Emerging Bioreactor Research in Iowa: Design and Performance

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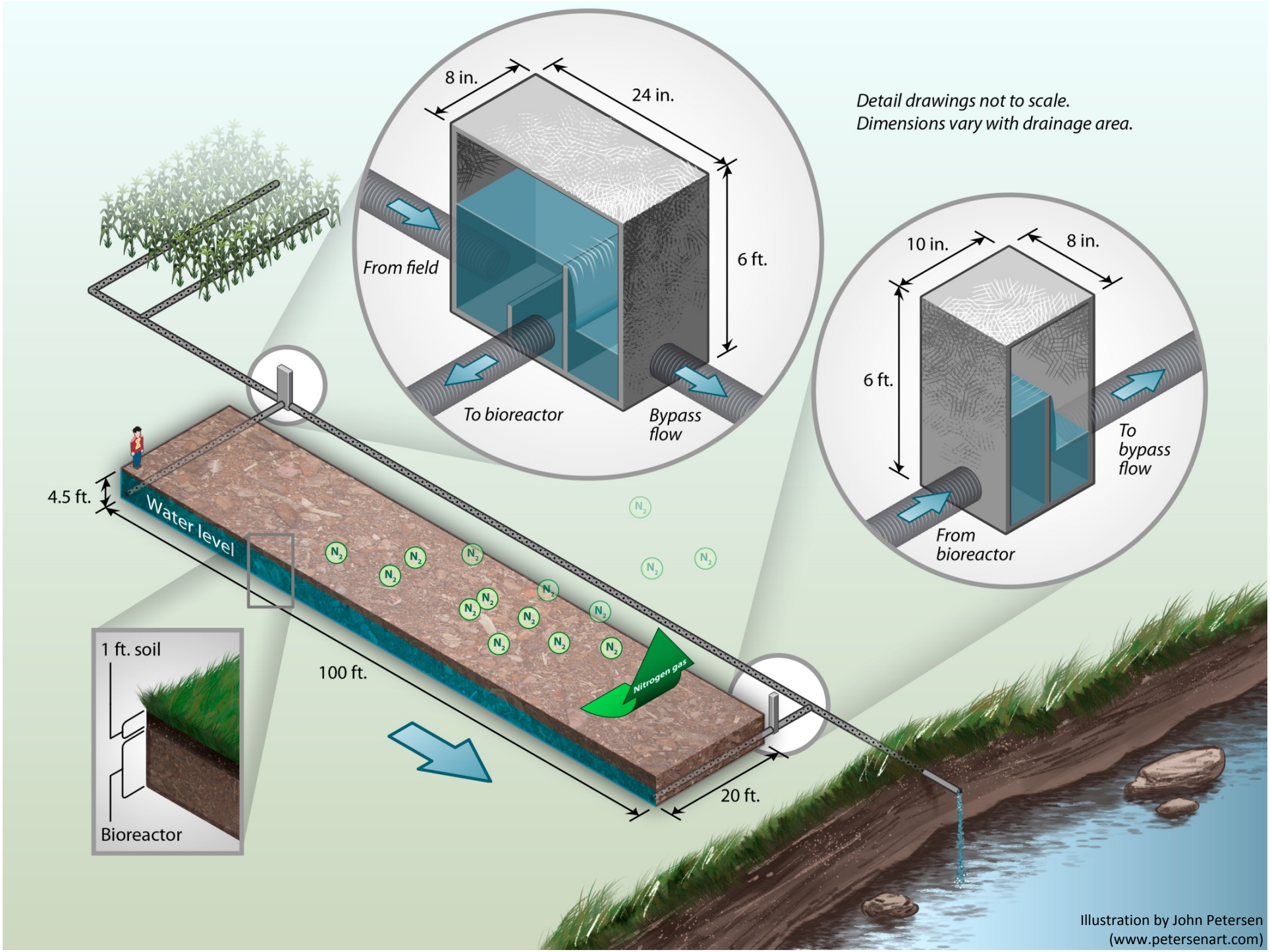
NIFA Water Quality Conference
May 21-24, 2012
Portland, Oregon


8 in.
24 in.
6 ft.
From field
To bioreactor
Bypass flow
Detail drawings not to scale.
Dimensions vary with drainage area.
10 in.
8 in.
6 ft.
To bypass flow
From bioreactor
4.5 ft.
Water level
100 ft.
20 ft.
Nitrogen gas
1 ft. soil
Bioreactor
Illustration by John Petersen
(www.petersenart.com)

Design Model User Interface

Subsurface Drainage Bioreactor Design

Developed by M. Helmers and L. Christianson, ABE Iowa State Unviersity

Instructions: Enter values in gray cells

Field Information:		
Tile Size (in)	7.7386	Known from site
Tile Grade (%)	1	Known from site
Dual Wall	no	no
Velocity in Pipe (ft/s)	2.94	Mannings Gravity Driven Flow Equation = $1.49 \times \sqrt{\left(\frac{Tile\,Grade}{100}\right)} \times \frac{\left(\frac{Tile\,Size}{(Conversion)}\right)^{\frac{2}{3}}}{0.012(for\,dual\,wall)OR\,0.015(for\,non-dual\,walled)}$
Peak Flow from Tile Size (cfs)	0.9611	Flow rate = Velocity x Area of Tile
Media Information:		
Conductivity of Wood Media (ft/s) (K)	0.31168	Converted from 9.5 cm/s to ft/s; value determined in Porous Media Lab, ABE-ISU
Porosity of Wood (ρ)	0.7	Taken from van Driel et al., 2006
Bioreactor Inputs and Calculations:		
Flow Length (ft) (L)	80	Iteratively choose
Trench Width (ft) (W)	33	Iteratively choose
Inlet height (ft)	2	Iteratively choose
Outlet height (ft)	1	Iteratively choose
Head Drop (ft) (ΔH)	1	Calculated based on diffference between inlet and outlet
Flow Depth (ft) (d)	1.5	Calculated to be in bioreactor middle (average of inlet and outlet height)
Hydraulic Gradient (i)	0.0125	Head Drop / Flow Length
Results:		
Bioreactor Flow Rate (cfs) (Q)	0.19	Darcy's Law for Porous Media Flow = $Hyd.Conductivity \times Hyd.Gradient \times Flow\,Area = KiA = Ki(W \times d)$
Hydraulic Retention Time (hours) (HRT)	**3.99**	HRT = $\tau = \frac{Volume \times porosity}{Flow\,rate} = \frac{V\rho}{Q} = \frac{l \times w \times d \times \rho}{Q}$ (conversions included)
% of peak flow that can be passed through bioreactor	**20.07**	Bioreactor Flow Rate / Peak Flow from Tile

Bioreactors are designed to treat approximately 20% of the peak flow rate.
The design retention time is between 4 - 8 hours (Robertson et al., 2000; van Driel et al., 2006; Christianso

