TECHNICAL MEMORANDUM

Cranberry Bog Restoration and Management:

Nutrient Removal Pilot Update within the Hamblin Bog System, Town of Barnstable, MA.

UPDATED - Final Assessment and Quantification of the Nutrient Loading/Uptake through the Upper Marston s Mills River Bogs in Barnstable

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Overview: The Massachusetts Estuaries Project (MEP) Nitrogen Threshold Report for the Three Bays System indicated that the Marstons Mills River is one of the main collection points for freshwater and nitrogen (N) discharging from the Marstons Mills River sub-watershed to the headwaters of the Three Bays estuary.
The MEP Watershed-Embayment Assessment and Modeling effort for the Three Bays estuary found that this large complex estuarine system is presently impaired by N enrichment from sources within its watershed and that the tidal flushing of bay waters was efficient.

Restoration of this system will involve the reduction in the nitrogen load from the watershed to meet the Mass DEP/USEPA Total Maximum Daily Load (TMDL) restoration threshold for this estuary. After considerations over which potential site along the River would be suitable for restoration, the Upper Marstons Mills River cranberry bogs (also called Hamblin Bogs, after the late owner John Hamblin) was considered an ideal location. This site is located south of Bog Road and east of River Road.

Nitrogen loading from Hamblin Bogs to the Marstons Mills River has been quantified, at a multitude of sites along the main and branching channels, weekly from 2018-2020 then bi-weekly from 2020-2021 to determine the inputs of highest load to the system. This site is up-gradient of the Three Bays Estuarine system and is an ideal location for pilot projects to restore natural processes for N attenuation that have been lost through man-made modifications (conversion of wetlands to cranberry bogs). By restoring natural ecological functions, nitrogen attenuation will be enhanced over present conditions, resulting in reduced N transport to the head of the Three Bays estuary. To ensure success in the implementation of a pilot project, the Barnstable Clean Water Coalition (BCWC) partnered with the Coastal Systems Group (CSP) to monitor the water flow and nutrient inputs/outputs throughout the Hamblin Bogs to accurately determine the present sources and sinks of N within the Hamblin Bogs system. Monitoring flow and nutrient levels across the system was to set a baseline for comparison with future restoration and supported the identification of areas presently exhibiting N attenuation and suggested areas where increased attenuation might be possible with habitat restoration.

Naturally, cranberry bogs can attenuate up to 30% of the nitrogen load passing through them (MEP analysis), making them an important restoration tool. Critical to understanding the potential for enhanced natural attenuation in restored cranberry bogs is quantifying the uptake and release of nutrients throughout the current bog system. Presently, the Hamblin Bogs are fed by Middle Lake and Muddy Pond and form the headwaters of the Marstons Mill River, which runs through the center of the bog network, and finally discharges to the head of the Three Bays Estuary.

Previous Work:

In 2019, CSP scientists: a) determine freshwater flow volumes and directions within the Hamblin Bog system, b) conduct frequent open channel flow sampling to determine nutrient concentrations at multiple locations throughout the bog system, c) with the volumetric flow (a) and nutrient concentration data (b) quantify the baseline nutrient input and output N loads from the component bog cells, d) assess the speciation of nutrients throughout the bog system to clarify regions where transformations are occurring and where denitrification may be enhanced, e) provide recommendation for evaluating nitrogen removal by this bog system. The present effort covers monitoring conducted throughout 2020 and is the companion report to the one on the 2019 monitoring, previously submitted.

For 2020 the monitoring followed mostly the same sampling locations and the same procedures used in 2019. However, in 2020, CSP scientists: a) removed station HB6 due to flow being confounded by recycling of irrigation water, b) added stations HB10, c) added continuous stage recorders to HB1, HB4, HB5, HB10, with a recorder temporarily at HB11 for capture release of harvest flood water, d) added a component bog cell, Box5, between HB10 and HB4, and e) performed hydrologic and land use analysis for groundwater flow and load inputs to the component bog cells. These changes were performed to further refine the annualized flow, nutrient load, and speciation of those nutrients throughout the component bog cells.

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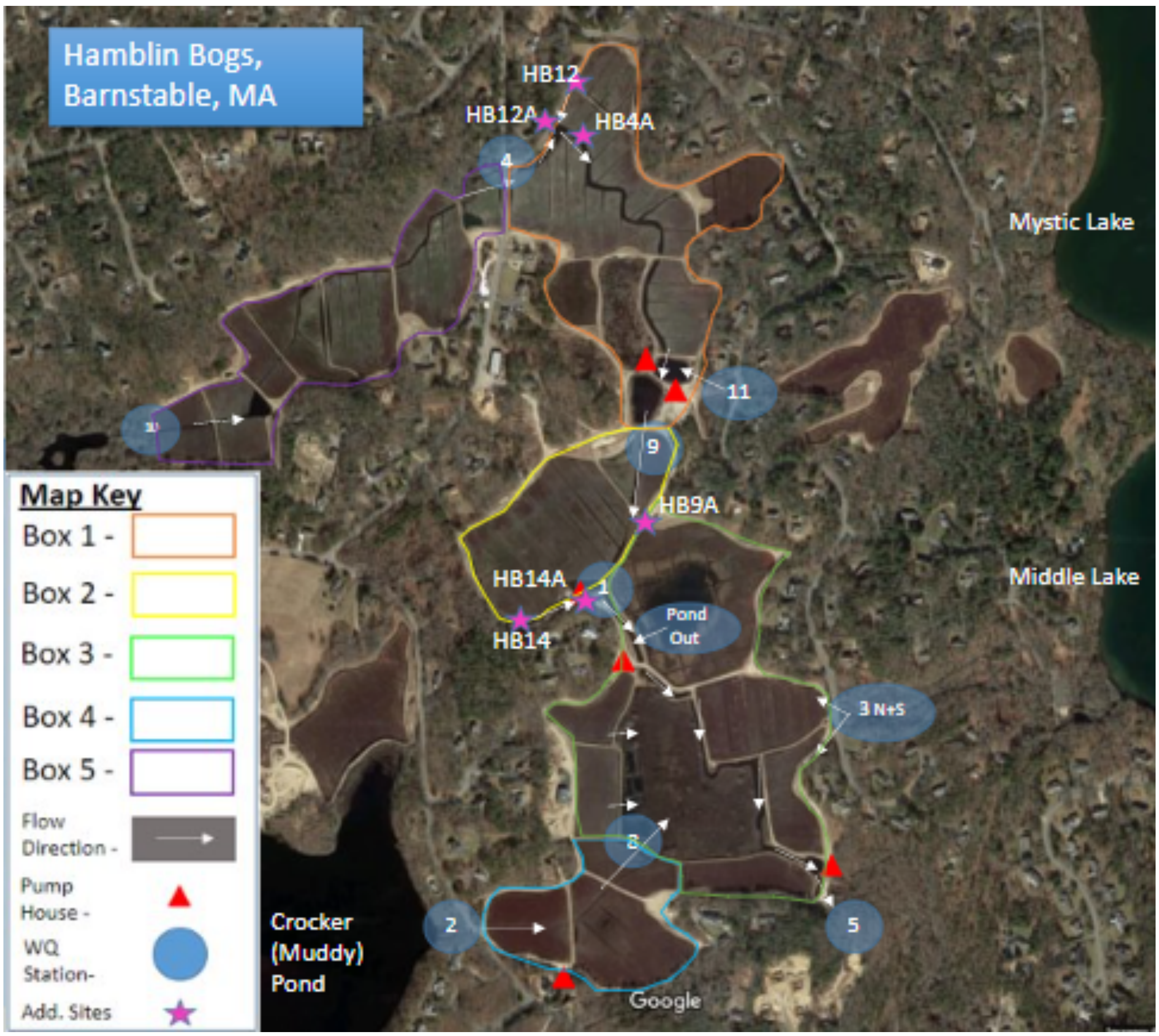


Figure 1. 2019-2020 sampling map. Station map (blue circles), with arrows indicating flow under "normal" conditions (i.e. no harvest or winter floods). Outlined in different colors are the five component cells of Hamblin Bogs, which are used to assess nitrogen attenuation within each box. The stars indicate the new sampling sites added to assess box model N sources.

Methods

Measurements of Stream Flow and Nutrient Concentrations

Field data collection was initiated July 25, 2018, and continued through December 2020, with some archived samples collected through November 2021. The field effort was focused on weekly measurement of stream velocity for calculation of flow and stream sampling to determine nutrient concentrations. Pairing stream flow (m^3/day) with sample nutrient concentration (mg/L) yields mass load of nutrients (kg/day) at each measurement location within the bog system. Stream velocities were measured approximately weekly using a Marsh McBirney electromagnetic flow meter. Water samples were collected in parallel with velocity measurements and analyzed for nutrients (nitrogen and phosphorus) at the Coastal Systems Analytical Facility. For sites without a continuous stage recorder (HB2, HB8, HB9 and the additional new sites), volumetric discharge (m^3/d) and nutrient concentrations were interpolated between sampling dates to determine the approximate volumetric flow and nutrient concentrations on dates between sampling events. Coupling the flow and nutrient concentrations results in total nutrient load at critical junctures throughout the Upper Marstons Mills River Bogs. For sites with a continuously recording stage recorder (HB1, HB4, and HB5), the water depths were used to develop a stage-discharge relationship, therefore the analysis of loads throughout the bog system was based on average daily stage measurements. Use of continuous stage recorders provides daily flow measurements throughout the bog system. Thus, providing a more robust flow determination for assessing nutrient attenuation in the Hamblin Bogs.

Bi-weekly sampling began in 2021 for HB1, HB4, HB5, HB9, HB9A, HB12, HB12A, HB13, HB13A, HB14, and HB14 after weekly sampling in 2020. HB 2 was sampled when flooded. Stream velocities at HB1, HB4, HB9, HB9A, and HB14 were measured in culverts with dimensions ranging from 2ft to 3.4ft in diameter. Stream velocities at HB2, HB4A, HB5, HB12, HB12A, HB13, HB13A, and HB14A were measured using open-channel flow methods in a natural stream channel. Nutrient assays performed on samples collected were conductivity, dissolved nutrients, TP, POC/N. These additional sites (see Figure 1 purple stars) were chosen based on previous 2019 data collection. Figure 1 indicated different Boxes to determine individual load contributions from each. Box1 and Box 2 had the highest levels of N with Box 1 only having 6% (422 kg/yr) N attenuation, while Box 2 has 14% (1258 kg/yr).

It should be noted that cranberry bogs are engineered systems, where water is impeded and stored, released, and potentially recycled or lost through frost and summer irrigations. The installation of continuously recording vented calibrated water level gauges, installed at multiple sites to yield the level of water fluctuations throughout the bog channels would be necessary to determine changes in water movement throughout the system. These have been implemented at HB4, HB1, and HB5, yet use of rating curve was not possible at any site due to inaccuracies in flood and release timing. Use of traditional rating curves requires careful logging of weir board adjustments made to hold/release water. Under these circumstances, a multi-phase stage discharge relationship would need to be used. However, the high frequency of direct measurement of flow was sufficient to determine input/output and internal N transport.

Table 1. Stations where parallel measurements of volumetric flow and nutrient concentrations were sampled within the Hamblin Bog System at nominal weekly intervals. If there was no flow at a station, then water samples were not collected. For example, HB1 had 103 flow measurements and 100 water samples collected out of 107 sampling events.

