Probabilistic assessment of geogenic arsenic distributions for risk management in the Kwu Tung North New Development Area

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ABSTRACT

In the search for new sources of land supply, difficult ground or contamination issues may be encountered with potentially harmful trace elements existing in subsurface soils. On many occasions, these substances are naturally occurring and are not the result of anthropogenic contamination. This paper presents the multi-disciplinary efforts in characterising the spatial variability and evaluating the distributions of arsenic in the Kwu Tung North New Development Area (KTN NDA), and the soil stabilisation/solidification (S/S) works to further mitigate the associated health risks. Arsenic is a naturally occurring trace element that may pose a threat to human health and the ecosystem, and it is found in large variations of concentration at the KTN NDA. Based on data from over 1,300 samples obtained across the site, probabilistic estimates were made regarding the distributions of arsenic-containing soil, and soil volumes that may require S/S treatment. Through this probabilistic approach, the volume estimates are presented with various levels of confidence, and subsequent S/S treatment works can be planned in a time-efficient and cost-effective way according to the tolerable risk levels and availability of resources. Successful application of the approach at the KTN NDA demonstrates its applicability for other projects with geogenic trace elements in soil.

KEYWORDS Geogenic trace elements; risk assessment; spatial variability; new development area
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1. Introduction

Given Hong Kong's mountainous terrain and scarce land resources, the search for new sources of land supply to sustain its housing, social and economic development has not been an easy task. Development within an increasingly congested urban environment means that sites with difficult ground or contamination issues are inevitably encountered in land formation projects. This calls for more efforts to be exerted in relation to site characterisation and investigation works for better understanding of the geoenvironmental conditions and to control the associated risks. While our knowledge of the geochemical properties of contaminants and trace elements have improved, and various soil stabilisation techniques have advanced significantly in recent years (Tsang et al., 2014; Tsang and Yip, 2014; Li et al., 2017), success in site-specific planning for ground treatment – including cost estimation, procurement and equipment mobilisation – still hinges on the ability to properly estimate the extent and spatial distributions of these harmful substances.

This paper presents the geostatistical approach to characterise and assess the spatial variations in the occurrence of trace elements. The proposed method has been successfully applied in the planning of a large-scale new development area in Hong Kong, where a metalloid substance, arsenic, was naturally formed and distributed with high variability across the development footprint. The approach provides a systematic and rational means to evaluate the arsenic profile at locations where samples could not be obtained due to site constraints, enabling the assessments of uncertainty in these estimates, which may be linked to the risk levels across the site. These further allow informed decisions to be made regarding resource planning, where soil stabilisation and remediation strategies can be formulated in a rational and pragmatic manner to mitigate the risk to tolerable levels.

2. Project background

Located in the North East New Territories, the Kwu Tung North New Development Area (KTN NDA) covers a total area of about 447 hectares and will be the next-generation new town to meet the economic and population growth for Hong Kong in the medium to long term. According to the Environmental Impact Assessment (EIA) study conducted for the project (CEDD, 2013), it was confirmed that the arsenic-containing soil in KTN NDA is naturally linked to the formation of ash crystal tuff in the region and is environmentally safe. Although high arsenic concentrations were spotted at random locations with sporadic levels recorded across their depths, geochemical analyses of the retrieved samples affirmed that the arsenic is physically stable and has low leachability due to its dominating inorganic arsenate (V) speciation. Nevertheless, to safeguard public health, an independent health risk assessment was included as part of the EIA study to determine the suitable health risk baseline and the corresponding treatment method. By assessing the proportions of arsenic received by the human body through different exposure pathways with reference to international guideline values from the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA), it was established that soil with an arsenic concentration exceeding the threshold of 571 mg/kg requires treatment by solidification/stabilisation (S/S) in order to further enhance public safety.

