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In-situ Monitoring of the Legacy Ponds and Silos at Sellafield

Spatial representation and uncertainties in particle sizing

Olusola Ayoola
University of Manchester

Supervised by:

Prof. Barry Lennox
University of Manchester

Dr Simon Watson
University of Manchester

Geoff Randall
Sellafield Ltd.

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Highlights of Presentation

- Introduction
- The Need
- The Issues
- The Observations
- What Next?

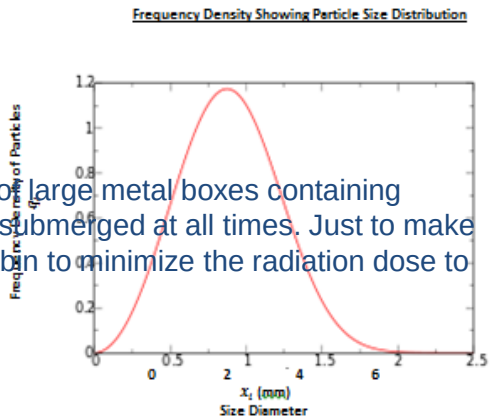
Introduction

- **What is Particle Size Distribution (PSD)**

  PSD is a representative indication of the array of sizes of particles present and their respective proportions in the particulate sample group measured. [1]

- **The pond and sludge situation**

  "What makes the job more difficult is that the pond is very congested and full of large metal boxes containing nuclear fuel, so we need to work around these and ensure these remain fully submerged at all times. Just to make matters more difficult we have to drive the platform remotely from a control cabin to minimize the radiation dose to the workforce," Leafe. [2]



The Frequency Density Function

- **Extended applications**

  Long-term stability of stored waste, Turbidity, Sediment Settling, etc.

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The Need

- **To monitor PSD and other qualifiers of the sludge in the pond**.
  - To support transportation system design [3] and choice of test materials
  - To monitor chemical, physical and biological changes

- **To identify and evaluate significant components of variability in measurements.**
  - To improve optimisation and robustness of technical procedures.
  - To support confidence in decision making.

- **To develop spatial maps of sludge characteristics and their associated confidence levels.**

- **To explore in-situ autonomous sampling and analysis solutions**

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The Issues - Resources

- **Identify Relevant Resources**
  - The PSD challenge in the Pharmaceutical, Food Processing, Detergent-making and Sewage/Water Treatment plants
  - The spatial mapping challenge in the field of Geostatistics, Geology, Geography, Ecological sciences and spatiotemporal industrial processes.
  - Relevant past experiences (PSD data, sampling guides and ISOs)
  - Data Quality Objectives

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The Issues - Uncertainties

Sampling/Analysis Procedure Uncertainties

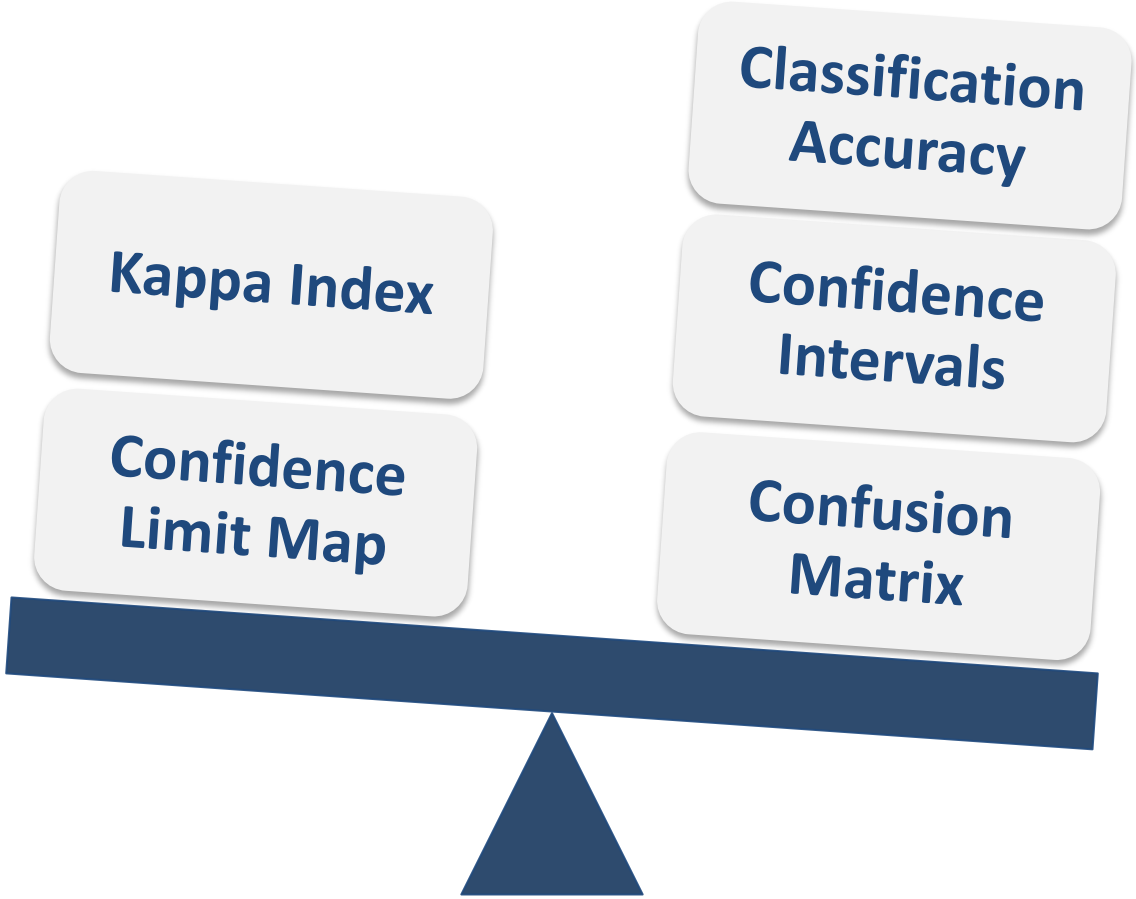
Analytical/Measurement Uncertainties

1. Analyser Technique
2. Data Interpretation
3. Parameter Reliability
4. Dispersion Medium
5. Sample Size and Concentration
6. Sample Preparation
7. Chemical/Physical Activity of Sample

Sampling/Spatial Uncertainties

1. Number of Samples
2. Number of Runs
3. Sampling Strategy
4. Sampler Device
5. Sampler Positioning
6. Sample Handling.
7. Spatial Extrapolation
8. Spatial Autocorrelation

The Issues – Performance indices



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The Issues – Statistical tools

- **Screening factorial components of uncertainties required the following tools:**
  - 2^k Factorial Analysis of Variance (ANOVA) Approach
  - Half-Normal Plot of Effects.

- **Estimating PSDs of non-sampled pixels from sampled data required:**
  - Kriging Interpolation Method
  - Delaunay Triangular Algorithm
  - Inverse Distance Method

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THE Issues – Data Presentation

- **The aim is to provide the following experimental data at the end of the Sampling and Analysis procedure:**
  - PSD measurements of sludge collected at sampled points and their nugget properties.
  - Predicted PSD measurements of sludge at non-sampled points.
  - 99% Confidence Intervals or Variance on a spatial map for the PSD data of the pond.

