North Gullies Berm Surface Inlet Monitoring Program

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1.0 INTRODUCTION

Agricultural based sediment and nutrient loading have been linked to downstream freshwater ecosystem issues such as eutrophication and habitat loss (*e.g.,* Alexander *et al.* 2007). Past research has shown that a majority of this sediment and nutrient loading occurs during peak hydrological events and further, that bankfull flow can transport the greatest proportion of sediment load. In the past, nutrient monitoring has been focused on rainfall events occurring during the growing season and much less focus has been given to non-growing season (NGS) rainfall events, including snowmelt. The importance of year-round monitoring of nutrient and sediment loads will become increasingly crucial as climate change is expected to cause an increase in extreme weather events as well as increase the number of yearly snowmelt events and freeze-thaw cycles.

Agricultural best management practices (BMPs) have been developed to mitigate the ecosystem degradation caused by peak hydrological events, and include Water and Sediment Control Basins (WASCoBs). WASCoBs are thought to decrease sediment loads by diverting surface runoff to subsurface drainage tiles, thereby reducing erosion. The decrease in sediment leaving the field should then also reduce the amount of nutrients, particularly phosphorus (P), that are exported from the field.

WASCoBs are comprised of a berm that is perpendicular to the flow of an ephemeral channel with the installation of basin outlet structures (often referred to as “Hickenbottoms”, the name of the manufacturer) just “upstream” of the berm. These outlet structures, generically referred to as surface riser inlets, are perforated pipes that rise above the ground surface and are connected to the subsurface drainage tile. The basin, in which surface water collects, is usually created in a field by a berm constructed across a low swale, or concentrated flow path. To control gully erosion in a Huron County, Ontario field, a series of WASCoBs were constructed. This project took advantage of these installations to subsequently monitor the peak flow mitigation measure (PFMM) performance of these structures. Year-round monitoring of water quality is necessary to verify the anticipated erosion control benefits and water quality improvements of these common agricultural erosion control structures.

The objective of the project is to improve our knowledge of peak flow events on a full hydrological year basis, including winter and snowmelt periods. Additionally, the effectiveness of WASCoBs and riser inlet modifications were examined by quantifying the loads of nutrients and sediments exported from the basins.

2.0 METHODOLOGY

In order to monitor the effectiveness of the WASCoBs, water quantity and quality were monitored year-round at three basins within the same field (Figure 1). Water quantity was measured with a combination of 5 minute interval stage readings from a level logging device, a series of mass balance equations and GIS tools, all of which are described in further detail by Wilson (2016).

