

**Appendix C**  
**Dredging and Material Transport Design Support**  
**Documents and Calculations**

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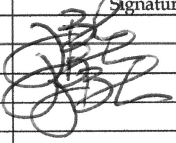
Calculation Cover Sheet



CH2MHILL

ES-P04-0501.03-F3 Calculation Sign Off Form

Project Name/Title:	Lower Passaic River, RM 10.9 Removal Action	Project Number:	436870
Document Name:	RM 10.9 Removal Action Basis of Design Report	Preparer Name:	Kent Galloway
Project Manager:	Roger McCready	Design Manager:	James Brinkman

Calculation Title:		Estimated Dredge Volume		
Calculation Identifier:				
Date Prepared	Rev. No.	Preparer Signature/Date	Checker Signature/Date	For Professional Seal When Required
11/30/2012	0		 11/30/12	
2/7/2013	1		2/8/13	
7/16/2013	2		7/17/13	
STC/SME Signature/Date				
LTR Signature/Date (if required)				
Comments:				
Calculation includes the following worksheets:				
- Triangle Volume Report: Output from Triangle Volume Estimating tool				
- Pre-Dredge Surface: Existing bathymetric surface used for volume estimation				
- Post -Dredge Surface: Design Post-Dredge Surface used for volume estimation				
Volume estimate revised for Rev1 due to inclusion of "No Dredge Zone" for United Water pipelines. Also included estimate for inclusion of overdredge tolerance of 4 inches.				
Volume estimate revised for Rev2 due to reduction in size of "No Dredge Zone".				
Information Requiring Confirmation:				

## Triangle Volume Report

Report Created: 7/15/2013  
Time: 12:30pm

**Mode:** Entire Surface

**Input Grid Factor:** 1.000000

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**Original Surface:** LPR\_DTM

**Design Surface:** LPR\_Design\_NE

Cut Factor: 1.000

Fill Factor: 1.000

Cut: 253955.7 cu ft

Fill: 135.3 cu ft

Net: 253820.4 cu ft

Cut: 9405.8 cu yd

Fill: 5.0 cu yd

Net: 9400.8 cu yd

**Original Surface:** LPR\_DTM

**Design Surface:** LPR\_Design\_SW

Cut Factor: 1.000

Fill Factor: 1.000

Cut: 201277.6 cu ft

Fill: 0.1 cu ft

Net: 201277.5 cu ft

Cut: 7454.7 cu yd

Fill: 0.0 cu yd

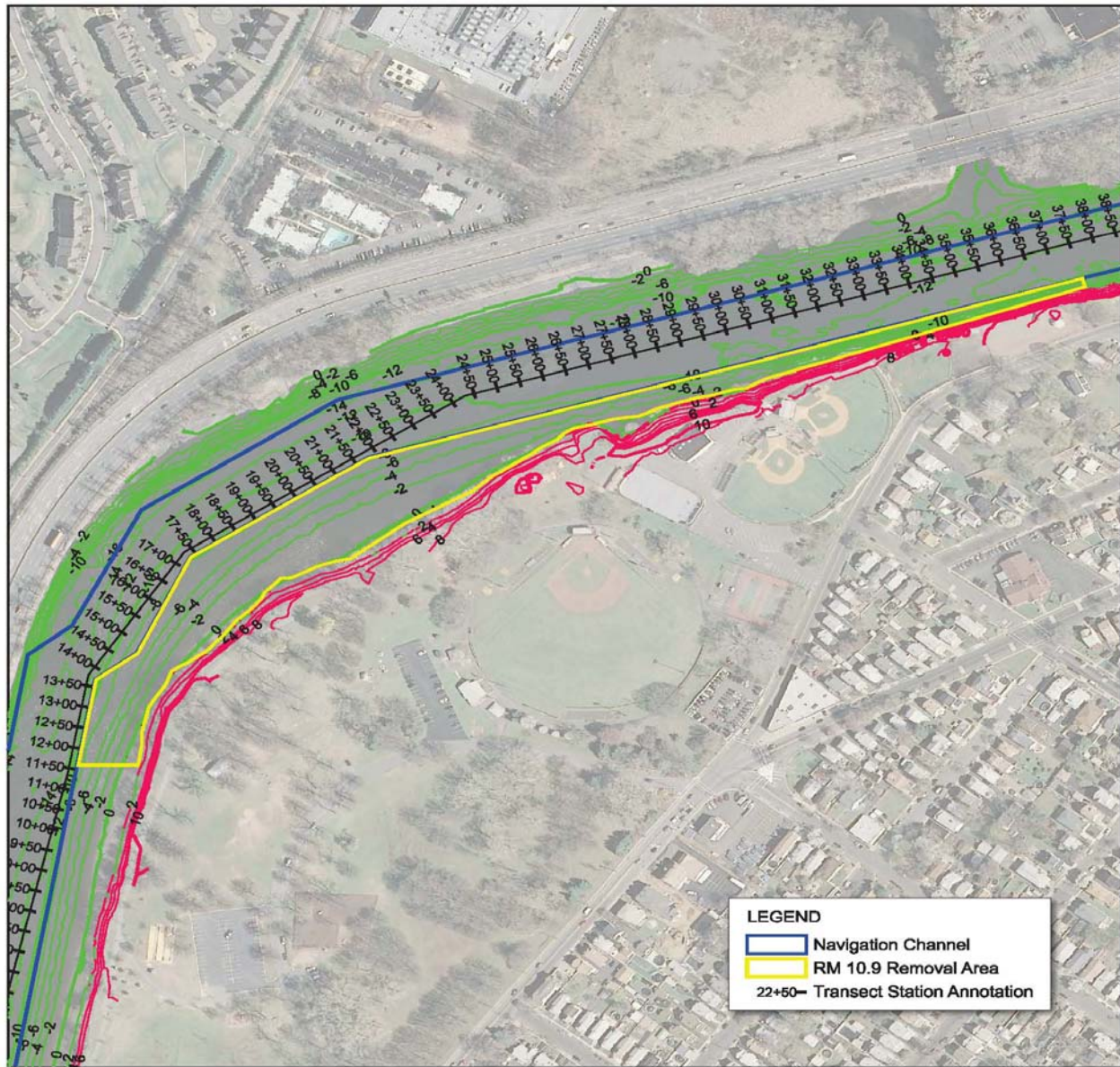
Net: 7454.7 cu yd

Lower Passaic River, RM 10.9 Removal Action  
 PN#: 436870  
 Calculation Title: Estimated Dredge Volume  
 Rev: 2  
 Date: 07/16/2013

<b>Original Surface:</b>	<b>LPR_DTM</b>					
<b>Design Surface:</b>	<b>LPR_Design_NE</b>					
	Cut					
	Factor:	1.0				
	Fill					
	Factor:	1.0				
	Cut:	253,955.7 cu ft	95,885.8	0.3	31,961.9	1,183.8
	Fill:	135.3 cu ft				10,589.6
	Net:	253,820.4 cu ft				
	Cut:	9,405.8 cu yd				
	Fill:	5.0 cu yd				
	Net:	9,400.8 cu yd				

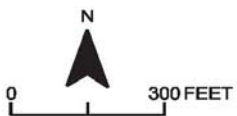
<b>Original Surface:</b>	<b>LPR_DTM</b>					
<b>Design Surface:</b>	<b>LPR_Design_SW</b>					
	Cut					
	Factor:	1.0				
	Fill					
	Factor:	1.0				
	Cut:	201,277.6 cu ft	107,810.3	0.3	35,936.8	1,331.0
	Fill:	0.1 cu ft				8,785.7
	Net:	201,277.5 cu ft				
	Cut:	7,454.7 cu yd				
	Fill:	0.0 cu yd				
	Net:	7,454.7 cu yd				

2 ft dredge volume = 9,405.8 cu yds + 7,454.7 cu yds = 16,855.5 cu yds  
 2.3 ft dredge volume = 10,980 cu yds + 8,469.5 cu yds = 19,375.3 cu yds



**LEGEND**

- Navigation Channel
- RM 10.9 Removal Area
- 22+50- Transect Station Annotation

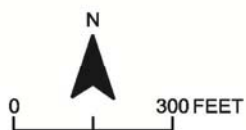
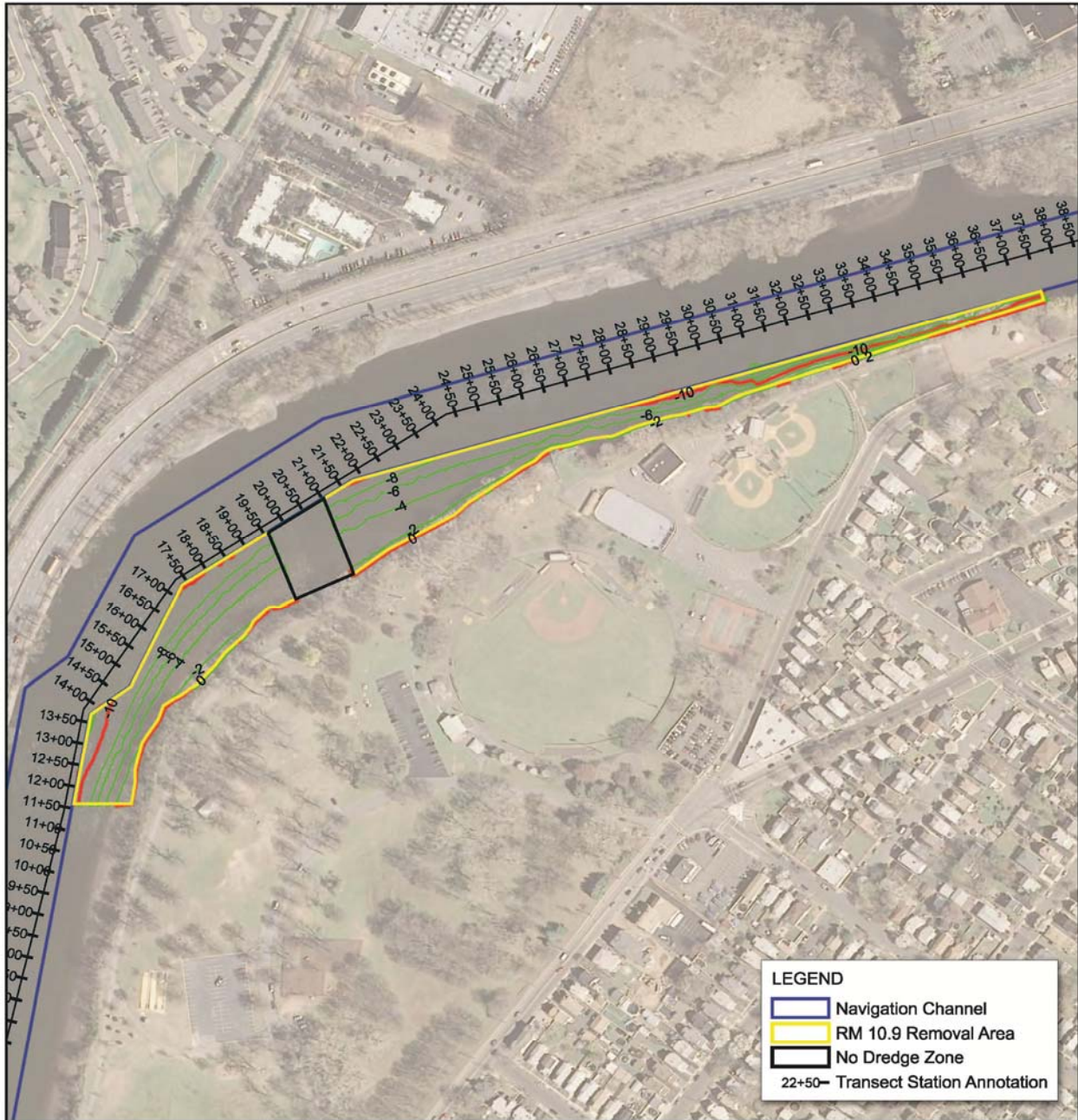


- Notes:**
1. Orthophoto: NJGIS, 2007
  2. Contour Interval = 2 ft NGVD29
  3. The October 2011 Multibeam bathymetry measurements were taken in the portion of the study area with water depths greater than 6 ft. The July 2011 Single-beam survey measurements were taken where water depths were between 2 and 6 ft. The datasets generated from these surveys were combined to provide a continuous dataset (CH2M HILL & AECOM, 2012).

**Figure 4-2**  
 Existing Site Conditions  
 RM 10.9 Removal Action Final Design Report  
 Lower Passaic River Study Area, New Jersey

**CH2MHILL**





Notes:  
 1. Orthophoto: NJGIS, 2007  
 2. Contour Interval = 2 ft NGVD29  
 3. The October 2011 Multibeam bathymetry measurements were taken in the portion of the study area with water depths greater than 6 ft. The July 2011 Single-beam survey measurements were taken where water depths were between 2 and 6 ft. The datasets generated from these surveys were combined to provide a continuous dataset (CH2M HILL & AECOM, 2012).

Figure 4-3  
 Postdredge Bathymetry  
 RM 10.9 Removal Action Final Design Report  
 Lower Passaic River Study Area, New Jersey

**RM 10.9 Removal Project Bridges Supplemental Information**

River Mile 10.9 Draft Final Design Report, Lower Passaic River Study Area, New Jersey

Bridge Name	River Mile	Bridge Type	Max. Horizontal Clearance (ft)	Max. Vertical Clearance - Approx. at Low Tide (ft)*	Maximum Vertical Clearance - Approx. at High Tide (ft)	Contact Information <sup>†</sup>			
						Name / Number	Owner	How is opening coordinated (lead time, restrictions, etc.)?	Is any constructions or maintenance planned or scheduled (when, duration, how will it affect navigation)?
Central Railroad of NJ ( <i>not in use</i> )	0.91	NA - Dismantled	NA	NA	70	NA	NA	NA	NA
Lincoln Highway Bridge (US-1 Truck)	1.57	Lift deck	300	45 (140)	40	Mr. Howard Paranto NJDOT. Supervisor of Bridge Operations, Office: 732-528-9494	NJDOT	Call North Electrical (need to obtain their # from North Com. [602-522-6211]). I tried calling North Com. and no one answered. There was no option to leave a voicemail. Per Howard Paranto, at least 4 hours is needed to open the bridge.	There will be minor bridge construction activity and maintenance on-going, but nothing major that should affect our work.
Pulaski Skyway (Rt 1 & 9)	1.75	Fixed span	520	140	136	--	--	--	--
Point-No-Point Conrail	2.33	Swing	103	21	16	Larry Henshaw/Conrail, 732-267-6730.	--	--	--
NJ Turnpike Bridge (I-95)	2.41	Fixed span	352	105	100	W. Scott Johnson. Supervising Engineer-Structures Design. New Jersey Turnpike - 732-442-8600x2232	--	--	--
Jackson Street Bridge (Frank E. Rodgers Blvd S./County Rd 697)	4.37	Swing	72	20	18	Sal Macaluso (973-239-3366 ext. 2380)	--	--	--
Amtrak Dock Bridge	4.75	Lift deck	200	29 (143)	24	Jack Flannery (Division Engineer) (646-300-0582)	Amtrak	At least 24 hrs notice is required for opening. Bridge will NOT be opened between 6am and 10am and 4pm and 8pm Monday thru Friday except holidays. Bridge opening can be requested for any other time. There are no hours during which the bridge will not be opened on Sat, Sun, and holidays. Commerical vessels can sometimes necessitate opening during times when the bridge is normally closed. Full regs are being e-mailed by Jack to Angela. Bridge opening can be coordinated by calling the Chief Dispatcher at 212-630-7465. If there are any issues with opening via the Chief Dispatcher, call Jack Flannery at: 646-300-0582 (cell) or 212-630-7340 (office). Cell is preferred.	No construction or maintenance is planned.
Penn RR at Market Street	4.75	Draw	75	21	--	See Amtrak Dock Bridge, above	See Amtrak Dock Bridge, above	See Amtrak Dock Bridge, above	See Amtrak Dock Bridge, above
Penn RR at Center Street	4.75	Draw	80	10	--	See Amtrak Dock Bridge, above	See Amtrak Dock Bridge, above	See Amtrak Dock Bridge, above	See Amtrak Dock Bridge, above
Bridge Street Bridge	5.41	Swing	80	12	7	Sal Macaluso (973-239-3366 ext. 2380)	--	--	Jack Flannery (Division Engineer) (646-300-0582) - Amtrak reported that there has been some trouble opening the Bridge Street Bridge lately (though this bridge is not the responsibility of Amtrak).
Morristown Line RR Bridge / (Newark-Harrison) Erie Swing Bridge	5.57	Swing	77	20	15	Lisa Fannin (Director of Rail Maintenance) or Jim Galvin . NJ Transit Operation - 973-491-8086	NJ Transit Operations	Call Jim Glavin (Supervisor of Bridges) at 973-879-2697 or 973-491-8104 during regular business hours. After hours, call the 24-hour line at 201-714-2958. At least 4 hours advance notice is required, but 24 hours is preferred.	The bridge just went through a major rehab, so any additional/new major construction or maintenance work is highly unlikely.
Stickel Bridge (I-280)	5.61	Lift deck	200	40 (140)	35	Mr. Howard Paranto NJDOT. Supervisor of Bridge Operations, Office: 732-528-9494	NJDOT	Call North Electrical (need to obtain their # from North Com. [602-522-6211]). I tried calling North Com. and no one answered. There was no option to leave a voicemail. Per Howard Paranto, at least 24 hours is required to open the bridge.	There will be minor bridge construction activity and maintenance on-going, but nothing major that should affect our work.
Clay Street Bridge (Central Ave)	5.83	Swing	75	13	8	Sal Macaluso (973-239-3366 ext. 2380)	--	--	--
Fourth Ave Conrail Bridge	6.07	Single-leaf truss bascule (fixed open)	126	12	Unkn.	Larry Henshaw/Conrail, 732-267-6730.	--	--	--
Erie/Montclair-Greenwood Lake RR Bridge (West Arlington Street Bridge)	7.81	Fixed rail (decommissioned swing)	48	40	Unkn. (7)	Larry Henshaw/Conrail, 732-267-6730.	--	--	--
Rutgers (Rte 7) Bridge	8.53	Lift deck	--	13	9	DOT Street-wide operations - 732-697-7360; Felipe Hernandez (Director of Traffic Operations)	--	--	--
DeJessa Park Avenue Bridge	10.37	Open truss swing	--	11	7	Sal Macaluso (973-239-3366 ext. 2380)	--	--	--



**RM 10.9 Removal Project Bridges Supplemental Information**

*River Mile 10.9 Draft Final Design Report, Lower Passaic River Study Area, New Jersey*

Bridge Name	River Mile	Bridge Type	Max. Horizontal Clearance (ft)	Max. Vertical Clearance - Approx. at Low Tide (ft)*	Maximum Vertical Clearance - Approx. at High Tide (ft)	Contact Information <sup>†</sup>			
						Name / Number	Owner	How is opening coordinated (lead time, restrictions, etc.)?	Is any constructions or maintenance planned or scheduled (when, duration, how will it affect navigation)?
Lyndhurst-Delaware Rail Bridge	11.4	Opening swing	—	30	26	Lisa Fannin (Director of Rail Maintenance) or Jim Galvin . NJ Transit Operation - 973-491-8086	NJ Transit Operations	Lisa Fannin believed that this bridge is now Fixed Closed (no longer opens at all).	Lisa was not aware of any current or upcoming construction or maintenance.
Rutherford Avenue (Rte 3) Bridge	11.65	Double leaf bascule	—	40	36	Mr. Howard Paranto NJDOT. Supervisor of Bridge Operations, Office: 732-528-9494	NJDOT	Call North Electrical (need to obtain their # from North Com. [602-522-6211]). I tried calling North Com. and no one answered. There was no option to leave a voicemail. Per Howard Paranto, at least 24 hours is required to open the bridge.	Howard was fairly certain that they were currently performing construction on this bridge to transform it into a fixed span. Otherwise, there will be minor bridge construction activity and maintenance on-going.

Source: Lower Passaic River Commercial Navigation Analysis Rev 2 (USACE, 2010); Lower Resolution Coring Characterization Summary, Lower Passaic River Study Area RI/FS (AECOM, 2011).

\*If a lift bridge, vertical clearance in parenthesis refers to clearance when bridge is open.

<sup>†</sup>Informaiton Obtained in September/October 2012.

NA, not applicable, since bridge was removed. —, data not available.

RM data was sourced from Table 2-5 of LRC report, for consistency (AECOM, 2011).

**Information from a variety of sources - including: Lower Passaic River Commercial Navigation Analysis Rev 2 (USACE, 2010); Lower Resolution Coring Characterization Summary, Lower Passaic River Study Area RI/FS (AECOM, 2011). Information should be verified prior to field activities.**

**Additional Contacts:**

Joe Glembocki  
Hudson County Engineer Tel: 201-369-4340

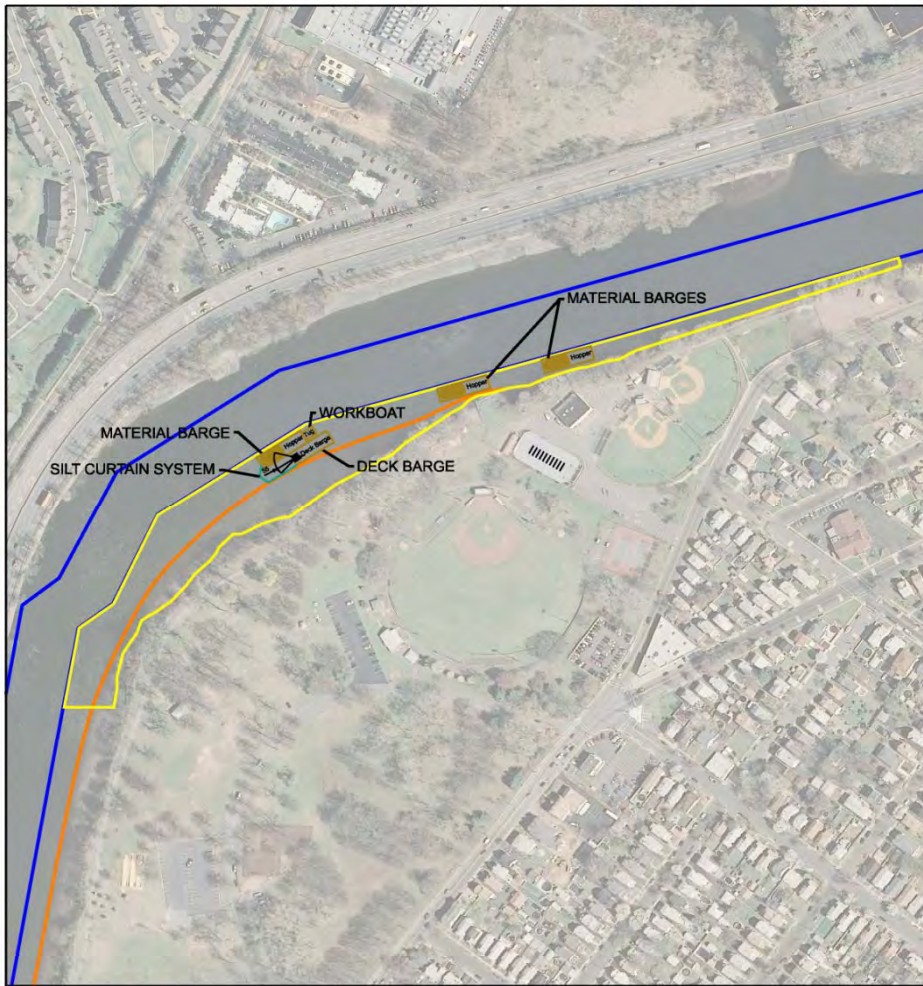
Sanjev Varghese  
Essex County Engineer 973-226-8500

Joe Fermia  
Bergen County 201-336-6808

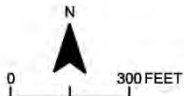


Project Name/Title:	Lower Passaic River, RM 10.9 Removal Action	Project Number:	436870
Document Name:	RM 10.9 Removal Action Basis of Design Report	Preparer Name:	James Brinkman
Project Manager:	Roger McCready	Design Manager:	James Brinkman

Calculation Title:		LPR Estimated Dredging Production Rates		
Calculation Identifier:				
Date Prepared	Rev. No.	Preparer Signature/Date	Checker Signature/Date	For Professional Seal/When Required
7/23/2012	0			
10/18/2012	1			
11/20/2012	2			
2/4/2013	3			
SIC/SME Signature/Date				
LIR Signature/Date (if required)				
Comments:				
The following worksheets are included:				
- Dredging Operation - Planview: Provides proposed equipment configuration				
- Dredging Operations - Xsections: Illustrates drafts of marine equipment at Low and High Mean Water				
- 3 CY - 12 hrs: Estimated dredging production rate using a 3 CY bucket based on a 12 hr day				
- 3 CY - 24 hrs: Estimated dredging production rate using a 3 CY bucket based on a 24 hr day				
- 5 CY - 12 hrs: Estimated dredging production rate using a 5 CY bucket based on a 12 hr day				
- 5 CY - 24 hrs: Estimated dredging production rate using a 5 CY bucket based on a 24 hr day				
- Sediment Property Calc: Sample calculations for sediment property values				
- Dredging Production Sample Calc: Sample calculations for estimated dredging production rates				
Figures showing plan and cross sectional views of dredging operation added for Rev 2. No additional changes were made.				
"Dredge Movement" added to "Barge Movement" on production rate spreadsheets for Rev 3. No other changes made				
Information Requiring Confirmation:				



- NOTES**
1. Orthophoto: N.J.GIS, 2007
  2. The Extent of Potentially Exposed Surface Sediment was generated from the -2ft (NGVD29) elevation, which represents the Mean Low Water for this part of the river. The data source was the July 2011 Bathymetry Survey conducted as part of the RM 10.9 Characterization Program (CH2M HILL & AECOM, 2012)
  3. Dredging layout is shown for illustrative purposes and that actual layouts will vary during the work



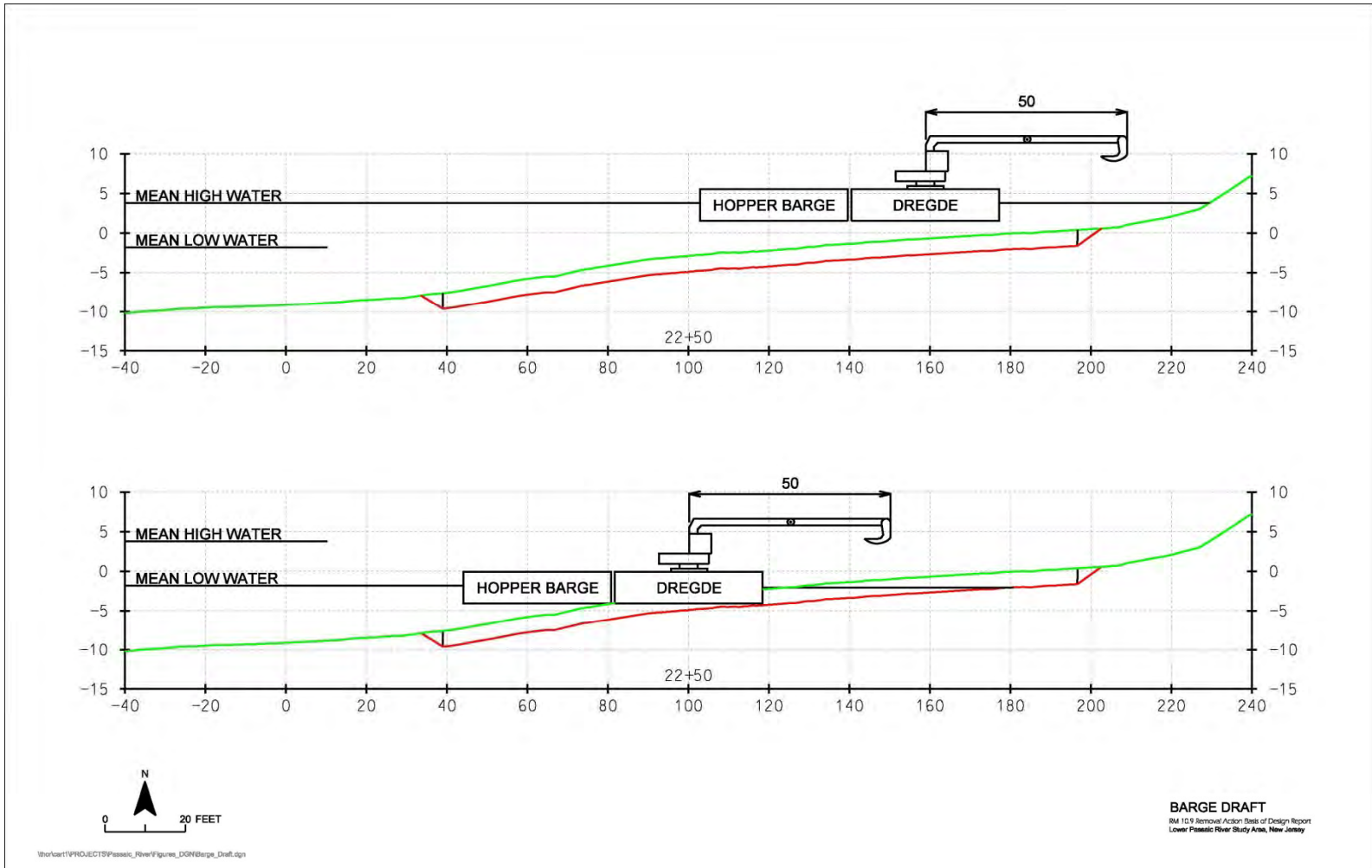
- LEGEND**
- Navigation Channel
  - RM 10.9 Removal Area
  - Extent of Potentially Exposed Surface Sediment

**FIGURE 4-7**  
**Dredging Operations Layout**  
 RM 10.9 Removal Action Basis of Design Report  
 Lower Passaic River Study Area, New Jersey

\\fs01\PROJECTS\PassaicDredgeRiver\Working\Figure\_4\_7.dwg

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Lower Passaic River, RM 10.9 Removal Action  
 PN#: 436870  
 Calculation Title: Estimated Dredging Production Rate  
 Rev: 3  
 Date: 02/04/13

