Development of a Line Source Dispersion Model for Gaseous Pollutants by Incorporating Wind Shear near the Ground Under Stable Atmospheric Conditions

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Abstract

Transportation sources are a major contributor to air pollution in urban areas. The role of air quality modelling is vital in the formulation of air pollution control and management strategies. Many models have appeared in the literature to estimate near-field ground level concentrations from mobile sources moving on a highway. However, current models do not account explicitly for the effect of wind shear (magnitude) near the ground while computing the ground level concentrations near highways from mobile sources. This study presents an analytical model based on the solution of the convective-diffusion equation by incorporating the wind shear near the ground for gaseous pollutants. The model input includes emission rate, wind speed, wind direction, turbulence, and terrain features. The dispersion coefficients are based on the near field parameterization. The sensitivity of the model to compute ground level concentrations for different inputs is presented for three different downwind distances. In general, the model shows Type III sensitivity (i.e. the errors in the input will show a corresponding change in the computed ground level concentrations) for most of the input variables. However, the model equations should be re-examined for three input variables (wind velocity at the reference height and two variables related to the vertical spread of the plume) to make sure that that the model is valid for computing ground level concentrations.

Introduction

Classification of air quality models based on various attributes and model categories

Attributes	*Model category*
Source	Point, line, area, volume, flare
Receptor	Street Canyon, intersection model
Frame	Lagrangian, Eulerian
Dimensionality	Single, double, triple, or multidimensional
Scale	Microscale and mesoscale, small synoptic, large synoptic, planetary
Structure	Analytical, statistical
Approach	Numerical, experimental
Applicability	Simple terrain, complex terrain, rural flat terrain, urban flat terrain, coastal terrain
Complexity	Screen models, refined models

Model Development

The analytical solution of the convective-diffusion equation to calculate the concentration of pollutants at any downwind distance is given by

$$C_{(x,z)} = \frac{q}{u_1 * \gamma(s)} * \left[\frac{u_1}{(m-n+2)^2 * K_1 * x}\right]^s * exp\left[-u_1 * \frac{z^{m-n+2}}{((m-n+2)^2 * K_1 * x)}\right]$$

where, C is the concentration of pollutants at a point (x, z), x is the downwind distance, z is the vertical height of the receptor above the ground, q is the emission rate of the mobile source per unit length, m and n are the exponents of power-law velocity profile and eddy diffusivity profile respectively, s is the stability parameter based on m and n, u_1 and K_1 are the wind velocity and eddy diffusivity at a reference height z_1 respectively.

Vertical Dispersion Coefficient

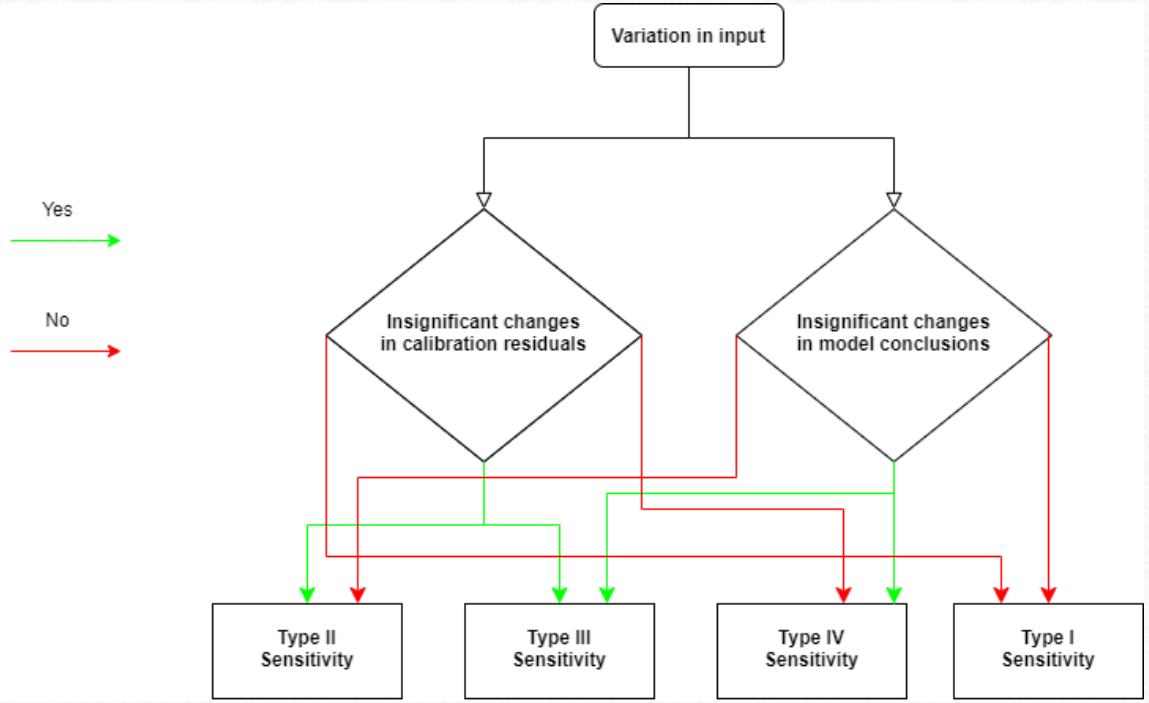
$$\sigma_z = \frac{a\, u_* x}{U_e * \left(1 + b_s \frac{u_*}{U_e}\left(\frac{x}{L}\right)^{\frac{2}{3}}\right)} + m_t$$

m_t - vertical spread due to the turbulence created by moving vehicles
U_e is the effective wind velocity,
u_* is the surface friction velocity, and
L is the Monine-Obukhov length
a and b_s are empirically found coefficients

SLINE – Final Equation

$$C = \frac{q}{u_1 * \gamma(s)} * \left[\frac{u_1}{(m-n+2)^2 * \left[\frac{a\,u_* \,x}{u_1 + b_s u_* \left(\frac{x}{L}\right)^{\frac{2}{3}}} + m_t\right]^2 * \frac{u_1}{2}}\right]^s * exp\left[-u_1 * \frac{z^{m-n+2}}{((m-n+2)^2 * \left[\frac{a\,u_* \,x}{u_1 + b_s u_* \left(\frac{x}{L}\right)^{\frac{2}{3}}} + m_t\right]^2 * \frac{u_1}{2})}\right]$$

Sensitivity analysis



The categories' sensitivity analysis and output changes

	Categories	Changes in calibration residuals	Changes in model conclusions
Variation in input parameters	Type I	X	X
	Type II	✓	X
	Type III	✓	✓
	Type IV	X	✓

Ranges of the independent input variable used for the sensitivity analysis

Run. S.No.	Emission rate of pollutants q (g/m/sec)	Wind velocity u_1 (m/s)	Coefficient m	Surface friction velocity u_* (m/s)	Coefficient a	Coefficient b_s	Vertical spread due to the height of the vehicle m_t (m)
1	0.0001	0.9	0.25	0.03	0.32	2.04	0.6
2	0.0024	1.2	0.32	0.04	0.4	2.56	0.7
3	0.003	1.5	0.4	0.06	0.5	3.2	0.8
4	0.0036	1.8	0.48	0.07	0.6	3.84	0.9
5	0.0043	2.1	0.57	0.08	0.72	4.6	1

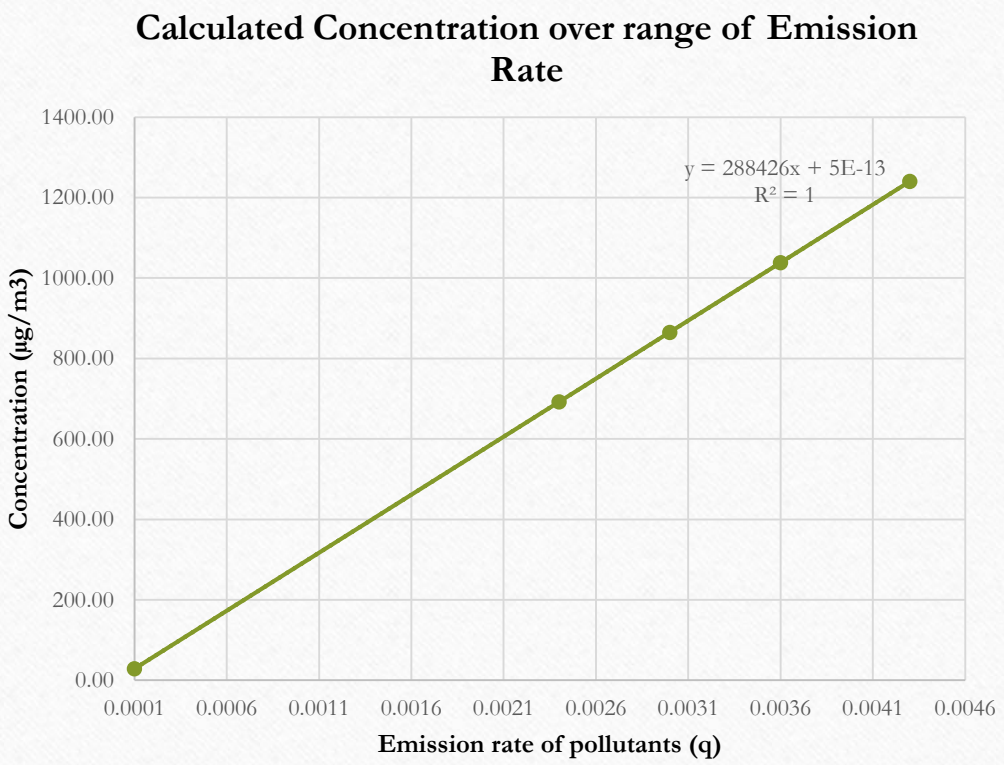
Standard input values considered for sensitivity analysis

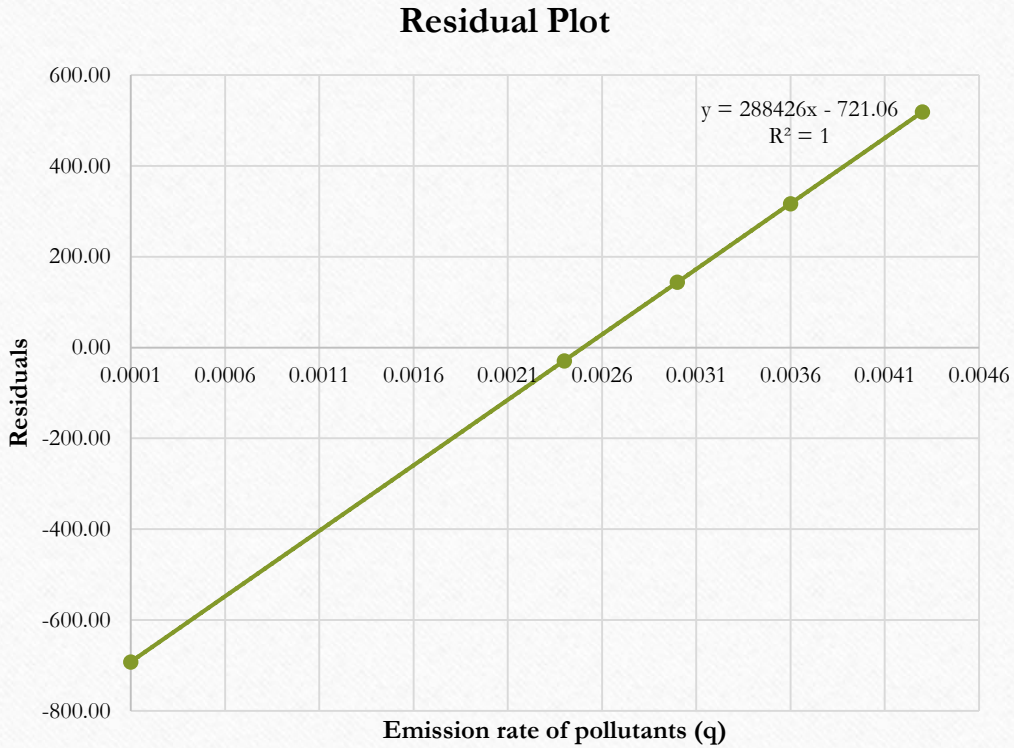
q (g/m/sec)	u_1 (m/s)	m	u_* (m/s)	a	b_s	m_t (m)
0.0025	1.4	0.57	0.05	0.3	3	0.825

Sensitivity Analysis Results

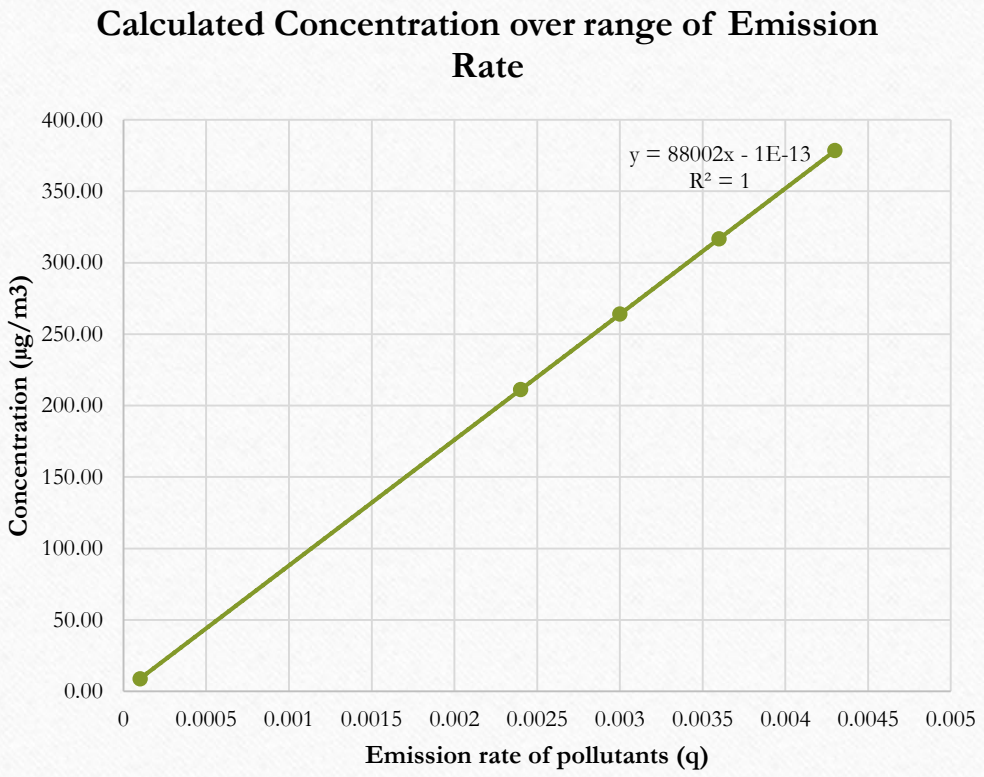
- The variable parameters considered in the sensitivity analysis are emission rate of pollutant (q), wind velocity at the reference height (u_1), coefficient a, coefficient m, coefficient bs , surface friction velocity (u_*), and additional vertical spread due to the turbulence created by the vehicles (m_t).
- The parameters are vital in describing the sensitivity of the gaseous dispersion model. The plots given in the following figures between the modeled outputs and residuals determine the type of sensitivity for each parameter.