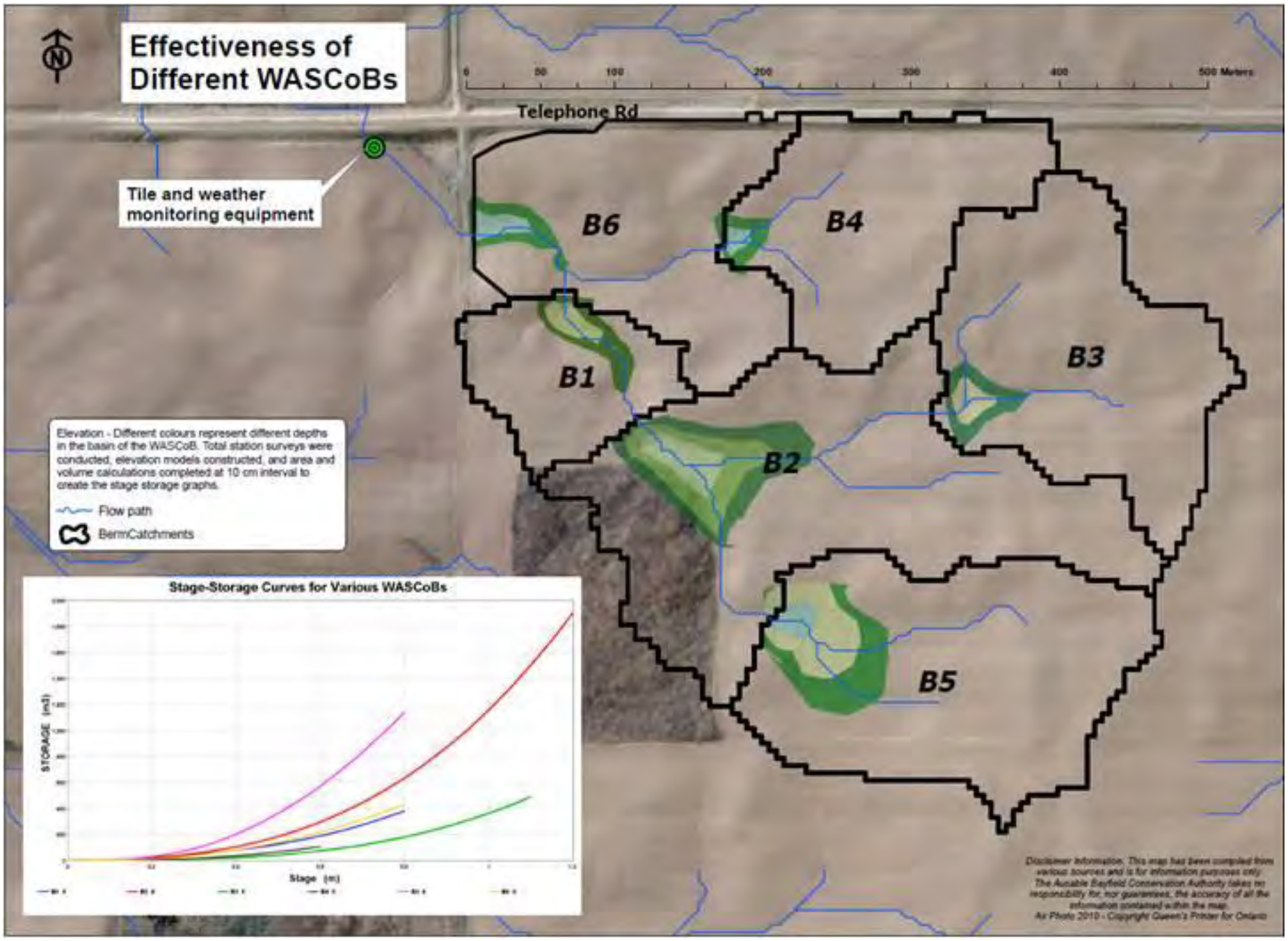

Figure 1: Map of the monitored field on the south side of Telephone Road in the Gully Creek watershed. Three berms (B2, B3, and B5) are monitored for water quantity and quality, while B4 is monitored for stage (quantity) only.

2.1 WATER QUANTITY

Water level, referred to as stage, was recorded at 5 minute data intervals on water level logging devices (Schlumberger 10-metre mini-DIVER). The logging devices were installed at the lowest possible point in the basin and attached to the base of the surface riser inlet structures to best capture the depth of water. The pressure values obtained from the loggers were compensated to convert pressure values to water levels using local barometric pressure values which were recorded on an atmospheric barometric pressure transducer (Schlumberger baro-DIVER) on 15 minute data intervals.

The basin inflow rate and basin outflow rate can be determined by deriving a series of stage relationships using basin physiographic characteristics and are described in detail in Wilson (2016). The mass balance equation used to determine inflow rate, outflow rate and change in storage for each event is as follows:

$$I = \frac{(O_1 + O_2)}{2} + \frac{(S_2 - S_1)}{dt} \qquad \text{(Equation 1)}$$

Where,

I = the mean inflow rate into the basin over the interval (m^3/s)
O_1 and O_2 = the initial and final outflow rate over the interval (m^3/s)
S_1 and S_2 = the initial and final storage volumes over the interval (m^3)
dt = length of the time interval (s)

A Stage- Storage relationship was generated for each basin using a GIS tool (3-D Analyst) which uses a Digital Elevation Model (DEM) to determine storage values associated with each stage value. The stage-storage curves for all six basins are shown in Wilson (2016).

The outflow rate is a function of two water transport pathways, tile outflow and groundwater outflow. Tile outflow rate increases linearly with stage, up to a threshold depth, with stage values and associated flowrates shown in Wilson (2016). For example, a 200mm diameter riser at B5 has a maximum flowrate of 29 L/s at 0.3m water depth and 1.5% slope, and any additional increase in stage will not result in increased flowrate.