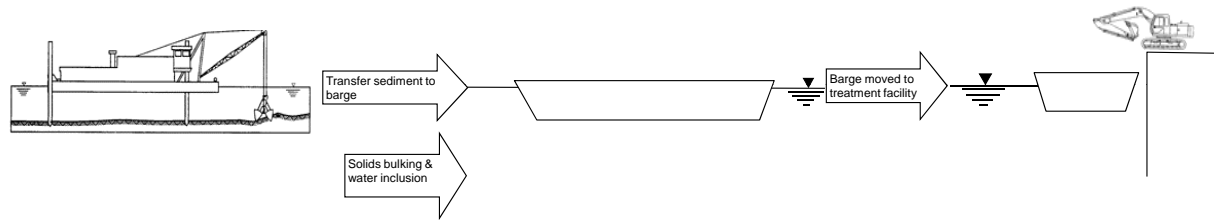


**MECHANICAL CLAMSHELL DREDGE, 3 CU YD ENVIRONMENTAL BUCKET, 250 CU YD SCOW, 12 hrs/day**

In-Situ Sediment Properties		
Solids Content (% by weight; $X_s$ ) =	52	
Specific Gravity Sediment ( $SG_s$ ) =	2.5	
Volume of Solids ( $V_s$ ) =	0.3023	ft <sup>3</sup>
Volume of water ( $V_w$ ) =	0.6977	ft <sup>3</sup>
Weight of Solids ( $W_s$ ) =	47.14	lbs/ft <sup>3</sup>
Weight of Water ( $W_w$ ) =	43.51	lbs/ft <sup>3</sup>
Weight of Sediment ( $W_T$ ) =	90.66	lbs/ft <sup>3</sup>
=	1.22	tons/yd <sup>3</sup>
Sediment Bulking Factor	1.15	

Water Properties		
Specific Gravity ( $SG_w$ ) =	1	
Density of water @ 60 F ( $\rho_{H_2O}$ ) =	62.371	lbs/ft <sup>3</sup>
	8.3378	lbs/gallon
	7.4805	gallon/ft <sup>3</sup>

Dredging Bucket Size	yd <sup>3</sup>	3.0
Excess Water per Bucket Grab	%	31%
Bucket Cycle Time	min	2.5
Buckets per hour	per hr	24
Barge Volume	yd <sup>3</sup>	250
Dredge Movement/Barge Changeover time	hr	0.33
% Excess Water to be Pumped Out of Barge	%	95%
Available Dredging Hours Per Day	hrs/day	10
Dredging Days Per Week	days/week	6
Dredge Uptime Average	%	65%
Normal Working Day	hrs/day	24
Normal Working Week	days/week	6
Number of Dredges	each	1



Total volume in barge	yd <sup>3</sup>	250	
Buckets per barge	buckets	83	
Hours to fill barge (water + sediment)	hr	3.5	
Hours to place second barge	hr	0.33	
Total Hours for barge loading and transfer	hr	3.8	
Excess Water	yd <sup>3</sup> /hr	22.5	
In situ Sediment+ pore water	yd <sup>3</sup> /hr	49	
Total In situ sediment plus pore water in barge	yd <sup>3</sup>	171.1	
Total water volume in barge	yd <sup>3</sup>	77.9	
Average In-situ Sediment plus pore water volume transfer to shore	In-situ yd <sup>3</sup> /hr	29.3	
	tons/hr	35.9	
Daily water transfer to shore	yd <sup>3</sup> /day	127	25,619 gal/day

Daily Production Rates		
Average In situ Sediment Transfer per day	yd <sup>3</sup> /day	293
	tons/day	359
Weekly Production Rates		
Average In situ Sediment Dredging	yd <sup>3</sup> /week	1,760
	tons/week	2,154

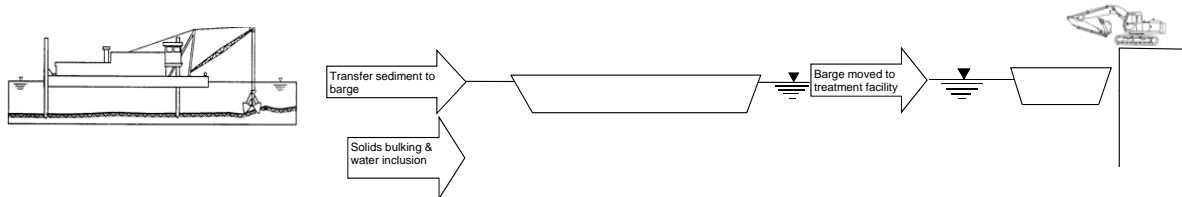


**MECHANICAL CLAMSHELL DREDGE, 3 CU YD ENVIRONMENTAL BUCKET, 250 CU YD SCOW, 24 hrs/day**

In-Situ Sediment Properties		
Solids Content (% by weight; $X_s$ ) =	52	
Specific Gravity Sediment ( $SG_s$ ) =	2.5	
Volume of Solids ( $V_s$ ) =	0.3023	ft <sup>3</sup>
Volume of water ( $V_w$ ) =	0.6977	ft <sup>3</sup>
Weight of Solids ( $W_s$ ) =	47.14	lbs/ft <sup>3</sup>
Weight of Water ( $W_w$ ) =	43.51	lbs/ft <sup>3</sup>
Weight of Sediment ( $W_T$ ) =	90.66	lbs/ft <sup>3</sup>
=	1.22	tons/yd <sup>3</sup>
Sediment Bulking Factor	1.15	

Water Properties		
Specific Gravity ( $SG_w$ ) =	1	
Density of water @ 60 F ( $\rho_{H_2O}$ ) =	62.371	lbs/ft <sup>3</sup>
	8.3378	lbs/gallon
	7.4805	gallon/ft <sup>3</sup>

Dredging Bucket Size	yd <sup>3</sup>	3.0
Excess Water per Bucket Grab	%	31%
Bucket Cycle Time	min	2.9
Buckets per hour	per hr	24
Barge Volume	yd <sup>3</sup>	250
Dredge Movement/Barge Changeover time	hr	0.33
% Excess Water to be Pumped Out of Barge	%	95%
Available Dredging Hours Per Day	hrs/day	20
Dredging Days Per Week	days/week	6
Dredge Uptime Average	%	65%
Normal Working Day	hrs/day	24
Normal Working Week	days/week	6
Number of Dredges	each	1



Total volume in barge	yd <sup>3</sup>	250	
Buckets per barge	buckets	83	
Hours to fill barge (water + sediment)	hr	3.5	
Hours to place second barge	hr	0.33	
Total Hours for barge loading and transfer	hr	3.8	
Excess Water	yd <sup>3</sup> /hr	22.5	
In situ Sediment+ pore water	yd <sup>3</sup> /hr	49	
Total In situ sediment plus pore water in barge	yd <sup>3</sup>	171.1	
Total water volume in barge	yd <sup>3</sup>	77.9	
Average In-situ Sediment plus pore water volume transfer to shore	In-situ yd <sup>3</sup> /hr	29.3	
	tons/hr	35.9	
Daily water transfer to shore	yd <sup>3</sup> /day	254	51,239 gal/day

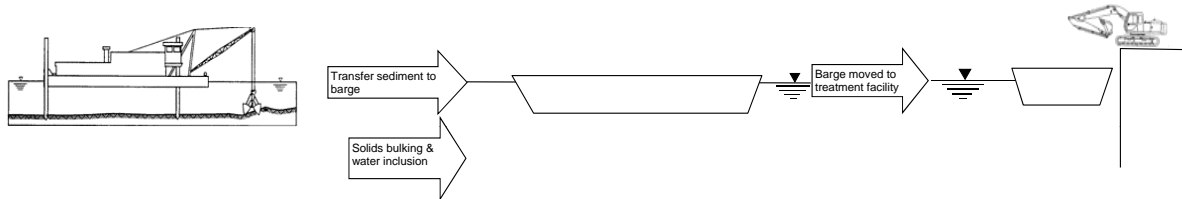
Daily Production Rates		
Average In situ Sediment Transfer per day	yd <sup>3</sup> /day	587
	tons/day	718
Weekly Production Rates		
Average In situ Sediment Dredging	yd <sup>3</sup> /week	3,520
	tons/week	4,308

**MECHANICAL CLAMSHELL DREDGE, 5 CU YD ENVIRONMENTAL BUCKET, 250 CU YD SCOW, 12 hrs/day**

In-Situ Sediment Properties	
Solids Content (% by weight; $X_s$ ) =	52
Specific Gravity Sediment ( $SG_s$ ) =	2.5
Volume of Solids ( $V_s$ ) =	0.3023 ft <sup>3</sup>
Volume of water ( $V_w$ ) =	0.6977 ft <sup>3</sup>
Weight of Solids ( $W_s$ ) =	47.14 lbs/ft <sup>3</sup>
Weight of Water ( $W_w$ ) =	43.51 lbs/ft <sup>3</sup>
Weight of Sediment ( $W_T$ ) =	90.66 lbs/ft <sup>3</sup>
=	1.22 tons/ft <sup>3</sup>
Sediment Bulking Factor	1.15

Water Properties	
Specific Gravity ( $SG_w$ ) =	1.0
Density of water @ 60 F ( $\rho_{H_2O}$ ) =	62.371 lbs/ft <sup>3</sup>
	8.3378 lbs/gallon
	7.4805 gallon/ft <sup>3</sup>

Dredging Bucket Size	yd <sup>3</sup>	5.0
Excess Water per Bucket Grab	%	31%
Bucket Cycle Time	min	2.5
Buckets per hour	per hr	24
Barge Volume	yd <sup>3</sup>	250
Dredge Movement/Barge Changeover time	hr	0.33
% Excess Water to be Pumped Out of Barge	%	95%
Available Dredging Hours Per Day	hrs/day	10
Dredging Days Per Week	days/week	6
Dredge Uptime Average	%	65%
Normal Working Day	hrs/day	24
Normal Working Week	days/week	6
Number of Dredges	each	1



Equation

1	Total volume in barge	yd <sup>3</sup>	250	
2	Buckets per barge	buckets	50	
3	Hours to fill barge (water + sediment)	hr	2.08	
4	Hours to place second barge	hr	0.333	
5	Total Hours for barge loading and transfer	hr	2.42	
6	Excess Water	yd <sup>3</sup> /hr	38	
7	In situ Sediment+ pore water	yd <sup>3</sup> /hr	82	
8	Total In situ sediment plus pore water in barge	yd <sup>3</sup>	172	
9	Total water volume in barge	yd <sup>3</sup>	78	15,794 gal/barge
10	Average In-situ Sediment plus pore water volume transfer to shore	In-situ yd <sup>3</sup> /hr	46	
		tons/hr	57	
	Daily water transfer to shore	yd <sup>3</sup> /day	200	40,357 gal/day

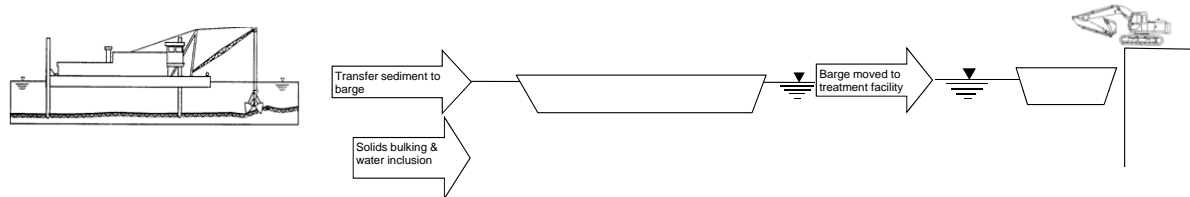
Daily Production Rates			
10	Average In situ Sediment Transfer per day	yd <sup>3</sup> /day	462
		tons/day	566
Weekly Production Rates			
10	Average In situ Sediment Dredging	yd <sup>3</sup> /week	2,772
		tons/week	3,393

**MECHANICAL CLAMSHELL DREDGE, 5 CU YD ENVIRONMENTAL BUCKET, 250 CU YD SCOW, 24 hrs/day**

In-Situ Sediment Properties	
Solids Content (% by weight; $X_s$ ) =	52
Specific Gravity Sediment ( $SG_s$ ) =	2.5
Volume of Solids ( $V_s$ ) =	0.3023 ft <sup>3</sup>
Volume of water ( $V_w$ ) =	0.6977 ft <sup>3</sup>
Weight of Solids ( $W_s$ ) =	47.14 lbs/ft <sup>3</sup>
Weight of Water ( $W_w$ ) =	43.51 lbs/ft <sup>3</sup>
Weight of Sediment ( $W_T$ ) =	90.66 lbs/ft <sup>3</sup>
=	1.22 tons/yd <sup>3</sup>
Sediment Bulking Factor	1.15

Water Properties	
Specific Gravity ( $SG_w$ ) =	1
Density of water @ 60 F ( $\rho_{H_2O}$ ) =	62.371 lbs/ft <sup>3</sup>
	8.3378 lbs/gallon
	7.4805 gallon/ft <sup>3</sup>

Dredging Bucket Size	yd <sup>3</sup>	5.0
Excess Water per Bucket Grab	%	31%
Bucket Cycle Time	min	2.5
Buckets per hour	per hr	24
Barge Volume	yd <sup>3</sup>	250
Dredge Movement/Barge Changeover time	hr	0.33
% Excess Water to be Pumped Out of Barge	%	95%
Available Dredging Hours Per Day	hrs/day	20
Dredging Days Per Week	days/week	6
Dredge Uptime Average	%	65%
Normal Working Day	hrs/day	24
Normal Working Week	days/week	6
Number of Dredges	each	1



Total volume in barge	yd <sup>3</sup>	250	
Buckets per barge	buckets	50	
Hours to fill barge (water + sediment)	hr	2.1	
Hours to place second barge	hr	0.33	
Total Hours for barge loading and transfer	hr	2.4	
Excess Water	yd <sup>3</sup> /hr	37.5	
In situ Sediment+ pore water	yd <sup>3</sup> /hr	82	
Total In situ sediment plus pore water in barge	yd <sup>3</sup>	171.8	
Total water volume in barge	yd <sup>3</sup>	78.2	
Average In-situ Sediment plus pore water volume transfer to shore	In-situ yd <sup>3</sup> /hr	46.2	
	tons/hr	56.6	
Daily water transfer to shore	yd <sup>3</sup> /day	400	80,715 gal/day

Daily Production Rates		
Average In situ Sediment Transfer per day	yd <sup>3</sup> /day	924
	tons/day	1,131
Weekly Production Rates		
Average In situ Sediment Dredging	yd <sup>3</sup> /week	5,545
	tons/week	6,786

**SAMPLE CALCULATIONS FOR IN SITU SEDIMENT PROPERTIES**

$$V_T = V_W + V_S$$

$$W_T = W_W + W_S$$

Where:

$V_T$  = Total Volume  
 $V_W$  = Volume of Water  
 $V_S$  = Volume of Solids

$W_T$  = Total Weight per ft<sup>3</sup>  
 $W_W$  = Weight of Water per ft<sup>3</sup>  
 $W_S$  = Weight of Solids per ft<sup>3</sup>

$$\% \text{ Solids (by weight)} = W_S/W_T$$

$$= W_S/(W_S + W_W)$$

$$W_S = V_S * \rho_S = V_S * SG_S * \rho_{H2O @ 60oF}$$

$$W_W = V_W * \rho_W = V_W * SG_W * \rho_{H2O @ 60oF}$$

Where:

$\rho_{H2O @ 60oF}$  = density of water @ 60°F = 62.371 lbs/ft<sup>3</sup>  
 $SG_W$  = Specific gravity of water = 1.0  
 $SG_S$  = Specific gravity of sediment = 2.5  
 $\rho_S$  = density of solids =  $SG_S * \rho_{H2O @ 60oF} = 155.93$  lbs/ft<sup>3</sup>  
 $\rho_W$  = density of water =  $SG_W * \rho_{H2O @ 60oF} = 62.371$  lbs/ft<sup>3</sup>

$$\% \text{ Solids (by weight)} = V_S * \rho_S / [(V_S * \rho_S) + (V_W * \rho_W)] = X_S$$

$$V_W = 1 - V_S$$

Therefore:

$$X_S = V_S * \rho_S / [(V_S * \rho_S) + (V_W * \rho_W)]$$

$$X_S = V_S * \rho_S / [(V_S * \rho_S) + ((1 - V_S) * \rho_W)]$$

$$X_S = 155.93 \text{ lbs/ft}^3 * V_S / [(155.93 \text{ lbs/ft}^3 * V_S) + 62.371 \text{ lbs/ft}^3 - (62.371 \text{ lbs/ft}^3 * V_S)]$$

$$X_S = 155.93 \text{ lbs/ft}^3 * V_S / [(93.559 \text{ lbs/ft}^3 * V_S) + 62.371 \text{ lbs/ft}^3]$$

$$X_S * (93.559 \text{ lbs/ft}^3 * V_S + 62.371 \text{ lbs/ft}^3) = 155.93 \text{ lbs/ft}^3 * V_S$$

$$93.559 \text{ lbs/ft}^3 * V_S * X_S + 62.371 \text{ lbs/ft}^3 * X_S = 155.93 \text{ lbs/ft}^3 * V_S$$

$$62.371 \text{ lbs/ft}^3 * X_S = (155.93 \text{ lbs/ft}^3 * V_S) - (93.559 \text{ lbs/ft}^3 * V_S * X_S)$$

$$V_S = 62.371 \text{ lbs/ft}^3 * X_S / [155.93 \text{ lbs/ft}^3 - (93.559 \text{ lbs/ft}^3 * X_S)]$$

For a in situ solids content of 52% ( $X_S = 0.52$ ):

$$V_S = 62.371 \text{ lbs/ft}^3 * 0.52 / [155.93 \text{ lbs/ft}^3 - (93.559 \text{ lbs/ft}^3 * 0.52)]$$

$$V_S = 0.3023 \text{ ft}^3/\text{ft}^3$$

$$V_W = 1 - V_S$$

$$= 1 - 0.3023 \text{ ft}^3/\text{ft}^3 = 0.6977 \text{ ft}^3/\text{ft}^3$$

$$W_S = V_S * \rho_S = V_S * SG_S * \rho_{H2O @ 60oF}$$

$$= 0.3023 \text{ ft}^3/\text{ft}^3 * 2.5 * 62.371 \text{ lbs/ft}^3 * 1 \text{ ft}^3$$

$$= 47.14 \text{ lbs/ft}^3$$

$$W_W = V_W * \rho_W = V_W * SG_W * \rho_{H2O @ 60oF}$$

$$= 0.6977 \text{ ft}^3/\text{ft}^3 * 2.5 * 62.371 \text{ lbs/ft}^3 * 1 \text{ ft}^3$$

$$= 43.52 \text{ lbs/ft}^3$$

$$W_T = 90.65 \text{ lbs/ft}^3$$

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## **SAMPLE CALCULATIONS FOR DREDGE PRODUCITON RATE (5 yd<sup>3</sup> bucket, 12 hours/day)**

### Equation #1 - Bucket per Barge

$$\begin{aligned}\text{Bucket per barge} &= \text{volume of barge}/\text{volume of bucket} \\ &= 250 \text{ yd}^3/5 \text{ yd}^3 \\ &= 50 \text{ buckets per barge}\end{aligned}$$

### Equation #2 - Hours to fill barge (water + sediment)

$$\begin{aligned}\text{Hours to fill barge} &= (\# \text{ buckets per barge} * \text{cycle time (min/bucket)})/60 \text{ min/hour} \\ &= (50 \text{ buckets/barge} * 2.5 \text{ min/bucket})/60 \text{ min/hr} \\ &= 2.08 \text{ hours}\end{aligned}$$

### Equation #3 - Total Hours for barge loading and transfer

$$\begin{aligned}\text{Total Hours for barge loading and transfer} &= \text{Hours to fill barge} + \text{hours to place 2}^{\text{nd}} \text{ Barge} \\ &= 2.08 \text{ hours} + 0.333 \text{ hrs} \\ &= 2.42 \text{ hours}\end{aligned}$$

### Equation #4 - Excess Water (yd<sup>3</sup>/hr)

$$\begin{aligned}\text{Excess water per bucket} &= \text{volume of bucket} * \text{Percent excess water} * \text{Buckets per hour} \\ &= 5 \text{ yd}^3 * (31.28/100) * (60 \text{ min per hour})/(2.5 \text{ min per bucket}) \\ &= 38 \text{ yd}^3/\text{hr}\end{aligned}$$

### Equation #5 - In situ Sediment+ pore water (yd<sup>3</sup>/hr)

$$\begin{aligned}\text{In situ Sediment+ pore water} &= \text{volume of bucket} * \text{Percent Full} * \text{Buckets per hour} \\ &= 5 \text{ yd}^3 * (1 - 31)/100 * (60 \text{ min per hour})/(2.5 \text{ min per bucket}) \\ &= 82 \text{ yd}^3/\text{hr}\end{aligned}$$

### Equation #6 - Total In situ sediment plus pore water in barge

$$\begin{aligned}\text{Total In situ sediment plus pore water in barge} &= [\text{In situ sediment} + \text{pore water (EQ \#5)}] * [\text{Hours to fill barge (EQ \#2)}] \\ &= 82 \text{ yd}^3/\text{hr} * 2.08 \text{ hours} \\ &= 172 \text{ yd}^3\end{aligned}$$

### Equation #7 - Total Excess Water Volume in Barge

$$\begin{aligned}\text{Total excess water volume in barge} &= [\text{Excess water rate (EQ \#4)}] * [\text{Hours to fill barge (EQ \#2)}] \\ &= 38 \text{ yd}^3/\text{hour} * 2.08 \text{ hours} \\ &= 78 \text{ yd}^3\end{aligned}$$



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Equation #8 - Average In-situ Sediment plus pore water volume transfer to shore (yd<sup>3</sup>/hr)

$$\begin{aligned} \text{Average In-situ Sediment plus pore water volume transfer to shore} &= ([\text{total in situ sediment} + \text{pore water in barge (EQ \#6)}]/[\text{Total time to fill and transfer barge (EQ \#3)}]) * \text{Average Dredge Uptime} \\ &= (172 \text{ yd}^3/2.42 \text{ hrs}) * (65/100) \\ &= 46 \text{ yd}^3/\text{hr} \\ &= (46 \text{ yd}^3/\text{hr}) * (1.22 \text{ tons}/\text{yd}^3) = 57 \text{ tons}/\text{hr} \end{aligned}$$

Equation #9 - Average additional water transfer to shore rate (gallons/day)

$$\begin{aligned} \text{Avg additional water transfer to shore rate} &= ([\text{total excess water in barge (EQ \#7)}]/[\text{Total time to fill and transfer barge (EQ \#3)}]) * \text{Avg Dredge Uptime} * \text{dredge hrs per day} * \text{Percent excess water removed} \\ &= (78 \text{ yd}^3/2.417 \text{ hrs}) * 10 \text{ hrs}/\text{day} * (65/100) * (95/100) \\ &= 200 \text{ yd}^3/\text{day} \\ &= 200 \text{ yd}^3/\text{day} * 201.974 \text{ gallons}/\text{yd}^3 = 40,357 \text{ gallons}/\text{day} \end{aligned}$$

Equation #10 - Daily Dredge Rate (yd<sup>3</sup>/day)

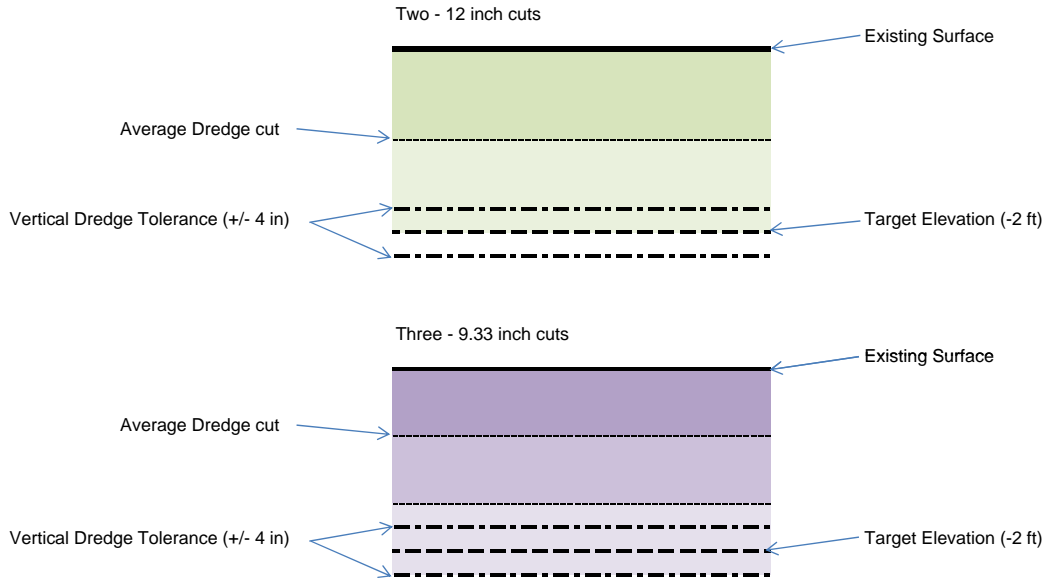
$$\begin{aligned} \text{Daily Dredge Rate} &= \text{Hourly dredge rate (Equation \#8)} * \text{Dredge Hours per Day} * \# \text{ of dredges} \\ &= 46 \text{ yd}^3/\text{hr} * 10 \text{ hours}/\text{day} * 1 \text{ dredge} \\ &= 462 \text{ yd}^3/\text{day} \\ &= 462 \text{ yd}^3/\text{day} * 1.22 \text{ tons}/\text{yd}^3 = 566 \text{ tons}/\text{day} \end{aligned}$$



### CALCULATION FOR PERCENT EXCESS WATER IN DREDGE BUCKET

Environmental Bucket <sup>1</sup>	Footprint			Depth to Fill 100%	
	Length (Ft)	Width (Ft)	Area (Ft <sup>2</sup> )	Feet	Inches
The Grab Specialist (TGS): 5 yd <sup>3</sup>	14.7	7.1	104.37	1.29	15.52

Notes: 1 - Based on information provided in Hudson River PCBs Site EPA Phase I Evaluation Report (March 2010)



Sample Calculation:

Assume 12 inch dredge cut.

Volume of sediment removed (ft<sup>3</sup>) = 104.37 ft<sup>2</sup> \* (12 inches/12 inches/ft) = 104.37 ft<sup>3</sup>

Volume of sediment removed (yd<sup>3</sup>) = 104.37 ft<sup>3</sup> / (27 ft<sup>3</sup>/yd<sup>3</sup>) = 3.87 yd<sup>3</sup>

Percentage of sediment in bucket (%) = (3.87 yd<sup>3</sup> / 5 yd<sup>3</sup>) \* 100 = 77.31%

**Percent Full vs Depth of Dredge Cut**

Depth of Cut (Inches)	Volume of Sediment (yd <sup>3</sup> )	% Full	Comment
5	1.61	32.21%	
6	1.93	38.66%	
7	2.25	45.10%	
8	2.58	51.54%	
9	2.90	57.98%	
9.33	3.01	60.13%	Three cuts to 28 inches (2 feet + 4 inch vertical Tolerance)
9.5	3.06	61.20%	
10	3.22	64.43%	
10.67	3.44	68.72%	Assumed average depth of cut (31.28% excess water)
11	3.54	70.87%	
12	3.87	77.31%	Two cuts to 24 inches (2 feet)
13	4.19	83.75%	
14	4.51	90.20%	
15	4.83	96.64%	
15.5	4.99	99.86%	

The tree trimming operation was assisted by a number of small skiffs that managed harbor booms surrounding the larger barges and collected tree parts that fell into the river during removal (see Figure III-2-5).

The debris removal barge consisted of two barges constructed from FlexiFloat sections and pinned together. The main barge held a CAT 320 excavator fitted with a claw type extractor. This barge also held a barge control office, CONEX supply boxes, sanitary facilities and power generators. The second barge section was a mini-hopper barge into which debris was placed (see Figure III-2-6).

### 2.3.2 Dredges

The dredges used during Phase 1 of the project consisted of fixed arm, hydraulic excavators mounted on deck barges and equipped with hydraulically operated, enclosed buckets that produce a relatively level cut. A total of 12 dredges were available for most of the season. Five of these were Caterpillar 385 excavators equipped with 5-CY buckets, one was a Caterpillar 345 excavator equipped with a 2-CY bucket, and six were Caterpillar 320 excavators equipped with 1-CY buckets.

The enclosed buckets were manufactured by The Grab Specialists, BV of the Netherlands. The 5-CY bucket had a footprint of 14.7 feet by 7.1 feet (104.4 sq. ft.) when fully opened and, assuming no expansion or swelling of the sediment as it was excavated, required a 15.6-inch depth of cut to fill. The 1-CY bucket had a footprint of 9.3 feet by 4.3 feet (40 sq. ft.) and was filled when the depth of cut was about 8 inches. The 2 CY bucket had a footprint of 5.05 feet by 10.69 feet and was filled when the depth of cut was about 12 inches.

The dredges were equipped with a Real-Time Kinematic (RTK) Differential Global Positioning System (GPS) to position the dredge bucket within tolerances of plus-or-minus 2 inches vertically and plus-or-minus 3 inches horizontally, as produced by HyPack, Inc. Hypack's Dredgepack® software was programmed with dredge prism input files on a gridded interval of 1 foot by 1 foot to control the position of the bucket for each bite of sediment. This system also provides a record of each successful dredge bucket bite and records the real-time movement and position of the excavator and bucket for review at any time. Dredging bites that are unsuccessful due to a partial closing of the bucket from debris or other malfunction are not logged as a successful bite and are reacquired to obtain the removal of material initially acquired from the original location. Once successful, the bite is logged into the system. Additional detail on the data review and analysis of Dredgepack® logs generated during the Phase 1 activities is provided in Section III 3.4.1.