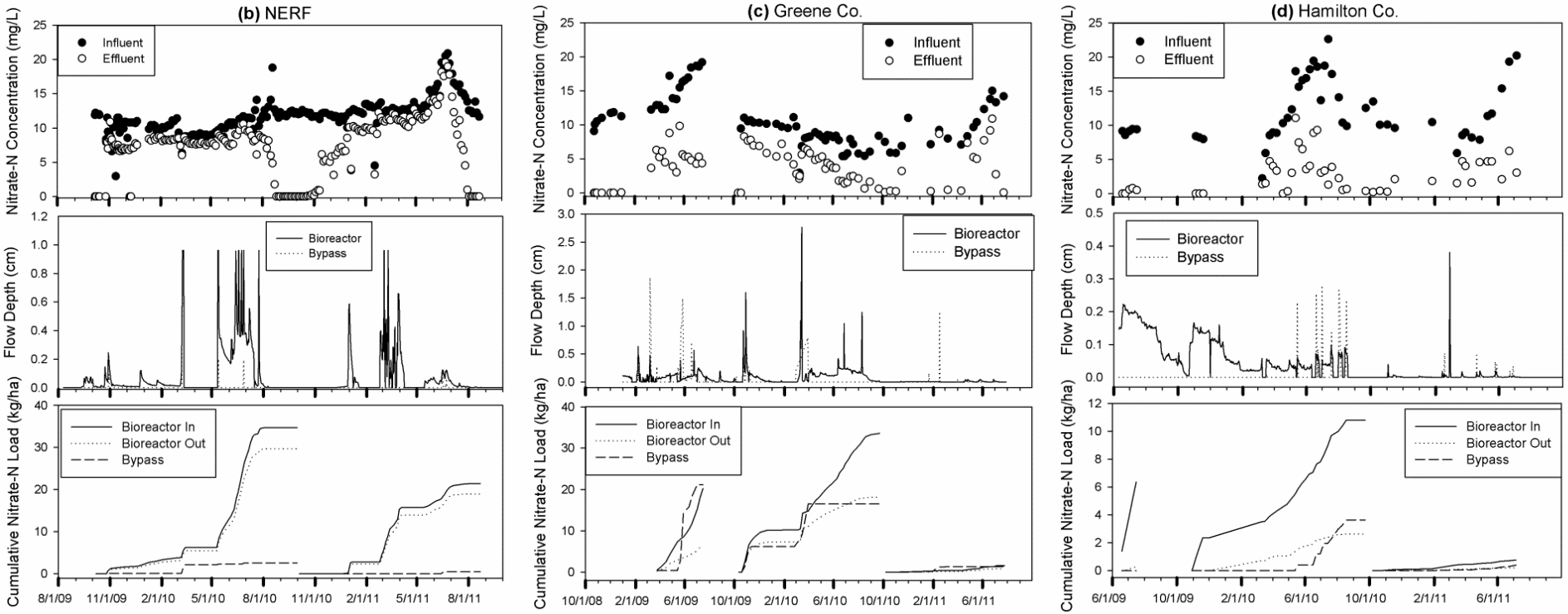
Three Sites in Iowa

Northeast Research Farm - NERF (Nashua)
Installed April 2009
14.2 ha drainage area
36.6 x 4.6 x 1.0 m

Three Sites in Iowa

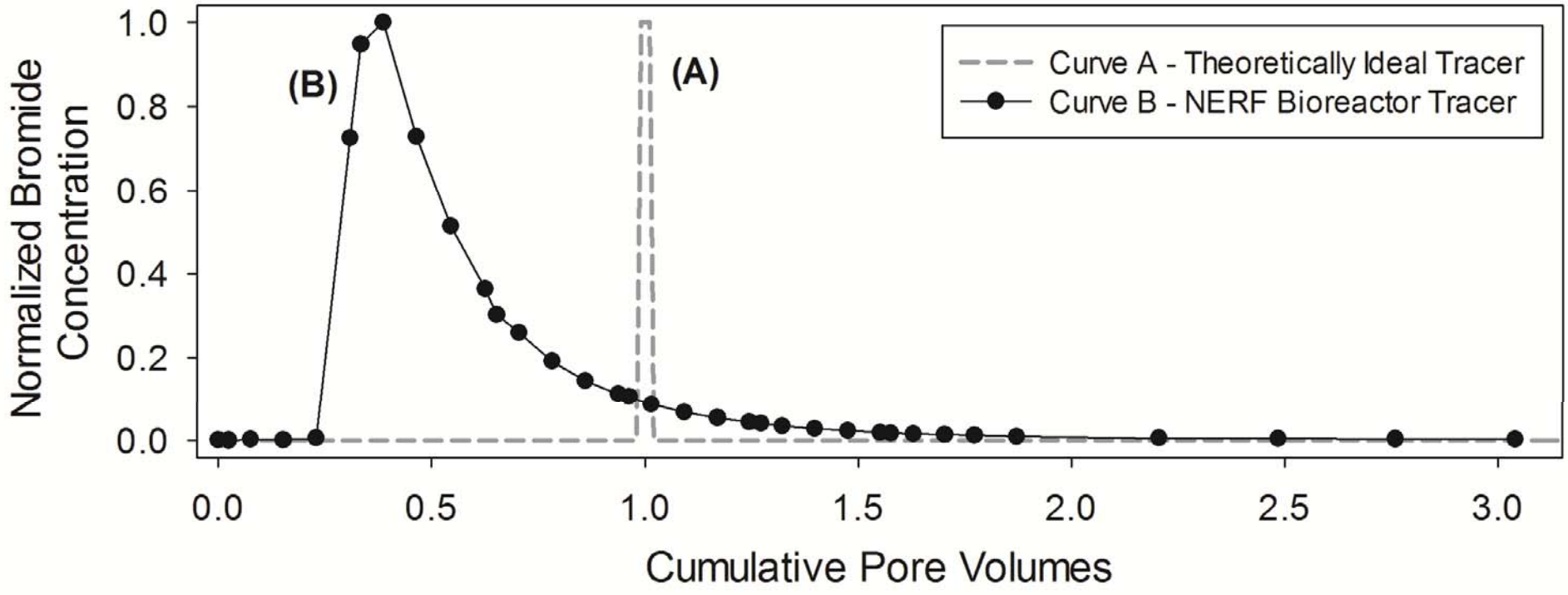
Greene Co.
Installed Aug. 2008
19 ha drainage area
15.2 x 7.6 x 1.1 m

Hamilton Co.
Installed June 2009
20.2 ha drainage area
30.5 x 3.7 x 0.9 m



Mean annual total load reduction	12%-14%	27%-33%	49%-57%
Load removed (kg N/ha)	2.5-5.1	0.8-15.5	0.6-8.1
Percent of water treated	91%-99%	51%-68%	73%-87%
Removal Rate (g $N/m^3/dy$)	0.86-1.56	0.41-7.76	0.42-5.02

NERF Bioreactor Design Evaluation



Tracer Residence Time: 3.5 hrs
Theoretical Retention Time: 6.3 hrs
Effective Volume (*e*): 0.55
Hydraulic Efficiency (λ):0.40

Effective plug flow, but ineffective utilization of flow volume

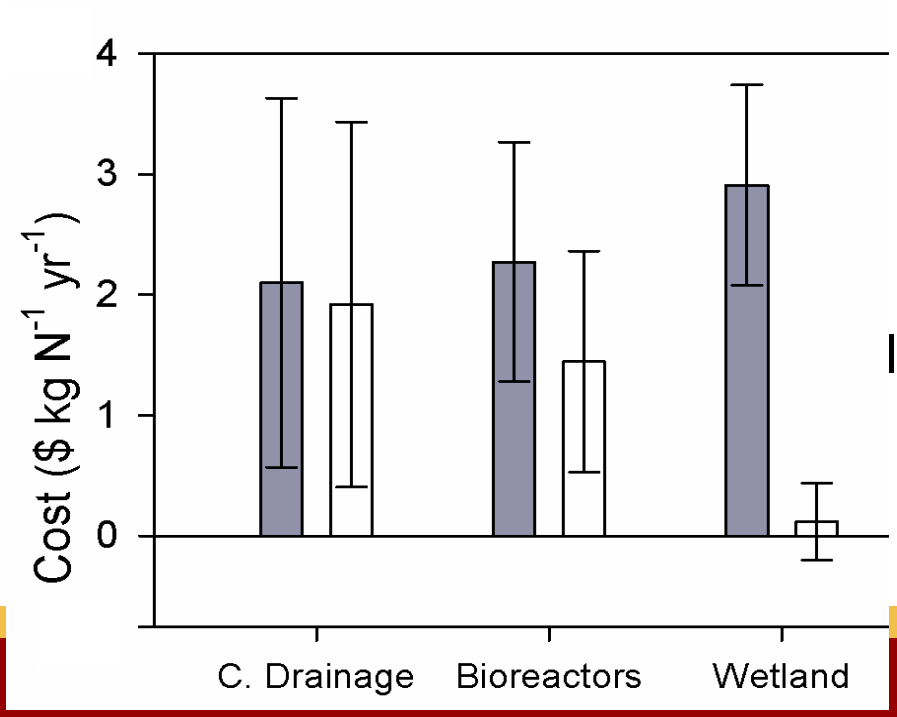
What do bioreactors cost?