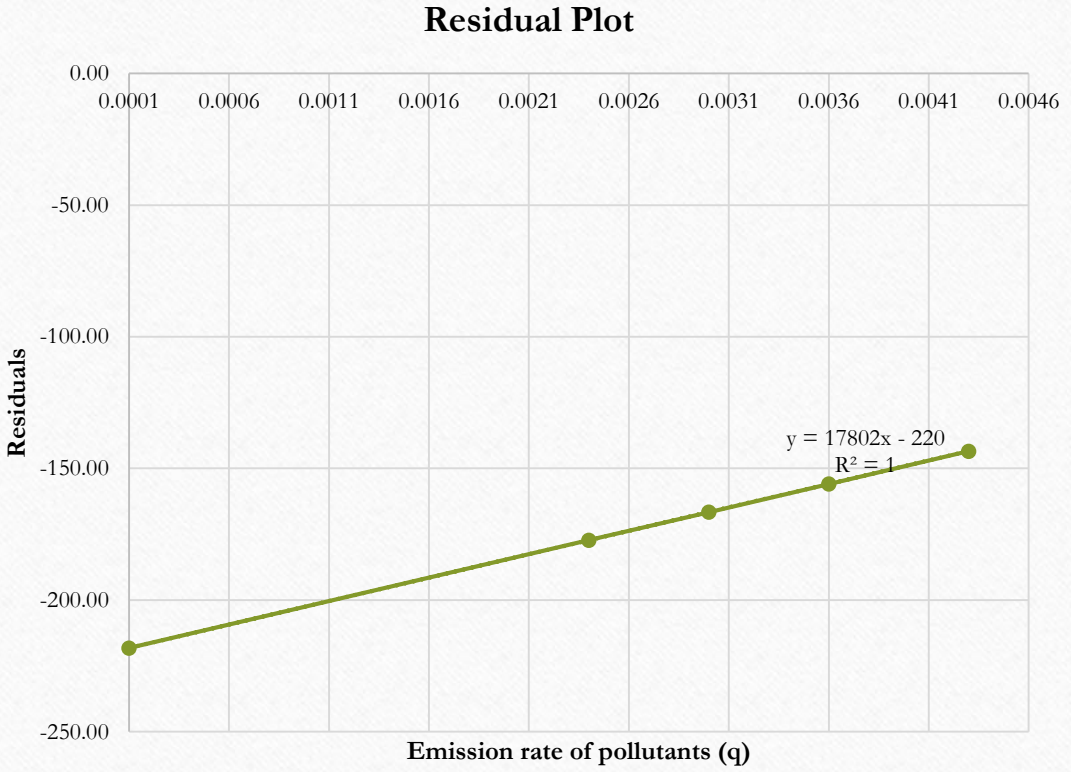
At Distance = 10m



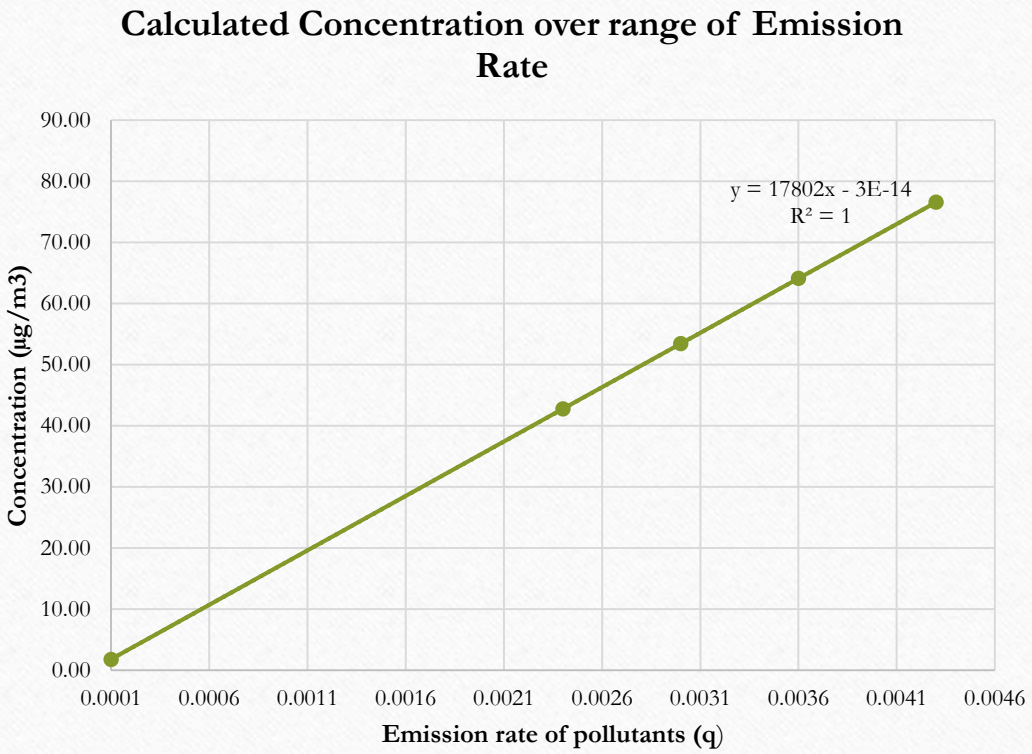


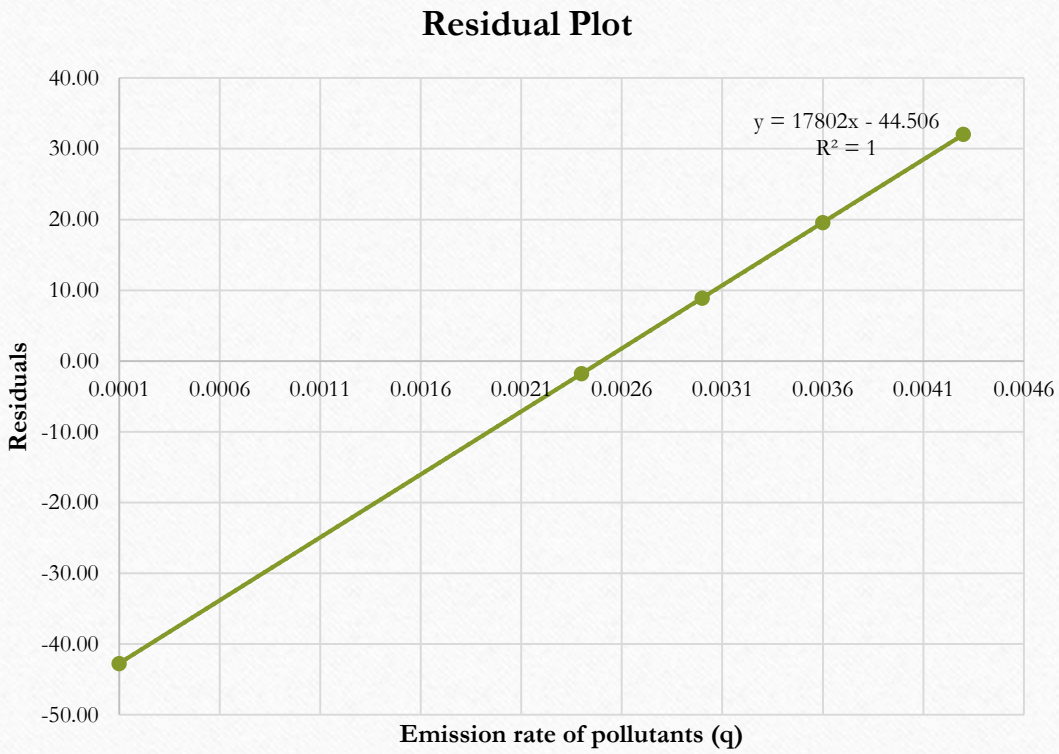
At Distance = 50m





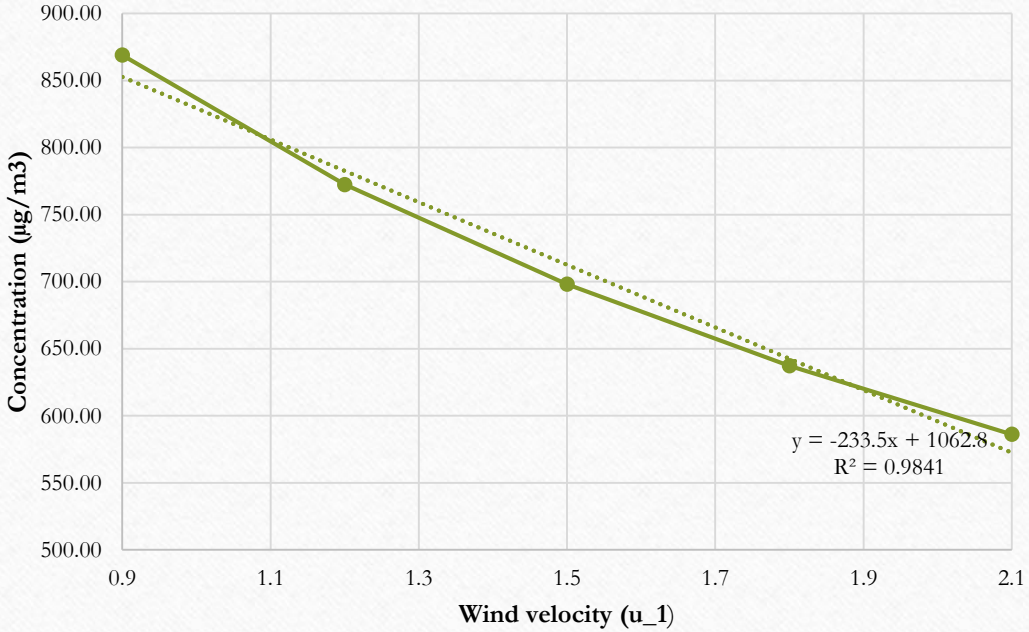
At Distance = 250m



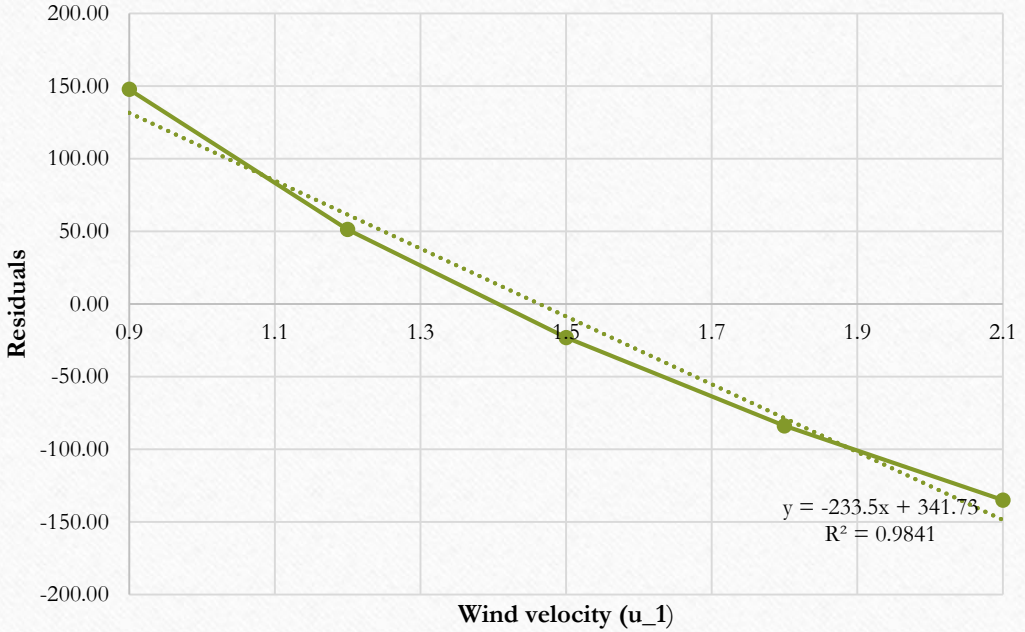


At Distance = 10m

Calculated Concentration over range of Wind velocity



Residual Plot



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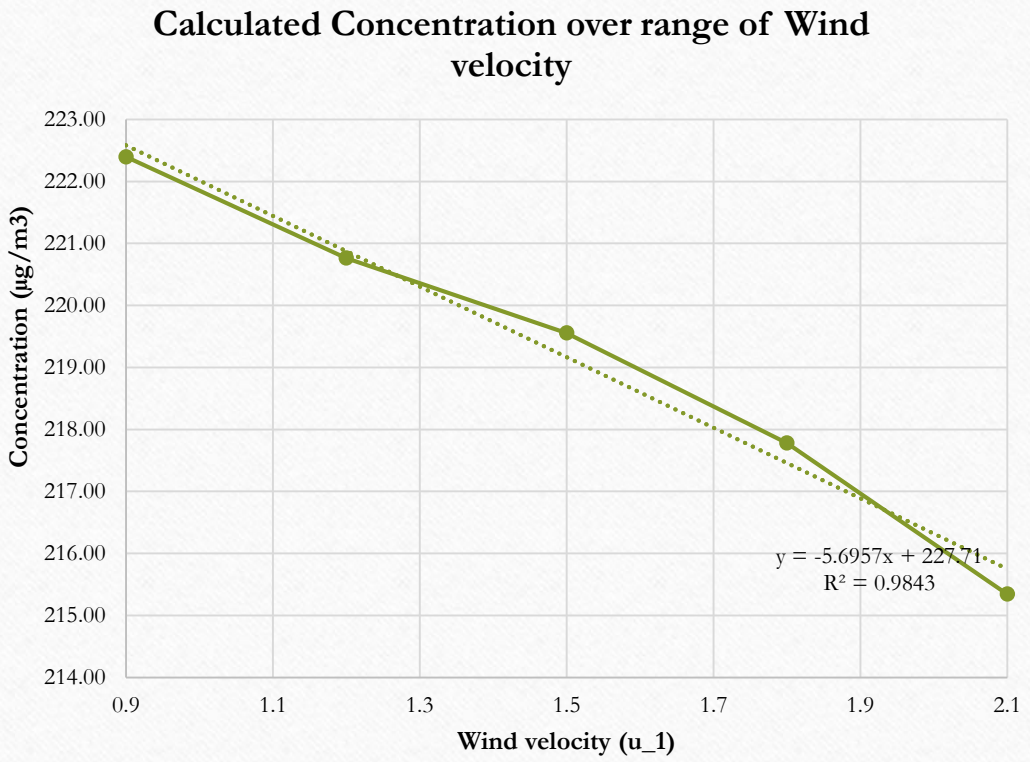