			Field Data	Assays Performed			
Station	Sampling Period	# Samples	Flow	Conductivity	Dissolved Nutrients	TP	POC/N
HB1	7/25/18 - 12/22/20	107	103/107	101/107	101/107	100/107	99/107
HB2	7/25/18 - 7/27/20	94	91/94	90/94	90/94	90/94	90/94
HB3	7/25/18 - 8/26/20	99	75/99	90/99	90/99	90/99	90/99
HB4	7/25/18 - 12/22/20	134	127/134	126/134	126/134	127/134	127/134
HB4A	7/25/18 - 12/22/20	37	35/37	36/37	37/37	37/37	37/37
HB5	7/25/18 - 12/22/20	115	107/115	113/115	113/115	113/115	112/115
HB6	7/25/18 - 1/2/20	50	50/50	50/50	50/50	50/50	50/50
HB8	10/17/18 - 10/21/20	87	76/87	75/87	75/87	75/87	74/87
HB9	10/17/18 - 12/22/20	115	111/115	105/115	106/115	107/115	106/115
HB9A	3/5/20 - 12/22/20	40	37/40	40/40	39/40	40/40	40/40
HB10	8/8/19 - 9/16/20	54	29/54	52/54	52/54	52/54	50/54
HB11	8/8/19 - 1/20/20	22	0/22	1/22	1/22	1/22	1/22
HB12	3/5/20 - 12/22/20	39	35/39	39/39	38/39	39/39	39/39
HB12A	3/5/20 - 12/22/20	38	35/38	37/38	37/38	37/38	37/38
HB13	3/5/20 - 12/22/20	40	35/40	39/40	38/40	38/40	36/40
HB13A	3/12/20 - 12/22/20	37	35/37	36/37	35/37	35/37	34/37
HB14	3/5/20 - 12/22/20	44	39/44	43/44	43/44	43/44	43/44
HB14A	3/5/20 - 12/22/20	44	37/44	43/44	43/44	43/44	42/44
HB15A	6/29/20 - 9/28/20	14	0/14	14/14	14/14	14/14	13/14
Pond Outfall	9/12/18 -4/23/20	73	71/73	56/73	56/73	56/73	55/73
Totals		1283	1128/1283	1186/1283	1109/1283	1187/1283	1125/1283

Water samples were field filtered (0.2 µm) for dissolved nutrients into 60-mL acid-washed bottles with parallel whole water samples collected in 1-L acid washed brown HDPE bottles. Water quality samples were analyzed by the Coastal Systems Analytical Facility at the University of Massachusetts Dartmouth School for Marine Science and Technology. All sample processing occurred within 24 hours of sample collection. Water samples were assayed for ammonium (NH_4^+) by indophenol/hypochlorite method, nitrate + nitrite (NO_x^-) by cadmium reduction on QuikChem8000 Lachat auto analyzer and dissolved organic nitrogen (DON) by persulfate digestion and total phosphorus (TP) with persulfate oxidation and determination of ortho-phosphate by molybdate/ascorbic acid method. Upon return to the laboratory the whole water sample was processed for particulate organic carbon and nitrogen and specific conductivity. Particulate carbon and nitrogen samples were filtered through pre-combusted 25mm Whatman glass fiber filters, dried at 65 ˚C, and combusted in a Perkin Elmer Series II CHN analyzer. Specific conductivity was determined using a calibrated temperature compensated probe with meter.

Site Description:

The present study area consists of approximately 100 acres of wetland, known as Hamblin Bogs. The bogs and pump houses within this study area, once entirely owned by John Hamblin, were sub-divided into functional components for analysis as seen in Figure 1. Additional sites,were included to surmise the sources of nitrate by measuring load and nutrient concentration in the individual channels of Box 1 and Box 2. Box 1 and Box 2 were chosen as it has the highest levels of nitrate flowing into the rest of the bogs. Surface water sources entering Hamblin Bogs are comprised of the Marstons Mills River and two small streams from Muddy Pond and Middle Lake. The Marstons Mills River enters the bog system at station HB10 and flows through stations HB4, HB9, HB9A, and HB1. The Marstons Mills River exits the bog system at station HB5. Along the main stem of the river between its point of entry (HB10) and where it exits (HB5), additional flow enters from several known water sources: 1) springs in the northern bog area (Big Coombs), 2) flood and irrigation water from M&M bogs, and 3) direct groundwater discharges. The small stream from Muddy Pond enters the system at station HB2, flows through LaPointe West Bogs, with most of the water passing through station HB8, entering the swamp, before combining with the main bog channel. The small stream from Middle Lake once entered at station HB3, which has a small holding area where water then flows to either the north or south side of Run Bog, before eventually joining with the main bog channel.

Results and Discussion

Water Flow Analysis:

As an active flow-through bog system there is always significant water movement through the system in the River channels and as water is transferred around the various bog cells as required for agricultural practices. To effectively maintain the cranberries, water is transferred for frost protection, pesticide applications, summer irrigation, harvest floods (if wet harvest), and winter floods (to protect the vines from freezing. During The months of November 2020 and February 2021 the bogs were flooded which limited sampling and flow measurements. In addition, some uncertainty exists due to the pumping of water for irrigation (through a multitude on on-site pump houses) and flooding which complicates the determination of water volumes and associated nitrogen and phosphorus loads through the Hamblin Bogs system.

Sampling within the main channel (Figure 2) was done at HB4A. In Box1, HB4 captures the surface water entering Box1 and HB9 captures all the water leaving. HB4A captures the water from HB4, HB12, HB12A, HB13, and HB13A. In Box2, HB9 flows to HB9A and captures the water, leaving BOX2, before it exits to HB1 and then the system permanently at HB5, through Box3. HB14, HB14A, and HB15A all flow into a small basin that flows outs to HB1.

Water Quality Analysis:

Nutrient samples collected at each site provide quantitative information on the nitrogen and phosphorus concentrations and how they vary throughout the system. The highest total nitrogen (TN) concentrations within Hamblin Bogs are typically found at HB10, with a range of 2.23 to 2.91 mg/L and HB4, with a range of 1.88 to 3.13 mg/L (Table 2). The TN concentrations along the Marstons Mills River stations (HB4, 6, 9, 1, and 5) decrease as the water flows toward HB5. The TN concentration at HB2, originating from Muddy Pond, is typically ~ 0.5 mg/L, except during November and December of 2018, when it reaches an average TN concentration of 0.8 mg/L, and February 2020 at 1.05 mg/L. The rise in this small pond coincides with nutrient release from the dense macrophyte community within the pond and likely explains the concentration rise in the Muddy Pond outflow. However, the rise in TN concentration during November and December 2019 was less in 2019 and there was no flow measured from August to December 2020. As the water passes from HB2 to HB8 the TN concentration remains nearly the same except in May to September of 2020 where the values were higher due to flow changes. Similar to HB2, the TN concentration at HB3, originating from Middle Lake, is quite low ranging from 0.2 to 0.7 mg/L at HB3N & 3S. The sites receiving surface water flows from ponds (HB2 and HB3) have the lowest TN concentration. This almost certainly result from nitrogen attenuation during passage through these ponds.

The total nitrogen of sites along the main channel of the bog system, upper Marstons Mills River (HB4, 9, 1, and HB5), are typically dominated by dissolved inorganic nitrogen (DIN = $NH4+$ + $NOx-$), where sites HB10, 4, and HB9 always have greater than 60% DIN, averaging ~80% DIN throughout the year. At HB2 and HB3S, the total nitrogen is dominated by organic nitrogen (DON+PON). These waters derive from ponds and lakes, as the inorganic nitrogen is generally transformed to organic nitrogen by biological processes in the lakes and ponds. Similarly, since most of the water at HB8 comes from HB2, the total nitrogen consists of mostly organic nitrogen, except for October 2018 and 2019, where there was no flow at HB2 and very low flows at HB8, likely from groundwater inputs, resulting in DIN being the main nitrogen constituent. In October 2019, HB2 continued to have flow, thus the nitrogen at HB8 mostly consisted of organic nitrogen. Sites with high DIN represent areas where enhanced nitrogen removal is likely possible.

In addition to nitrogen, it is important to assess the phosphorus concentration changes throughout Hamblin Bogs. The TP concentrations reveals that phosphorus concentrations increases from HB10 to HB9 as water passes through a different bog system and into HB4 where it travels through Box 1 to HB9. From HB9 to HB1 the phosphorus concentrations increase, a pattern in 2018, 2019, and 2020 (Table 4). The pond outfall has concentrations of total phosphorus ranging from 0.03 to 0.11 mg/L, with highest to lowest concentrations occurring in the following order: harvest, winter, September, and spring (2019 report). There was no 2020 data as this site was boarded but had leaks so an accurate concentration reading was not possible. Phosphorus concentrations at HB2 range from 0.02 to 0.04 mg/L. HB3 (S&N) has the lowest TP concentrations of all the sites at approximately 0.03 mg/L or lower, until August 2019 when concentrations rise, with highest TP concentrations measured in October 2019 at 0.12 and 0.16 mg/L which then lowers again from November 2019 until July 2020 within the initial range.

Table 2. Total nitrogen concentrations (monthly) at all stations in the Hamblin Bogs System, in order from up-gradient station (HB10) to the most down gradient station (HB5). The most up-gradient station (HB10) changes to HB4 when the HB10 culvert is retrofitted in August 2020. Total nitrogen concentrations are represented as monthly averages.

	TN (mg/L)										
	HB10	HB4	HB6	HB9	HB1	Pond Outfall	HB2	HB8	HB3N	HB3S	HB5
Aug-18	ND	2.42	2.42	ND	1.71	ND	0.48	ND	ND	ND	1.29
Sep-18	ND	2.27	2.41	ND	1.67	0.72	ND	ND	0.28	0.19	1.21
Oct-18	ND	1.71	1.48	ND	1.2	0.73	ND	ND	0.28	0.30	0.9
Nov-18	ND	1.83	1.72	1.7	1.47	0.74	0.79	0.66	0.35	0.36	0.87
Dec-18	ND	2.76	2.73	2.45	2.1	0.86	0.73	0.78	0.41	0.43	1.22
Jan-19	ND	1.77	1.91	1.7	1.37	0.73	0.59	0.58	0.33	0.32	0.82
Feb-19	ND	1.66	1.53	1.4	1.13	0.47	0.4	0.44	0.28	0.26	0.59
Mar-19	ND	2.55	2.55	2.34	1.94	0.47	0.45	0.45	0.31	0.32	1.02
Apr-19	ND	2.51	2.5	2.22	1.68	1.52	0.46	0.52	0.34	0.35	1.14
May-19	ND	2.49	2.54	2.14	2.03	1.52	0.47	0.57	0.43	0.42	1.20
Jun-19	ND	2.2	2.17	1.94	1.84	1.39	0.52	0.58	0.41	0.42	1.11
Jul-19	ND	2.03	2.11	1.92	1.78	1.80	0.55	0.52	0.63	0.55	1.08
Aug-19	ND	2.17	ND	1.92	1.72	1.05	0.52	0.61	0.41	0.4	1.15
Sep-19	2.86	2.28	ND	2.03	1.75	1.52	0.49	0.64	0.68	0.74	1.33
Oct-19	2.23	1.88	ND	1.64	1.46	ND	0.46	0.59	0.6	0.46	1.06
Nov-19	2.91	2.53	ND	1.7	1.99	ND	0.55	0.42	ND	ND	1.47
Dec-19	2.91	2.62	ND	2.43	2.18	ND	0.56	ND	ND	ND	1.45
Jan-20	2.88	2.49	ND	ND	0.08	ND	0.55	ND	ND	0.41	0.83
Feb-20	2.59	1.89	ND	ND	0.99	ND	1.05	ND	ND	0.43	1.72
Mar-20	2.48	2.5	ND	2.05	2.00	ND	0.56	0.63	ND	0.43	1.09
Apr-20	2.55	2.7	ND	ND	1.91	ND	0.57	0.57	ND	0.38	0.82
May-20	1.68	2.24	ND	2.00	1.61	ND	0.45	1.66	ND	0.32	1.31
Jun-20	2.63	ND	ND	2.39	ND	ND	0.49	1.68	ND	ND	ND
Jul-20	2.53	ND	ND	2.25	1.82	ND	0.56	0.71	ND	0.60	0.43
Aug-20	2.44	2.51	ND	1.74	1.77	ND	ND	3.35	ND	ND	2.09
Sep-20	ND	3.13	ND	2.18	1.61	ND	ND	1.16	ND	ND	3.76
Oct-20	ND	2.19	ND	1.79	1.77	ND	ND	-1.79	ND	ND	14.43
Nov-20	ND	2.2	ND	1.38	1.77	ND	ND	ND	ND	ND	ND
Dec-20	ND	2.19	ND	2.19	1.77	ND	ND	ND	ND	ND	2.55

Table 3. Total nitrogen concentrations (monthly) at all additional stations in the Hamblin Bogs System.