	Structure	Contractor	Woodchips	Supplies	Total	$ total/ha drained
Greene Co.	$2,750.00	$5,250.00	$1,245.00	$500.00	$9,745.00	$512.35
Hamilton Co.	$1,640.00	NA†	$2,400.00	$350.00	$4,390.00	$216.96
Iowa 1	$1,970.00	$1,800.00	$3,350.00	$560.00	$7,680.00	$316.30
Iowa 2	$1,270.00	$1,890.00	$3,000.00	$780.00	$6,940.00	$428.73
Iowa 3	$1,640.00	$5,030.00	$4,650.00	$500.00	$11,820.00	$194.72
Iowa 4	$1,480.00	$2,710.00	$2,520.00	$400.00	$7,110.00	$585.64

†contractor time donated

Range: $78.80/ac to $237.00/ac

Average: $152.07/ac



Amortized Drainage BMP Costs over 50 years:

Installation, Maintenance, Replacement

N-Based Equalized Annual Cost (EAC)

N-Based EAC with Government Payment

4% real discount rate

Acknowledgements

- Keegan Kult and Todd Sutphin at the Iowa Soybean Association
  - Agriculture's Clean Water Alliance
  - The Sand County Foundation
- Coldwater Palmer Watershed Association
- The Leopold Center for Sustainable Agriculture
- Agriculture and Food Research Initiative Competitive Grant no. 2011-67011-30648 from the USDA NIFA.
- Project number: GNC09-103 from the USDA Sustainable Agriculture Research and Education North Central Region Graduate Student Grant Program.

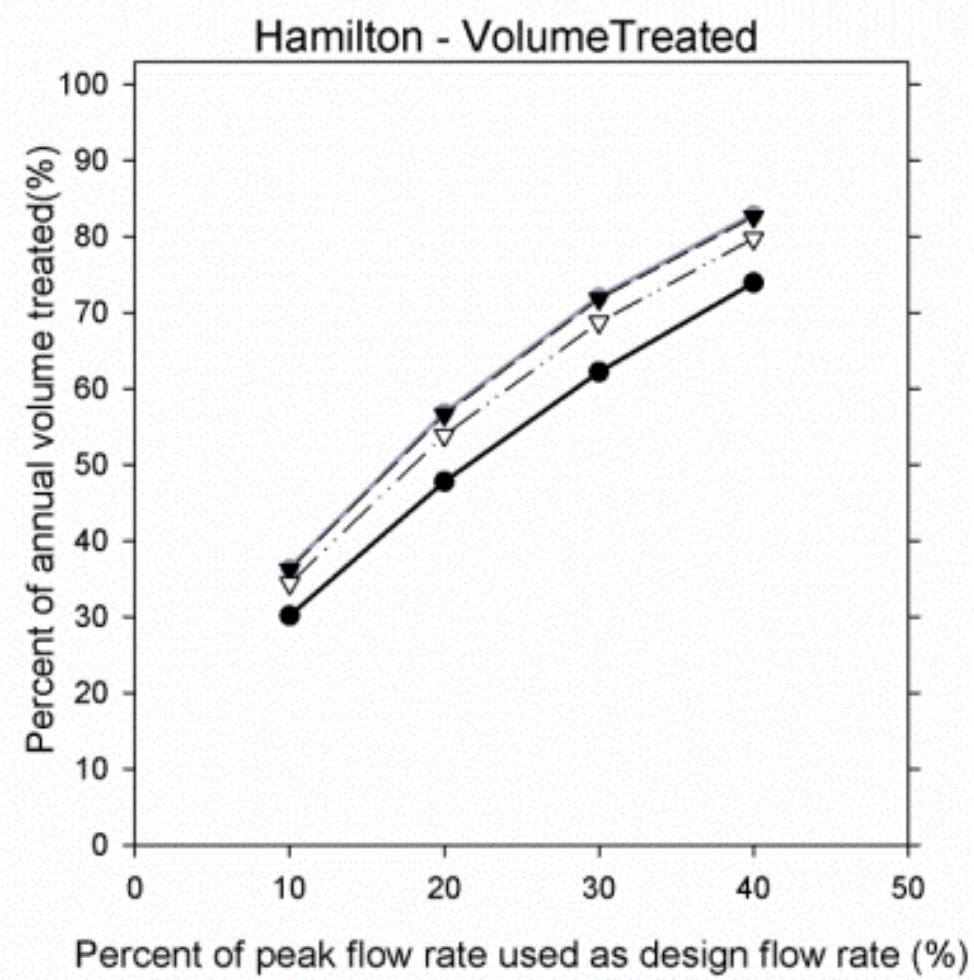
Do the woodchips matter?

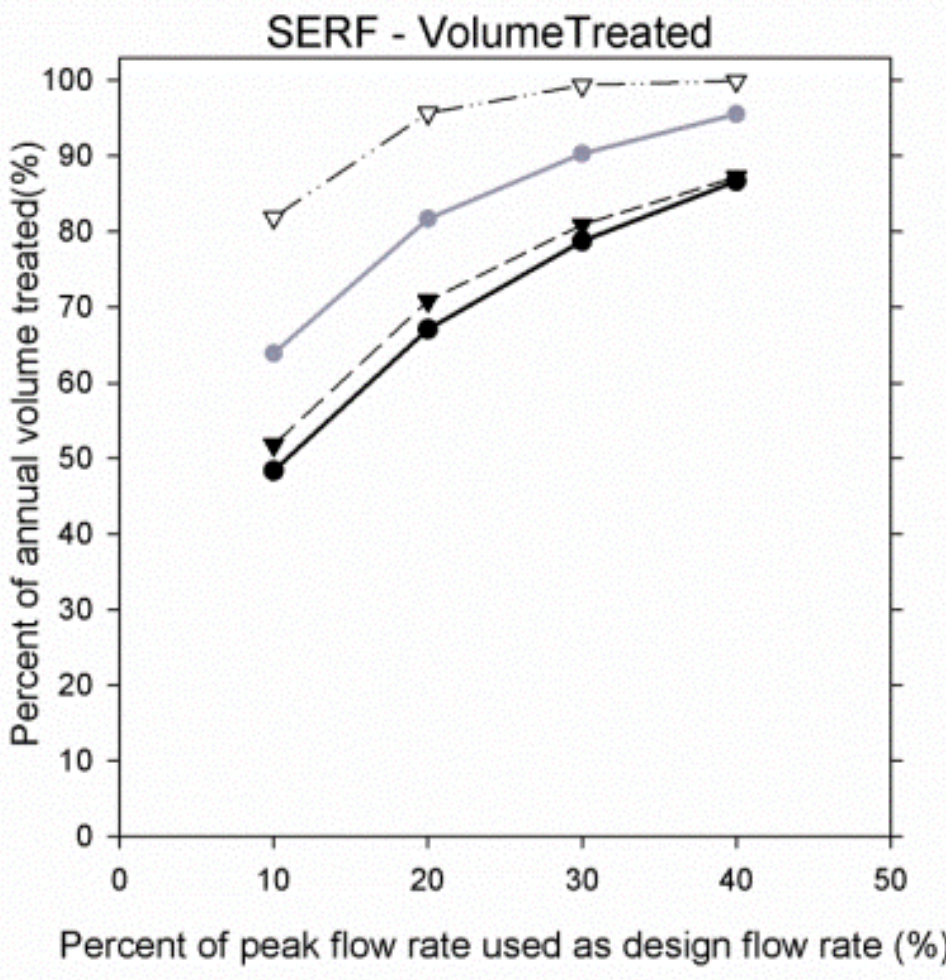
"Good" Chips

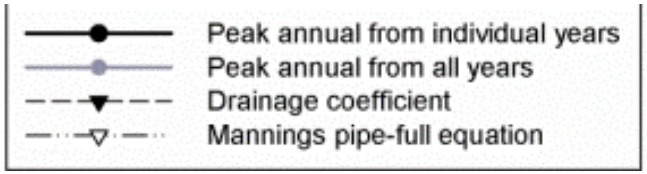
Better uniformity and consistent piece size

