Duck Creek and Duck Lake Sediment Investigation

Final Project Report

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Project Background and Description

The Duck Creek watershed is a relatively small watershed, extending to 13,952 acres within Muskegon County, Michigan. Duck Lake, a 271-acre drowned river mouth lake, receives waters from two major tributaries, Duck Creek and Scholes Creek, before emptying into Lake Michigan through a narrow, shallow channel at Duck Lake State Park (Figs. 1, 2). The two creeks converge 1.8 miles upstream of where Duck Creek empties into Duck Lake and both tributary headwaters are fed by a wetland complex that is located in both Dalton Township (for Duck Creek) and Fruitland Township (for Scholes Creek) (MCD 2012).

The Duck Creek watershed has had a history of land use changes. European settlers in the 1700s were interested in fur trade and developing the area for the lumber industry, much like the two larger watersheds to the south and north, the Muskegon River and White River watersheds, respectively. In the early 1900s, after the valuable timber was removed, the watershed was viewed as a potential area for agriculture or tourism development. Tourism became more favorable as the area developed. The watershed is a known vacation area for people from the Chicago area as well as around the upper Midwest. Michigan's Adventure, known as Michigan's largest combined amusement park and water park, is located in the uppermost reaches of the watershed. Duck Lake State Park borders the north side of the lake, which secures a long-term commitment for tourism and recreational use (MCD 2012). Land use/land cover is primarily deciduous forest and open grassland (>50%; Fig. 3), with only 2.5% composed of pasture and cropland (Fig. 3).

The Duck Lake basin is complex with shoals, sand bars, weed beds and drop-offs. Anglers have reported that the outdated lake basin map misrepresents some of the shallow shoals surrounded by deep areas within the lake. This suggests sedimentation could be an issue as there have been anywhere up to 7 shoals reported (Towns 1992). Since land use practices in the watershed influence sediment fate and transport, it is critical to assess not just the lake proper, but also its catchment. Sedimentation can bury areas that serve as habitat and refugia for fish and invertebrates, resulting in decreased habitat complexity that is less capable of supporting a diverse benthic community (Kovalenko 2012). Additionally, excess sediment in rivers is detrimental to salmonid fish such as brown trout (*Salmo trutta*), which are known to live in the Duck Lake watershed and prefer to spawn in areas with a specific range of gravel size, as finer sediment particles can cover and suffocate eggs (Olsson 1986). Excess sediment also may be linked to other environmental stressors such as low dissolved oxygen, high turbidity, high nutrient concentrations, and high *E. coli* counts (Wood 1997, Francy 2003, Steinman and Ogdahl 2015). These stressors can lead to a variety of problems for both the environment and human stakeholders, including harmful algae blooms from the increased nutrients, beach closures from high *E. coli* levels, and restricted navigation due to the shallowing of the lake.

This study was conducted as a preliminary investigation into sediment transport through the watershed. The goal was to identify the potential stream reaches that may be critical sources of sediment transport, as well as inform future research, restoration, and conservation initiatives within the watershed. With these goals in mind, we measured physical and chemical water quality parameters, including total phosphorus (TP), and quantified sediment movement in the water column and streambed to better understand the dynamics of stream discharge, sediment, and TP in the Duck Lake watershed.

Methods

Site Description

Three tributary sites were selected on May 25, 2017 at three road stream crossings: two sites were on Duck Creek, the furthest downstream at Nestrom Road (DC-1A) and the other at Simonelli Road (DC-3), and the third was on Scholes Creek at Simonelli Road (DC-2) (Figs. 1 and 2, Table 1).

The three tributary sites along with 10 additional sites were identified for a one time sediment sampling event: one additional site on Duck Creek that was upstream of the Nestrom Road bridge crossing (DC-1B), five sites in a marsh, south of Duck Creek where it empties into Duck Lake, and four sites in the alluvial fan (the geographical area where stream sediments are likely to fall from the water column onto the lake bottom) as Duck Creek enters Duck Lake (Fig. 2, Table 1). Alluvial fan core locations were sampled once approximately every 50 meters along a 150 meter transect from the shallow area adjacent to mouth of Duck Creek to straight out into Duck Lake. Marsh core locations were selected with stratified random sampling techniques to ensure a variety of sampling locations throughout the marsh. At the water level observed during the time of this study, a bay was present in the northern central region of the marsh, connecting the northwest corner of the marsh directly to Duck Lake. The marsh itself was dominated by cattails (*Typha spp.*), although hard-stemmed shrubs and trees were present on the perimeter of the wetland and were densely populated along the western marsh border near Duck Lake and along the Duck Creek channel (Fig. 4).