	TN(mg/L)								
	HB4A	HB9A	HB12	HB12A	HB13	HB13A	HB14	HB14A	HB15A
Jan-20	ND	ND	ND	ND	ND	ND	ND	ND	ND
Feb-20	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mar-20	ND	ND	ND	ND	ND	ND	ND	ND	ND
Apr-20	2.20	1.85	2.88	4.1	3.38	2.14	1.47	1.36	ND
May-20	2.32	1.94	3.02	3.03	3.46	2.24	1.78	1.54	ND
Jun-20	2.44	2.16	3.09	3.06	4.14	ND	1.83	1.68	ND
Jul-20	2.28	2.03	3.29	3.12	4.00	ND	1.90	1.74	ND
Aug-20	1.81	1.58	2.92	2.79	ND	ND	1.63	1.19	ND
Sep-20	2.24	1.89	3.11	3.39	ND	2.39	1.54	1.32	ND
Oct-20	12.28	1.68	2.79	ND	ND	ND	1.8	1.46	ND
Nov-20	2.11	ND	1.67	ND	ND	ND	ND	ND	ND
Dec-20	2.71	2.19	2.98	3.42	ND	ND	ND	ND	ND

Table 4. Total phosphorus concentrations (monthly) at all stations in the Hamblin Bogs system, in order from up-gradient station (HB10) to the most down gradient station (HB5). The most up-gradient station (HB10) changes to HB4 when the HB10 culvert is retrofitted in August 2020. Total phosphorus

concentrations are represented as monthly averages, and it appears that phosphorus pick-up in bog passage is most pronounced in spring and summer.

	TP (mg/L)										
	HB10	HB4	HB6	HB9	HB1	Pond Outfall	HB2	HB8	HB3N	HB3S	HB5
Aug-18	ND	0.03	0.04	ND	0.07	ND	0.03	ND	ND	ND	0.07
Sep-18	ND	0.03	0.04	ND	0.06	0.06	ND	ND	0.02	0.01	0.06
Oct-18	ND	0.11	0.08	ND	0.09	0.11	ND	ND	0.02	0.02	0.08
Nov-18	ND	0.07	0.11	0.10	0.09	0.07	0.03	0.05	0.02	0.02	0.10
Dec-18	ND	0.15	0.08	0.05	0.07	0.08	0.02	0.05	0.01	0.01	0.07
Jan-19	ND	0.04	0.04	0.05	0.06	0.06	0.03	0.04	0.02	0.02	0.05
Feb-19	ND	0.03	0.04	0.04	0.05	0.05	0.02	0.04	0.01	0.01	0.05
Mar-19	ND	0.03	0.04	0.04	0.05	0.03	0.02	0.03	0.01	0.01	0.06
Apr-19	ND	0.02	0.02	0.03	0.05	0.04	0.02	0.03	0.01	0.01	0.04
May-19	ND	0.02	0.02	0.03	0.04	0.05	0.02	0.04	0.01	0.01	0.03
Jun-19	ND	0.02	0.02	0.03	0.04	0.08	0.03	0.05	0.03	0.03	0.05
Jul-19	ND	0.01	0.02	0.02	0.03	0.09	0.03	0.05	0.03	0.03	0.06
Aug-19	ND	0.03	ND	0.04	0.04	0.08	0.03	0.06	0.04	0.04	0.06
Sep-19	0.02	0.03	ND	0.04	0.04	0.04	0.02	0.06	0.06	0.04	0.05
Oct-19	0.04	0.16	ND	0.08	0.08	ND	0.04	0.04	0.12	0.16	0.09
Nov-19	0.02	0.06	ND	0.06	0.09	ND	0.02	0.05	ND	0.06	0.11
Dec-19	0.02	0.03	ND	0.04	0.06	ND	0.02	ND	ND	0.02	0.08
Jan-20	0.01	0.03	ND	ND	ND	ND	0.03	ND	ND	0.01	0.02
Feb-20	0.02	0.02	ND	ND	0.03	ND	0.04	ND	ND	0.02	0.05
Mar-20	0.02	0.04	ND	0.03	0.04	ND	0.03	0.05	ND	0.02	0.05
Apr-20	0.01	0.03	ND	0.04	0.09	ND	0.03	0.03	ND	0.01	0.04
May-20	0.03	0.02	ND	0.04	0.11	ND	0.03	0.03	ND	0.01	0.08
Jun-20	0.01	ND	ND	0.03	ND	ND	0.03	0.03	ND	ND	ND
Jul-20	0.01	ND	ND	0.05	0.09	ND	0.03	0.05	ND	0.04	0.03
Aug-20	0.02	0.04	ND	0.04	0.05	ND	ND	0.47	ND	ND	0.10
Sep-20	ND	0.04	ND	0.04	0.06	ND	ND	0.14	ND	ND	0.14
Oct-20	ND	0.15	ND	0.07	0.05	ND	ND	0.89	ND	ND	0.67
Nov-20	ND	0.15	ND	0.14	0.05	ND	ND	ND	ND	ND	ND
Dec-20	ND	0.15	ND	0.06	0.05	ND	ND	ND	ND	ND	0.18

Table 5. Total phosphorus concentrations (monthly) at all additional stations in the Hamblin Bogs System.

	TP(mg/L)								
	HB4A	HB9A	HB12	HB12A	HB13	HB13A	HB14	HB14A	HB15A
Jan-20	ND	ND	ND	ND	ND	ND	ND	ND	ND
Feb-20	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mar-20	ND	ND	ND	ND	ND	ND	ND	ND	ND
Apr-20	0.03	0.04	0.02	0.02	0.02	0.02	0.01	0.02	ND
May-20	0.02	0.04	0.02	0.02	0.04	0.03	0.02	0.03	ND
Jun-20	0.02	0.03	0.03	0.02	0.12	0.01	0.01	0.02	ND
Jul-20	0.02	0.03	0.03	0.02	0.12	0.03	0.02	0.02	ND
Aug-20	0.03	0.03	0.03	0.03	0.06	ND	0.02	0.03	ND
Sep-20	0.03	0.04	0.05	0.03	0.00	0.03	0.02	0.06	ND
Oct-20	-1.11	0.07	0.03	ND	ND	ND	0.02	0.03	ND
Nov-20	0.09	ND	0.16	ND	ND	ND	0.05	0.06	ND
Dec-20	0.06	0.06	0.06	0.06	ND	0.06	ND	ND	ND

Table 6. Total phosphorus loads at all stations in the Hamblin Bogs system, in order from up-gradient station (HB10) to the most down gradient station (HB5). The most up-gradient station (HB10) changes to HB4 when the HB10 culvert is retrofitted in August 2020.

	TP (kg/month)										
	HB10	HB4	HB6	HB9	HB1	Pond Outfall	HB2	HB8	HB3N	HB3S	HB5
Aug-18	ND	4.31	8.09	0.00	23.05	0.00	0.48	ND	ND	ND	27.5
Sep-18	ND	3.01	5.99	0.00	19.09	0.05	ND	ND	0.05	0.70	24.07
Oct-18	ND	9.12	7.64	15.15	24.41	0.12	ND	ND	0.06	1.26	25.26
Nov-18	ND	8.37	23.21	34.05	40.76	2.90	0.85	2.77	0.25	1.7	62.46
Dec-18	ND	16.63	16.75	14.26	29.49	0.34	0.59	2.67	0.25	2.36	40.97
Jan-19	ND	5.10	9.38	7.91	16.33	ND	0.44	4.3	0.23	1.89	29.42
Feb-19	ND	5.45	9.56	8.52	12.19	ND	1.01	5.67	0.37	1.44	30.48
Mar-19	ND	5.44	11.13	13.4	24.57	ND	2.22	5.54	0.9	2.22	65.49
Apr-19	ND	2.59	6.68	9.68	20.09	ND	1.01	1.43	0.19	2.11	27.18
May-19	ND	3.91	6.85	9.57	15.18	ND	1.70	3.08	0.04	2.38	22.57
Jun-19	ND	2.88	6.05	9.8	15.41	ND	2.22	3.55	0.15	4.75	30.52
Jul-19	ND	2.13	2.54	8.39	13.20	0.56	1.2	2.63	0.26	3.71	39.75
Aug-19	ND	3.45	ND	10.73	14.88	0.70	0.55	1.54	0.19	1.61	25.14
Sep-19	0.20	2.75	ND	9.13	12.47	0.06	0.49	1.67	0.08	0.54	15.54
Oct-19	0.49	15.48	ND	14.02	15.88	ND	0.03	0.38	0.12	0.03	22.8
Nov-19	0.06	6.73	ND	13.17	33.3	ND	0.20	0.02	ND	0.00	49.51
Dec-19	0.23	4.73	ND	9.82	23.95	ND	1.20	ND	ND	1.49	57.31
Jan-20	0.15	3.76	ND	ND	0.35	ND	0.14	ND	ND	1.17	12.63
Feb-20	0.14	2.32	ND	ND	8.10	ND	1.56	ND	ND	3.05	29.27
Mar-20	0.20	5.30	ND	9.28	17.15	ND	0.84	1.4	ND	3.08	38.88
Apr-20	0.14	5.14	ND	12.14	38.96	ND	1.75	1.61	ND	2.42	33.62
May-20	0.26	3.04	ND	16.04	36.63	ND	2.28	2.08	ND	1.66	45.49
Jun-20	0.00	ND	ND	7.54	ND	ND	1.88	2.49	ND	ND	ND
Jul-20	0.03	ND	ND	4.22	8.22	ND	1.05	3.12	ND	0.28	7.23
Aug-20	0.07	3.15	ND	7.56	10.33	ND	-0.01	0.19	ND	ND	15.11
Sep-20	0.02	1.94	ND	6.4	9.72	ND	ND	-0.33	ND	ND	10.99
Oct-20	ND	11.61	ND	6.46	2.62	ND	ND	-0.17	ND	ND	20.95
Nov-20	ND	11.36	ND	30.03	ND	ND	ND	ND	ND	ND	ND
Dec-20	ND	11.61	ND	12.66	2.62	ND	ND	ND	ND	ND	43.34

Table 7. Total phosphorus concentrations (monthly) at all additional stations in the Hamblin Bogs System.