## CALCULATION FOR SEDIMENT UNLOADING RATE

### Assumptions:

- Bucket size = 4.5 yd<sup>3</sup> based on equipment at existing facility
- Bucket Cycle Time = 40 seconds based on observation of operations
- Bucket volume per Grab = 80% (3.6 yd<sup>3</sup>)
- Total volume of sediment and excess water in barge = 250 yd<sup>3</sup>
- Volume of excess water in barge = 77.9 yd<sup>3</sup> (See Dredge Production Calc)
- Percent of excess water removed prior to unloading = 90%
- Time to remove Excess Water = 30 minutes based on similar projects
- Time to remove oversized debris = 30 minutes
- Time to shift barge = 15 minutes

Bucket Size (yd <sup>3</sup> )		4.5	CY
Bucket Cycle time	40 sec.	0.7	minutes
Bucket Volume/cycle	80 % full	3.6	CY
Volume per hour		324	cy/hr
Time to remove Excess Water	30 min	0.50	hours
Time to remove debris	30 min	0.50	hours
Time to empty barge (250 yd <sup>3</sup> )	33 min	0.55	hours
Time to shift barge	15 min	0.25	hours
Barge unload/cycle time		1.80	hours
Run time per day	90%	21.6	hours
<b>Unloading Production:</b>		<b>3,590</b>	<b>CY/day</b>
Barges per day (max)		11.97	barges

### Sample Calculations:

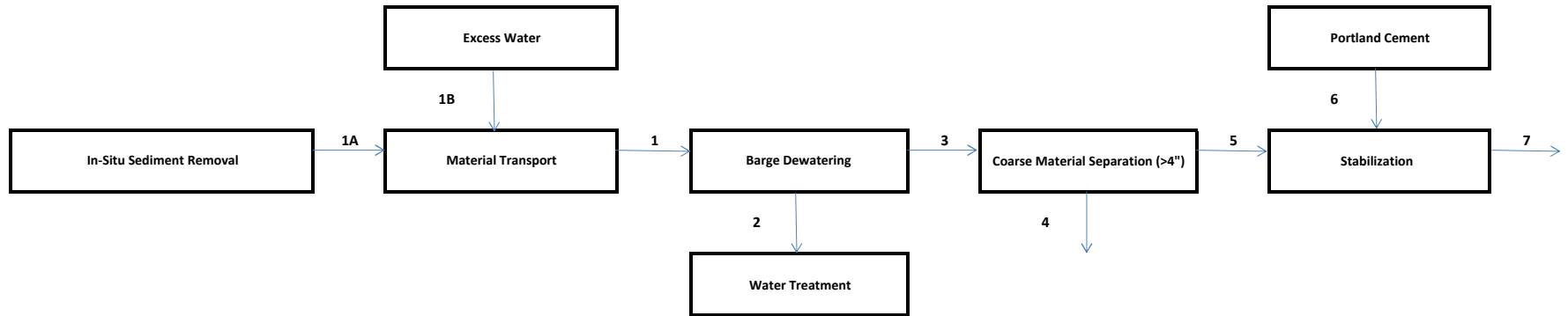
$$\text{Bucket volume per Grab} = 4.5 \text{ yd}^3 * 0.80 = 3.6 \text{ yd}^3$$

$$\text{Volume per hour} = (3.6 \text{ yd}^3 / 0.7 \text{ min}) * 60 \text{ min/hour} = 324 \text{ yd}^3/\text{hour}$$

$$\begin{aligned} \text{Time to Remove sediment} &= (\text{Total volume of material in barge} - 90\% \text{ of Excess Water in Barge}) / \text{dredge unloading rate} \\ &= (250 \text{ yd}^3 - (0.9 * 78 \text{ yd}^3)) / 324 \text{ yd}^3/\text{hr} \\ &= 0.55 \text{ hours (33 minutes)} \end{aligned}$$

$$\begin{aligned} \text{Total Time to Empty Barge} &= \text{Time to remove excess water} + \text{Time to remove debris} + \text{Time to Remove sediment} + \text{Time to shift barge} \\ &= (30 \text{ min} + 30 \text{ min} + 33 \text{ min} + 15 \text{ min}) = 108 \text{ min} = 1.8 \text{ hours} \end{aligned}$$





	From Dredge <sup>1</sup> 1A	Excess Water <sup>2</sup> 1B	Total From Dredge 1	Barge Dewatering <sup>3</sup> 2	To Coarse Separation 3	+ 4 inch Material <sup>4</sup> 4	To Pugmill 5	Portland Cement <sup>5</sup> 6	Stabilized Sediment 7
Total Weight (Tons/day)	566	168	734	151	583	50	533	53	586
Weight of Dry Solids (Tons/day)	294	0	294	0.03	294	49	245	53	299
Total Volume (CY/day)	462	210	672	189	483	23	460	42	502
Gallons/day		40,357		36,322					
% Solids (by weight)	52%	0%	40%	0.02%	50%	98%	46%	100%	

Notes:

- 1 - 5 yd<sup>3</sup> environmental bucket, 12 hrs/day
- 2 - 68.72% bucket efficiency
- 3 - 90% of excess barge water removed, 0.01% of solids is removed as suspended solids
- 4 - +4 inch material = 5% of total dredge volume; density = 2.15 tons/CY; material 98% solids
- 5 - 10% by weight

**Stream 1A - In-Situ Sediment in Dredge Bucket**

Total Weight = 566 tons/day (See attached dredge production rate; Cell N56)  
Weight of Dry Solids = total weight (tons/day) \* % solids  
= 294 tons/day  
Total Volume = 462 yd<sup>3</sup>/day (See attached dredge production rate; Cell N55)  
% Solids (by weight) = 52% (Based on characterization data for RM 10.9)

**Stream 1B - Excess Water in Dredge Bucket**

Total Weight = total volume \* density of water (8.329 lbs/ft<sup>3</sup>)\*(1 ton/2000 lbs)  
= 168 tons  
Total Volume = [(total volume dredged per day)/(% bucket full)] - (total in situ volume dredged)  
= [(462 yd<sup>3</sup>/day)/(68.72/100)] - 462 yd<sup>3</sup>/day  
= 210 yd<sup>3</sup>/day  
= 210 yd<sup>3</sup>/day \* 201.974 gallons/yd<sup>3</sup> = 40,357 gallons  
% Solids (by weight) = 0

**Stream 1 - Total Material Transferred to Barge from Dredge**

Total Weight = Weight of in situ sediment (Stream #1A) + Weight of Excess Water (Stream #1B)  
= 734 tons/day  
Weight of Dry Solids = 294 tons/day  
Total Volume = Volume of in situ sediment (Stream #1A) + Volume of Excess Water (Stream #1B)  
= 672 yd<sup>3</sup>/day  
% Solids (by weight) = [Total weight of dry solids removed]/[Total weight of material removed]  
= (318 tons/day)/(786 tons/day)  
= 40%

**Stream 2 - Excess Water Removed from Barges**

Total Weight = total volume \* density of water (8.329 lbs/ft<sup>3</sup>)\*(1 ton/2000 lbs)  
= 151 tons  
Total Volume = total volume of excess water \* % Water Removed  
= 40,537 gallons/day \* 0.90 or 207 yd<sup>3</sup>/day \* 0.90  
= 36,322 gallons/day  
= 189 yd<sup>3</sup>/day  
% Solids (by weight) = 0

**Stream 3 - Material Removed from Barge and Transferred to Coarse Separation**

Total Weight = Total Weight of Stream #1 - Total Weight of Stream #2  
= 734 tons/day - 151 tons/day  
= 583 tons/day  
Total Volume = Total volume of Stream #1 - Total Volume of Stream #2  
= 483 yd<sup>3</sup>/day

$$\begin{aligned} \% \text{ Solids (by weight)} &= \text{weight of dry solids/total weight of Steam \#3} \\ &= (294 \text{ tons/day})/(582 \text{ tons/day}) \\ &= 50\% \end{aligned}$$

#### **Stream 4 - +4 inch Material Removed During Coarse Separation**

---

$$\begin{aligned} \text{Total Weight} &= \text{Total Volume of Steam \#4 * density of solids (tons/yd}^3\text{)} \\ &= 23 \text{ yd}^3/\text{day} * 2.15 \text{ tons/yd}^3 \\ &= 50 \text{ tons/day} \end{aligned}$$

$$\begin{aligned} \text{Total Volume} &= \text{Total volume of Steam \#3 * 5\%} \\ &= 462 \text{ yd}^3/\text{day} * (5/100) \\ &= 23 \text{ yd}^3/\text{day} \end{aligned}$$

$$\begin{aligned} \% \text{ Solids (by weight)} &= \text{total weight of Stream \#4 * \% Solids Stream \#4} \\ &= [(50 \text{ tons/day}) * (98/100)]/50 \\ &= 98\% \end{aligned}$$

#### **Stream 5 - Material Transferred to Pugmill**

---

$$\begin{aligned} \text{Total Volume} &= \text{Total Volume of Steam \#3 - Total Volume Stream \#4} \\ &= 483 \text{ yd}^3/\text{day} - 23 \text{ yd}^3/\text{day} \\ &= 460 \text{ yd}^3/\text{day} \end{aligned}$$

$$\begin{aligned} \text{Total Weight} &= \text{Total Weight Stream \#3 - Total Weight Stream \#4} \\ &= 583 \text{ tons/day} - 50 \text{ tons/day} \\ &= 533 \text{ tons/day} \end{aligned}$$

$$\begin{aligned} \text{Weight of dry solids} &= \text{weight of dry solids Stream \#1A - Weight of dry solids Stream \#4} \\ &= 294 \text{ tons/day} - (50 \text{ tons/day} * (98/100)) \\ &= 245 \text{ tons/day} \end{aligned}$$

$$\begin{aligned} \% \text{ Solids (by weight)} &= \text{total weight of dry solids Stream \#5/total weight of Stream \#5} \\ &= (245 \text{ tons/day})/(533 \text{ tons/day}) \\ &= 46\% \end{aligned}$$

#### **Stream 6 - Portland Cement**

---

$$\begin{aligned} \text{Total Weight} &= \text{Total Weight Stream \#5 * 10\%} \\ &= 533 \text{ tons/day} * (10/100) \\ &= 53 \text{ tons/day} \end{aligned}$$

$$\text{Total Weight Dry Solids} = \text{Total Weight Stream \#6} = 53 \text{ tons/day}$$

$$\begin{aligned} \text{Total Volume} &= \text{Total Weight/density of portland cement (1.269tons/yd}^3\text{)} \\ &= 42 \text{ yd}^3/\text{day} \end{aligned}$$

#### **Stream 7 - Stabilized Material**

---

$$\begin{aligned} \text{Total Weight} &= \text{Total Weight Stream \#5 + Total Weight of Stream \#6} \\ &= 533 \text{ tons/day} + 53 \text{ tons/day} \\ &= 587 \text{ tons/day} \end{aligned}$$

$$\begin{aligned} \text{Total Weight Dry Solids} &= \text{Weight of Dry Solids Stream \#5 + Total Weight Stream \#6} \\ &= 245 \text{ tons/day} + 53 \text{ Tons/day} \\ &= 299 \text{ tons/day} \end{aligned}$$

$$\begin{aligned} \text{Total Volume} &= \text{Total Volume Stream \#5 + Total Volume Stream \#6} \\ &= 460 \text{ yd}^3/\text{day} + 42 \text{ yd}^3/\text{day} \\ &= 502 \text{ yd}^3/\text{day} \end{aligned}$$



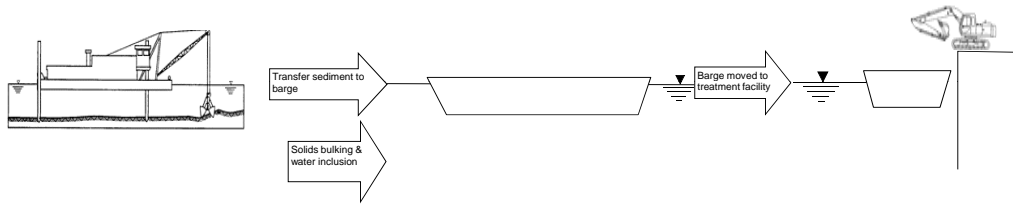
**MECHANICAL CLAMSHELL DREDGE, 5 CU YD ENVIRONMENTAL BUCKET, 250 CU YD SCOW, 12 hrs/day**

In-Situ Sediment Properties	
Solids Content (% by weight: $X_s$ ) =	52
Specific Gravity Sediment ( $SG_s$ ) =	2.5
Volume of Solids ( $V_s$ ) =	0.3023 ft <sup>3</sup>
Volume of water ( $V_w$ ) =	0.6977 ft <sup>3</sup>
Weight of Solids ( $W_s$ ) =	47.14 lbs/ft <sup>3</sup>
Weight of Water ( $W_w$ ) =	43.51 lbs/ft <sup>3</sup>
Weight of Sediment ( $W_T$ ) =	90.66 lbs/ft <sup>3</sup>
=	1.22 tons/ft <sup>3</sup>
Sediment Bulking Factor	1.15

Water Properties	
Specific Gravity ( $SG_w$ ) =	1.0
Density of water @ 60 F ( $\rho_{620}$ ) =	62.371 lbs/ft <sup>3</sup>
	8.3378 lbs/gallon
	7.4805 gallon/ft <sup>3</sup>

Dredging Bucket Size	yd <sup>3</sup>	5.0
Excess Water per Bucket Grab	%	31%
Bucket Cycle Time	min	2.5
Buckets per hour	per hr	24
Barge Volume	yd <sup>3</sup>	250
Dredge Movement/Barge Changeover time	hr	0.33
% Excess Water to be Pumped Out of Barge	%	90%
Available Dredging Hours Per Day	hrs/day	10
Dredging Days Per Week	days/week	6
Dredge Uptime Average	%	65%
Normal Working Day	hrs/day	24
Normal Working Week	days/week	6
Number of Dredges	each	1

68.72%



Equation				
	Total volume in barge	yd <sup>3</sup>	250	
1	Buckets per barge	buckets	50	
2	Hours to fill barge (water + sediment)	hr	2.1	
	Hours to place second barge	hr	0.33	
3	Total Hours for barge loading and transfer	hr	2.4	
4	Excess Water	yd <sup>3</sup> /hr	38	
5	In situ Sediment+ pore water	yd <sup>3</sup> /hr	82	
6	Total In situ sediment plus pore water in barge	yd <sup>3</sup>	172	
7	Total water volume in barge	yd <sup>3</sup>	78	15,794 gal/barge
8	Average In-situ Sediment plus pore water volume transfer to shore	In-situ yd <sup>3</sup> /hr	46	
		tons/hr	57	
9	Daily water transfer to shore	yd <sup>3</sup> /day	200	40,357 gal/day

Daily Production Rates			
10	Average In situ Sediment Transfer per day	yd <sup>3</sup> /day	462
		tons/day	566
Weekly Production Rates			
	Average In situ Sediment Dredging	yd <sup>3</sup> /week	2,772
		tons/week	3,393



**CONVERSION CALCULATOR**

[Conversion Calculator](#)

In the construction aggregates industry, it is often necessary to convert between cubic yards and tons of a given resource. This can be a difficult process since cubic yards is a volumetric measurement while tons is a weight measurement. There is no definite standard for converting between cubic yards and tons. In fact, the conversion factor can vary greatly based on the type and density of material involved. The conversion factors for construction aggregate materials, both raw and recycled, can vary from \_\_\_ tons per cubic yard to \_\_\_ tons per cubic yard. If you know the density of the material in question, it is possible to calculate the conversion factor of tons to cubic yards. If you know the density in pound per cubic foot, multiply that density by 0.0135 (27/2000) to determine tons per cubic yard.

Material	Conversion Factor (Tons per Cubic Yard)
Ashes - wet (low)	0.6152
Ashes - wet (high)	0.7500
Ashes - dry (low)	0.4803
Ashes - dry (high)	0.5478
Asphalt, crushed	0.6076
Cement - clinker (low)	1.0871
Cement - clinker (high)	1.2978
Cement, Portland	1.2691
Cement, mortar	1.8219
Cement, slurry	1.2152
Cinders, furnace	0.7694
Cinders, Coal, ash	0.5402
Clay, dry excavated	0.9177
Clay, wet excavated	1.5388
Clay, dry lump	0.9042
Clay, fire	1.1478
Clay, wet lump	1.3500
Clay, compacted	1.4713
Coal, Anthracite, solid	1.2691
Coal, Anthracite, broken	0.9312
Coal, Bituminous, solid	1.1343
Coal, Bituminous, broken	0.7020
Coke (low)	0.4803
Coke (high)	0.5478
Concrete, Asphalt	1.8902
Concrete, Gravel	2.0250
Concrete, Lime stone with Portland	1.9980
Dolomite, solid	2.4430
Dolomite, pulverized	0.6211
Dolomite, lumpy	1.2826
Earth, <u>loam</u> , dry, excavated	1.0525
Earth, moist, excavated	1.2152
Earth, wet, excavated	1.3500
Earth, dense	1.6871
Earth, soft loose mud	1.4579
Earth, packed	1.2826
Earth, Fullers, raw	0.5671
Gneiss, bed in place	2.4160
Gneiss, broken	1.5657
Granite, solid	2.2677
Granite, broken	1.3904
Gravel, loose, dry	1.2826
Gravel, with sand, natural	1.6197
Gravel, dry 1/4 to 2 inch	1.4174
Gravel, wet 1/4 to 2 inch	1.6871
Gypsum, solid	2.3486
Gypsum, broken (low)	1.0871
Gypsum, broken (high)	1.3483
Gypsum, crushed	1.3500
Gypsum, pulverized	0.9447
Limestone, solid	2.2003
Limestone, broken	1.3096
Limestone, pulverized	1.1747



Project Name/Title:	Lower Passaic River, RM 10.9 Removal Action	Project Number:	436870
Document Name:	RM 10.9 Removal Action Basis of Design Report	Preparer Name:	Phil Gaebler
Project Manager:	Roger McCready	Design Manager:	James Brinkman

Calculation Title:		Estimated Sediment Resuspension			
Calculation Identifier:					
Date Prepared	Rev. No.	Preparer Signature/Date	Checker Signature/Date	For Professional Seal When Required	
11/21/2012	0	<i>Phil Gaebler</i> 11/21/2012	<i>[Signature]</i> 11/21/12		
2/23/2013	1	<i>Phil Gaebler</i> 2/23/2013	<i>[Signature]</i> 2/23/13		
STC/SME Signature/Date					
LTR Signature/Date (if required)					
Comments:					
The following worksheets are included:					
- Introduction					
- Input Data					
- Diffusion Data					
- Dry Density Data					
- Stokes Law Data					
- Scenario A (Avg Flow of 600) - 0.5% Resuspension, Settling assuming all particles 1 um					
- Scenario A - 0.5% Resuspension, Settling, assuming all particles 50 um					
- Scenario A - 0.5% Resuspension, Difference between 1 um & 50 um Settling					
- Scenario A - 1.0% Resuspension, Settling assuming all particles 1 um					
- Scenario A - 1.0% Resuspension, Settling, assuming all particles 50 um					
- Scenario A - 1.0% Resuspension, Difference between 1 um & 50 um Settling					
- Scenario B (Year Max Flow of 6,000 cfs) - 0.5% Resuspension, Settling assuming all particles 1 um					
- Scenario B - 0.5% Resuspension, Settling, assuming all particles 50 um					
- Scenario B - 0.5% Resuspension, Difference between 1 um & 50 um Settling					
- Scenario B - 1.0% Resuspension, Settling assuming all particles 1 um					
- Scenario B - 1.0% Resuspension, Settling, assuming all particles 50 um					
- Scenario B - 1.0% Resuspension, Difference between 1 um & 50 um Settling					
- Changes: Avg Flow rate revised to 0.47 m/s and 1 year maximum flow revised to 0.89 m/s based on maxium predicted river velocity					
Information Requiring Confirmation:					

Lower Passaic River, RM 10.9 Removal Action

PN#: 436870

Calculation Title: Estimated Sediment Resuspension

Rev: 1

Date: 02/23/13

#### LPR RM 10.9 Sediment Plume Calcs

Date 2232013

Created by PDG

Description This spreadsheet calculate the deposited sediment by subtracting Dredge model outputs. A plume that has no settling is subtracted from a plume that has settling. The difference between the two plumes is assumed to have settled.

The A series results used the Average Month flows for Months July to Oct

The B Series results used the Max 1 year flows and depths.

Detailed results are in the A nd B 5pct\_Differ and 1PCT\_Differ

Lower Passaic River, RM 10.9 Removal Action

PN#: 436870

Calculation Title: Estimated Sediment Resuspension

Rev: 1

Date: 02/23/13

A			B		
Low flow conditions			1 Year Max flow conditions		
flow	600		flow	6000	
Average Velocity	0.47 m/s		Average Velocity	0.89 m/s	
Production Rate	86 yd <sup>3</sup> /hr		Production Rate	86 yd <sup>3</sup> /hr	
Bucket size	5 yd <sup>3</sup>	3.822774 m <sup>3</sup>	Bucket size	5 yd <sup>3</sup>	3.822774
cycles per hour	17.2 cycles		cycles per hour	17.2 cycles	
seconds per cycle	150 seconds		seconds per cycle	150 seconds	
total removed	18000 yd <sup>3</sup>		total removed	18000 yd <sup>3</sup>	
Loss rate	0.50%		Loss rate	0.50%	
Loss rate	1%		Loss rate	1%	
Depth	1.4 meters		Depth	1.8 meters	
Settling Particle	50.00 microns		Settling Particle	50.00 microns	
Diffusion Rate	98.44 cm <sup>2</sup> /sec		Diffusion Rate	143.51 cm <sup>2</sup> /sec	
% less than 74 microns	0.54		% less than 74 microns	0.54	

Lower Passaic River, RM 10.9 Removal Action  
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Flow from DNR  
 At cross section 0.97  
 Diffusion Coefficients

	Average	1yr max
S=	0.001	0.001
D=	1.4	1.8
g=	9.81	9.81
u*	0.11719215	0.13288341
Dy	0.098441406	0.14351408
Dy	98.44	143.51

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Sediment Properties

%solids by dry wt	Unit Wt	Gs solids	% solids by vol	% water by vol	%water by wt	w=Ww/Ws %	Void Ratio	Porosity	solids Con C g/l	WET	WET	WET	DRY	DRY	DRY	Vs = 1.0 cu ft				
	lbs/ft3						e	n		unit wt lbs/ft3	unit wt tons/cy	unit wt kg/m3	unit wt lbs/ft3	unit wt tons/cy	unit wt kg/m3	Ws	Ww	Vw	Wt	Vt
52.00	62.40	2.50	30.23	69.77	48.00	92.31	2.31	0.70	755.40	90.70	1.224	1452.98	47.16	0.64	755.55	156.00	144.00	2.31	300.00	3.31



Lower Passaic River, RM 10.9 Removal Action

PN#: 436870

Calculation Title: Estimated Sediment Resuspension

Rev: 1

Date: 02/23/13

Stokes law

$$V_t = g \cdot d^2 \cdot (\rho_s - \rho_m) / 18 \mu$$

Gravity (g)

9.81 m/s<sup>2</sup>

Diameter (d)

50 microns

density of particle ( $\rho_s$ )

2500 kg/M<sup>3</sup>

density of water ( $\rho_m$ )

1000 kg/M<sup>3</sup>

Viscosity of water ( $\mu$ )

0.001003 kg/meter-second

$V_t =$

0.002037637 m/sec























Dredge Type : Open Clamshell  
 Near-Field Model : User Input  
 Far-Field Model : Kuo's Model  
 Resuspended Material Selected : TSS

	200	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400	2600	2800	3000	3200	3400	3600	3800	4000	4200	4400	4600	4800	5000	5200	5400	5600	5800	6000	6200	6400	6600	6800	7000	7200	7400	7600	7800	8000	8200	8400	8600	8800	9000	9200	9400	9600	9800	10000								
-200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0						
-180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
-160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			
-140	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
-120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
-100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
-80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
-60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
-40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-20	0	0	0	0	0.002	0.006	0.012	0.019	0.024	0.028	0.029	0.029	0.028	0.026	0.023	0.021	0.018	0.016	0.013	0.011	0.009	0.008	0.007	0.005	0.004	0.004	0.003	0.002	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001			
0	14.985	8.427	5.471	3.768	2.68	1.946	1.432	1.066	0.799	0.603	0.457	0.348	0.266	0.204	0.157	0.121	0.093	0.072	0.056	0.043	0.033	0.026	0.02	0.016	0.012	0.01	0.007	0.006	0.005	0.004	0.003	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001					
20	0	0	0	0.002	0.006	0.012	0.019	0.024	0.028	0.029	0.029	0.028	0.026	0.023	0.021	0.018	0.016	0.013	0.011	0.009	0.008	0.007	0.005	0.004	0.004	0.003	0.002	0.002	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001				
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
140	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



Excerpt from *Lower Fox River Operable Unit 1 2009 Remedial Action Summary* (Foth et al. April 2010):

#### 7.4 Statistical Analysis of Engineered Cap Thickness Data

Post-placement measurements of the engineered cap were taken to demonstrate achievement of the applied material specifications. The verification sampling was performed to provide statistical confidence that specifications have been met. Minimum placement thickness in cap areas is 3 inches for the sand layer and 4 inches for the armor stone layer. Statistical methods were developed to verify minimum placement thickness has been achieved in these areas.

Specifications will have been obtained when the following criteria are demonstrated:

- ◆ The applied design thickness is met or exceeded throughout at least 80% of the CCU.
- ◆ The probability of applied design thickness being met in less than 80% of the CCU is no more than 10%.

Data used in demonstrating the achievement of thickness specifications (i.e., applied thickness) for sand were collected using a VPC. In the case of armor stone, a sediment trap was used.

##### **Method 1 – Primary Measurement Data Only**

Minimum thickness coverage of at least 80% of a CCU will be demonstrated with nonparametric lower confidence limits on a proportion. This method evaluates the observed proportion of verification samples exceeding the minimum thickness within a CCU. For example, the concept is to give statistical confidence that the true proportion (if measurements were taken at all possible locations) is at least 0.8. An example using a minimum 4-inch thickness specification is illustrated as follows:

Example of 25 Thickness Measurements (inches)				
8.5	9.6	5.2	3.8	7.2
10.4	7.2	5.5	6.4	9.9
7.2	4.3	8.0	8.1	6.0
5.2	9.8	8.0	10.0	8.3
7.5	7.6	8.5	7.0	6.9

24 Measurements  $\geq$  4 inches in Thickness  
 1 Measurement  $<$  4 inches in Thickness

Proportion  $\geq$  4 inches is  $24/25 = 0.96$   
 90% Lower Confidence Limit = 0.85

In the above example, the proportion of measurements greater than or equal to 4 inches in thickness is 0.96. A nonparametric lower 90% confidence limit on this observed proportion is 0.85. In this example, the probability of a minimum 4-inch thickness being met in less than 85% of the unit is no more than 10%. If this example represents a CCU with a minimum armor stone placement thickness requirement of 4 inches, the design criteria is attained. To provide statistical confidence that the minimum thickness is met or exceeded throughout at least 80% of the CCU, the lower 90% confidence limit is required to be at least 0.80.

In practice, the necessary number of samples needed to demonstrate coverage specifications can be calculated ahead of time for given sample sizes. To demonstrate 80% coverage with the above specified statistical confidence, the following steps are taken.

1. Collect  $n$  sample thickness measurements within CCU.
2. Determine  $x$ , the number of sediment trap samples exceeding the minimum thickness specification.
3. Find the row corresponding to  $n$  in Table 7-10 and compare  $x$  to the number found in the second column. If  $x$  is equal to or greater than the Table 7-10 value, minimum thickness specifications for that unit will have been met.



Table 7-10

Number of Samples Needed to Document Attainment of Minimum Thickness Requirement per CCU

(Based on Nonparametric 90% Confidence Limits)

Number of Samples Collected (n)	Number of Samples Needed to Exceed Minimum Thickness (x)	Number of Samples Collected (n)	Number of Samples Needed to Exceed Minimum Thickness (x)
11	11	21	20
12	12	22	21
13	13	23	22
14	14	24	23
15	15	25	23
16	16	26	24
17	17	27	25
18	17	28	26
19	18	29	27
20	19	30	28

Prepared by: MCC2  
Checked by: TAG

A minimum number of 11 samples are required per CCU to illustrate 80% coverage with 90% certainty. For sample sizes n between 11 and 30, x is found by solving the cumulative binomial distribution:

$$\sum_{k=0}^{x-1} \binom{n}{k} 0.8^k (1-0.8)^{n-k} \geq 0.9$$

### Cap Model Summary and Results: PCB-52

Selected System Properties	Values	References
Pore water concentration, µg/L	13.85	Site specific average
Darcy velocity, cm/yr	314	Site specific average
Dissolved organic matter concentration, mg/L	95	Site specific average
Deposition velocity, cm/yr	0	Conservative Assumption as deposited sediment layer adds thickness to the cap that can contribute to contaminant attenuation over time
Total consolidation, cm	23	Calculated value
Time to 90% consolidation, yr	1	Calculated value

**Active Layer Details:** Mixture of 25% (v/v) AquaGate+PAC™ (with 10% AC) and 75% (v/v) sand

Cap Layers Properties	Active Layer (Activated Carbon/ Sand Mixture)	Underlying Native Sediment
Thickness (cm)	25.4 (10 inches)	NA
Active Material	Activated Carbon (AquaGate+PAC™)	Native Sediment
Bulk density (g/cm <sup>3</sup> )	0.026 (bulk density of activated carbon fraction in mixture)	1.6
Porosity (weighted average of mixture) <sup>1</sup>	0.363	0.65
Sorption Isotherm	Freundlich	Linear-K <sub>oc</sub> f <sub>oc</sub>
Activated Carbon Freundlich K <sub>f</sub> coefficient <sup>2</sup>	8.13E+06	NA
Activated Carbon Freundlich N coefficient <sup>2</sup>	1.03	NA
Organic carbon fraction <sup>3</sup> (foc)	NA	0.056

Notes:

NA = Not applicable

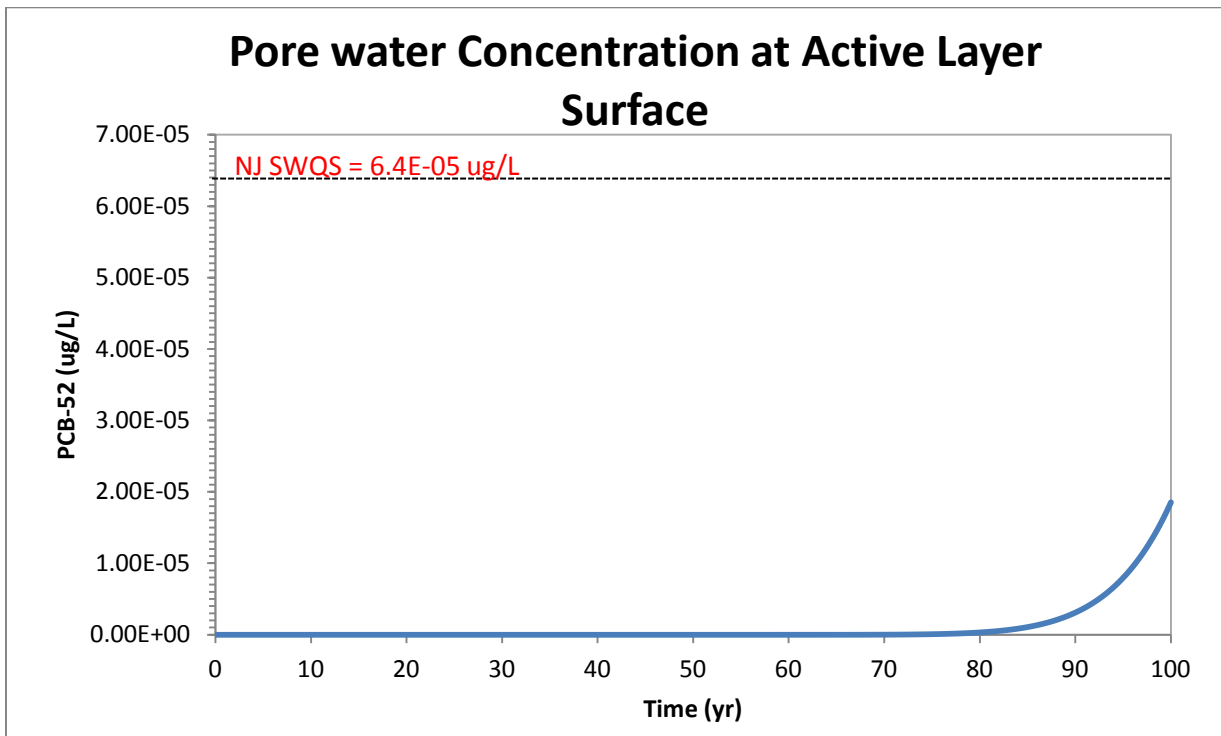
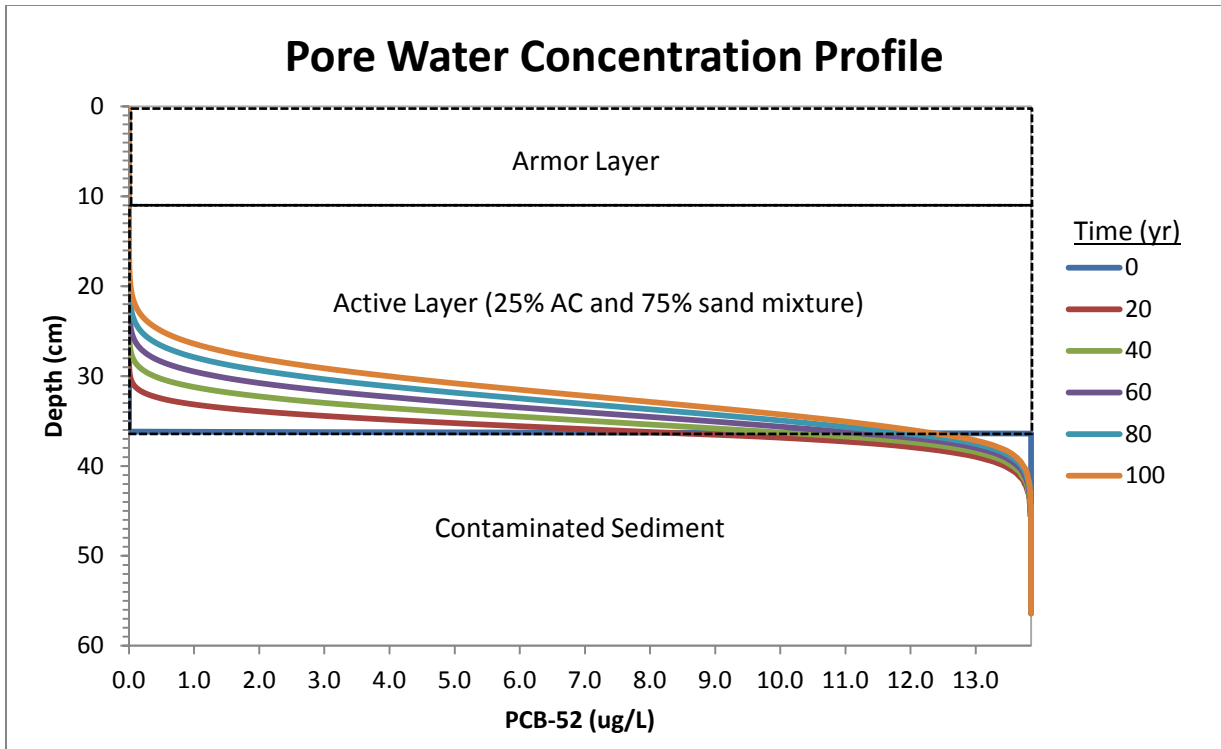
<sup>1</sup> US Department of Energy (2009). PNNL-18801, September, p. 2.1.