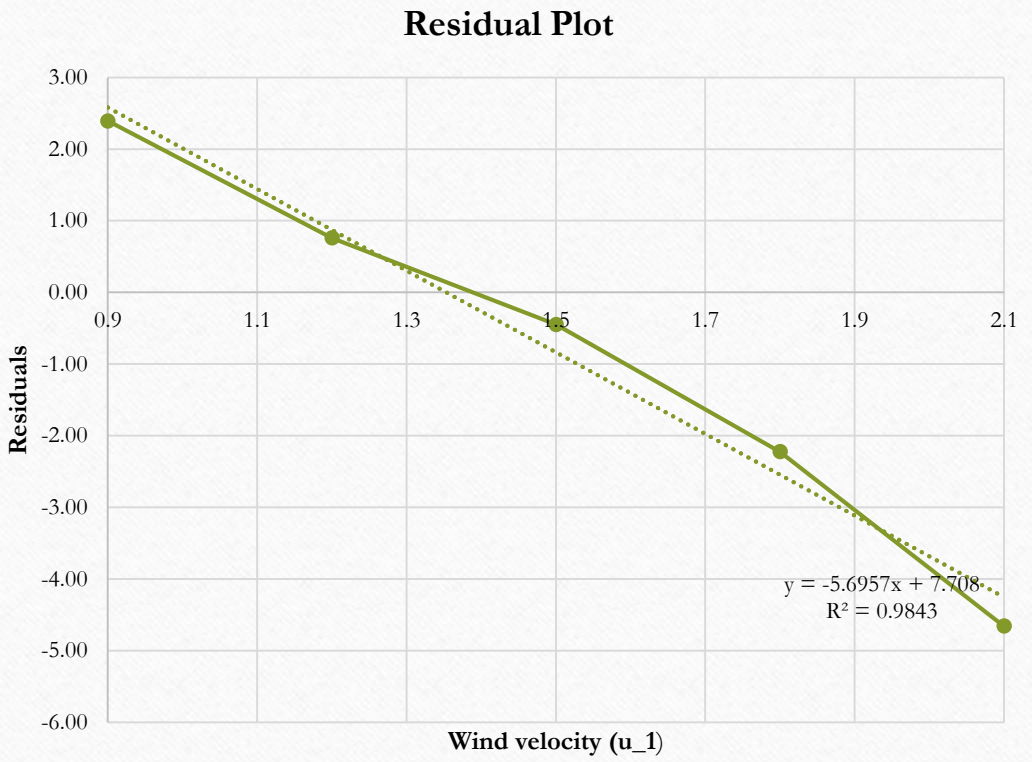

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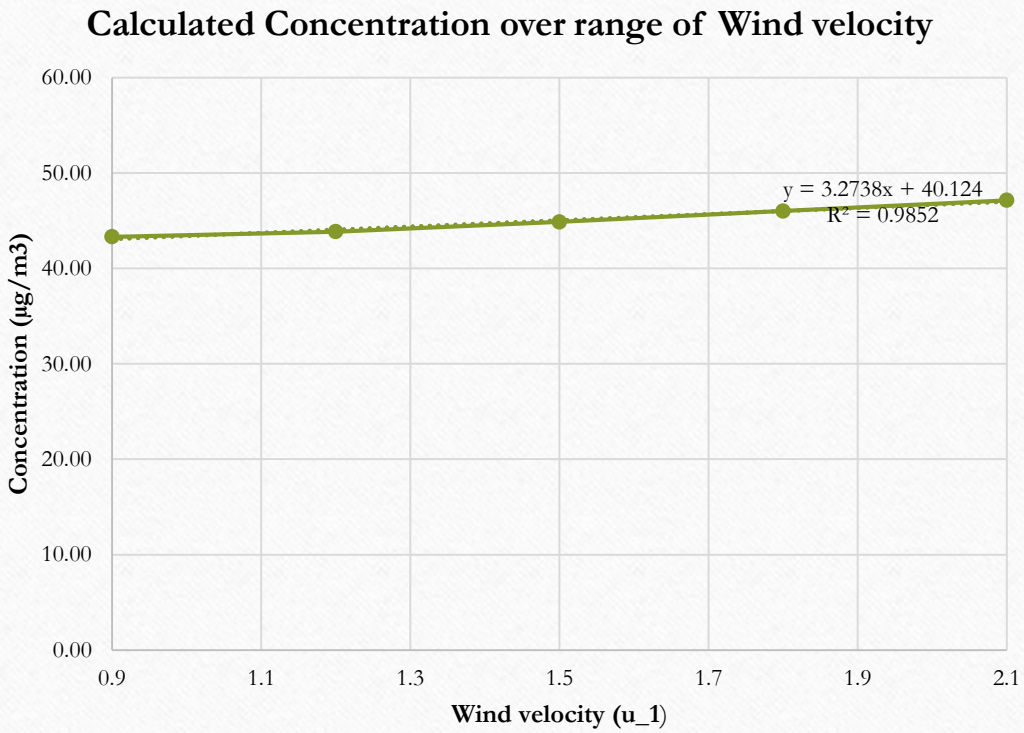

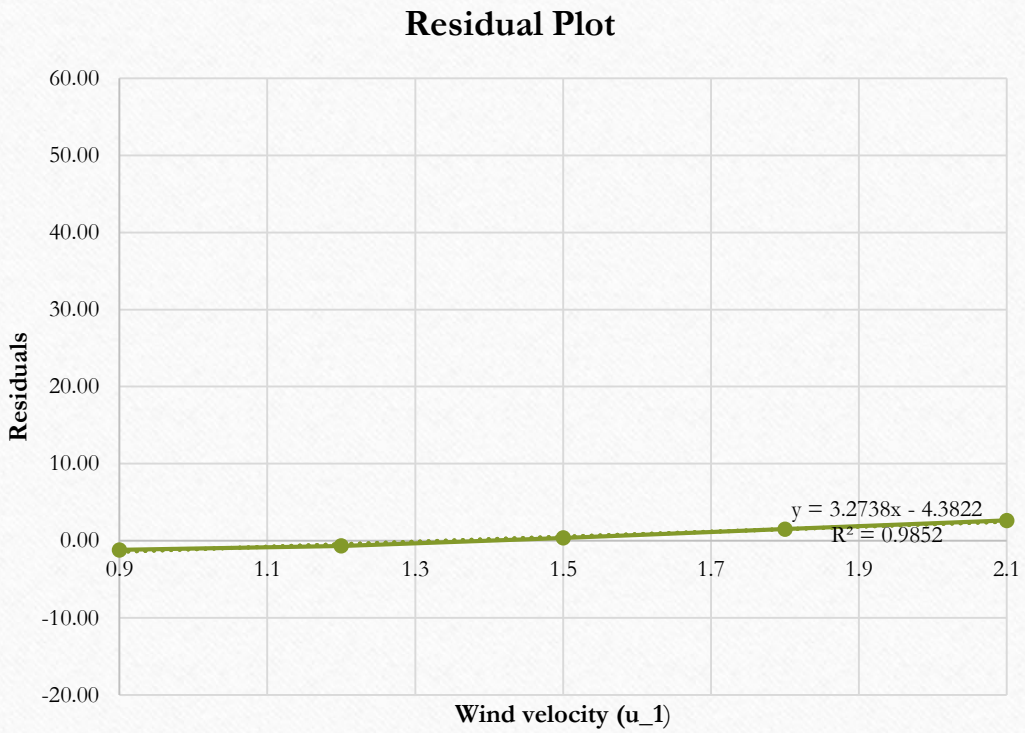

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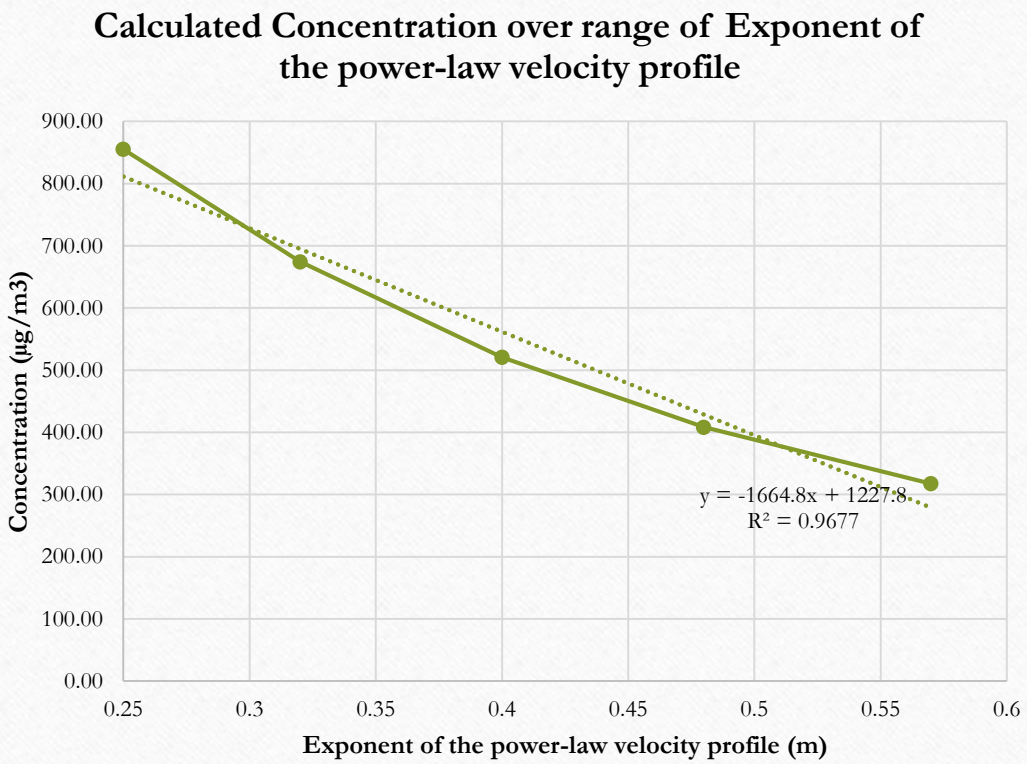