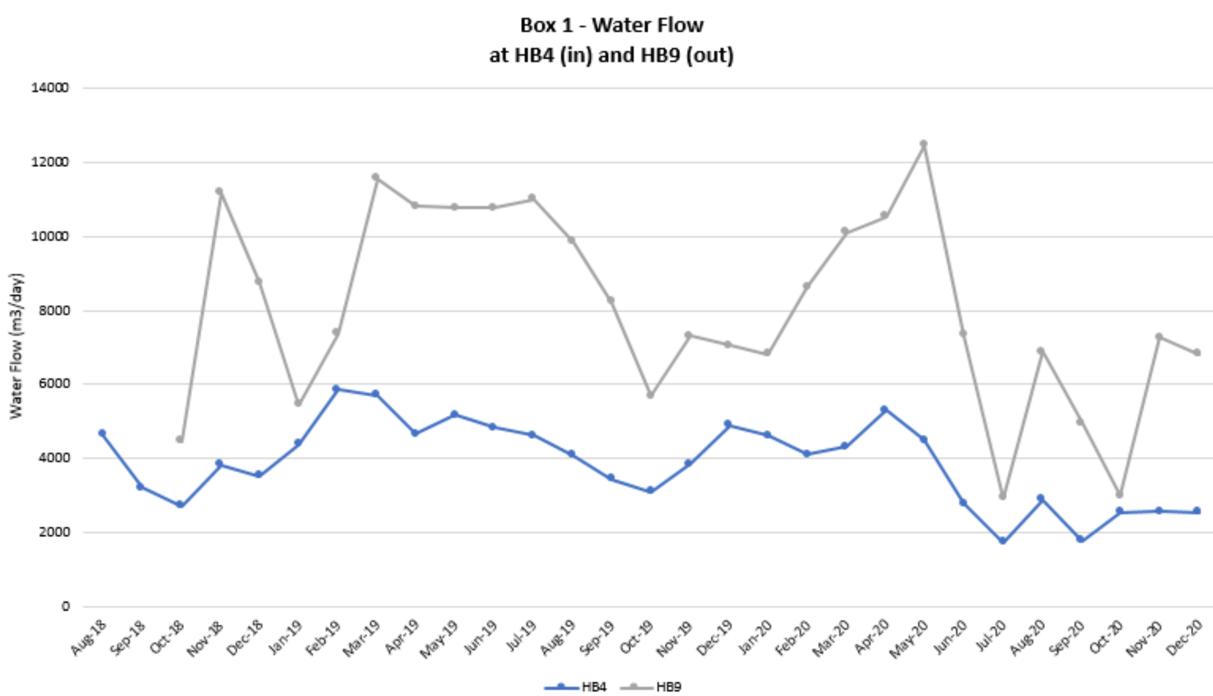
	TP (kg/month)								
	HB4A	HB9A	HB12	HB12A	HB13	HB13A	HB14	HB14A	HB15A
Jan-20	ND	ND	ND	ND	ND	ND	ND	ND	ND
Feb-20	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mar-20	ND	ND	ND	ND	ND	ND	ND	ND	ND
Apr-20	2.74	14.1	0.19	0.37	0.04	0.22	0.10	0.47	ND
May-20	6.71	13.1	0.44	0.49	0.61	0.26	0.20	0.49	ND
Jun-20	1.68	8.32	0.38	0.20	0.56	0.08	0.10	0.39	ND
Jul-20	2.62	6.02	0.32	0.27	0.02	0.31	0.20	0.34	ND
Aug-20	2.49	5.92	0.67	0.42	0.41	ND	0.10	0.34	ND
Sep-20	1.37	6.88	0.53	0.10	0.00	0.35	0.10	0.69	ND
Oct-20	1.38	7.76	-0.21	ND	ND	ND	0.40	0.32	ND
Nov-20	5.04	ND	0.16	ND	ND	ND	0.00	-0.30	ND
Dec-20	2.06	12.96	0.48	0.29	17.11	0.33	ND	ND	ND

Nutrient Load Uptake Analysis:

Nutrient concentrations and flows were paired to understand how the nutrient load (mass of nitrogen and phosphorus) varied from one box to the next as nutrients are taken up or released within the Hamblin Bogs system. The additional sites were included for Box1 and Box 2 to determine where the highest N is entering into the bogs. To identify the areas of greatest nutrient uptake/release, the system was divided into five functional units/boxes (Figure 1) as previously discussed in the 2019 report. Each of the boxes will be assessed using a box model with annualized inputs (stream, groundwater, and precipitation) and outputs (stream and evaporation). A balance of "salts" (e/g/ Specific Conductivity) was developed for each box to help confirm that all water inputs and outputs, were captured. Phosphorus concentrations and loads increase as water moves through the bogs. There was no attenuation of phosphorus on an annual basis in any component boxes (Table 4 and Table 5). Therefore, analysis of nitrogen attenuation will be the focus in these box models.

Box 1 –HB4, HB9, Big Coombs Pump House, and M&M bogs

Box 1 receives nutrient loads (flow and inputs), from an up-watershed bog through HB4, with additional inputs from groundwater and direct rainfall/dryfall. At the end of harvest flood (November) and winter flood (start of spring), water from Pond View bog and M&M bog is released, draining into Nursery Bog and then Reservoir 1 (see Figure 1). The loads from Box 1 exit through HB9 with some of the water being "recycled" during the summer and frost protection irrigations as it is pumped back up onto the bogs. There is a relatively insignificant amount of water loss through evaporation at HB9.



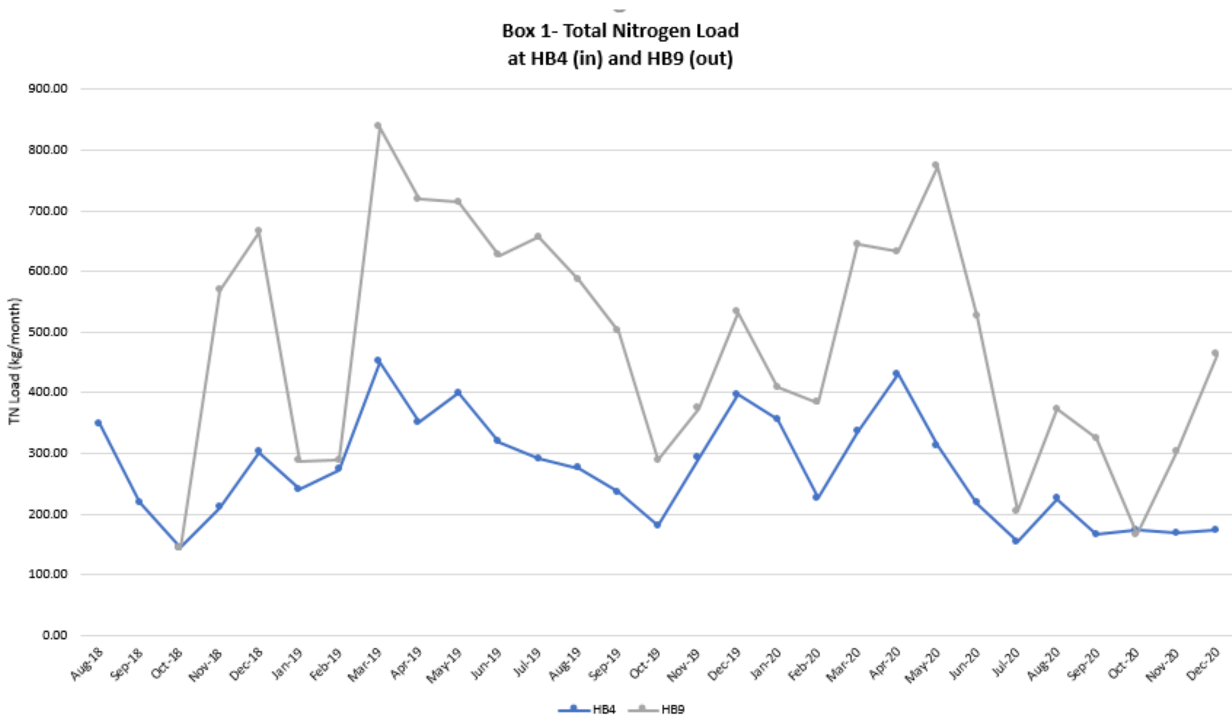


Figure 2. Monthly water flow and total nitrogen load at stations HB4 (IN) and HB9 (OUT) from August 2018 to December 2020.

The surface water input (HB4) and output (HB9), with associated TN loads, monthly from August 2018 to December 2020 is shown in Figure 2. There is a general increase in TN and surface flow from HB4 to HB9. In order to assess the likelihood of nitrogen attenuation within Box1, groundwater (GW), precipitation, and evaporation flows, salt load, and N load are included in the budget calculation. The water balances to 1%. The balance of water is very close because GW flow is determined by the difference of measured water inputs and outputs at HB4 and HB9. The salt balance is within 5% indicating that most water inputs and outputs were measured in Box1, therefore, N attenuation of 12% is representative for Box1 annual conditions (Table 8). The sum of all N load inputs (HB4 + GW + precip.) minus the sum of N load outputs (HB9) provides an estimate of 751 kg N attenuated per year in Box1 (Table 8).

Table 8. Water and salt balance to 1% and 5%, respectively, with 12% nitrogen attenuation in Box1 based on annualized inputs and outputs in Box1.

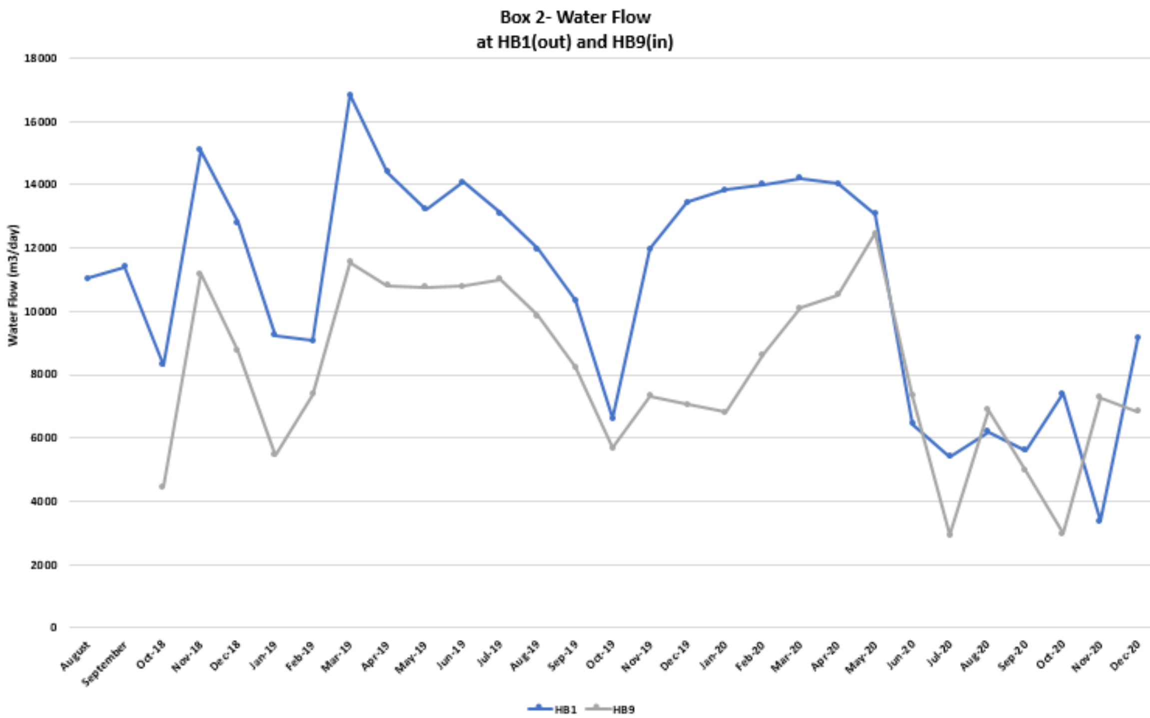
Hamblin Bogs - Box1 *Nov. 1, 2019 to Oct. 31, 2020*				
	Water Balance	Salt Balance	Nitrogen Mass Balance	
	(m3/d)	(kg/d)	(kg/yr)	% of inputs
Inputs:				
Stream input	3617	257	3331	54.5%
Groundwater*	3727	265	2752	45.0%
Precipitation**	76	2	30	0.5%
Total Inputs	7420	523	6113	
Outputs:				
Stream output	-7346	-500	-5362	-
Evaporation	0	0	0	-
Total Outputs	-7346	-500	-5362	
BOX1 Balance:	74	24	751	-
BOX1 Balance/ N atten. (%):	1%	5%	12%	-
Notes: * N determined from landuse analysis ** N determined from N loading factor in MEP				

Pilot Project-BOX 1

Within the Hamblin Bog system, the highest levels of N travel from HB4 through BOX1 and into BOX2. The design constraints for a pilot restoration project prohibited the use of the main channels of the boxes (see Figure 1) so inflowing smaller channels were the optimal location. The overall goal of the project was to restore natural attenuation of N processes that have been lost through man-made modifications. Within BOX1 the sample locations that were added are HB12, HB12A, HB13, and HB13A. HB12A is closest to HB4A (Figure 1) and is the outflow for channels in the upper NE corner of the bog. At HB12 there is an outflow pipe from an unnamed water source that contributes to the load leading to the main channel that is captured at HB4A. Flows were variable based on high levels of vegetation at these sites. Data at HB13 and HB13A was collected until the flow was reduced due to flooding at the HB13A site.

Box 2 –HB9, HB1, and Winnies Pump House

Box 2 receives surface water and nutrient inputs through HB9, with additional water and nutrient inputs from groundwater and direct rainfall/dryfall. Virtually all of the water and nutrient outputs is measured at HB1, with a relatively insignificant amount of water loss through evaporation. Within box two, water is also “recycled”, meaning that through summer and frost protection irrigations, water in the small reservoir above HB1 is pumped back into Winnies bog for irrigation. Although not measured directly, it is possible that there is some nutrient uptake through this irrigation.