Existing regulations and guidelines for managing chemicals of concern in the ground in Hong Kong (EPD, 2007) focus on the assessment and remediation of contaminants arising from anthropogenic sources, where standard sets of risk-based remediation goals (RBRGs) values have been developed for direct use under different land use scenarios (see Table 1). The use of RBRGs is confined to generic situations on sites with man-made contamination only (e.g. chemical spillage and brownfield sites) and are not applicable to the KTN NDA context due to the natural linkage of arsenic to the underlying geology at the site. Likewise, previous overseas studies (e.g. Waterhouse, 1980; Bell et al., 1983; Gilbert, 1987) and practice guidelines (UK CLR Report, 1994; EPD, 2011; MfE, 2016) have mainly focused on the detection and treatment of anthropogenic contaminants resulting from former industrial processes, or leakage/spillage of pollutants in the vicinity of the concerned site, with their distributions largely depending on the source and contaminant transport mechanisms. For the KTN NDA project, a major challenge in the characterisation of arsenic distributions stems from the lack of existing conclusive guidelines on the assessment of trace elements of a geogenic origin. A site-specific assessment is therefore required to assess the risk of this naturally occurring arsenic and to determine the appropriate soil treatment volumes and management strategies for the development of the KTN NDA.

Table 1. RBRG threshold values for arsenic metal (EPD, 2007).

Land use Scenarios	RBRGs
Rural residential	21.8 mg/kg
Urban residential	22.1 mg/kg
Public parks	73.5 mg/kg
Industrial	196 mg/kg

3. Distribution and concentration levels of arsenic-containing soil

Owing to the high natural variability associated with geogenic arsenic concentrations under subsurface conditions, and site accessibility issues that have hampered further sampling at some regions, it is necessary to employ a rational approach to characterise the spatial variability features thereof, in order to estimate the concentration levels at unsampled locations. Apart from obtaining "best estimates" of concentration levels, it would be useful to evaluate the uncertainty levels associated with the estimates where samples are not available. From the planning and risk management perspective, it is also essential to establish the extent of treatment zones (with concentrations exceeding 571 mg/kg) and hence the potential volume of soil requiring S/S treatment. The uncertainty in geogenic arsenic distributions also manifests itself in the volume and cost estimates for S/S treatment. The approach proposed in this paper allows such estimates to be rationally obtained, where the risk and uncertainty involved are quantified and properly communicated.

Figure 1 shows the locations of boreholes where soil samples were retrieved for testing the arsenic content. In the Stage 1 site investigation (2011), 388 soil samples were retrieved from 35 boreholes and tested for arsenic concentration. Subsequently, the Stage 2 site investigation commenced in 2016, and provided 914 additional samples from 73 boreholes across the NDA. Figure 2 shows the histogram of arsenic concentrations for the 1,302 test samples. A large variability is observed, with measured values ranging from 1 mg/kg to 3,680 mg/kg. Among the sample values, the median is approximately 50 mg/kg, while the 95th percentile is very close to the treatment threshold of 571 mg/kg. This indeed highlights the necessity for spatial variability analyses, as it is important to establish the spatial distributions of arsenic and pinpoint the high-risk zones for treatment. It is not cost-effective to base the judgement on spatial extent of arsenic, and hence resource planning for soil stabilisation, simply on the raw data across the entire development area.

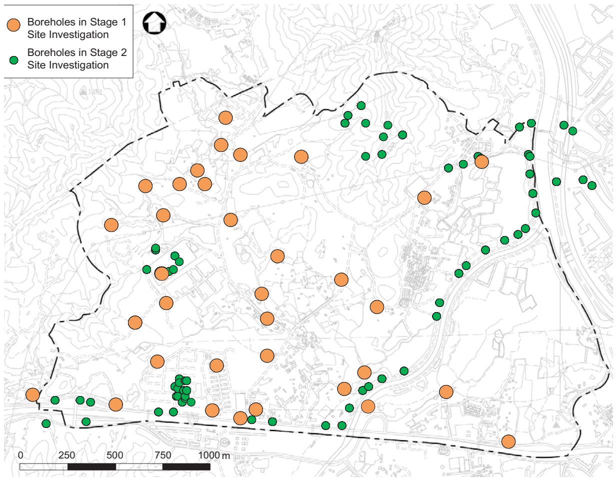

Figure 1. Locations of boreholes with samples retrieved from Stage 1 and Stage 2 site investigations at KTN NDA.