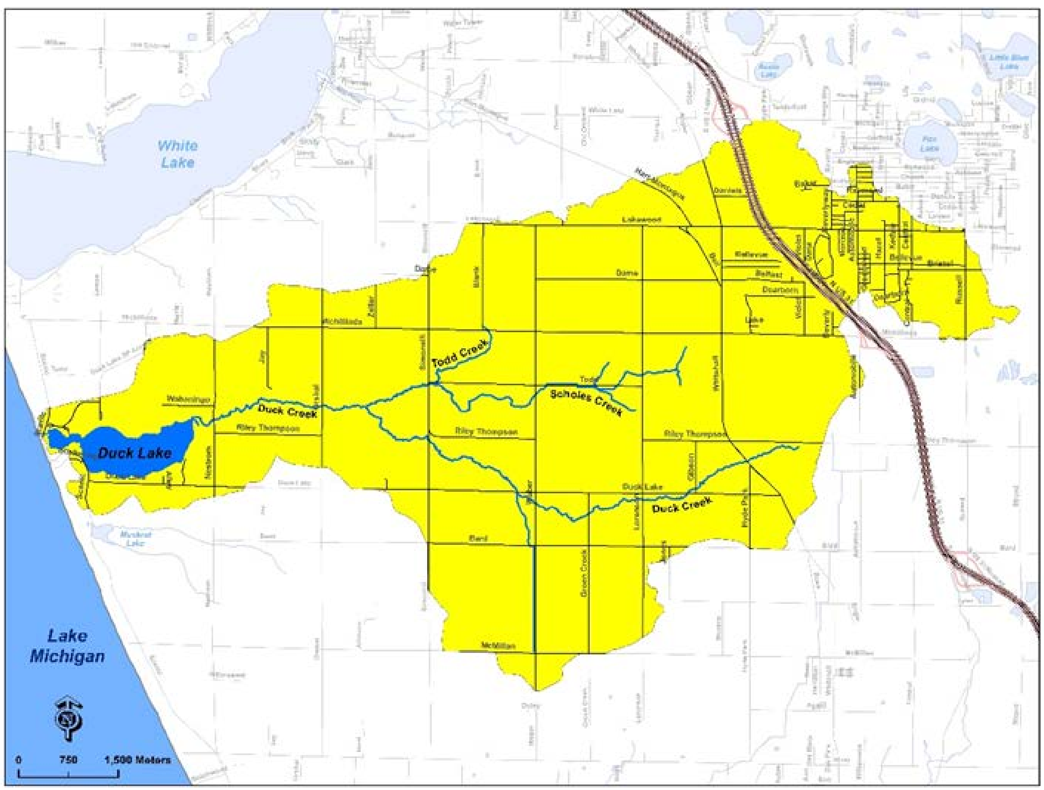

Figure 1. Map of Duck Creek watershed. Outline of watershed boundary (in yellow) and key water features.

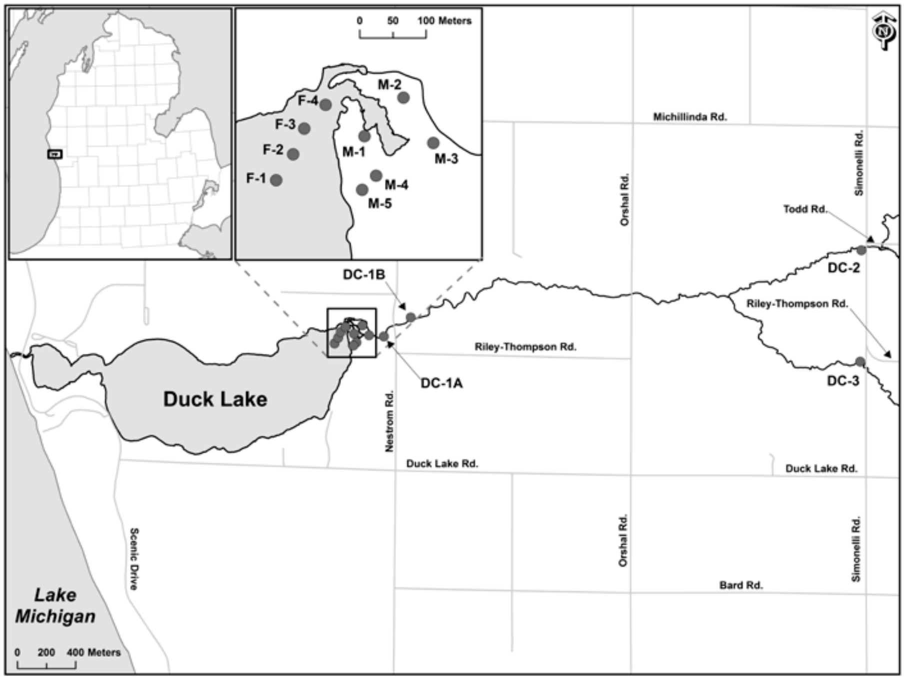

Figure 2. Map of Duck Creek watershed. Upper left: location in the lower peninsula of Michigan. Main figure: Sampling locations in three regions of the Duck Creek watershed: the alluvial fan area where Duck Creek enters Duck Lake (blown up above), the marsh at the downstream western end of Duck Creek, and the upper watershed of Scholes Creek and Duck Creek.