Groundwater outflow rate is determined by a stage-area relationship using the same methods as the stage-storage relationship. The outflow rate to groundwater can then be calculated by multiplying the area of ponded water by the soil infiltration rate, which was 10 mm/hr for the soils at the site (Wilson, 2016).

With these relationships, each logged stage value has outflow rates and storage values which can be used in Equation 1 to calculate the inflow rate. Therefore, by collecting stage, a continuous time-series dataset of storage, inflow rate and outflow rate can be derived for each event. More detailed information, including an example time-series spreadsheet calculation, can be found in Wilson (2016).

2.2 WATER QUALITY

Water quality was monitored with an event-based sampling regime whereby two ISCO® portable, automatic water samplers' collected water samples from each of the three monitored surface riser inlets. Further, the three surface riser inlets each had different water quality treatment modifications (Figure 2) to test the effect of inlet modifications on water quality results. B2 had half the holes on the inlet blocked (mod), B3 had an Agri-Drain® water quality inlet, and B5 had a silt sock. Simultaneous samples were collected before (pre) and after (post) the water entered the surface riser inlet. The paired ISCOs were programmed to collect samples simultaneously through the extended programming function on the ISCO® 6712 automated water sampler (collecting pre samples) which was connected to an ISCO® 2700 automated water sampler (collecting post samples). The ISCOs were set to trigger when water began ponding through the use of ISCO® 1640 liquid level actuators which were installed 5 cm above the soil surface.

A total of 235 water samples were collected over the period from July 2014 to August 2016 from the three monitored sites; however, on occasion some samples were not collected simultaneously between the pre- and post-treatments. As a result, 105 paired water quality samples (34 from B2, 44 from B3, and 27 from B5) were collected over the period from June 2015 to August 2016. While the sampling regime was event-based, not every flow event was sampled during the study period as some events were missed due to equipment malfunction, staffing issues, or the equipment needing to be removed for farming work.

Water samples were collected from the field and stored in coolers during transport to ALS Laboratory in Waterloo, Ontario where the samples were analyzed for total phosphorus (TP), phosphate- phosphorus (PO_4-P), nitrate- nitrogen (NO_3-N) and total suspended solids (TSS), using standard laboratory analytical methods.

For the purposes of this report, concentration data and load calculations are presented for all three sites. Berm loads (kg/ha) were calculated by dividing the mass load (equal to the concentration multiplied by the instantaneous flow) by the basin area and using the linear interpolation method in Water Quality Analyzer (WQA) to estimate loads over the duration of the event.

Figure 2: Inlet modifications for the three berm sites. B2 (top left) where 3 of the first 5 rows of holes were covered; B3 (top right) the Agri-Drain® straw system; B5 (bottom) the silt sock.

3.0 RESULTS

3.1 WATER QUALITY

While the primary outcome of WASCoBs is the reduction of peak flow, there is an anticipated accompanied reduction in nutrient and sediment loads from the basin. When looking at instantaneous concentrations of TP and TSS in the pre versus post treatment, B2 (the modified inlet) had the overall highest proportion of samples that showed a decrease in concentration in the post treatment, while B3 (Agri-Drain®) showed the lowest proportion of samples with concentration reductions (Table 1).

Table 1: Summary of the percentage of water samples that had a decrease in TP and TSS in the post-treatment samples compared to the pre-treatment samples.

WASCoB ID	Events Captured	Total number of samples	Samples which observed a decrease in TP concentration after modification (%)	Samples which observed a decrease in TSS concentration after modification (%)
B2 (mod)	8	34	79	85
B3 (Agri-Drain®)	9	44	45	59
B5 (silt sock)	6	27	81	48

Based on the bulk collection of water samples, B5 (silt sock) appeared to be most effective at reducing the concentration of TP (81% of samples) from the outflow, while B2 (modified inlet) was most effective at reducing the concentration of TSS (85% of samples).