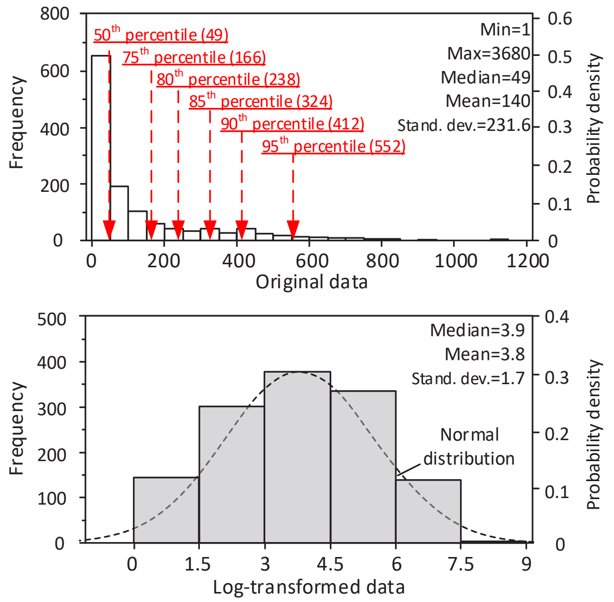

Figure 2. Statistics of sampled data on arsenic concentration levels across the KTN NDA.

4. Geostatistical modelling for 3D anisotropic correlation

The geostatistical approach adopted in this study was developed and discussed in detail by Liu and Leung (2018) and Leung et al. (2018). Essentially, the main objective of geostatistical analyses is to characterise the spatial variability/correlation patterns of arsenic, based on the existing measured data. Many properties of natural geomaterials are observed to be spatially correlated. For example, the arsenic concentrations z_i and z_j may be similar to each other if the locations i and j are close to each other, while greater variations are observed for larger separation distances. Mathematically, these patterns are expressed as "autocorrelation functions", with key parameters θ referred to as "autocovariance distances". The θ values also represent the ranges of autocorrelation: the correlations in properties (i.e. arsenic concentrations) are considered to be insignificant when the separation distances exceed these range parameters. Within a 3D subsurface domain, the values of θ may differ in horizontal and vertical directions (i.e. θ_1 and θ_2), meaning that the correlation ranges and patterns are different along various directions. Figure 3 illustrates this concept graphically, and it can be further shown that using θ_1 and θ_2, the θ values along other directions in 3D space can be represented by an ellipsoid, an example of which is also presented in the figure. Figure 3 also shows that the data are represented as combinations of a trend and residual values. The trend is modelled as a quadratic function in this study, while the residuals are spatially correlated with the autocorrelation modelled as a squared exponential function. Utilising the observed data, the parameters for the trend and autocorrelation functions are obtained using the restricted maximum likelihood method. The details of the mathematical framework have been reported earlier by Liu and Leung (2018).

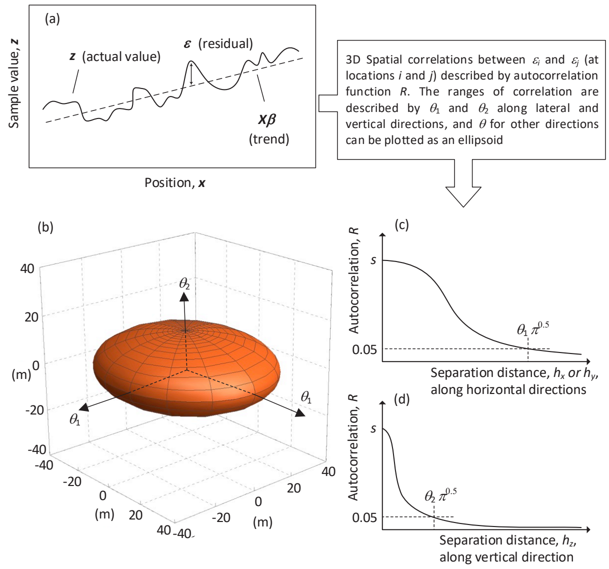

Figure 3. Trend and residual effects in sample values, with the latter simulated by a 3D spatial variability model.