<sup>2</sup> McDonough et al., 2008. Water Research, 42, p 575-584.

<sup>3</sup> Site specific average value for the 2.5'-3.5' bgs sediment interval.

**Breakthrough Criteria:** New Jersey Surface Water Quality Standards (NJSWQS). NJAC 7:9B Fresh Water (FW2) Criteria for Human Health.

NJ SWQS criterion for total PCBs =  $6.4 \times 10^{-5}$  µg/L



### Cap Model Summary and Results: Phenanthrene

Selected System Properties	Values	References
Pore water concentration, µg/L	1.298	Site specific average
Darcy velocity, cm/yr	314	Site specific average
Dissolved organic matter concentration, mg/L	95	Site specific average
Deposition velocity, cm/yr	0	Conservative Assumption as deposited sediment layer adds thickness to the cap that can contribute to contaminant attenuation over time
Total consolidation, cm	23	Calculated value
Time to 90% consolidation, yr	1	Calculated value

**Active Layer Details:** Mixture of 25% (v/v) AquaGate+PAC™ (with 10% AC) and 75% (v/v) sand

Cap Layers Properties	Active Layer (Activated Carbon/ Sand Mixture)	Underlying Native Sediment
Thickness (cm)	25.4 (10 inches)	NA
Active Material	Activated Carbon (AquaGate+PAC™)	Native Sediment
Bulk density (g/cm <sup>3</sup> )	0.026 (bulk density of activated carbon fraction in mixture)	1.6
Porosity (weighted average of mixture) <sup>1</sup>	0.363	0.65
Sorption Isotherm	Freundlich	Linear-K <sub>oc</sub> f <sub>oc</sub>
Activated Carbon Freundlich K <sub>f</sub> coefficient <sup>2</sup>	1.65E+06	NA
Activated Carbon Freundlich N coefficient <sup>2</sup>	0.41	NA
Organic carbon fraction <sup>3</sup> (foc)	NA	0.056

Notes:

NA = Not applicable

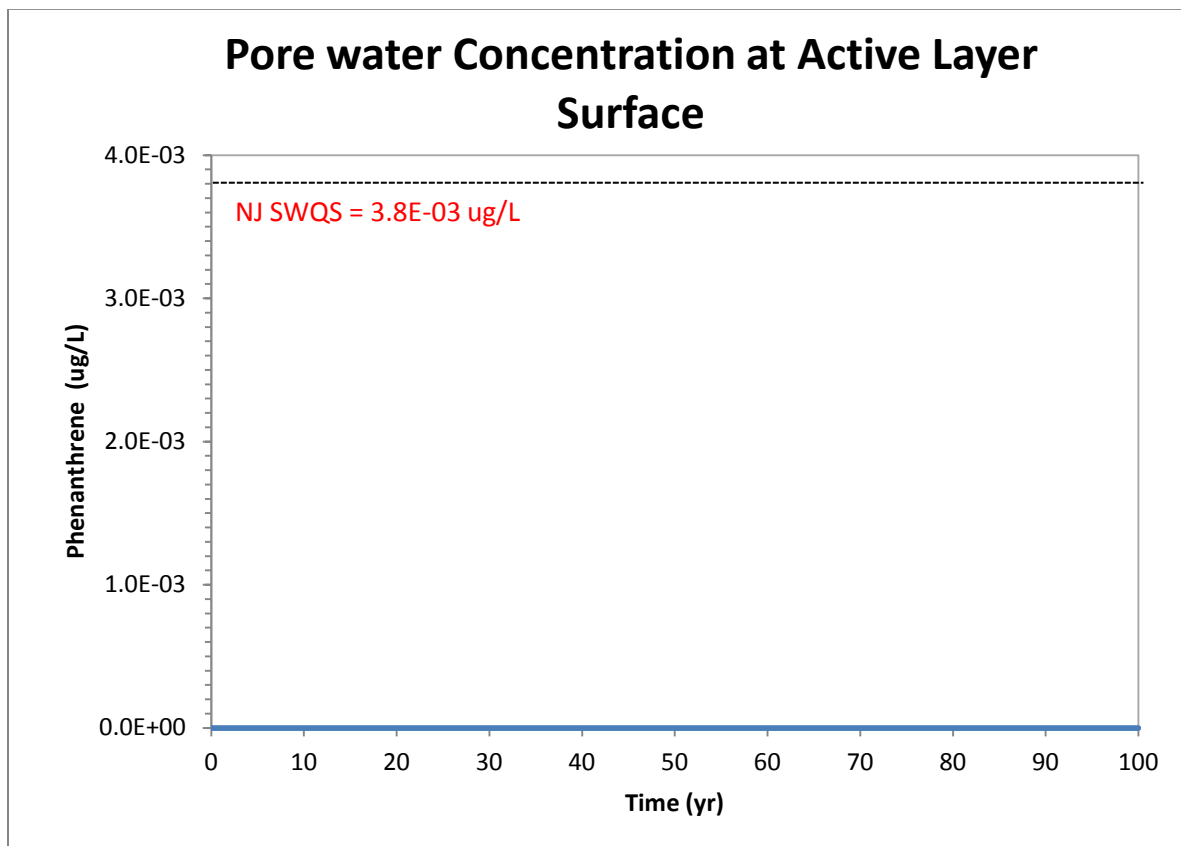
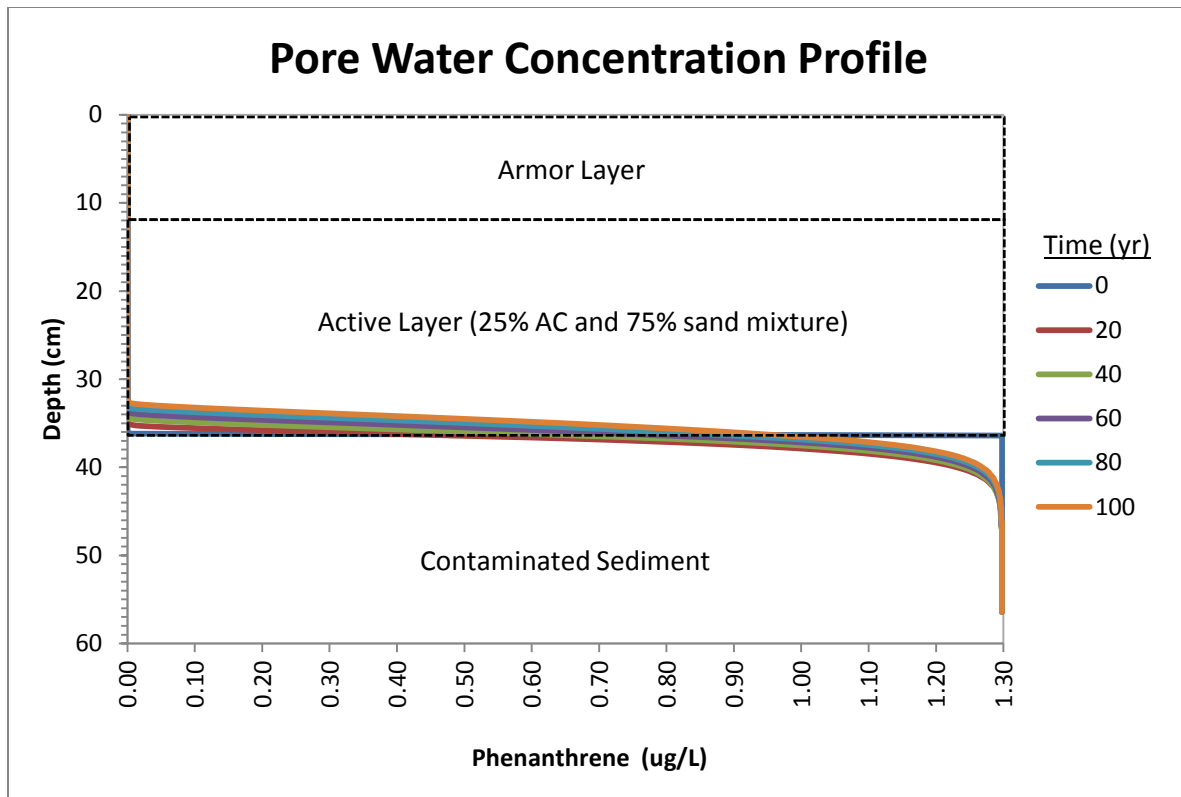
<sup>1</sup> US Department of Energy (2009). PNNL-18801, September, p. 2.1.

<sup>2</sup> Walters & Luthy, 1984. ES&T, Vol.18, No.6, p 395-403.

<sup>3</sup> Site specific average value for the 2.5'-3.5' bgs sediment interval.

**Breakthrough Criteria:** New Jersey Surface Water Quality Standards (NJSWQS). NJAC 7:9B Fresh Water (FW2) Criteria for Human Health.

NJ SWQS criterion for Phenanthrene =  $3.8 \times 10^{-3}$  µg/L (No NJSWQS available for phenanthrene, therefore value for benzo(a)pyrene was used)



### Cap Model Summary and Results: 2,3,7,8-TCDD

Selected System Properties	Values	References
Pore water concentration, µg/L	0.00458	Site specific average
Darcy velocity, cm/yr	314	Site specific average
Dissolved organic matter concentration, mg/L	95	Site specific average
Deposition velocity, cm/yr	0	Conservative Assumption as deposited sediment layer adds thickness to the cap that can contribute to contaminant attenuation over time
Total consolidation, cm	23	Calculated value
Time to 90% consolidation, yr	1	Calculated value

**Active Layer Details:** Mixture of 25% (v/v) AquaGate+PAC™ (with 10% AC) and 75% (v/v) sand

Cap Layers Properties	Active Layer (Activated Carbon/ Sand Mixture)	Underlying Native Sediment
Thickness (cm)	25.4 (10 inches)	NA
Active Material	Activated Carbon (AquaGate+PAC™)	Native Sediment
Bulk density (g/cm <sup>3</sup> )	0.026 (bulk density of activated carbon fraction in mixture)	1.6
Porosity (weighted average of mixture) <sup>1</sup>	0.363	0.65
Sorption Isotherm	Freundlich	Linear-K <sub>oc</sub> f <sub>oc</sub>
Activated Carbon Freundlich K <sub>f</sub> coefficient <sup>2</sup>	5.89E+07	NA
Activated Carbon Freundlich N coefficient <sup>2</sup>	0.94	NA
Organic carbon fraction <sup>3</sup> (foc)	NA	0.056

Notes:

NA = Not applicable

<sup>1</sup> US Department of Energy (2009). PNNL-18801, September, p. 2.1.

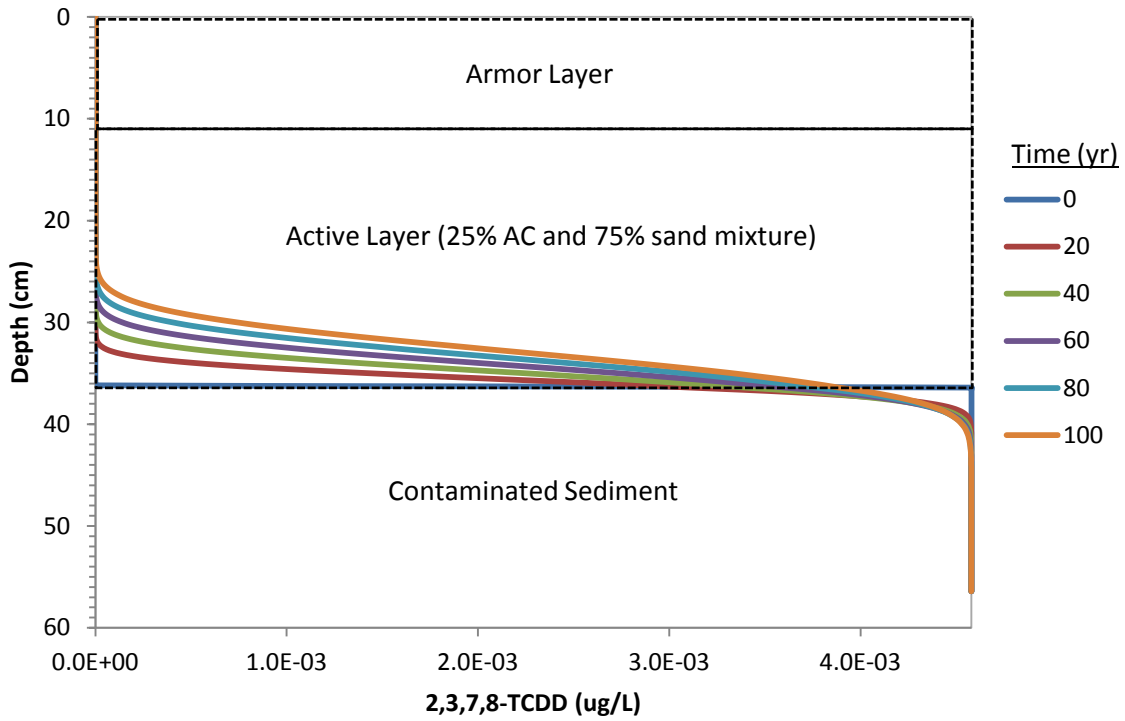
<sup>2</sup> Freundlich Coefficients for PCB-126 were used to conservatively estimate 2,3,7,8-TCDD adsorption onto activated carbon as recommended by Dr. Ghosh. The PCB-126 congener was selected for this purpose because its octanol water partition coefficient is similar to that of 2,3,7,8-TCDD. Source for Freundlich coefficient: McDonough et al., 2008. Water Research, 42, p 575-584.

<sup>3</sup> Site specific average value for the 2.5'-3.5' bgs sediment interval.

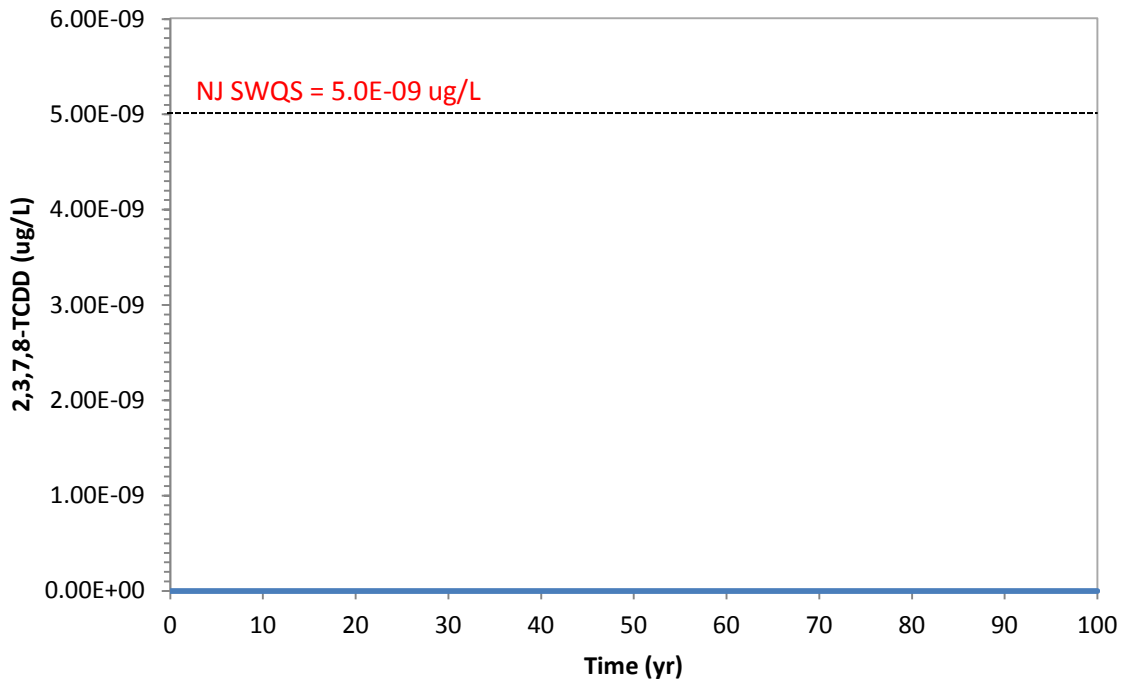
**Breakthrough Criteria:** New Jersey Surface Water Quality Standards (NJSWQS). NJAC 7:9B Fresh Water (FW2) Criteria for Human Health.

NJ SWQS criterion for 2,3,7,8-TCDD = 5 x 10<sup>-9</sup> µg/L

## Pore Water Concentration Profile



## Pore water Concentration at Active Layer Surface





### Cap Model Summary and Results: Mercury

Selected System Properties	Values	References
Pore water concentration, µg/L	0.00196	Site specific average
Darcy velocity, cm/yr	314	Site specific average
Dissolved organic matter concentration, mg/L	95	Site specific average
Deposition velocity, cm/yr	0	Conservative Assumption as deposited sediment layer adds thickness to the cap that can contribute to contaminant attenuation over time
Total consolidation, cm	23	Calculated value
Time to 90% consolidation, yr	1	Calculated value

**Active Layer Details:** Mixture of 25% (v/v) AquaGate+PAC™ (with 10% AC) and 75% (v/v) sand

Cap Layers Properties	Active Layer (Activated Carbon/ Sand Mixture)	Underlying Native Sediment
Thickness (cm)	25.4 (10 inches)	NA
Active Material	Activated Carbon (AquaGate+PAC™)	Native Sediment
Bulk density (g/cm <sup>3</sup> )	0.026 (bulk density of activated carbon fraction in mixture)	1.6
Porosity (weighted average of mixture) <sup>1</sup>	0.363	0.65
Sorption Isotherm	Linear K <sub>d</sub> specified	Linear-K <sub>oc</sub> f <sub>oc</sub>
Activated Carbon-water partition coefficient <sup>2</sup>	4.0E+06	NA
Organic carbon fraction <sup>3</sup>	NA	0.056

Notes:

NA = Not applicable

<sup>1</sup> US Department of Energy (2009). PNNL-18801, September, p. 2.1.

<sup>2</sup> Activated Carbon-water partition coefficient = K<sub>AC</sub> range (4.0E+06 – 2.0E+07) provided by Dr. Upal Ghosh.

<sup>3</sup> Site specific average value for the 2.5'-3.5' bgs sediment interval.

**Breakthrough Criteria:** New Jersey Surface Water Quality Standards (NJSWQS). NJAC 7:9B Fresh Water (FW2) Criteria for Human Health.

NJ SWQS criterion for Mercury =  $5 \times 10^{-2}$  µg/L



*Memorandum*

10300 Indigo Broom Loop  
Austin, TX 78733

*From:* Danny D. Reible, PhD, PE



*Date:* June 2, 2013

*To:* Bhawana Sharma, CH2M-Hill

*Re:* *Cap Design – Lower Passic River*

I have conducted a review of the cap design prepared by CH2M-Hill for the southern shore near RM 10.9 on the Lower Passiac River (LPR). Materials reviewed included the following.

- Section 7 Capping of a Remedial Action Draft Final Design Report
- Draft Data Report of the LPR Seepage Survey, April 2013
- Summary concentration data from the area to be capped
- Belleville Tide Charts for 2013
- Various cap model (CapSim) outputs, summaries and sensitivity analyses

The proposed cap design involves placement of a cap layer of 10 inch minimum average thickness containing activated carbon in an Aquagate<sup>®</sup> formulation. Overlying this layer will be an armoring layer with a minimum average thickness of 12 inches. Additional material may need to be placed to meet these design thicknesses due to intermixing with the underlying sediment. A typical intermixing depth is 1-2 inches. The Aquagate<sup>®</sup> contains 10 % activated carbon and will be mixed in a 30% Aquagate<sup>®</sup>/70% sand mixture. Monitoring will be required to ensure that the Aquagate<sup>®</sup> is mixed effectively with the sand as placed although the relatively small density difference between the two materials should aid placement.

The design was assessed using the model CapSim (developed by the Reible research group and building upon models employed since the mid-1980's for cap design). The model was used to predict the porewater concentration at the top of the Aquagate<sup>®</sup> chemical isolation layer (i.e. below the armoring layer) and ensure that it would not exceed surface water quality criteria for at least 100 years. Dioxin, PCBs, PAHs and mercury migration were simulated. A relatively mobile PCB (congener 52) was used to conservatively simulate PCB migration and relatively mobile PAH (phenanthrene) was used to conservatively simulate PAH migration. The model simulations indicated a cap performance that was well in excess of the specified performance criteria. A review of the model evaluations indicated that the model was being used properly and using input parameters that are consistent with cap designs used elsewhere. A number of conservatisms were also appropriately incorporated in the model evaluations to reflect uncertainty.

- Porewater concentrations were estimated from the most highly contaminated areas to be capped (primarily east of a water line utility near the middle of the area to be capped) providing an overestimate of average porewater concentration.
- Porewater concentrations were estimated from total unfiltered concentrations from porewater generated by centrifugation for hydrophobic organic compounds and filtered porewater for

mercury. Unfiltered samples are expected to contain more colloiddally bound and natural organic matter bound contaminants than are likely to migrate through a sediment cap. The processing of sediment to generate porewater also tends to increase the colloidal material and contaminant concentration in the generated porewater compared to passive sampling techniques. Thus this method of generating porewater will also lead to overestimates of porewater concentration migrating into and through a cap.

- Sorption onto activated carbon in the chemical isolation layer of the cap was estimated from lower confidence limits of sorption measurements on organic matter loaded activated carbon from McDonough et al.(2008)<sup>1</sup>. This provides reasonable estimates of the reduction in performance expected from natural organic matter loading and is approximately an order of magnitude less than measured in virgin activated carbon.
- Average groundwater upwelling was estimated from the average of site-specific measurements. Significant upwelling was only observed west of a water utility corridor, in regions of generally lower sediment contamination concentration that used to estimate the migrating porewater concentration. Thus the use of the average upwelling rate and the higher porewater concentration is a conservative design. The sensitivity to the highest measured upwelling rate was also assessed and indicated that porewater concentrations at the top of the chemical isolation layer, even using the biased high estimates of porewater concentration in the underlying sediment, will not exceed surface water quality criteria for at least 180 years.
- Armoring design was appropriately based upon low frequency return flows, i.e. 100 year return flows.
- Due to the potentially large difference in particle grain size between the chemical isolation and armoring layer, filtering layers or a separating geotextile would be required. In this case, a separating geotextile was included in the design.

The use of the conservative design basis builds confidence that the proposed cap, if constructed as designed, will exceed the cap's 100 year performance criteria.

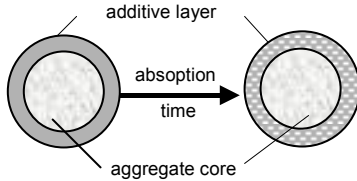
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<sup>1</sup> McDonough, K.M., Fairey, J.L., and Lowry, G.V. 2008. Adsorption of Polychlorinated Biphenyls to Activated Carbon: Equilibrium Isotherms and a Preliminary Assessment of the Effects of Dissolved Organic Matter and Biofilm Loadings. *Water Research*, 42, 575-584.

# AquaGate+PAC™

## Background

AquaGate+PAC (Powdered Activated Carbon) is a patented, composite-aggregate technology resembling small stones typically comprised of a dense aggregate core, clay or clay-sized materials, polymers, and fine-grained activated carbon additives.



**Figure 1. Configuration of PAC-coated particle.**

AquaGate+PAC serves as a delivery mechanism to reliably place reactive capping materials into aquatic environments.




---

## Product Specifications

Aggregate:	Nominal AASHTO #8 (1/4-3/8") or custom-sized to meet project-specific needs * Limestone or non-calcareous substitute, as deemed project-appropriate
Clay:	Bentonite (or montmorillonite derivative) * Typically 15% by weight
Activated Carbon:	Powdered – Iodine Number 800 mg/g (minimum) <ul style="list-style-type: none"> <li>o 99% (minimum) through 100 mesh sieve</li> <li>o 95% (minimum) through 200 mesh sieve</li> <li>o 90% (minimum) through 325 mesh sieve</li> </ul> * Target 10% by weight - Range of 7.5 – 12.5% by weight
Binder:	Cellulosic polymer
Permeability:	$1 \times 10^{-4}$ to $1 \times 10^{-7}$ cm/sec (Variations will exist and permeability can be influenced by particle size distribution, placement, and cover materials – surcharge load)
Dry Bulk Density:	60 – 70 lbs/ft <sup>3</sup>
Moisture:	10 – 12% (maximum)



For more information, Contact AquaBlok, Ltd. at:  
 Phone: (800) 688-2649  
 Email: [services@aquablokinfo.com](mailto:services@aquablokinfo.com) visit us at our  
 Web: [www.aquablokinfo.com](http://www.aquablokinfo.com)

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## TEST REPORT #16 Drop Test of Cap Material Blended With Two Forms of Activated Carbon

### Background and Purpose of Testing

Stokes Law states that solids of varying size and density will fall at varying speeds through a liquid of a constant viscosity (water). This law suggests that placing a blended granular cap material through a water column could result in a layering effect of the material at the bottom of the column based on the size and density of the particles.

A series of column drop tests were done in order to illustrate the relative difficulty, as predicted by Stokes Law, of achieving a uniform mixture of dissimilar materials within an as-placed capping layer. The drop tests were performed using an existing specification for blending carbon materials into a granular cap.

The cap specification used was taken from an actual project – “Type 2 Granular Cap”, outlined below, which calls for the addition of 2% Total Organic Carbon (TOC) by weight. For these tests, Activated Carbon (AC) in various forms was substituted for TOC materials called out in the actual Hudson River

Backfill Type 2 Gradation Table (by weight)	
Percent (%) Passing	Sieve Size
100	3 inch
85-100	1 inch
50-75	No. 4
30-65	No. 10
10-45	No. 40
3-35	No. 100
0-12	No. 200

specification.

The four different forms of AC tested are dry Granular Activated Carbon (GAC), saturated GAC, Graded AquaGate+PAC, and AquaGate+PAC. The goal of this testing is to illustrate the effect of Stokes Law on “Type 2 Granular Cap” blended with these four forms of Activated Carbon.

### Methods

Water columns of 5-feet in depth and 4-inches in diameter were used for all tests. The blended samples were dropped into the water columns through a funnel with a five and one half-inch opening; the material falls 12 inches prior to entering the water.

The quantity of AC required to achieve the 2% specification was calculated based on bulk density and percent weight and does not take into account relative sorption rates of the powder versus granular form.

It was determined that 0.144 lbs of AC was required to meet an equivalent active loading of 2% within the 9-inch thick AC isolation layer. As GAC is 100% AC, 0.144 lbs satisfies the 2% requirement. Both AquaGate+PAC and Graded AquaGate+PAC contain 5% PAC and therefore 2.88 lbs of each is required in order to get 0.144 lbs of AC.

The Graded AquaGate+PAC includes a range of particle sizes from sand-sized material up through the larger particles of the more uniform AquaGate+PAC material. The saturated GAC was soaked in water for 24 hours prior to testing.