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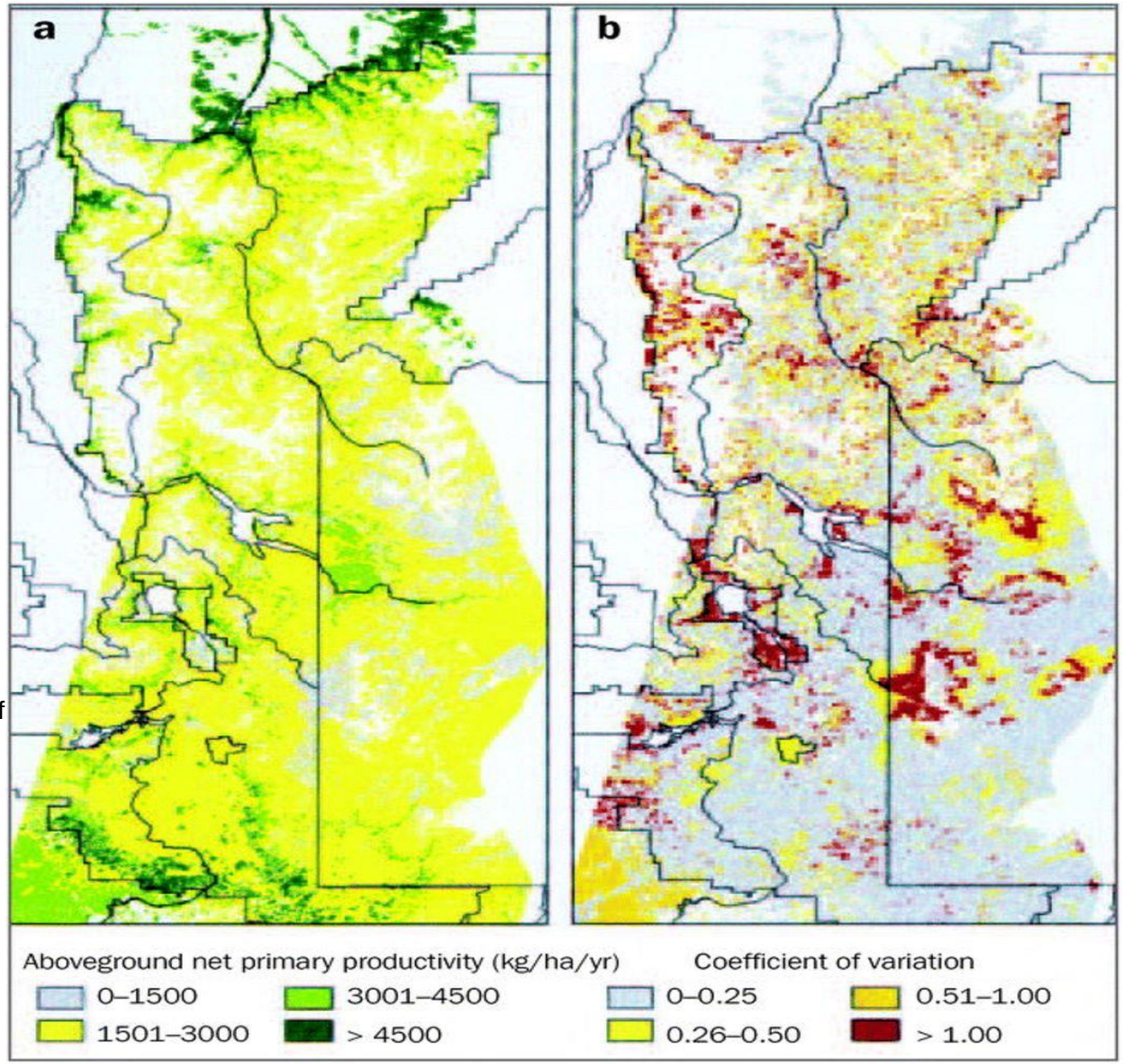
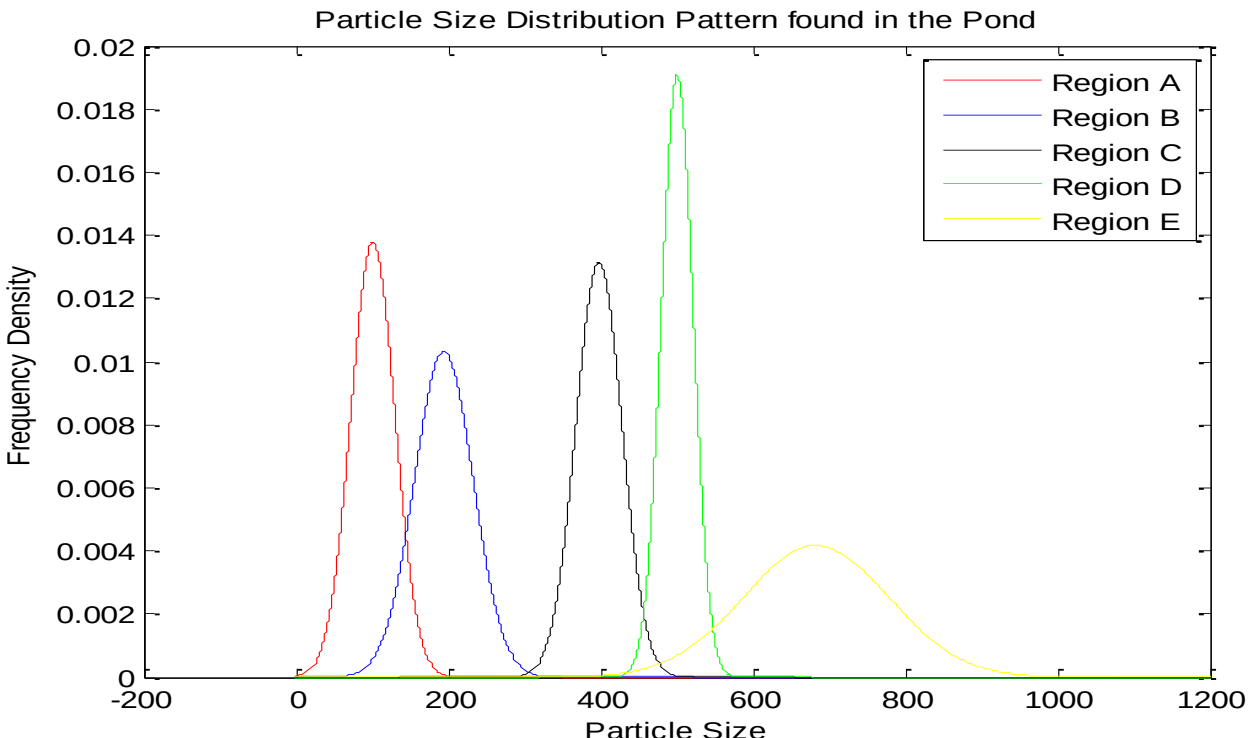
a) Predicted Distribution of the Aboveground Net Primary Productivity for Greater Yellowstone ecosystem [4]