The spatial variability features from all 1,302 test samples at the KTN NDA can be characterised by obtaining the set of θ_1 and θ_2 parameters which best match the site measurements. Once these parameters are determined, predictions on arsenic concentration can be made at unsampled locations, including the best estimates of concentration level ($\hat{z}$) at various locations, and the level of uncertainty at these locations. This uncertainty is quantified by an indicator known as the prediction variance (σ_z^2). In general, the uncertainty is low and close to previously obtained samples, and increases with the separation distance away from existing sample points. From the risk evaluation and management perspective, $\hat{z}$ and σ_z^2 also determine the probability of arsenic concentration exceeding the treatment threshold of 571 mg/kg at a certain location. It is then possible to estimate the concentration levels at various "non-exceedance probabilities", such as 50%, 75% or 95%, etc. To illustrate this concept, Figure 4 shows a hypothetical example, where the best estimate of arsenic concentration ($\hat{z}$) at an unsampled location and the prediction variance (σ_z^2) are shown together with concentration levels at 75% and 95% non-exceedance levels. At this hypothetical location, there is less than a 5% probability that the actual concentration will exceed 571 mg/kg. Similar probabilistic assessments can be performed for every unsampled location in the 3D subsurface domain across the entire site.

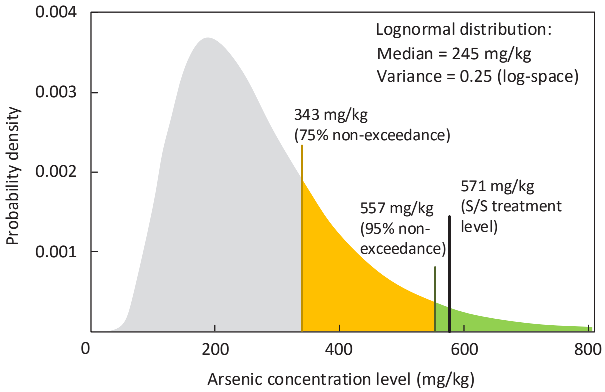

Figure 4. Example of the probability distribution of predicted arsenic concentration at an unsampled location.

5. Results of geostatistical analyses

The 1,302 test results of arsenic concentrations were classified into three groups depending on the soil type where the sample was retrieved. The three soil types are fill material, alluvium and saprolites, which are mainly completely decomposed tuff/sandstone. Separation of the dataset into these sub-groups allowed the different mineralogy and geological origins of the soils, and their arsenic contents, to be taken into account during characterisation of the spatial variability features. The autocovariance distances were determined using the corresponding samples for each category, after which the best estimates $\hat{z}$ and prediction variance σ_z^2 were evaluated for the unsampled locations across the KTN NDA site. The large site area was discretised into grids of horizontal spacing of 37 m (east-west direction) × 27 m (north-south direction), with each grid representing approximately 1,000 m^2. There were a total of about 5,500 calculation points for each elevation, with the calculation grid across the KTN NDA also shown in Figure 5. Along the vertical (depth) direction, the calculation interval was assigned to be 5 m. The soil types at different elevations of the unsampled locations were interpolated from the subsurface stratigraphy model interpolated from the borehole records. The figure also shows the planned development areas at the KTN NDA, and the calculation grid points were defined to match the future development plans.

Table 2. Spatial correlation parameters of arsenic concentrations in three soil types.

Soil type	s	θ_1 (m) (horizontal directions)	θ_2 (m) (vertical direction)
Fill	0.72	15.2	3.1
Alluvium	0.65	30.5	3.12
Completely decomposed tuff/ sandstone	0.59	38.5	10.6