### Observations and Results

For every drop test, the water column became very cloudy (high turbidity). At a point no less than 18 inches below the surface of the water, the blended material began to separate. The largest particles separated almost immediately upon hitting the water. Smaller particles became suspended in the water column, descending at a slower velocity.

Over the first two minutes, some of the suspended material could be observed settling to the bottom on top of the larger particles. Within 5 minutes, the water began to regain transparency.

There was a clear separation of the size ranges, appearing as if they were added in sequence as opposed to dropped as a blended mixture. The photo on the right shows how evident the separation of large and small particles is during descent.

No significant difference was observed between the dry and saturated GAC drop test results. Neither dry nor saturated GAC remain evenly distributed throughout the capping layer and end up in the top half of the amended/reactive capping layer.

The graded AquaGate+PAC exhibited the widest dispersion, with particles mixed throughout the amended/reactive capping layer. The AquaGate+PAC settled into the bottom half of the column leaving very few particles incorporated with the fine-grained material at the top of the capping layer.

### Conclusions

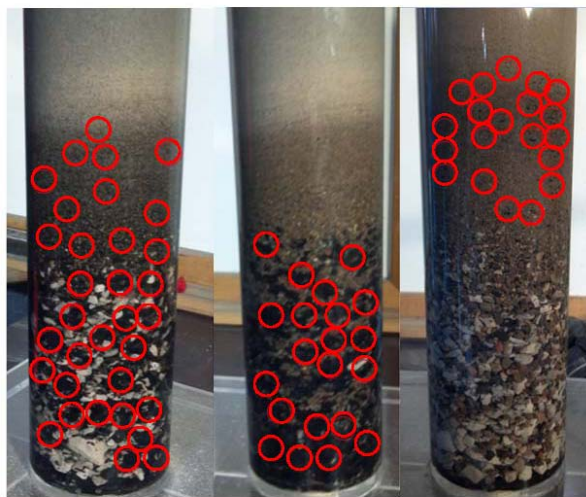
The column tests demonstrate that the materials in the amended/reactive capping layer proposed from the “Type 2 Granular Cap” project separate almost immediately upon entering the water column leading to distinct layering according to grain size. It appears as if the mixture was added in sequence as opposed to being dropped as a blended mixture.

The GAC behaved similarly to the smaller particles from the Type 2 Granular Capping material. In addition as GAC has a lower specific gravity, it is more susceptible to being affected by current or wave action.

The AquaGate+PAC particles were present throughout the entire thickness of the amended/reactive capping layer.

Of the drop tests performed, AquaGate+PAC enabled the placement of the highest percentage of AC near the bottom half of the amended/reactive capping layer.

Graded AquaGate+PAC      AquaGate+PAC      GAC



Red circles indicate relative location of particles within the as-placed cap. They do not denote the number of particles in a given location.



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You can also email us at: [services@aquablokinfo.com](mailto:services@aquablokinfo.com) or visit us at our web site at: [www.aquablokinfo.com](http://www.aquablokinfo.com)

Last Revised 02/24/12



# FINAL REPORT

Activated Biochars with Iron for In-Situ  
Sequestration of Organics, Metals, and Carbon

SERDP Project ER-2136

April 2012

Upal Ghosh  
Jose Gomez-Eyles  
Carmen Yupanqui  
Huan Xia  
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**University of Maryland Baltimore County**

*This document has been cleared for public release*





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## **List of Acronyms**

Activated Carbon (AC)

Polycyclic Aromatic Hydrocarbons (PAHs)

Polychlorinated Biphenyls (PCBs)

Dichlorodiphenyltrichloroethanes (DDTx)

Total Organic Carbon (TOC)

Zero Valent Iron (ZVI)

Polyoxymethylene (POM)

Tetrachloroethylene (PCE)

Trichloroethylene (TCE)

Mercury (Hg)

Methylmercury (MeHg)

## **Keywords**

Biochar, Activated Carbon, PCBs, PAHs, Mercury, Methylmercury, contaminant, sediment, sequestration, bioavailability

## **Acknowledgements**

We would like to thank SERDP for providing financial support for this project. We would also like to thank Cynthia Gilmour and Georgia Riedel at the Smithsonian Environmental Research Centre (SERC) for their help with the low concentration mercury and methylmercury analysis.

## Abstract

### Objectives

This research follows from previous work that has demonstrated that suitable sorbent amendments to sediments can lead to contaminant sequestration and reduction of contaminant bioavailability for in-situ management of impacted sites. The primary objective of this research was to test a range of available biochars and especially formulated biochars that can reduce the bioavailability and leaching of toxic chemicals like PAHs, PCBs, DDTs, mercury and methylmercury in sediments. To address this objective five key research questions were addressed:

1. Are biochars effective sorbents for PAHs, PCBs, DDT, mercury and methyl mercury?
2. Do biochars need activation to increase specific surface area and be effective sorbents for PAHs, PCBs, DDT, mercury and methyl mercury?
3. Can addition of zero valent iron in biochars enhance the dechlorination of chlorinated organic compounds?
4. Can incorporation of iron oxide in biochars enhance the metal binding capacity of biochars?
5. Can incorporation of iron and iron oxides increase the density of biochars to make them more stable in the sediment environment and allow separation for mass transfer calculations?

### Technical Approach

A range of biochars made from a number of agricultural residues, phragmites, and hardwoods were evaluated in this research. In addition, the biochars were activated either physically or chemically to enhance their organic contaminant sorption properties, impregnated with zero valent iron to evaluate their potential for the dechlorination of chlorinated compounds, and with iron oxides to evaluate the enhancement of sorption of mercury and methylmercury. Contaminant sorption to the carbons was evaluated in the aqueous phase by conducting sorption isotherms and pH edge sorption studies, followed by effectiveness testing in the sediment phase. The impregnation of iron/iron-oxides created a denser carbon so the increased stability of iron amended biochars was also assessed. The magnetic properties of these iron amended carbons also allowed for the separation of the carbon after contact with sediment enabling contaminant mass transfer assessments.

### Results

Biochars were able to sorb organic contaminants, Hg and MeHg, making them attractive alternatives to ACs in sites contaminated with both organic and inorganic contaminants. However, due to their lower surface area, unactivated biochars have a lower affinity for organic contaminants than ACs, so activation is necessary for their performance to match that of ACs. Unactivated biochars were able to reduce PCB porewater concentration by 18-80%, while the activated carbons and activated biochars consistently reduced organic contaminant porewater concentration by >99% in a DoD impacted sediment. Hg isotherms and pH edge sorption experiments indicate that some of the ACs were the most effective in removing Hg from solution at low concentrations. However, they also suggest that these ACs could have a limited amount of sorption sites available for inorganic contaminants relative to the biochars as their performance dropped with increasing Hg concentrations. The biochars, particularly poultry litter derived

chars, were able to remove more Hg from solution at higher Hg concentrations compared to other carbons (>99% Hg removal in pH edge study). It is possible that the high phosphate content of these poultry litter biochars are responsible for this enhanced Hg sorption. These biochars are therefore attractive from an Hg remediation standpoint, but the stability of the phosphate within the carbon needs to be evaluated before field application. Iron oxide amended chars could be separated magnetically to assess PCB mass transfer from sediment to carbon. The use of iron to impregnate the carbons was effective in improving their density and settling characteristics but had limited success in improving the sorption capacity of the carbons to Hg and MeHg or in enhancing the dechlorination of chlorinated organic compounds. Refinement of the iron amendment technique and longer-term studies are required to fully explore the potential of iron amended chars.

### **Benefits**

This study provides the proof-of-concept that can lead to further development of biochars for full-scale sediment remediation through scale-up to large-scale production of the synthesized biochars, evaluation of full-scale economics of the manufacturing, and finally benthic organism bioavailability and toxicity studies to evaluate the impact of the new sorbents in aquatic ecosystems. Activated biochars produced from waste biomass can provide strong sorbents for the remediation of contaminated sediments, reducing treatment costs and possibly reversing the carbon footprint of the remediation strategy. This could be particularly attractive in contaminated wetlands invaded by Phragmites, as the Phragmites itself could be used to produce the activated biochars necessary for sediment remediation on site.



## Objectives

Previous work by us and others has demonstrated that contaminant exposure pathways in contaminated sediments can be controlled by modifying and enhancing the binding capacity of natural sediments with sorbent amendments. The primary objective of this research was to test a range of available biochars and especially formulated biochars that can reduce the bioavailability and leaching of toxic chemicals like PAHs, PCBs, DDTs, mercury and methyl mercury in sediments. Utilization of biomass-derived as opposed to fossil carbon-derived black carbons affords the additional opportunity for carbon storage in sediments along with the sequestration of toxic contaminants.

To address the primary objective of this study, five key research questions were addressed:

1. Are biochars effective sorbents for PAHs, PCBs, DDT, mercury and methyl mercury in freshwater and saltwater matrices?
2. Do biochars need activation to increase specific surface area and be effective sorbents for PAHs, PCBs, DDT, mercury and methyl mercury in freshwater and saltwater matrices?
3. Can addition of zero valent iron in biochars enhance dechlorination of chlorinated organic compounds?
4. Can incorporation of iron oxide in biochars enhance the metal binding capacity of biochars?
5. Can incorporation of iron and iron oxides increase the density of biochars to make them more stable in the sediment environment and allow separation for mass transfer calculations?

A range of biochars and activated biochars derived from agricultural residues and other biomass source materials were evaluated to achieve this objective. These biochars are commercially available or have been developed by other research groups. In addition, a series of enhanced biochars were produced in the laboratory. The properties of these biochars were modified by activating them chemically to improve their organic contaminant sorption properties, and also by impregnating them with iron oxides to enhance the sorption of mercury and methyl mercury. Biochars impregnated with zero valent iron were also synthesized to evaluate their potential for the dechlorination of chlorinated compounds. The impregnation of iron/iron-oxides can create a denser carbon so the increased stability of iron amended biochars was also evaluated. The magnetic properties of these iron amended carbons also allow for the separation of the carbon after contact with the sediment enabling contaminant mass transfer assessments.

Since there are several recently concluded and ongoing studies that have advanced the technology of in-situ sorbent amendment to sediments (ER-1491, ER-0510, CU-1207; Grasse River Activated Carbon Pilot Study), we anticipate that the most effective sorbents tested or synthesized in this project will require only little effort to be included in potential field demonstration or full-scale remediation efforts. The additional studies will require scale-up to large-scale production of the synthesized biochars, evaluation of full-scale economics and carbon budget of the manufacturing process, and finally benthic organism bioaccumulation and toxicity studies to evaluate impact of the new sorbents to aquatic ecosystems.

## **Relevance to SERDP**

This proposal responds to SERDP FY 2011 SEED Statement of Need (SON): In-situ Remediation of Contaminated Aquatic Sediments. Specifically, this proposal addresses three of the four issues that were suggested for addressing in the SON as explained below:

- 1) Ability to achieve contaminant degradation or sequestration: This study evaluates the use of biomass based chars and activated chars with amendments designed to enhance the sequestration of organic compounds, mercury and methyl mercury and achieve the degradation of chlorinated organic compounds.
- 2) Bioavailability of sequestered contaminants: The research evaluated the bioavailability of sequestered contaminants through aqueous equilibrium partitioning studies using sediment samples from a DoD site.
- 3) Amendment placement, distribution, and stability: As mentioned previously, sorbents synthesized in this project included biochars impregnated with iron that will make the material denser thereby enhancing its stability in the sediment environment compared to regular biochars.

In addition, the proposed research evaluated the effectiveness of the sorbents in both freshwater and saltwater environments, and the focus was on contaminants of most concern in sediments including PAHs, PCBs, DDT, mercury and methyl mercury.

## Background

Remediation of PCB-impacted sediment. The cleanup process of sediment sites is complex and creates unique challenges due to expensive cleanup strategies, large and diverse sediment sites, and presence of ecologically valuable resources or legislatively protected species or habitats (USEPA, 2005). As indicated in USEPA (2005), removal options such as dredging and excavation have certain clear advantages, especially in situations where hot spots exist and there is a desire to reduce sources and risks quickly and to insure a permanent solution. However, the limitations and disadvantages of these methods have also become better understood. Dredging and disposal can be expensive and disruptive to existing ecosystems (USEPA, 2005). Moreover, contaminants can be released into the water and air environments during sediment dredging, transportation, and storage (USEPA, 1996; Valsaraj et al., 1998; NRC, 2002). Capping with clean sediments may not be practicable in sensitive ecosystems and at sites where there is concern with changing the sediment bathymetry. New developments in in-situ remediation approaches are needed that are less energy-intensive, less expensive, less disruptive of the environment, able to reduce human and ecosystem exposure, and defensible through well-grounded scientific understanding of contaminant fate processes and bioavailability in field conditions.

In-situ control of PCB bioavailability in sediment. Recent findings indicate that the bioavailability and leachability of contaminants in sediment are affected strongly by the nature of binding of the contaminants to the sediment particle types (Cornelissen et al., 1997; Kraaij et al., 2002; Ghosh et al., 2003a; Kukkonen et al., 2004; Lohmann et al., 2005; Moermond et al., 2005). For example, Jonker and Koelmans (2002) found that soot and soot-like materials have very high affinities for PCBs and PAHs and that the presence of these materials can lower aqueous concentrations of the contaminants, implying a reduction in the potential uptake by aquatic organisms. In our earlier work (Ghosh et al., 2000; Talley et al., 2002; Ghosh et al., 2003a), we demonstrated that PAHs associated with coal-derived particles are much less available for biological uptake. These findings suggest that the presence of black carbonaceous particles in sediments naturally reduces contaminant availability. McLeod et al (2004) showed in clam particle feeding studies that the assimilation efficiency for a tetrachloro-PCB was only 1-2% via ingestion if the PCB was sorbed to activated carbon, compared to > 90% for PCBs sorbed to diatoms.

In our recent work with PCB-contaminated sediments we have demonstrated that addition of activated carbon reduces PCB bioavailability greatly. Reductions in total PCB bioaccumulation of 69% by *Macoma* clams, 72% by *Leptocheirus* amphipods, and 83% by *Neanthes* worms were observed in laboratory tests on sediment treated for one month with activated carbon (Ghosh et al., 2003b; Millward et al., 2005). We also find that sediment treated with activated carbon attains aqueous equilibrium PCB concentrations 85 and 92% lower than untreated sediment in one month and six-month contact experiments, respectively (Zimmerman et al., 2004). For freshwater sediments we have demonstrated that bioaccumulation in oligochaetes decreased after the addition of 2.6% activated carbon (amounting to half the sediment TOC). Based on total PCB concentration in wet tissue, the mean bioaccumulation reductions were 70% for placement of activated carbon as a layer without mixing, 70% for placement and mixing of activated carbon for 2 minutes, and 90% for the placement and slow mixing of activated carbon for one month

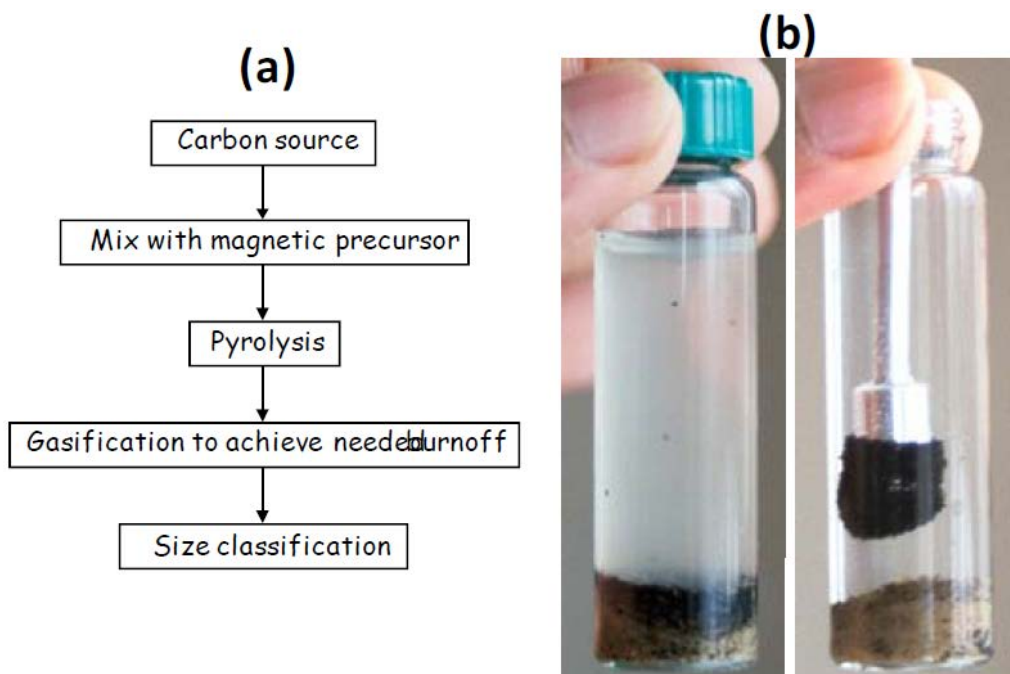
prior to worm addition (Sun and Ghosh, 2007). This demonstrates the potential for application of activated carbon to the biologically active layer of PCB-contaminated sediment to be an effective in situ stabilization method to reduce contaminant bioavailability to sediment organisms at the base of the aquatic food web. In situ bioavailability reduction using carbon amendment may be applicable at sites where reducing bioaccumulation can limit exposures and consequent risk to acceptable levels and is being demonstrated through several pilot-scale field trials (Beckingham and Ghosh, 2011; Ghosh et al., 2011).

Potential use of biochars and carbon sequestration. While, activated carbon made from coal has been demonstrated to work as a suitable sorbent for bioavailability reduction, carbons manufactured from biomass waste products offer an exciting opportunity for efficient resource utilization with the added potential opportunity for carbon sequestration in the process of sediment remediation (Beesley et al., 2010; Beesley et al., 2011). Additionally, new types of activated carbons made from renewable resources such as biomass waste and poultry litter are being developed and are claimed to have superior metal sorption characteristics (Fitzmorris et al., 2006; Cao et al., 2009; Cao et al., 2011). Black carbons from natural sources (such as forest fires) and man-made sources are known to persist naturally in soils and sediments and form the basis for carbon dating of soil and sediment cores. Also, recent findings indicate that carbon storage opportunities exist for black carbon introduction in soils because in this form the carbon is stable and not prone to microbial oxidation processes (Marris, 2006; Lehmann, 2007). In addition, the US EPA's new Green remediation strategy aims to minimize the environmental footprints of a cleanup (<http://www.epa.gov/superfund/greenremediation/>). Therefore, technologies that can reduce or reverse the carbon footprint while reducing risks will likely be favored in the future. A major unknown currently is whether biochars or activated biochars can be effective in reducing organic and metal contaminant bioavailability in sediments. Further, it is not known if amendment of the biochars with iron and iron oxides can enhance sorption capacity for metals, allow dechlorination of chlorinated organics, make the carbon denser and enhance stability, and allow separation for mass transfer evaluations. We aim to address each of these knowledge gaps in this study.

Activated carbons have been impregnated by various salts, elements, and oxides to attribute unique sorption properties in other studies. Activated carbon impregnated with Fe(III) oxides have been investigated for the removal of several anionic and cationic metals (Reed, 2000; Vaughan and Reed, 2005). Metal removal increased significantly over that observed for the virgin carbon and also was a strong function of pH. Impregnation of the carbon decreased the surface area (21%), total pore volume (23%), and iodine number (20%). Recent work by Choi et al. (2009) demonstrated that zero valent iron impregnated activated carbons can dechlorinate PCBs in aqueous systems. They found that the reaction rate can be enhanced by including palladium as a catalyst. However, the wet chemistry method of impregnation used by these researchers and the use of a noble metal (Pd) increases the cost of the final product.

Development of iron/ironoxide amended Activated Carbon. Recent development of a magnetic activated carbon offers a wonderful opportunity as a sorbent in contaminated sediments that may be retrieved from the sediment after repartitioning along with the toxic contaminants. The iron amended carbon is produced by mixing a carbon source (agricultural waste) with a magnetic precursor (Miller et al., 2004). After a series of heat treatments under controlled conditions, an

activated carbon with magnetic properties is obtained. The product carbon has residual iron in various states of oxidation that can be controlled by the nature of impregnating iron, pyrolysis process, and the activation process. Typically some zero valent iron and a mixture of iron oxides, including magnetite remains embeded in the carbon imparting the material a diamagnetic behavior. A simple schematic process flowsheet for the production of the magnetic activated carbon in shown in Figure 1. The manufacturing steps are quite similar to a traditional process for the manufacture of activated carbons, except for the inclusion of an iron salt (typically  $\text{FeCl}_3$ ). The final product consists primarily of carbon (87-97 %), as well as other elements (e.g., H, O, S and N) that form surface functional groups. Surface areas are typically in the range of 500-800  $\text{m}^2/\text{g}$  as measured by the nitrogen BET method. Tests in our laboratory has demonstrated that even at low additions of the magnetic precursor to the activated carbon, greater than 98% recovery of the carbon is possible as demonstrated in Figure 1b. Embedding of iron and iron oxides in the carbon offer the following new opportunities: 1) the zero valent iron may be utilized in the reductive dechlorination of chlorinated organics that are sorbed to the carbon, 2) iron oxides may act to enhance the sorption capacity of certain metal contaminants, 3) the impregnation of iron/iron-oxides will increase carbon density and also allow separation of the carbon after contact with sediment for contaminant mass transfer assessments and potential contaminant removal in a field application.



**Figure 1. a) Steps involved in the production of magnetic activated carbon and b) demonstration of magnetic activated carbon added to sediment (left) and retrieved using a permanent magnet (right).**

## Material and Methods

### Task 1: Selection/synthesis of biochars and testing of freshwater and saltwater isotherms for PAHs, PCBs, DDT, mercury and methyl mercury

Carbon Selection. The carbons tested in this study are listed in Table 1 and include commercially available activated carbons and biochars, biochars obtained from the US Department of Agriculture through an existing cooperative agreement and laboratory produced biochars.

**Table 1. List of carbons**

Carbon Type	Abbreviation	Manufacturer	Cost (\$/lb)
Bituminous coal based AC	CAC-Coal	Calgon Corp.	3-4
Coconut shell based AC	CAC-Coco	Calgon Corp	1
Lignite coal based AC	CAC-Darco	Norit	3-4
Regenerated AC	CAC-RAC	Siemens	0.50
Pine dust biochar	Bio-PD	BEC	<1
Peanut hull biochar	Bio-PH	BEC	<1
Barley straw biochar	Bio-BS	BEC	<1
Acai pit biochar	Bio-AP	BEC	<1
Hardwood lump Charcoal	Bio-HW	Milazzo Industries	<1
Activated turkey litter biochar	Act Bio-CL	USDA	NA
Activated chicken litter	Act Bio-TL	USDA	NA
Pine dust biochar	Lab-PD	UMBC	<1
Phragmites biochar	Lab-PHR	UMBC	<1
Activated pine dust biochar	Lab-APD	UMBC	<1
Activated Phragmites biochar	Lab-APHR	UMBC	<1
Iron oxide impregnated pine dust biochar	Lab-FePD	UMBC	NA
Zero valent iron impregnated pine dust biochar	Lab-HW-ZVI	UMBC	NA
Iron amended granulated biochar	Bio-GFe	Pilot production	NA

Carbon characterization. Total C analysis was performed using a Shimadzu TOC analyzer with a solids sample module (TOC-5000A and SSM-5000A). Surface area measurements were carried out by Particle Technology Labs (Chicago, Illinois). The continuous flow method at 77 K was employed for quantification of adsorbed and desorbed N<sub>2</sub>, using a QUANTACHROME QUANTASORB QS-13 Surface- Area Particle-Size Analyzer and ultra-high purity gaseous nitrogen (99.999%, from BOC Gases). Surface areas were calculated from a five-point regression, based on the Langmuir equation.

PAH, PCB and DDT isotherm studies. Isotherm studies were performed in freshwater and saltwater matrices to compare the organic sorption capacity of the different carbons. This was tested by measuring aqueous equilibrium concentrations using polyoxymethylene (POM) strips. Briefly, 24 mg of each sorbent (<250µm) was added to amber glass jars containing 240 ml of sodium azide solution (100 mg/L) in freshwater or saltwater. Each jar was then spiked with a known amount of PCB, PAH and DDT stock solution to obtain 4 different spike levels for each sorbent. The PCB stock solution contained a 1:1 (vol) mixture of Aroclor 1242 and 1260

(Supelco, Bellefonte, PA, USA), the PAH stock contained acenaphthene, phenanthrene and fluoranthene, and the DDT solution contained 4,4'-DDE and 4,4'-DDD. POM strips (90  $\mu\text{m}$  thick) were then added to the jars and mixed at 32 rpm in the dark for 28 days. The POM samplers were then removed, rinsed briefly with water to ensure they were visibly clean, wiped dry and extracted with a 1:1 hexane and acetone mixture. The extracts were split into two equal parts for PCB and DDT analysis by GC-ECD, and for PAH analysis by GC-MS.

Mercury pH-edge sorption isotherms. Hg pH-edge sorption isotherm studies in freshwater matrices were performed to compare the Hg sorption capacity of the various carbons. A known mass of the different sorbents carbons ( $<250\mu\text{m}$ ) was added to a range of mercury feed solutions. The concentrated stock solutions of mercury were prepared by dissolving mercury chloride ( $\text{HgCl}_2$ ) salt into freshwater. The initial concentration of mercury was 20 mg/L. While stirring rapidly, a wide-mouth pipette was used to remove 40 ml aliquots of the adsorbent slurry, which were then placed in 50 ml plastic vials. The pH of the vials was then adjusted using either 0.1 N sodium hydroxide or 0.1 N nitric acid, obtaining solutions ranging from 3 to 10 in pH. The samples were then shaken for 48 hours. Upon removal from the shaker, sample pH was measured; filtered using a 0.45  $\mu\text{m}$  filters, and preserved using concentrated nitric acid. Samples were then analyzed for divalent metal concentration using an inductively coupled plasma mass spectrometer (ICP-MS).

Mercury and methylmercury sorption isotherms. Mercury and methylmercury sorption isotherms were carried out in a saltwater matrix. A known mass of each sorbent was added to PTEG bottle containing 50ml of water. Each jar was then spiked with a known amount of mercury or methylmercury solution to obtain 5 different spike levels for each sorbent. The bottles were then allowed to equilibrate for 1 week at 4° C, after which they were filtered and the solutions analyzed by ICP-MS.

Mercury and methylmercury analysis were performed at the Smithsonian Environmental Research Center. Total mercury analysis (EPA Method 1631) was performed following digestion, reduction, and gold-trapping. Methylmercury analysis (EPA Method 1630) was done by distillation, ethylation, and gas chromatographic separation. Methylmercury samples were distilled (Horvat et al., 1993) and then derivatized using sodium tetraethylborate. After distillation and ethylation, volatile mercury species are purged and concentrated onto traps filled with Tenax®, thermally desorbed, separated on an OV 3/Chromasorb column, and directly introduced on a stream of argon into an inductively coupled plasma-mass spectrometer (ICP-MS) (Perkin-Elmer Elan DRC II) for detection. For quantification, SERC used isotope dilution techniques (Hintelmann et al., 1995; Hintelmann and Ogrinc, 2002), in which trace amounts of enriched methyl<sup>199</sup> mercury are added to each sample as an internal standard. For each batch of total mercury or methylmercury samples, a suite of quality assurance and quality control (QA/QC) measures are run and reported. These include the analysis of blanks, analytical duplicates, and certified reference materials (CRMs) where available and appropriate. Typical detection limits for total mercury are  $<1$  ng/L for pore waters,  $<0.5$  ng/L for surface waters, and 0.1 ng/g for sediments and tissue. Typical detection limits for methylmercury are  $<0.5$  ng/L for pore waters,  $<0.25$  ng/L for surface waters, and  $<0.1$  ng/g for sediments and tissue. Details of SERC methods and quality assurance can be found in recent publications (Mitchell and Gilmour, 2008; Hollweg et al., 2009).

## **Task 2: Synthesizing and testing chemically activated biochars and biochars with iron and iron oxides embedded.**

Synthesis of activated and iron impregnated biochars. Chemically activated biochars were produced as described in (Lim et al., 2010). Briefly, Phragmites and pine dust source materials were mixed with 65 % phosphoric acid solution with an impregnation ratio of 3:1. Each source material was then dried at 100° C before being pyrolyzed at 600° C.

Iron oxide impregnated biochar was produced following the methods described by Miller et al. (2004). Briefly, pine dust was soaked in an FeCl<sub>3</sub> solution (0.024M) and homogenized for 24 hours in an orbital shaker. The material was then dried at 100° C for 24 hours before being pyrolyzed at 600° C for 2 hours.

Zero valent iron (ZVI) impregnated biochar was produced following the incipient wetness method described by Choi et al. (2008). Here a hardwood derived biochar (Milazzo Industries) was impregnated with ZVI by melting Fe(NO<sub>3</sub>)<sub>3</sub>·9H<sub>2</sub>O at 55-60° C with a small quantity of water (5 mL) onto the carbon. The slurry was then dried at room temperature, put in an oven overnight (at 105° C), and further calcined in a muffle furnace at 300° C for 4 hours to remove nitrate ions. The iron oxide impregnated onto the biochar was then reduced to elemental Fe using a NaBH<sub>4</sub> solution.

Dechlorination studies. To assess the dechlorination potential of the ZVI impregnated biochar an aqueous PCE solution was prepared in previously boiled and nitrogen purged distilled water. The carbon was contacted with the solution for a month, and aliquots of the solution were analyzed at different timepoints (0, 1, 2 and 4 weeks) for dechlorination products (TCE) by GC-ECD. The aqueous PCE solution was also contacted with the unamended hardwood derived biochar and iron filings in separate treatments.

Effectiveness testing in the sediment phase. Carbons were tested using a PCB impacted sediment from a DoD site (Upper Canal Creek, Aberdeen Proving Grounds, MD). The sediment was mixed with the carbons at a dosing rate of 5% by mass of dry sediment, and equilibrated for a month in the presence of polyoxymethylene (POM) passive sampling strips to evaluate PCB porewater concentrations using methods presented in Sun and Ghosh (2008). Changes in PCB porewater concentrations can be related to changes in PCB bioavailability in the sediment (Beckingham and Ghosh, 2011), and can therefore give an indication of the success of the carbon amendment.

## **Task 3: Test density, settling, and separation characteristics of biochars with or without iron amendments.**

Density and settling characteristics. Skeletal and bulk density of carbons were measured in the laboratory by a gravimetric method. For skeletal density measurement, the carbon was first filled in tared 10 ml volumetric flasks and then filled with acetone up to the volumetric mark. The volume of acetone required was calculated from the mass and density of acetone and used to calculate by difference the volume occupied by the carbon. Bulk density of the carbons was measured by filling up a known volume with the carbon and measuring the mass. To evaluate the effect of adding iron amendments to biochars settling test were performed on a selection of



carbons. Settling tests consisted of measuring the time taken for replicates of 10 carbon particles (500um-600um) to fall through a 1m column of freshwater and 10 ppt seawater.