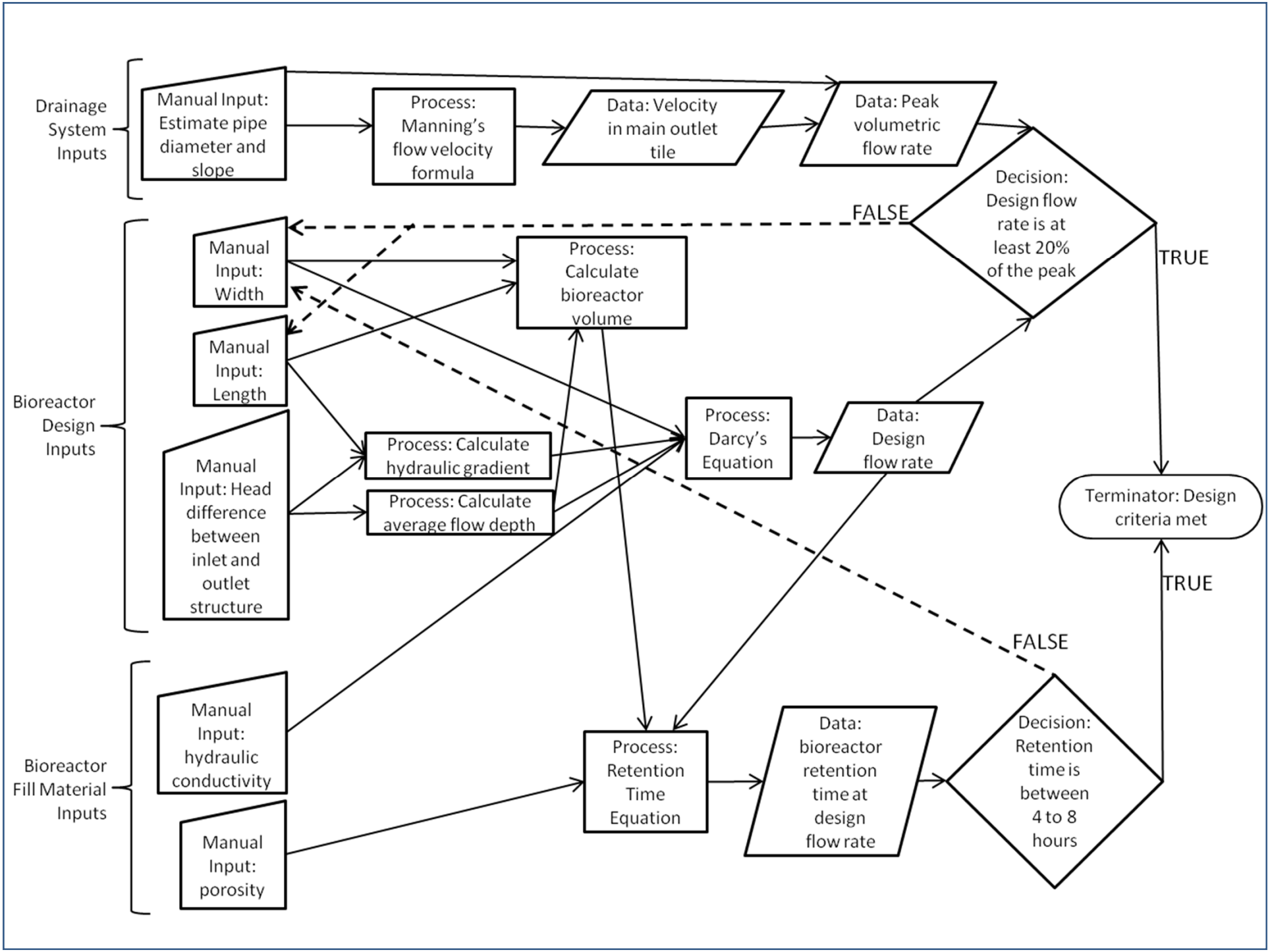
"Bad" Chips

	Area	D Coeffici	Tile Dia (in)	Slope (%)	cfs Mannings	cfs D coefficient	Notes
SERF	27	0.75	12	0.74	2.66	0.85	coefficient calculated from flow data, single wall tile; slope from Reid (Google maps)
Hamilton	38.25	0.5	8	0.5	0.74	0.80	"very small slope", single wall tile







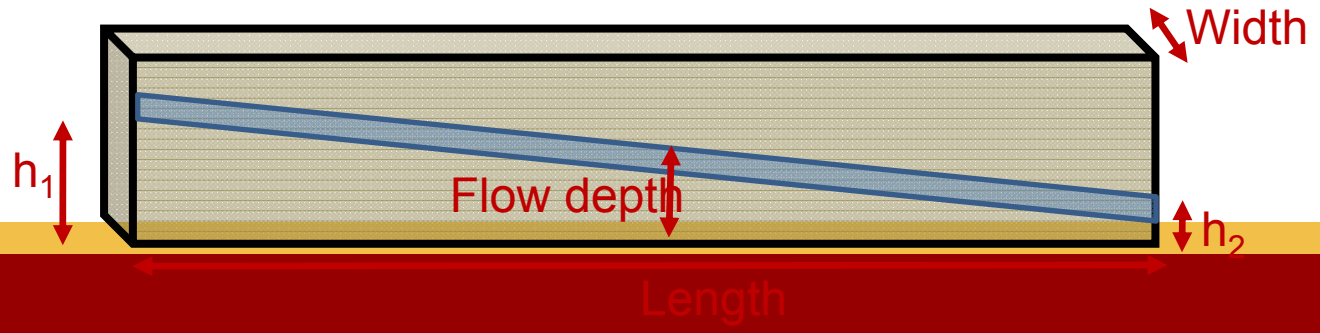

Drainage System Inputs
Manual Input: Estimate pipe diameter and slope
Process: Manning's flow velocity formula
Data: Velocity in main outlet tile
Data: Peak volumetric flow rate
Decision: Design flow rate is at least 20% of the peak
FALSE
TRUE
Bioreactor Design Inputs
Manual Input: Width
Manual Input: Length
Manual Input: Head difference between inlet and outlet structure
Process: Calculate bioreactor volume
Process: Calculate hydraulic gradient
Process: Calculate average flow depth
Process: Darcy's Equation
Data: Design flow rate
Terminator: Design criteria met
TRUE
FALSE
Bioreactor Fill Material Inputs
Manual Input: hydraulic conductivity
Manual Input: porosity
Process: Retention Time Equation
Data: bioreactor retention time at design flow rate
Decision: Retention time is between 4 to 8 hours

Darcy's Equation: Flow Through Porous Media

$$Q = KiA$$

What % of the peak flow rate do these bioreactor dimensions allow?

- Q: Volumetric Flow Rate (m^3/sec)
- K: Hydraulic Conductivity (cm/sec):
  - 0.35-1.6 cm/sec for sawdust to 61 mm chips (Cameron & Schipper 2010)
  - Hardwood chips commonly used in Iowa bioreactors = 9.5 cm/sec
  - Can change over time
- i: Hydraulic Gradient (m/m), head drop divided by the bioreactor length
- A: Cross-sectional Area (m^2)