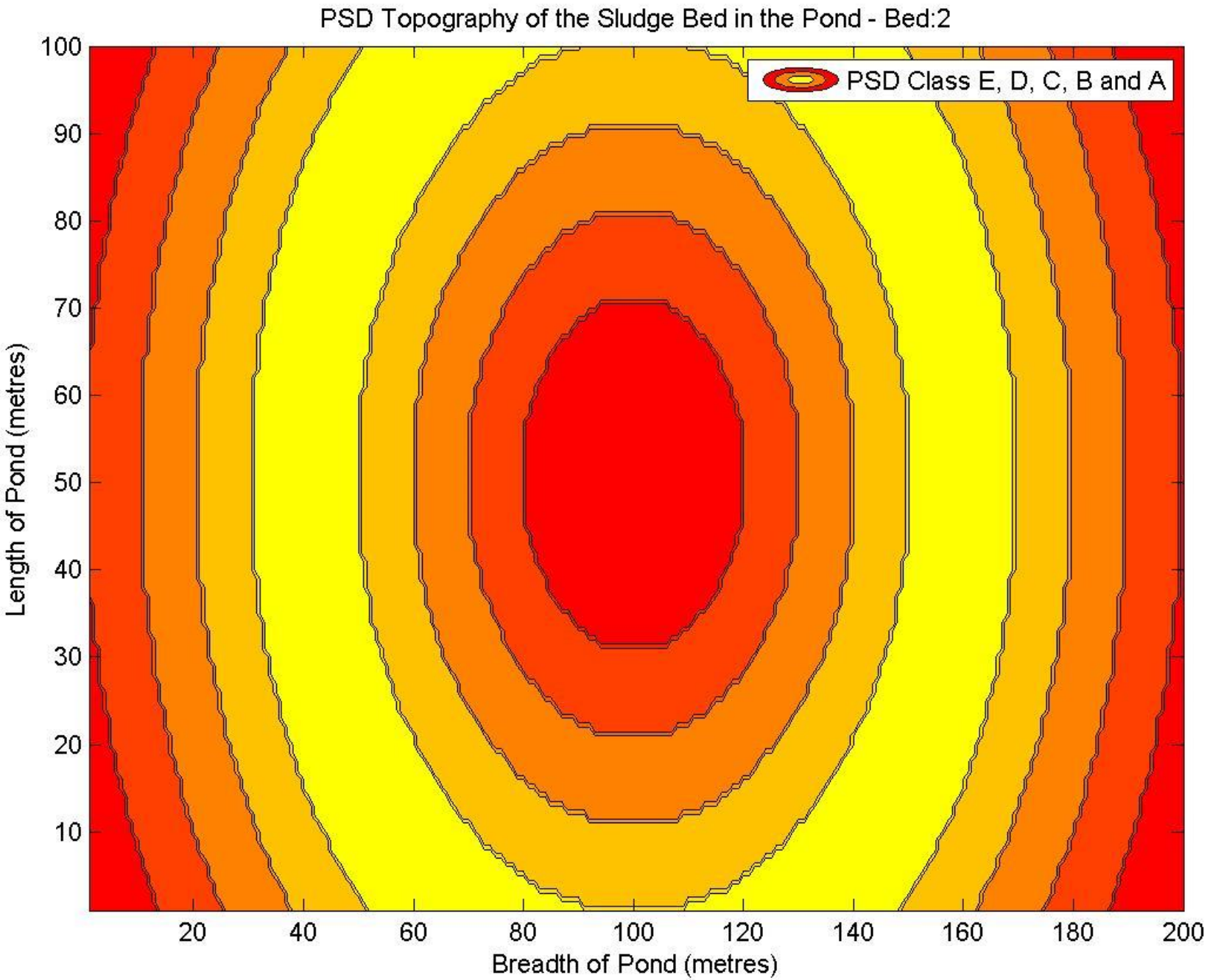


b) Estimates of Coefficient of Variance in the predicted ANPP [4]

The Observations - Introduction

- **Sludge Bed Topography Models:**
  - Without spatial autocorrelation (Bed 1)
  - With spatial Autocorrelation (Bed 2)




PSD Topography of the Sludge Bed in the Pond - Bed:2
PSD Class E, D, C, B and A
Length of Pond (metres)
Breadth of Pond (metres)
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
120
140
160
180
200

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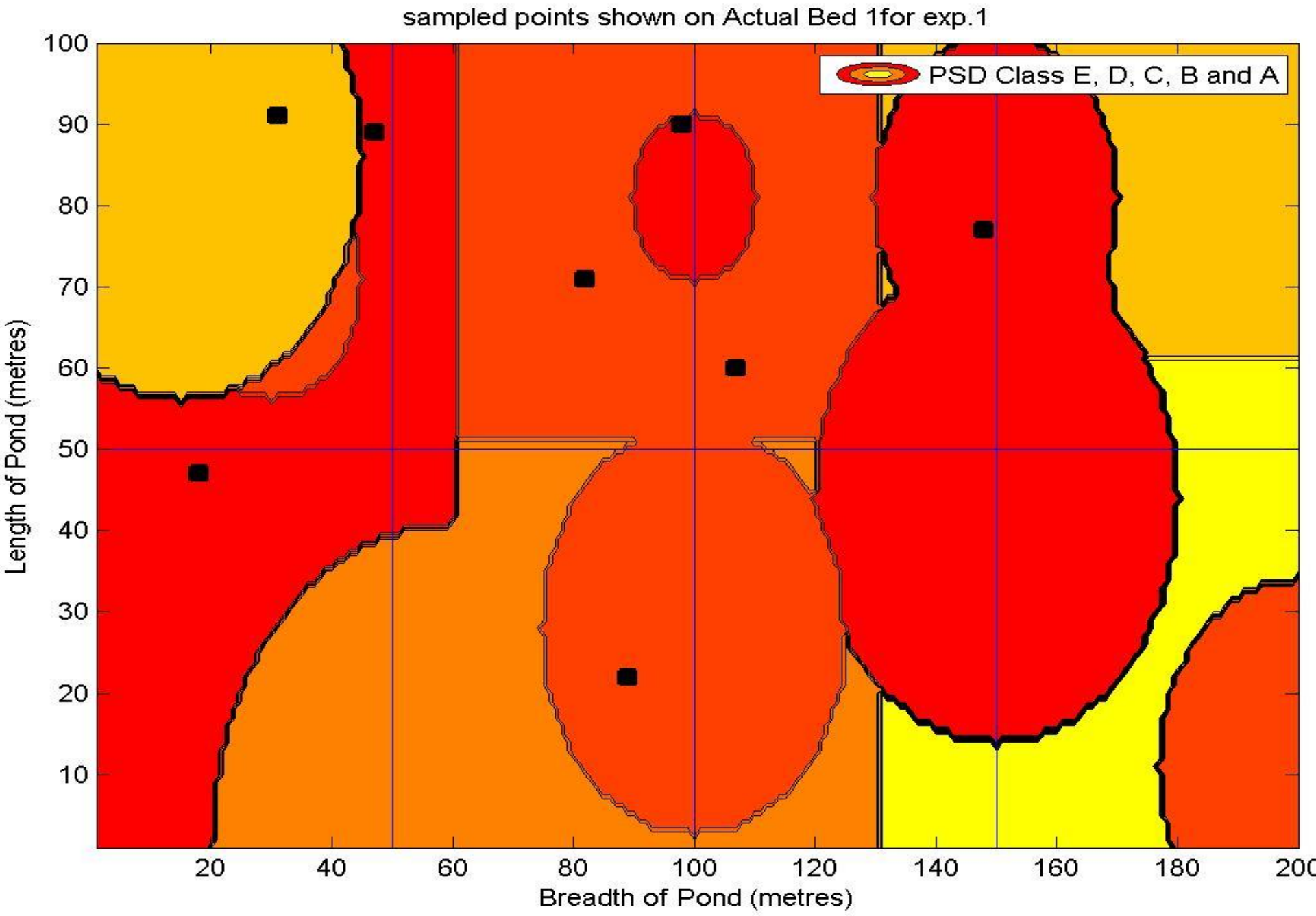
The Observations - Introduction

- Sludge Bed Topography Models:
  - Without spatial autocorrelation (Bed 1)
  - With spatial Autocorrelation (Bed 2)
- Sampler Device Models:
  - Suitable for particles less than 300 microns
  - Suitable for al particle sizes
- Sampling Strategy Models:
  - Simple Random Sampling
  - Stratified Random Sampling


sampled points shown on Actual Bed 1for exp.1
PSD Class E, D, C, B and A
Length of Pond (metres)
Breadth of Pond (metres)
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
120
140
160
180
200

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The Observations - Introduction

- Sludge Bed Topography Models:
  - Without spatial autocorrelation (Bed 1)
  - With spatial Autocorrelation (Bed 2)
- Sampler Device Models:
  - Suitable for particles less than 300 microns
  - Suitable for al particle sizes
- Sampling Strategy Models:
  - Simple Random Sampling
  - Stratified Random Sampling
- Number of Sampled Points (Sampling Density:)
  - 8 and 200 Samples
- Temperature of the Environment (Dummy Model):
  - 20 deg.C and 25 deg C.