Measurement of mass transfer kinetics of target contaminants from sediment into iron-amended biochars. The previously mentioned PCB impacted sediment from Upper Canal Creek was amended (5% by weight) with an iron amended granulated biochar. The magnetic properties of the biochar enabled a separation of the carbon from the sediments at different timepoints (0, 1, 2 and 4 weeks). The carbon and the sediment were then extracted and tested for PCBs using EPA standard methods for extraction, clean up and analysis.

## Results and Discussion

### Carbon characterization

The results of the carbon characterization are displayed in Table 2. As expected the commercially available activated carbons and the biochars activated chemically in the laboratory had a larger surface area than the unactivated biochars. The steam activation of the poultry litter biochars produced by the USDA only had a moderate impact on their surface area.

**Table 2. Carbon properties**

Carbon Type	C (%)	Surface area (m <sup>2</sup> /g)
CAC-Coal	80.9±1.4	1116.1±18.0
CAC-Coco	90.8±2.7	1305±8.4
CAC-Darco	ND	ND
CAC-RAC	ND	ND
Bio-PD	22.1±0.5	109.4±0.8
Bio-PH	31.9±6.8	107.3±1.3
Bio-BS	49.2±2.5	26.1±0.2
Bio-AP	77.2±0.3	197.9±4.4
Bio-HW	70.8±0.3	223.6
Act Bio-CL	26.8±1.2	300.4±6.7
Act Bio-TL	26.9±0.8	270.4±1.7
Lab-PD	77.9±0.8	542.2
Lab-PHR	69.6±0.9	464.3
Lab-APD	71.0±0.3	2265.6
Lab-APHR	64.6±0.14	1578.8
Lab-FePD	77.1±2.0	586.2
Lab-HW-ZVI	38.4±2.1	ND
Bio-GFe	59.6±0.1	ND

## **PAH, PCB and DDT sorption**

### Aqueous equilibrium isotherms

Isotherms studies were carried out in two batches. The first set was carried out using the already available biochars and ACs while the methods for synthesizing the biochars in the laboratory were being optimized. Once the laboratory biochars were synthesized a second set of isotherms was performed. Due to the large amounts of carbons tested, graphs and tables displaying these results are split into these two categories (readily available carbons and laboratory synthesized carbons) for clarity.

The sorption of PAHs, PCBs and DDTs onto the carbons was mostly non-linear, so isotherms were fitted using the Freundlich equation. Activated carbons consistently removed more organic contaminants from solution than the unactivated biochars at the environmentally relevant concentrations tested. The difference in sorption capacity between activated carbons and unactivated biochars was around 2 orders of magnitude for the readily available carbons. This is illustrated in Figures 2-5 showing the sorption of two PCB congeners (PCB 18 and PCB 158 as representative tri- and hexachloro PCBs) to the different carbons, and additionally Figures 6 and 7 displaying the sorption of fluoranthene and 4,4'-DDE to the laboratory synthesized carbons. The figures also include the expected sorption of the contaminants to natural organic matter (OM), derived using generic  $K_{ow}$  to  $K_{oc}$  relationships obtained from the literature (Schwarzenbach et al., 2003).

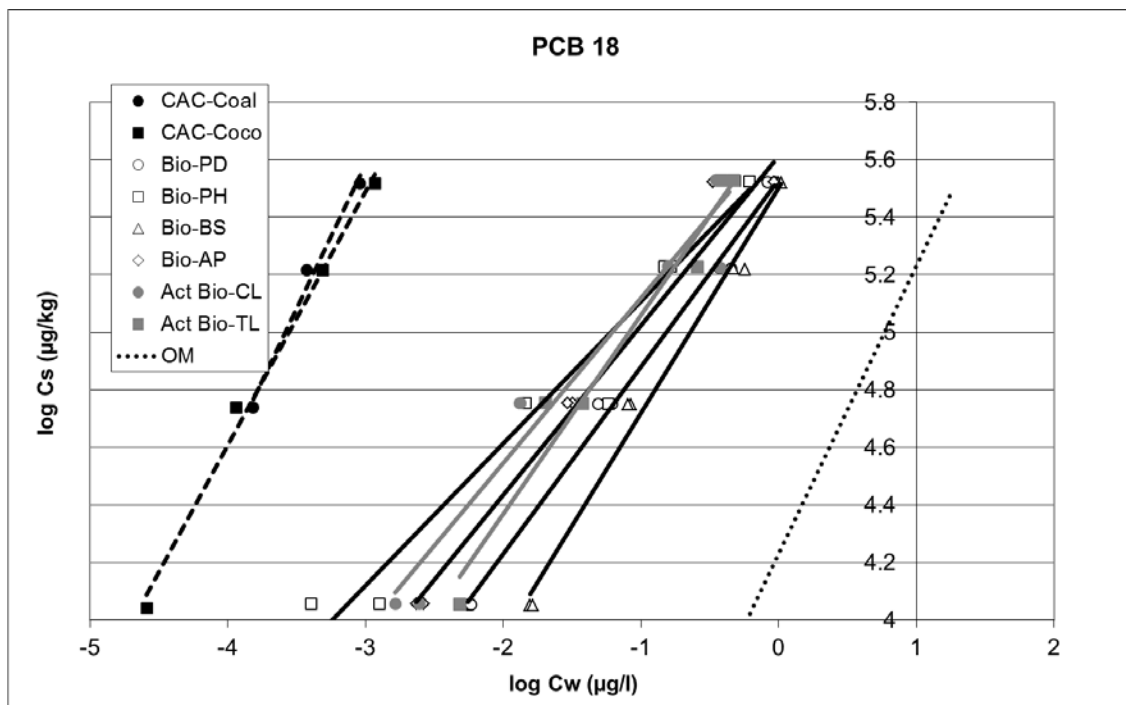


Figure 2. PCB 18 isotherms for the readily available carbons. Isotherms are plotted with dashed lines for the activated carbons, with straight grey lines for the activated poultry litter biochars and with straight black lines for the remainder of the biochars. Modeled isotherms for organic matter are plotted with black dotted lines.

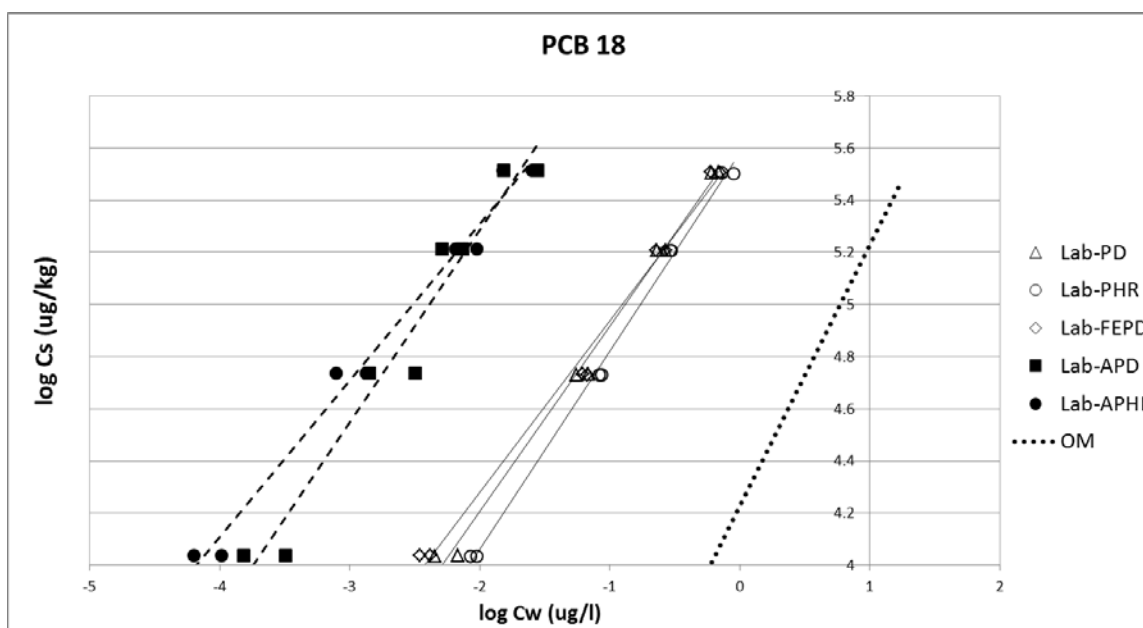


Figure 3. PCB 18 isotherms for the laboratory synthesized carbons. Isotherms are plotted with dashed lines for the biochars activated chemically in the laboratory, and with straight black lines for the remainder of the biochars. Modeled isotherms for organic matter are plotted with black dotted lines.

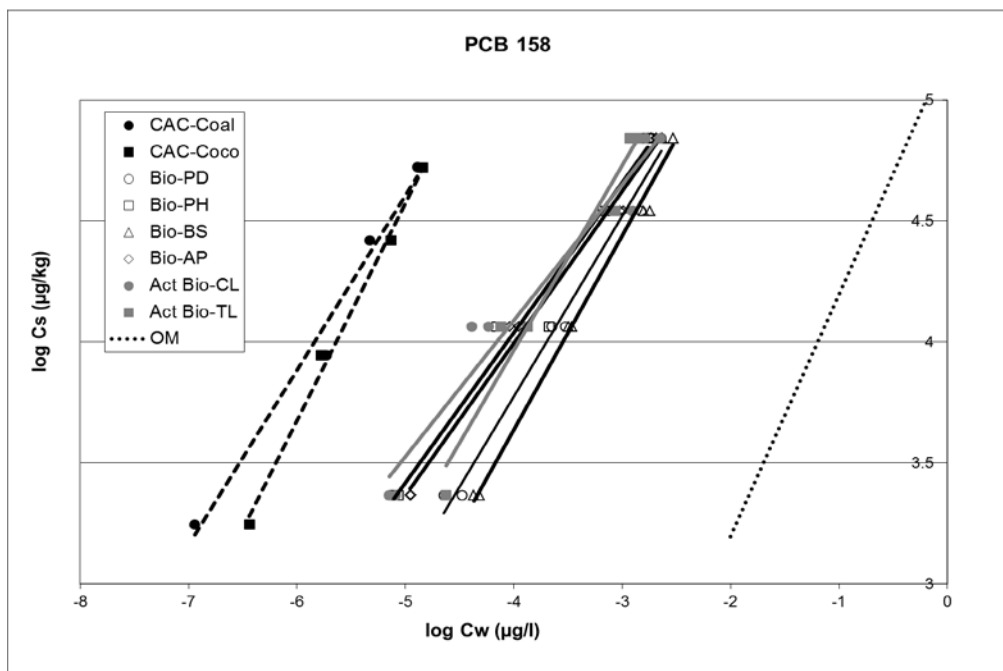


Figure 4. PCB158 isotherms for the readily available carbons. Isotherms are plotted with dashed lines for the activated carbons, with straight grey lines for the activated poultry litter biochars and with straight black lines for the remainder of the biochars. Modeled isotherms for organic matter are plotted with black dotted lines.

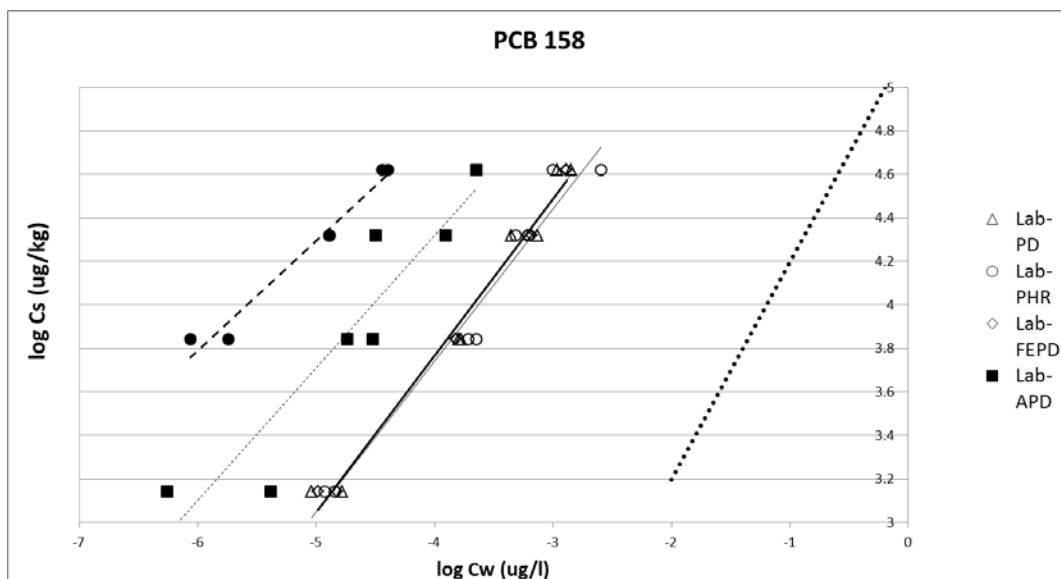
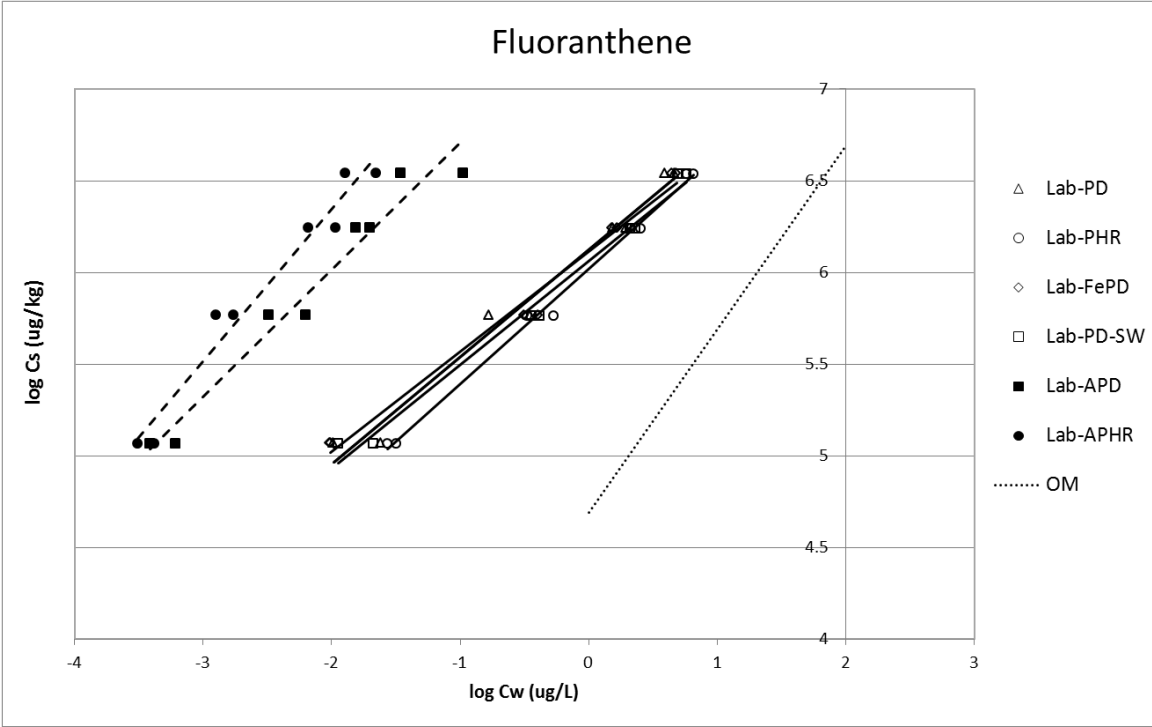
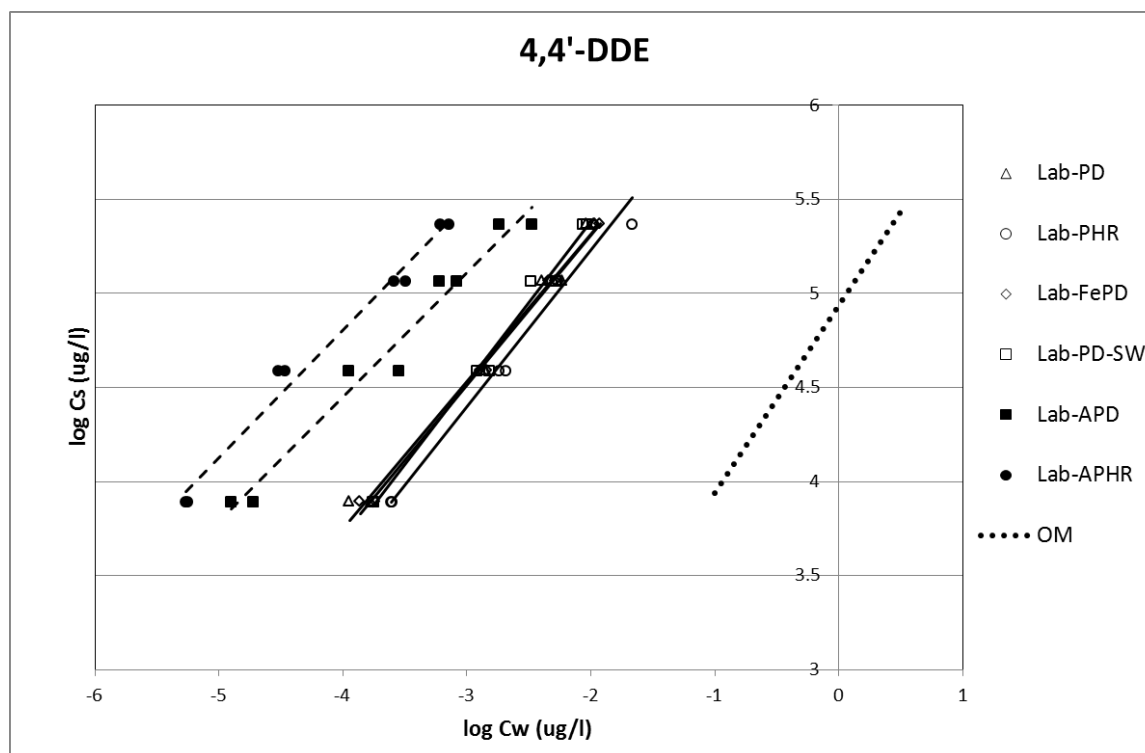


Figure 5. PCB158 isotherms for the laboratory synthesized carbons. Isotherms are plotted with dashed lines for the biochars activated chemically in the laboratory, and with straight black lines for the remainder of the biochars. Modeled isotherms for organic matter are plotted with black dotted lines.



**Figure 6. Fluoranthene isotherms for the laboratory synthesized carbons. Isotherms are plotted with dashed lines for the biochars activated chemically in the laboratory, and with straight black lines for the remainder of the biochars. Modeled isotherms for organic matter are plotted with black dotted lines.**



**Figure 7. 4,4'-DDE isotherms for the laboratory synthesized carbons. Isotherms are plotted with dashed lines for the biochars activated chemically in the laboratory, and with straight black lines for the remainder of the biochars. Modeled isotherms for organic matter are plotted with black dotted lines.**

Isotherms like the ones in the figures above were plotted for individual PCBs, PAHs and DDTs for all the carbons, and their Freundlich isotherms parameters are summarized in Table 3 and 4. A representative PCB congener from a selection of the different PCB homolog groups is presented together with the PAHs and DDTs tested. The fact that the  $K_f$  values for the different sorbents was higher for the commercially available activated carbon and the biochars chemically activated in the laboratory, suggests the surface area of the carbon has a major influence on organic contaminant sorption. This increased sorption with increasing carbon surface area has been previously reported for organic compounds (Bornemann et al., 2007; Zhou et al., 2009; Wang et al., 2010). The steam activation of the poultry litter biochars did not increase the surface area of these biochars to the levels of the commercially activated carbons and the chemically activated biochars produced in the laboratory, so their pyrolysis and activation process could be optimized further to improve their organic contaminant sorption characteristics. Also, as shown in Table 2, the carbon content of poultry litter biochars is much smaller (27%) compared to commercial activated carbons. The poultry litter likely contains other inorganic constituents that are not very effective sorbents for organic compounds.

**Table 3. Freundlich isotherm parameters for the readily available carbons**

Contaminant	Kow	Bio-PD		Bio-PH		Bio-BS		Bio-AP		Bio-HW		Act Bio-CL		Act Bio-TL		CAC-Coal		CAC-Coco	
		Kf	n	Kf	n	Kf	n	Kf	n	Kf	n	Kf	n	Kf	n	Kf	n	Kf	n
PCB 8+5	5.02	5.6	0.52	5.78	0.44	5.7	0.49	5.6	0.47	5.4	0.64	5.8	0.53	5.9	0.64	8.4	0.91	7.9	0.78
PCB 18	5.24	5.5	0.65	5.6	0.49	5.7	0.50	5.6	0.59	5.6	0.76	5.7	0.57	5.8	0.69	8.6	1.0	8.1	0.88
PCB 47	5.85	6.8	0.67	6.4	0.53	6.6	0.61	6.6	0.59	5.9	0.77	6.6	0.57	7.1	0.70	8.0	0.82	8.6	0.96
PCB 99	6.39	6.0	0.75	7.1	0.66	7.1	0.68	7.1	0.68	6.3	0.79	6.9	0.61	6.2	0.75	7.7	0.71	8.8	0.94
PCB 158	7.02	6.8	0.75	7.6	0.62	7.9	0.70	6.5	0.63	6.6	0.70	7.3	0.56	7.0	0.76	8.2	0.72	9.1	0.9
PCB 180	7.36	7.3	0.83	7.0	0.65	8.6	0.77	8.3	0.68	7.9	0.79	6.9	0.56	9.0	0.85	9.1	0.82	9.5	0.93
Acenaphthene	3.92	5.4	0.47	5.8	0.49	5.1	0.63	5.6	0.43	6.3	0.55	5.9	0.59	5.8	0.69	7.9	0.89		
Phenanthrene	4.46	5.6	0.52	5.9	0.60	5.3	0.70	5.7	0.50	6.3	0.51	6.1	0.61	6.0	0.63	8.3	1.1		
Fluoranthene	4.95	5.9	0.55	6.3	0.64	5.8	0.72	6.1	0.49	7.1	0.57	6.5	0.60	6.4	0.61	10.4	1.1		
4,4'-DDE	6.51	6.7	0.74	6.5	0.58	6.8	0.83	6.6	0.63	6.9	0.83	6.5	0.57	7.0	0.82	8.46	0.69		
4,4'-DDD	6.02	6.2	0.76	6.0	0.55	6.3	0.86	6.1	0.60	6.3	0.81	6.2	0.58	6.4	0.72	8.3	0.73		

**Table 4. Freundlich isotherm parameters for the laboratory synthesized carbons**

Contaminant	Kow	Lab-PD		Lab-PD-SW		Lab-PHR		Lab-FePD		Lab-APD		Lab-APHR	
		Kf	n	Kf	n	Kf	n	Kf	n	Kf	n	Kf	n
PCB 8+5	5.02	5.5	0.59			5.4	0.63	5.5	0.52	6.6	0.63	6.3	0.49
PCB 18	5.24	5.6	0.71			5.6	0.76	5.6	0.66	6.8	0.74	6.5	0.60
PCB 47	5.85	5.9	0.76			5.9	0.78	5.9	0.74	6.6	0.73	5.9	0.44
PCB 99	6.39	6.4	0.83			6.3	0.80	6.3	0.80	6.8	0.73	6.9	0.68
PCB 158	7.02	6.7	0.72			6.5	0.70	6.6	0.72	6.7	0.61	6.8	0.50
PCB 180	7.36	7.8	0.87			7.6	0.82	7.7	0.85	8.1	0.72	8.5	0.78
Acenaphthene	3.92	5.6	0.43	5.9	0.42	5.6	0.52	5.9	0.39	8	0.65	7.1	0.66
Phenanthrene	4.46	5.9	0.5	6.3	0.55	5.8	0.52	5.9	0.44	8.1	0.8	7.2	0.7
Fluoranthene	4.95	6.9	0.59	7.3	0.66	6.9	0.63	6.9	0.54	8.6	0.69	9.2	0.84
4,4'-DDE	6.51	6.9	0.78	7.1	0.86	6.9	0.83	6.9	0.8	7.1	0.67	7.52	0.68
4,4'-DDD	6.02	6.3	0.75	6.4	0.78	6.3	0.81	6.3	0.74	6.8	0.65	7.24	0.68



The non-linearity of the isotherms as indicated by the Freundlich  $n$  term displayed in Table 3 and 4 gives an indication of how the sorption capacity changes (typically decreases) with increasing aqueous concentration. As Freundlich  $n$  values get lower than 1 they indicate more sorption non-linearity suggesting the carbon is less sorbing at higher aqueous concentrations. A Freundlich  $n$  value of 1 indicates linear sorption. To illustrate the difference in  $n$  values between carbons more clearly, the  $n$  values for the isotherms of PCBs 18 and 158 are graphed in Figures 8 and 9 for the readily available carbons. The fact that the  $n$  term is generally lower for the biochars than the activated carbons suggests strong sorption sites are more limited in the biochars, and that they are getting saturated at high contaminant concentrations. The Freundlich  $n$  term for activated carbons is closer to 1 especially for the lower chlorinated PCBs indicating strong sorption affinity even at the high aqueous concentration tested.

Although these sorption experiments were not designed to investigate competition effects, it is likely for the competition for sorption to be much greater in the biochars than in the CACs due to the large differences in surface area between them. This issue of pore blocking and sorption site saturation could limit the effectiveness of biochar as an organic contaminant remediation amendment. The blocking of sorption sites in activated carbons by organic matter (Rhodes et al., 2010), and a reduced efficiency of biochars sorbents due to competition between contaminants (Cao et al., 2009) has been previously reported. These factors are the likely causes for the diminished capability of aged biochar to adsorb organic contaminants (Zhang et al., 2010). This may raise questions on the long term effectiveness of sediment remediation strategies using biochars. However, a recent study where biochars were contacted with soils and artificially aged in the laboratory found they were still effective at reducing pyrene pore water concentrations after ageing (Hale et al., 2011). The fact that the unactivated biochars sorb all the organic contaminants more strongly than natural organic matter (OM) by at least 1-2 orders of magnitude (Figures 2-7) suggests that they can increase sediment  $K_{oc}$  considerably and hence reduce contaminant porewater concentrations after amendment. Also due to the benefits biochar offers in terms of lower cost and carbon sequestration re-applying fresh biochar could be a feasible solution to this lower capacity problem.

Taking a closer look at the Freundlich parameters in Table 3 it is apparent that the difference in sorption between the high surface area carbons and the biochars was larger for the less chlorinated PCBs ( $K_f$  values approximately 3 orders of magnitude apart) than for the more heavily chlorinated ones ( $K_f$  values approximately 2 orders of magnitude apart). The decreased sorption for the higher molecular weight PCBs have been attributed to the slower kinetics of internal mass transfer for these heavier compounds (Werner et al., 2006). In short-term experiments, activated carbons have been shown to be very effective for reducing porewater concentrations of lower chlorinated PCBs with longer time required to show similar effectiveness for the higher chlorinated PCBs (Zimmerman et al., 2004; Sun and Ghosh, 2008). Beckingham and Ghosh (2011) showed that in a pilot demonstration of AC amendment to sediment, reduction in porewater PCBs were lower for the higher chlorinated PCBs after 1 year.

However, three years after treatment, the reductions in porewater PCBs were the same for all homolog levels.

To investigate if the salinity had an effect on the sorption capacity of the biochars the laboratory, sorption isotherms were carried out in 10 ppt salt water using the laboratory synthesized pine dust biochar (Lab-PD-SW).  $K_f$  values were generally not affected or were slightly increased in saline conditions (Table 3). Similarly impregnating the carbon with iron oxides (Lab-FePD) had no apparent effect on the organic contaminant sorption properties of its analogous unimpregnated biochar (Lab-PD) (Table 3).