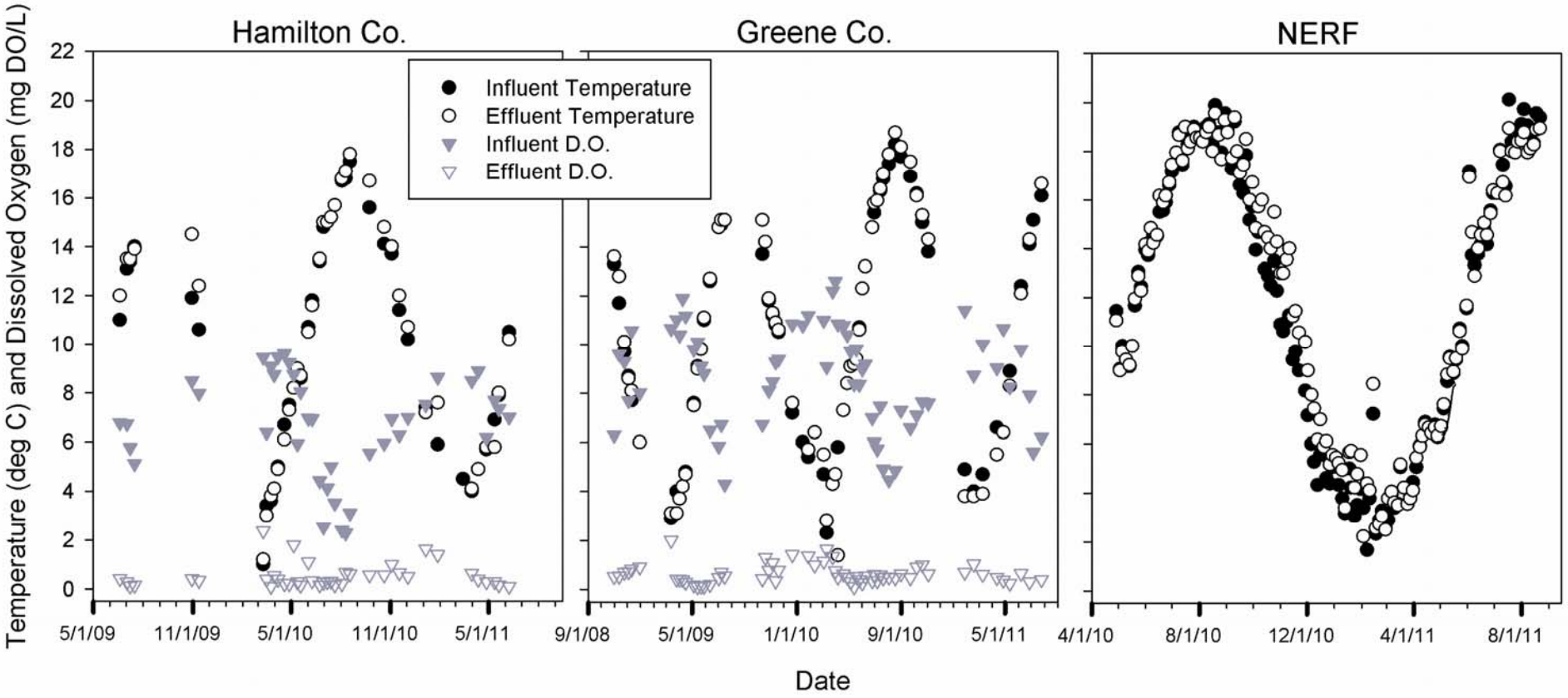
Retention Time Equation

$$\tau = \frac{\rho V}{Q}$$

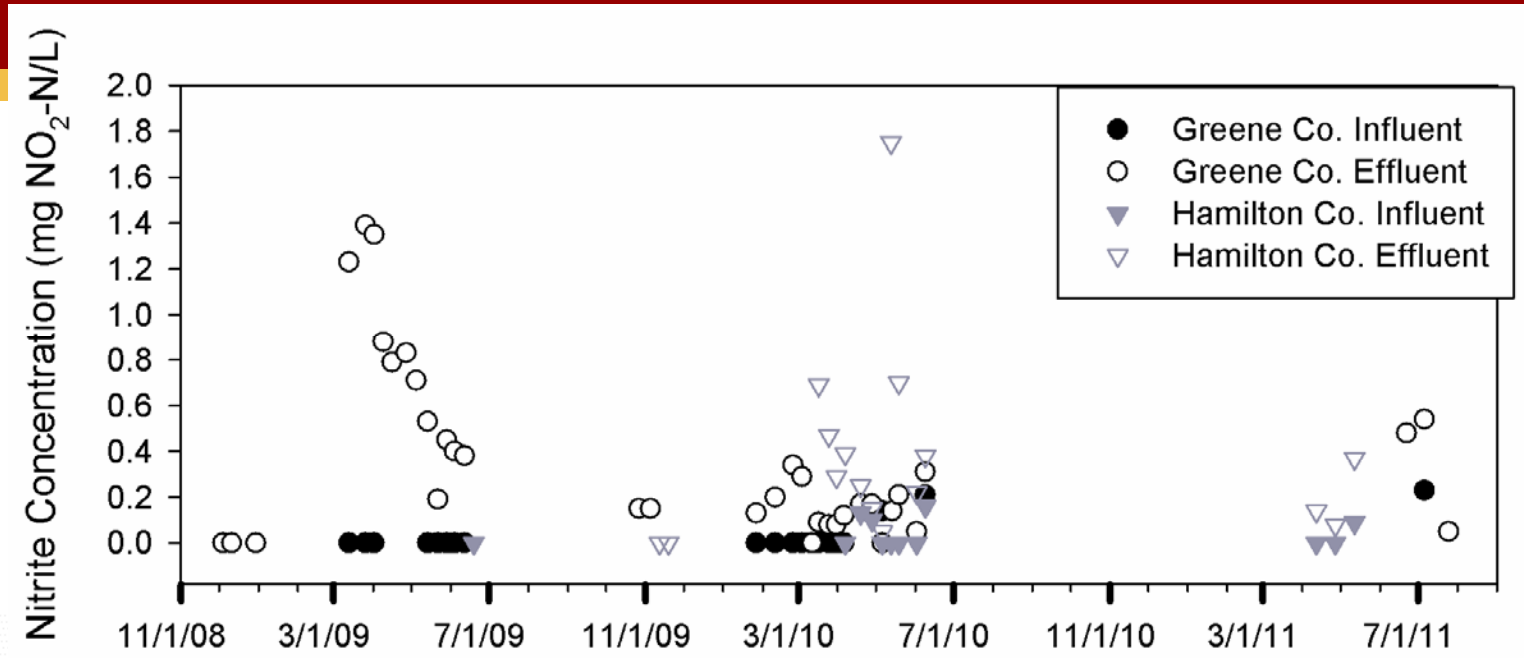
What retention time do these bioreactor dimensions allow?

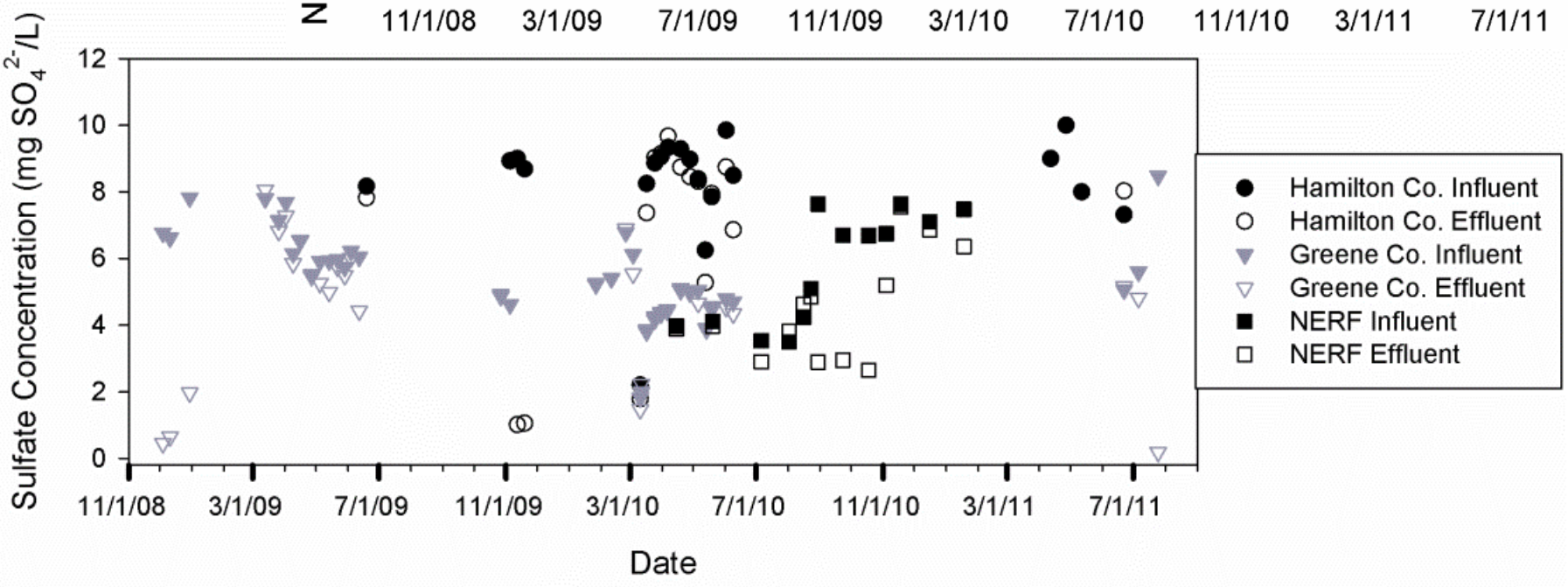
- τ: Retention Time
- V: Bioreactor Volume (m^3)
  - Depth of the bioreactor is set by the tile depth, but use average flow depth for volume.
- ρ: Porosity, range for woodchips: 0.63-0.86
  - Packing density, moisture content, chip size, and chip age
- Q: Flow rate (m^3/sec), Calculated from Darcy's equation
- Is a function of Length: $\tau = \frac{\rho V}{KiA} = \frac{\rho(l \times w \times d)}{Ki(w \times d)} = \frac{\rho l}{Ki}$