THE Observations – ANOVA RESULTS

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Analysis of Variance

Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
A	117775.7	1	117775.7	15404.8	0
B	0	1	0	0	1
C	0.1	1	0.1	0.02	0.8996
D	0	1	0	0	1
A*B	0	1	0	0	1
A*C	20.5	1	20.5	2.69	0.1033
A*D	-0	1	-0	-0	0
B*C	-0	1	-0	-0	0
B*D	-0	1	-0	-0	0
C*D	0	1	0	0	1
A*B*C	-0	1	-0	-0	0
A*B*D	-0	1	-0	-0	0
A*C*D	0	1	0	0	1
B*C*D	0	1	0	0	1
A*B*C*D	-0	1	-0	-0	0
Error	1100.9	144	7.6		
Total	118897.3	159			

Factor A – Number of Samples
Factor B – Sampler Device
Factor C – Sampling Strategy
Factor D – Temperature of Environment

THE Observations – The Effects

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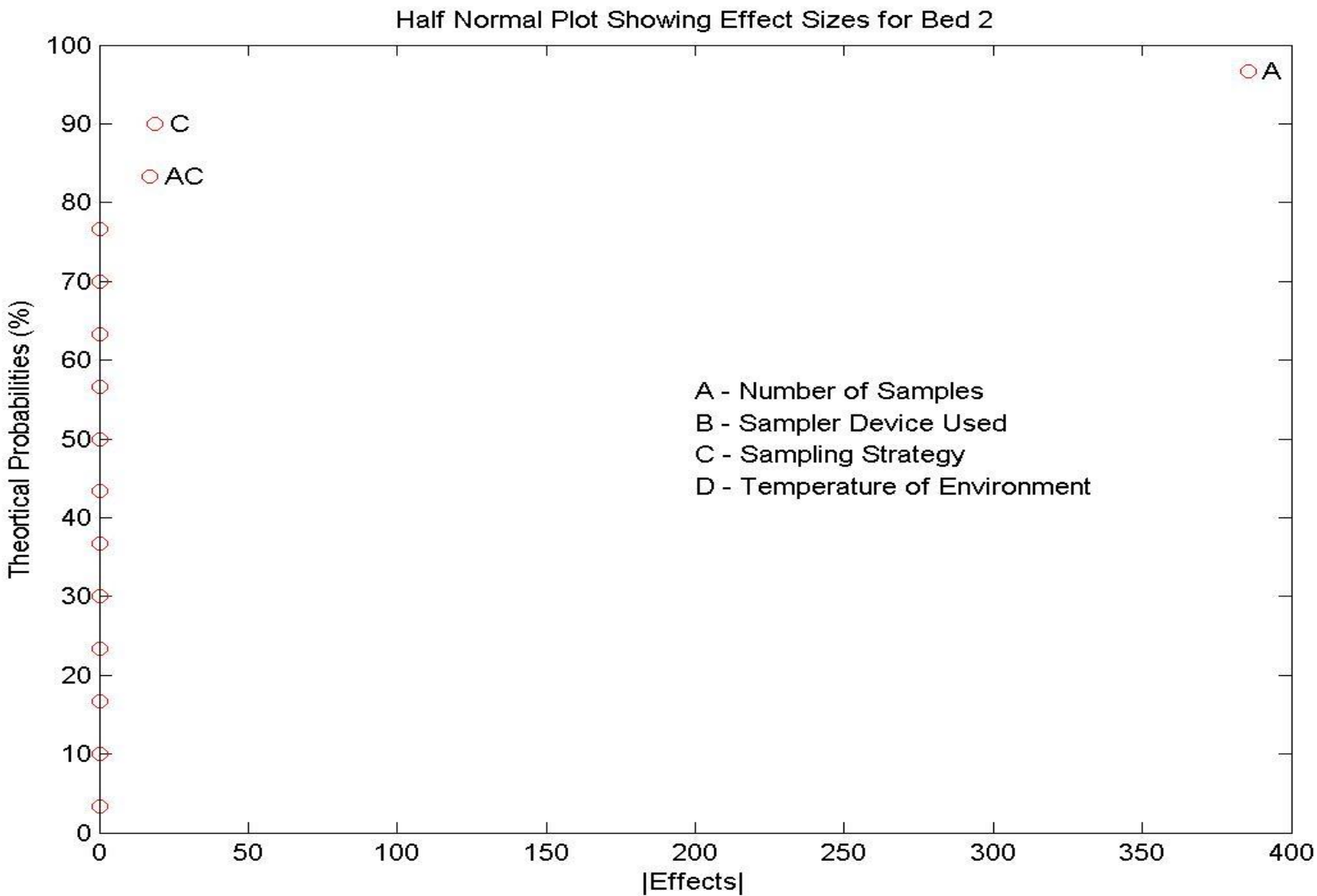
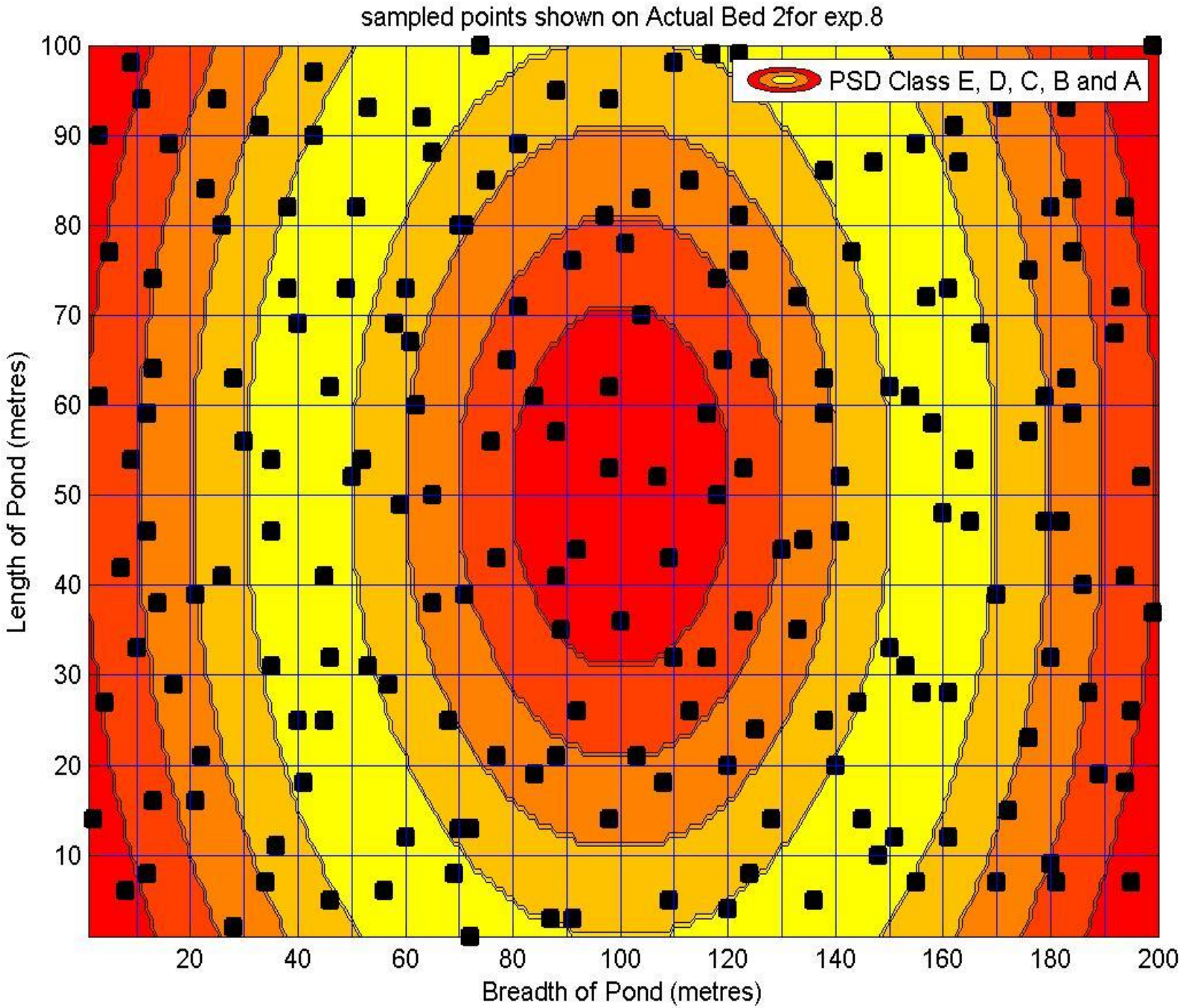
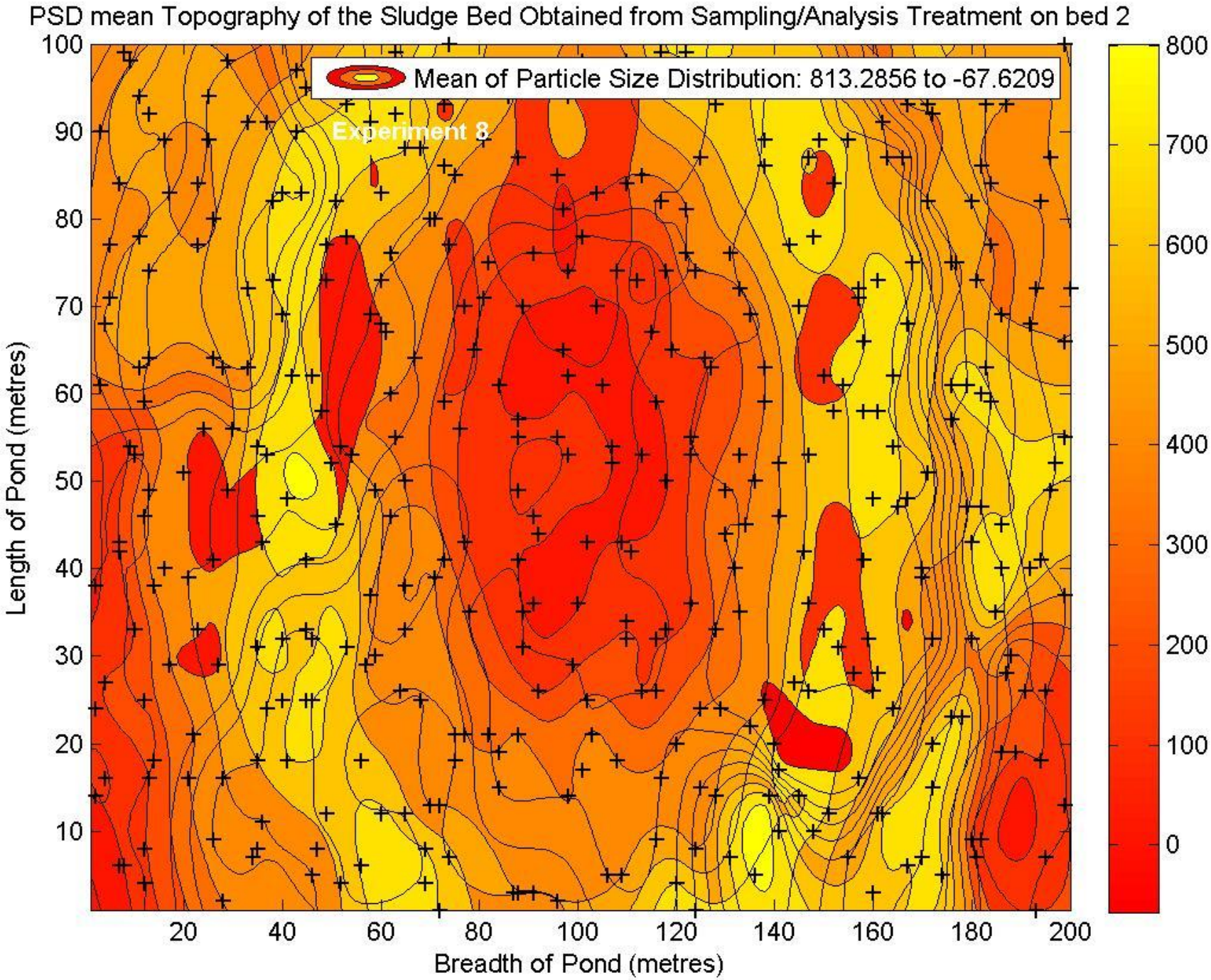


