Washington State Department of Health

Arsenic Treatment: Basis of Design, Detailed Mathematics of Treatment & Review of Operations Monitoring

Russell Mau

PUBLIC HEALTH
ALWAYS WORKING FOR A SAFER AND HEALTHIER COMMUNITY

Office of Drinking Water's Mission

To protect the health of the people of Washington State by ensuring safe and reliable drinking water.

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Outline

- Introduction
- Literature Review: Sorption Treatment Performance
- Treatment Mathematics
- Operations Management
- Summary

Outline

- **Introduction**
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Introduction

RESEARCH Open Access

A cross-sectional study of well water arsenic and child IQ in Maine schoolchildren

- Research (2014) *suggests* As $\leq$ 5 μg/L

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Introduction

- *Evidence* of As toxicity

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Outline

- Introduction
- **Literature Review: Sorption Treatment Performance**
- Treatment Mathematics
- Operations Management
- Summary

Literature Review Outline

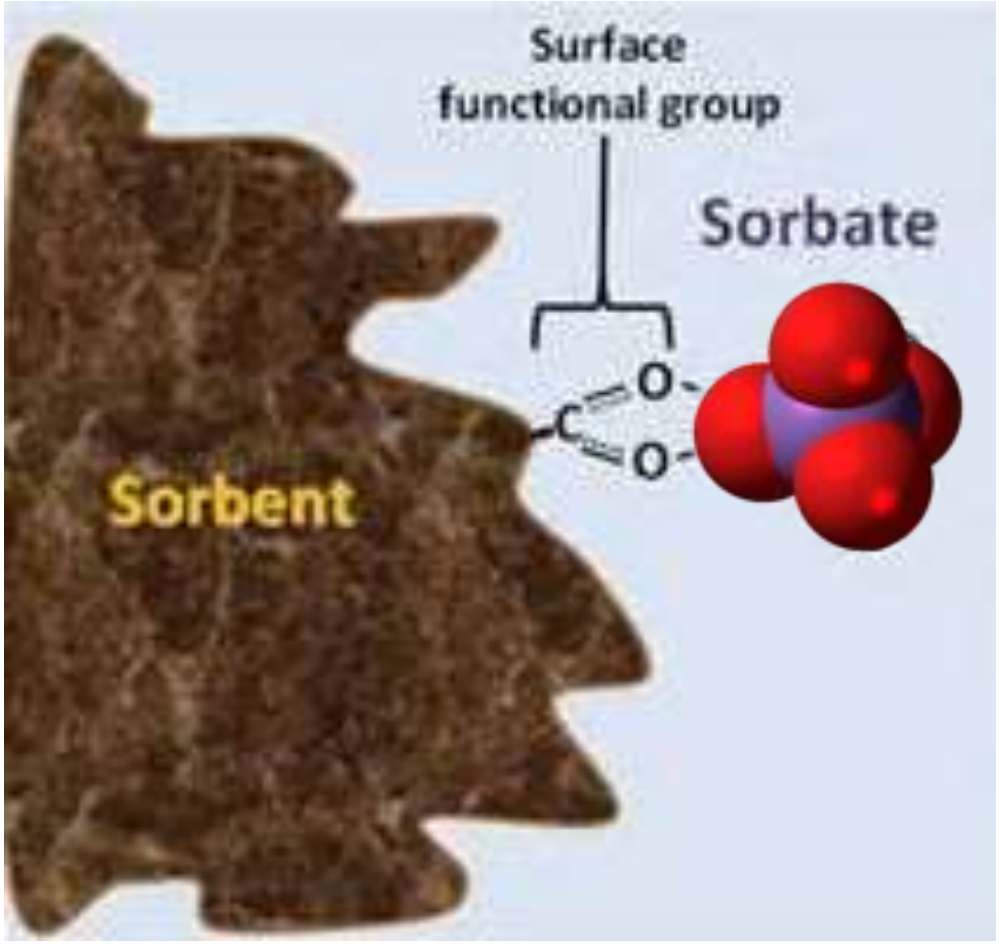
- Chemistry of Arsenic Sorption
- Arsenic Sorption Treatment Performance
- Summary

Literature Review Outline

- **Chemistry of Arsenic Sorption**
- Arsenic Sorption Treatment Performance
- Summary

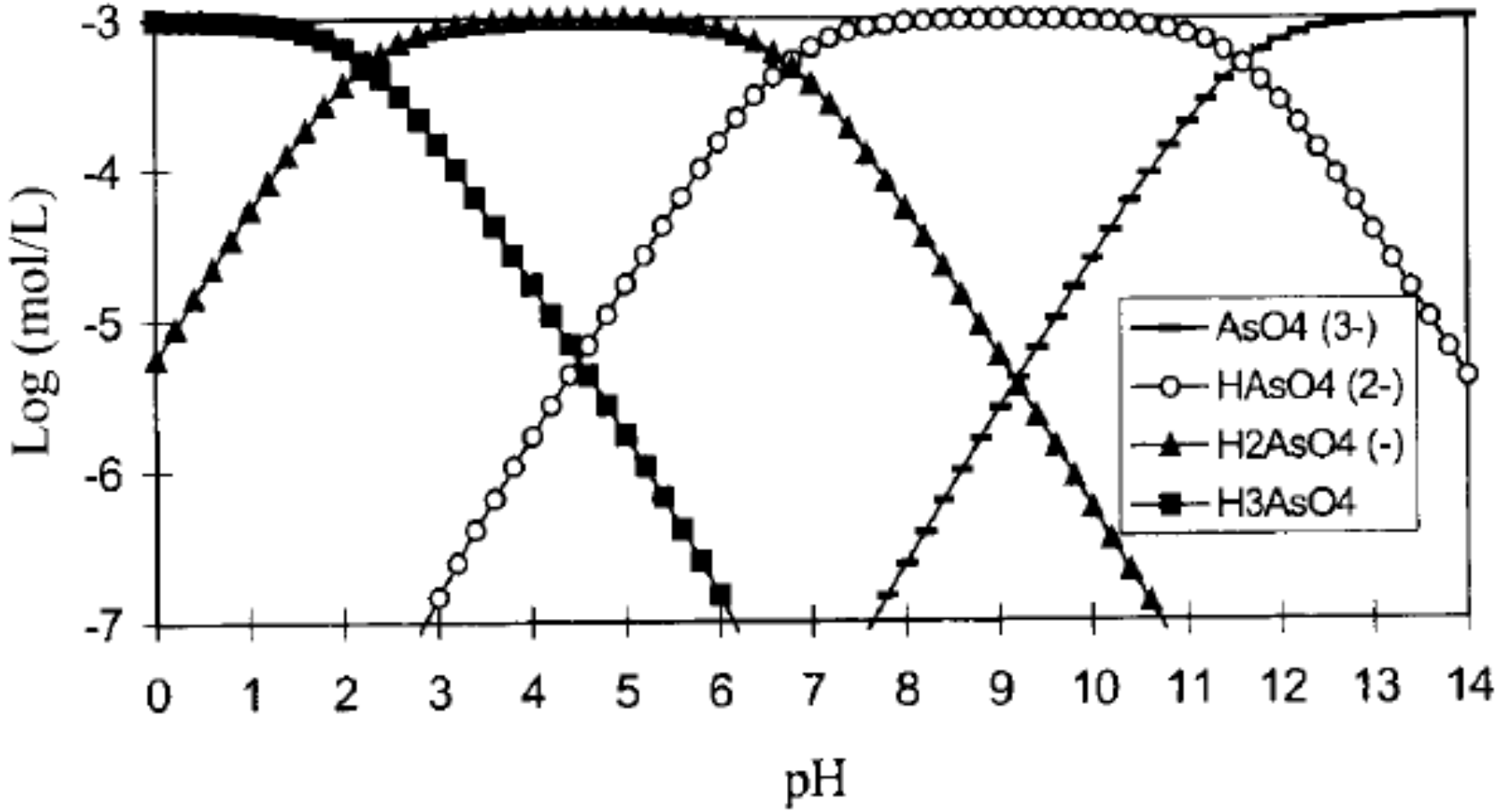
Chemistry of Arsenic Sorption

- Sorption Process - Concept



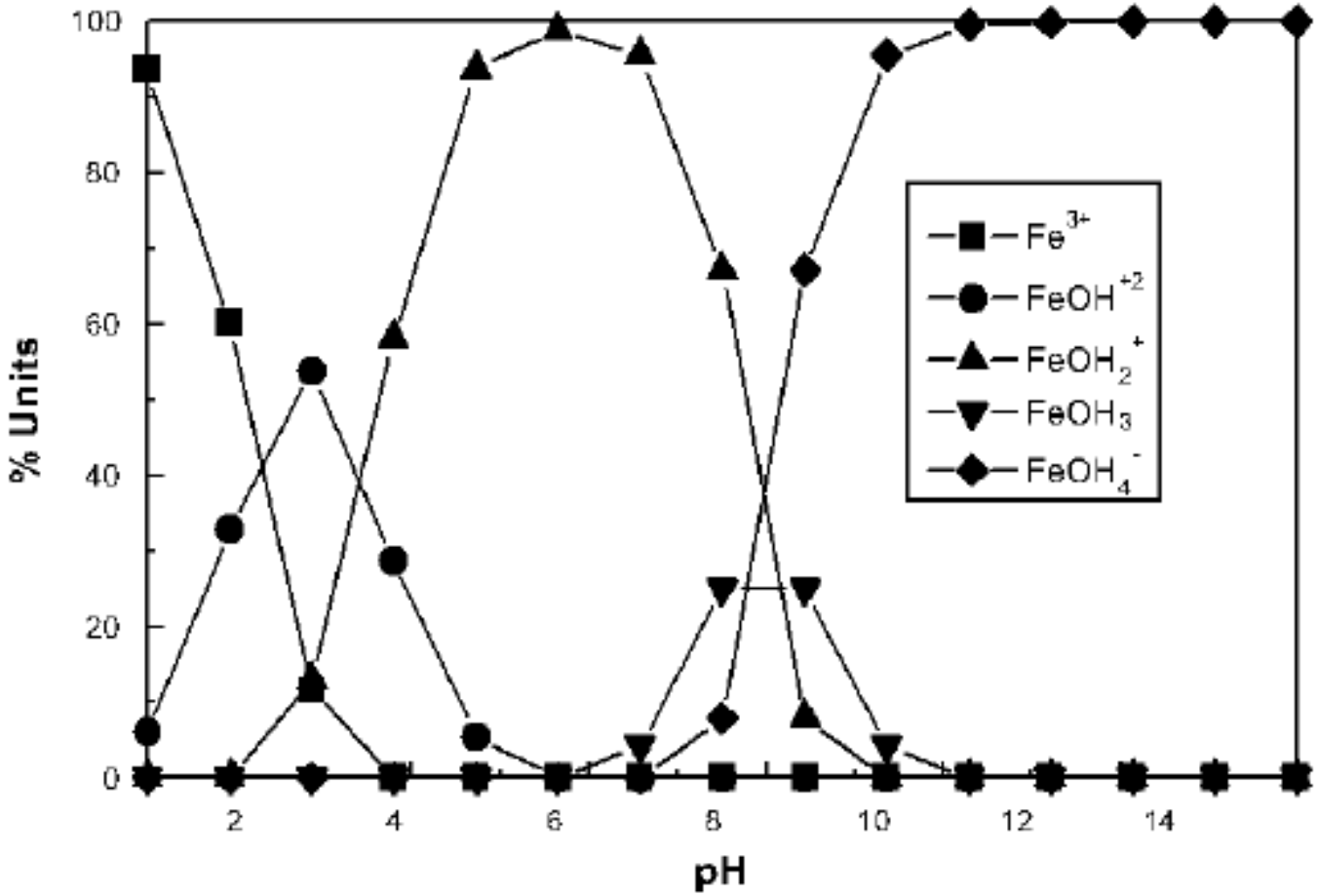
Chemistry of Arsenic Sorption

- Arsenic Speciation (Deliyanni 2003)



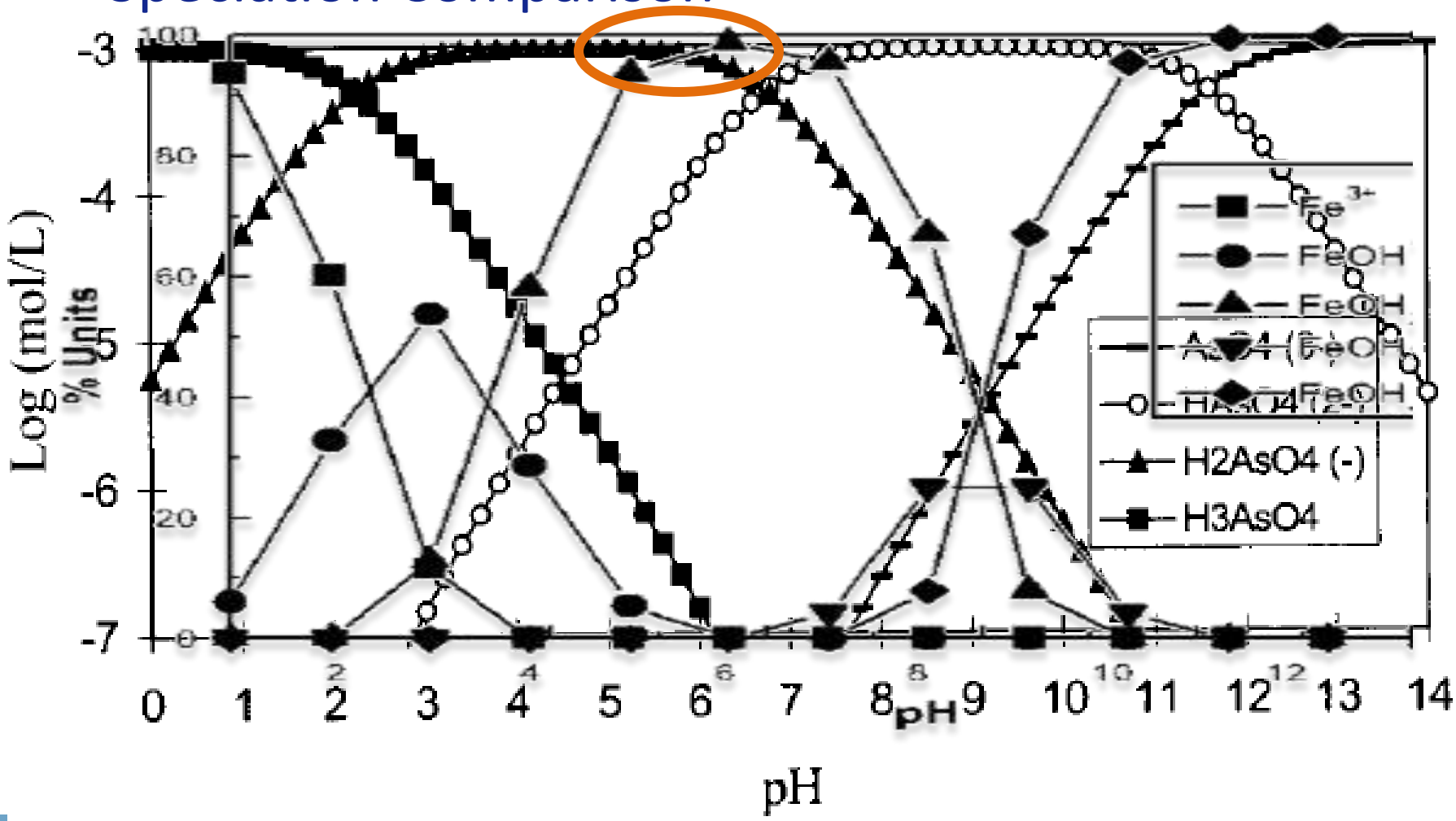
Chemistry of Arsenic Sorption

- Iron Speciation (Katsoyiannis 2002)



Chemistry of Arsenic Sorption

- Speciation Comparison



Chemistry of Arsenic Sorption

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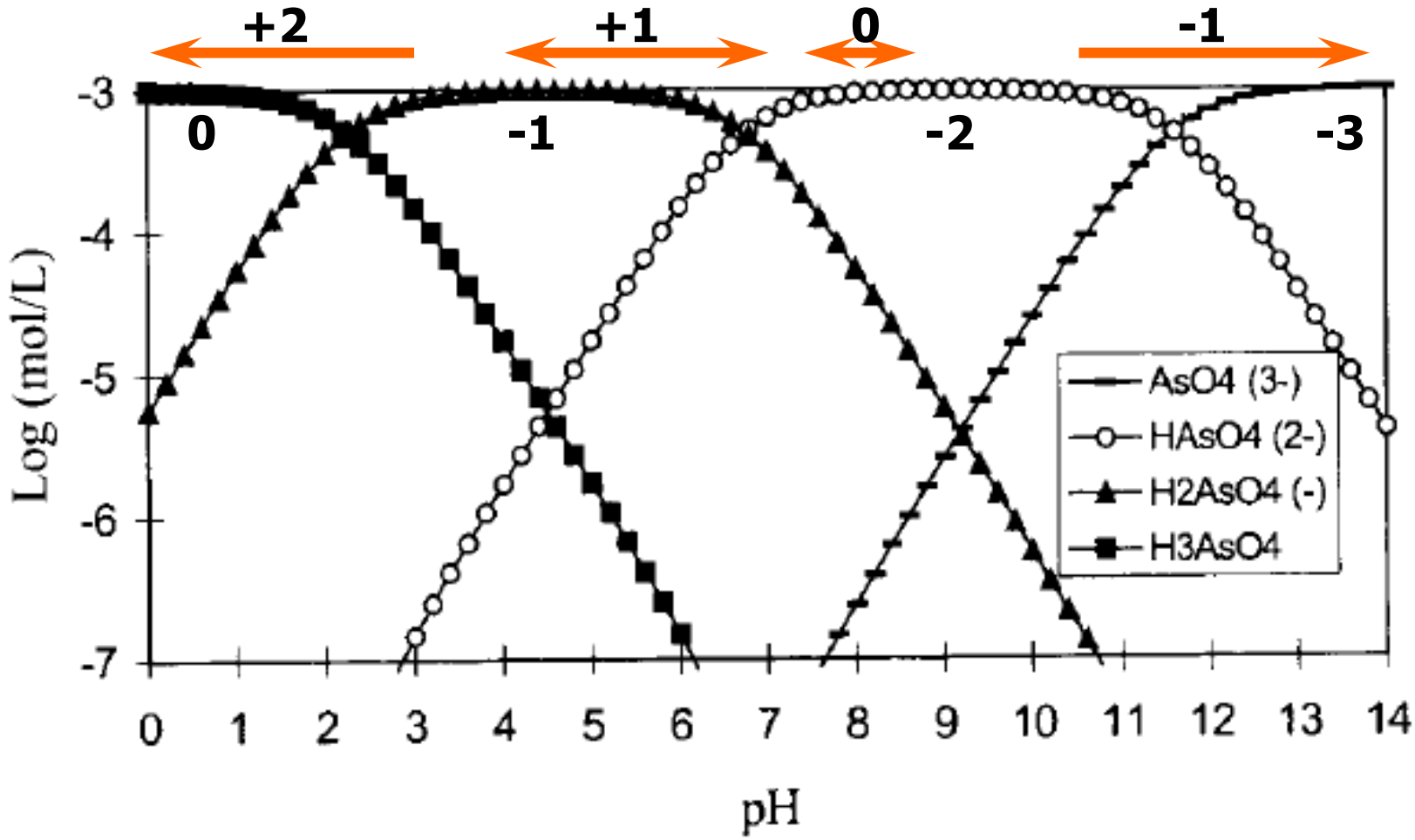

Literature Review Outline

- Chemistry of Arsenic Sorption
- **Arsenic Sorption Treatment Performance**
- Summary

Arsenic Sorption Treatment Performance Outline

- Removal Efficiency vs pH
- Mass Sorption Density vs pH
- Removal Efficiency vs Loading Rate
- Mass Sorption Density vs Loading Rate