Loads of TP, PO_4-P, NO_3-N, and TSS were calculated for each event at B2, B3, and B5 and the data are presented in Table 2, Table 3, and Table 4 respectively. B2 (modified inlet) had the greatest reduction of both TP and TSS loads during the monitored events (Table 2). TP was reduced by 1.05 kg and TSS was reduced by 600.1 kg during the study period, which indicates the berm is performing effectively in terms of both phosphorus and sediment reduction. A slight reduction of 0.21 kg (2%) of NO_3-N was observed, while PO_4-P increased by 1%.

At B3, we observed no change in TP load over the study period, slight increases of 0.19 kg in NO_3-N and 0.06 kg in PO_4-P and a decrease of 307.5 kg in TSS (Table 3).

The silt-sock modification at B5 appeared to have effectively reduced both TP and TSS loads over the study period with reductions of 0.30 kg of TP and 72.5 kg of TSS (Table 4). The silt-sock modification (B5) had no reduction in PO_4-P over the study period; however, compared to B3 (Agri-Drain®) which observed an increase in PO_4-P, the silk sock performed better. There was a minor increase in NO_3-N at B5 of 2%, which is again lower than the increase that was observed at B3. Overall, B2 (modified inlet) has been most effective at decreasing TP and TSS loads while B5 (silt-sock) appears to be performing more effectively than B3 (Agri-Drain®) with regards to nutrient load reduction, though all three berms were shown to decrease TSS loads.

Table 2: Summary of pre- and post-treatment event loads at DFTEL B2 (modified inlet).

Event Period	Total Phosphorus		Phosphate-Phosphorus		Nitrate-Nitrogen		Total Suspended Solids	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
November 26-27, 2015	2.45	1.83	0.13	0.12	1.85	1.79	658.5	568.6
December 21-22, 2015	1.23	1.10	0.13	0.14	2.27	2.30	339.5	288.6
January 10, 2016	0.10	0.09	0.01	0.01	0.43	0.52	13.3	18.1
March 24-25, 2016	0.93	0.90	0.05	0.05	0.44	0.43	399.6	365.8
March 27-28, 2016	1.34	1.24	0.05	0.05	0.36	0.39	1054.9	749.9
March 29, 2016	0.30	0.26	0.02	0.02	0.18	0.18	178.2	157.7
March 31-April 1, 2016	2.52	2.26	0.12	0.13	1.01	1.12	1316.5	1139.8
August 19-20, 2016	0.36	0.51	0.27	0.28	6.42	6.04	115.8	187.6
TOTAL (kg)	9.23	8.18	0.79	0.80	12.97	12.76	4076.2	3476.0
DIFFERENCE (kg)		-1.05		0.01		-0.21		-600.1
DIFFERENCE (%)		-11†		1		-2		-15†

†Possible evidence of a significant difference between pre- and post-treatment loads (one-sided Wilcoxon paired t-test, $0.05 < p < 0.1$).

Table 3: Summary of pre- and post-treatment event loads at DFTEL B3 (Agri-Drain®).

Event Period	Total Phosphorus		Phosphate-Phosphorus		Nitrate-Nitrogen		Total Suspended Solids	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
June 8, 2015	0.24	0.27	0.18	0.18	3.84	3.77	72.2	91.7
June 16, 2015	1.01	1.00	0.23	0.24	0.66	0.72	522.1	524.7
June 18-19, 2015	0.90	0.76	0.22	0.23	0.26	0.25	1225.1	1066.8
July 14, 2015	0.38	0.27	0.19	0.17	0.36	0.85	400.9	208.2
November 27, 2015	0.34	0.35	0.04	0.04	0.05	0.06	123.7	118.6
March 27-28, 2016	1.92	2.03	0.12	0.12	0.19	0.17	1418.2	1447.5
March 31, 2016	0.92	0.94	0.05	0.06	0.11	0.13	510.1	508.4
April 7, 2016	0.05	0.05	0.01	0.01	0.07	0.07	18.1	19.9
August 21, 2016	0.18	0.28	0.13	0.19	0.79	0.52	26.2	23.3
TOTAL (kg)	5.94	5.94	1.17	1.23	6.34	6.53	4316.5	4009.0
DIFFERENCE (kg)		0.00		0.06		0.19		-307.5
DIFFERENCE (%)		0		5†		3		-7

†Possible evidence of a significant difference between pre- and post-treatment loads (one-sided Wilcoxon paired t-test, $0.05 < p < 0.1$).