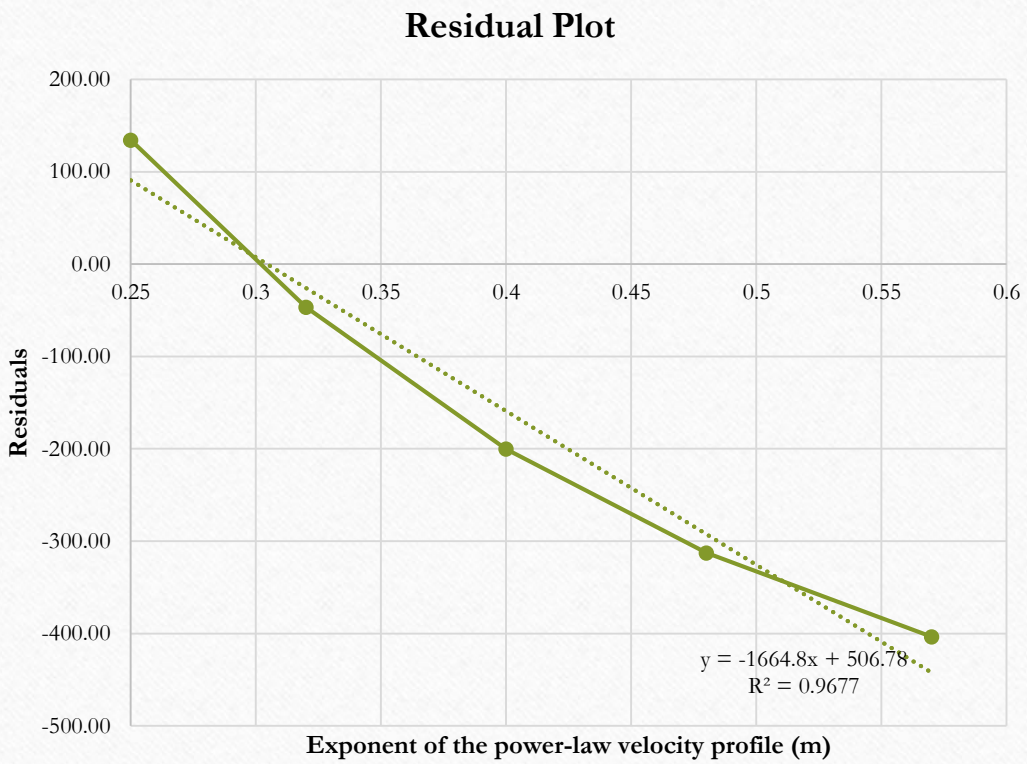

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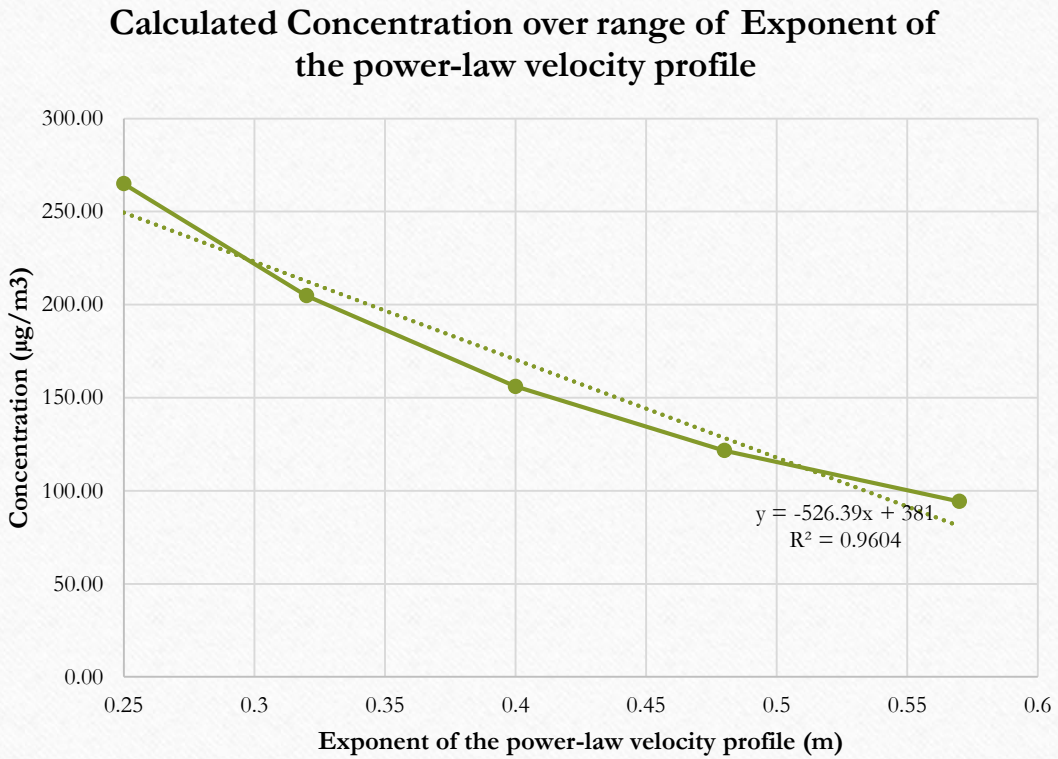

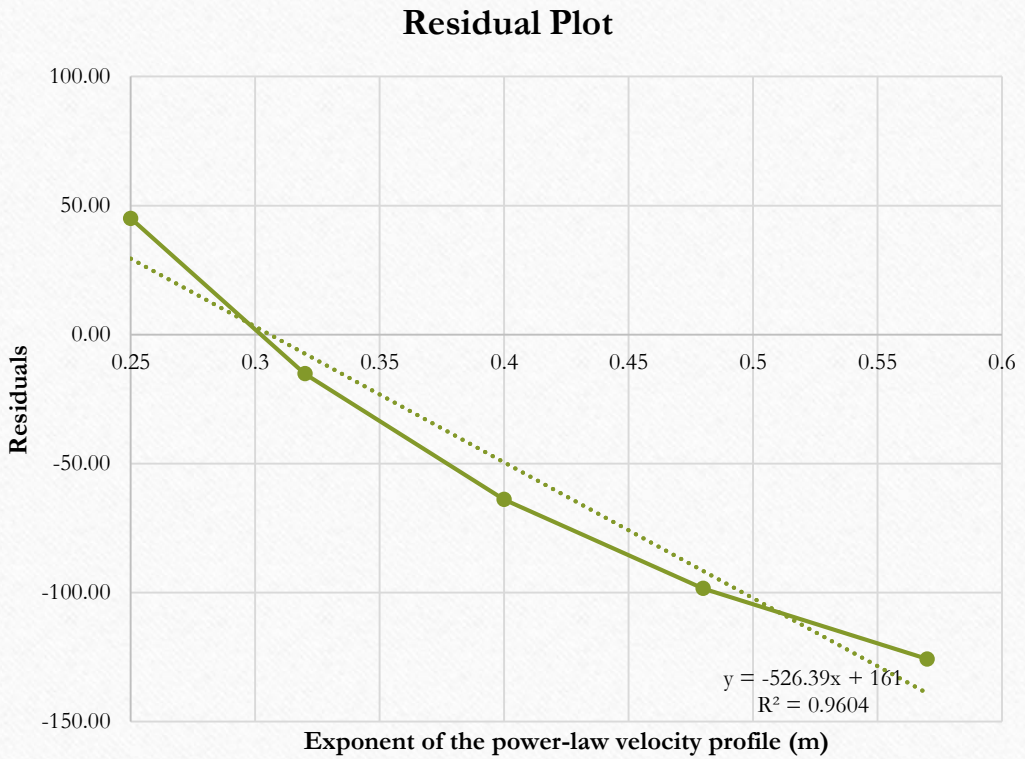

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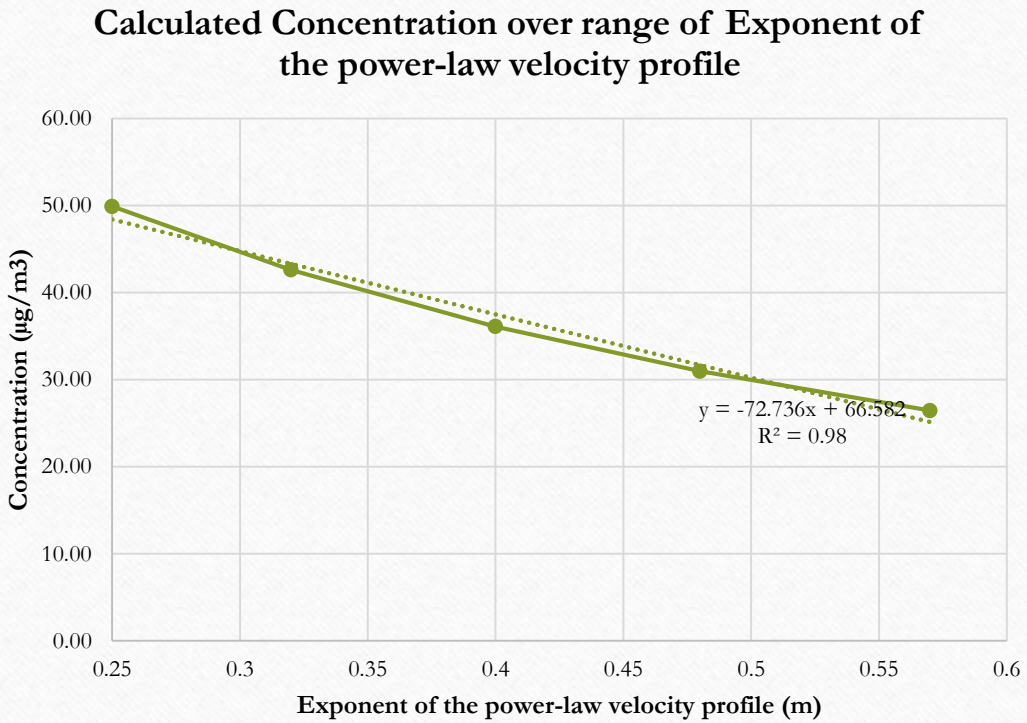

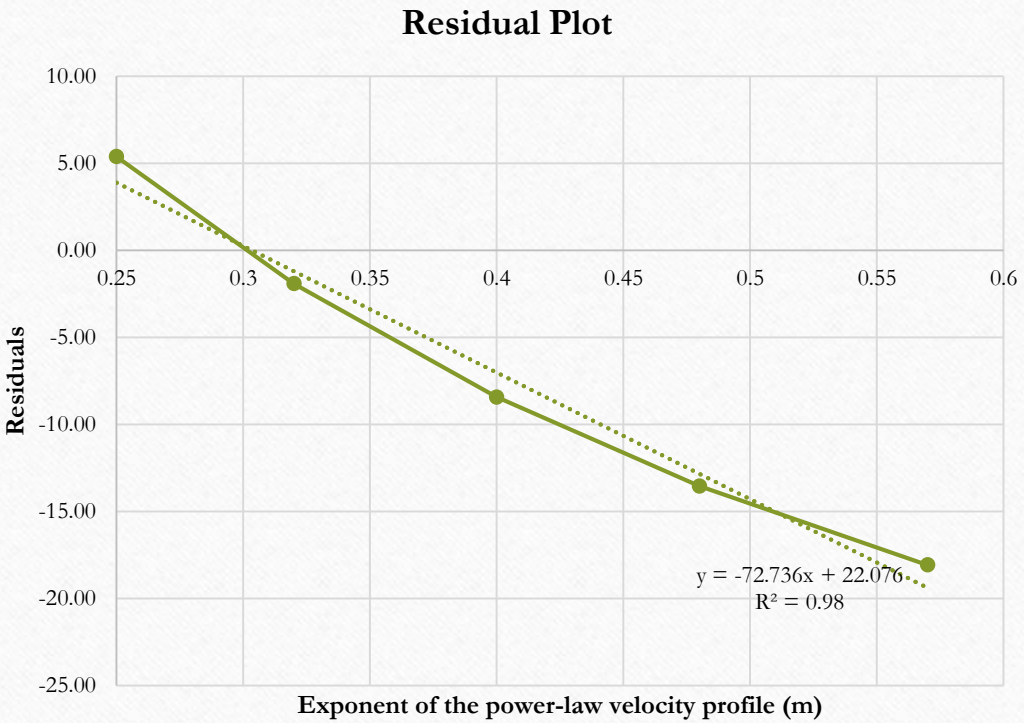

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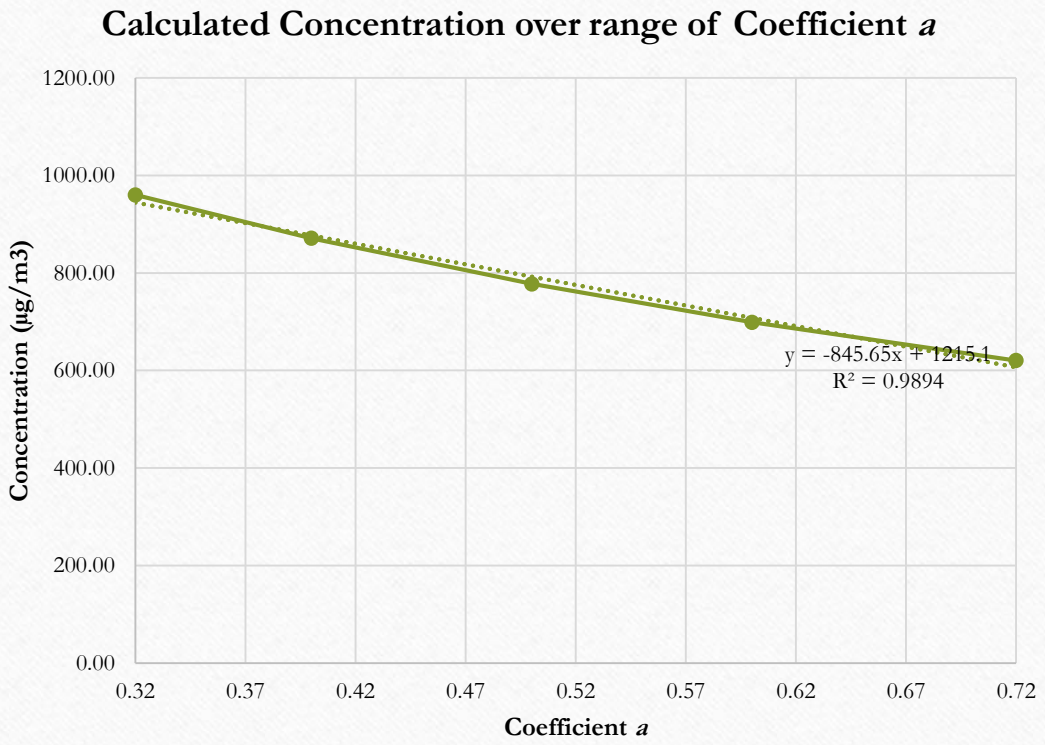