Arsenic Sorption Treatment Performance Outline

- **Removal Efficiency vs pH**
- Mass Sorption Density vs pH
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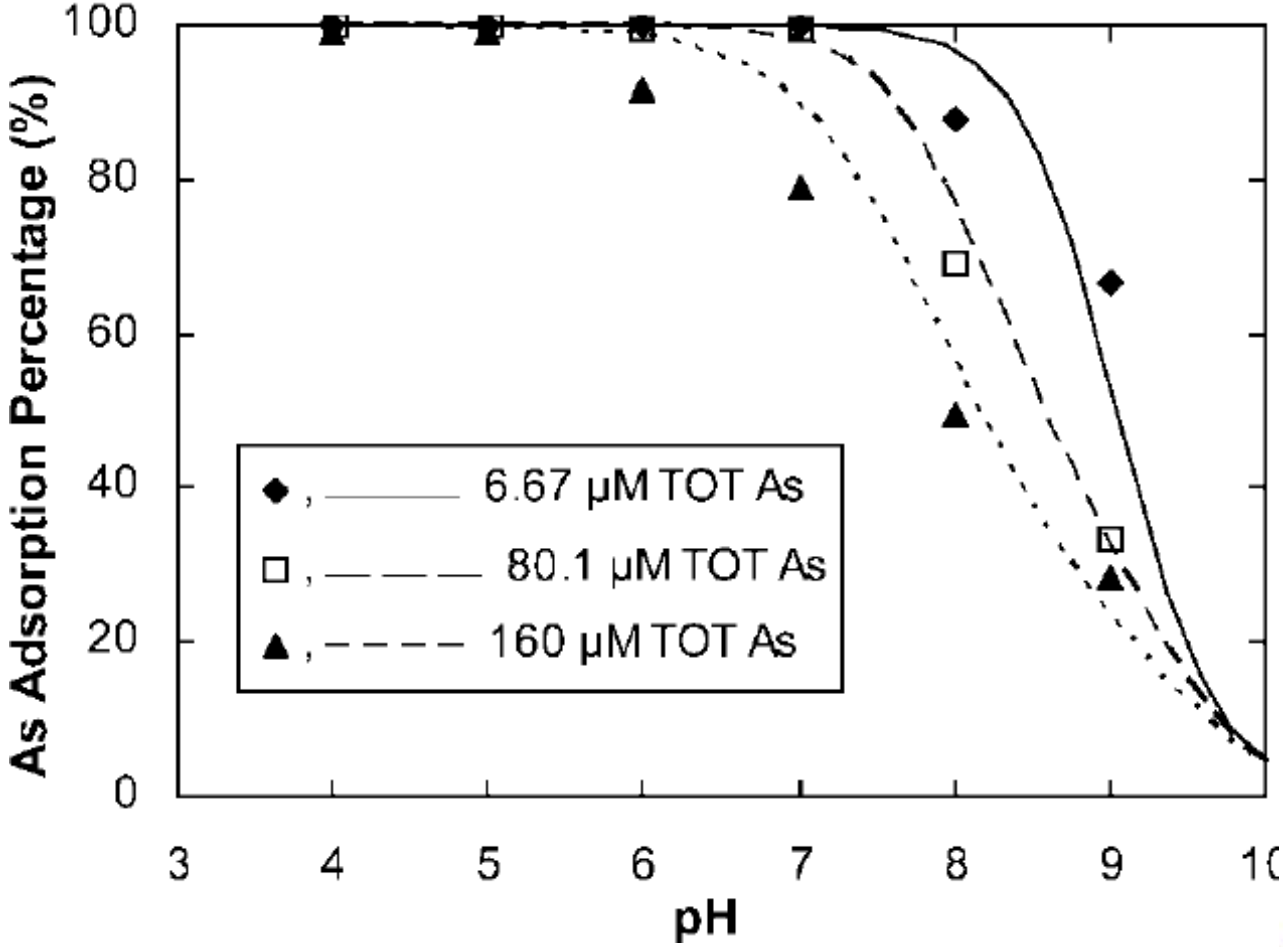
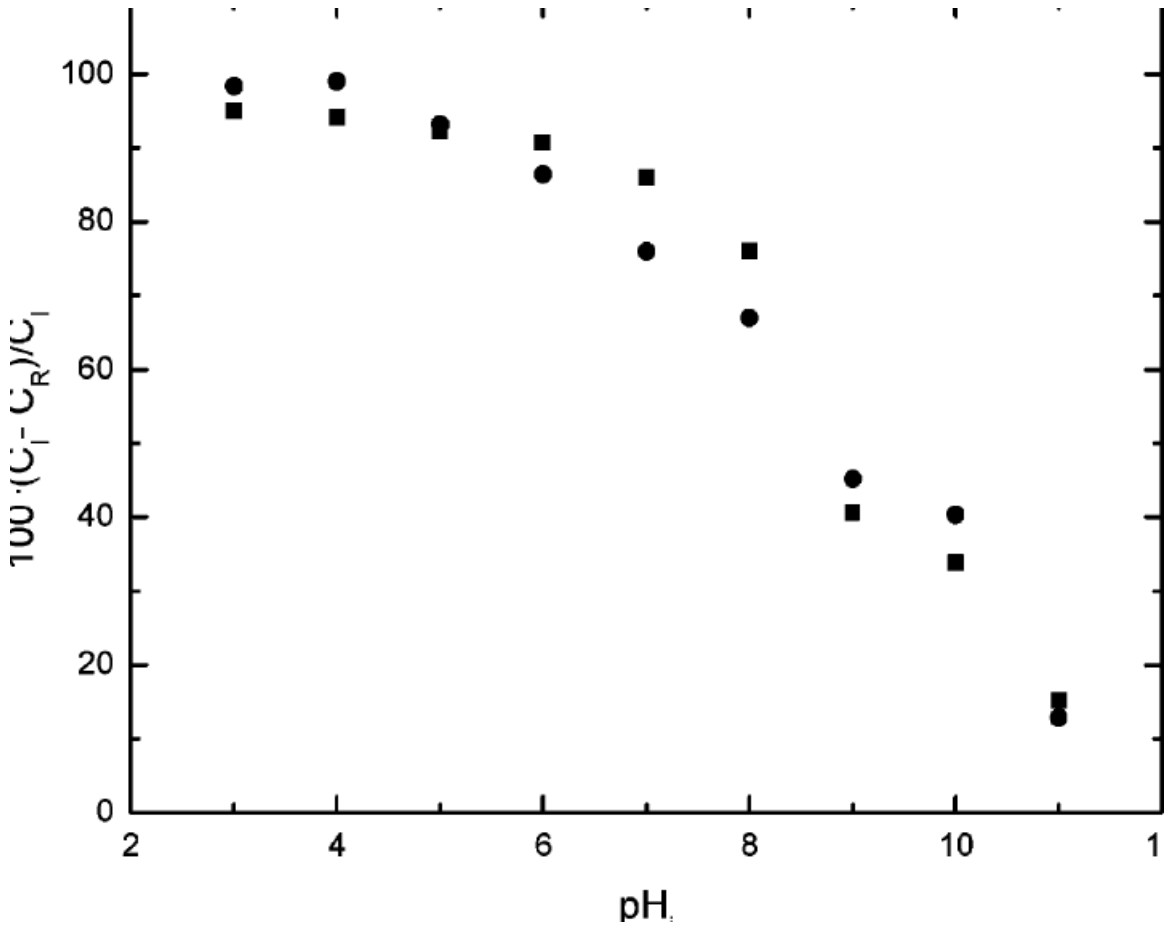
Removal Efficiency vs pH