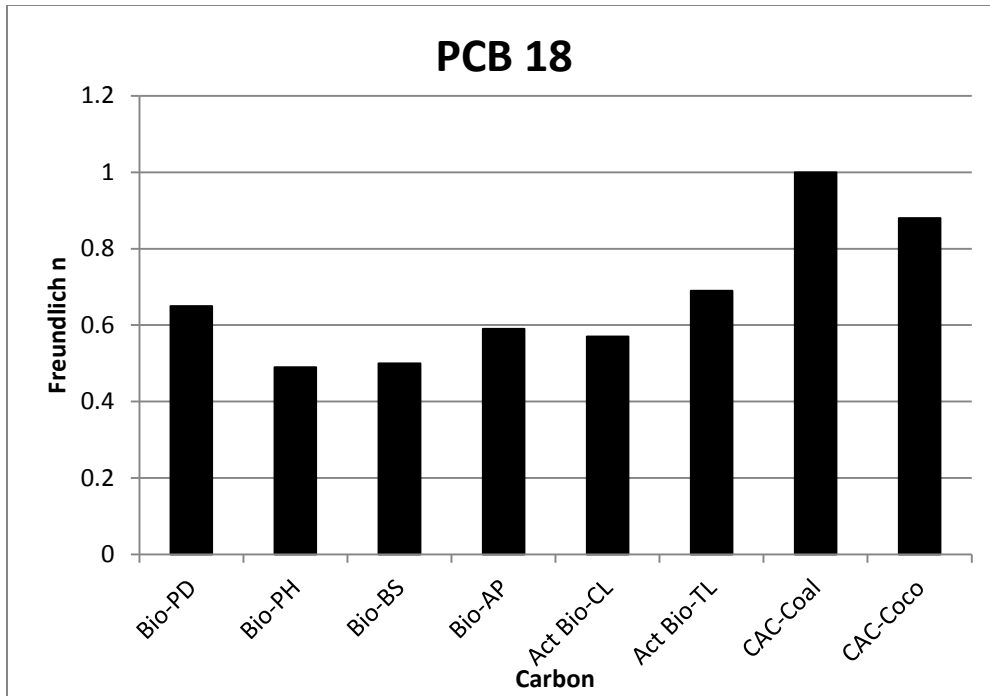


Figure 8. Freundlich  $n$  parameters for the readily available carbons in the PCB 18 isotherms

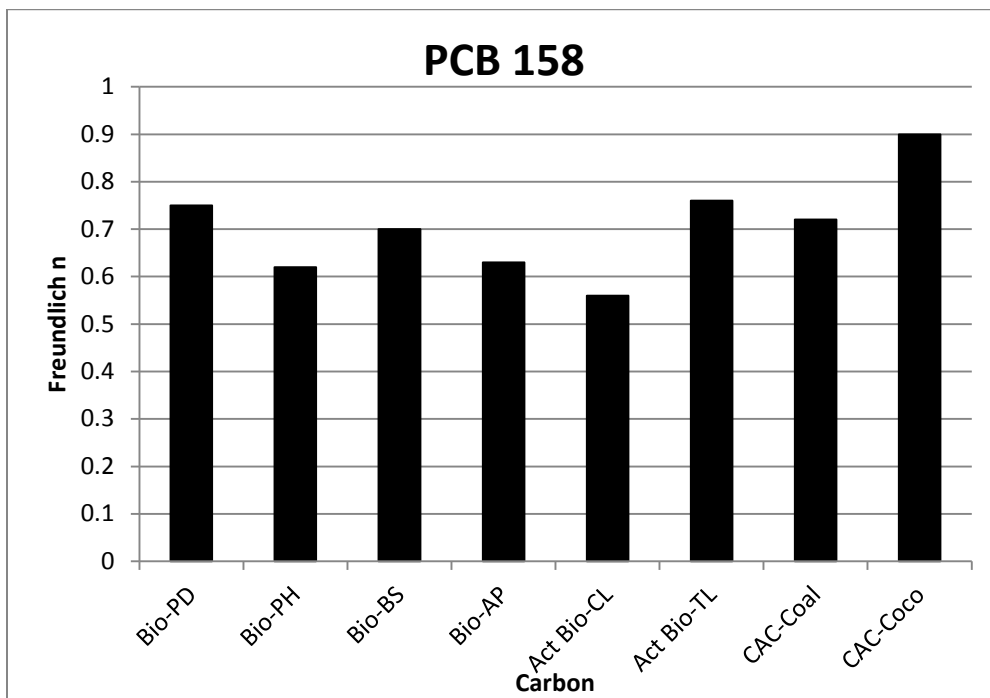


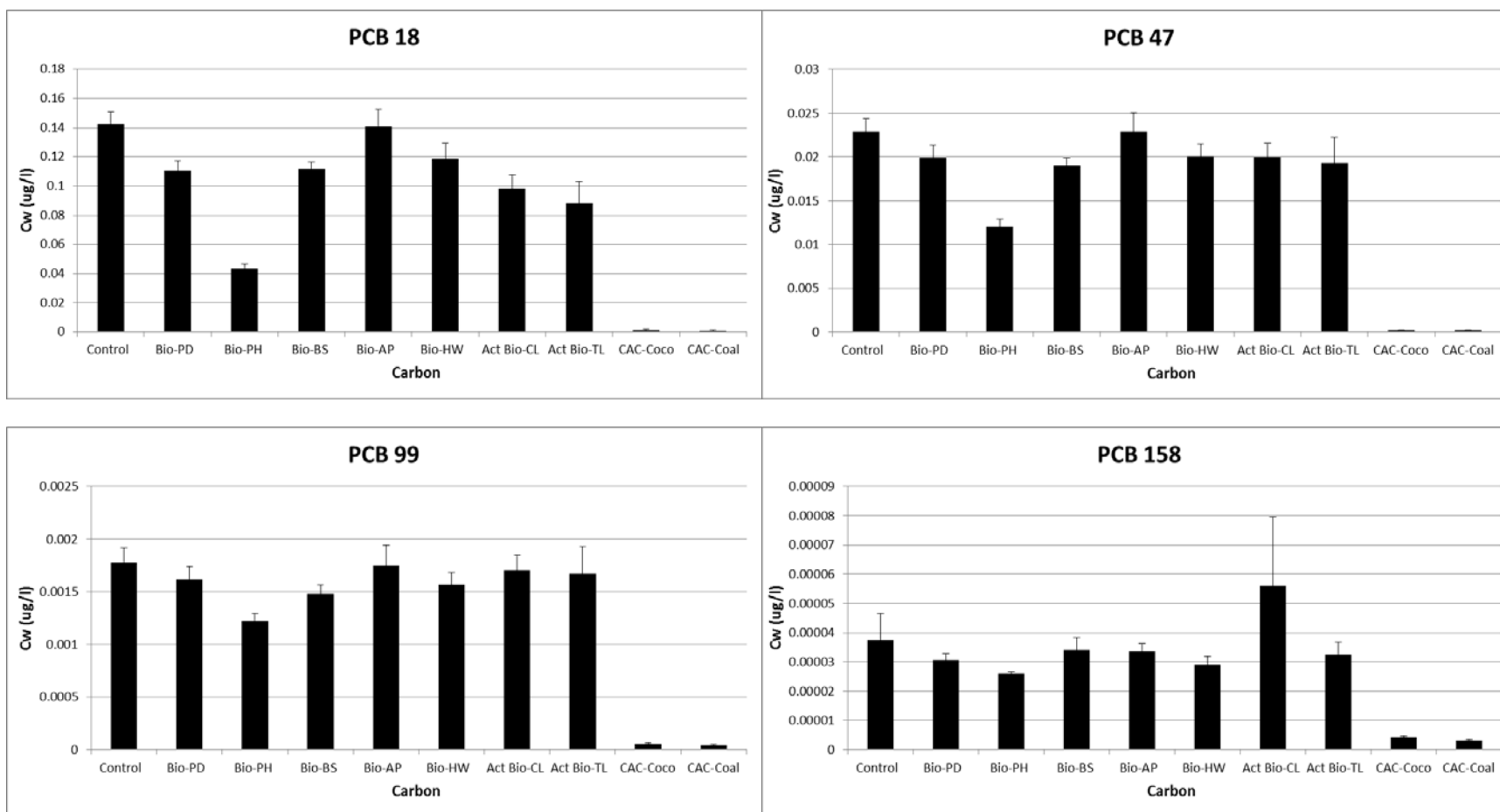
Figure 9. Freundlich  $n$  parameters for the readily available carbons in the PCB 158 isotherms.

### Sediment phase testing

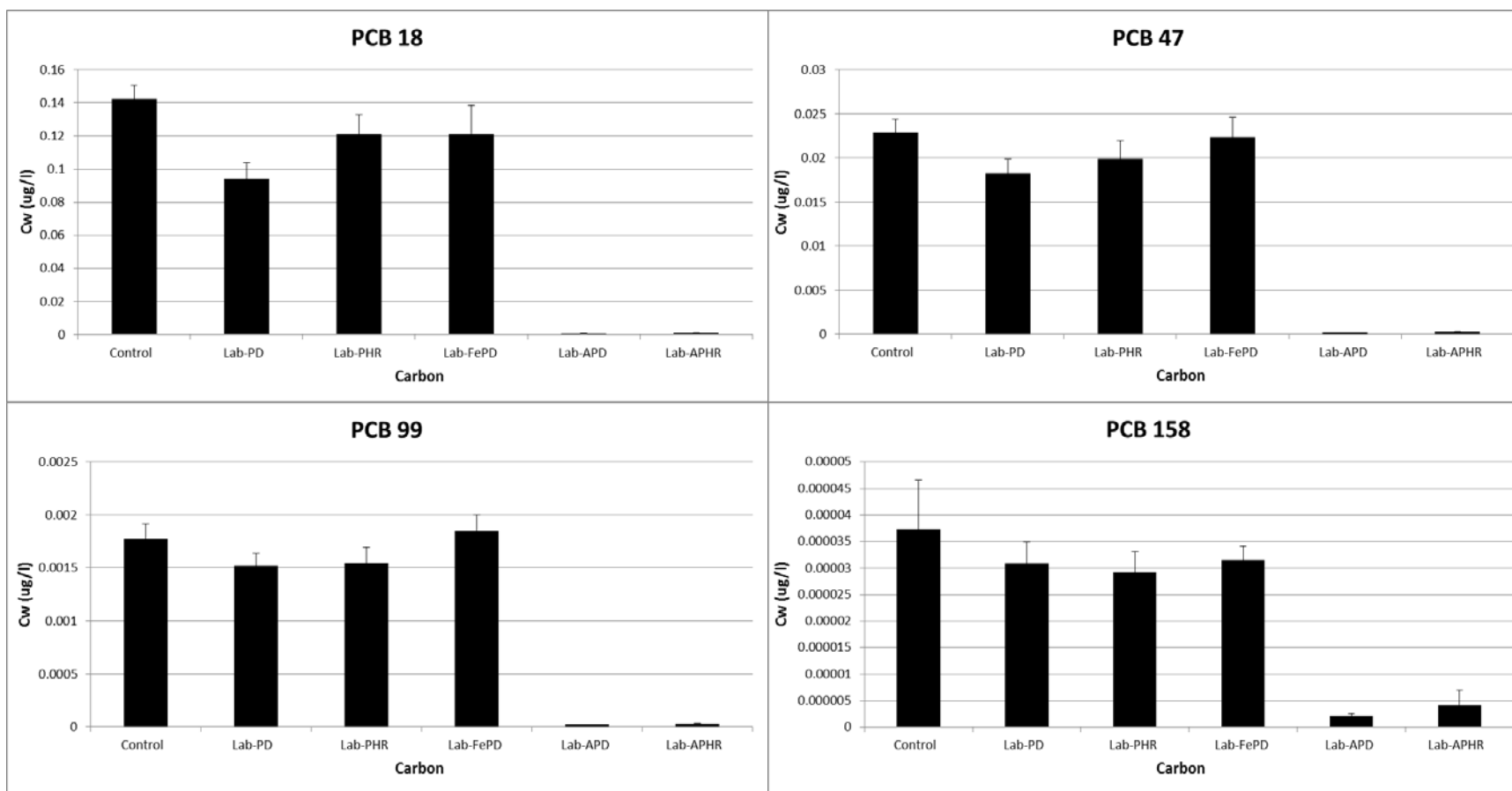
The results obtained from the isotherms studies translated well when testing the carbons in the sediment phase. Figures 10 and 11 show how the commercially activated carbons and the chemically activated biochars produced in the laboratory were able to reduce PCB pore water concentrations further than the other carbons for a selected range of PCB congeners. In terms of total PCBs, the commercially activated carbons and the chemically activated biochars produced in the laboratory, reduced aqueous PCBs by >99% relative to the control sediment. The other carbons on the other hand only reduced between 18-54% to the total PCB in the porewater relative to the control, with the exception of the peanut hull char that removed close to 80%.

Large reductions in organic contaminant pore water concentration have been previously reported after applying activated carbons in soils and sediments (Millward et al., 2005; Brändli et al., 2008; Cho et al., 2009; Fagervold et al., 2010). Although the effect of biochars on organic contaminant bioavailability has not been studied so extensively, the more modest reductions by biochars in this study are also in line with previous studies reporting >40% reduction in the rapidly desorbing PAH fraction (Beesley et al., 2010), >30% reduction in PAH bioaccumulation in earthworms (Gomez-Eyles et al., 2011) and >40% reduction in organic pesticide degradation (Yu et al., 2009) after biochar amendment. Recent work with dioxin contaminated soils showed that carbons with finer particle sizes or more macropores showed higher reduction efficiencies (Chai et al., 2012). In their study, powdered regenerated AC and powdered coconut AC demonstrated to be the most effective and the two biochars performed less effectively but reasonably well especially in the powdered form.

The results of this study show that biochars are able to reduce organic contaminant bioavailability to some degree, but they are not as effective in doing so as activated carbons. However, it is possible to synthesis biochars with high enough surface areas for them to be able to reduce organic contaminant bioavailability to the same degree or higher than regular coal derived activated carbons. Studies have shown that increasing the pyrolysis temperature at which biochars are produced can increase biochar surface area dramatically (Chen et al., 2008). A number of studies have shown that increasing biochar surface area can increase their ability to adsorb organic contaminants (Yu et al., 2006; Zhou et al., 2009; Kasozi et al., 2010; Wang et al., 2010), optimizing the pyrolysis and activation processes would increase the potential of biochars for the remediation of sediments impacted with organic contaminants.



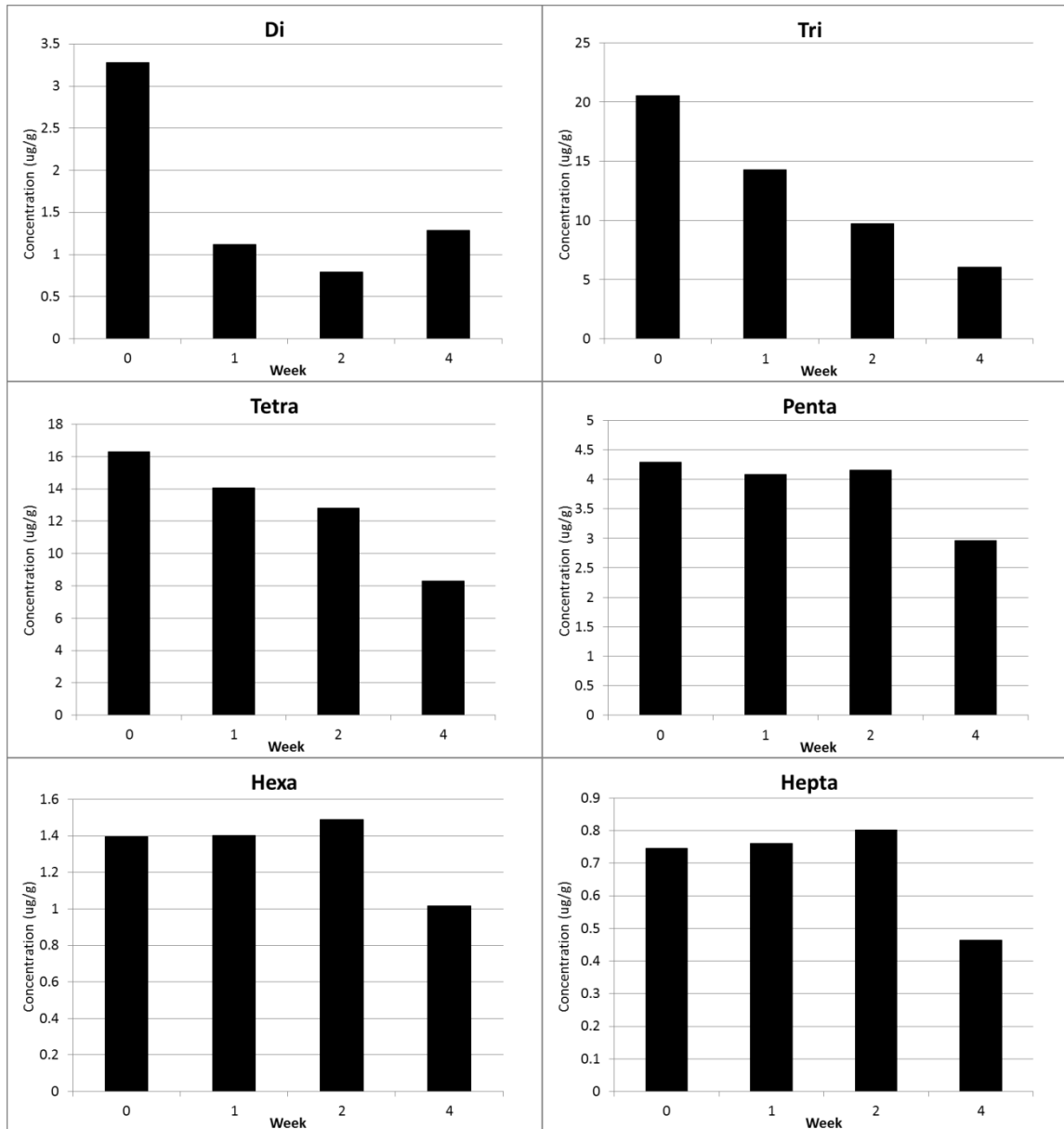
**Figure 10. Porewater PCB concentrations in sediments amended with the readily available carbons. Error bars represent the standard error (n=3).**



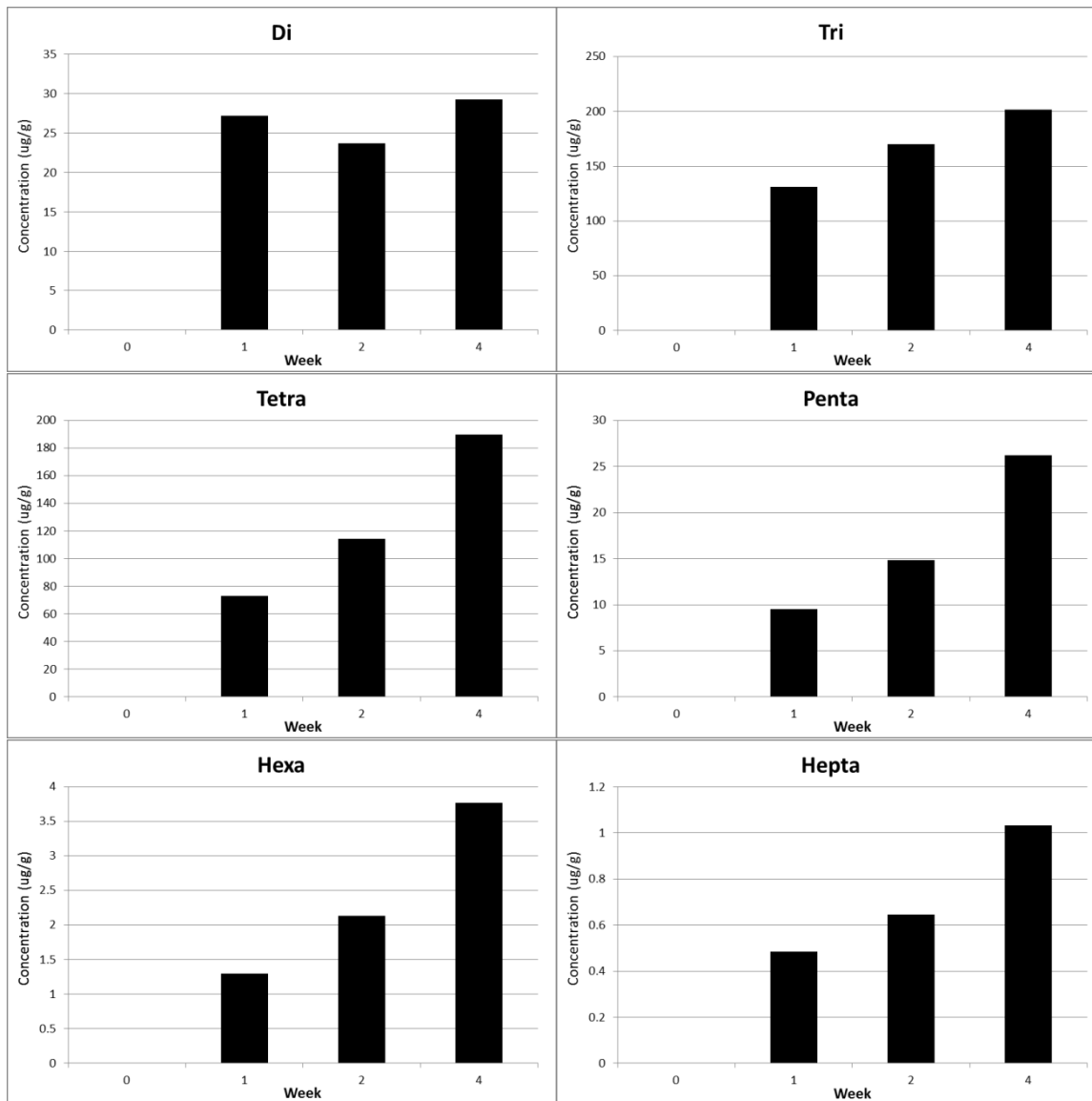
**Figure 11. Porewater PCB concentrations in sediments amended with the laboratory synthesized carbons. Error bars represent the standard error (n=3).**

## PCB mass transfer kinetics

Figure 12 shows the reductions in PCB concentrations in the sediment phase after being amended over one month exposure with the iron amended granulated biochar.



**Figure 12. Reductions in PCB homolog concentrations in sediment showing contaminant mass transfer out of the sediment phase.**



**Figure 13. Mass transfer of PCBs into the carbon phase.**

These reductions in PCB concentration in the sediment were accompanied with increases in the PCB concentration in the carbon with time (Figure 13).

These findings are in line with the previously mentioned short-term experiments using activated carbons that found quick reductions in porewater concentrations of lower chlorinated PCBs with a longer time required to show similar reductions for the higher chlorinated PCBs (Zimmerman et al., 2004; Sun and Ghosh, 2008). The mass transfer kinetics are quicker for the more water soluble less chlorinated PCBs, as they will more readily leave the sediment to enter the solution and become available for sorption by the carbons. Apart from being less water soluble, the more heavily chlorinated PCBs are likely to be more recalcitrant and more tightly bound up within the sediment, and this could also contribute towards the slower mass transfer of these more chlorinated compounds.



## Dechlorination studies

Although the oxidation of the ZVI impregnated carbon surface was visually apparent we were unable to detect any TCE in the aqueous PCE solution after 1 month. There was also visual evidence of oxidation in the surface of the iron filings, and although it was below quantitation limits, there was evidence of TCE formation in the chromatograms. The intermediate TCE may have also formed in the ZVI impregnated carbon treatment but it could be sorbed to the carbon reducing its concentration in the aqueous phase. It could have also been dechlorinated further compromising its detection using our current liquid-phase injection GC-ECD method. Other workers have reported PCB dechlorination using a ZVI impregnated activated carbon containing palladium (Choi et al., 2008; Choi et al., 2009), and a longer study is therefore needed to optimize the production of a dechlorinating zero valent iron impregnated biochar.

## **Mercury and methylmercury sorption**

Plots for the Hg (Figures 14 and 15) and MeHg (Figures 17 and 18) isotherms have been separated into readily available and laboratory synthesized carbons for clarity, as was done for the organic contaminants isotherms. The isotherms were fitted with a linear model and the resulting  $K_d$  values are summarized in Table X below.

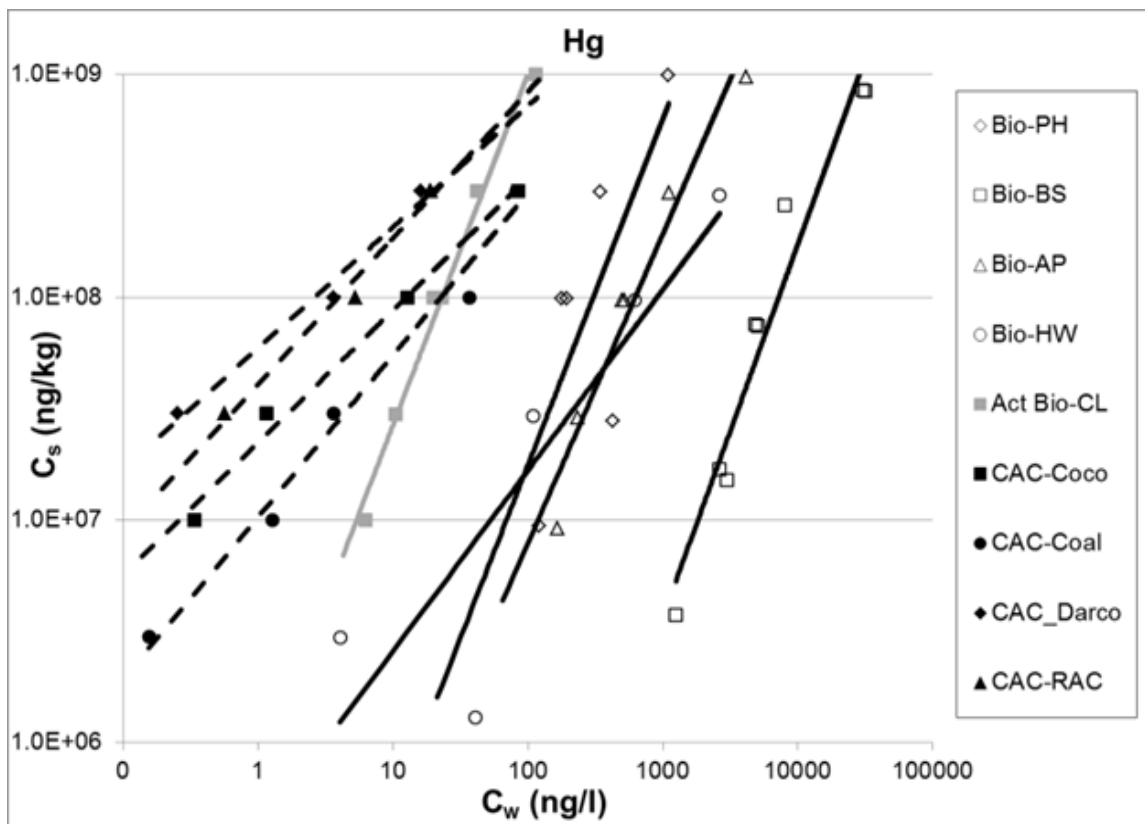
**Table 5.  $K_d$ s for Hg and MeHg sorption isotherms**

Carbon	Hg $K_d$	MeHg $K_d$	Hg $K_d$ : MeHg $K_d$
Bio-PH	7.83E+05	2.19E+05	3.58
Bio-BS	2.69E+04	9.61E+04	0.28
Bio-AP	2.36E+05	2.17E+05	1.09
Bio-HW	1.11E+05	2.72E+05	0.41
Act Bio-CL	8.30E+06	2.25E+05	36.83
CAC-Coco	3.64E+06	2.64E+05	13.74
CAC-Coal	3.55E+06	7.85E+04	45.22
CAC-Darco	1.59E+07	2.56E+05	62.3
CAC-RAC	1.92E+07	3.53E+05	54.4
Lab-PD	6.40E+04	2.62E+05	0.24
Lab-PHR	1.96E+05	1.30E+05	1.51
Lab-FePD	6.09E+04	3.24E+05	0.19
Lab-APD	4.16E+03	1.44E+04	0.29
Lab-APHR	5.92E+03	7.51E+03	0.79

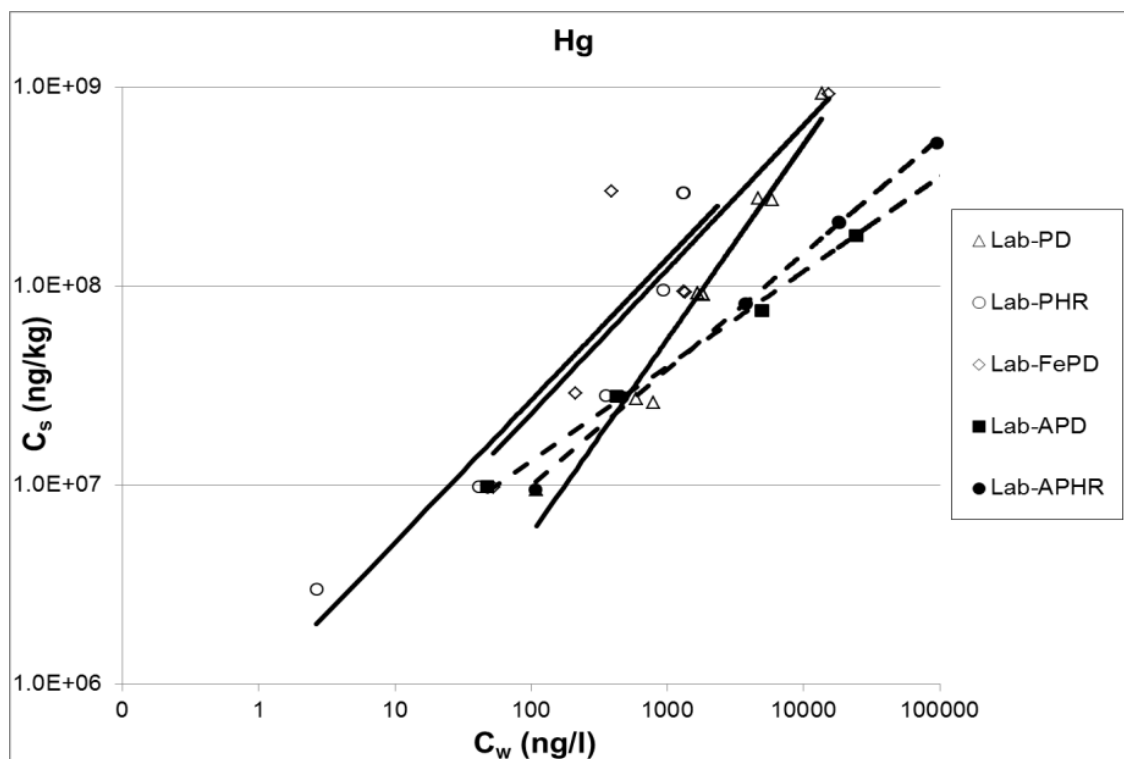
The pH in these isotherms was not buffered, but it was adjusted to near neutral at the beginning of the experiments. When the isotherms were taken down the pH was re-measured before Hg and MeHg analysis. pH values at the end of the experiment were consistently between 5-7 for all carbons except for the peanut hull biochar (BioPH, pH 7-8) and for the activated chicken litter biochar (Act Bio-CL, pH 9-10).

The Hg isotherms show that the commercially available activated carbons tested were the most effective at removing Hg from solution at the lowest concentrations. This could occur due to the presence of high energy sorption sites in the activated carbon surface for the Hg to sorb to. However the trends in the Hg isotherm plots suggest an experimental artifact could have contributed to the performance of the readily available biochars to be underestimated at the low Hg concentrations. Some of these carbons (specifically Bio-PH, Bio-BS, Bio-AP and Act Bio-CL) were sieved to a different particle size ( $<250\mu\text{m}$ ) than the other carbons ( $44\mu\text{m} - 177\mu\text{m}$ ), and therefore contained some finer particles that may have not been removed during the filtration process at the end of the isotherm study. Even though the amount of particles getting through the filter is believed to be very small they could still have an impact on the Hg concentrations measured in the solution after filtration due to their relatively higher Hg concentration. This artifact only has a significant effect at the lower Hg concentrations when lower levels of Hg are being measured.

Despite this artifact, the trends in the isotherm plots suggest that the number of sorption sites in the activated carbons may be more limited than in the biochars, as the difference between the carbons gets smaller with increasing Hg concentrations (Figure 14). This could be a problem when applying activated carbons in the field as their sorption sites could become saturated by other competing species in the sediment porewater.