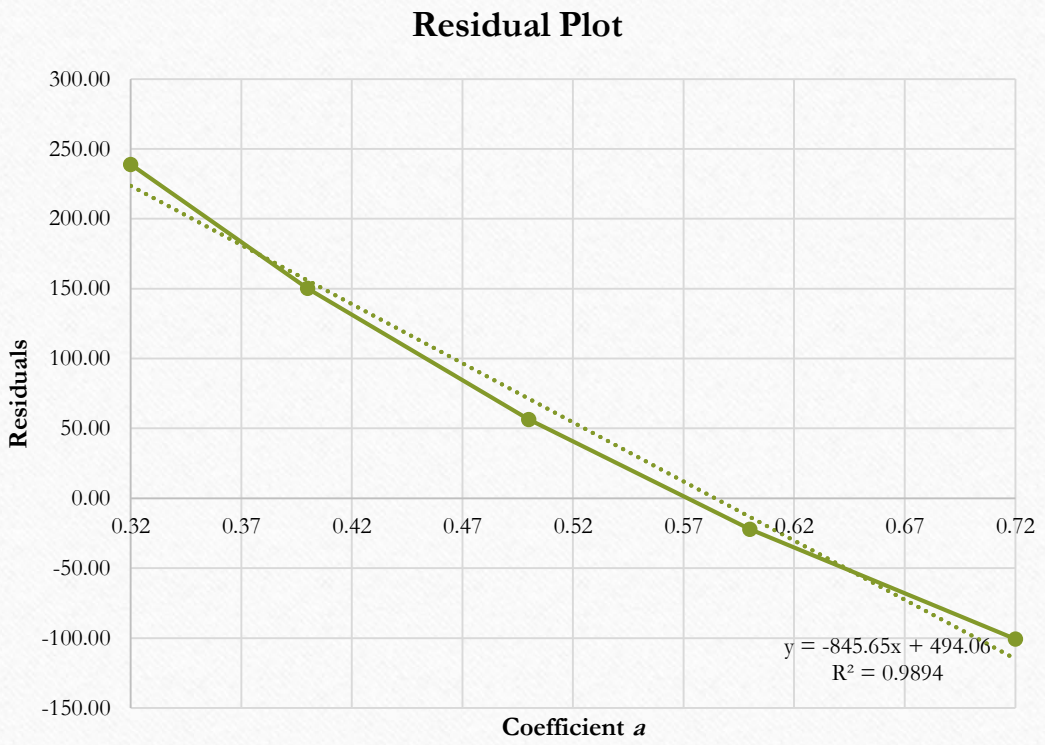

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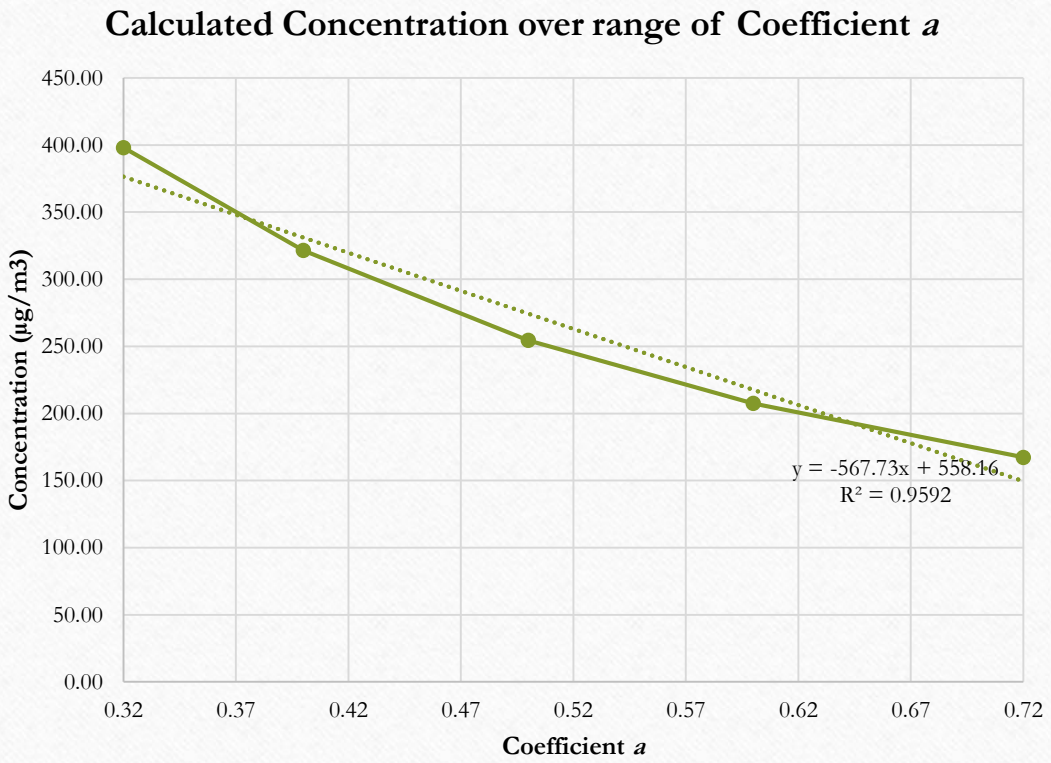
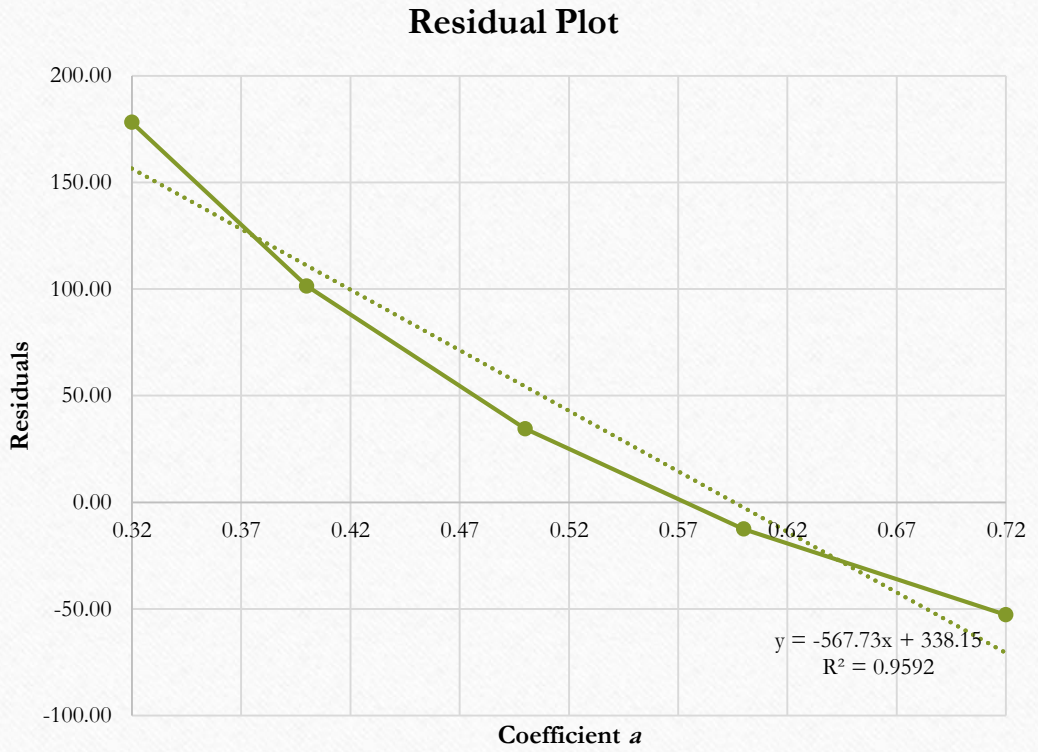
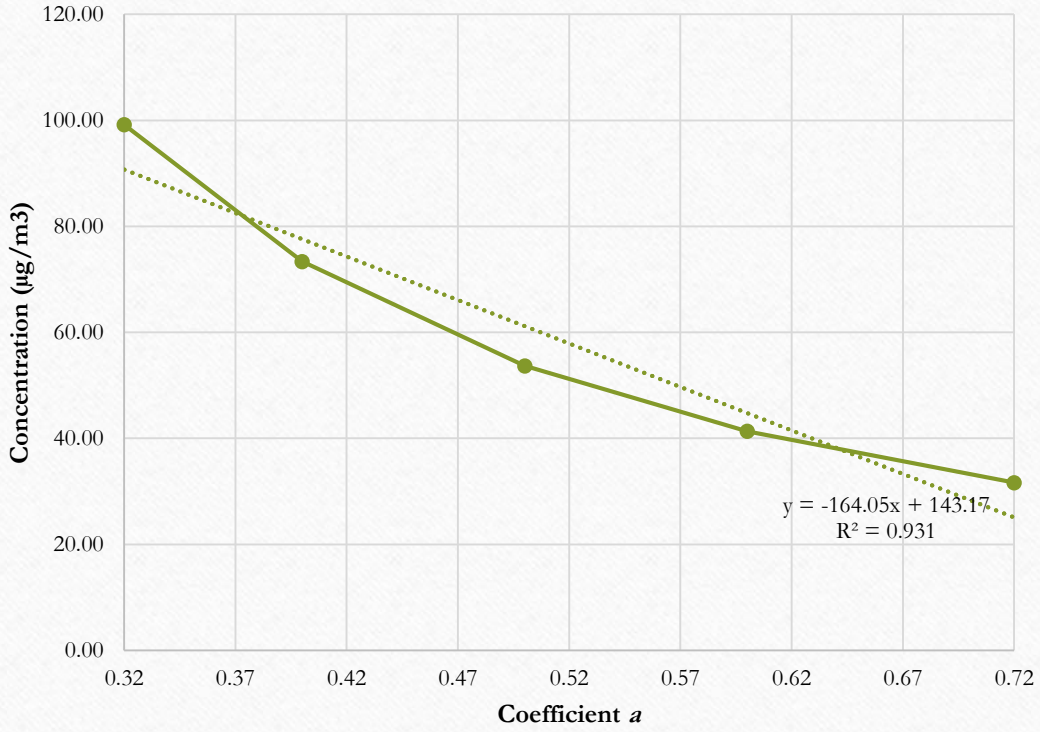


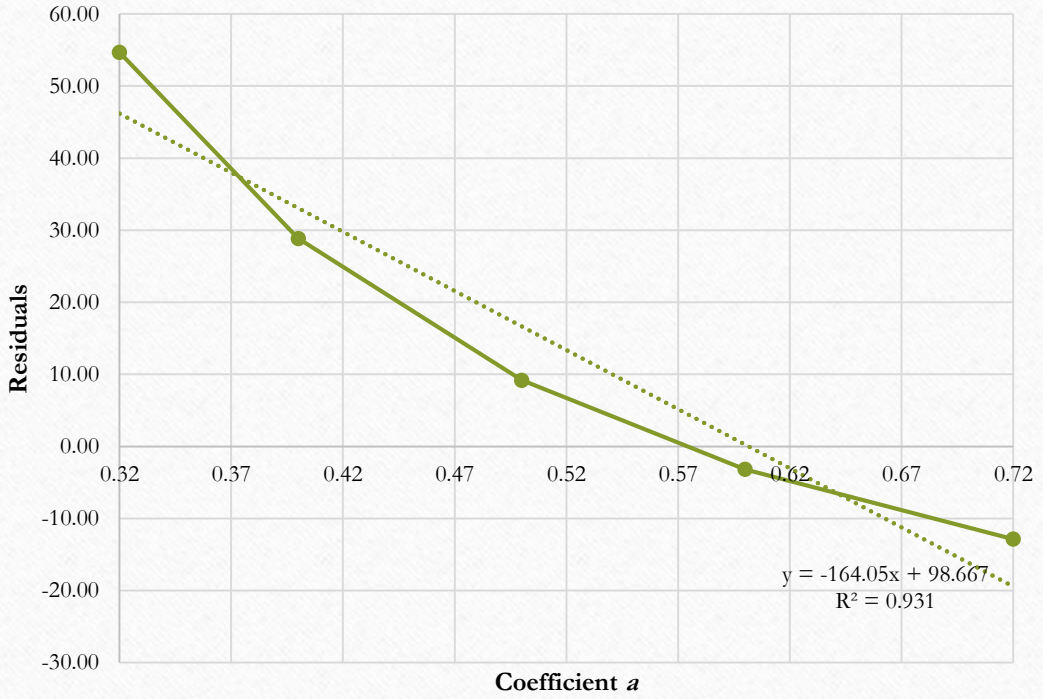


At Distance = 250m

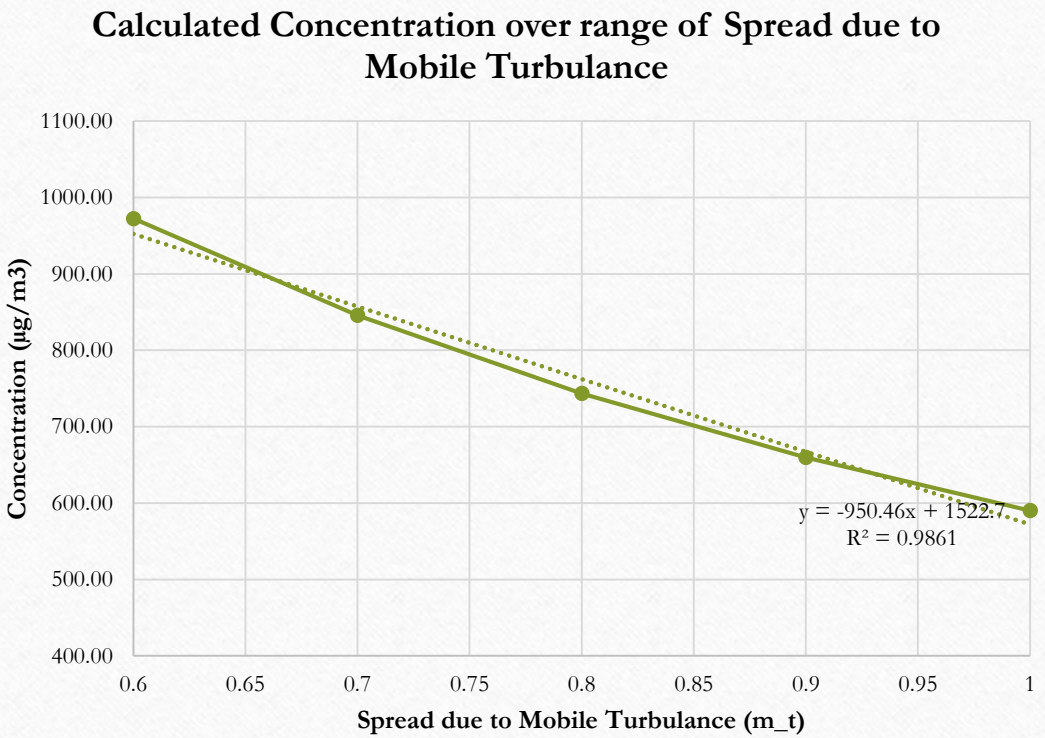
Calculated Concentration over range of Coefficient *a*