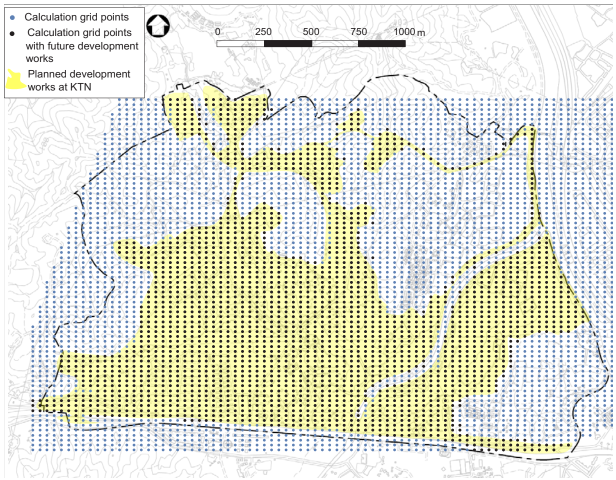

Figure 5. Development plans at the KTN NDA and calculation grid points in this study for prediction of arsenic concentrations.

Figure 6(a) shows the best estimates ($\hat{z}$) of arsenic concentrations across the KTN NDA in mg/kg, while Figure 6(b) presents the prediction variance (σ_z^2) in log-space (the concentrations are assumed to be lognormally distributed) at two elevations (0 mPD and +10 mPD). Through estimates of $\hat{z}$ and σ_z^2, the concentrations at various non-exceedance probabilities can also be evaluated. For instance, Figure 6(c) shows the estimated arsenic concentrations across the site at 75% non-exceedance probabilities. In this case, there is a probability of 25% that the actual concentrations may exceed the presented values. From the risk management perspective, another important aspect is the potential extent of regions where the arsenic concentrations may exceed the treatment threshold of 571 mg/kg. These regions are highlighted in Figure 7, which reveals the locations where S/S treatment is "likely" to be necessary, with the corresponding probabilities also presented on the same figure. The results indicate large differences in the extent of potential treatment zones when comparing 90% and 95% non-exceedance levels (or 10% versus 5% probability with a concentration exceeding 571 mg/kg), due to the long tails associated with the lognormal distributions with high uncertainty (large variance).