Table 4: Summary of pre- and post-treatment event loads at DFTEL B5 (silt sock).

Event Period	Total Phosphorus		Phosphate-Phosphorus		Nitrate-Nitrogen		Total Suspended Solids	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
June 8, 2015	0.30	0.30	0.17	0.20	6.66	6.67	64.6	58.5
November 27, 2015	0.05	0.03	0.01	0.01	0.03	0.02	14.4	16.9
December 21, 2015	0.18	0.18	0.02	0.02	0.06	0.06	49.3	53.1
March 28-29, 2016	3.17	2.98	0.13	0.12	0.45	0.62	1906.5	1722.4
March 31-April 1, 2016	1.85	1.77	0.07	0.05	0.30	0.26	824.6	937.6
April 7, 2016	0.06	0.05	0.01	0.01	0.10	0.09	21.2	19.6
TOTAL (kg)	5.60	5.30	0.40	0.40	7.60	7.73	2880.57	2808.06
DIFFERENCE (kg)		-0.30		0.00		0.13		-72.5
DIFFERENCE (%)		-5*		0		2		-3

*Statistically significant difference between pre- and post-treatment loads (one-sided Wilcoxon paired t-test, $p < 0.05$).

As mentioned previously, over the study period of 14 months, there was no observed reduction in TP loads at B3. However, if we look at TP loads on a yearly basis (Table 5), B3 reduced TP loads by greater than 8% and TSS loads by greater than 14% in 2015 which was followed in 2016 by increases of nearly 8% and ~1% for TP and TSS respectively. These data suggest a saturation point for the Agri-Drain® surface riser inlet modification, after which point sediment and associated phosphorus is re-released from the straws (note: sediment buildup in the Agri-Drain® straws was observed by visual inspection). The reduction of TP and TSS in 2015 was proportionately greater than B5 (silt-sock) but the effectiveness of the modification was countered by the subsequent re-release of sediment and TP the following year.

Table 5: Yearly TP and TSS loads at Berm 3 (Agri-Drain®).

Year	Total Phosphorus (kg)		Total Suspended Solids (kg)	
	Pre	Post	Pre	Post
2015	2.87	2.64	2344.0	2009.9
2016	3.06	3.30	1972.5	1999.1
	Diff. (kg)	Diff. (%)	Diff. (kg)	Diff. (%)
2015	-0.23	-8.11	-334.1	-14.25
2016	0.23	7.61	26.6	1.35

None of the 2016 events at B3 showed a decrease in TP load post-modification, regardless of the size of the event which suggests that sediment and TP that was reduced in 2015 is re-released throughout the year in 2016 (Figure 3). Moreover, there does not appear to be a relationship between the size of the event and the effectiveness of the modification which further points to the cause of the TP load increase in 2016 to be the saturation of the Agri-Drain® straws.