- On Iron, Zeng, et al. 2008



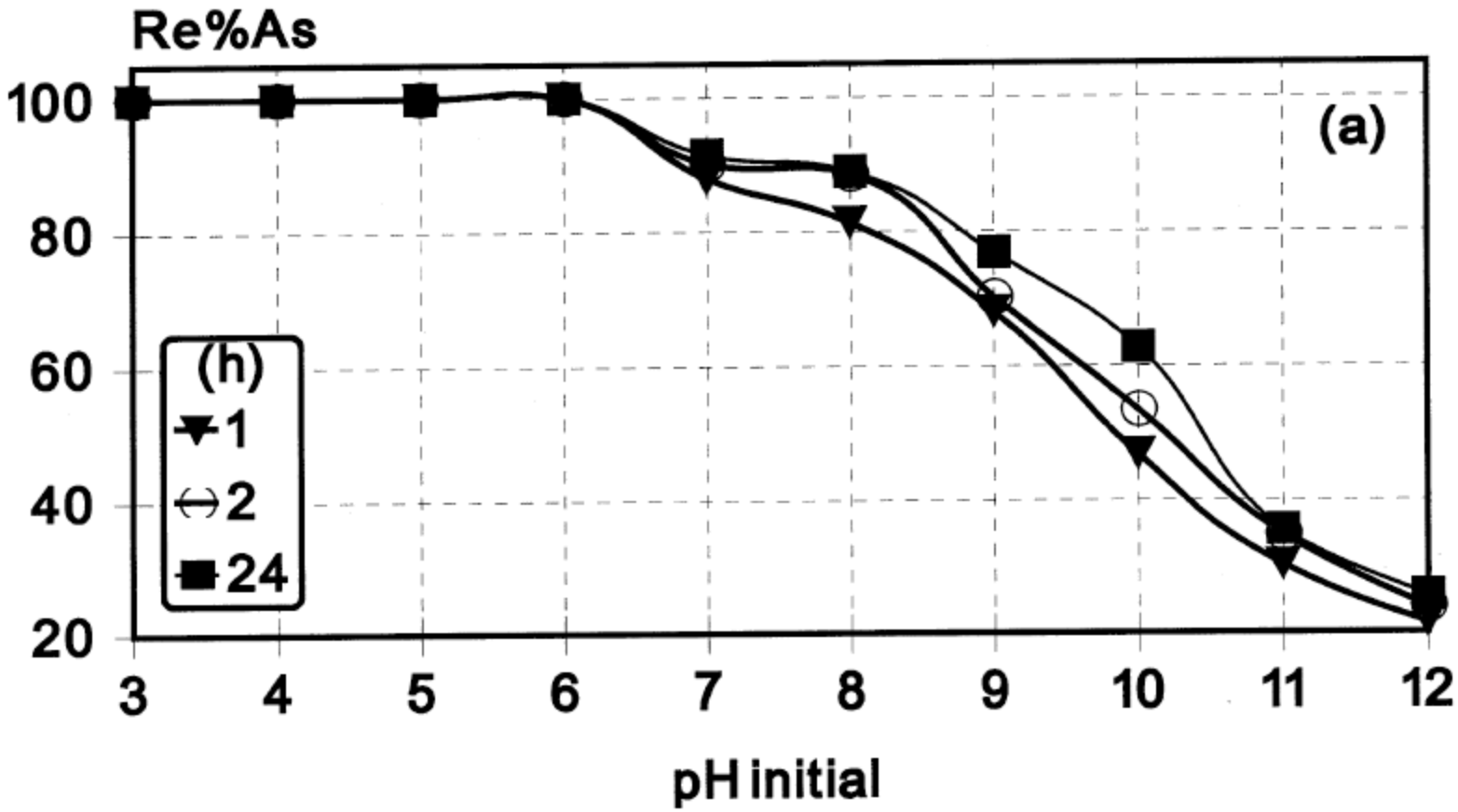
Removal Efficiency vs pH

- On Iron, Gupta, et al. 2009



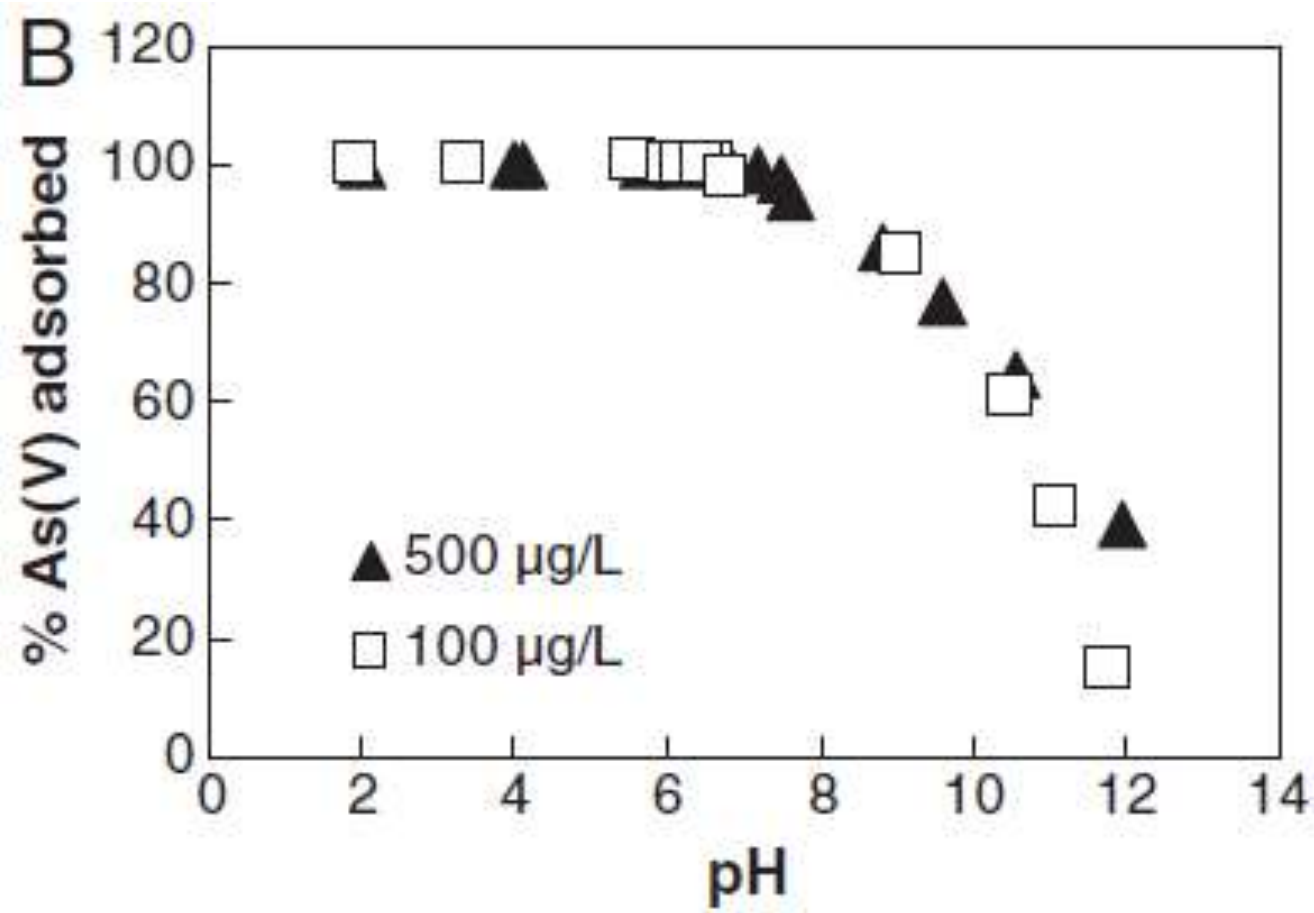
Removal Efficiency vs pH

- On Goethite, Matis, et al. 1998



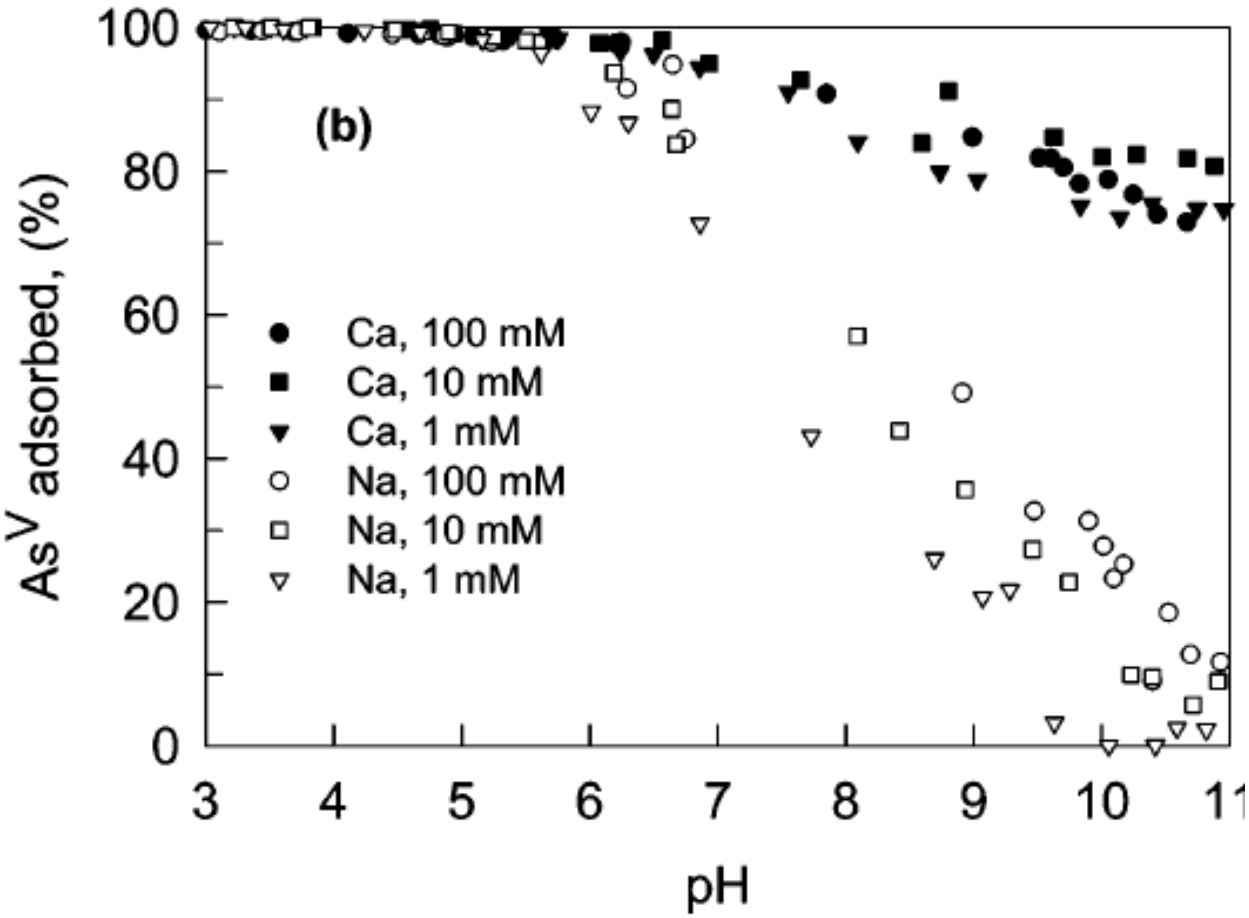
Removal Efficiency vs pH

- On Hematite, Mamindy-Pajany, 2011



Removal Efficiency vs pH

- On Aluminum-Iron Hydroxides, Masue, 2007



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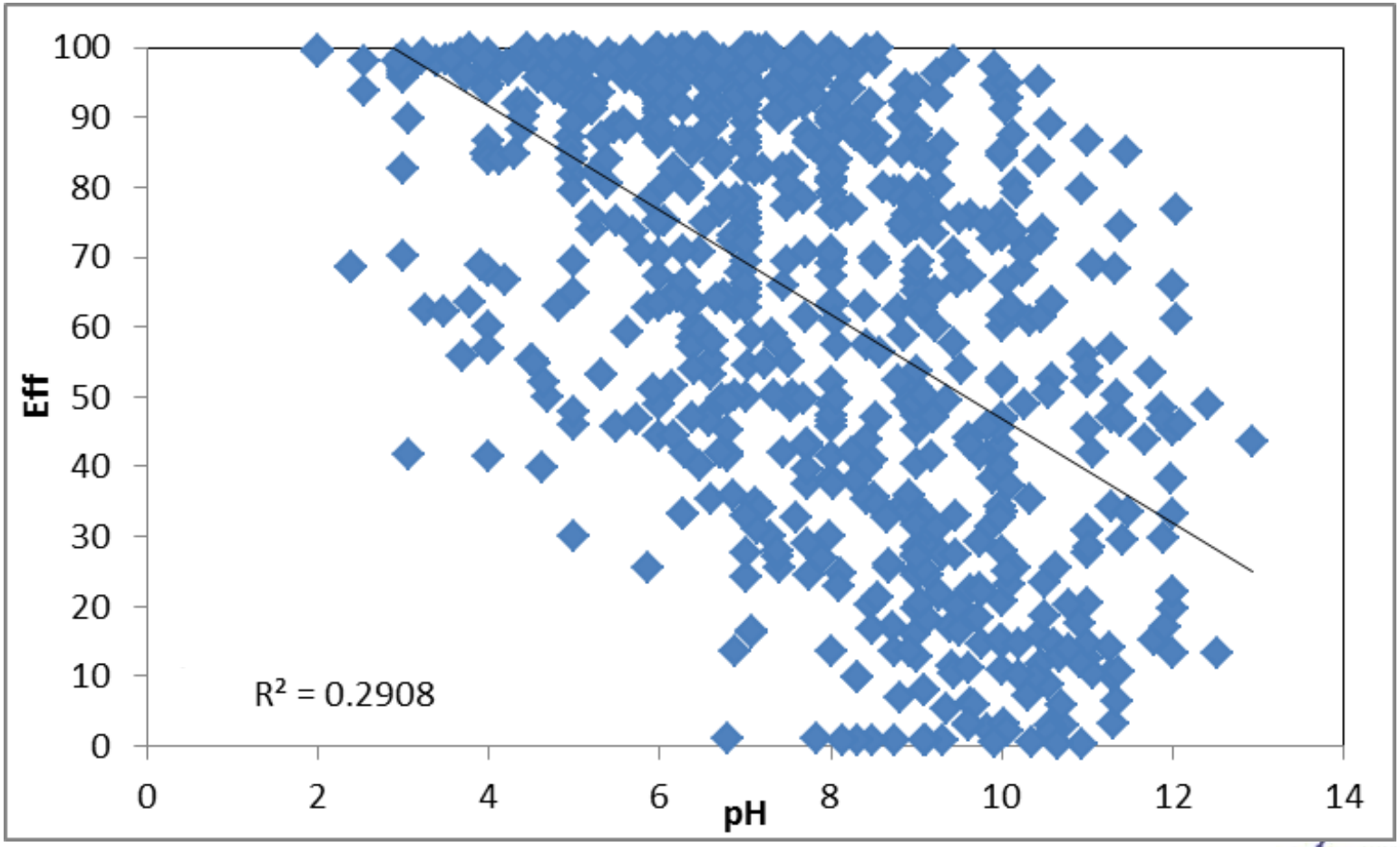
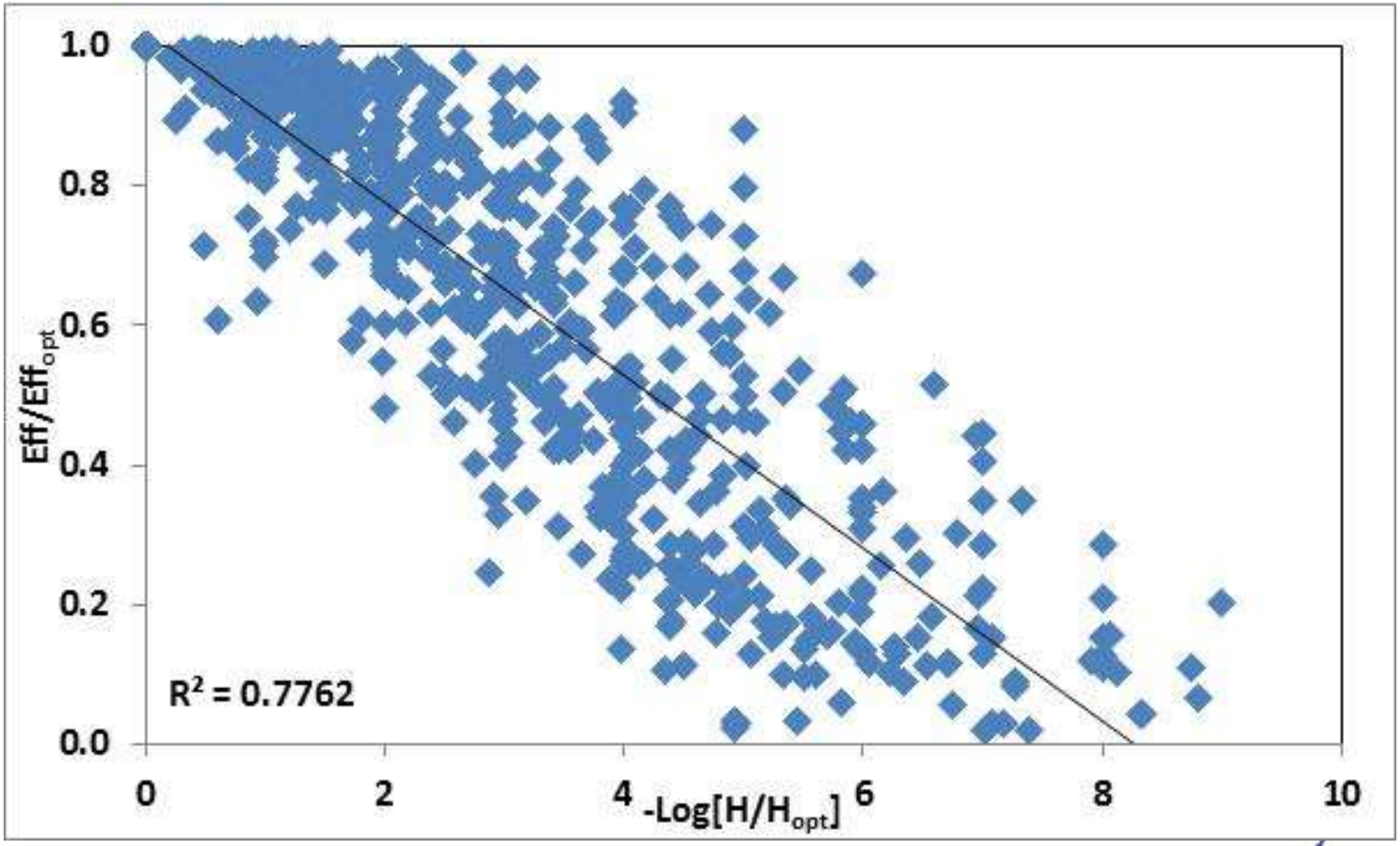
Removal Efficiency vs pH

- Summary



Removal Efficiency vs pH

- Updated Summary



Removal Efficiency vs pH

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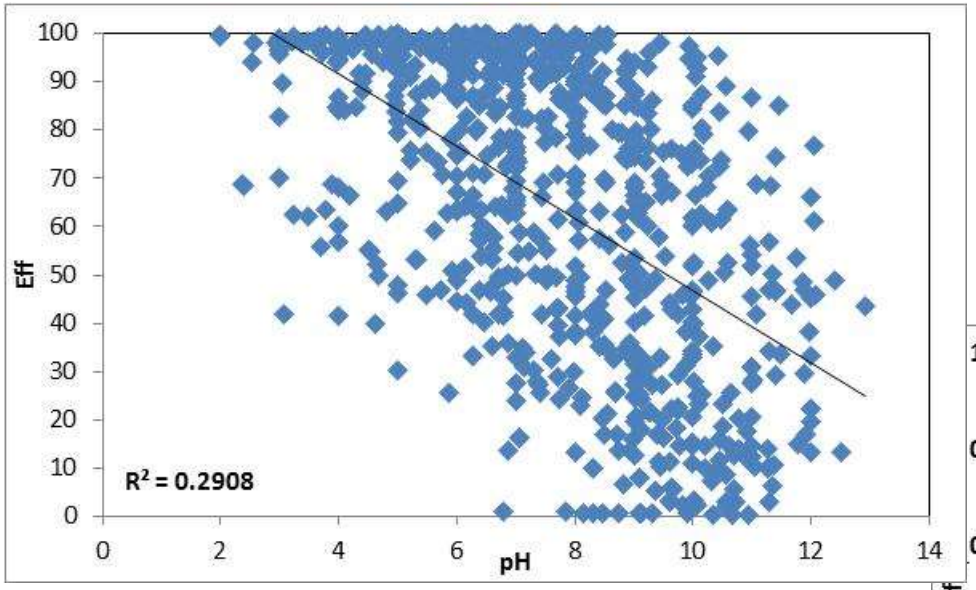

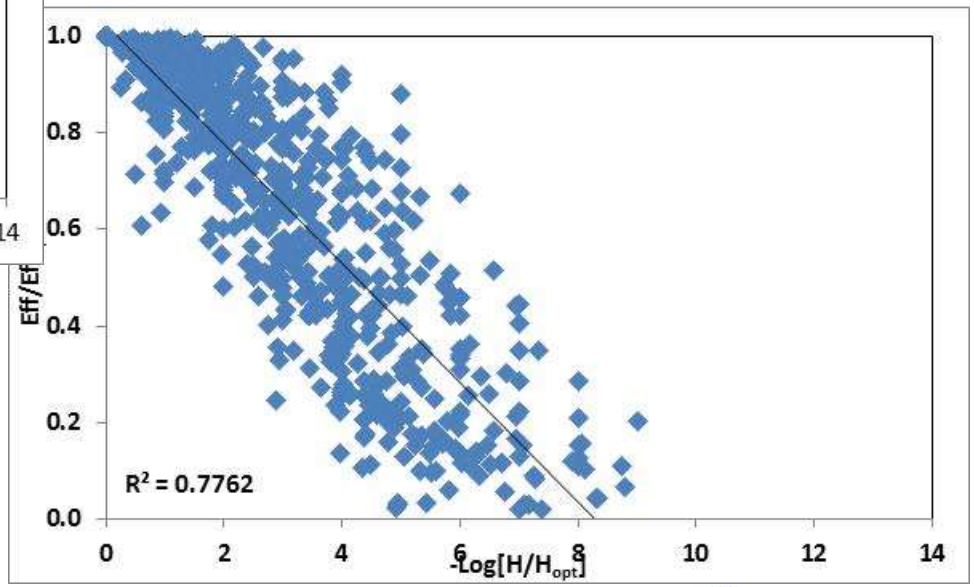

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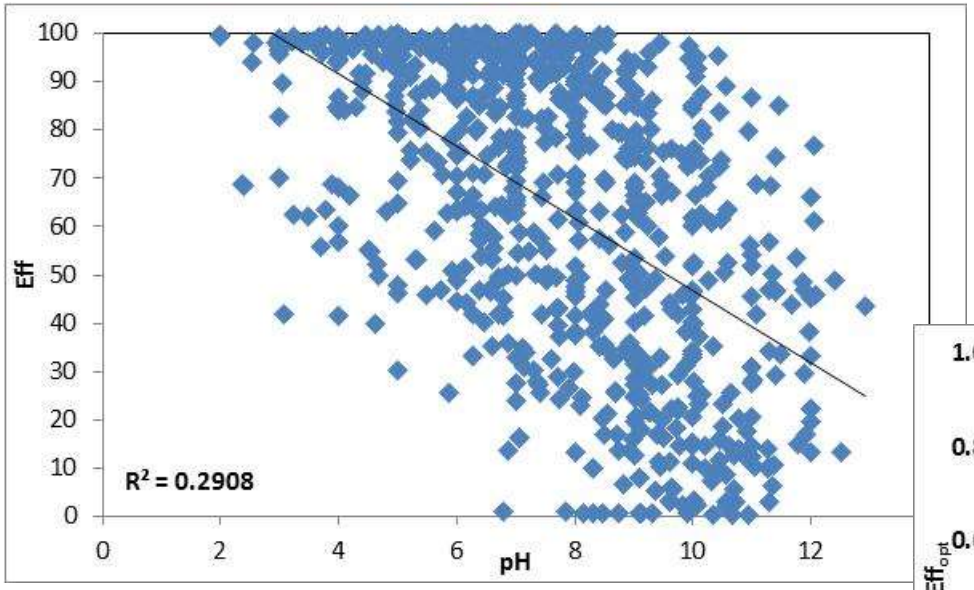
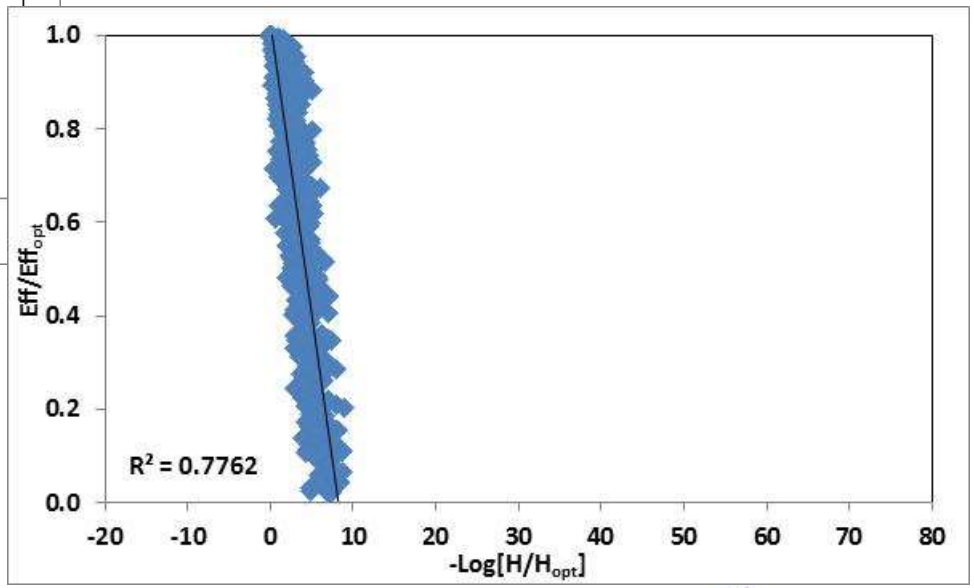
Removal Efficiency vs pH

- Updated Summary





Removal Efficiency vs pH

- Summary

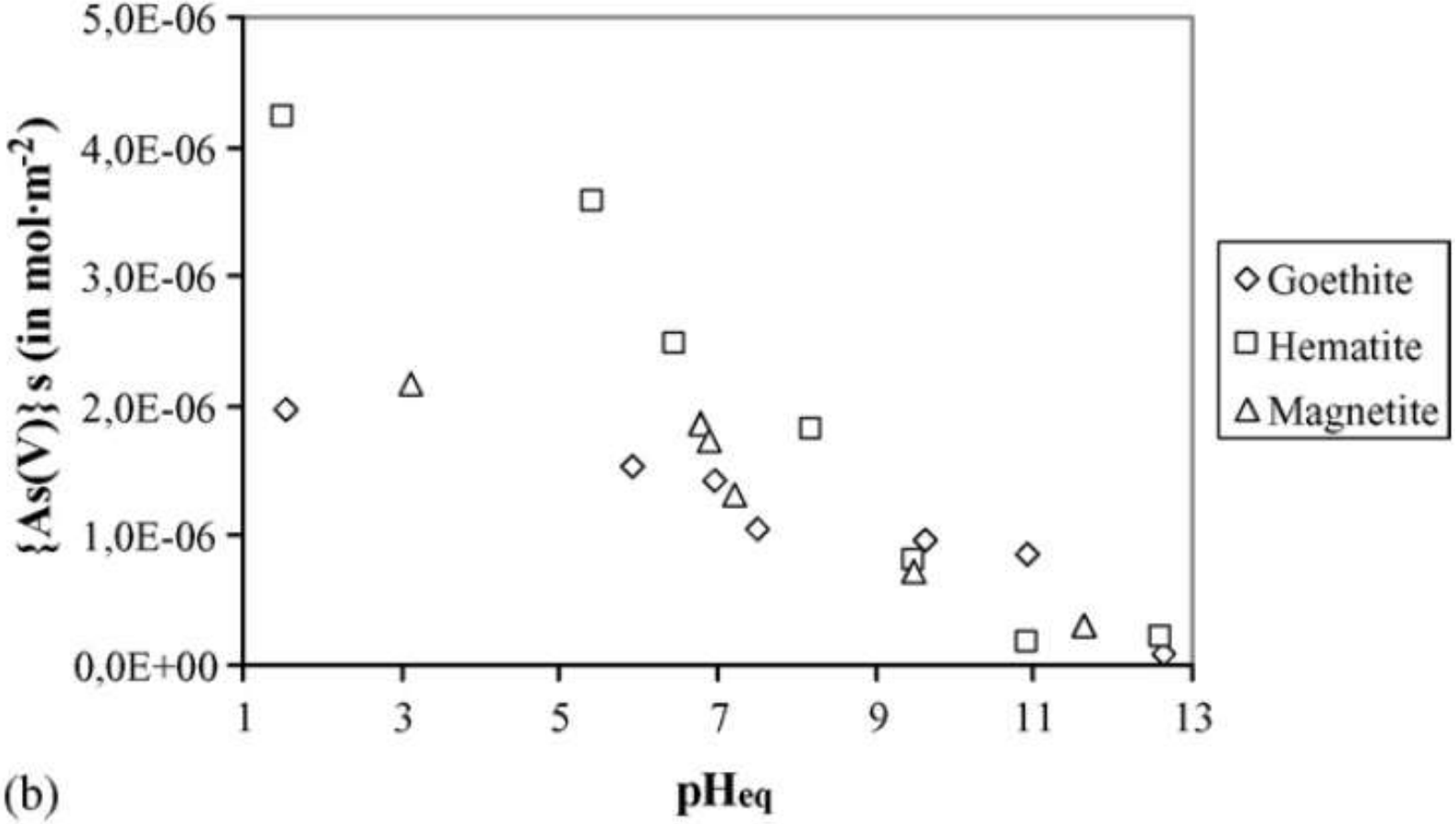
$$\Delta 1\ pH = 0.12\ \Delta(Eff/Eff_{opt})$$

Arsenic Sorption Treatment Performance Outline

- Removal Efficiency vs pH
- **Mass Sorption Density vs pH**
- Removal Efficiency vs Loading Rate
- Mass Sorption Density vs Loading Rate

Mass Sorption Density vs pH

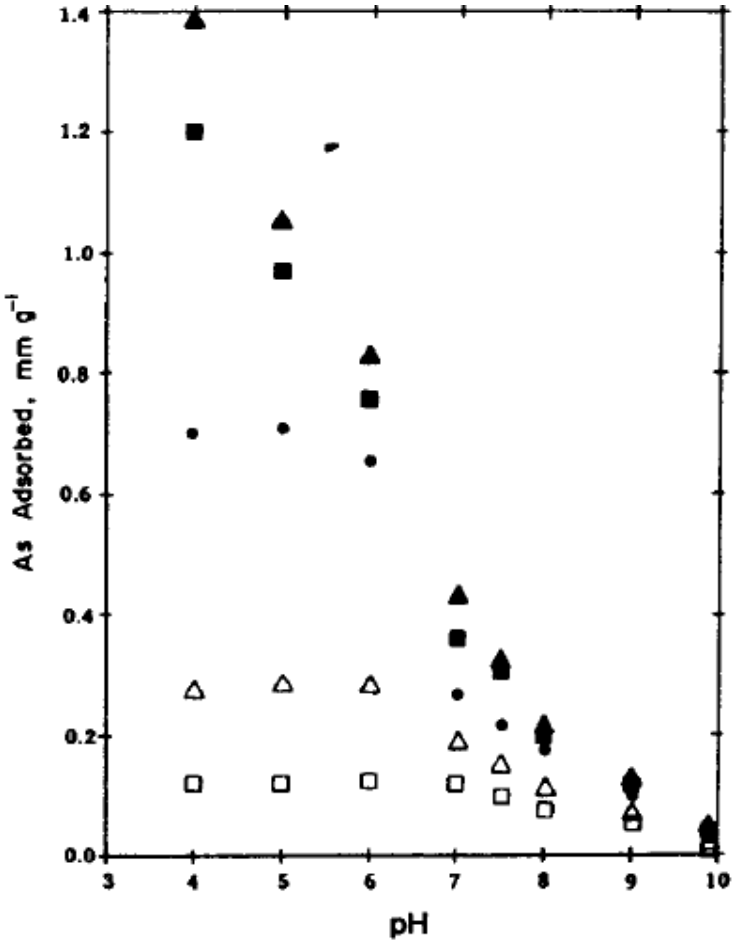
- On various irons, Gimenez 2007



(b)