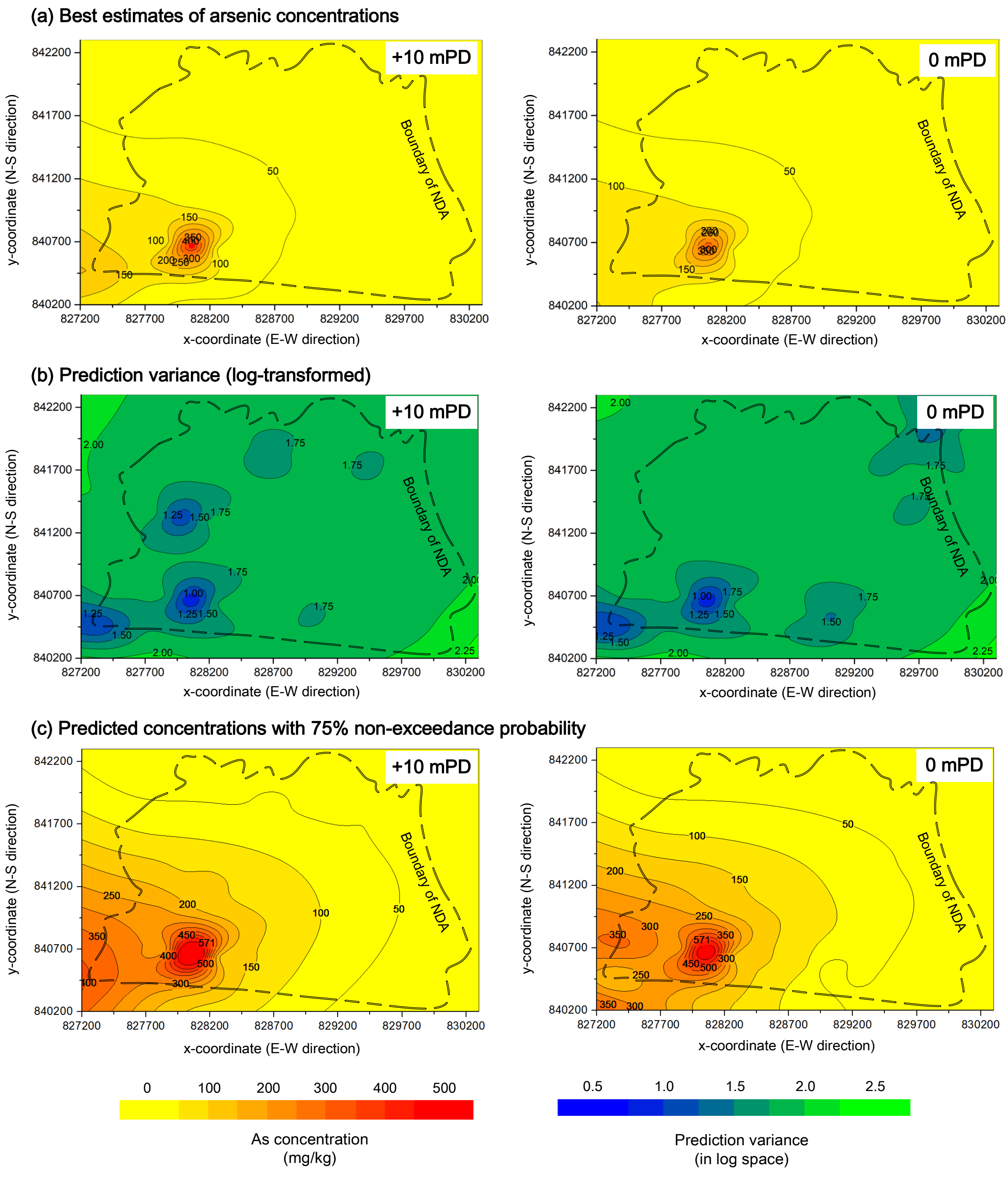

Figure 6. (a) Best estimates ($\hat{z}$); (b) prediction variance (σ_z^2); and (c) estimated concentrations at 75% non-exceedance probability across the NDA at two elevations.