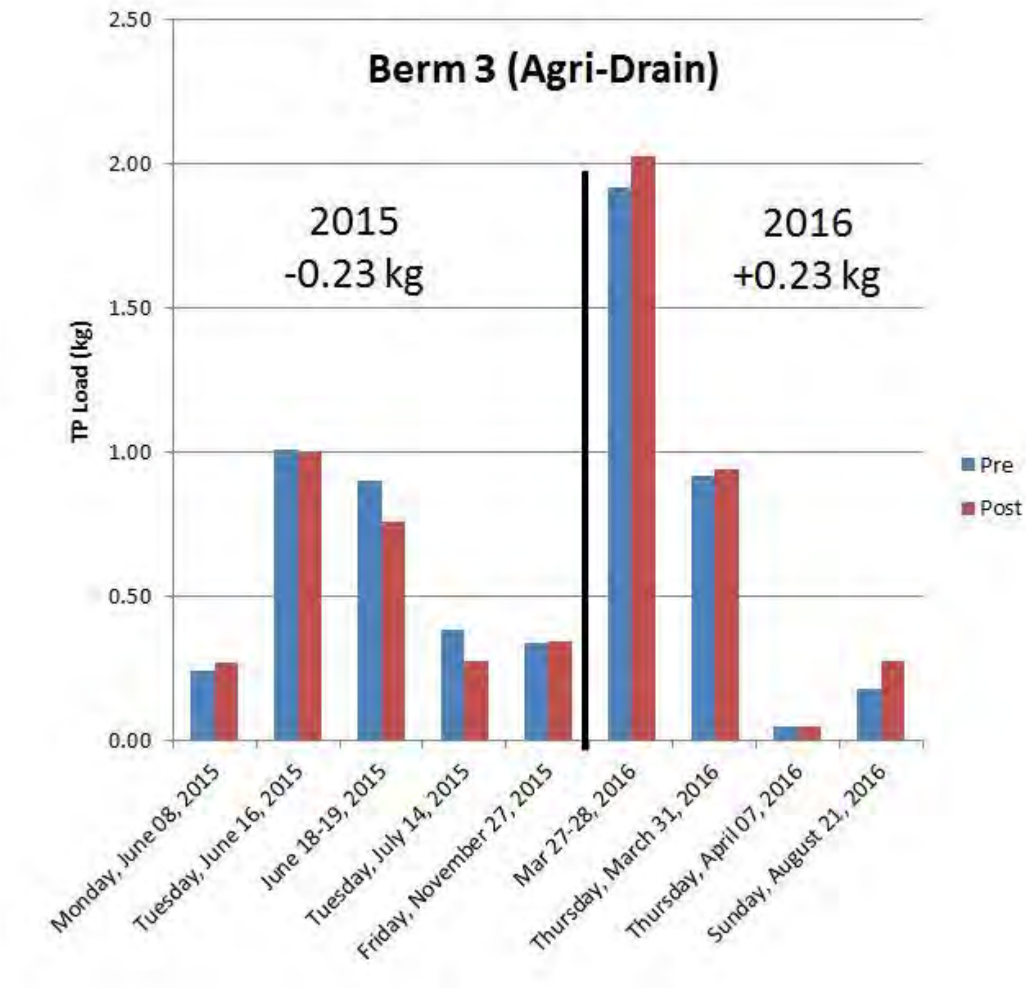

Figure 3: The total phosphorus (TP) load for each event at B3 with the Agri-drain® modified surface inlet riser. In 2015, there was a 0.23 kg *reduction* in TP post modification, followed by a 0.23 kg *increase* in 2016.

3.2 WATER QUANTITY

Water and Sediment Control Basisn (WASCoBs) reduce peak flows during events by holding water in the surface basins and allow for a slower release into the tile drains which drain the field (*e.g.,* Bittman *et al.* 2016). By increasing the residence time of the water and decreasing the peak flows, WASCoBs should reduce erosion and TSS export and therefore it would be expected that TP loads would decrease as well. The previous section showed that these modified surface riser inlets can contribute to decreases in TP loads at the field scale. We then examined the residence times during each event for all three berm sites. B2 has the longest residence times which are influenced by whether or not B3 and B5 are filled with water. The mean residence time at B2 was significantly greater than both B3 (p = <0.001) and B5 (p = 0.002). As B3 and B5 drain into B2 (Figure 1), the residence times at these two berms were compared directly. There were a total of 15 runoff events (5 in the growing season, 10 in the non-growing season (NGS)) during the study period in which both B3 and B5 experienced surface flow.

The data were analyzed using a one-tailed t-test to determine whether or not there was a difference in the mean residence times of the two basins. The mean residence times during the growing season did not differ significantly; $p = 0.272$ (Table 6), and the data for the NGS and all combined events did not pass the assumption of normality, therefore non-parametric statistics were used for subsequent analyses. A Wilcoxon sign ranked test showed significant differences in NGS ($p = 0.049$) and combined ($p = 0.008$) events over the study period with B5 having significantly longer residence times than B3 (Table 7).

This difference is likely due to basin morphology and/or the diameter of the inlet pipe, which limits the maximum flowrate, as mentioned in section 2.1. The morphology of the basins differ as B3 has a catchment area of 3.14 ha and maximum surface water storage of ~500m^3, whereas B5 has a catchment area of 3.61 ha and maximum surface water storage of ~1075m^3. The larger basin size and storage capacity of B5 may be allowing for longer residence time which is likely to have a positive impact on water quality and limit erosion. Further, the size of the inlet pipes will influence the maximum flowrate which can also impact residence time. B3 has a 6 inch diameter pipe while B5 has an 8 inch diameter pipe, indicating that B5 has a greater maximum flowrate and could theoretically drain quicker, resulting in shorter residence times. This is not the case however, as B5 has longer residence times despite the larger inlet pipe, suggesting that basin morphology is the controlling factor on residence time. Moreover, this shows the importance of sizing the outlet tiles for the berms. More evidence is required to draw more definitive conclusions as the flowrates are further complicated by B2 which drains both B3 and B5 (Figure 1).