Mass Sorption Density vs pH

- On Iron, Pierce & Moore 1982



Mass Sorption Density vs pH

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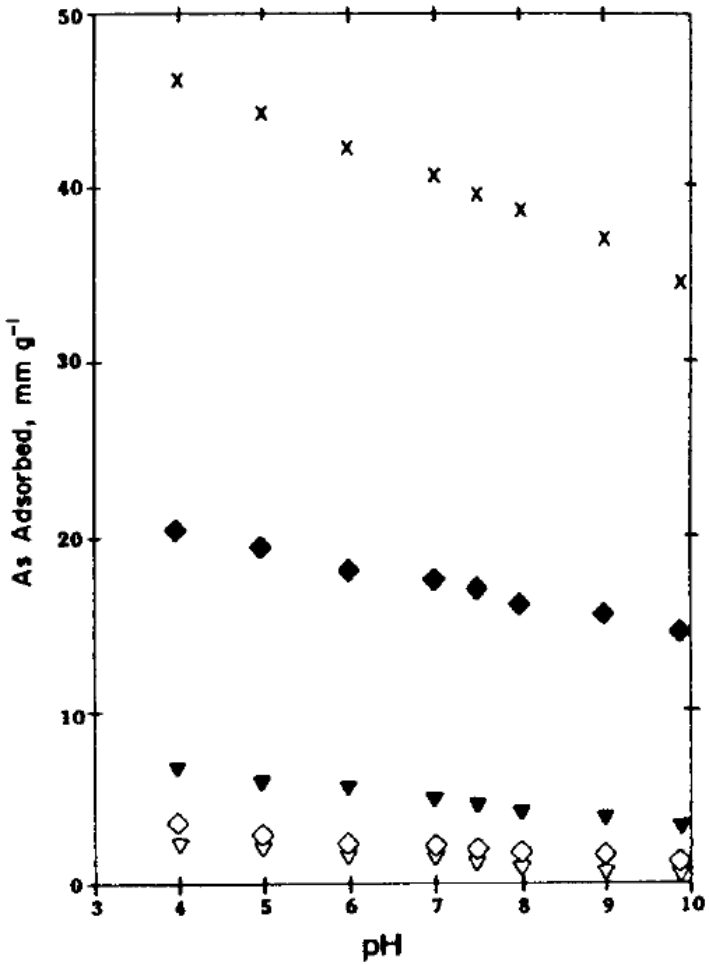
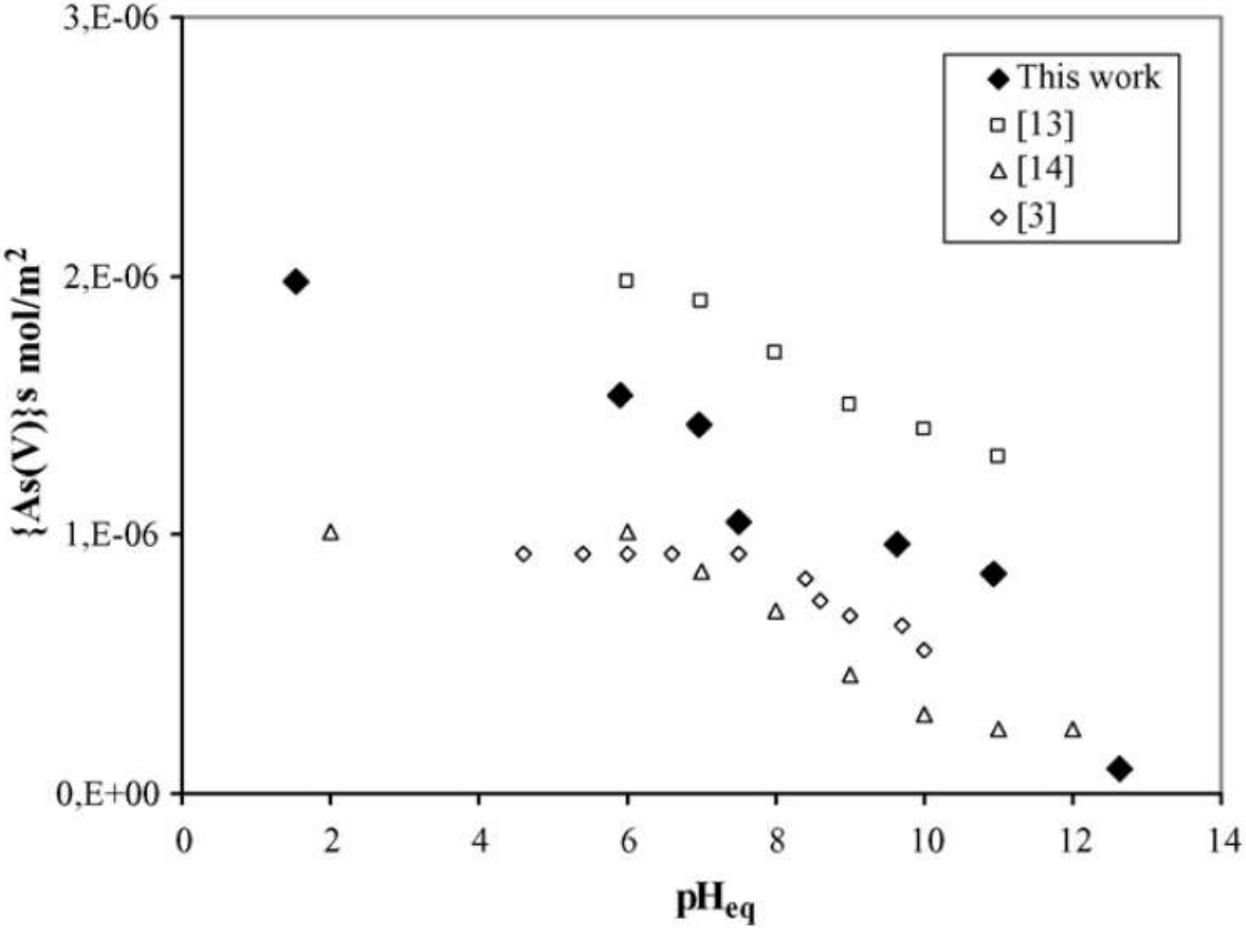


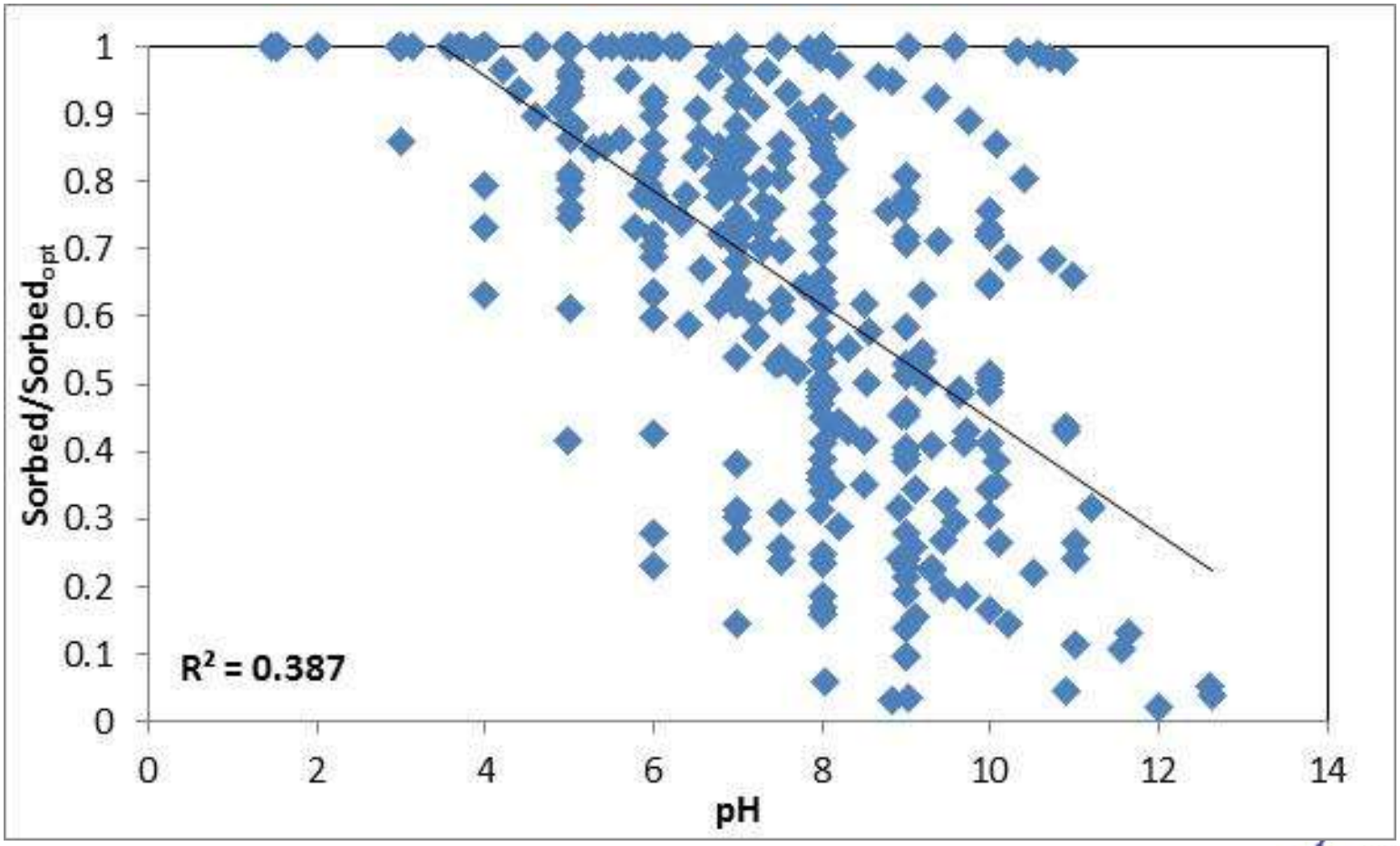
Mass Sorption Density vs pH

- On Goethite, Gimenez 2007



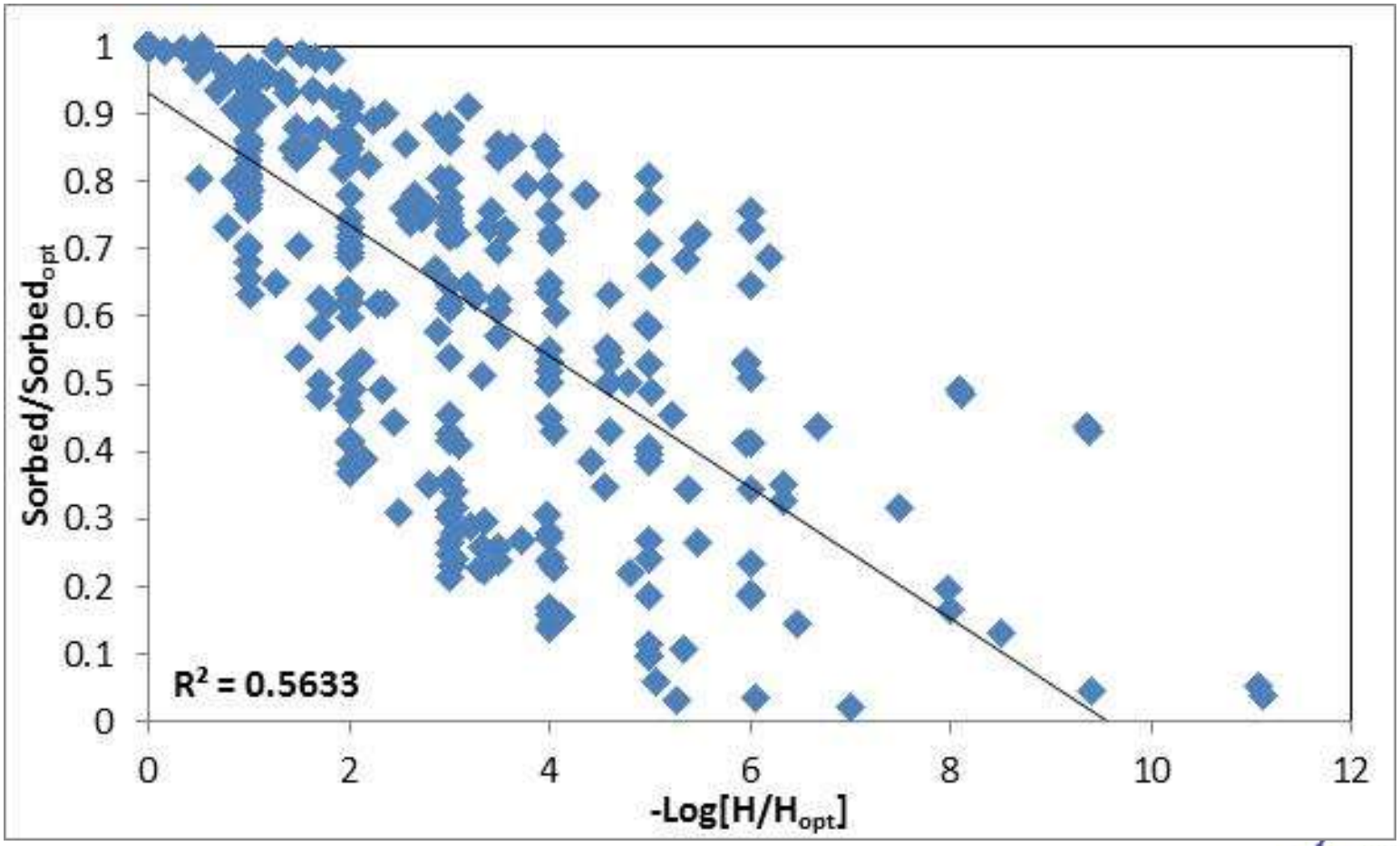
Mass Sorption Density vs pH

- Summary



Mass Sorption Density vs pH

- Updated Summary



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Mass Sorption Density vs pH

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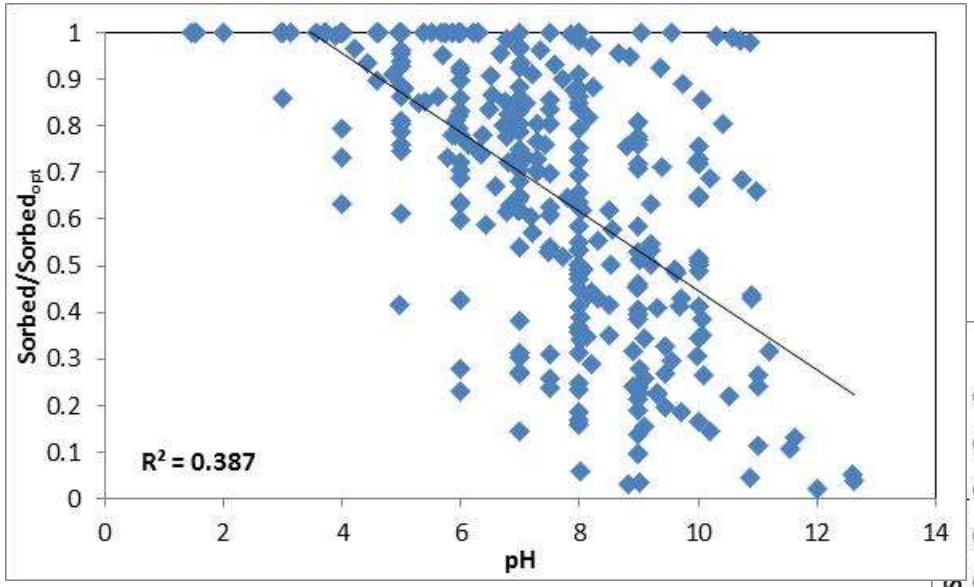
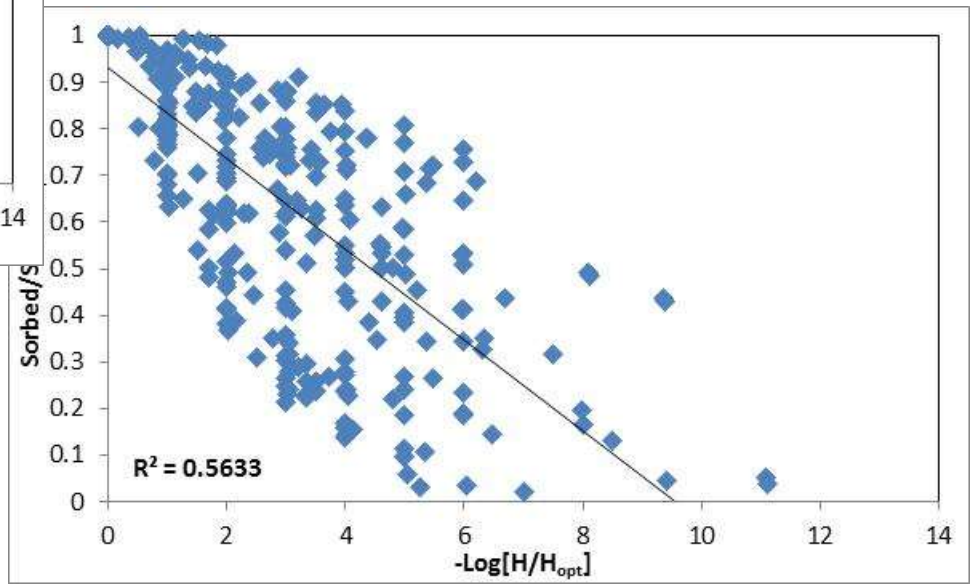




Mass Sorption Density vs pH

- Summary

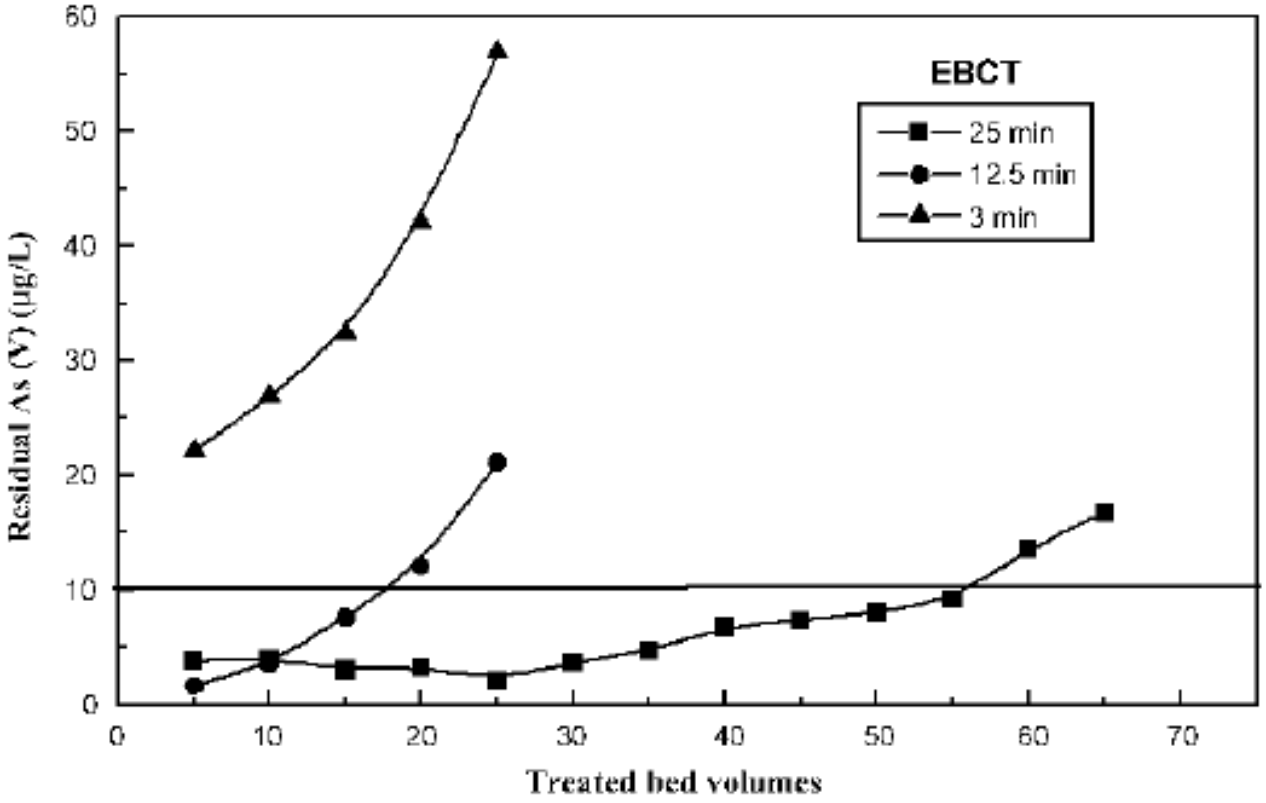
$$\Delta 1\ pH = 0.10\ \Delta(Sorbed/Sorbed_{opt})$$

Arsenic Sorption Treatment Performance Outline

- Removal Efficiency vs pH
- Mass Sorption Density vs pH
- **Removal Efficiency vs Loading Rate**
- Mass Sorption Density vs Loading Rate