THE Observations –PSD Spatial Map Assessment


sampled points shown on Actual Bed 2for exp.8
PSD Class E, D, C, B and A
Length of Pond (metres)
Breadth of Pond (metres)
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
120
140
160
180
200


PSD mean Topography of the Sludge Bed Obtained from Sampling/Analysis Treatment on bed 2
Mean of Particle Size Distribution: 813.2856 to -67.6209
Experiment 8
Length of Pond (metres)
Breadth of Pond (metres)
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
120
140
160
180
200
800
700
600
500
400
300
200
100
0

THE Observations – Confidence limit Map {Inverse Distance Method}

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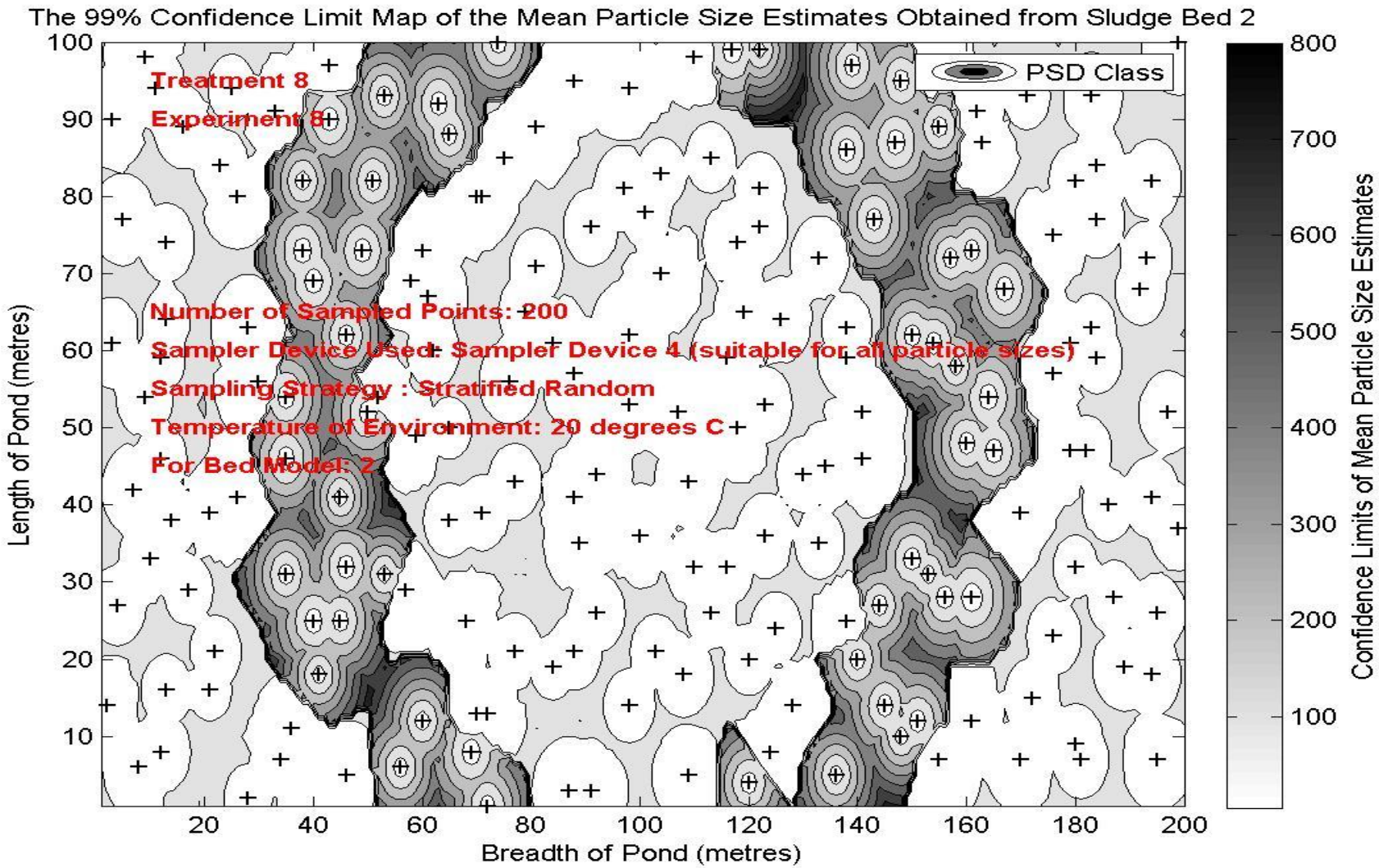
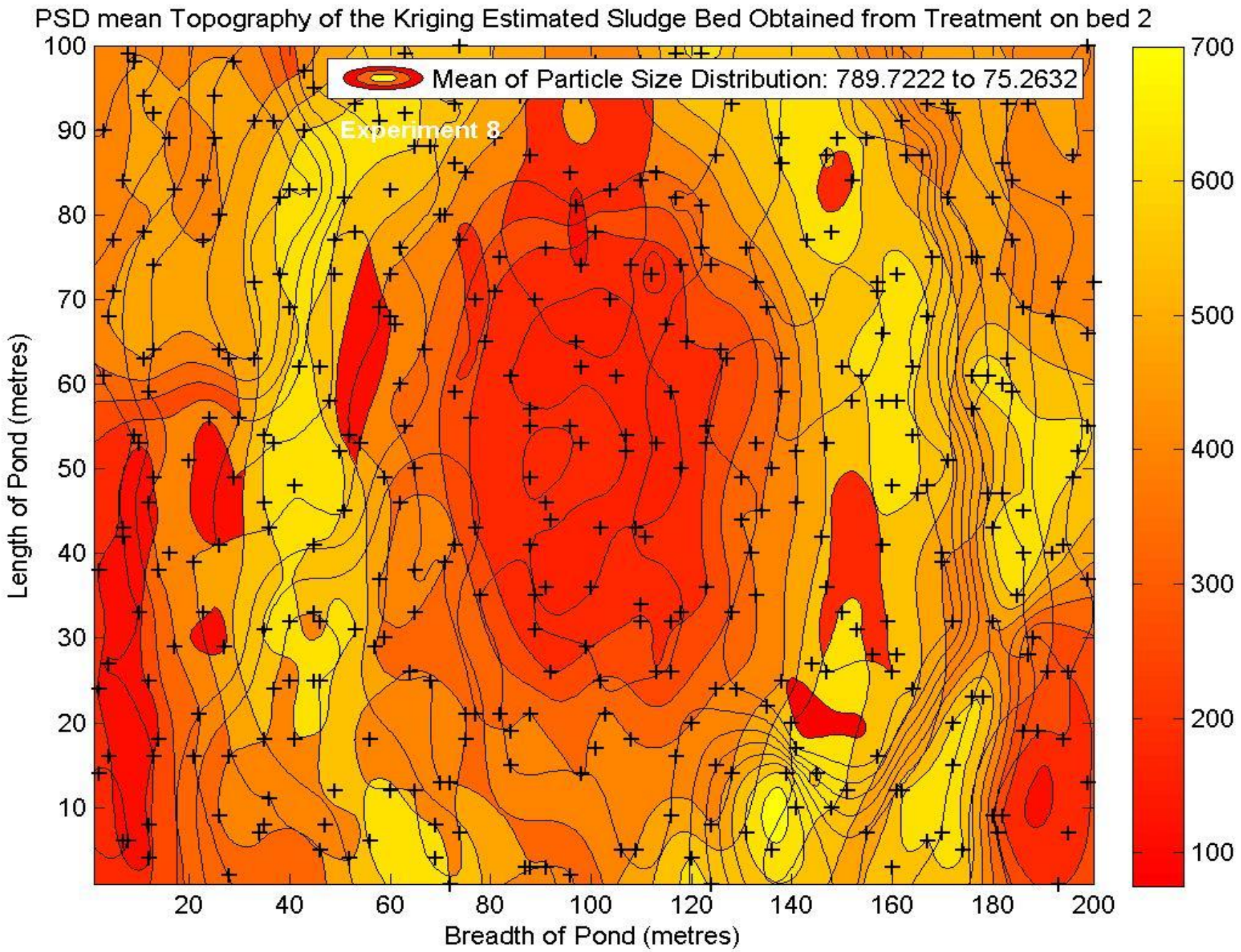
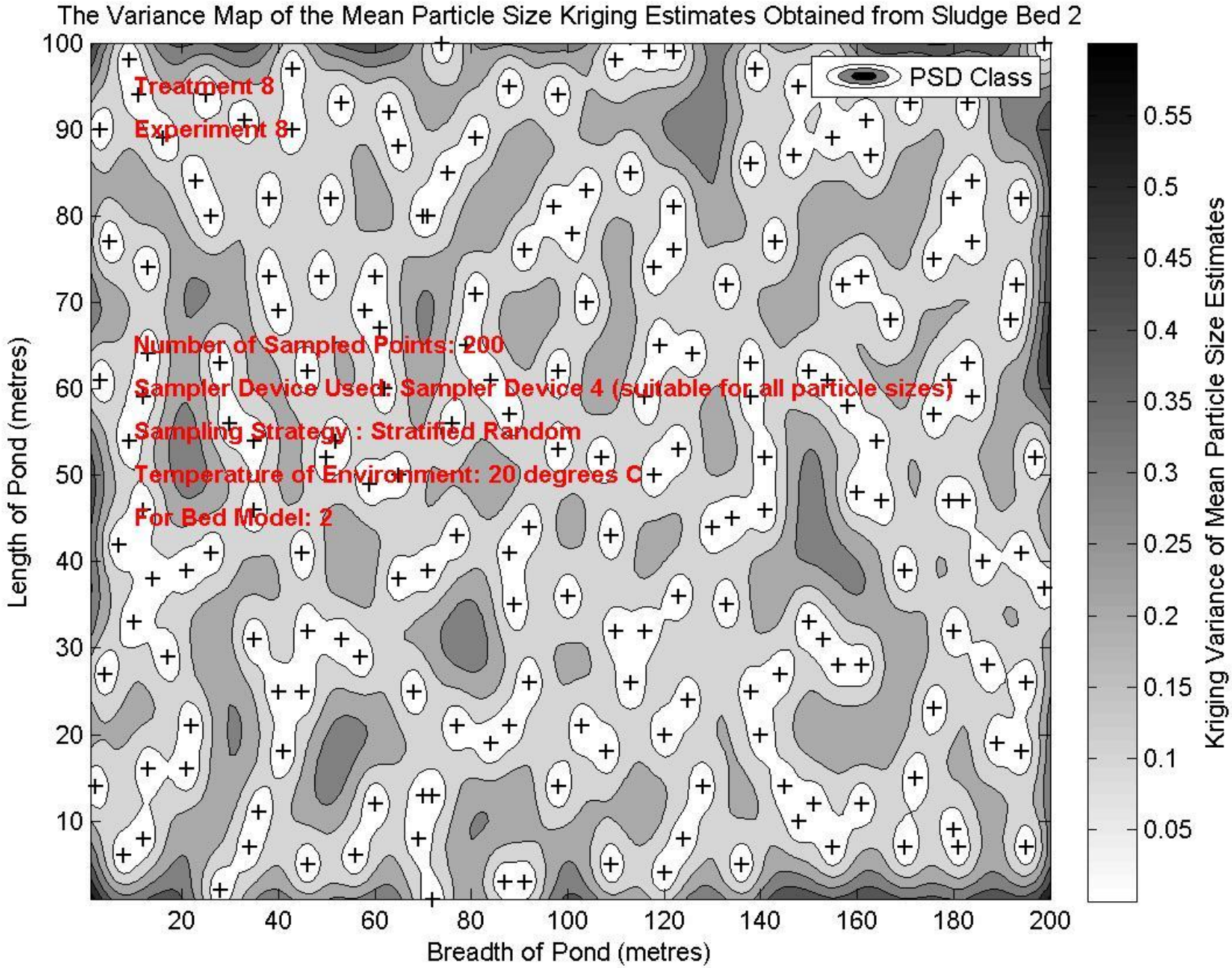


THE Observations –PSD Spatial Map Assessment {Kriging}


PSD mean Topography of the Kriging Estimated Sludge Bed Obtained from Treatment on bed 2
Mean of Particle Size Distribution: 789.7222 to 75.2632
Experiment 8
Length of Pond (metres)
Breadth of Pond (metres)
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
120
140
160
180
200
700
600
500
400
300
200
100

THE Observations – Kriging Variance Map


The Variance Map of the Mean Particle Size Kriging Estimates Obtained from Sludge Bed 2
Treatment 8
Experiment 8
Number of Sampled Points: 200
Sampler Device Used: Sampler Device 4 (suitable for all particle sizes)
Sampling Strategy : Stratified Random
Temperature of Environment: 20 degrees C
For Bed Model: 2
PSD Class
Length of Pond (metres)
Breadth of Pond (metres)
Kriging Variance of Mean Particle Size Estimates
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
120
140
160
180
200
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05

With Only 8 Sampled Points?