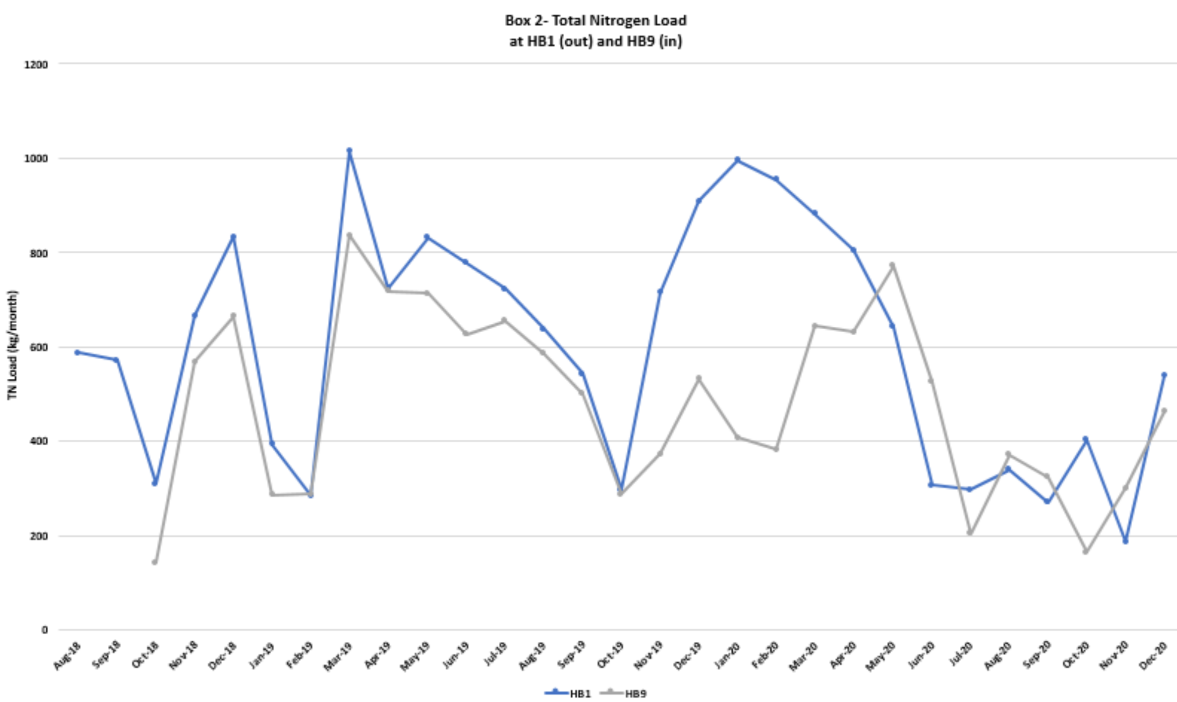


Figure 3. Monthly water flow and total nitrogen load at stations HB9 (IN) and HB1 (OUT) from Aug 2018 to Dec 2020.

Figure 3 shows the surface water input (HB9) and surface water output (HB1), with associated N loads at each site through each month. In general, the total N load and water flow increases between HB9 and HB1, except for in March, October of 2019 and again in March 2020 where there was little change in N load and again in August and September 2020. In Box2, GW inputs are assessed similar to Box1, the water inputs between HB9 and HB1 are used to estimate groundwater flow inputs, which is coupled with the average GW nitrogen concentration of 2.02 mg/L to estimate the GW nitrogen load input. The water balances to 0%. The balance of water is very close because GW flow is determined by the difference of measured water inputs and outputs at HB9 and HB1. The salt balance is within 2% indicating that most water inputs and outputs were measured in Box2. The sum of all N load inputs (HB9 + GW) minus the sum of N load outputs (HB1) provides an estimate of N attenuation of -7% (-481 kg/yr) is representative for Box2 annual conditions (Table 9). The negative attenuation could have been from the road construction being done during the sampling season that saw the road running parallel to the bog being completely redesigned.

Table 9. Water and salt balance to 0% and 2 %, respectively, with -7% nitrogen attenuation in Box2 based on annualized inputs and outputs in Box2.

Hamblin Bogs - Box2 *Nov. 1, 2019 to Oct. 31, 2020*				
	Water Balance	Salt Balance	Nitrogen Mass Balance	
	(m3/d)	(kg/d)	(kg/yr)	% of inputs
Inputs:				
Stream input	7346	500	5336	78.5%
Groundwater*	3136	235	1442	21.2%
Precipitation**	41	1	16	0.2%
Total Inputs	10523	736	6794	
Outputs:				
Stream output	-10491	-724	-7275	-
Evaporation	-22	0	0	-
Total Outputs	-10513	-724	-7275	
BOX2 Balance:	10	12	-481	-
BOX2 Balance/ N atten. (%):	0%	2%	-7%	-
Notes: * N determined from landuse analysis ** N determined from N loading factor in MEP				

Box1+Box2 Combined – HB4, HB1, Big Coombs Pump House, Winnies Pump House, and M&M bogs

Box1 and Box2 combined is defined by the outer of perimeter of Box1 & Box2 (Figure 2). These two boxes are combined to provide information on N attenuation during the summer months, since HB9 was not sampled until October 2018. Box1 & Box2 receives surface water and nutrient inputs through HB4, with additional water and nutrient inputs from groundwater and direct rainfall/dryfall. Virtually all of the water and nutrient outputs are measured at HB1, with a relatively insignificant amount of water loss through evaporation. Within Box1 & Box2 water is also "recycled", meaning that through summer and frost protection irrigations, water in the small reservoirs near Big Coombs and Winnies Pump Houses is pumped back up onto Big Coombs and Winnies bogs for irrigation, harvest, and winter flood. Although not measured directly, it is possible that there is some nutrient uptake through this irrigation of the bog surface.

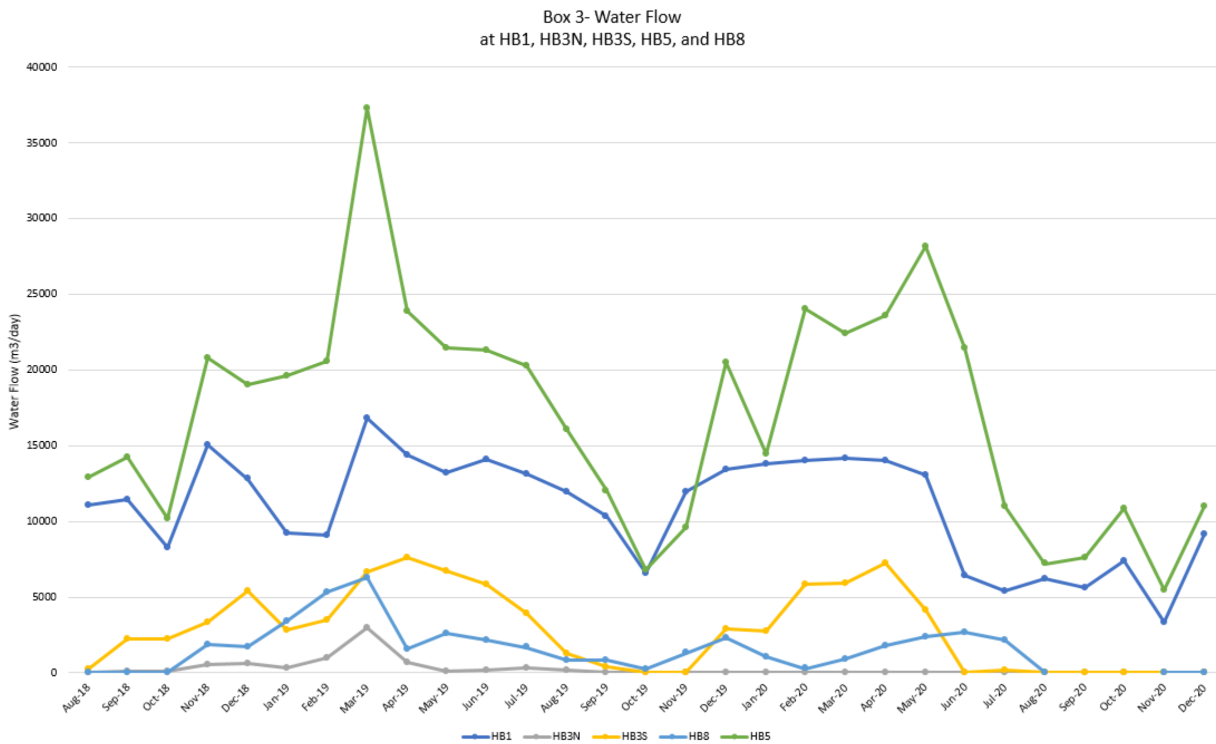
In Box1 & Box2, GW inputs are assessed in a similar manner as for Box1 and Box2, the water inputs between input (HB4) and output (HB1) are used to estimate groundwater flow inputs. Then applying the derived average GW nitrogen concentration of 2.02 mg/L, the GW nitrogen load input was determined. The sum of all N load inputs (HB4 + GW) minus the sum of N load outputs (HB1) provides an estimate of N attenuation in Box2 (Table 10).

Table 10. Analysis of annual flow and load inputs in Box1 and Box2 combined.

BOX1 and BOX2 Combined			
Annual (Nov. '19 - Oct. '20)	Flow (m3/d)	NOx (kg/d)	TN (kg/d)
Inputs:			
HB4 Stream Input	3617	6.8	9.0
GW Input	6874	13.9	13.9
Total Inputs:	10491	20.7	22.9
Outputs:			
HB1 Stream Output	-10491	-17.4	-20.6
Total Outputs:	-10491	-17.4	-20.6
Box1 and Box2 Combined Attenuation of N:			
% N Removal	-	16%	10%
Total N Attenuation	0	3.3	2.3

Box 3 –HB1, HB8, HB3 (S&N), Lovell's Cove Pump House, and LaPointe East Pump House

Box3 receives surface water and nutrient inputs through HB1, 8, and 3, with additional water and nutrient inputs from groundwater and direct rainfall/dryfall. Virtually all of the water and nutrient output is measured at HB5, with an insignificant amount of water loss through evaporation. Within Box3 water is also "recycled", meaning that through summer and frost protection irrigations, water in the small channel near Lovell's Cove Pump House is pumped back up onto Lovell's Cove bogs for irrigation, harvest, and winter flood. Similarly, water in the channel near the LaPointe East Pump House is pumped onto Run Bogs, LaPointe, and Howes bogs. Water irrigated on LaPointe bogs is lost from Box3 into Box4, reentering Box3 through HB8. Although not measured directly, it is possible that there is some nutrient uptake through this irrigation of the bog surface.