Temperature and Dissolved Oxygen



Chapter 4: Nitrite and Sulfate

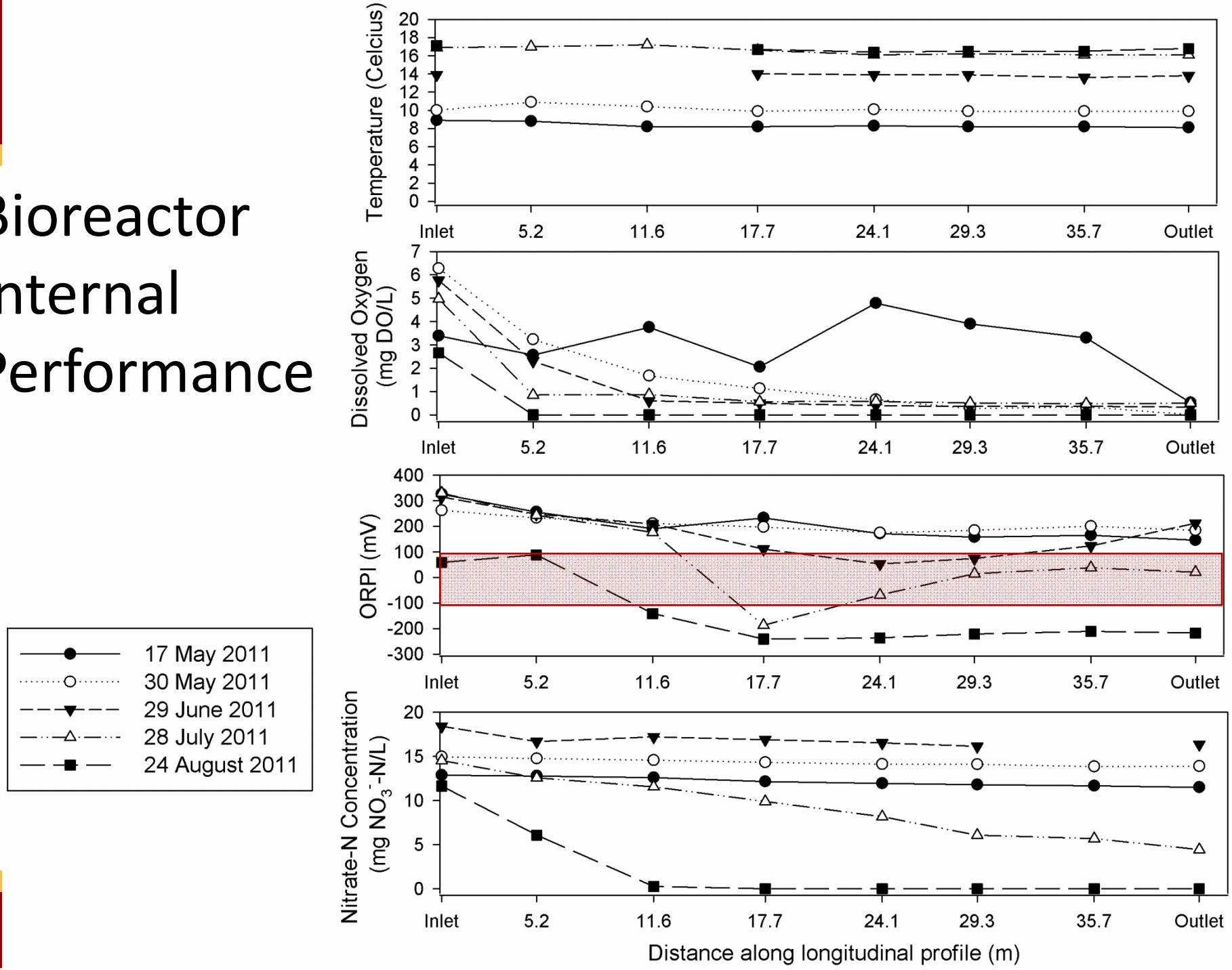




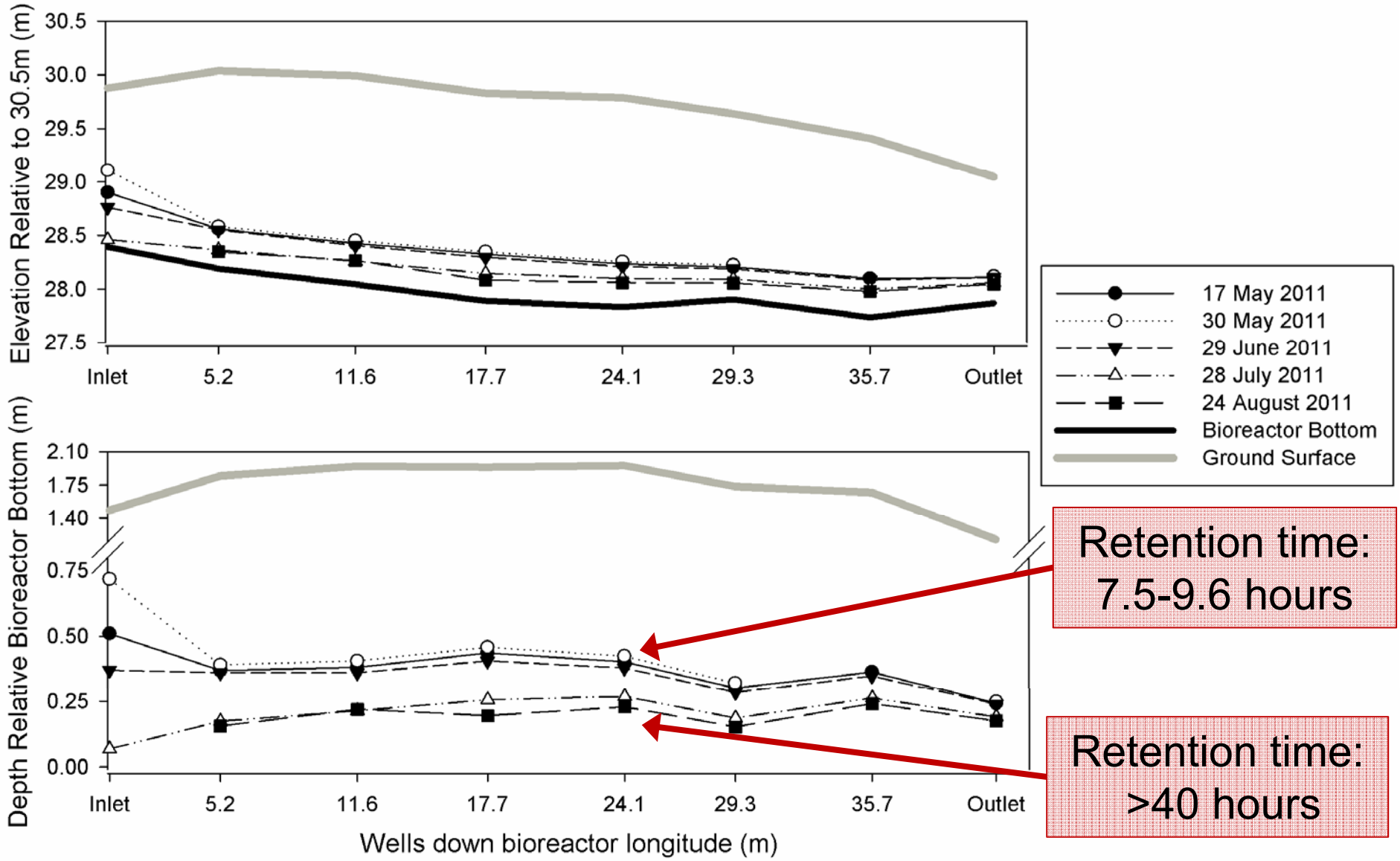
Bioreactor Monitoring

- Inflow and outflow
  - Nitrate-N
  - Flow rate
- Well sampling
  - Temperature
  - Dissolved oxygen
  - Oxidation reduction potential (ORP)
  - Nitrate-N
  - Flow depth (continuous)
- Tracer testing