Removal Efficiency vs Loading Rate

- On Iron-coated Polystyrene, Katsoyiannis, et al. 2002



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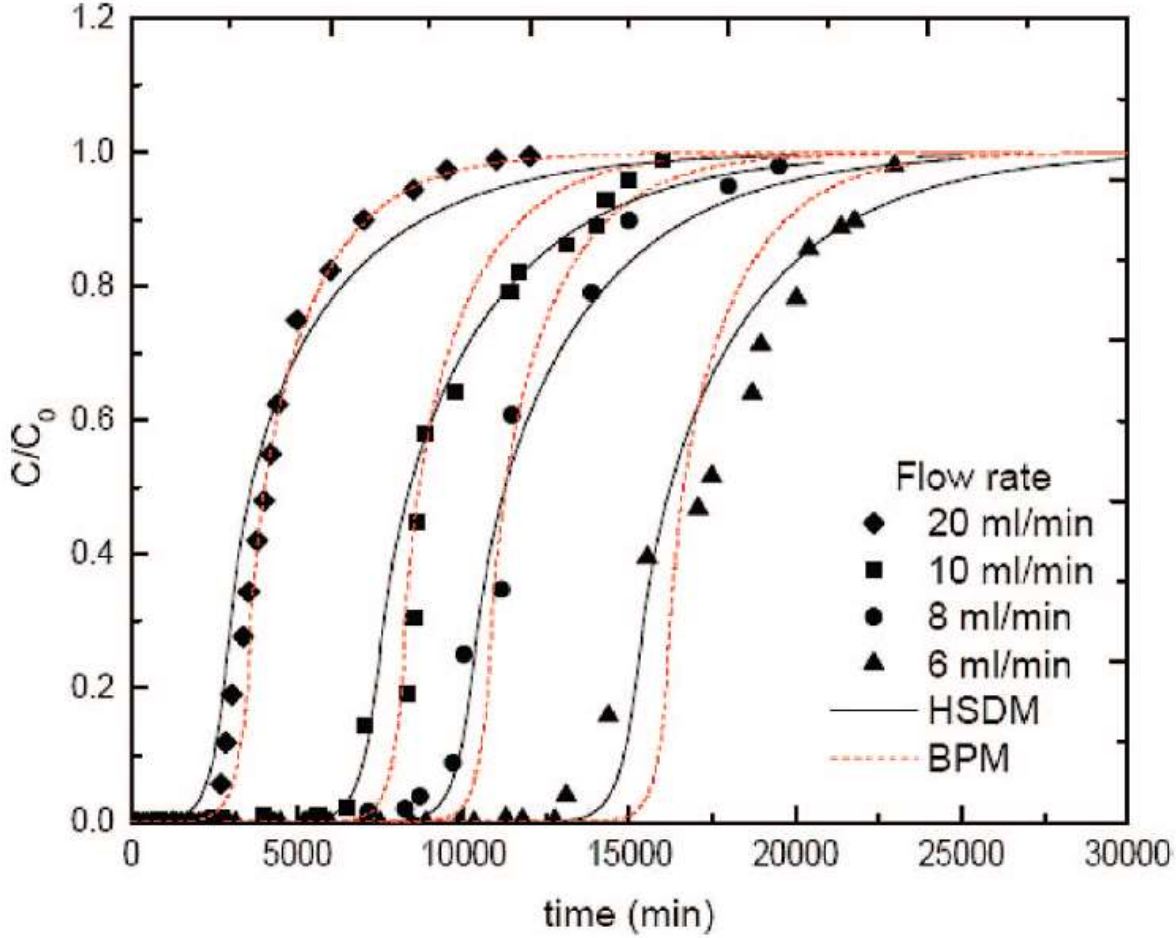
Removal Efficiency vs Loading Rate

- On Magnesium-Aluminum, Dadwhal 2009



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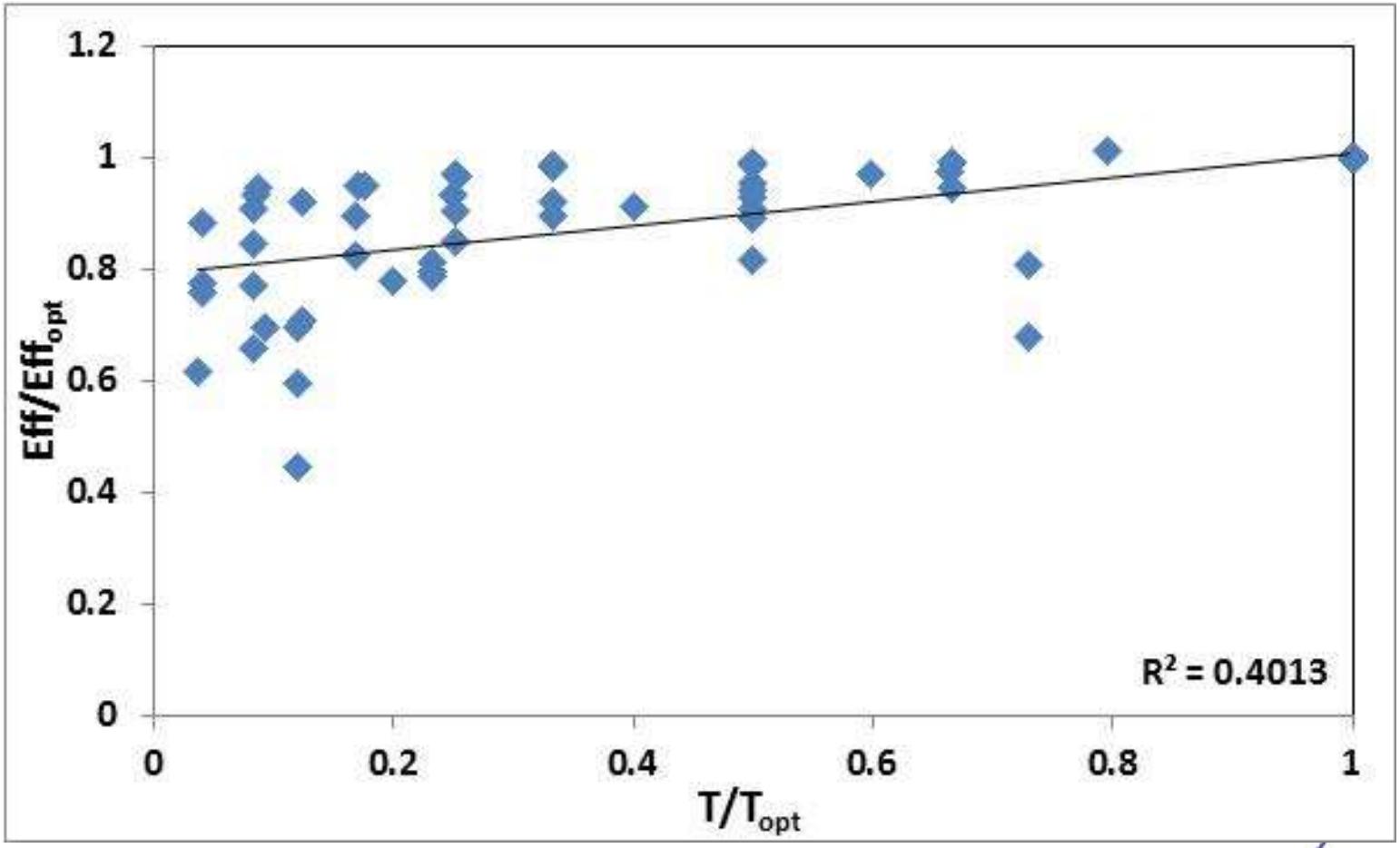
Removal Efficiency vs Loading Rate

- Summary



Removal Efficiency vs Loading Rate

- Summary

$$\Delta 0.1\ T = 0.025\ \Delta(Eff/Eff_{opt})$$

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Arsenic Sorption Treatment Performance Outline

- Removal Efficiency vs pH
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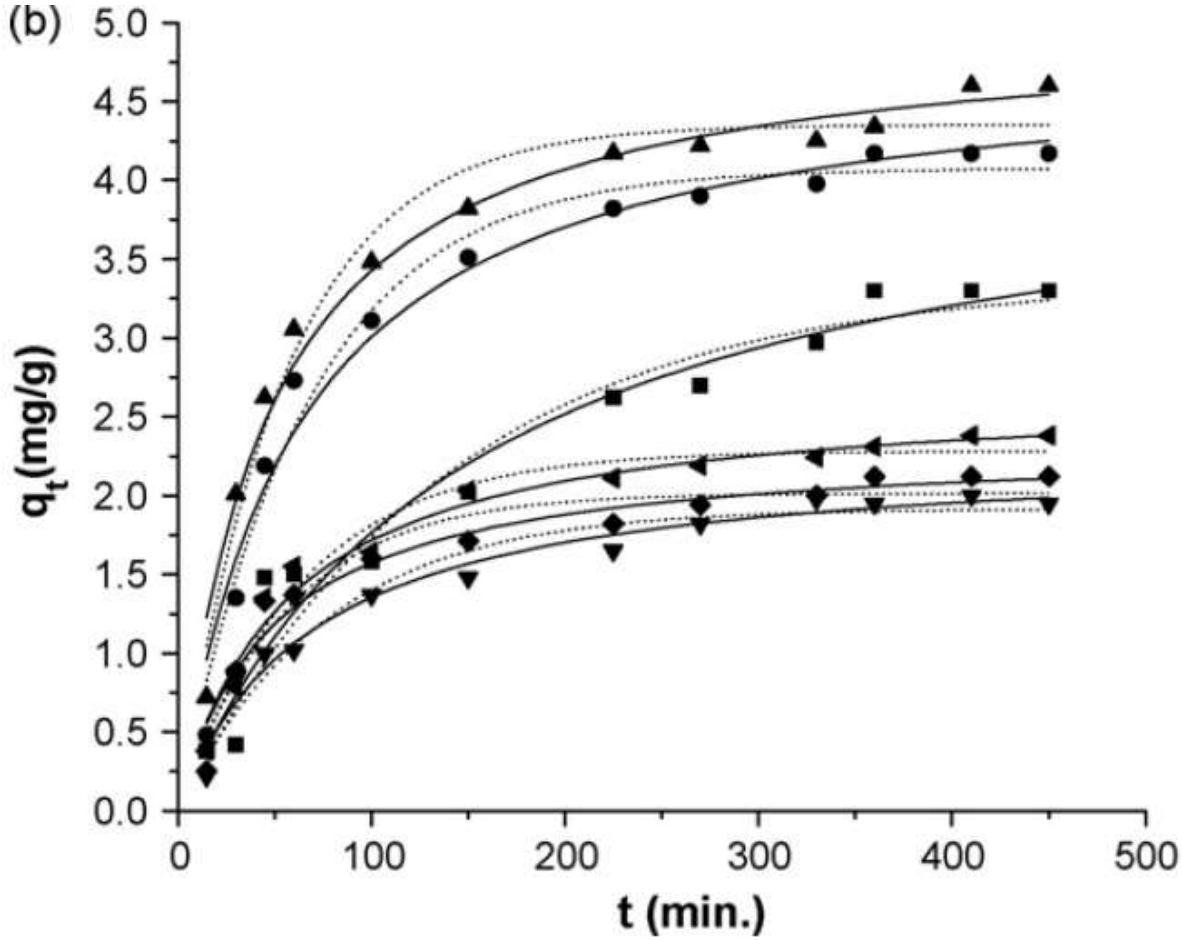
- Removal Efficiency vs Loading Rate
- **Mass Sorption Density vs Loading Rate**

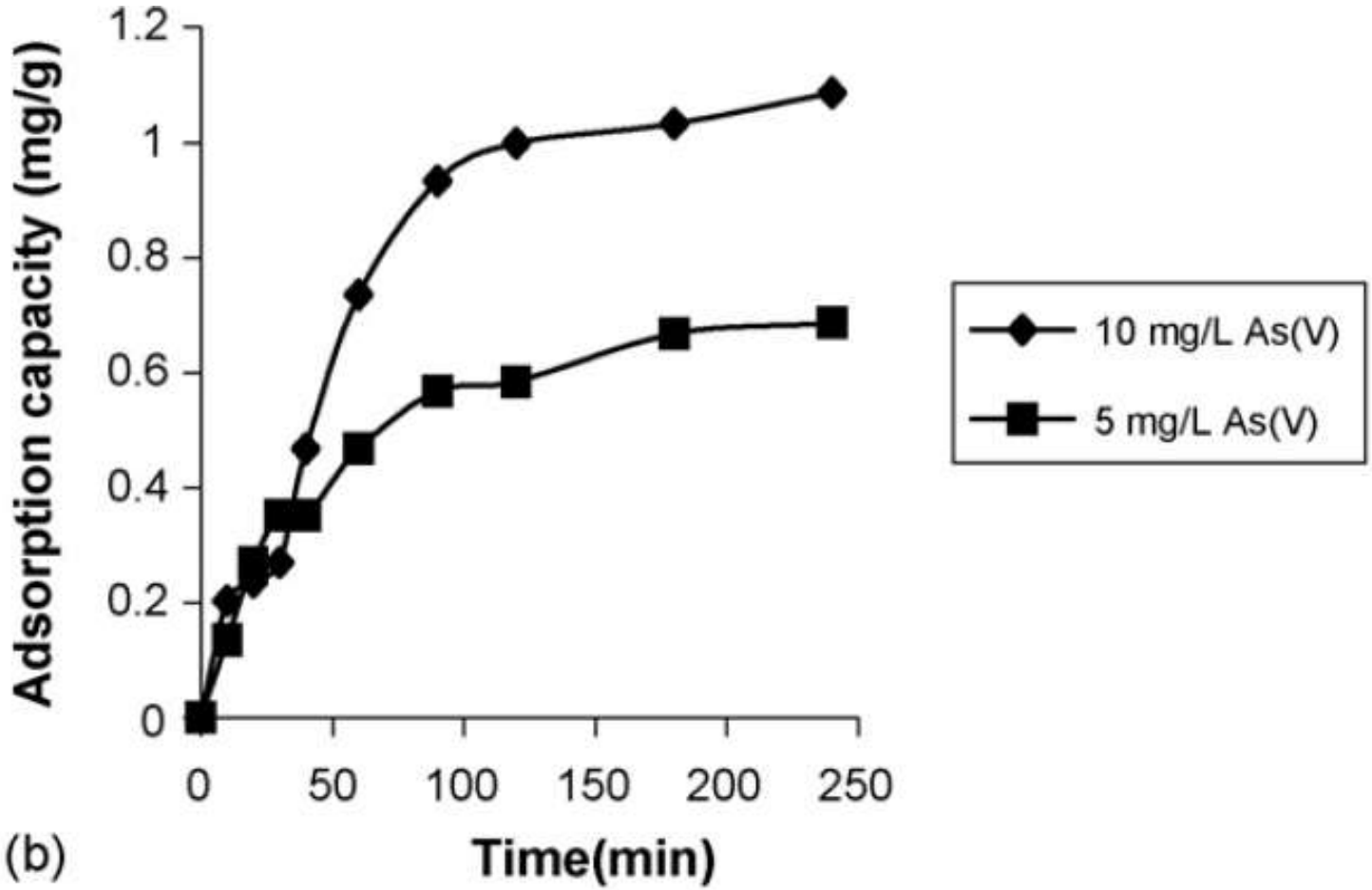
Mass Sorption Density vs Loading Rate

- On Iron, Gupta & Ghosh 2009



Mass Sorption Density vs Loading Rate

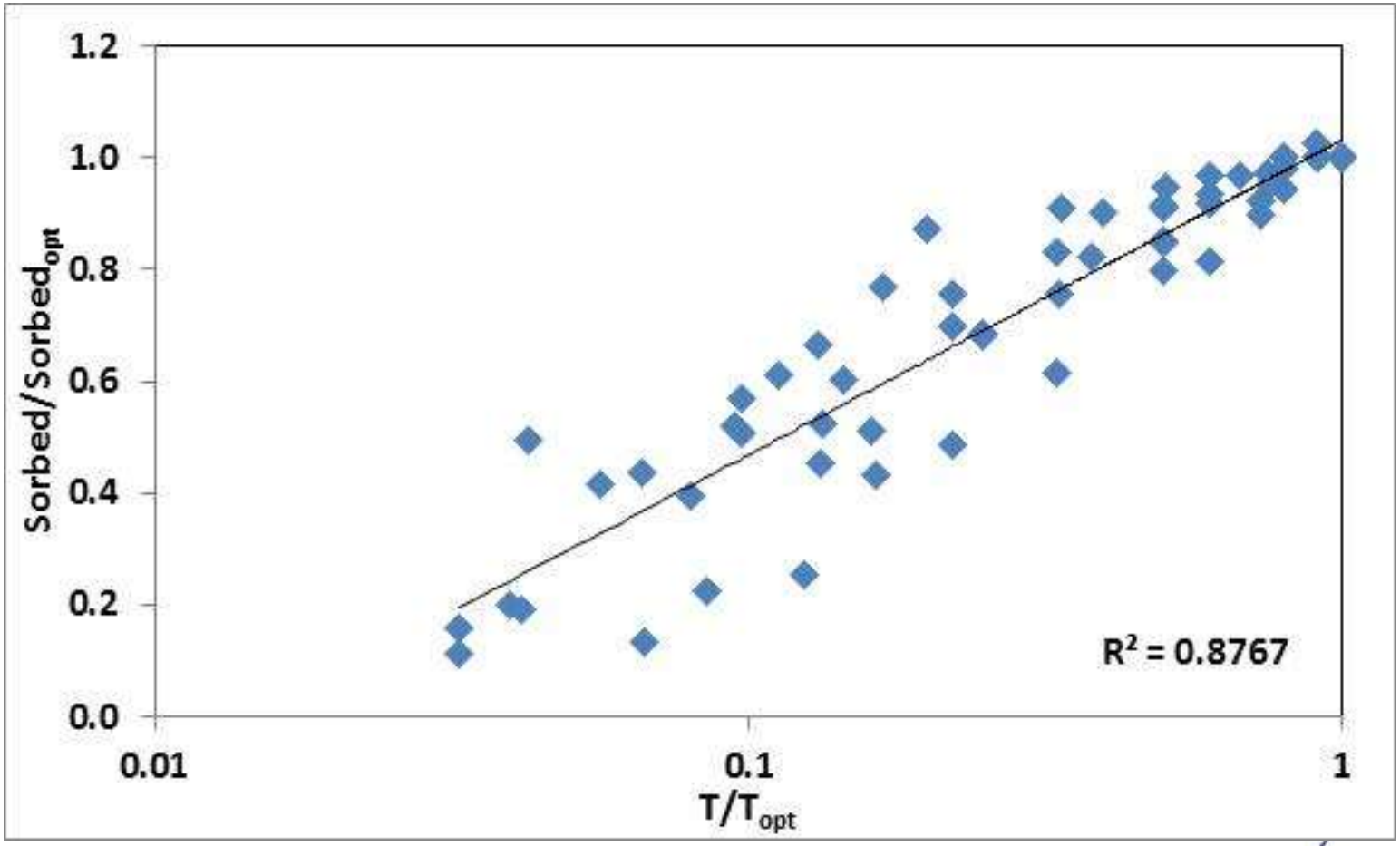
- On Iron, Manna & Ghosh 2007



(b)

Mass Sorption Density vs Loading Rate

- Summary



Mass Sorption Density vs Loading Rate

- Summary

$$\Delta 1 \text{ Log}[T/T_{opt}] = 0.56\ \Delta(\text{Sorbed}/\text{Sorbed}_{opt})$$

Mass Sorption Density vs Loading Rate

- Summary – Example:

Design for 2T → 2V:

- Results in Initial **Vessel** Cost Increase:
  - x1.41 – due to 2V
- Results in Media Useful Life Extension:
  - x2 – due to 2V
  - x1.14 – due to improved/enhanced sorption site availability

Mass Sorption Density vs Loading Rate

- Summary – Example:

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Literature Review Outline

- Chemistry of Arsenic Sorption
- Arsenic Sorption Treatment Performance
- **Summary**

Sorption Treatment Performance

- Summary

Decrease:

- pH
- Loading Rate

Increase:

- Removal Efficiency
- Mass Sorbed

Sorption Treatment Performance

- Summary

Design Factor	Δ	Δ(Improved Treatment)
pH	1 pH	0.12 Efficiency
pH	1 pH	0.10 Sorption Density
Loading Rate	0.1T	0.025 Efficiency
Loading Rate	1 pT	0.25 Sorption Density

Outline

- Introduction
- Literature Review: Sorption Treatment Performance
- **Treatment Mathematics**
- Operations Management
- Summary