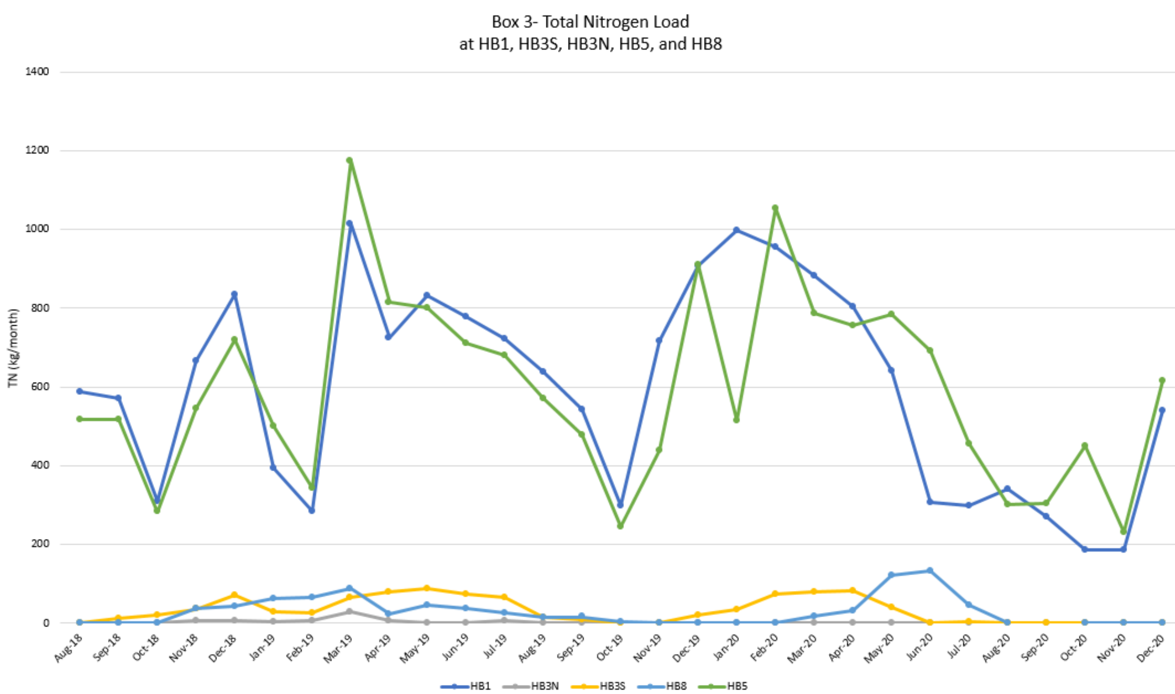


Figure 4. Monthly water flow and total nitrogen load at INPUT stations HB1, 3N, 3S, 8 and OUTPUT at station HB5 from August 2018 to December 2020.

Figure4 shows the surface water inputs (HB1, 3N, 3S, and 8) and surface water output (HB5), with associated N loads at each site through each month. In Box3, GW inputs are assessed as for Box1 and Box2, the water inputs between sources (HB1, 3N, 3S, and HB8) and output (HB5) are used to estimate groundwater flow inputs. Then applying the derived average GW nitrogen concentration of 2.02 mg/L the GW nitrogen load input was determined. The sum of all N load inputs (HB1, 3N, 3S, HB8, + GW) minus the sum of N load outputs (HB5) provides an estimate of N attenuation of 6% (518kg/yr) is representative for Box3 annual conditions (Table 5). Site HB3N was discontinued in 2019 and HB3S stopped its data collection in August 2020 due to changes in bog use. HB8 has no data after July 2020 or from November through February 2019. The latter due to flooded or too low water levels that stopped sampling and velocity collection. Sampling of HB8 ceased after July 2020 as the water would seep through the boards and did not give an accurate velocity. This led to the water and salt balance not being as close to the other boxes. Missing inputs would be from the HB3S and the HB8 flows that could not be accounted for.

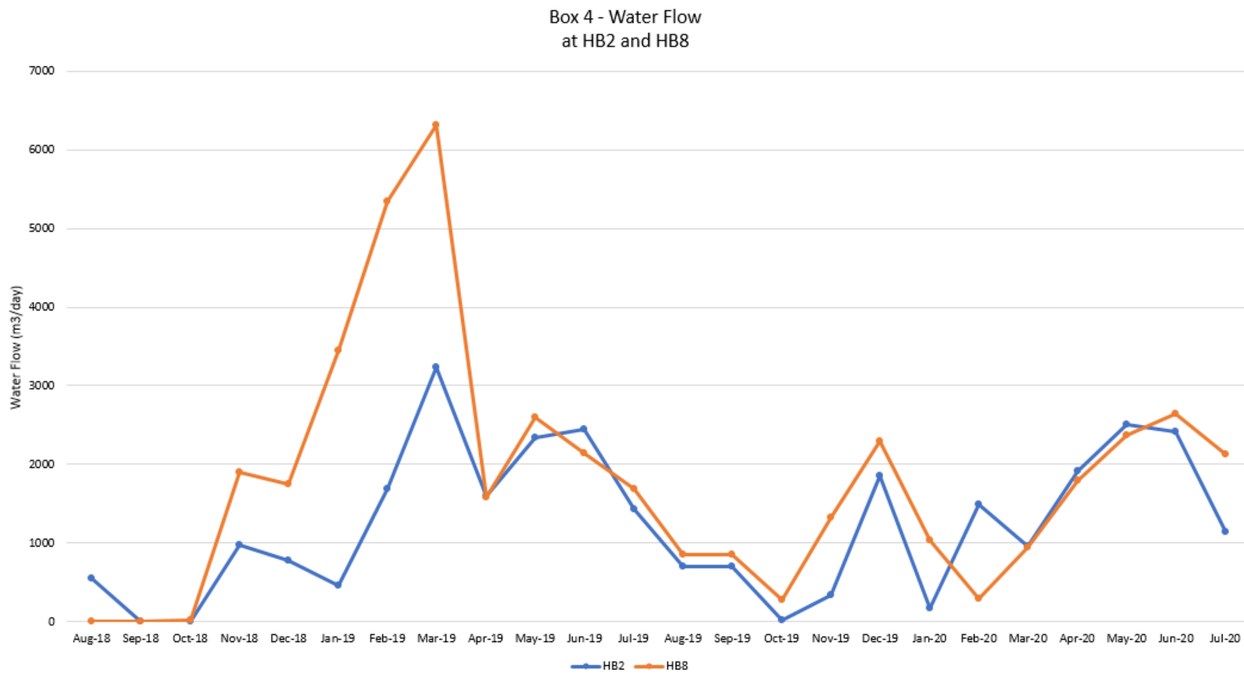
Table 11. Water and salt balance to -14% and -12 %, respectively, with 6% nitrogen attenuation in Box3 based on annualized inputs and outputs in Box3.

Hamblin Bogs - Box3 *Nov. 1, 2019 to Oct. 31, 2020*				
	Water Balance	**Salt Balance**	**Nitrogen Mass Balance**	
	(m3/d)	**(kg/d)**	**(kg/yr)**	**% of inputs**
Inputs:				
Stream input	14145	886	7837	95.1%
Groundwater*	487	37	360	4.4%
Precipitation**	116	3	46	0.6%
Total Inputs	14747	926	8243	
Outputs:				
Stream output	-16769	-1040	-7724	-
Evaporation	-63	0	0	-
Total Outputs	-16832	-1040	-7724	
BOX3 Balance:	-2085	-114	518	-
BOX3 Balance/ N atten. (%):	-14%	-12%	6%	-
Notes: * N determined from landuse analysis ** N determined from N loading factor in MEP				

Box 4 –HB2, HB8, and LaPointe Pump House

Box 4 receives most of the surface water and nutrient inputs through HB2, with three additional water and nutrient inputs: 1) groundwater, 2) direct rainfall/dryfall inputs, 3) irrigation water from Lapointe Pump House for the LaPointe bogs and potentially 4) from Howes bog which has very low and intermittent flow. Virtually all of the water and nutrient output is measured at HB8, with an insignificant amount of water loss through evaporation. Within Box4 water is also “recycled”, meaning that through summer and frost protection irrigations, water in the channel near LaPointe Pump House is pumped back up onto Run

Bog, Howes, and LaPointe bogs for irrigation. Although not measured directly, it is possible that there is some nutrient uptake through this irrigation of the bog surface.



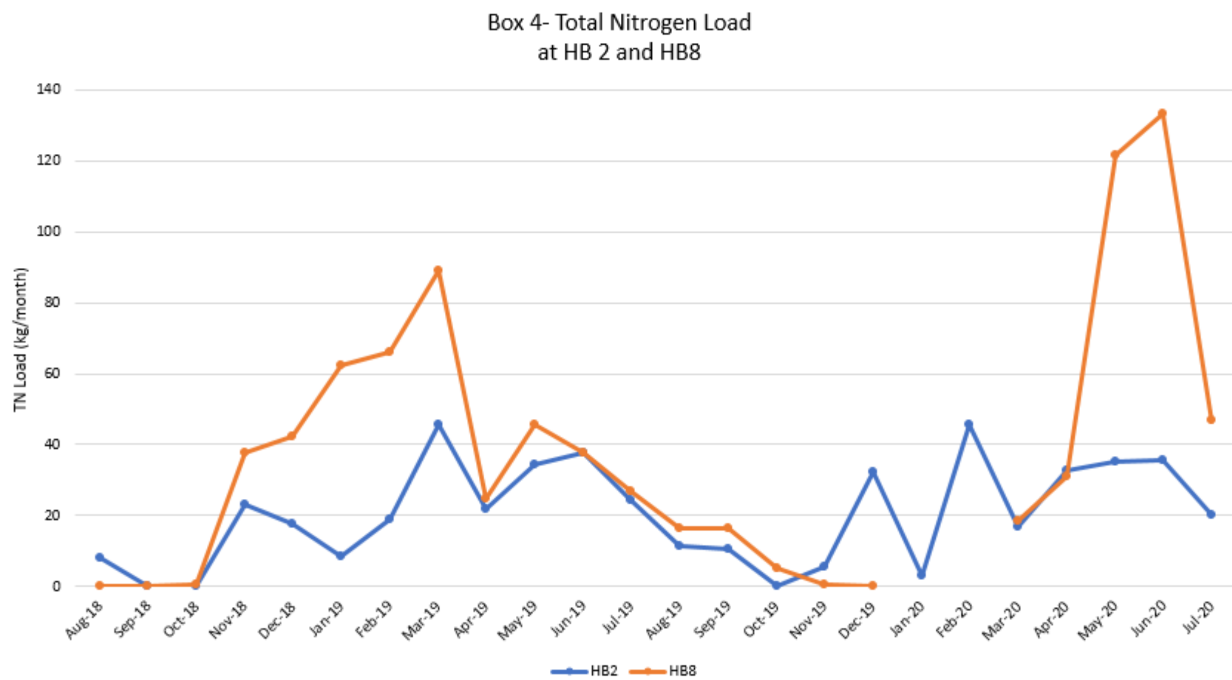


Figure 5. Monthly water flow and total nitrogen load at stations HB2 (IN) and HB8 (OUT) from August 2018 to July 2020.

Figure 5 shows the surface water input (HB2) and surface water output (HB8), with associated N loads at each site through each month, which need to be adjusted for groundwater to accurately calculate attenuation. In general, the total N load and water flow increases between HB2 and HB8. In Box4, GW inputs are assessed in the same manner as the other boxes. First, the groundwater flow inputs are estimated as the difference between HB2 and HB8 since the major water inputs have been measured directly (i.e., GW flow is 226 m^3/day). Then applying the box specific derived average GW nitrogen concentration of 0.45 mg/L the GW nitrogen load input was determined. The GW nitrogen concentration is estimated at a time of year when there was no flow from HB2, but water was flowing out at HB8, such that all of the outflowing water was from groundwater discharge to Box4. This GW concentration is different from Box1-3 because it was inferred through assessment of the surrounding watershed of Box4 the outflow measurements and is consistent with this small subwatershed having few contributing N sources. The sum of all N load inputs (HB2 + GW) minus the sum of N load outputs (HB8) provides an estimate of a negative N attenuation (N contributed by bog cell) of which is representative for Box4 annual conditions.

Box3 and Box4 Combined – HB1, HB2, HB3S, HB3N, Lovell's Cove Pump House, and LaPointe Pump House

Box3 and Box4 combined is defined by the outer of perimeter of Box3 & Box4 (Figure 2). These two boxes are combined to provide information on N attenuation during only the summer months, since HB8 was not sampled until October and completed in July 2020. Box3 & Box4 receive surface water and nutrient inputs through HB1, HB2, and HB3S, with additional water and nutrient inputs from groundwater and direct rainfall/dryfall (HB3N not sampled in 2020). Virtually all of the water and nutrient outputs is measured at HB5, with an insignificant amount of water loss through evaporation. Within Box3 & Box4 water is also "recycled", meaning that through summer and frost protection irrigations, water in the small reservoirs near Lovell's Cove and LaPointe Pump Houses is pumped back up onto Lovell's Cove, LaPointe, Run Bog, and Howes bogs for irrigation, harvest, and winter flood. Although not measured directly, it is likely that there is some nutrient uptake through this irrigation.