THE Observations – PSD Spatial Map Assessment {Kriging}

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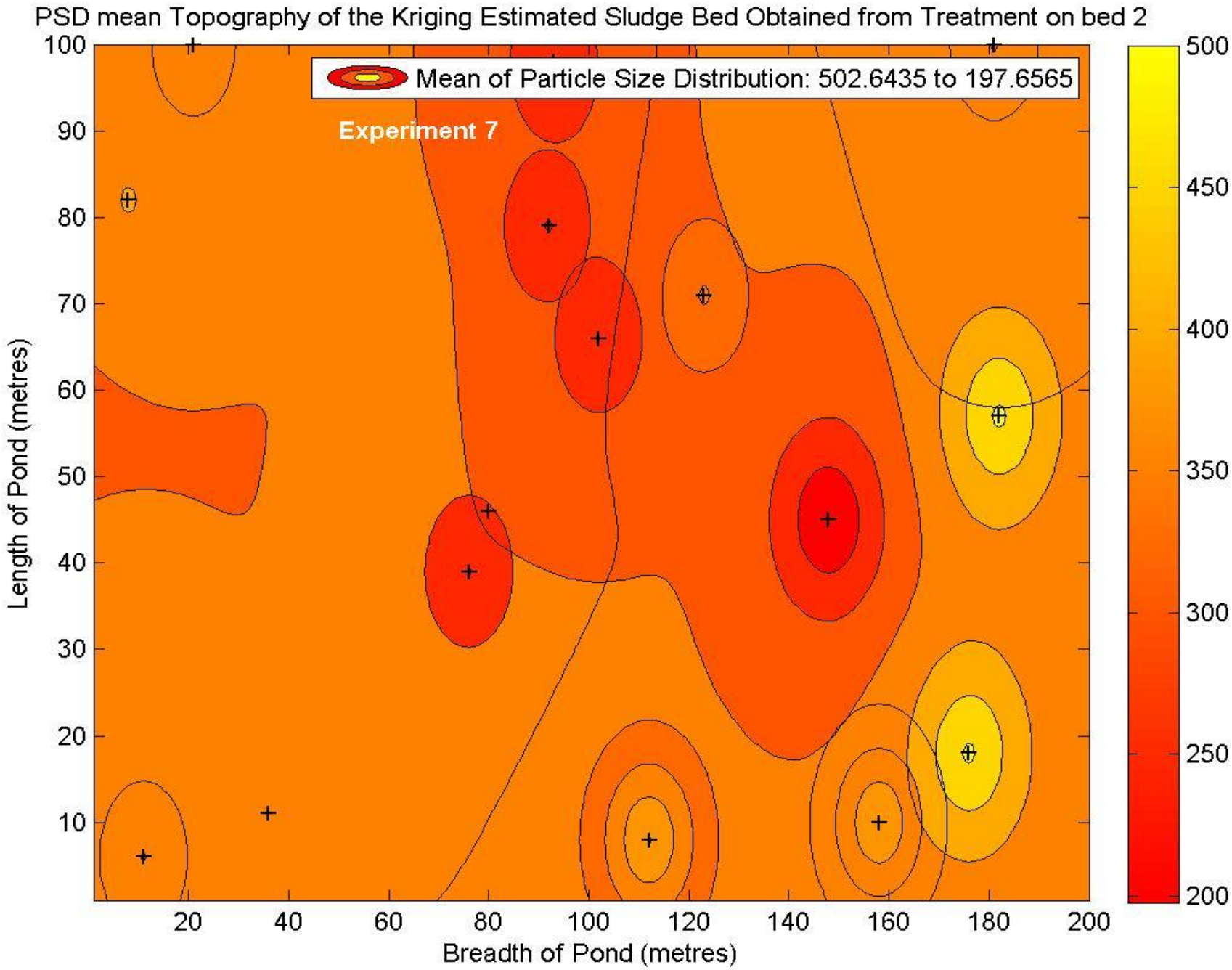
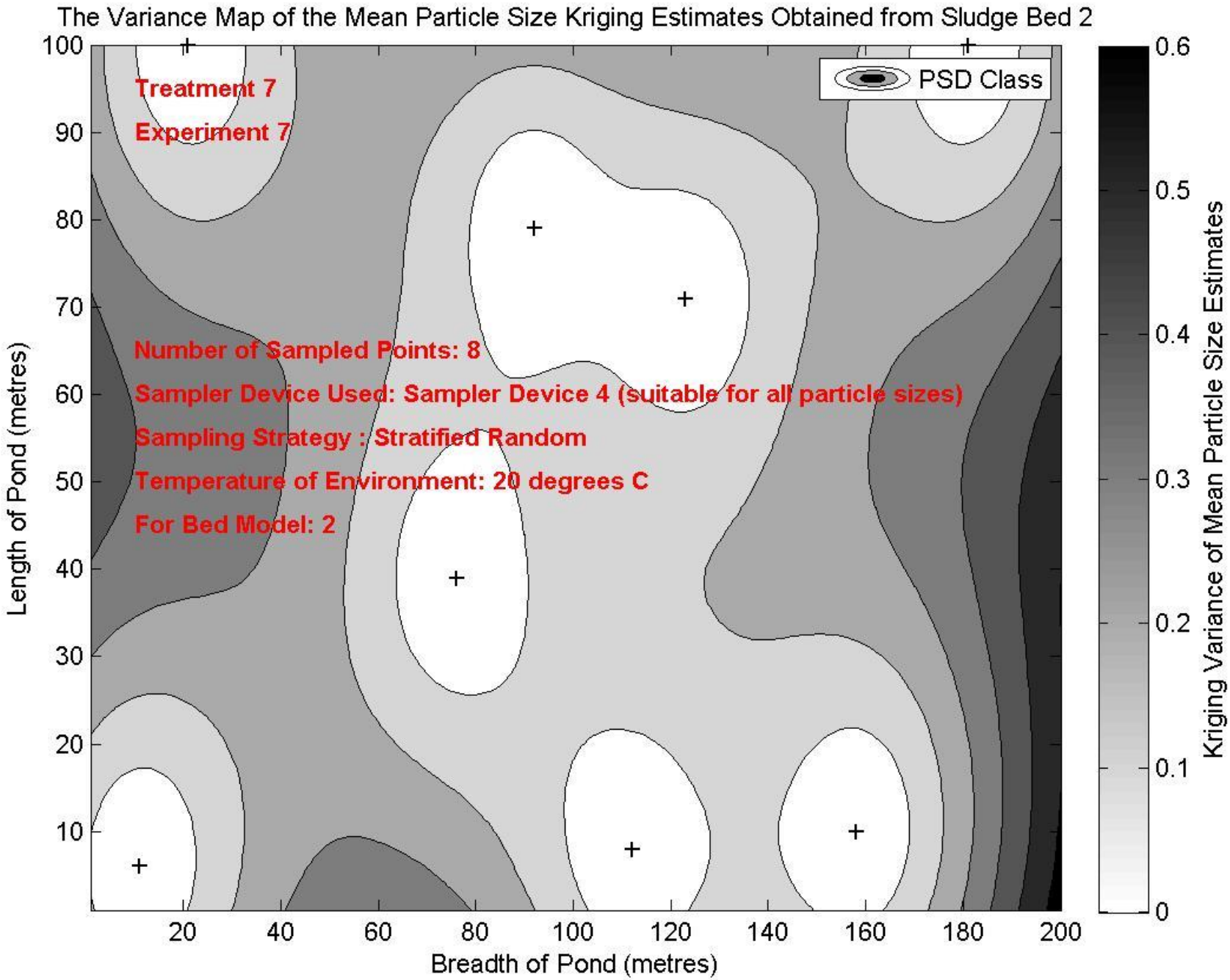
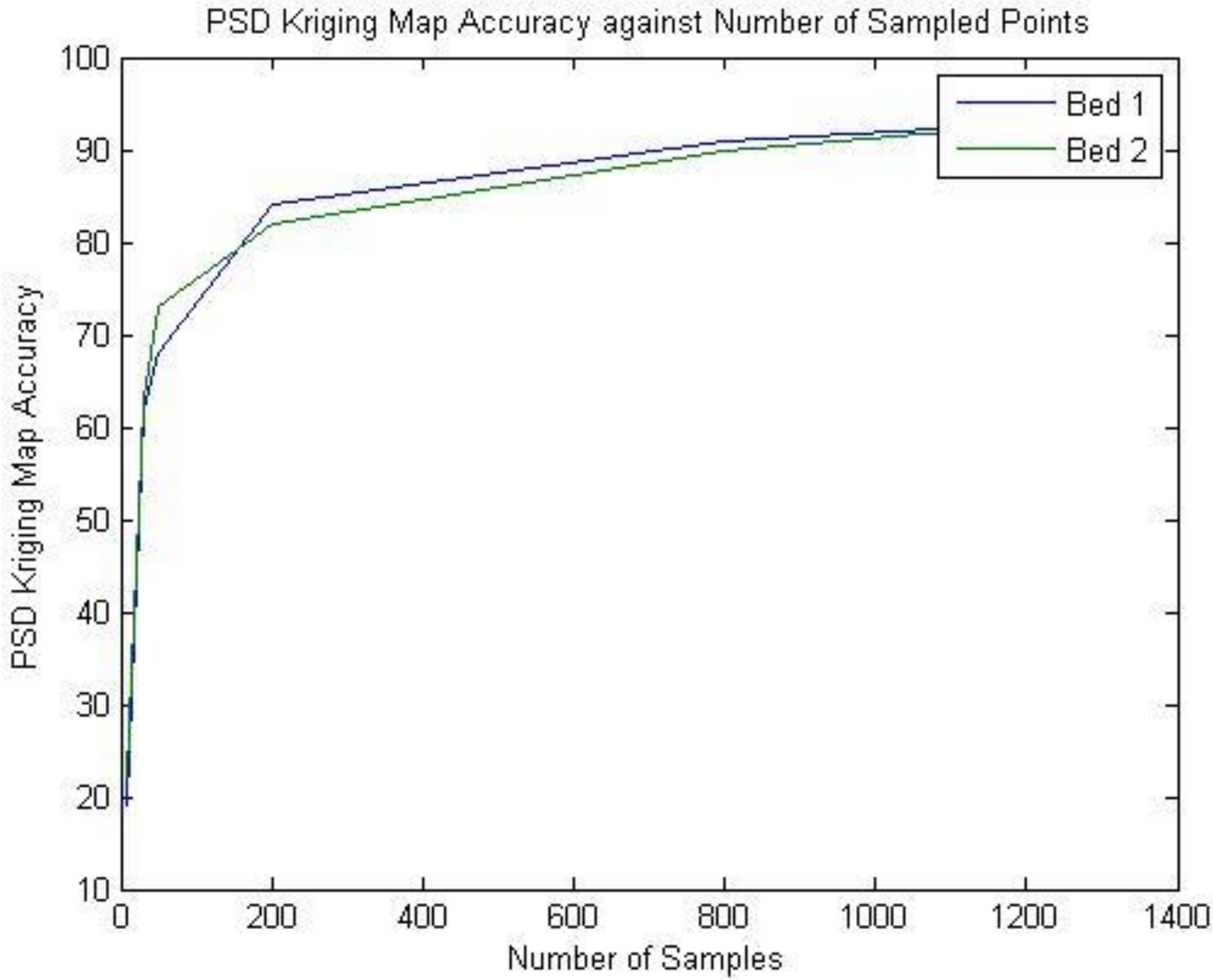