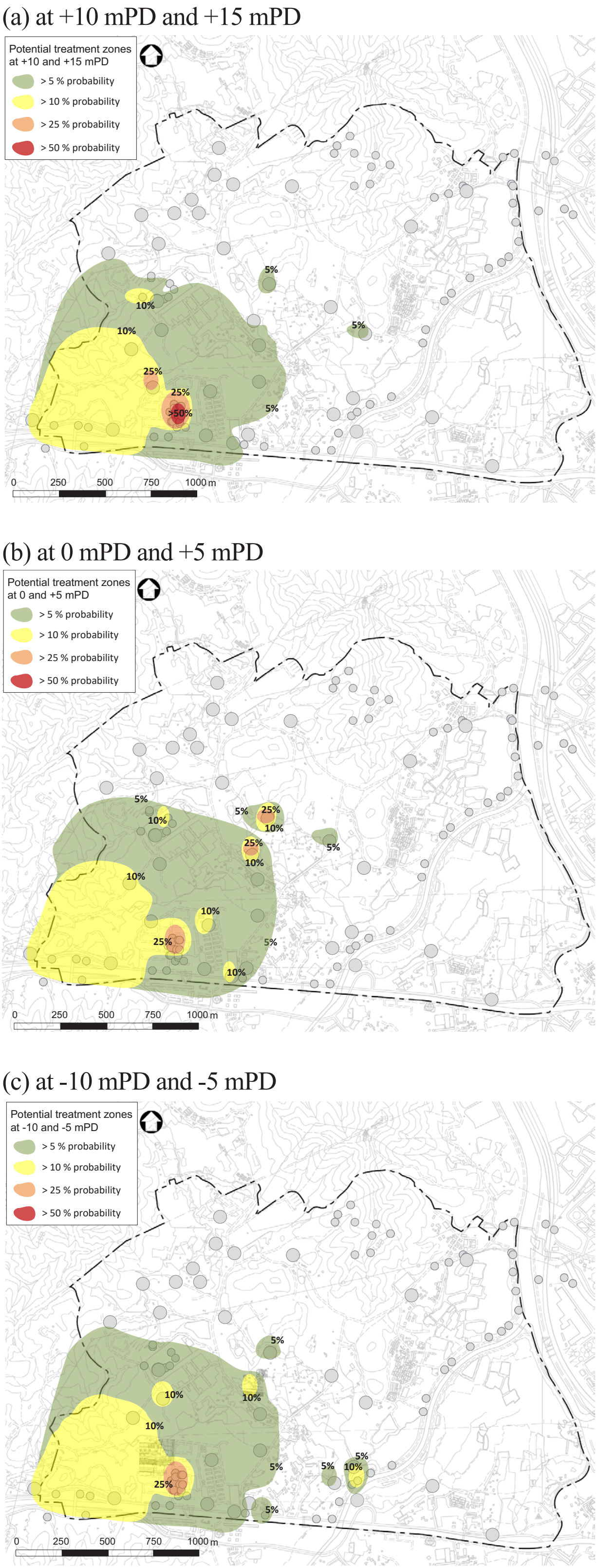

Figure 7. Potential extent of S/S treatment with different probabilities of arsenic concentrations exceeding 571 mg/kg (green-5%; yellow-10%; orange-25%; red-50%).

6. Volume estimates for the potential S/S treatment zone

For the planning of S/S treatment and cost estimation purposes, this study also predicted the total volume of zones where arsenic concentrations are likely to exceed the threshold value of 571 mg/kg. While Figure 7 illustrates the potential locations and extent of these treatment zones under different non-exceedance probabilities, these zones should not be simply summated in the estimation of S/S treatment volumes. For example, it is highly unlikely that all of the highlighted green zones will eventually require S/S treatment, since these regions are only associated with a 5% probability of concentration levels exceeding the threshold. Summing all these areas will lead to gross overestimations of the potential treatment volumes.

To rationally estimate the treatment volumes at different confidence levels, this study employed a Monte Carlo-type simulation approach, taking into account the best estimates ($\hat{z}$) of arsenic concentrations and their uncertainty levels (σ_z^2) evaluated previously. In addition, accounting for the future development plans at the KTN NDA, the following assumptions were adopted in the evaluations:

(1) Potential S/S treatment was only considered for regions with future development works (Figure 5);
(2) Along the depth direction, potential S/S treatment was considered from the existing ground surface down to 4 m below the site formation level, under the current development plans; and
(3) A minimum treatment depth of 5 m was adopted where information on site formation levels was not yet available.

It should be noted that the above assumptions were adopted at the planning stage of the project, to facilitate rational estimates of treatment volume according to the information known at the time. Under these assumptions, the treatment volumes and the corresponding confidence levels were estimated through 10,000 realisations. For each realisation, a series of random numbers r_i were generated, with i counting from 1 to the number of grid points under the development areas and following the standard normal distribution. Subsequently, for each prediction point (calculation grid), the arsenic concentration for a particular realisation was therefore:

$$\tilde{z_i} = e^{\left(\hat{z_i}+r_i\sqrt{\sigma_{z,i}^2}\right)}, \quad (1)$$

where $\hat{z_i}$ and $\sigma_{z,i}^2$ are the best estimate and prediction variance at location i, represented in the log-space. If $\hat{z_i}$ exceeds 571 mg/kg, the volume represented by i (with a plan area of 1,000 m^2 and thickness of 5 m) will be included for soil treatment. For each realisation, this calculation is performed for all zones under the development plans, and a total of 10,000 realisations were generated and analysed in the current probabilistic assessment. This allowed the probability density, and hence confidence levels of potential treatment volumes to be determined. Figure 8 shows the probability density of estimated treatment volumes from the 10,000 realisations. The mean estimate was close to the median of 470,000 m^3, while the coefficient of variation (c.o.v. = standard deviation divided by mean) was approximately 10%. The cumulative distribution of all results is also shown in Figure 8, which can be used for interpretations for different levels of confidence. For example, the 75th percentile of estimates corresponds to a S/S treatment volume of 505,000 m^3, meaning that there is a 25% probability of the actual treatment volume being larger than this value. The 95th percentile corresponds to a treatment volume of 555,000 m^3.