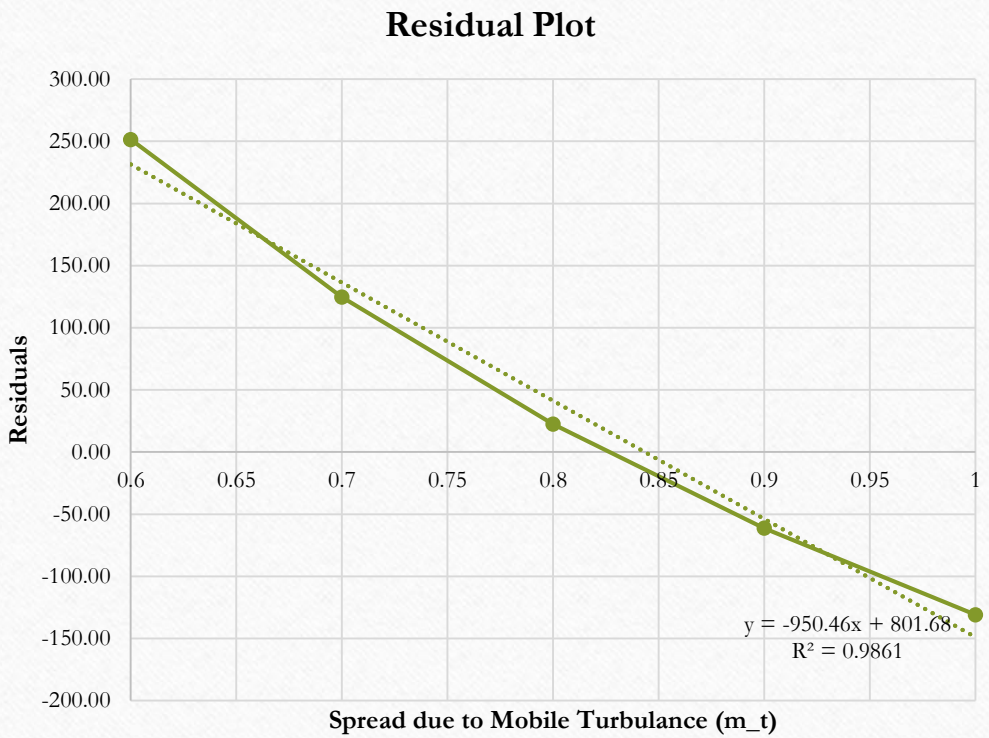


Residual Plot



At Distance = 10m





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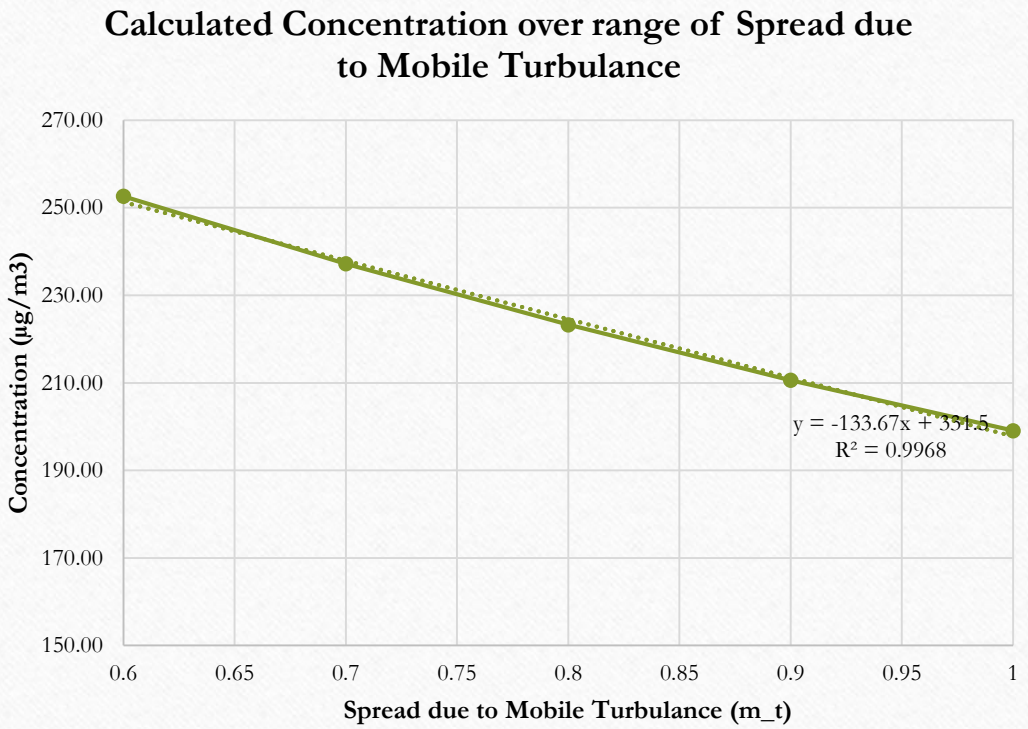

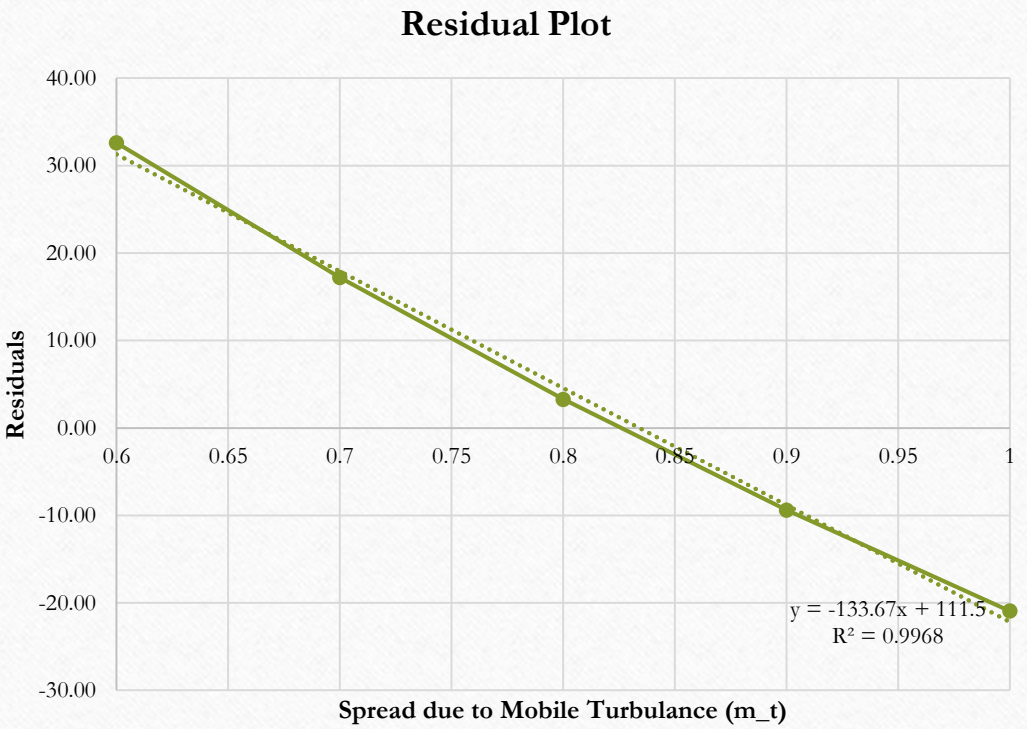

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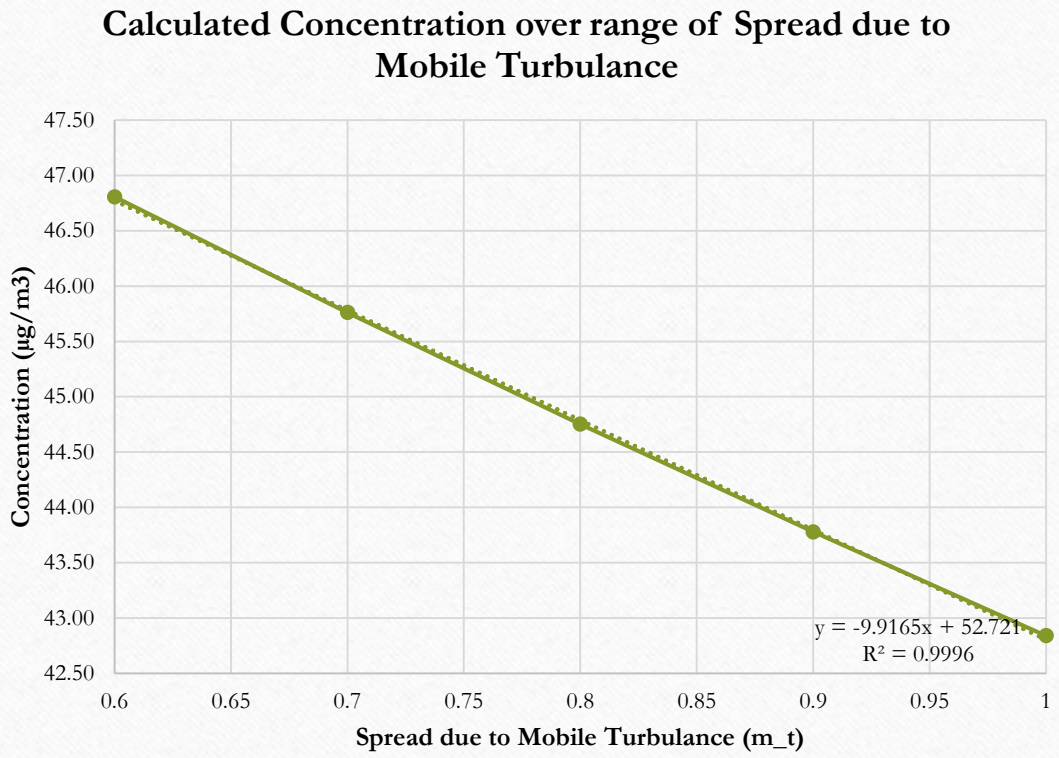
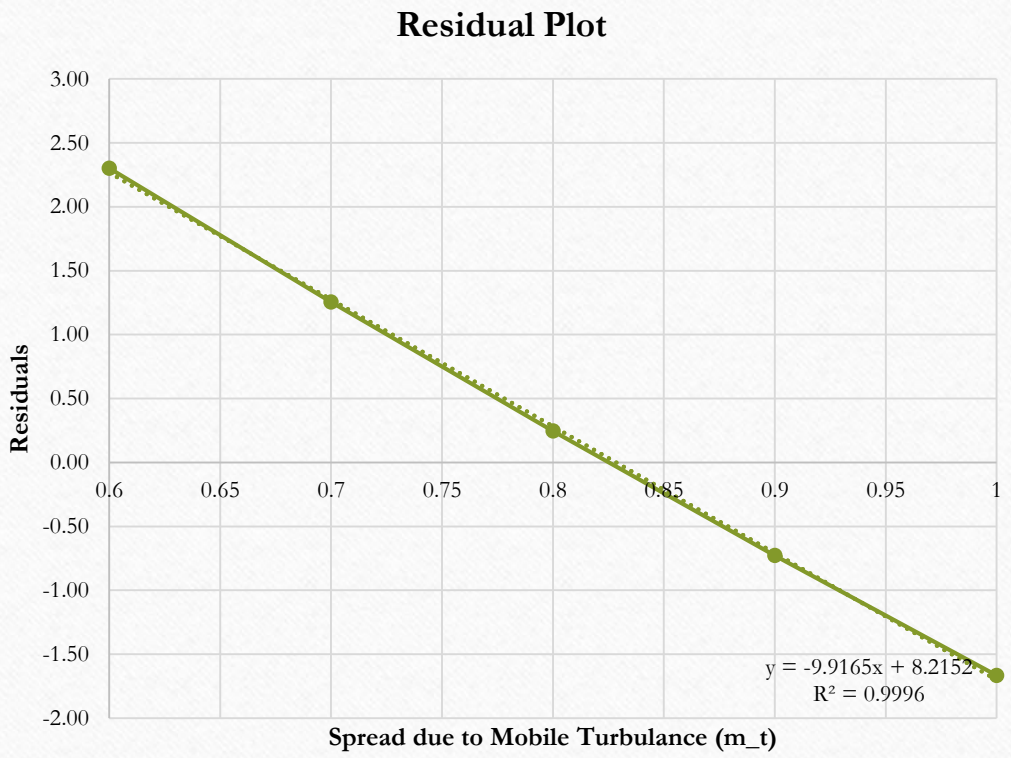
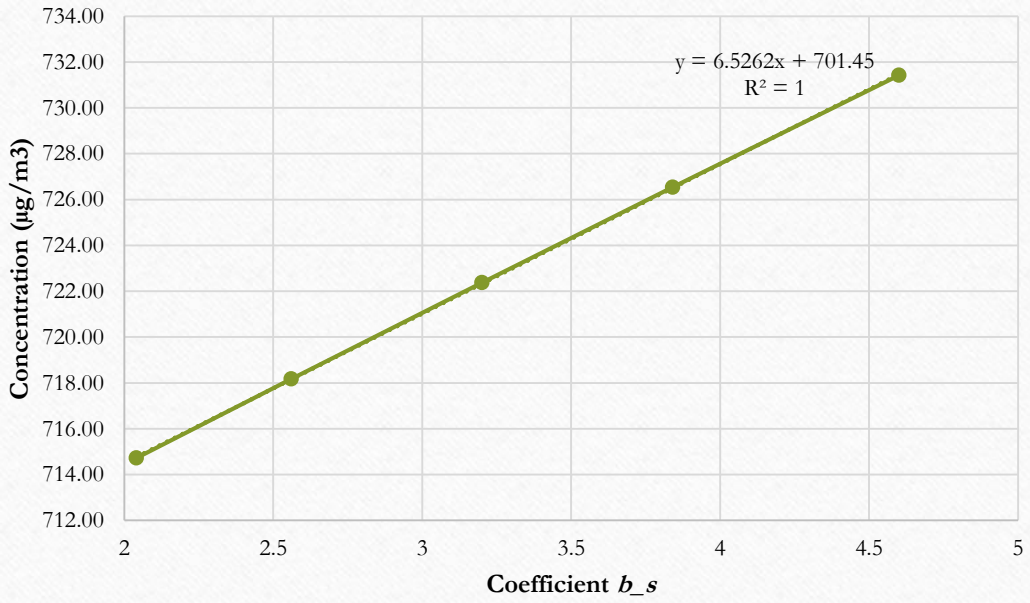