Treatment Math Outline

- Types of Sorption Treatment
- Blending Math
- Summary

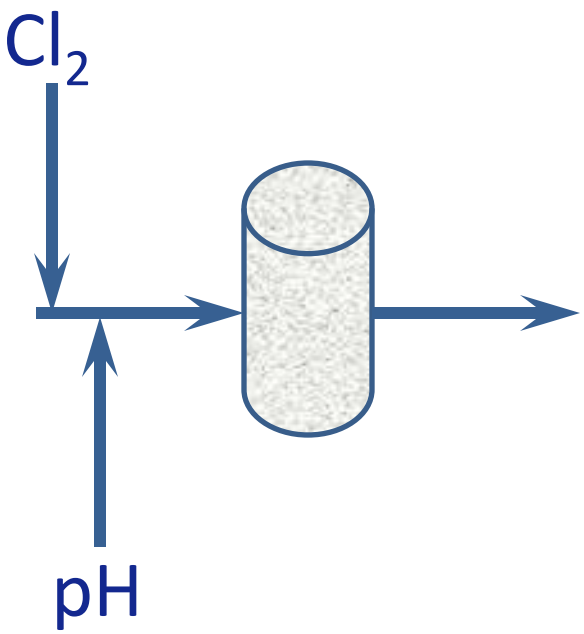
Treatment Math Outline

- **Types of Sorption Treatment**
- Blending Math
- Summary

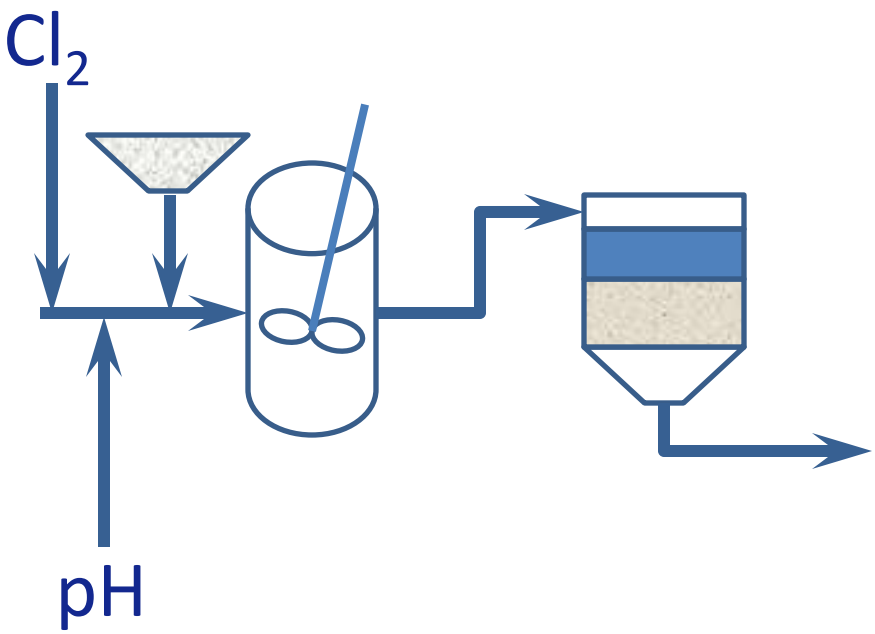
Types of Sorption Treatment

- Flow Schematics:

Fixed Bed Media



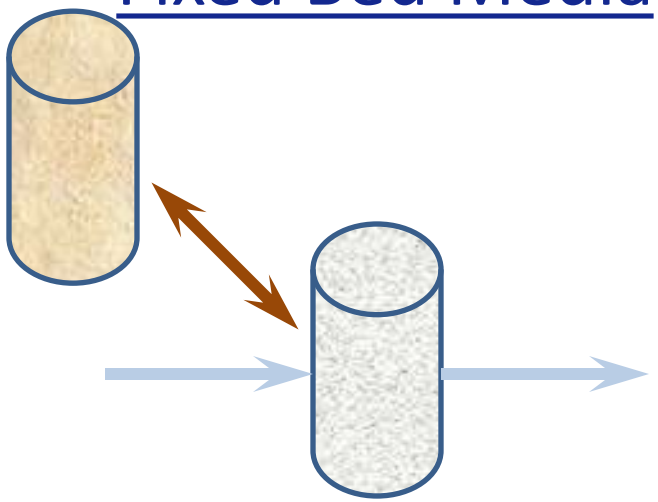
Fed Media



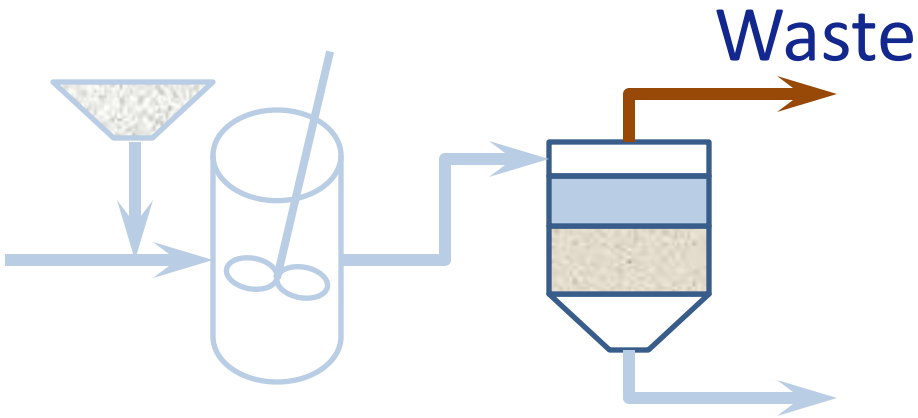
Types of Sorption Treatment

- Mass Schematics:

Fixed Bed Media

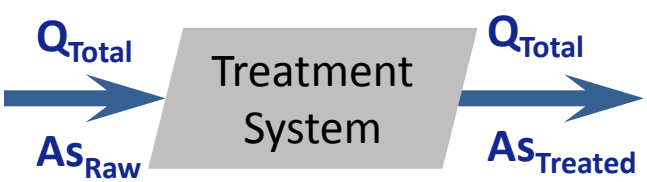


Fed Media

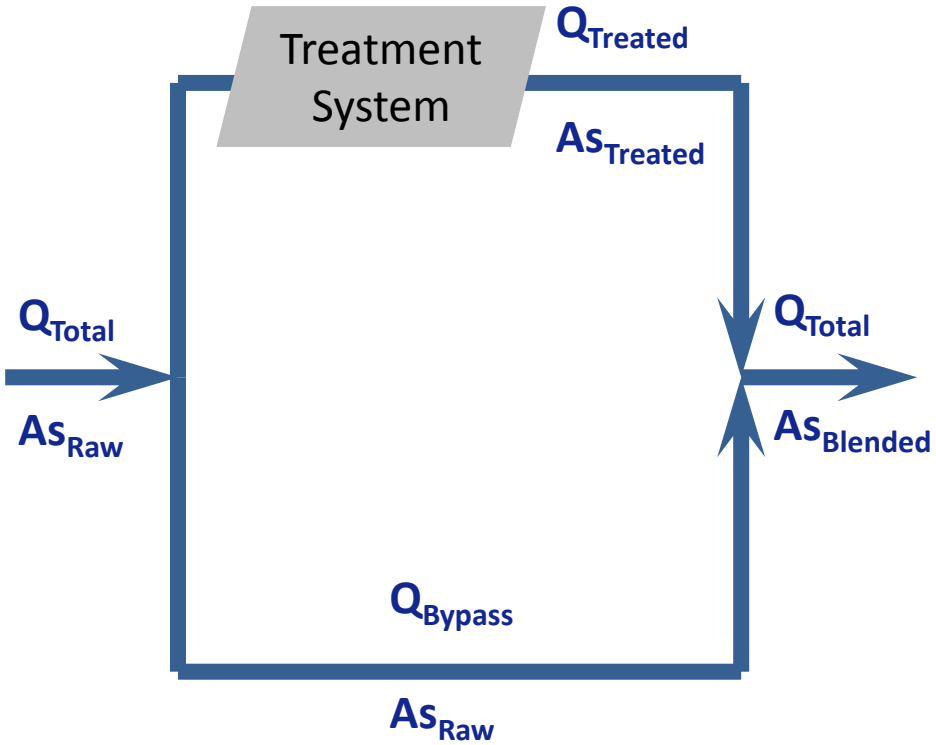


Types of Sorption Treatment

No Flow Blending



Flow Blending



Treatment Math Outline

- Types of Sorption Treatment
- **Blending Math**
- Summary

Blending Math Outline

- Blending Math:
  - Fed Media
  - Fixed Bed Media

Blending Math

- Treatment Implementation Scenarios:

Sorption

Fed Media

$C_T = Constant$

All Flow

Blending

Fixed Bed Media

$C_T = F[t]$

All Flow

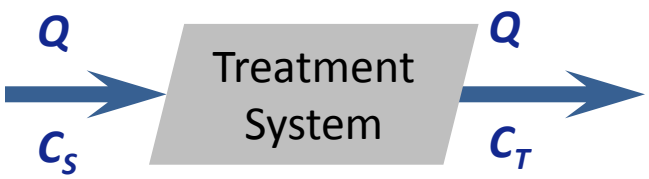
Blending

Blending Math Outline

- Blending Math:
  - **Fed Media**
  - Fixed Bed Media

Blending Math: Fed Media

- Treat all flow:

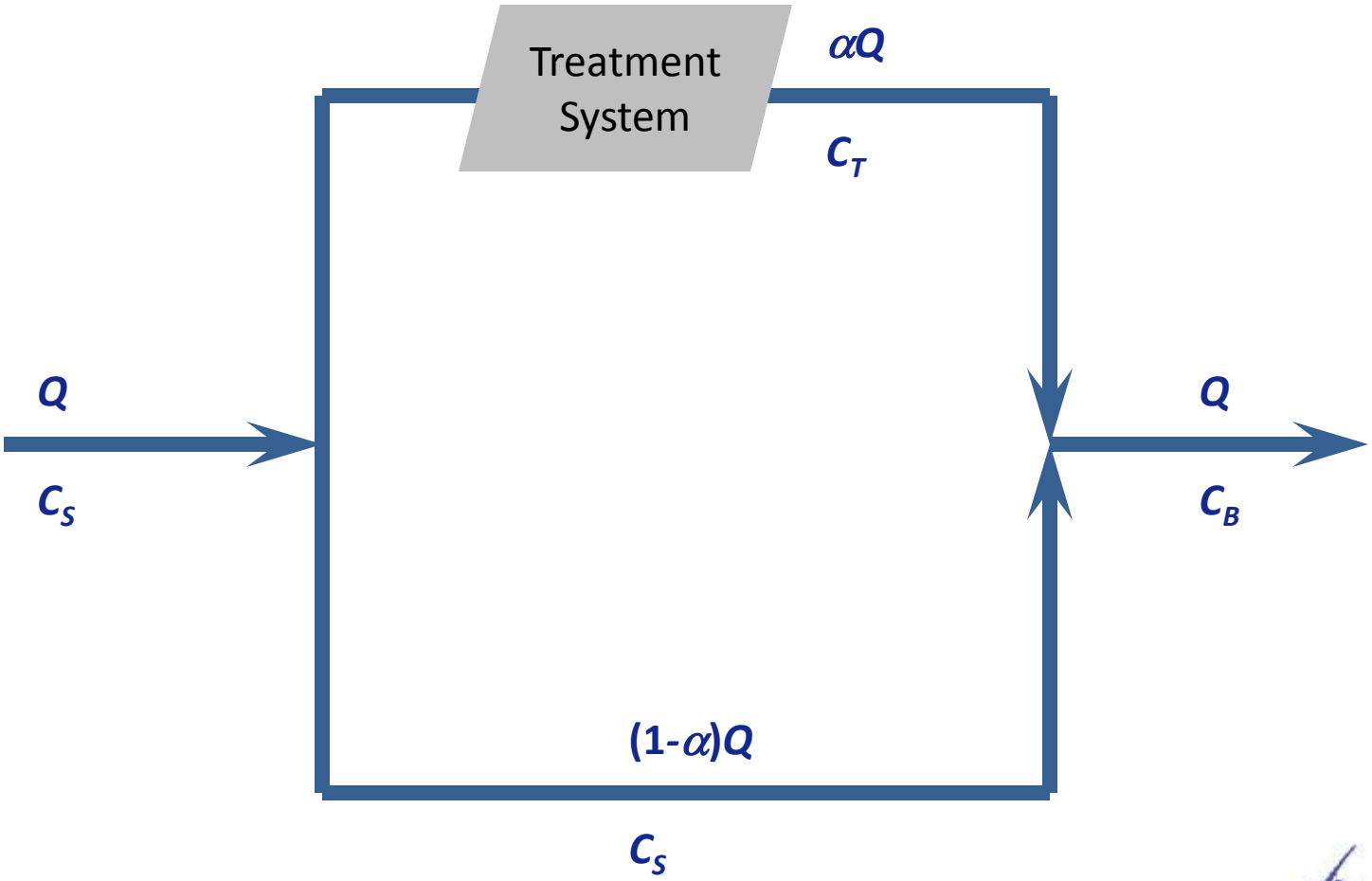


- Mass Balance Gives:

$$C_T = Constant$$

Blending Math: Fed Media

- Flow Blending Schematic:



Blending Math: Fed Media

- Blending Mass Balance Gives:

$$\alpha = \frac{C_S - C_B}{C_S - C_T}$$

Blending Math: Fed Media

- Select or Calculate α based on:

  Known C_S

  Desired/Required C_B

  Expected/Controlled C_T

$$\alpha = \frac{C_S - C_B}{C_S - C_T}$$

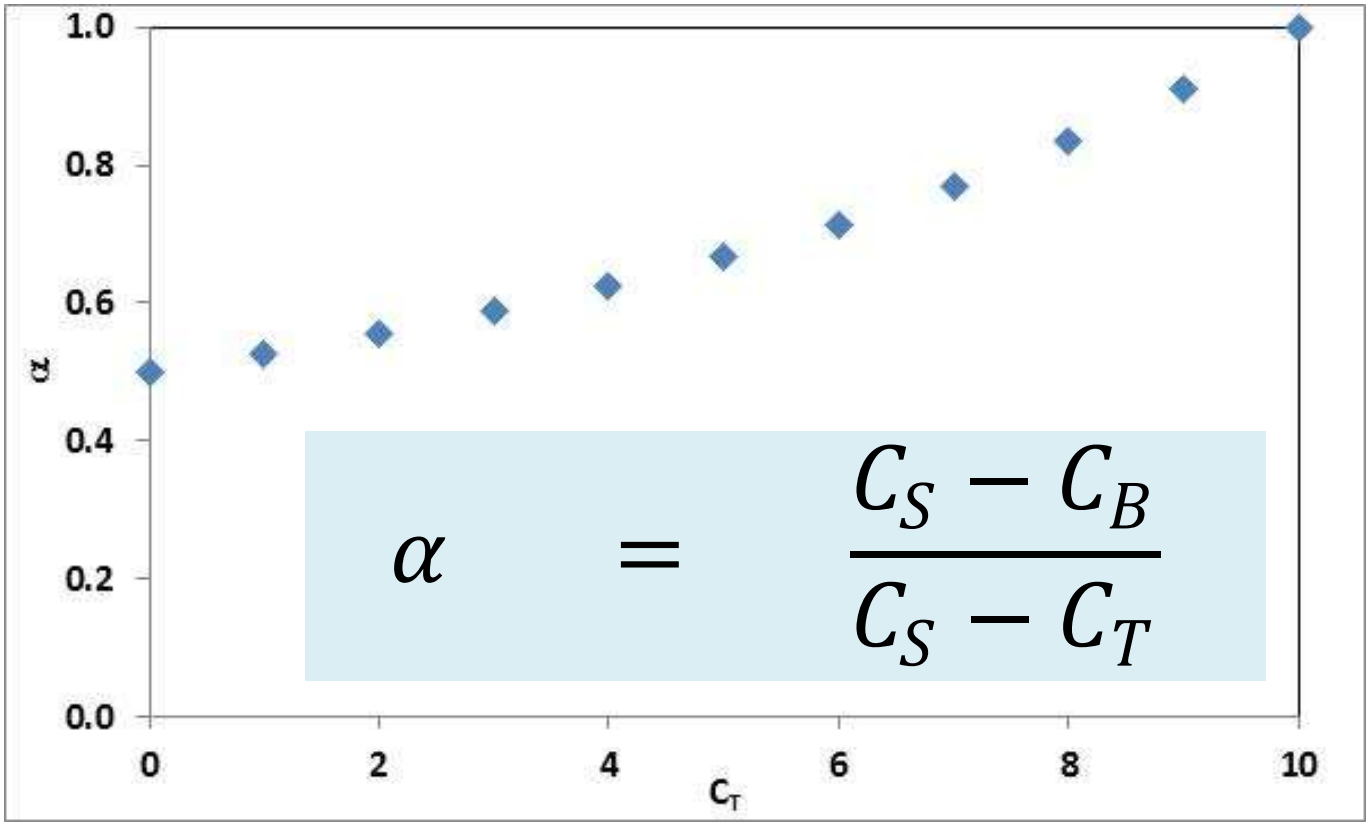
Blending Math: Fed Media

- Example:

  $C_S = 20.0$

  $C_B = 10.0$

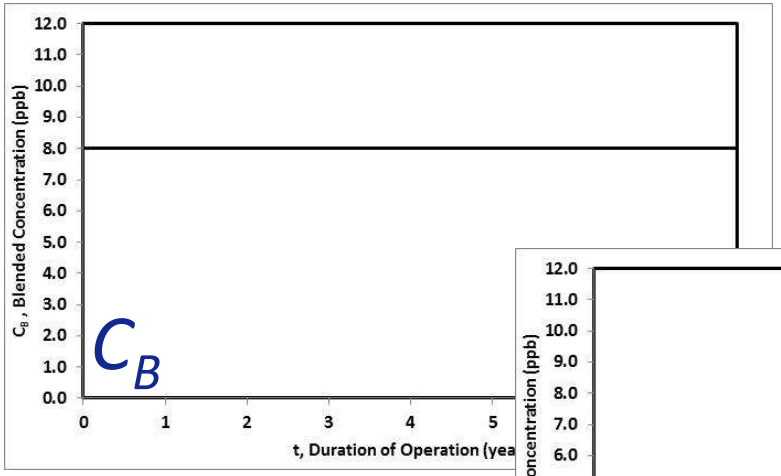
  Vary C_T

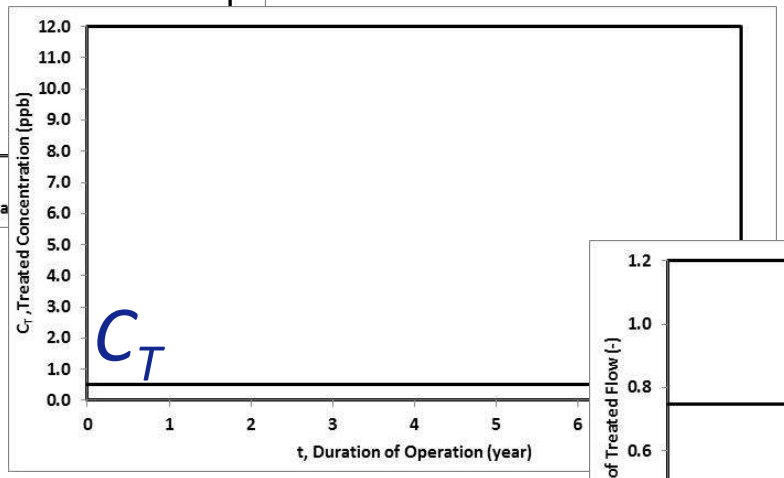


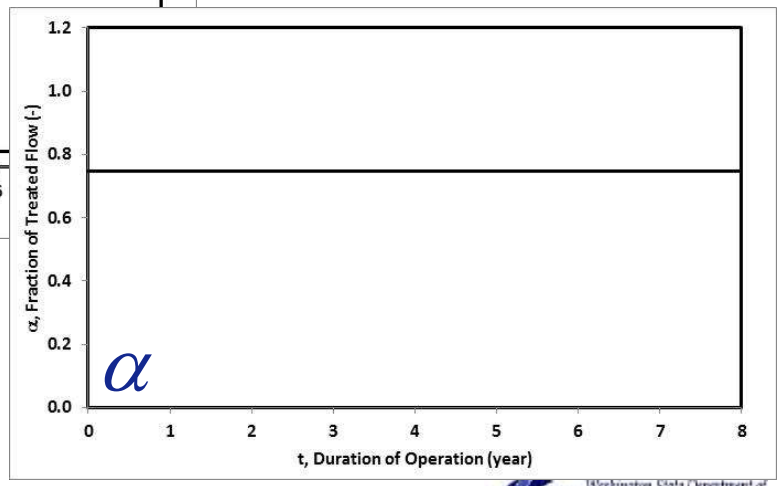
$$\alpha = \frac{C_S - C_B}{C_S - C_T}$$

Blending Math: Fed Media

- Results:







C_S = 30.0 ppb

C_B = 8.0 ppb

C_T = 0.5 ppb

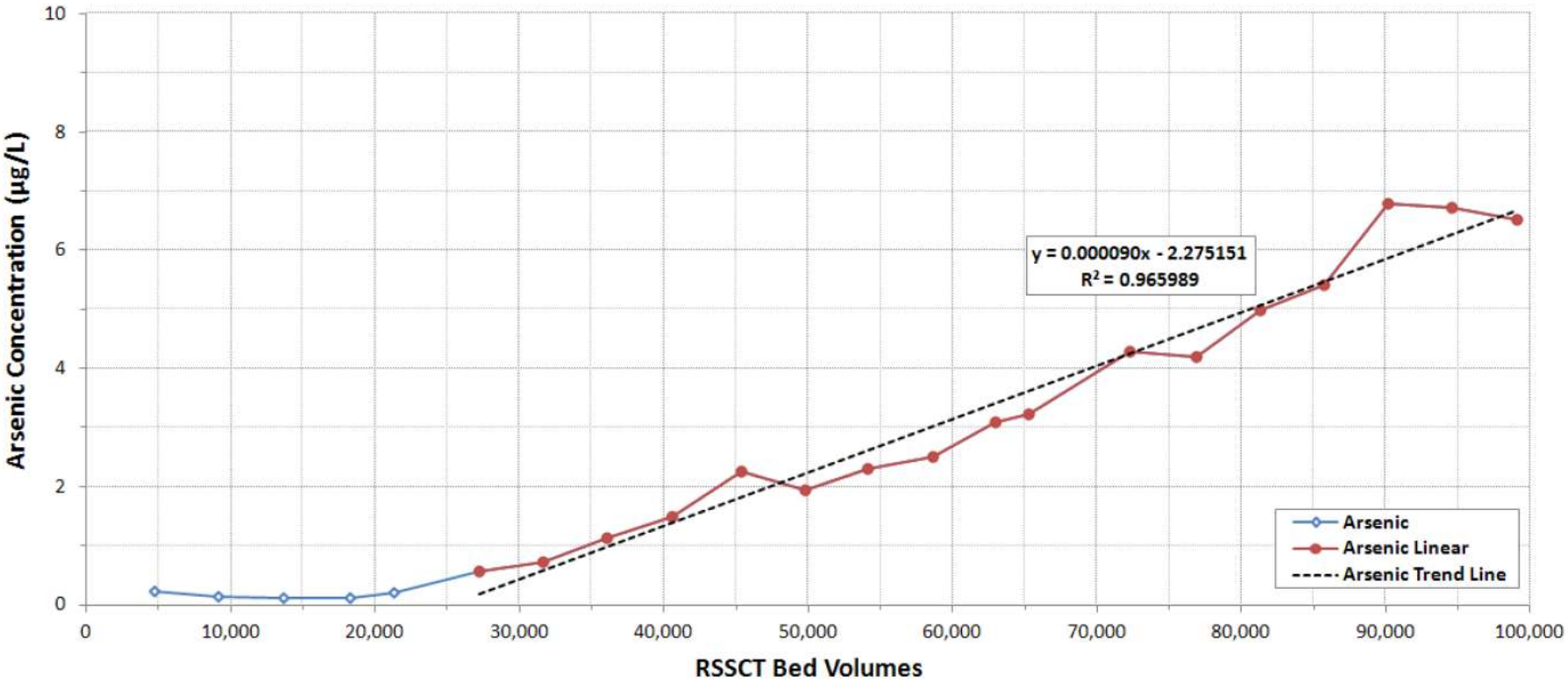
Blending Math Outline

- Blending Math:
  - Fed Media
  - **Fixed Bed Media**

Blending Math: Fixed Bed Media

- Treated Concentration Depends on Treated Volume:

$$C_T(t) = V(t) * m + b$$



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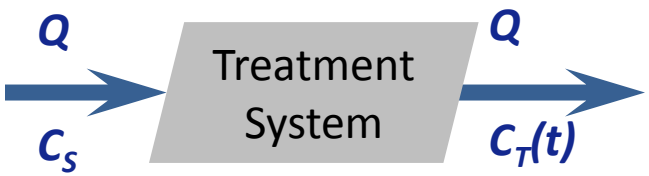
Blending Math: Fixed Bed Media

- Treat all flow:



Blending Math: Fixed Bed Media

- Treated Concentration in terms of Treated Volume:

$$
\begin{aligned}
C_T(t) &= V[t] * m + b \\
&= \left(\int Q[t]dt\right) * m + b \\
&= \left(Q_{avg} * t\right) * m + b
\end{aligned}
$$

$$
t = \frac{C_T(t) - b}{Q_{avg} * m}
$$

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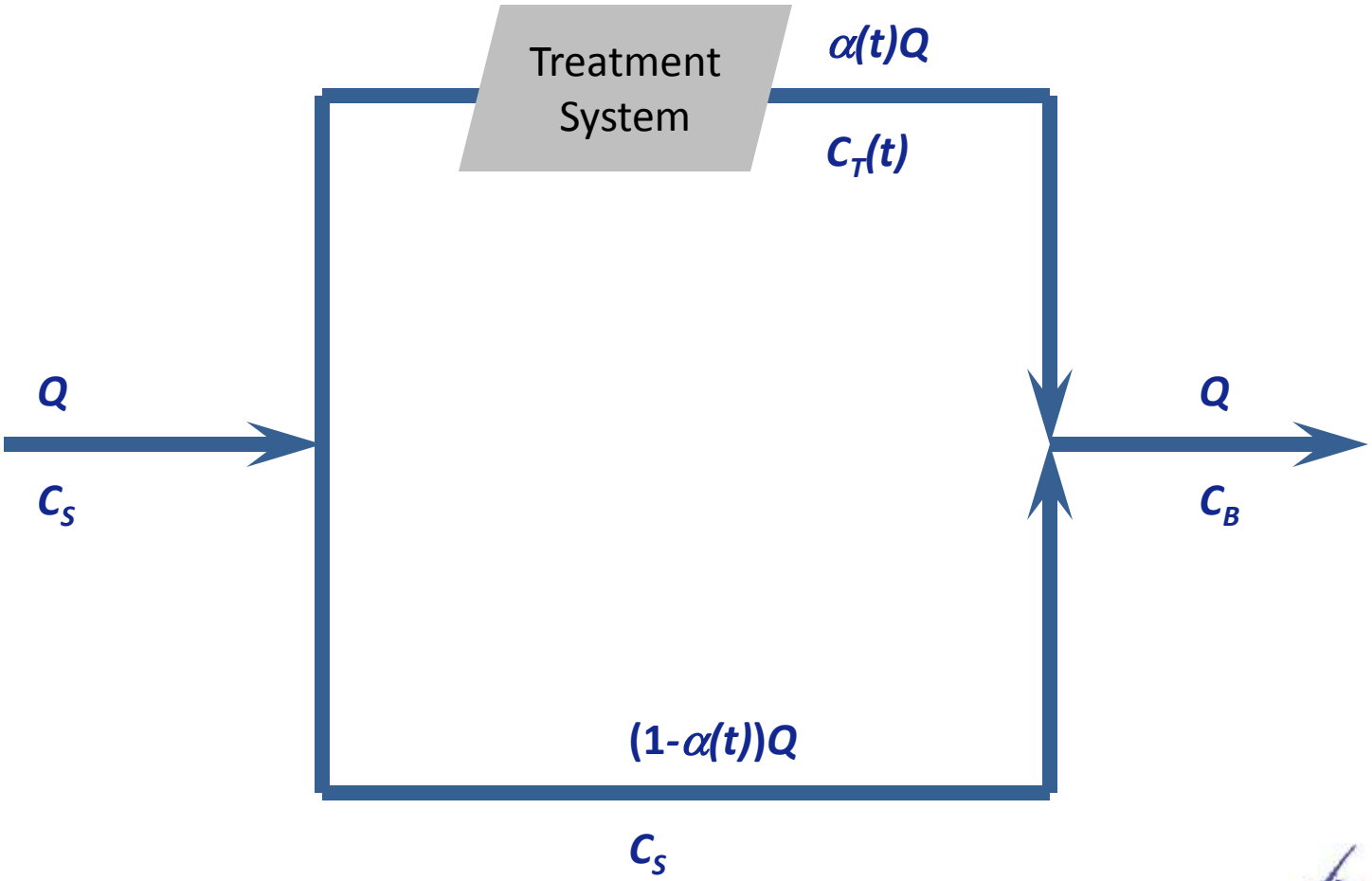
Blending Math: Fixed Bed Media

- Flow Blending Schematic:



Blending Math: Fixed Bed Media

- Completing Mass Balance Gives:

$$\alpha(t) = \frac{C_S - C_B}{C_S - C_T(t)}$$

Continuous or Incremental changes in α

Blending Math: Continuous, Fixed

- Treated Concentration in terms of Treated Volume:

$$
\begin{aligned}
C_T(t) &= V(t) * m + b \\
&= \left(\int Q(t) * dt\right) * m + b \\
&= \left(\int \alpha(t) * Q * dt\right) * m + b
\end{aligned}
$$

Blending Math: Continuous, Fixed

- Rearranging by factoring constants:

$$C_T(t) = \left(\int \alpha(t)dt\right) * Q * m + b$$

Blending Math: Continuous, Fixed

- Substituting:

$$\alpha(t) = \frac{C_S - C_B}{C_S - C_T(t)}$$

$$= \frac{C_S - C_B}{C_S - \left(\left(\int \alpha(t)dt\right) * Q * m + b\right)}$$

Blending Math: Continuous, Fixed

- To solve, let:

$$x = \int \alpha(t)dt$$

- Then:

$$\frac{dx}{dt} = x' = \alpha(t)$$

Blending Math: Continuous, Fixed

- Substituting:

$$\alpha(t) = \frac{C_S - C_B}{C_S - \left(\left(\int \alpha(t)dt\right) * Q * m + b\right)}$$

$$x' = \frac{C_S - C_B}{C_S - (Q * m * x + b)}$$

Blending Math: Continuous, Fixed

- Rearranging:

$$x' - \frac{Q * m}{C_S - b} x x' = \frac{C_S - C_B}{C_S - b}$$

- Or:

$$x' + h x x' = i$$

Blending Math: Continuous, Fixed

- Deriving:

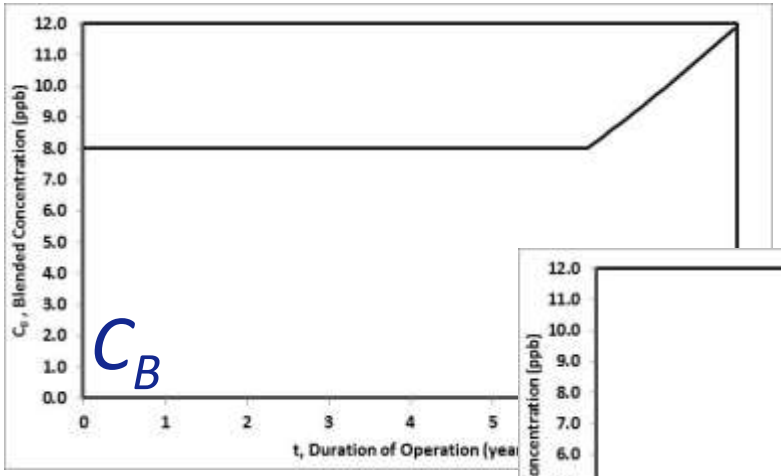
$$\alpha(t) = \pm \frac{\left(\frac{C_S - C_B}{C_S - b}\right)}{\sqrt{\left(2\left(-\frac{Q * m}{C_S - b}\right)\left(\frac{C_S - C_B}{C_S - b}\right)t + 1\right)}}$$

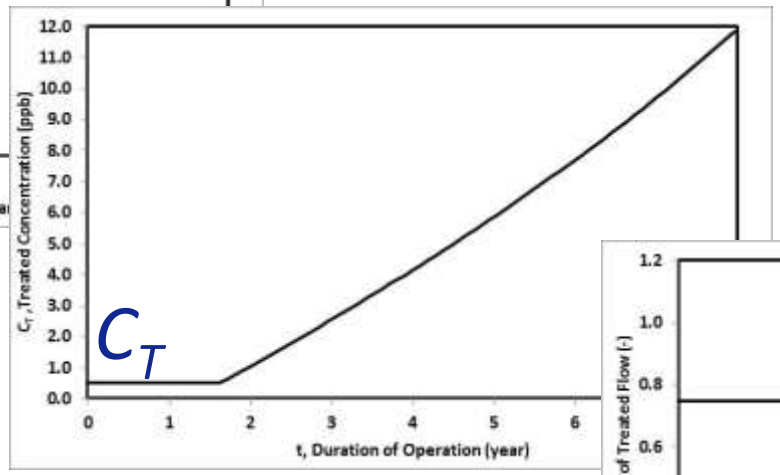
$$C_T(t) = \frac{-1 \pm \sqrt{2\left(-\frac{Q * m}{C_S - b}\right)\left(\frac{C_S - C_B}{C_S - b}\right)t + 1}}{\left(-\frac{Q * m}{C_S - b}\right)} * Q * m + b$$

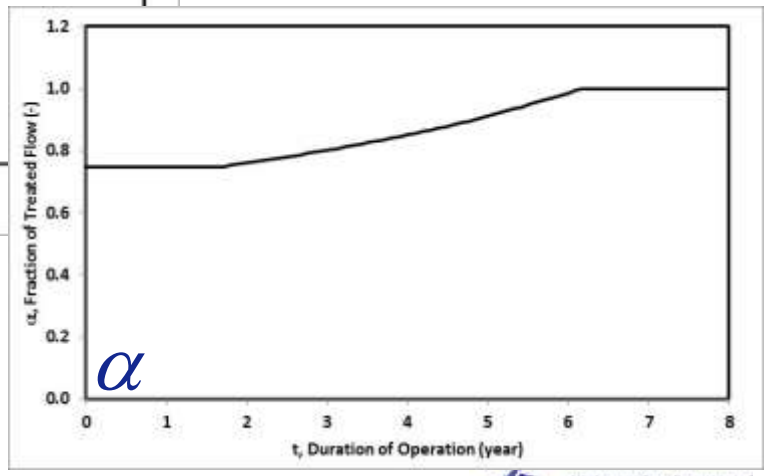
$$C_B = C_S + \left(\pm \frac{\left(\frac{C_S - C_B}{C_S - b}\right)}{\sqrt{\left(2\left(-\frac{Q * m}{C_S - b}\right)\left(\frac{C_S - C_B}{C_S - b}\right)t + 1\right)}}\right)\left(\left(\frac{-1 \pm \sqrt{2\left(-\frac{Q * m}{C_S - b}\right)\left(\frac{C_S - C_B}{C_S - b}\right)t + 1}}{\left(-\frac{Q * m}{C_S - b}\right)} * Q * m + b\right) - C_S\right)$$

Blending Math: Fixed Media

- Results:







C_S = 30.0 ppb

C_B = 8.0 ppb

C_T = 0.5 ppb

Blending Math: Incremental, Fixed

- Recall:

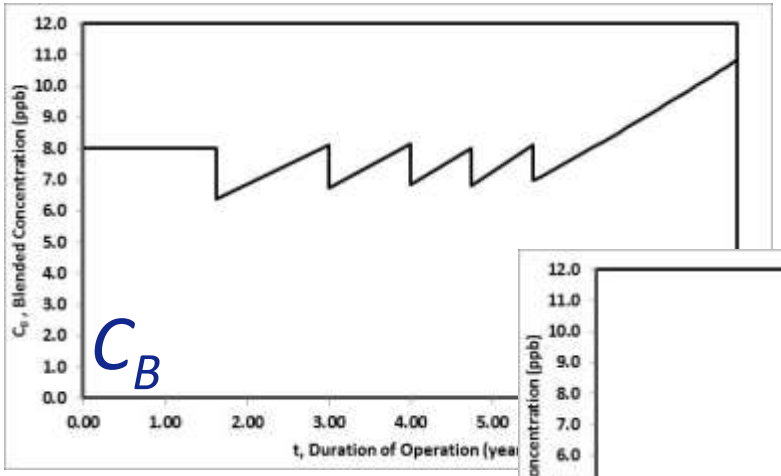
$$
\begin{aligned}
C_T(t) &= V(t) * m + b \\
&= \left(\int Q(t) * dt\right) * m + b \\
&= \left(\int \alpha(t) * Q * dt\right) * m + b
\end{aligned}
$$

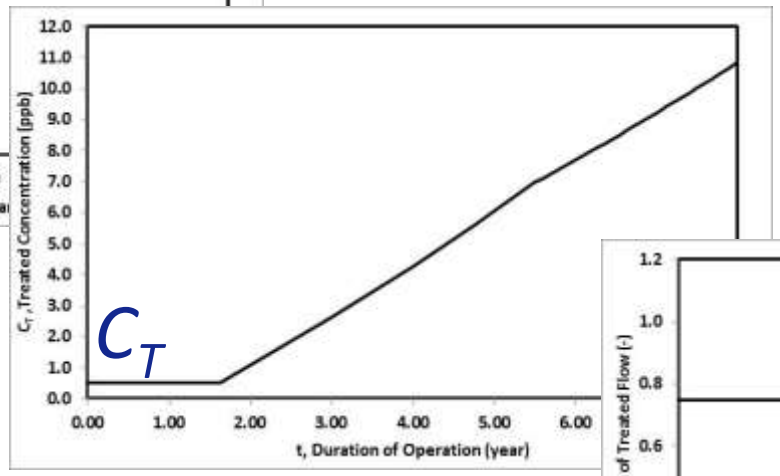
- Now:

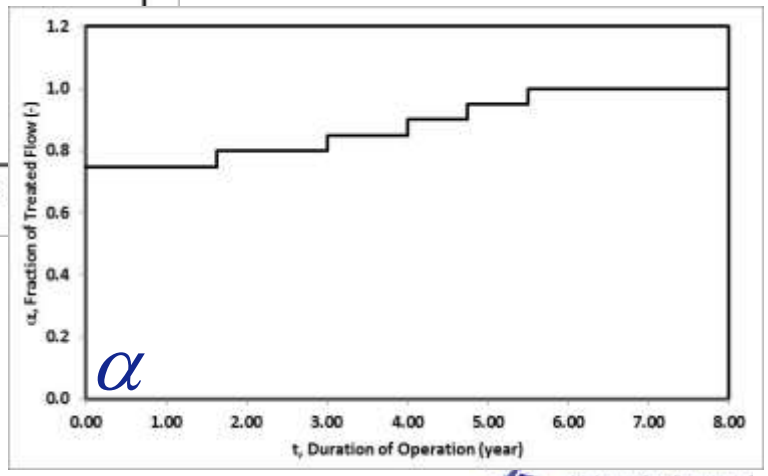
$$
\begin{aligned}
C_T(t) &= \left(V_1 + V_2 + \cdots + V_n(t)\right) * m + b \\
&= \left(V_1 + V_2 + \cdots + \int \alpha_n * Q * dt\right) * m + b \\
&= \left(V_1 + V_2 + \cdots + \alpha_n * Q * (t - t_{n-1})\right) * m + b
\end{aligned}
$$

Blending Math: Incremental, Fixed

- Results:







C_S = 30.0 ppb

C_B = 8.0 ppb

C_T = 0.5 ppb

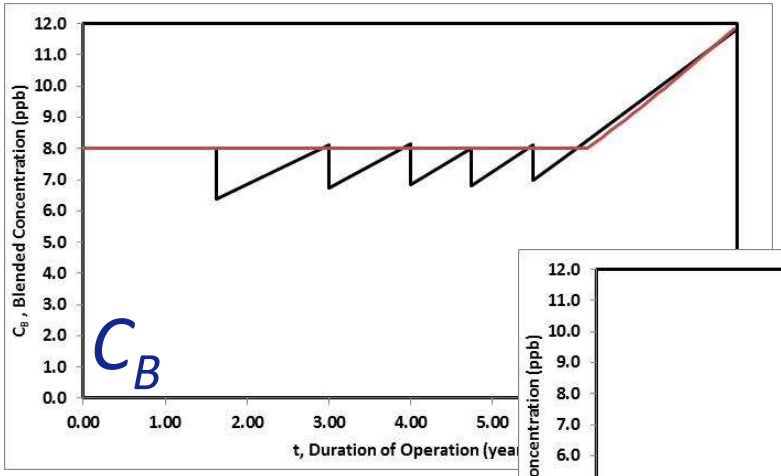
Blending Math: Compare Fixed

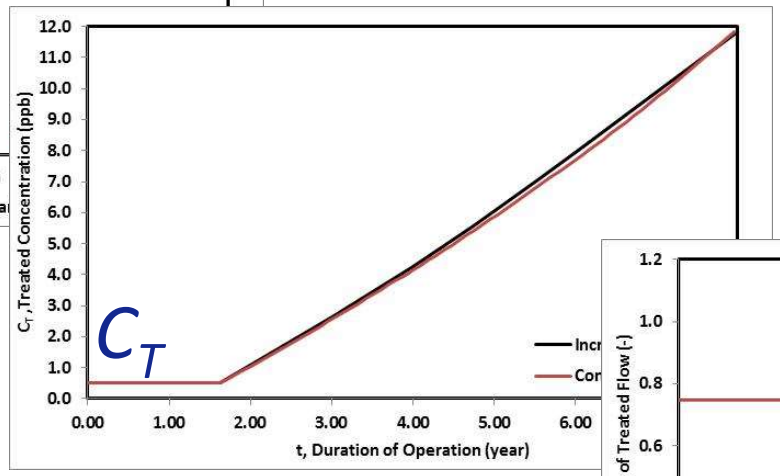
- Results:

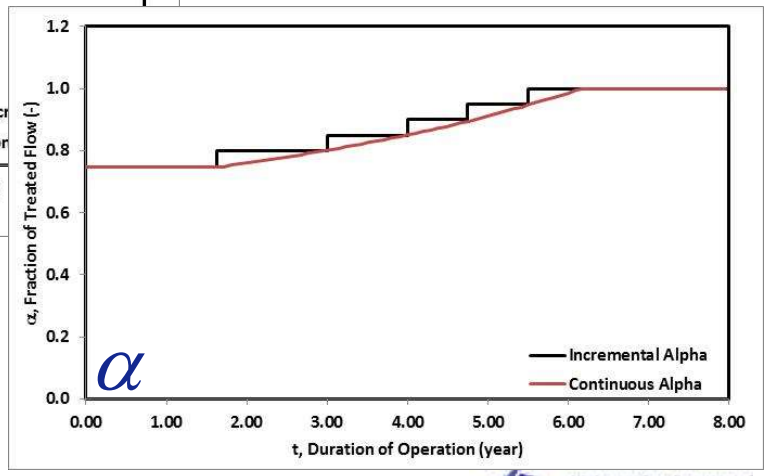
C_S = 30.0 ppb

C_B = 8.0 ppb

C_T = 0.5 ppb







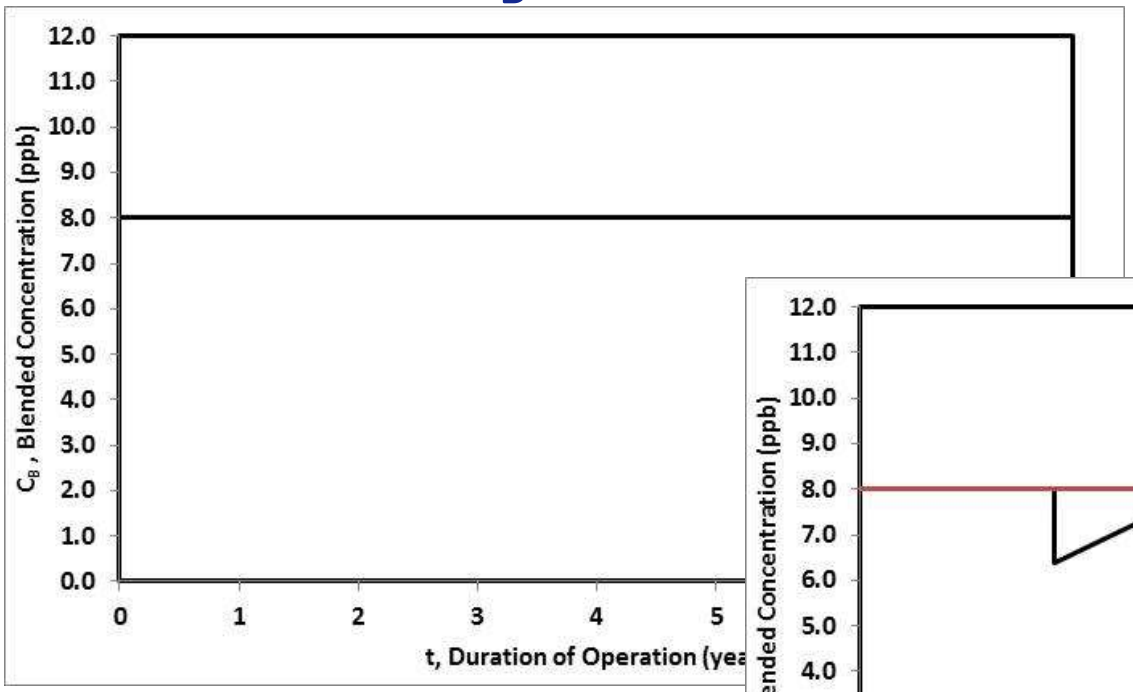
Blending Math: Comparison

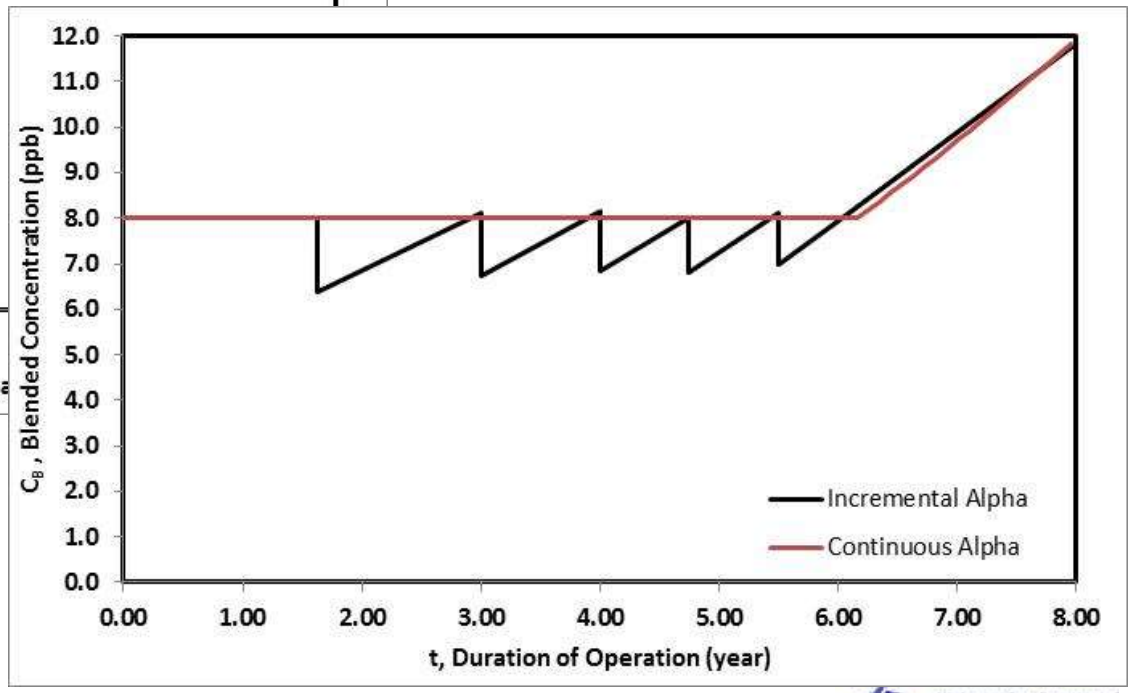
- Results - C_B:

C_S = 30.0 ppb

C_B = 8.0 ppb

C_T = 0.5 ppb





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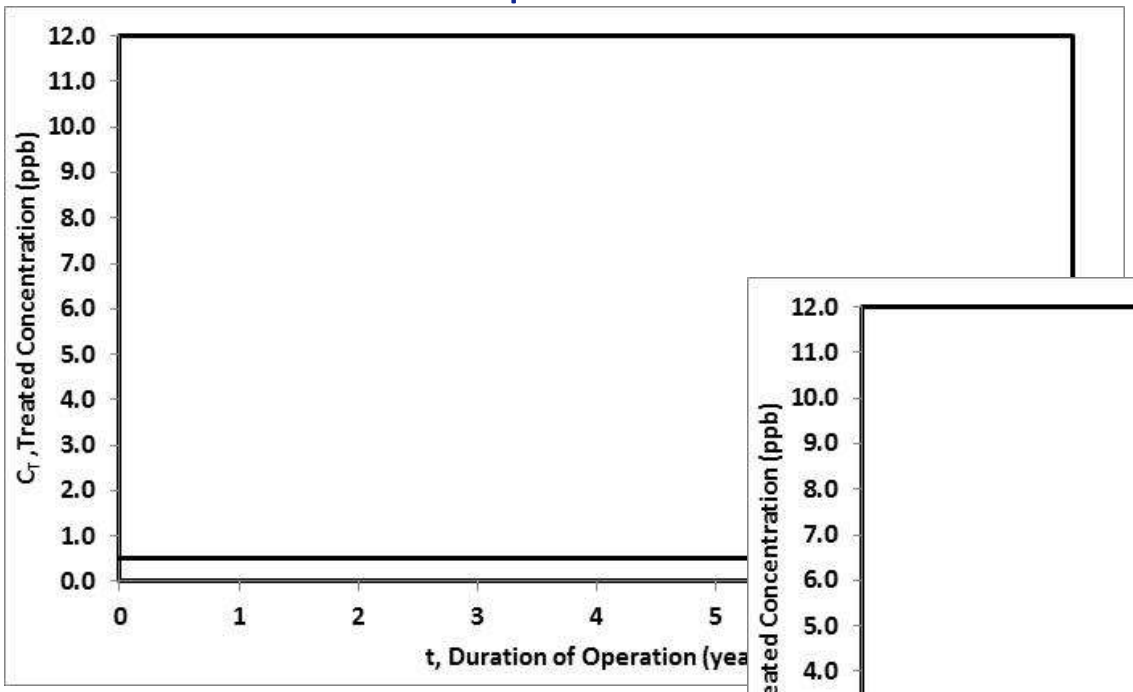
Blending Math: Comparison

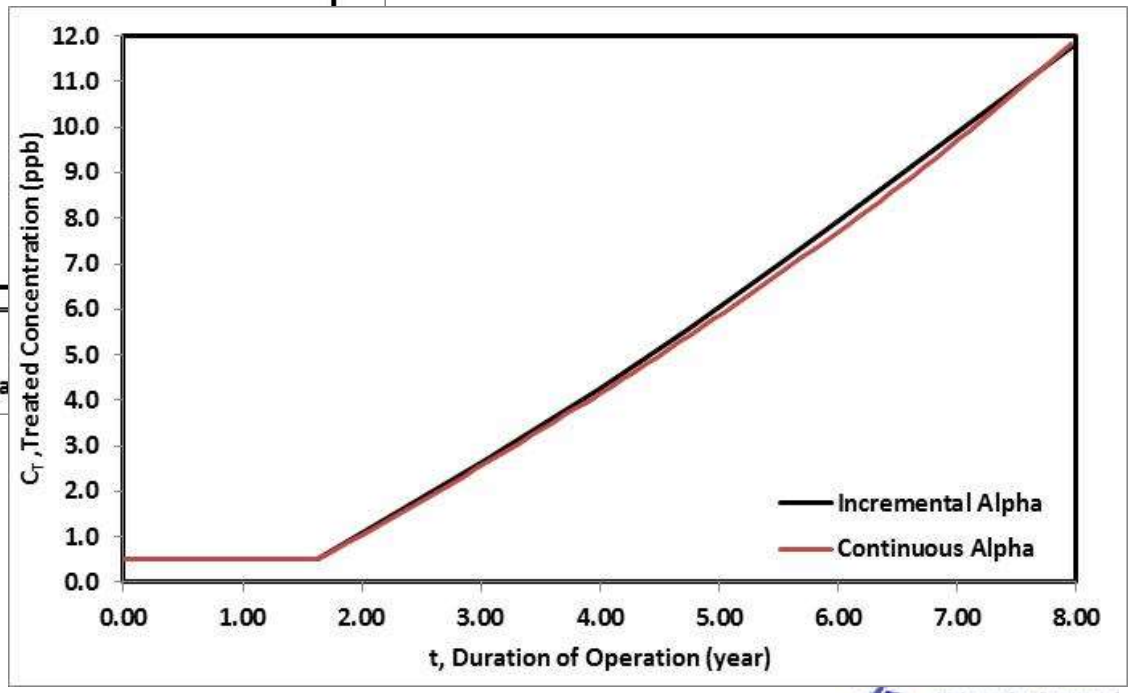
- Results - C_T:

C_S = 30.0 ppb

C_B = 8.0 ppb

C_T = 0.5 ppb





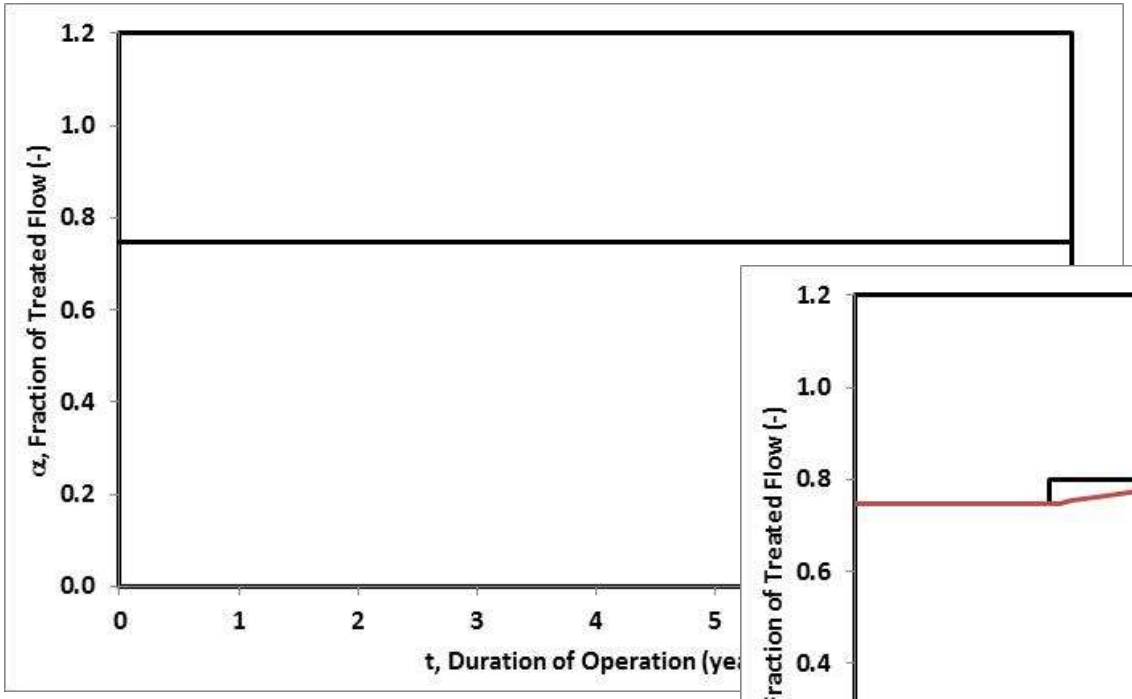
Blending Math: Comparison

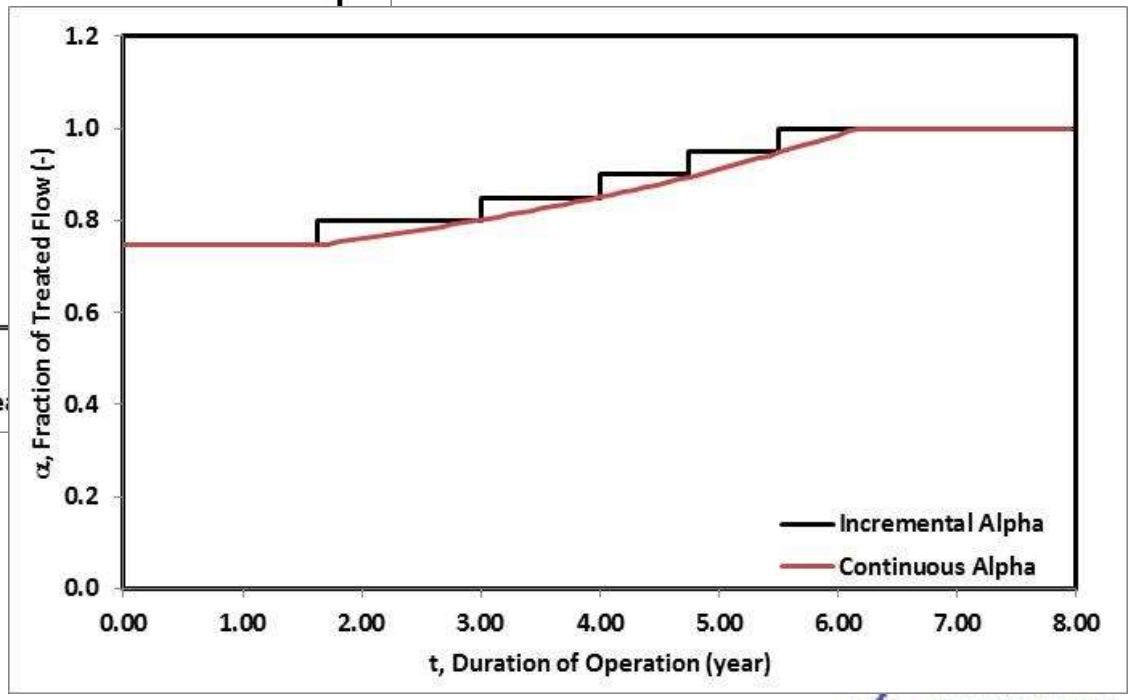
- Results – α:

C_S = 30.0 ppb

C_B = 8.0 ppb

C_T = 0.5 ppb



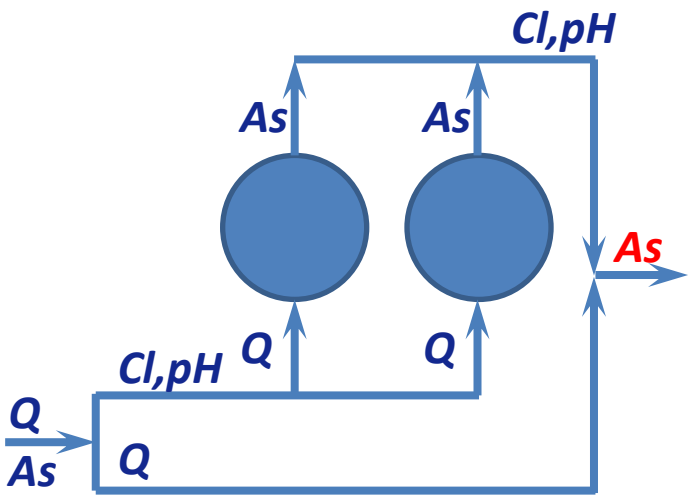


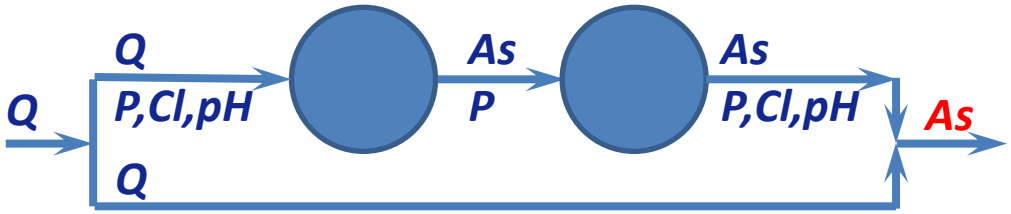
Outline

- Introduction
- Literature Review: Sorption Treatment Performance
- Treatment Mathematics
- **Operations Management**
- Summary

Operations Management

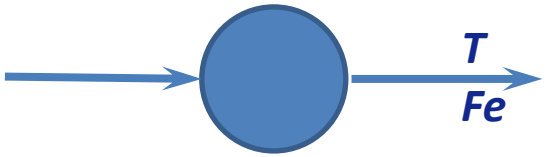
Monitoring – Fixed Bed **AND** Fed Media:





Operations Management

Additional Monitoring – Fed Media:



Outline

- Introduction
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- **Summary**

Summary

- Optimize Treatment
- “Precise” Predictions of Treatment
- “Thorough” Monitoring Reveals (Exposes) Treatment Process Behavior

Summary

Summary

QUESTIONS (ANSWERS)?