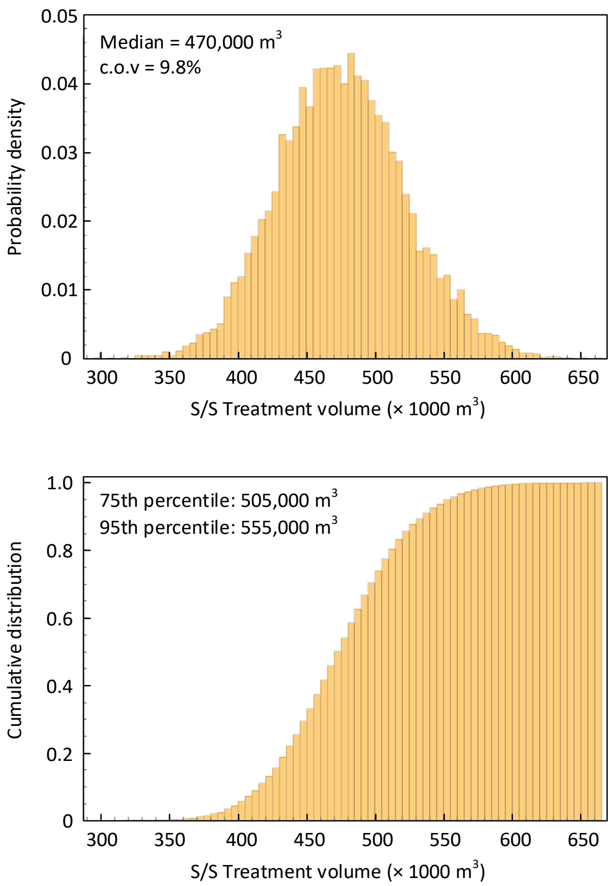

Figure 8. Probability density and cumulative distribution of estimated S/S treatment volumes (with arsenic concentration > 571 mg/kg).

The previous EIA study (CEDD, 2013) made a preliminary estimate of treatment volume based on the development plans and the relatively limited data available at the time. While this was within the same order of magnitude as the values presented in Figure 8, it is worth noting that the previous estimate inevitably involved certain degrees of conservatism or qualitative expert opinion that were difficult to trace or express quantitatively. By adopting the proposed approach in this study, new information has been incorporated rationally to provide a scientific estimate of the treatment volume, and the levels of confidence in these estimates are also reported in an explicit and quantitative manner, which serve as an important reference for project planning and implementation.

7. Conclusions

This paper introduces a probabilistic approach to make rational predictions on the best estimates and prediction variance of the concentration levels of trace elements in the 3D subsurface domain. We investigated the distributions and spatial correlations of geogenic arsenic across the KTN NDA, where 1,302 samples had been retrieved from the fill, alluvium and completely decomposed tuff/sandstone layers, and tested for arsenic concentration levels. Different spatial variability features were observed in these soil types, which are deemed reasonable considering their geological origins and that of the geogenic arsenic. The probabilistic framework allows these variations to be quantified and explicitly incorporated into the analyses, leading to estimates of arsenic concentration levels at different probability levels (or levels of confidence). From the risk assessment and management perspective, the approach allows probabilistic estimates to be made on the extents and volumes of soils that require S/S treatments as parts of the site formation works. The volume estimates are presented with various levels of confidence, and hence the soil treatment works can be planned according to the availability of resources and tolerable risk levels. While the approach has been successfully applied in the analysis for the KTN NDA, it can also be adopted to the planning of soil treatment and site formation at other new development areas with potentially harmful trace elements in the soil.

Besides the approach proposed in this paper, other non-parametric methods such as Bayesian compressive sampling (Wang and Zhao, 2017; Zhao and Wang, 2020) have recently been developed and applied to quantify uncertainty levels in subsurface material properties and distributions. These methods may also be considered in future development projects that involve risk assessments of a similar nature.

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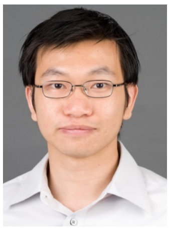

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