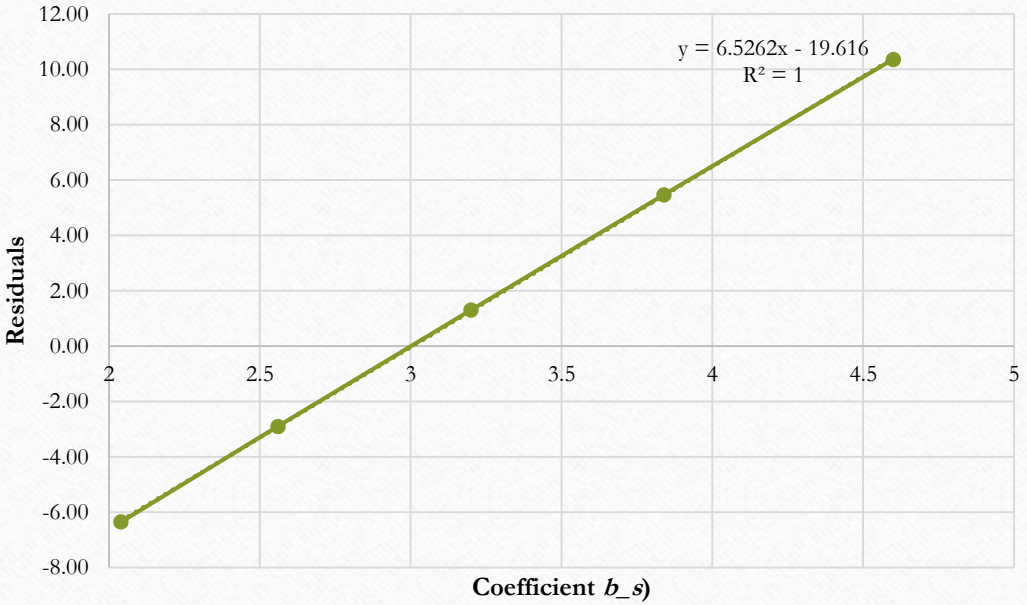


At Distance = 10m

Calculated Concentration over range of Coefficient *b_s*



Residual Plot



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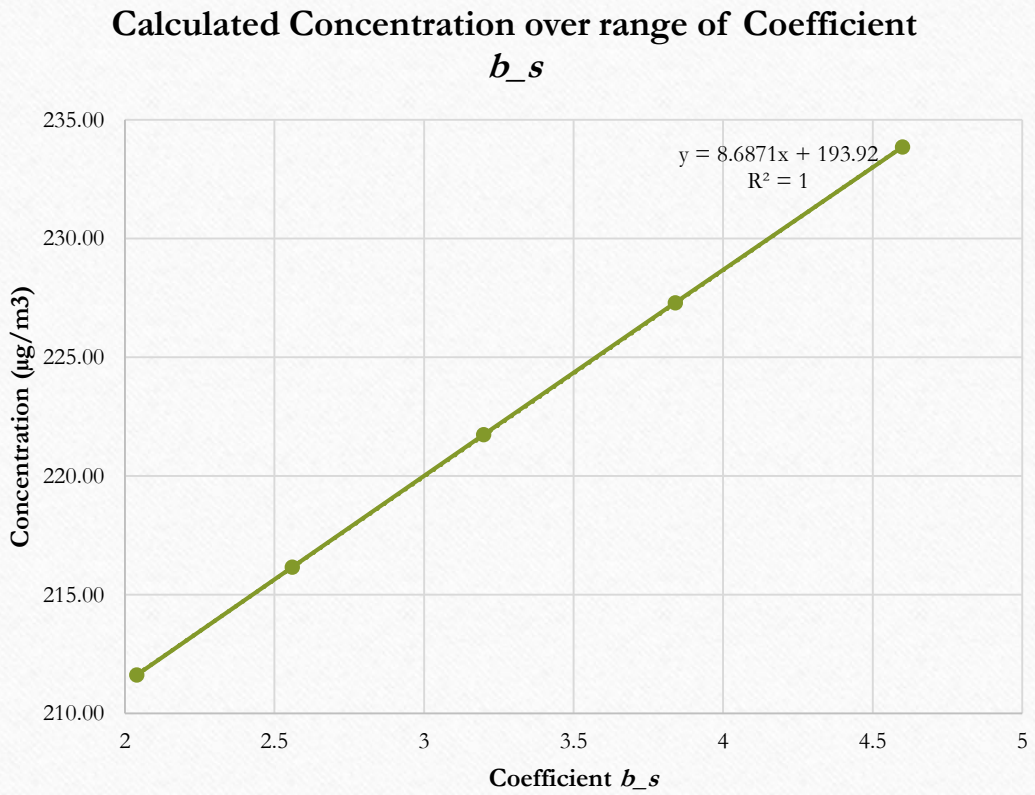

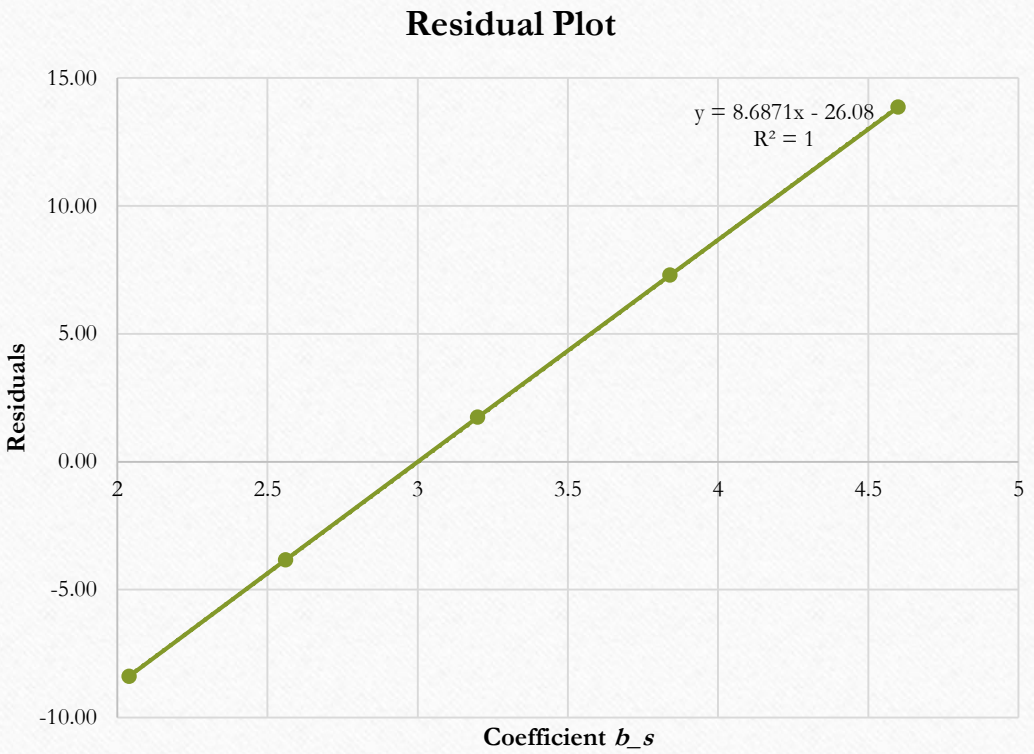

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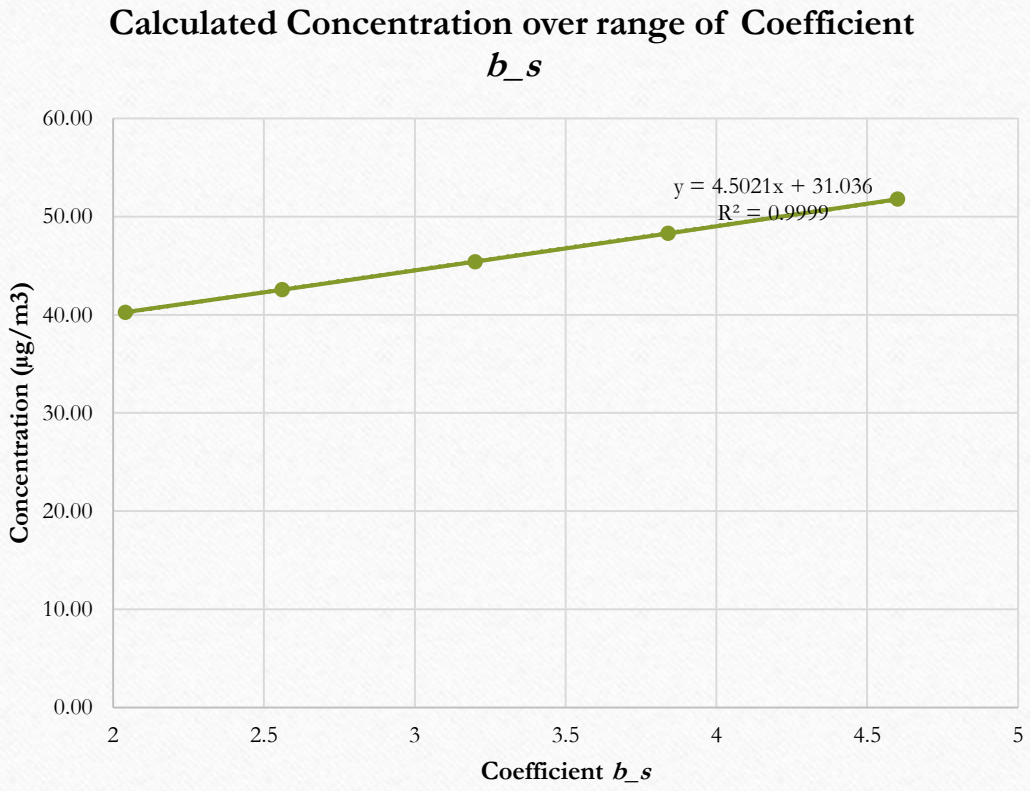

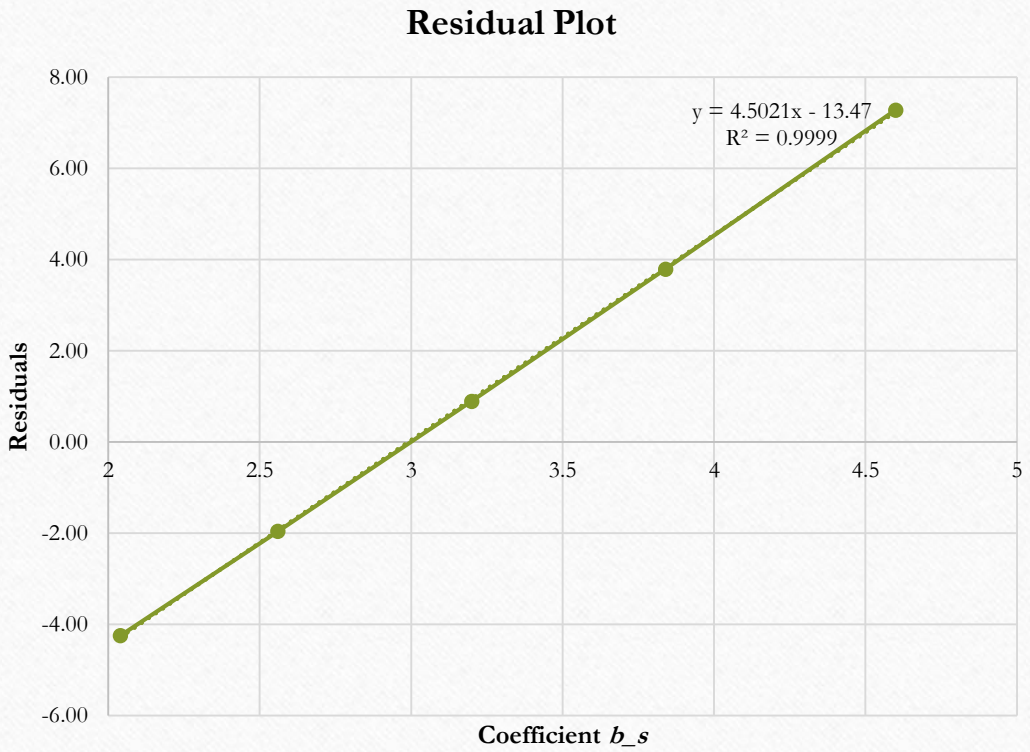

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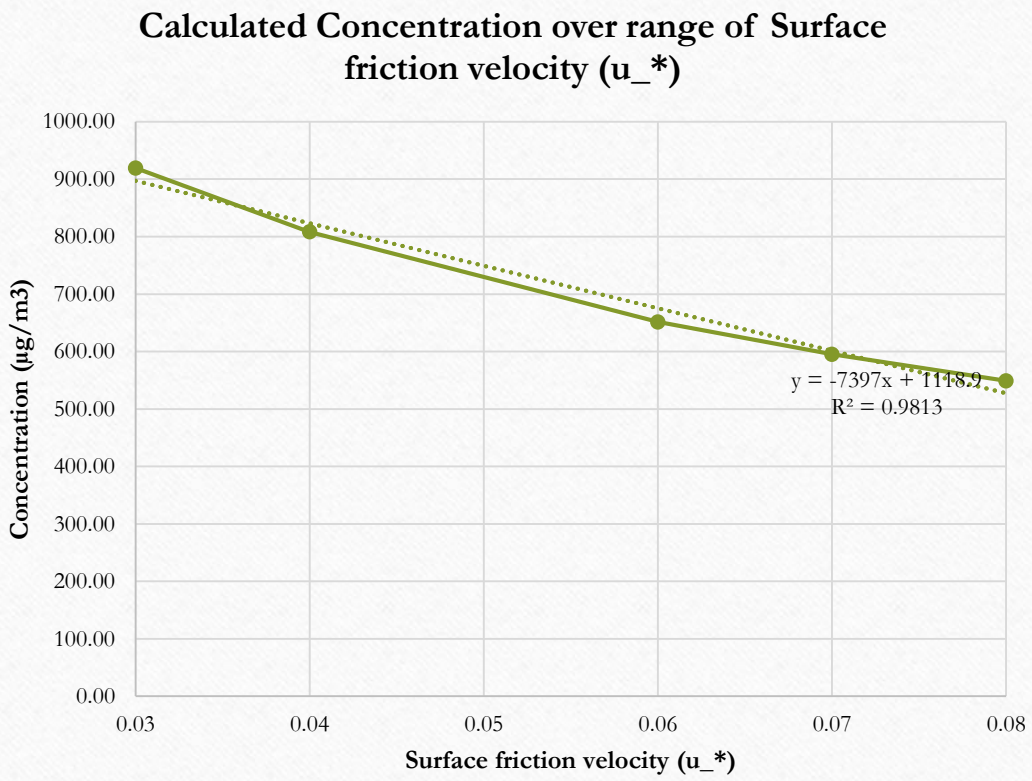