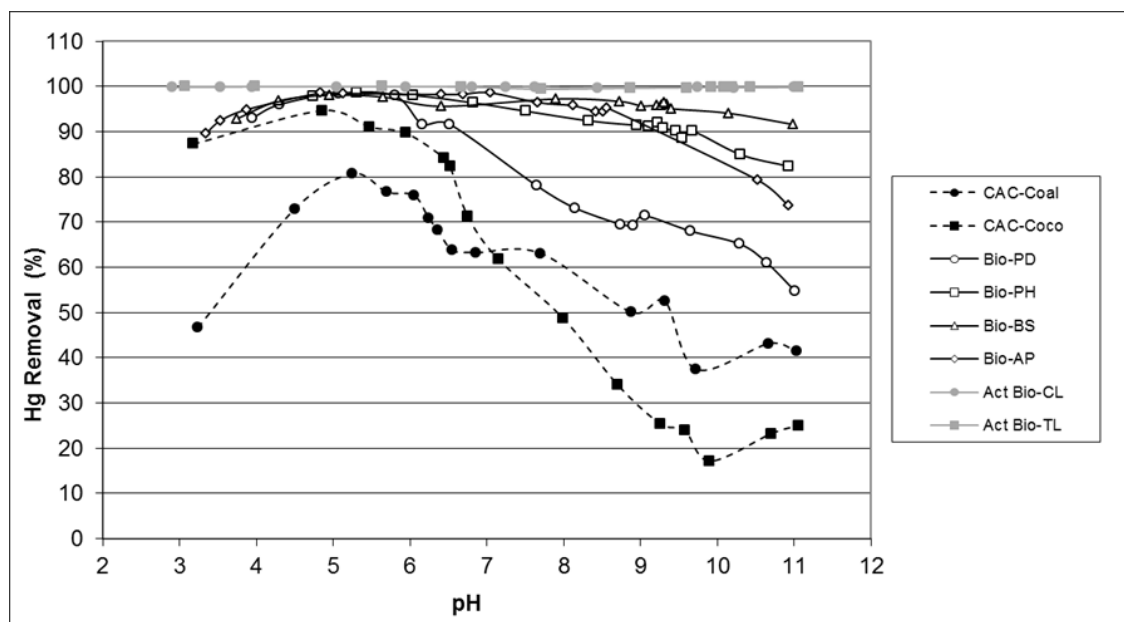


**Figure 14. Mercury sorption isotherms for commercially available carbons. Isotherms are plotted with dashed lines for the activated carbons, with a straight grey line for the activated chicken litter biochar and with straight black lines for the remainder of the biochars.**



**Figure 15. Mercury sorption isotherms for laboratory synthesized carbons. Isotherms are plotted with dashed lines for the biochars activated chemically in the laboratory, and with straight black lines for the remainder of the biochars.**

This lower capacity of the ACs to remove high concentrations of Hg from solution was also apparent in the high Hg concentration pH edge sorption experiment Figure 16. Here the poultry litter biochar consistently removed >99% of the Hg from solution over the whole pH range. The other biochars also consistently removed more Hg than the ACs from solution throughout the whole pH range. Carbons were generally less effective at higher and lower pHs except the poultry litter ones.



**Figure 16. Mercury removal by the readily available carbons at different pHs. Activated carbons are plotted with dashed lines, poultry litter activated biochars with grey lines and the remainder of the biochars are plotted with solid black lines.**

Despite the experimental artifact potentially underestimating the sorption of the chicken litter derived biochar, it still was one of the most effective carbons at removing Hg from solution in the Hg isotherms studies ( $K_d = 8.30E+06$ ) and they were consistently the most effective carbon at removing high Hg concentrations from solution in the pH edge study. Apart from having relatively high levels of sulfur, broiler litter biochars have been reported to have relatively higher phosphorus contents (3.7%) than chars produced from other source materials like coal, coconut shell or wood (<0.2%) (Lima et al., 2009). It has been postulated that the presence of phosphorus, primarily in the form of phosphate, can create a negative charge on the carbon that can ionically bind positively charged metal ions like  $Hg^{2+}$  (Lima and Marshall, 2007; Lima et al., 2009). Cao et al., (2009) found that low temperature cow manure derived biochars were more effective at immobilizing  $Pb^{2+}$  than a CAC. The authors confirmed by X-ray diffraction that the main mechanism behind this increased  $Pb^{2+}$  immobilization by the biochars was the formation of a Pb-phosphate precipitate. It is therefore likely for the presence of phosphate groups on the poultry litter char surface to be at least in part responsible for their increased  $Hg^{2+}$  removal relative to the other carbons. It is important to note that their steam activation may have also improved their surface area relative to the other biochars which may have also been a contributing factor to this increased sorption. Also the fact that they increased the pH concentration to a much higher level than the other biochars should not be overlooked as this could have also had an impact on the amount of Hg removal from solution.

Although the exact mechanism by which this poultry litter char is removing Hg from solution cannot be identified in the current study, these results are particularly encouraging with respect to the use of these kinds of chars for the remediation of Hg impacted sediments. Further studies to elucidate this sorption mechanism would enable the identification of the necessary characteristics needed in a carbon to improve its Hg binding properties, which could in turn

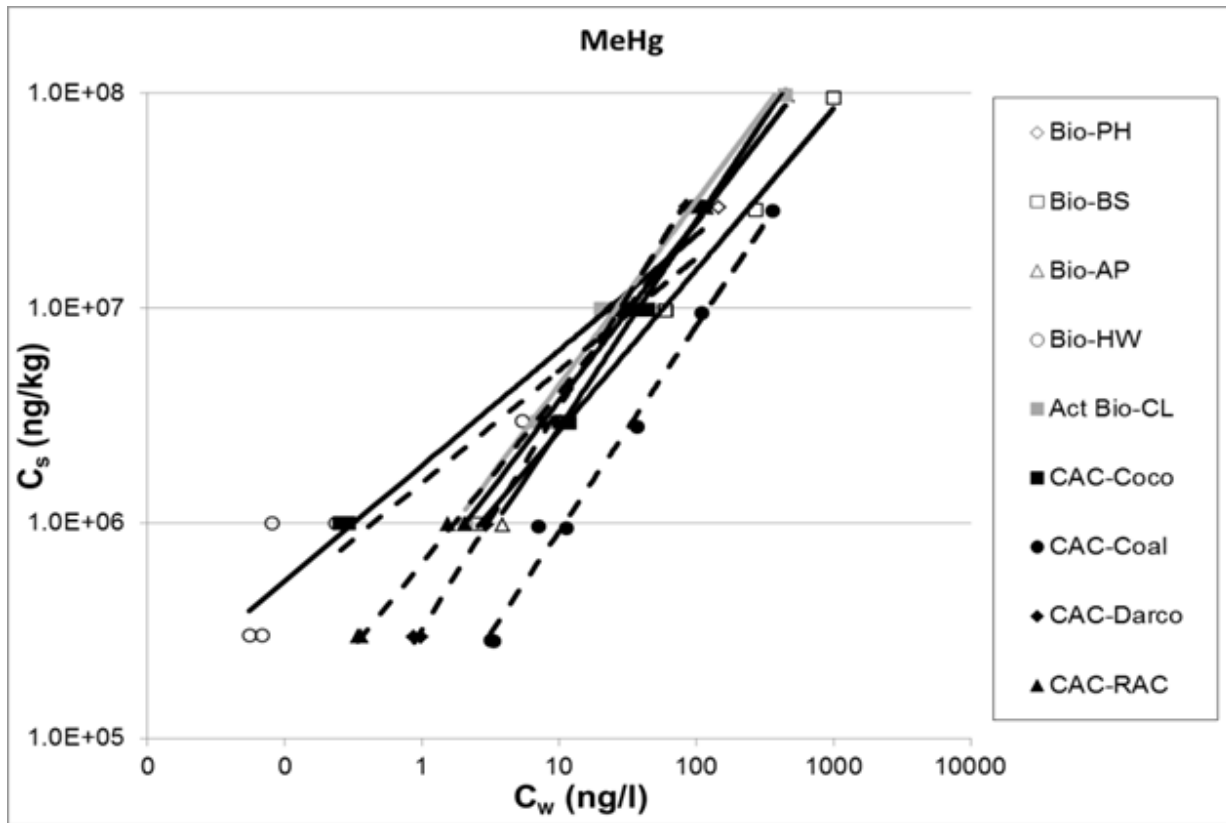
provide the necessary information for the synthesis of biochars especially adapted for Hg sorption. However, it will also be important to quantify the amount of phosphate that could be leached from these biochars if released to the sediment environment as this could create an environmental impact of its own.

The chemical activation of the laboratory produced biochar was counterproductive in terms of Hg sorption (Figure 15) and it was these chemically activated biochars that had the weakest Hg binding properties. Despite their large surface areas they did not appear to have the higher energy sorption sites that seemed to be present in the commercially available steam activated carbons favoring Hg sorption at low concentration. It therefore seems like steam activation is a more favorable method of activation when considering Hg sorption. One issue we found with phosphoric acid chemical activation is the challenge of washing the acid off after activation and the resulting low pH of the carbon that can impact sorption of Hg. Activation with steam could also potentially produce more oxygen containing functional groups in the carbon surface than a chemical activation would. As occurred with the steam activated carbons, the performance of these chemically activated biochars also dropped relative to that of the other biochars with increasing Hg concentrations. This again suggests their sorption potential could be reduced substantially further in the field due to competition effects. ACs have been shown to have a relatively low affinity to other heavy metal cations like  $\text{Cu}^{2+}$  or  $\text{Pb}^{2+}$  despite their high surface areas (Cao et al., 2009; Jaramillo et al., 2009). The governing role of surface functional groups over that of surface area has been reported when applying biochars to soil to sequester heavy metals (Uchimiya et al., 2011). ACs are usually produced at higher temperatures than the biochars used in this study, which together with their activation process contributes to their increased surface area relative to the biochars. However, using Fourier transform infrared spectra Uchimiya et al. (2011) showed that as pyrolysis temperature are increased above  $350^{\circ}\text{C}$  the presence of surface carboxyl and other functional groups that could enhance  $\text{Hg}^{2+}$  sorption is reduced. In increasing the potential of the carbon to sorb organic contaminants the ability of the carbon to sorb inorganic contaminants could therefore be compromised (Beesley et al., 2011). A better understanding of how biochar manufacturing parameters (e.g source material, pyrolysis temperature or activation process) impact the sorption of inorganic contaminants like Hg could enable the synthesis of a carbon suited for the remediation of sediments impacted with both organic and inorganic contaminants.

Despite the success of impregnating activated carbons with iron oxides for the treatment of waters contaminated with inorganic contaminants (Reed, 2000; Vaughan and Reed, 2005), the impregnation of iron oxides onto the biochar in this study has a negligible effect on the sorption capacity of the carbon for mercury (Figure 15). In another study Reed et al. (2000) found that iron impregnated ACs were substantially more effective at removing arsenic from solution than virgin activated carbon, however they were only slightly more effective than the virgin AC at removing  $\text{Pb(II)}$  and  $\text{Hg(II)}$  at high aqueous concentrations.

Differences in sorption capacity for MeHg were not as large between carbons relative to Hg (Figures 17 and 18). The commercial activated carbons (coconut, reactivated carbon, and lignite based Darco) performed quite well for MeHg adsorption. However, the chemically activated carbons prepared in the laboratory were not as effective in removing MeHg from solution, again suggesting this form of activation may not be the most appropriate when considering carbons for the remediation of MeHg impacted sediments. Interestingly the steam activated commercial

carbons and biochars were 13-62 times better at removing Hg from solution than MeHg, whereas the difference in Hg and MeHg sorption was not that pronounced for other carbons (see  $K_d$  Hg : MeHg  $K_d$  ratio in Table 5.) This suggests Hg and MeHg could have different sorption mechanisms, and that activation using steam may contribute to an enhanced sorption of Hg relative to MeHg. Further characterization of the sorption of Hg and MeHg to the carbon surface is needed to inform about what these different sorption mechanisms could be.



**Figure 17. Methyl mercury sorption isotherms for commercially available carbons. Isotherms are plotted with dashed lines for the activated carbons, with a straight grey line for the activated chicken litter biochar and with straight black lines for the remainder of the biochars.**

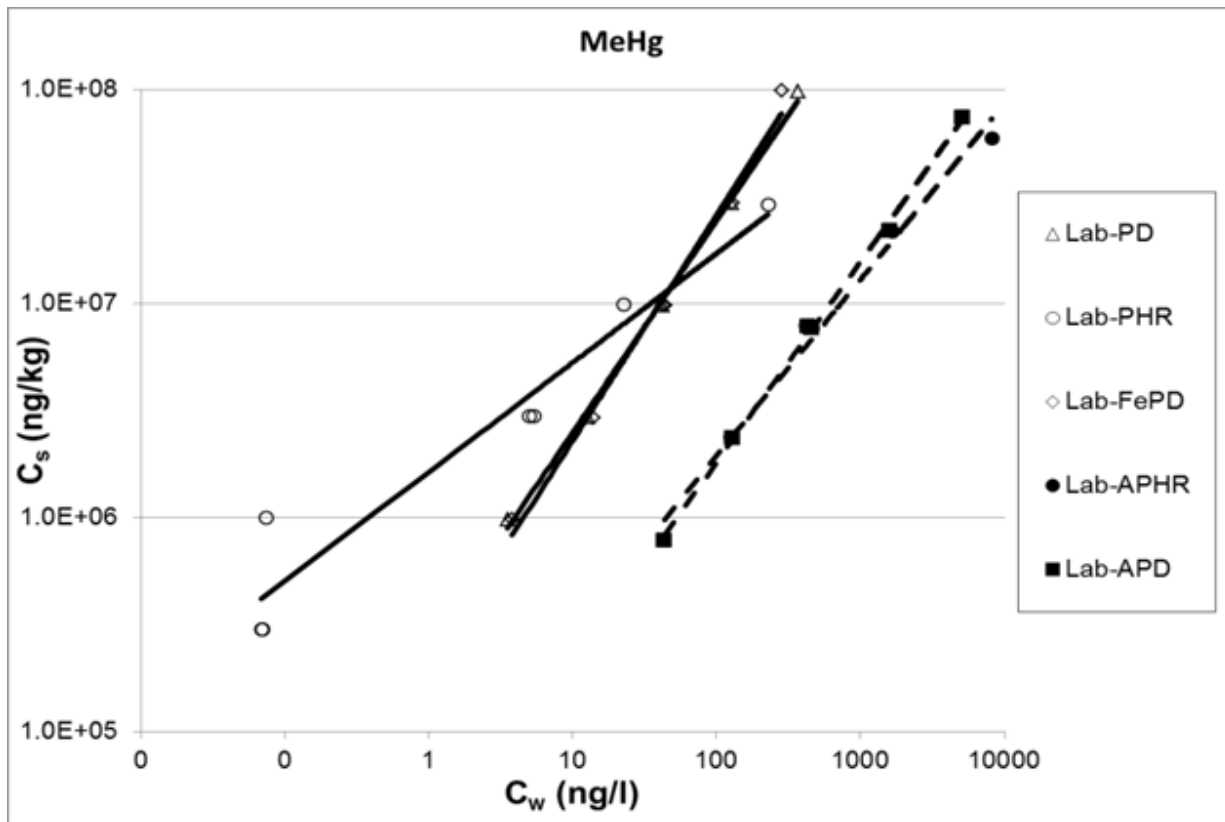


Figure 18. Methyl mercury sorption isotherms for laboratory synthesized carbons. Isotherms are plotted with dashed lines for the biochars activated chemically in the laboratory, and with straight black lines for the remainder of the biochars.

## Carbon structural and settling characteristics

The structural properties of a selection of carbons are displayed in Table 6.

**Table 6. Structural properties of the carbons**

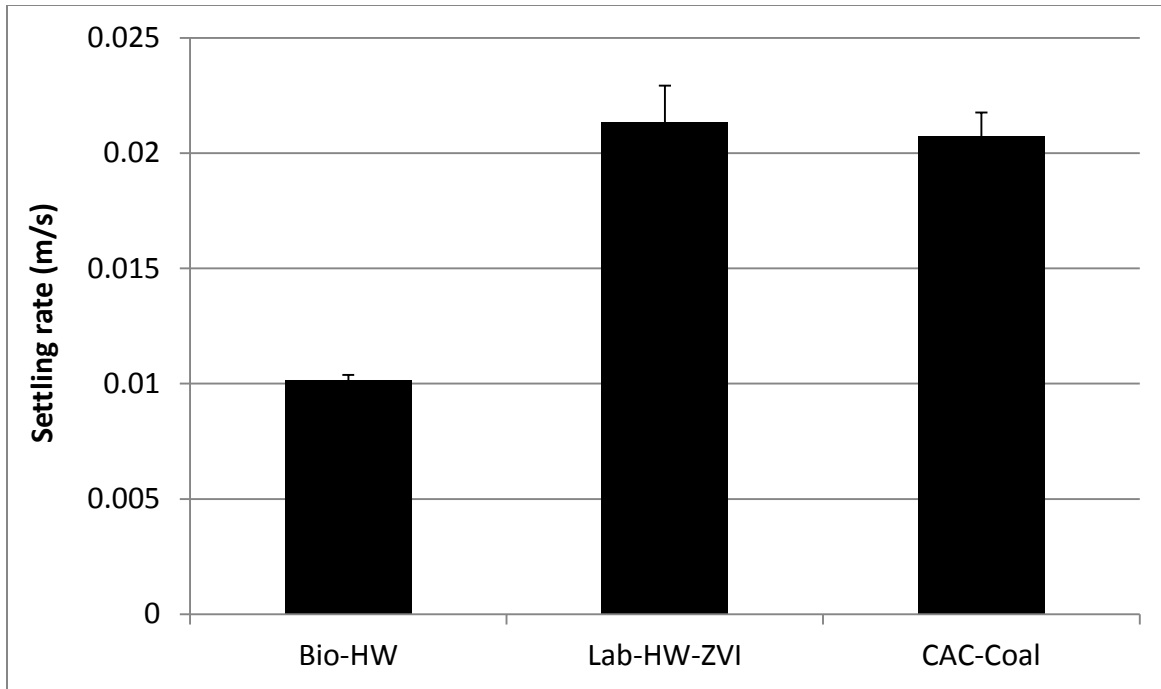
Carbon	Skeletal density (g/cm <sup>3</sup> )	Avg Bulk Density (g/cm <sup>3</sup> )
Bio-HW	1.29	0.638
Bio-PH	1.28	0.598
Bio-AP	1.23	0.653
Act Bio-CL	1.97	0.920
CAC-Coal	1.61	0.640
Lab-HW-ZVI	1.43	0.807

The unactivated biochars have a skeletal density between 1.2-1.3 g/cm<sup>3</sup>. Thus all biochars after becoming wet should settle in water. However, the density of the biochars is smaller compared to the activated carbons tested. The raw material used for making the carbons has a significant impact on the final density and hardness of the product. For this reason, most commercially available activated carbons are made from either coal or coconut shell which is a very dense form of biomass. The bulk density of all carbons tested was less than 1 g/cm<sup>3</sup> due to the high internal porosity of the carbons and also inter-particle porosity of the packed materials. These inter-particle and intra-particle pores are filled with water upon contact allowing the carbon to settle in water. Among the carbons tested, the chicken litter activated carbon and the iron amended activated carbon had the highest bulk density.

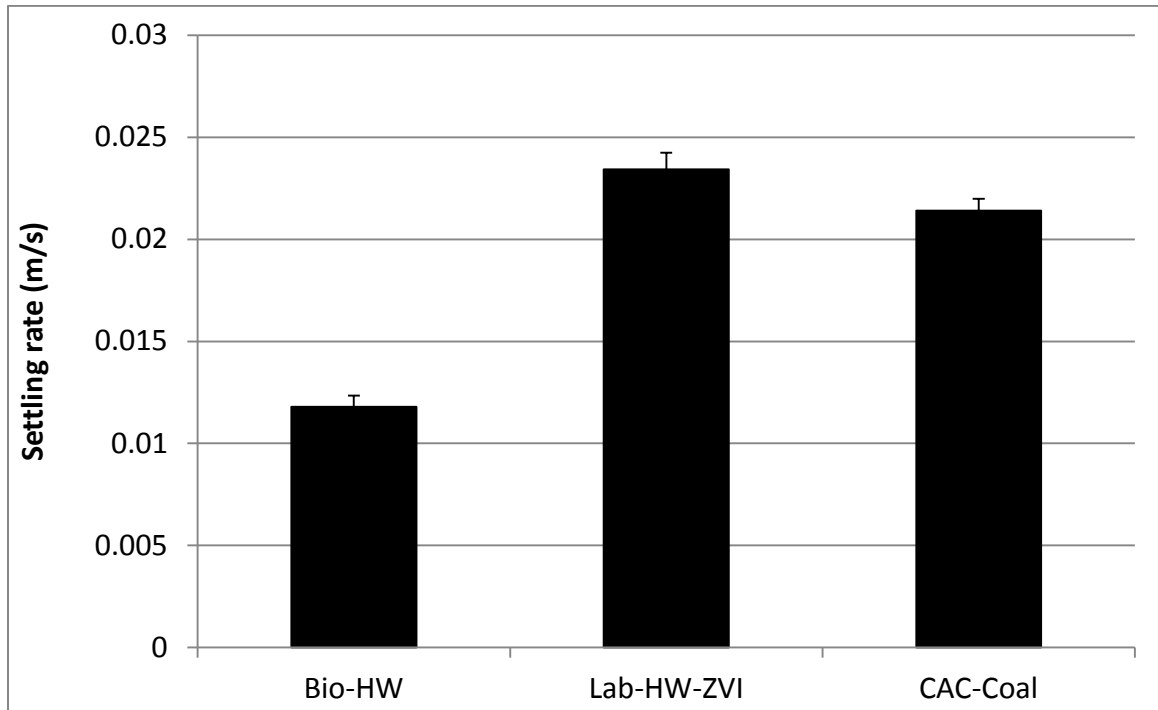
These results shown in Table 6 confirm that unactivated biochars are less dense than activated carbons. Biochar stability in the sediment environment may therefore be compromised in high energy systems. However, impregnating hardwood biochar with iron (Lab-HW-ZVI) increased the density reducing the differences relative to activated carbons in terms of skeletal density and actually making them denser than commercially available activated carbons (CAC-Coal) in terms of bulk density.

This increase in density by iron impregnation was also tested using carbon settling tests. Figures 19 and 20 show how the biochar settles at considerably lower rates than the activated carbons in both fresh and salt water, but after the biochar is impregnated with iron its settling rates are similar to those of the AC. These results suggest that impregnating biochars with iron could be a feasible way of improving their stability in sediment environments.





**Figure 19. Carbon settling rates in freshwater. Error bars represent the standard error (n=5).**



**Figure 20. Carbon settling rates in saltwater (10ppt). Error bars represent the standard error (n=5).**

## Conclusion and Implications for Future Research

### Conclusions and Implications

Biochars were able to sorb organic contaminants, Hg, and MeHg, making them attractive alternatives to ACs in sites contaminated with both organic and inorganic contaminants. However, due to their lower surface area, unactivated biochars have a lower affinity for organic contaminants than ACs. The results of this study suggest that waste biomass products could be used for the in-situ remediation of sediments impacted with organic contaminants, but including an activation step in their manufacture is needed to enable a reduction in porewater concentrations to the level close to what is achieved using commercially available ACs. To our knowledge this study is the first comprehensive assessment of sorption isotherms at low environmentally relevant concentrations of PCBs, PAHs, DDx, Hg, and MeHg for a large range of biochars and activated carbons.

Commercial steam activated carbons showed strong sorption of Hg and MeHg from solution at environmentally relevant low concentrations in the range of tens of ng/L. Laboratory activation of two biochars using phosphoric acid treatment was not successful in enhancing the sorption characteristics for Hg and MeHg. It was in fact the biochars (especially poultry litter activated carbon) that was able to remove more Hg from solution than any other carbons at high Hg concentrations.

The ability of the poultry litter carbons was particularly encouraging with respect to Hg sorption. We hypothesize this could be due to their high phosphate content. Identifying the exact mechanism by which Hg binds to the carbons by X-ray diffraction would enable the identification of the desirable carbon properties to maximize Hg sorption, enabling the production of carbons with optimized Hg binding properties. The results of the Hg isotherms and pH edge sorption studies suggest it is challenging to find a carbon with both a high surface area, and therefore high organic contaminant sorption potential, and a large capacity for Hg sorption. However, improving our understanding of the mechanisms by which Hg sorbs to carbon could enable the synthesis of carbons that combine optimized organic and inorganic contaminant binding properties. The production of these carbons will therefore require a detailed investigation of how the activation and pyrolysis processes can be adjusted to maximize carbon surface area without compromising the specific surface functionality necessary for inorganic contaminant sorption. Alternatively, a combination of biochars could be used at the same time. This could include an activated biochar derived from waste biomass (e.g Phragmites activated biochar) for organic contaminant sorption and a poultry litter biochar for Hg sorption.

If it is indeed the high phosphate content in the biochars that enables this enhanced sorption, it will be important to understand the stability of this phosphate within the biochar and the risk associated with its deployment in the field in terms of phosphate nutrient contamination.

The use of iron to impregnate the carbons was effective in improving their density and settling characteristics but had limited success in improving the sorption capacity of the carbons to Hg and MeHg or in enabling the dechlorination of chlorinated organic compounds. The density of the unactivated biochars was lower than that of the activated carbons before impregnation, so

their amendment in high energy systems could be problematic unless their settling characteristics are improved by techniques like the one described in this study. Other workers have been successful in dechlorinating PCBs using ZVI amended activated carbons (Choi et al., 2008; Choi et al., 2009), so longer term focused experiments are needed to optimize the production of ZVI impregnated biochars that are able to enhance PCB dechlorination as well as improving their density and settling characteristics.

### **Leveraged funding and technology transition.**

1. Low level sorption isotherm studies for MeHg. Low-level (1- 100 ng/L) sorption isotherm studies with MeHg was not planned as a part of the proposed SEED project but was made possible through additional leveraged support from DuPont and the Dow Chemical Company. This allowed collaboration with Dr. Cindy Gilmour at the Smithsonian Environmental Research Center and further exploration of MeHg sorption characteristics of the biochars. The high cost of low level MeHg analysis would not have allowed us to perform these isotherm studies within the scope of the SEED project.

2. Feasibility of using biochars for dioxin and furan impacted soils. Sorption of dioxins and furans on biochars was not planned as a part of the proposed SEED project primarily due to the high cost of analysis of these chemicals at environmentally relevant low concentrations. Collaboration with Dow Chemical Company and internal funding from Dow allowed the comparison of commercial activated carbons (coal, lignite, coconut shell based, and regenerated) and biochars (pine and corn stover based) for the sorption of dioxins and furans using test methods similar to the ones adopted in this study. Results of these laboratory studies with dioxins and furans were recently published (Chai et al. 2012). A pilot study has been initiated at Dow Chemical facilities to evaluate the effectiveness of selected activated carbons biochar for the reduction of bioavailability of dioxins and furans in floodplain soils.

## **Future research**

This SEED project explored a range of biochars and activated/amended biochars for the potential use in sediment amendment for reducing the bioavailability of PCBs, PAHs, DDTx, Hg, and MeHg. Based on the results from this study, the following future research areas are proposed:

1. Further exploration of the use of native phragmites activated biochar for the treatment of marshes impacted with organics.

- Investigate pilot-scale production of phragmites activated biochar maximizing contaminant sorption properties
- Investigate biomass/unit area in a phragmites marsh and evaluate carbon sequestration potential

2. Further exploration of the mercury sorption of poultry litter activated biochar.

- Investigate mechanism of Hg adsorption in poultry litter activated biochar
- Collaborate with USDA and a carbon manufacturer (Calgon pilot facilities) to test feasibility and scale up production
- Explore the extent of and ways to reduce nutrient leaching from poultry litter activated biochar
- Explore the potential of reducing methylation rates of Hg with poultry litter activated biochars

3. Explore combination of Phragmites and poultry litter activated biochars to achieve sequestration of organics and Hg. While the product made from phragmites has excellent organic sorption capability as demonstrated in the SEED project, the poultry litter based product has superior mercury sorption characteristics. The combination of the two products either before or after the activation process may yield a biomass derived activated carbon that is suitable for organics and Hg sequestration.

4. Evaluate the feasibility and cost of pilot-scale production of iron amended biochars to enhance settling characteristics. Work will involve collaboration with an activated carbon manufacturing industry. We believe longer-term focused experiments are necessary to fully understand the capability of iron-amended biochars to induce dechlorination of low molecular weight chlorinated organics.

5. Perform laboratory treatability and bioaccumulation studies with two DoD field site sediments containing organics and mercury (Aberdeen Proving Grounds, Quantico) and evaluate the feasibility of using selected biochars in the field.

## Publications and Presentations

### Publications

The potential of biochar amendments to remediate contaminated soils. Gomez-Eyles, J.L., Beesley, L., Moreno-Jiménez, E., Ghosh U., and Sizmur, T. (in press). In Ladygina N. & Rineau F. [eds.]. Biochar and soil biota. Science Publishers, Enfield, New Hampshire 03748, USA/Jersey, British Isles.

*(Some of the literature review for this study was used to write this book chapter)*

Effectiveness of Activated Carbon and Biochar in Reducing the Availability of Polychlorinated Dibenzo-p-dioxins/dibenzofurans in Soils. Yunzhou Chai, Rebecca J. Currie, John W. Davis, Michael Wilken, Greg D. Martin, Vyacheslav N. Fishman, and Upal Ghosh. Environ. Sci. Technol., 46, 1035-1043, 2011.

*(Leveraged funding and effort by Dow Chemical Company resulted in this publication)*

### Presentations

Biochars and activated carbons for the in-situ sequestration of organic contaminants and mercury in sediments. Gomez-Eyles J.L., Yupanqui, C., Xia, H., Beckingham B., Kwon, S.J., Riedel, G., Gilmour, C. and Ghosh, U. Society of Environmental Toxicology and Chemistry (SETAC) – Chesapeake Bay Chapter, College Park, MD. April 2012 – Platform presentation.

Sorption of Priority Pollutants to Biochars and Activated Carbons For Application to Soil and Sediment Remediation. Beckingham B., Gomez-Eyles J.L., Riedel, G., Gilmour, C. and Ghosh, U. European Geosciences Union (EGU) General Assembly 2012 Vienna, Austria. April 2012 – Poster presentation.

Biochars and activated carbons for the in-situ sequestration of organic contaminants and mercury in sediments. Gomez-Eyles J.L., Beckingham B., Kwon, S.J., Riedel, G., Gilmour, C. and Ghosh, U. Society of Environmental Toxicology and Chemistry (SETAC) – North America Annual Meeting, Boston, MA. November 2011 – Platform presentation.

Activated biochars with iron for in-situ sequestration of organics, metals, and carbon. U. Ghosh and J. L. Gomez-Eyles. SERDP/ESTCP Annual Symposium, Washington, DC, December 1, 2010.

Evaluating the potential of biochars for the in situ remediation of sediments contaminated with organic contaminants, mercury and methylmercury. Jose L. Gomez-Eyles, Carmen Yupanqui, Barbara Beckingham, Seokjoon Kwon, Georgia Riedel, Cynthia Gilmour and Upal Ghosh. Gordon Research Conference: Environmental Sciences – Water. June, 2012. Poster presentation and best poster award winner.

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