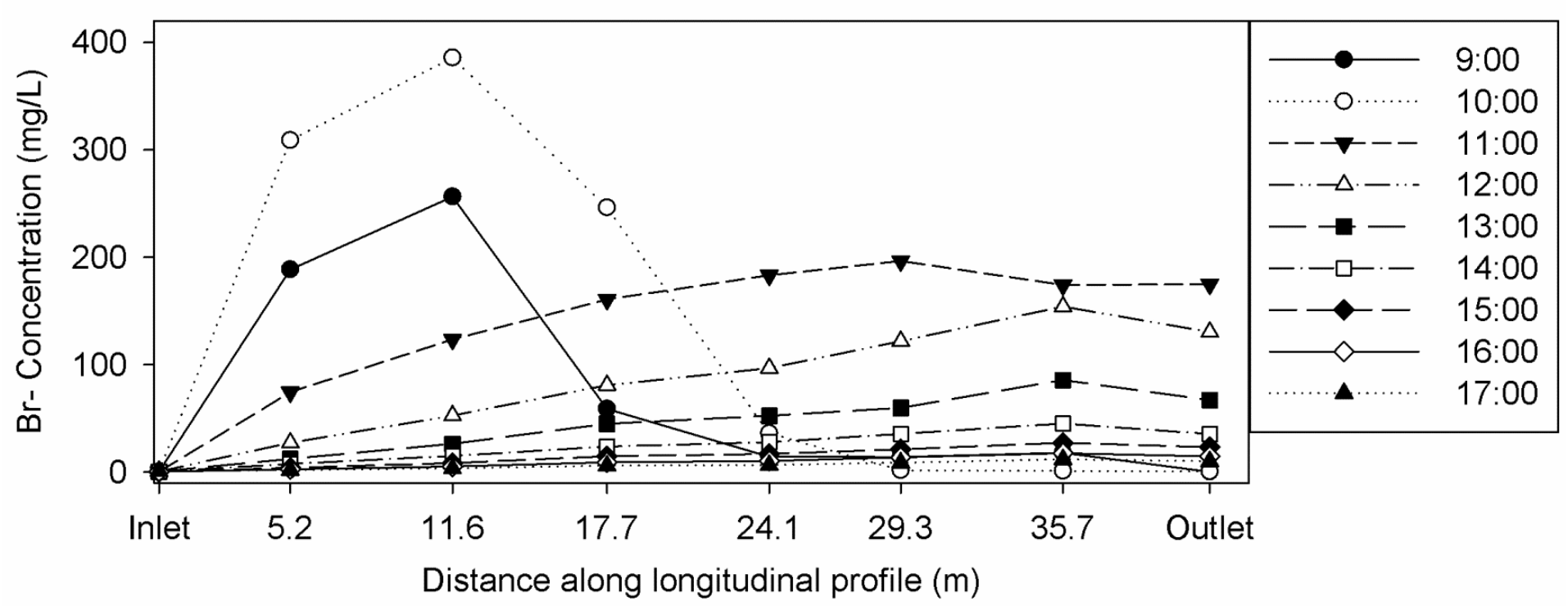
Bioreactor Internal Performance



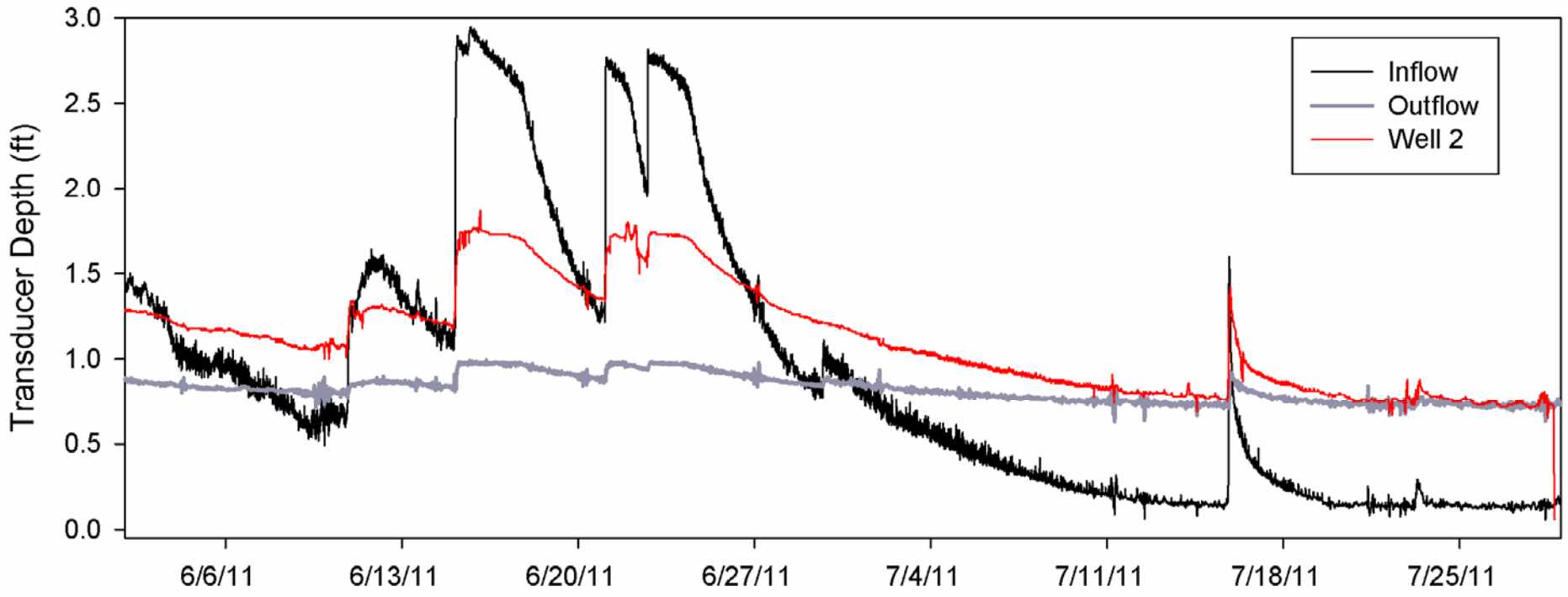
Bioreactor Water Depths



Bioreactor Internal Performance: Tracer Testing



Bioreactor Internal Performance: Hydrograph Progression

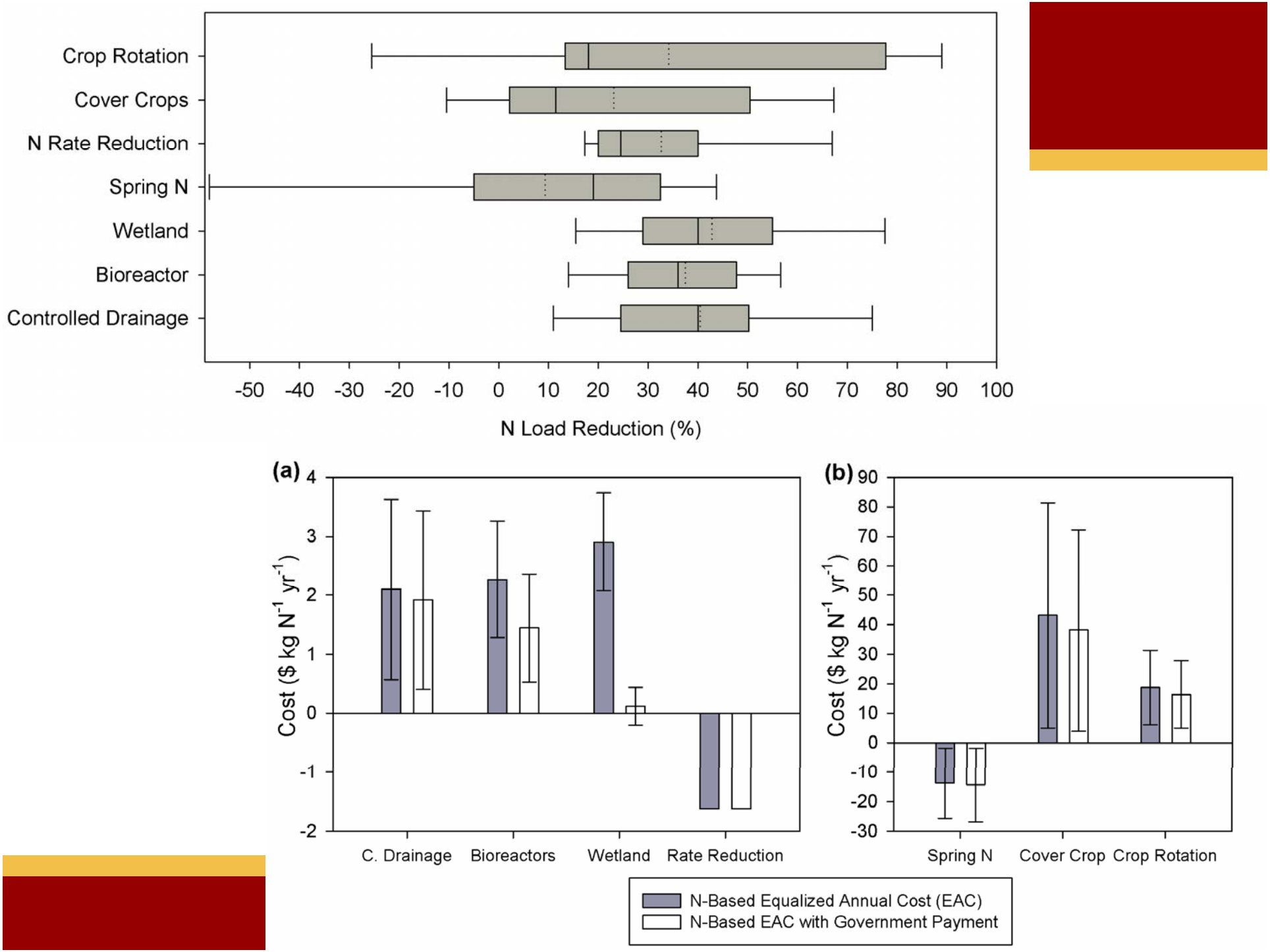


Chapter 4: Bioreactor Load Reduction

	Water Year	Bio. In (kg N/ha)	Bio. Out (kg N/ha)	Mean Bio. Reduction %‡	Removal Rate ($g/m^3/dy$)
Pekin	2004-2005	5.0	2.8	43.7	1.07
	2005-2006	1.2	0.7	43.5	0.75
	2006-2007	33.6	21.1	37.4	3.78
	2007-2008	14.8	8.4	43.8	2.53
	2008-2009	7.1	5.0	29.1	0.57
	2009-2010	7.4	5.8	22.0	0.67
	2010-2011	2.0	0.5	74.0	0.38
NERF	2009-2010	34.7	29.7	14.6	1.56
	2010-2011¶	21.4	18.9	11.7	0.86
Greene Co.	2008-2009#	20.2	6.5	68.0	7.76
	2009-2010	33.6	18.1	46.0	6.69
	2010-2011††	1.6	0.8	50.4	0.41
Hamilton Co.	2009-2010	10.8	2.6	75.7	5.02
	2010-2011‡‡	0.8	0.2	73.9	0.42

Chapter 4: Total Load Reduction

	Water Year	Total In (kg N/ha)	Total Out (kg N/ha)	Mean Total Reduction %‡
Pekin	2004-2005			
	2005-2006			
	2006-2007			
	2007-2008		NA§§	
	2008-2009			
	2009-2010			
	2010-2011			
NERF	2009-2010	37.3	32.2	13.6
	2010-2011¶	21.9	19.4	11.5
Greene Co.	2008-2009#	41.4	27.6	33.3
	2009-2010	50.1	34.6	30.9
	2010-2011††	2.9	2.1	27.3
Hamilton Co.	2009-2010	14.4	6.3	56.6
	2010-2011‡‡	1.2	0.6	48.6


Crop Rotation
Cover Crops
N Rate Reduction
Spring N
Wetland
Bioreactor
Controlled Drainage
-50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100
N Load Reduction (%)
(a)
Cost ($ kg N-1 yr-1)
4 3 2 1 0 -1 -2
C. Drainage
Bioreactors
Wetland
Rate Reduction
(b)
Cost ($ kg N-1 yr-1)
90 80 70 60 50 40 30 20 10 0 -10 -20 -30
Spring N
Cover Crop
Crop Rotation
N-Based Equalized Annual Cost (EAC)
N-Based EAC with Government Payment

Item	Cost Timing	Minimum cost	Mean cost	Maximum cost	Notes	Reference
	yr	----------	$ ha^{-1}	----------		
Both control structures	1	$49.42		$197.68	Two control structures at $500 to $2000 ea.; 20.2 ha treatment area	Agri Drain Corp, personal comm., 2011
Structure transport	---				Assumed included above	Assumption