Table 6: Comparison of B3 and B5 residence time.

Season	**Mean Residence Time (hours)**		**One-tailed *p*-value**
	DFTEL B3	**DFTEL B5**	
Growing	7.7	9.5	$p = 0.272$
Non-growing	6.9	10.2	$p = 0.161$*
Combined	7.2	10.0	$p = 0.117$*

*normality test failed for NGS and combined data

Table 7: Berm residence time comparison (non-parametric).

Season	**Median Residence Time (hours)**		**Wilcoxon Sign Ranked Test *p*-value**
	DFTEL B3	**DFTEL B5**	
Growing	*normal data, see one tailed t-test		
Non-growing	4.5	5.8	$p = 0.049$
Combined	5.0	7.5	$p = 0.008$

4.0 NEXT STEPS

Based on our current analysis, it appears that B3 (Agri-Drain®) has a finite time period during which it is effective at reducing TP and TSS loads (Figure 3). Moving forward, we would like to investigate the approach of replacing the Agri-Drain® modification and cleaning it on a yearly basis. From a practical view, this approach would require two Agri-Drain® straw systems for each surface riser inlet as a clean one would need to be installed when the used one is removed for cleaning. Based on our preliminary data, this will likely increase the long term effectiveness of the Agri-drain® modification, however field implementation and further testing is required before conclusions can be drawn.

A preliminary analysis of TP export coefficients (kg/ha) at B3 and B5 for five events during the study period, show that there may be a strong predictive relationship between TP export coefficients and the magnitude of the event (Figure 4). This has implications for modelling efforts as predictive TP export coefficients (Figure 5) may be able to be made once more baseline data has been collected (currently n=5). Currently, the five analyzed events indicate a strong predictive capability using flow data alone, with Nash-Sutcliffe Efficiency values of 0.88 for B3 and 0.95 for B5 (Figure 5). This would reduce input requirements for a model as continuous stage data would be sufficient to estimate TP export within a reasonable magnitude of error and sample collection could be reduced dramatically.