PSD mean Topography of the Kriging Estimated Sludge Bed Obtained from Treatment on bed 2
Mean of Particle Size Distribution: 502.6435 to 197.6565
Experiment 7
Length of Pond (metres)
Breadth of Pond (metres)
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
120
140
160
180
200
500
450
400
350
300
250
200

THE Observations – Kriging Variance Map


The Variance Map of the Mean Particle Size Kriging Estimates Obtained from Sludge Bed 2
Treatment 7
Experiment 7
Number of Sampled Points: 8
Sampler Device Used: Sampler Device 4 (suitable for all particle sizes)
Sampling Strategy : Stratified Random
Temperature of Environment: 20 degrees C
For Bed Model: 2
PSD Class
Length of Pond (metres)
Breadth of Pond (metres)
Kriging Variance of Mean Particle Size Estimates
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
120
140
160
180
200
0.6
0.5
0.4
0.3
0.2
0.1
0

THE OBSERVATIONS - OTHERS

- **PSD Map Accuracy increased with increasing number of samples**


PSD Kriging Map Accuracy against Number of Sampled Points
PSD Kriging Map Accuracy
Number of Samples
Bed 1
Bed 2
100
90
80
70
60
50
40
30
20
10
0
200
400
600
800
1000
1200
1400

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The Observations – MAIN DEDUCTIONS

- Number of Samples (Sampling Density) contribute majorly to sampling uncertainties.
- Sampling Strategy has a significant role to play on uncertainties.
- Extrapolation Algorithm is a significant determinant of map accuracy where spatial autocorrelation is largely unknown.

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The Observations – MAIN DEDUCTIONS

- Confidence maps provide insight into areas where more sampling is needed.

- Sampler devices (as modelled) have no significant contribution to variability, this posses a need for more insight into the practical limitations of samplers used.

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What Next?

- To create sludge simulants and carry-out experimental verification.
- To investigate experimental uncertainties due to laser diffraction method, image analysis and microscopy and ultrasonic spectroscopy.
- To construct an in-situ based sampling and analysis system based on a modification of the AVEXIS ROV system.
- To simulate radiation mapping for radiation source localisation.

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References

- 1. Shimadzu Corporation, “Particle Size Distribution Dependent on Principle of Measurement,” *Lecture on Partical Analysis - Hands-on Course,* 2015.
- 2. http://www.sellafieldsites.com/press/sludge-removal-marks-significant-step-in-sellafield-clean-up/
- 3. “Technical Report - Sampling,” Sellafield Ltd Technical Directorate.
- 4. James R. Miller et al. BioScience

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References

1. Shimadzu Corporation, “Particle Size Distribution Dependent on Principle of Measurement,” *Lecture on Partical Analysis - Hands-on Course,* 2015.
2. http://www.sellafieldsites.com/press/sludge-removal-marks-significant-step-in-sellafield-clean-up/
3. “Technical Report - Sampling,” Sellafield Ltd Technical Directorate.
4. James R. Miller et al. BioScience 2004;54:310-320, 2004 American Institute of Biological Sciences

Appendix

$$Confusion\ Matrix\ (CM) = \begin{array}{c|ccccc} & A & \boldsymbol{B} & \boldsymbol{C} & \boldsymbol{D} & \boldsymbol{E} \\ \hline \boldsymbol{A} & 13 & 54 & 8 & 3 & 1 \\ \boldsymbol{B} & 45 & 12 & 5 & 4 & 54 \\ \boldsymbol{C} & 1 & 3 & 65 & 27 & 2 \\ \boldsymbol{D} & 23 & 2 & 32 & 67 & 9 \\ \boldsymbol{E} & 12 & 43 & 23 & 45 & 34 \end{array}$$

$$Observed\ Accuracy = \frac{sum \text{ of diagonals of CM}}{\text{sum of all elements in CM}}$$

$$KappaIndex = \frac{(Observed\ Accuracy\ - Random\ Accuracy)}{(1 - \text{Random Accuracy})}$$

$$\textbf{Actual} = \textbf{Mean Observed} \pm Z_{\frac{\alpha}{2}} * \frac{\sigma}{\sqrt{n}}$$

Where,

$Z_{\frac{\alpha}{2}}$ = z-score

σ = Population Standard Deviation

n = Number of Observations

α = Risk of Error

$$Confidence\ Limit(x_0) = t_{nn-2}\sqrt{\hat{\sigma}^2\left(1 + \frac{1}{nn} + \frac{(x_0 - \bar{x}_h)^2}{S_{xx}}\right)}$$

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Thank You for listening