GSR in recent decades in order to preserve the more sparse natural resources in the country, whereas China, with greater access to space and resources, has not historically focused on this need as much. Though in recent years, this has changed. As discussed, GSR goals have been successfully implemented in countries seeking to preserve natural resources. One of the more effective approaches in this area is the use of multiple types of remediation methods to tailor to a specific remediation situation, i.e. treatment trains. This method helps reduce costs overall but most importantly reduces waste and makes the remediation operation more efficient.

When planning a remediation method for Roseworthy, this investigation recommends a treatment train approach to accommodate the varied contamination profile and geography of the area. The heavily contaminated area downstream of the calciner waste dump will require encapsulation to reduce contamination over time and to avoid large amounts of As being released into the local water system. The remaining contaminated soil around the stack and upstream of the calciner waste dump will be mechanically excavated and dumped, with the possibility of it being reused as aggregate material. This operation will cost between £3,500,000 and £3,850,000 approximately and will result in the complete restoration of the area, however it will not alter the infrastructure already there as this investigation has determined this isn't required.

When reusing the area, there are only two likely possibilities of uses for the site. The use of this site as an academic resource coupled with the alleviating of the cost via reuse of the excavated material is the best use of the area according to the findings and predictions of this investigation. This is providing the material is tested and found to have acceptable levels of As contamination within it to be used in commercial industries such as aggregates.

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