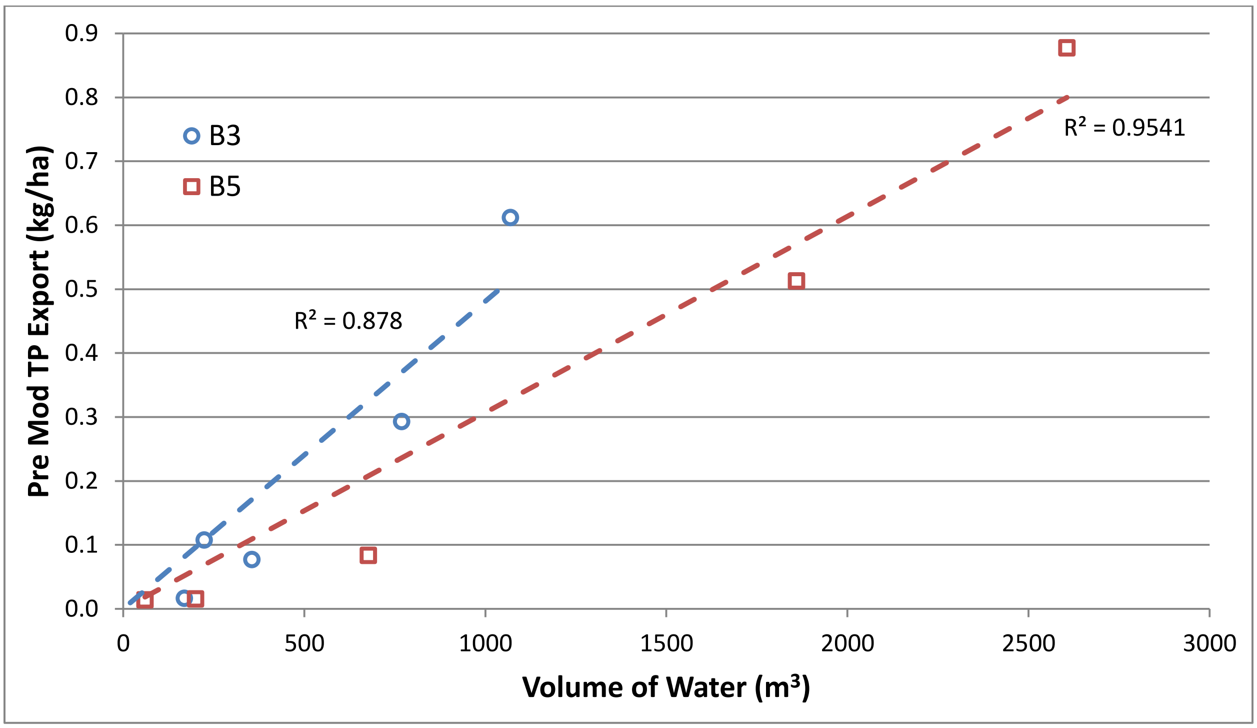

Figure 4: Linear relationships between volume of water during an event (discharge) and TP export coefficient for B3 and B5.

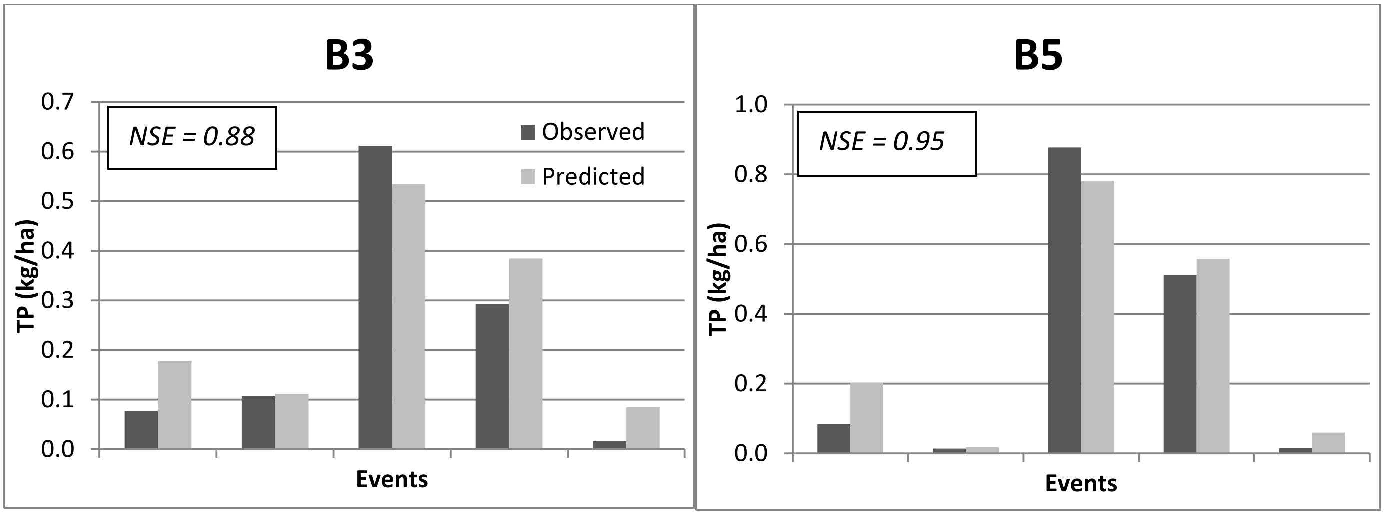

Figure 5: Comparison of observed total phosphorus (TP) export coefficients compared to predicted TP export coefficients derived from the linear equations in Figure 4. Events 1 through 5 represent the events during the study period where both water quantity and quality were measured at both berm sites. Nash-Sutcliffe efficiency coefficients indicate strong model performance (n=5). More events are required before conclusions can be made regarding the accuracy of modelling TP export coefficients based on the size of the event.

5.0 REFERENCES

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