Woodchip cost	1		$116.14		Two semi loads at $975 chips + $200 transport ea.; 20.2 ha treatment area	ISA, personal comm., 2011
Woodchip transport to farm	---				Included above	
Design cost	1	$0.00		$31.63	Assumed: $40 h^{-1} for 2 days of work or NRCS service provider; 20.2 ha treatment	Assumption
Contractor fees	1	$27.68	$60.61	$98.84	Back hoeing at $35.00 h^{-1}, $76.65 h^{-1}, $125.00 h^{-1} for 16 hours to treat 20.2 ha	ISU Extension, 2010; Assumptions
Seeding bioreactor surface	1	$0.05	$0.11	$0.15	Seeding grass, broadcast with tractor; for 20.2 ha treatment and 0.10 ha bioreactor at $9.88, $22.61, and $29.65 per ha	ISU Extension, 2010
Seed cost	1		$1.11		Seed costs from dealer: $222.27 ha^{-1} for CRP Mix (CP23) Diversified mix; bioreactor surface 0.005 of treatment area	Prairie Land Management: http://www.habitatnow.com/store/shop/shop.php?pn_selected_category=37
Misc. materials	1		$8.80		6" tile $890 per 305 m(1000 ft); Assume 61 m needed for control structure connections for 20.20 ha treatment area	Agri Drain Corp, personal comm., 2011
Total cost of establishment		**$203.19**		**$454.35**	**TPVC**	
Time to raise/lower	1-n	$1.19		$2.97	Three hours per yr with farm labor wages at $8-$20 h^{-1}, 20.20 ha treatment area	Assumption; ISU Extension, 2010
Mowing/maintenance	1-n	$0.12		$0.62	Spot mowing bioreactor at $24.71 to $123.55 ha^{-1} for 20.2 ha treatment	ISU Extension, 2009
Total cost of establishment and maintenance		**$231.33**		**$531.32**	**TPVC**	
Replacement yr 20	20	$65.66		$98.18	Single sum TPVC at 20 years: woodchips, contractor, seeding	
Replacement yr 40	40	$40.26		$85.98	Single sum TPVC at 40 years: woodchips, contractor, structures, seeding	
Gate replacement	8, 16, 24,...		$16.76		Summation of single sum TPV every 8 years for 5 gates per structure ($14.17 to $15.32 per ea. for 15 cm structure) 2 structures per 20.2 ha	Agri Drain Corp, personal comm., 2011
Total cost of establishment, maintenance, and replacement		**$354.01**		**$732.25**	**TPVC**	