Table 1. Coordinates of sampling locations throughout the Duck Creek watershed.

Site Location	Site ID	Latitude (°N)	Longitude (°W)
Tributaries	DC-1A	43.34293	86.37743
	DC-1B	43.34410	86.37513
	DC-2	43.34805	86.33687
	DC-3	43.34114	86.33704
Marsh	M-1	43.34311	86.37996
	M-2	43.34363	86.37923
	M-3	43.34301	86.37868
	M-4	43.34257	86.37975
	M-5	43.34238	86.38001
Alluvial Fan	F-1	43.34252	86.38161
	F-2	43.34287	86.38129
	F-3	43.34322	86.38108
	F-4	43.34354	86.38068

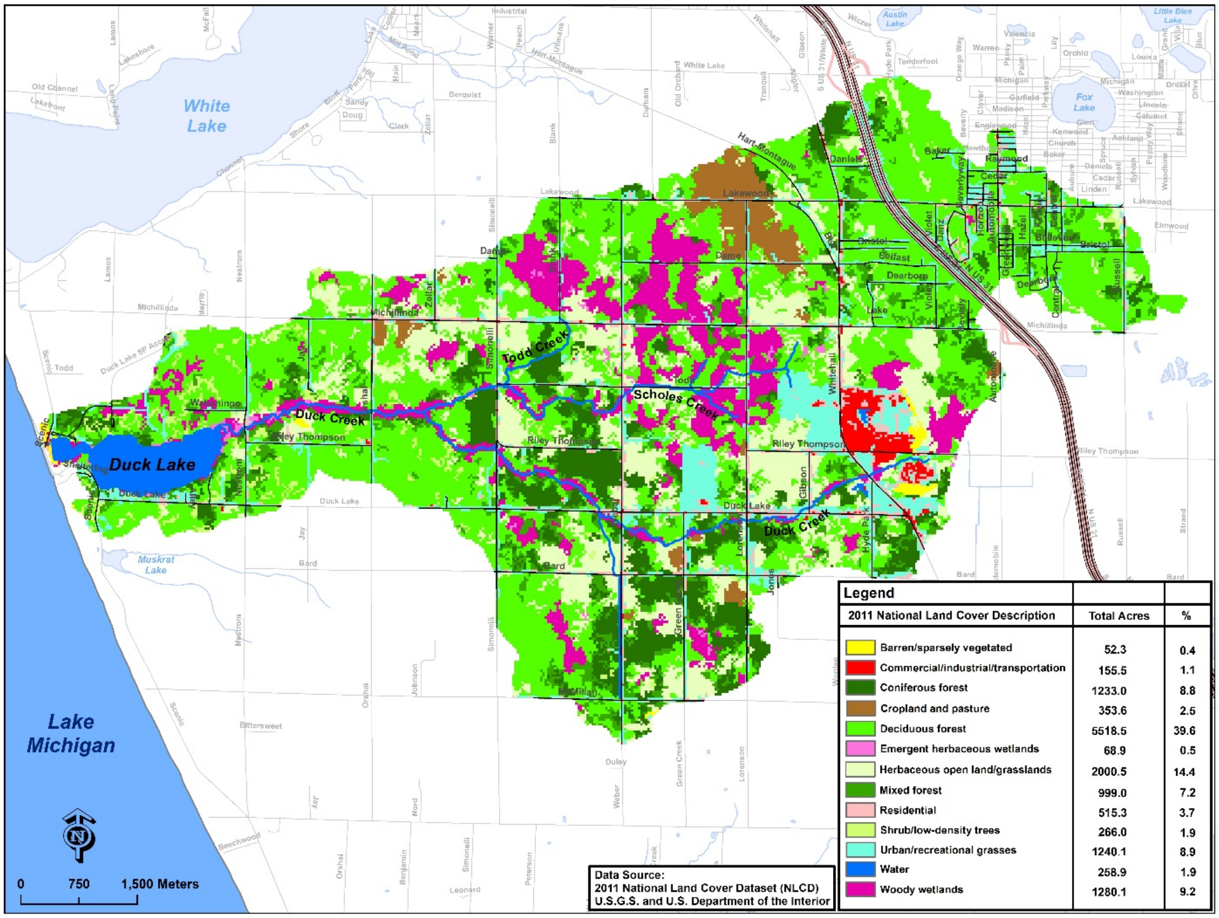

Figure 3. Land use/land cover of the Duck Creek watershed based on the 2011 National Land Cover Dataset.