In Box3 & Box4, GW inputs are assessed similar to the individual assessment for Box3 and Box4, the difference in water inputs (HB1, HB2, HB3S) and the output (HB5) are used to estimate groundwater flow inputs. Then applying the derived average GW nitrogen concentration of 2.02 mg/L the GW nitrogen load input was determined. The sum of all N load inputs (HB1, HB2, HB3N, HB3S + GW) minus the sum of N load outputs (HB5) provides an estimate of N attenuation (Table 12).

Table 12. Analysis of annual flow and load inputs in Box3 and Box4 combined.

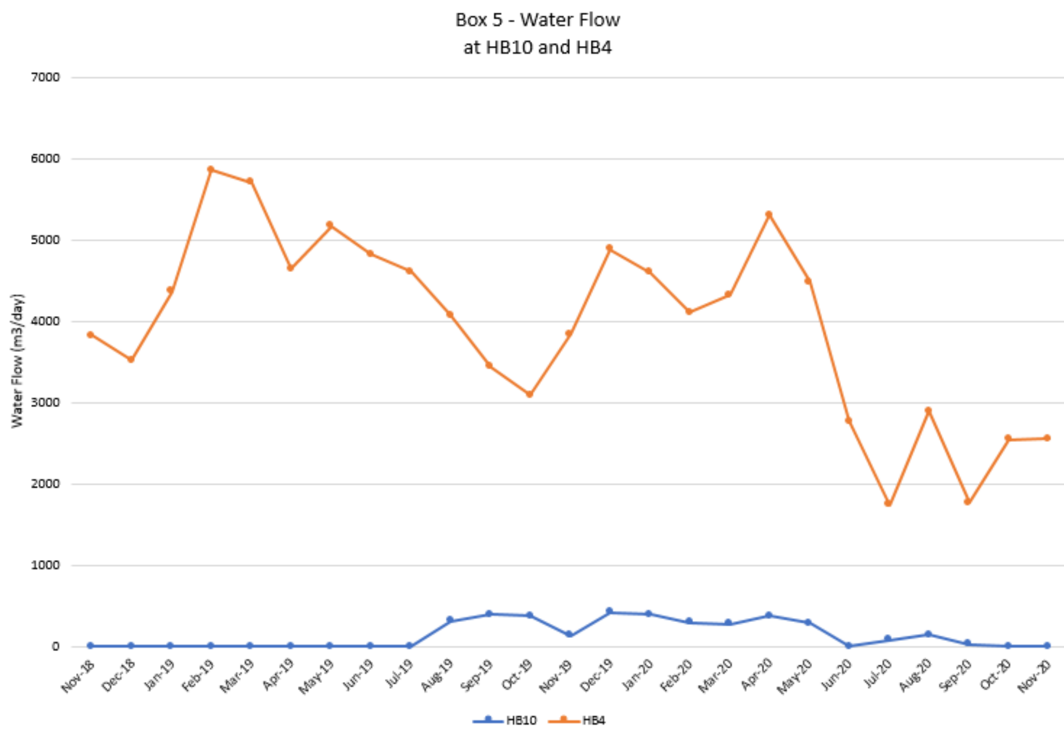
BOX3 and BOX4 Combined			
Annual (Nov. '19 - Oct. '20)	Flow (m3/d)	NOx (kg/d)	TN (kg/d)
Inputs:			
HB1 Stream Input	10491	17.4	20.0
HB3N Stream Input	ND	ND	ND
HB3S Stream Input	3624	0.3	1.4
HB2 Stream Input	1277	0.1	0.7
GW Input	1377	2.8	2.8
Total Inputs:	16769	20.6	24.9
Outputs:			
HB5 Stream Output	-16769	-14.8	-20.4
Total Outputs:	-16769	-14.8	-20.4
Box3 and BOX4 Combined Attenuation of N:			
% N Removal	-	28%	18%
Total N Attenuation	0	5.7	4.5

Table 13. Analysis of annual flow and load inputs in Box3 and Box4 combined.

BOX3			
Annual (Nov. '19 – Oct. '20)	Flow (m3/d)	NOx (kg/d)	TN (kg/d)
Inputs:			
HB1 Stream Input	10491	17.4	20
HB3N Stream Input	ND	ND	ND
HB3S Stream Input	3624	0.3	1.4
HB8 Stream Input	1235	0.9	1.5
GW Input	1419	2.9	2.9
Total Inputs:	16769	21.5	25.7
Outputs:			
HB5 Stream Output	-16769	-14.8	-20
Total Outputs:	-16769	-14.8	-20.4
Box3 Attenuation of N:			
% N Removal	-	31%	21%
Total N Attenuation	0	6.7	5.3

Box5 –HB10 and HB4

Box5 receives surface water and associated nutrient inputs through HB10, with additional water and nutrient inputs from groundwater and direct rainfall/dryfall inputs. Virtually all of the water and nutrient output is measured at HB4, with an insignificant amount of water loss through evaporation. Within Box5 water is also "recycled", meaning that through summer irrigations, water from the pump house on this section of bog is pumped back up onto the bogs for irrigation. Although not measured directly, it is possible that there is some nutrient uptake through this irrigation.



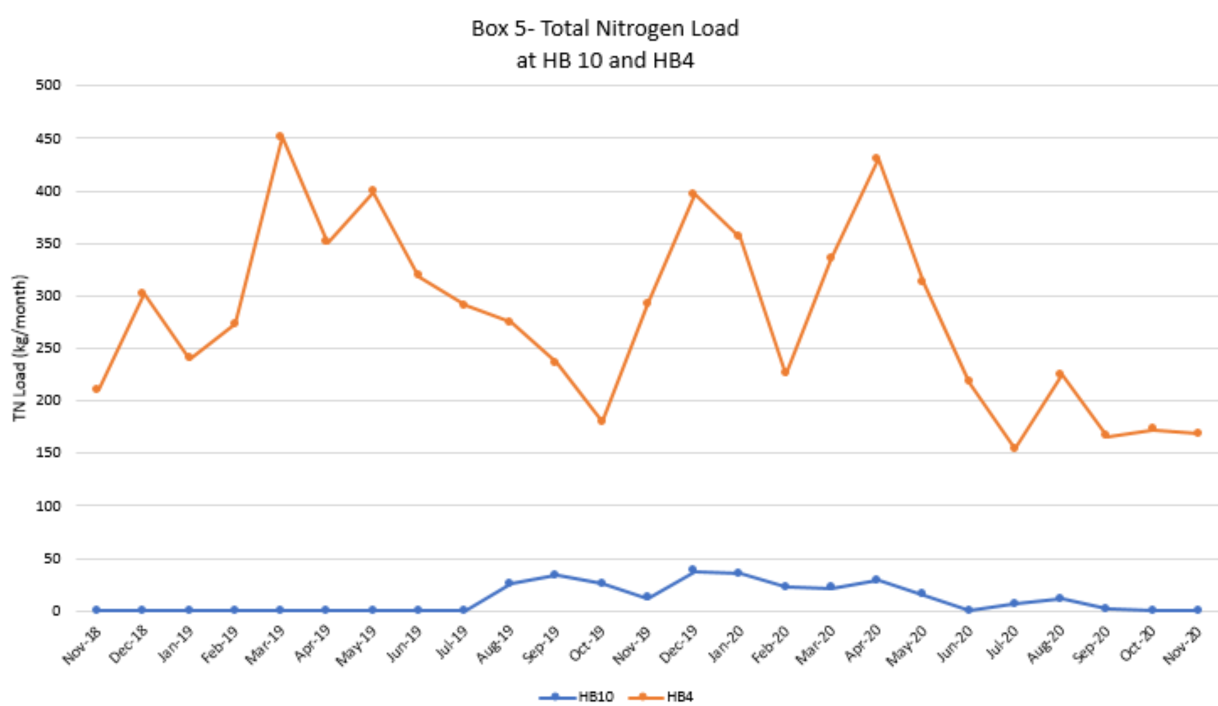


Figure 6. Monthly water flow and total nitrogen load at stations HB2 (IN) and HB8 (OUT) from August 2018 to July 2020.

Figure 6 shows the surface water input (HB10) and surface water output (HB4), with associated N loads through each month, which need to be adjusted for groundwater to accurately calculate attenuation. The total N load and water flow increases between HB10 and HB4 substantially, with an average of 221 m3/day measured flow through HB10 and at least 3,600 m3/day measured flow through HB4 which mirrors the same flows seen in 2019. This indicates that Box5 has significant GW inputs. The nitrogen attenuation of Box5 is determined using the modeled landuse flow for HB10, since there are only measured flows from 8/8/2019 to 9/16/2020. The groundwater flow inputs are estimated as the difference between HB10 (modeled) and HB4 (measured) since they are the only other identified water inputs in Box5. The approximate GW flow is 3,319 m3/day. Based on the landuse analysis, Box5 has a total nitrogen concentration of 2.65 mg/L. Therefore, the total nitrogen load from GW to Box5 is 6.92 kg/day. The sum of all N load inputs (HB10 + GW) minus the sum of N load outputs (HB4) provides an estimate of N attenuation of 5% (186 kg/yr).

Table 14. Water and salt balance to 2% and 8 %, respectively, with 5% nitrogen attenuation in Box4 based on annualized inputs and outputs in Box5.

Hamblin Bogs - Box5 *Annual*				
	Water Balance	Salt Balance	Nitrogen Mass Balance	
	(m3/d)	(kg/d)	(kg/yr)	% of inputs
Inputs:				
Modeled Stream input*	999	79	906	25.9%
Groundwater*	2609	196	2528	72.2%
Precipitation**	174	5	69	2.0%
Total Inputs	3782	279	3504	
Outputs:				
Stream output	-3608	-256	-3319	-
Evaporation	-95	0	0	-
Total Outputs	-3703	-256	-3319	
BOX5 Balance:	79	23	186	-
BOX5 Balance/ N atten. (%):	2%	8%	5%	-
Notes: * N and flow determined from landuse analysis ** N determined from N loading factor in MEP				

Entire Hamblin Bogs System – HB2, HB3N, HB3N, HB4, and HB5

By assessing the inputs and outputs of the Hamblin Bogs system as a whole, the nitrogen attenuation of the entire system can be determined. This also helps confirm N attenuation of calculated for individual boxes. For instance, the sum of Harvest attenuation in Box1-5, should be nearly equal to the N attenuation of the entire Hamblin Bogs system if all flows and concentrations are accounted for. The Hamblin Bogs system receives surface water and nutrient inputs through HB2, HB3S, HB10 and HB4 with additional water and nutrient inputs from groundwater and direct rainfall/dryfall. Virtually all the water and nutrient outputs is measured at HB5, with an insignificant amount of water loss through evaporation. Within the Hamblin Bogs, water is also "recycled", meaning that through summer and frost protection irrigations, water in the small reservoirs near all pump houses is pumped back up onto the respective bogs for irrigation, harvest, and winter flood. Although not measured directly, it is likely that there is some nutrient uptake through this irrigation of the vegetated bog surface.

For the Hamblin Bogs system, GW inputs are assessed as the difference in water inputs (HB2, HB3S, and HB4) and the output (HB5) are used to estimate groundwater flow inputs. Then applying the derived average GW nitrogen concentration of 2.02 mg/L the GW nitrogen load input was determined. The sum of all N load inputs (HB2, HB3N, HB3S, HB4 + GW) minus the sum of N load outputs (HB5) provides an estimate of N attenuation (Table 15). In the case of Spring conditions, the N load cannot be determined due to the unknown amount of stream flow from Nursery Bog into the system (Table 15). Harvest conditions cannot be determined as HB10 was removed with HB3N and variable water levels in HB2 were captured.

Table 15. Analysis of flow and load inputs in the entire Hamblin Bogs. The lower N attenuation in winter likely results from lower microbial activity at lower temperatures.