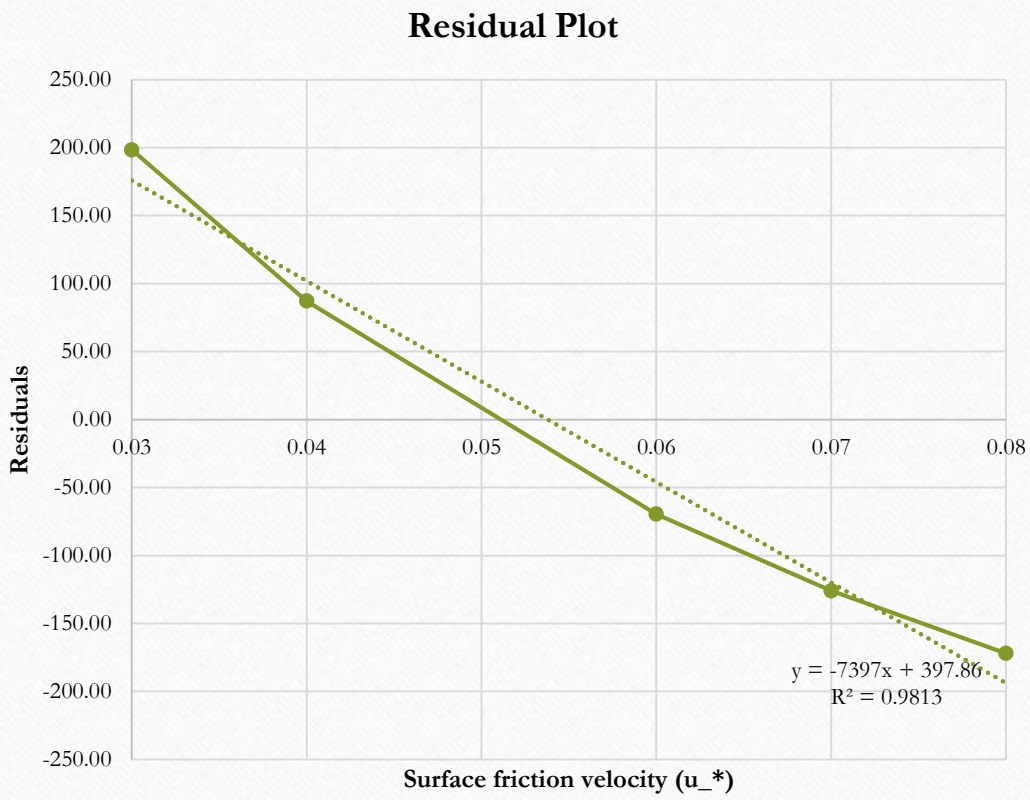

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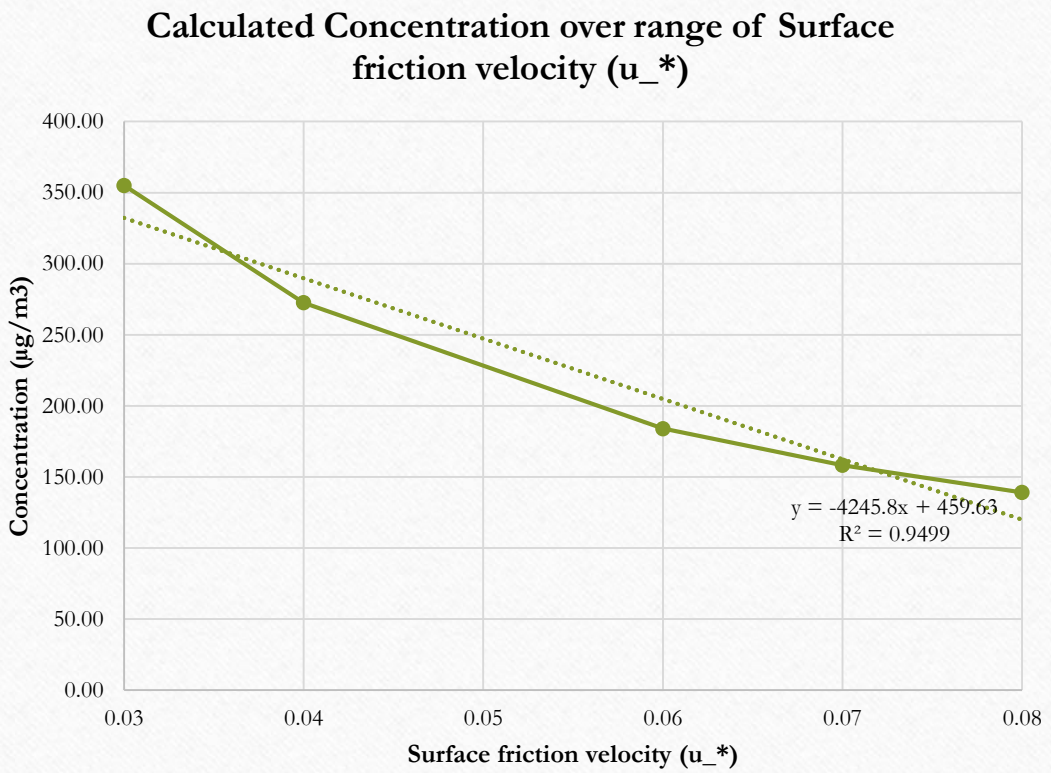

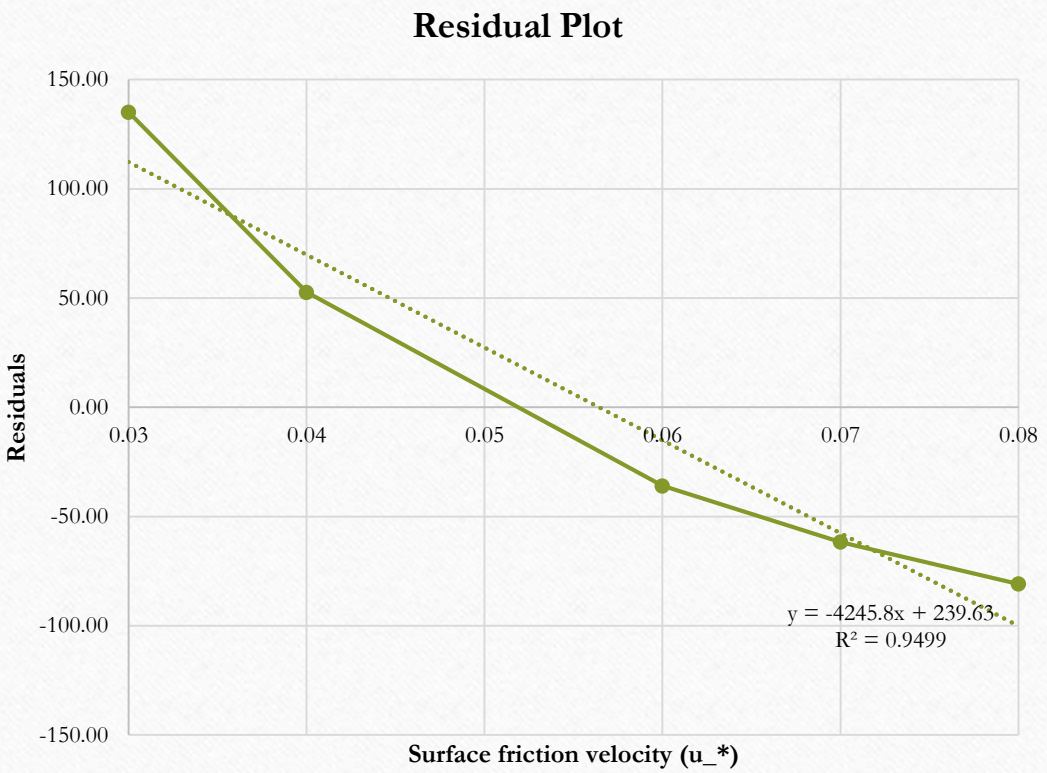

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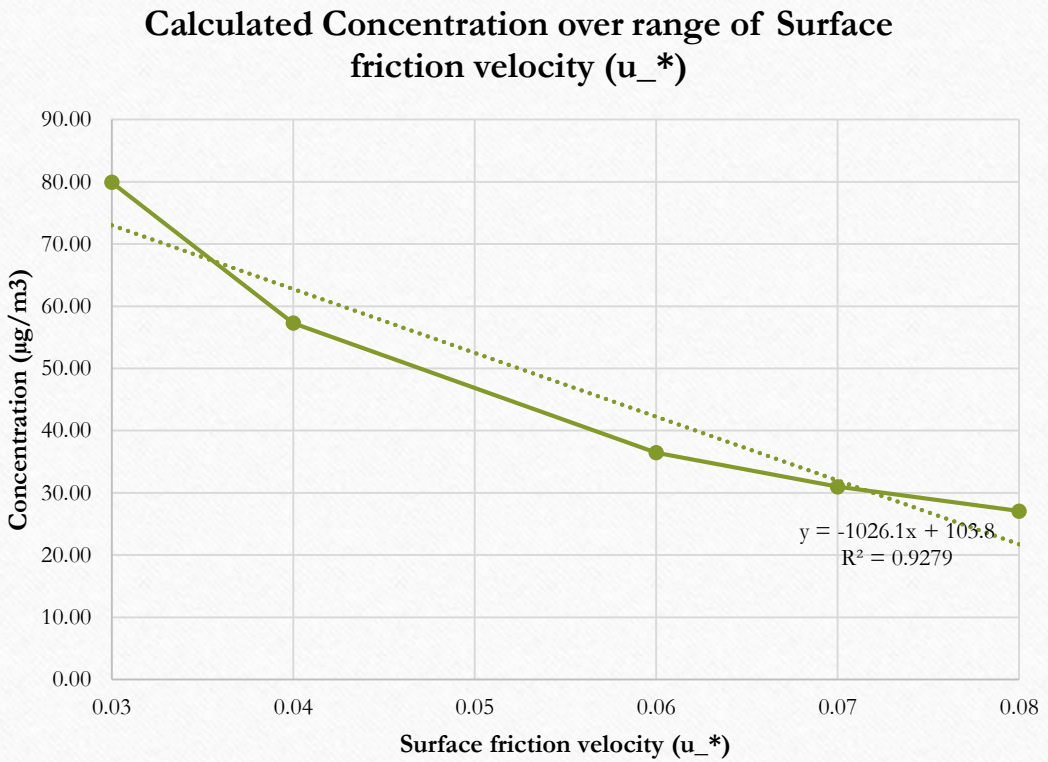

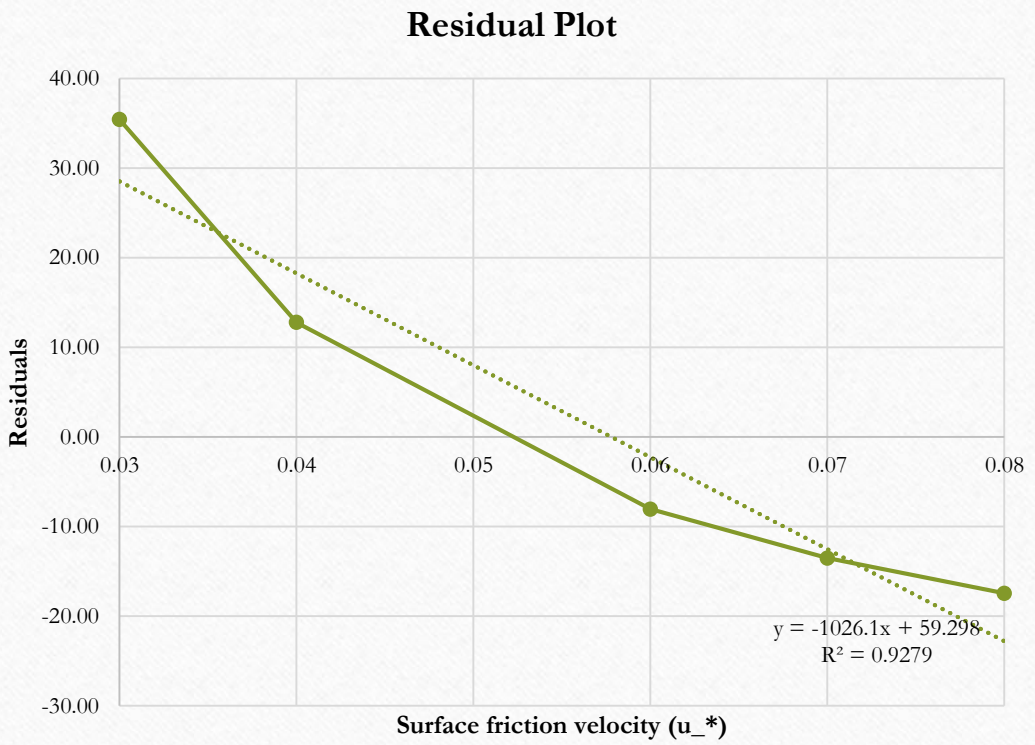

Conclusion

A new model SLINE is presented to compute downwind concentrations from line sources on a highway. The sensitivity analysis shows that the model does not exhibit Type III sensitivity for all the input variables. However, the model show Type III sensitivity for the input parameters q, m, u_* , a and m_t in computing concentration at all the downwind distance. One of the vertical spread variables b_s to compute the vertical spread of the plume shows Type II sensitivity. The type of model sensitivity for the reference wind velocity is mixed at different downwind distances. It is important to note that the model formulation should be reexamined for u_1, b_s , and m_t so that the model is not invalidated as outlined in the ASTM Guide (1994). Further study should focus on evaluating the model against the observed data and to determine the sensitivity of the model using simultaneous changes in model inputs.

References

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