Entire Hamblin Bogs Summer 2020 (June - Sept.)	Flow (m3/d)	NOx (kg/d)	TN (kg/d)
Inputs:			
HB2 Stream Input	1765	0.0	0.9
HB3N Stream Input	ND	ND	ND
HB3S Stream Input	200	0.0	0.1
HB4 Stream Input	1830	3.4	5.0
HB10 Stream Input	65	0.1	0.2
GW Input	7916	17.5	17.5
Total Inputs:	11776	21.0	23.7
Outputs:			
HB5 Stream Output	-11776	-10.5	-14.4
Total Outputs:	-11776	-10.5	-14.4
Box3 and BOX4 Combined Attenuation of N:			
% N Removal	-	50%	39%
Total N Attenuation	0	10.5	9.4

Entire Hamblin Bogs Winter 2019-20 (Dec-Feb.)	Flow (m3/d)	NOx (kg/d)	TN (kg/d)
Inputs:			
HB2 Stream Input	1177	0.4	0.9
HB3N Stream Input	ND	ND	ND
HB3S Stream Input	3830	0.0	0.0
HB4 Stream Input	4597	9.2	10.9
GW Input	10193	20.6	20.6
Total Inputs:	19797	30.2	32.4
Outputs:			
HB5 Stream Output	-19797	-19.8	-27.6
Total Outputs:	-19797	-19.8	-27.6
Box3 Attenuation of N:			
% N Removal	-	34%	15%
Total N Attenuation	0	10.4	4.8

Table 16. Water and salt balance to -17% and -952 %, respectively, with 17% nitrogen attenuation in Box4 based on annualized inputs and outputs in Box5. However, from the above table most of the N attenuation is during the warmer months when the receiving waters of the estuary are most sensitive to N inputs.

Entire Hamblin Bogs *Nov. 1, 2019 to Oct. 31, 2020*				
	Water Balance	Salt Balance	Nitrogen Mass Balance	
	(m3/d)	(kg/d)	(kg/yr)	% of inputs
Inputs:				
Stream inputs - HB2,3,10	3446	183	1118	12.0%
Groundwater*	10370	778	7745	83.5%
Precipitation**	1048	27	417	4.5%
Total Inputs	14864	988	9280	
Outputs:				
Stream output	-16769	-10397	-7712	-
Evaporation	-571	0	0	-
Total Outputs	-17340	-10397	-7712	
Entire Bogs Balance:	-2476	-9409	1567	-
Entire Bogs Balance/ N atten. (	-17%	-952%	17%	-
Notes: * N determined from landuse analysis ** N determined from N loading factor in MEP				

In Table 16 Due to the lack of a good salt balance, this attenuation could contain significant error. If salt, were balanced then the N attenuation could be much lower. The N attenuation throughout the Hamblin Bogs system can be standardized by the total acreage. In Table 17, the N attenuation over each season is summarized to allow comparison of the standardized N attenuation by the functional units/boxes. With changing amounts of N attenuation over the seasons, the N attenuated per acre also varies significantly. Table 18 also reveals that assessing the Hamblin Bogs into four boxes has some error associated with the N attenuation of the entire Hamblin Bogs. Summer and Winter comparison of Box1+2+3+4 and Entire Hamblin Bogs have some error (around 10%). Interestingly, the entire Hamblin Bogs appears to be consistently attenuating N from August to April with 0.06 to 0.09 kg N/ac/d attenuated. Additionally, Box 2 and 3 appear to have the highest N attenuation per acre (except in Winter for Box 2).

The Box1+2+3+4 and Entire Hamblin Bogs are not able to be compared in the winter as there is no data for HB10 so there is an inability to fully state the total contributed amount to HB4.In the Winter, Box 4 was unable to be quantified as the site was flooded. There is ND (no data) designation for Box 4 as HB8 was not recorded due to flooding.

Table 17. Summary table of nitrogen attenuation in each box and the entire Hamblin Bogs system for 2019 to Harvest 2020. Nitrogen attenuation is standardized by area.

Location	Surface Area (ac)	Summer (Aug.&Sept.) N Atten. (kg/d)	Summer Standardized N Atten. (kg/ac/d)	Harvest (Oct.&Nov.) N Atten. (kg/d)	Harvest Standardized N Atten. (kg/ac/d)	Winter (Dec.-Feb.) N Atten. (kg/d)	Winter Standardized N Atten. (kg/ac/d)	Spring (Mar&Apr.) N Atten. (kg/d)	Spring Standardized N Atten. (kg/ac/d)
Box 1	24	3.6	0.10	3.1	0.13	2.1	0.09	Unk	Unk
Box 2	12.8			9.2	0.7	-4.2	-0.33	1.0	0.08
Box 3	36.2	3.1	0.07	0.6	0.02	7.4	0.20	7.7	0.21
Box 4	10.2			0.0	0.0	ND	ND	0.0	0.0
Box1+2+3+4	83.2	6.7	0.08	12.9	0.16	5.3	0.06	-	-
Entire Hamblin Bogs	83.2	7.6	0.09	5.9	64.59	4.8	0.06	Unk	Unk

In Table 17, for BOX 3 harvest there was no data for HB3N, HB3S, and HB8 so the accuracy of the total N attenuated was affected by the flows. This is also the case for the entire Hamblin Bogs calculation. HB2 HB3S, HB3N, and HB10 had either no flow or too much flow for an accurate velocity reading.

Conclusions of Hamblin Bogs Stream Flow Assessment:

Synthesis of the data collected during this 29-month preliminary assessment of the Hamblin Bogs system, while not yet an annual sampling, did capture late summer, fall (harvest), winter, and spring conditions for water flow and nitrogen loading. This preliminary synthesis was performed to allow decisions as to revisions to protocols and how to continue. While incomplete, the data to date does support some clear conclusions:

1. Removed HB8 sampling location. This sampling location is affected by the use of water during irrigation as it floods or goes dry periodically. There is also no control over the boards and the water that is allowed to seep through them. HB10 was removed as it was altered by the change in the culvert onto land that is owned by another bog owner. Also, all flow should have been captured through HB4.

2. During summer, harvest and winter, Box 1 receives surface water and nutrient inputs through HB4 with some additional groundwater discharge. However at the end of winter flood (start of spring), water from the Pond View and M&M bogs is released and is accounted for in the outflow (HB9), but was not measured directly. Therefore, attenuation during the flood release period cannot be determined as the inflow N load is only partially accounted for. However, it is clear that Box1 does have significant N attenuation during the other three periods, specifically 2018 into 2019 in the harvest and winter months at 1.6 and 1.0 kg N day^{-1}, respectively and again in 2019 and 2020 with the harvest months having 3.0 and 3.1 kg N day^{-1}.

3. In Box2, containing Winnies bogs and a small reservoir at the southern end of the box, shows significant N attenuation during harvest, winter, and spring seasons for 2019. Under high spring time flow conditions the bogs/small reservoir was attenuating nitrogen at approximately 17% N removal (6.05 kg N day^{-1}), but in 2020 it dropped to 3% removal (1.0 kg N day^{-1}). HB1 has incredibly high flow so the data for 2019 is confounded because generally high flow conditions result in less attenuation which is showcased in 2020. Summer attenuations less at 6% (2.0 kg N day^{-1}) for 2019 and then increased to 20% (3.1 kg N day^{-1}). In comparison to the summer conditions harvest attenuation is higher while the winter is negligible with the frozen and flooded conditions. Note it is possible that attenuation during this brief high flow interval may be very low due to the limited contact time with the sediments.

4. Box3, receives multiple water and nutrient inputs, with two pump houses that move water around Box3 for irrigation, and pumping some water to Box4 for frost protection and summer irrigation. Box3 shows most attenuation during the harvest and winter flood periods, attenuating 21% (3.6 kg N day^{-1}) and 27% (6.7 kg N day^{-1}), respectively in 2019. Winter 2020 mirrors that of 2019 with attenuation at 22% (7.4 kg N day^{-1}), but lower N attenuation at harvest as the only input accounted for was HB1. Whereas N attenuation is only 13% during high spring time flow conditions removing 4.9 kg N day^{-1} in 2019 and 23% (removing 7.7 kg N day^{-1}) in 2020. N attenuation in the summer of 2019 is at 19% (5.1 kg N day^{-1}) and 24%

3.1 (kg N day^{-1}). In the future, it will be important to closely observe flows that might be going from Box3 into Box4 via Howes bogs to LaPointe bogs culvert during flooded conditions. Additionally, it will be important to gather summertime measurements of irrigation water volume/nutrient concentrations from LaPointe East pumphouse onto LaPointe Bogs, resulting in a loss of water/nutrients from Box3 and an input of water/nutrients to Box4. Refining these flows and loads will increase the accuracy of N attenuation during the critical summer period.

5. Box4 has low volumetric inflow and outflow as HB2 and HB8 are variable due to flooding and release. Additionally, the nutrient concentrations in inflowing water to this box are lower than most other sites in the Hamblin Bogs system, likely due to nutrient attenuation occurring within Muddy Pond before water enters Hamblin Bogs. Groundwater nitrogen concentration within the box is also likely much lower due to a small relatively undeveloped surrounding subwatershed. Box4 shows no N attenuation -0.2 (releasing N) to 0.0 kg N day^{-1} removed during harvest, winter and spring time conditions in both 2019 and 2020 (2020 attenuation is negative with 0.0 kg N day^{-1}). There was no Harvest data for 2020 as HB8 was no longer a sampling site in 2020 as of July.

6. Box 5 was added in August 2019 to obtain a complete picture of the high concentrations of NO_x^- entering HB4, but due to someone pulling the gauge out and work on the culvert there was not sufficient data to round out inputs to HB4. HB10 has data from August 2019 until May 2020 with the Summer and Harvest attenuating -0.2 and -0.6 (releasing N) 0.0 kg N day^{-1} in 2019 with no increased attenuation in 2020.

7. There are high concentrations of NO_x^- entering Hamblin Bogs at station HB4. Also, all stations down gradient, located along the main flow path (Marstons Mills River) have high nitrate concentrations (HB9, HB1, HB5) which were maintained through 2020. During the harvest and flood periods NO_x^- declines more than TN, likely because when the bogs are flooded, NO_x^- is being denitrified and converted to organic N forms. Denitrification may be enhanced through projects like the one discussed above so that sediment oxygen levels can be reduced. However, Managing or restoring the bogs to improve habitat can also enhance nitrogen removal with the proper design.

8. Comparison of summer versus winter N attenuation indicates that during the warmer months when the receiving waters of the estuary are most sensitive to N inputs that N attenuation is more than double during winter (39% vs 15%). Therefore, judgement of the effectiveness of enhanced N removal for a restoration should include seasonal assessments and evaluation relative to the seasonal sensitivity of the receiving estuarine waters.

Recommendations for Continued Monitoring:

There is potential for a significant increase in nitrogen removal throughout the Hamblin Bogs system at Box 1 and Box 2. Under this preliminary study there is notable N uptake which has been seen in the past 3 years. Therefore, moving forward monitoring should continue with significant improvements to the data collection within this system to more accurately quantify this N uptake, which can potentially be used by the Town of Barnstable to offset the need for wastewater infrastructure (sewers), provided that the increase in nitrogen retention can be quantified and scientifically justified to Mass DEP. The following recommendations are recommended for more accurate determination of baseline flows and N uptake within Hamblin Bogs that should be performed prior to any significant changes within the Hamblin Bogs system that would likely increase N attenuation:

1. It is critical to continue the monitoring to a full annual cycle and preferably enough to capture 2 of the critical summer seasons and to analyze the data gathered by the CSP team and continuous monitoring devices. Ensuring that the boards on some of the culverts are water-tight will

further address unaccounted for flows and loads. Stage recorders could be useful at all culverts to ensure that all flows are captured.

2. As previously noted it would be important to invest in bog motor run time loggers/logging and sprinkler head flow determination. Irrigation flows are important to determine the rerouting of flow/load within the system and transfer to other bog units. The pumped flows act as recycled water (in the water budget) but might result in additional uptake of nitrogen as found in other systems
3. Construction is occurring between Box2 and Box 3 so monitoring of that will determine when large loads of nutrients are released as construction has been going on at the site.
4. If monitoring continues it will be important to capture the flood release flows and nutrient inputs from Pond View and M&M bogs to determine their individual input loads and determine if there is any N attenuation during this period.
5. The conversion of inactive cranberry bogs to modified wetlands will naturally allow for the increased attenuation of the N travelling through Hamblin Bogs.