Figure 4. May 5, 2017 photo of Duck Lake marsh taken from the interior bay and facing south to the tree line bordering the marsh and eastern shore of Duck Lake. Dense cattail (*Typha spp.*) coverage can be seen surrounding the open water and extends to the tree line.

Tributary Monitoring – Sampling and Analysis

Water quality samples were collected at each of the tributary sites during two baseflow events on July 19 and September 12 and one storm flow event on August 10 in 2017. Baseflow was sampled when there was no precipitation within the watershed 72 hours prior to sampling. Storm event sampling also required at least 72 hours of dry weather prior to the precipitation event; the rain event that we sampled had 0.22 inches of total rain. Total precipitation data were obtained from the nearest weather station on the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (www.ncdc.noaa.gov; Muskegon County Airport weather station). During base and storm flow sampling events, general water quality parameters were measured using a YSI 6600 multi-probe sonde, and included temperature, dissolved oxygen (DO), specific conductance, oxidation-reduction potential (ORP), turbidity, and total dissolved solids (TDS). Surface water grab samples were collected for TP and suspended sediment concentration (SSC). Samples were transported on ice back to the lab, where they were stored at 4°C in the laboratory until analysis (USEPA 1983). TP samples were analyzed on a SEAL AQ2 discrete automated analyzer (USEPA 1993). To determine SSC, the entire water sample in the 500 mL bottle was vacuum-filtered through pre-ashed glass fiber filters. Filters were dried at 105°C for 8 hours and weighed to determine sediment mass in grams (g). TP load and suspended sediment (SS) load were calculated for each sample by first multiplying TP concentration and SSC by discharge at the time of collection, then converting to units of g per second (g/s).

Water depth and velocity were measured during the two base and one storm flow tributary sampling events using a Marsh-McBirney Flow Mate 2000 flow meter attached to a top-setting wading rod, according to USGS protocols (Rantz et al. 1982). The Windows-based hydrologic software HYDROL-INF was used to calculate stream discharge (Chu and Steinman 2009).

In addition to the discrete, single point turbidity measurements taken during the two baseflow and one storm flow sampling events (see above), we measured turbidity in a more intensive manner at the three tributary sites (DC-1A, DC-2, and DC-3) through continuous measurements in 30 minute intervals from May 23 to September 12, 2017 using a Cyclops-7 logger (Precision Measurement Engineering, Inc., Vista, CA) with a Cyclops-7F turbidity sensor (Turner Designs, San Jose, CA). The sensors were cleaned and calibrated on a monthly basis.

Bedload transport was measured during the two baseflow and one storm flow events using a 3”×3” Helley-Smith sampler with a 250 µm mesh bag at 5 equally-spaced points along DC-1A, DC-2, and DC-3 transects. Mesh bag deployment lasted 1 minute per transect point for baseflow (5 minutes total) or 30 seconds per transect point at stormflow (2.5 minutes total). Instantaneous bedload rates (Q_b) in g/s for each site were calculated using the formula:

$$Q_b = \frac{M_b}{T} \times \frac{1}{N} \times \frac{W}{0.076\text{ m}}$$

where M_b = bedload sample dry mass (g), T = subsample duration (seconds), N = number of subsamples, W = wetted width of the channel (m), and 0.076 m is the width of the opening of a 3”×3” Helley-Smith sampler.

Sediment rating curves were created to show the relationship between discharge and sediment. A plot of SS load vs. discharge and bedload vs. discharge was created for each of three tributary sampling sites at DC-1A, DC-2, and DC-3, and then fit with a power function (Asselman 2000) using Microsoft Excel.

Scour chains were installed on May 25, 2017 following protocols of Bigelow (2003), at each of the three tributary sites (DC-1A, DC-2, and DC-3) to measure depth of sediment deposition (also known as sediment fill) or scour (removal) over time. Scour chains were installed ~1 foot upstream of the established transects for base and storm flow sampling near the thalweg of each transect, allowing for easy relocation during the last day of sampling to measure sediment fill and/or scouring. Upon installation, the initial elevation of the stream bed (i.e., the top of the scour chain) was measured using surveying equipment. At the end of the sampling period on September 12, 2017 (110 days after installation), each scour chain was located and assessed for scour, fill, or dynamic scour and fill. Sites that experience scouring have sediment removed, exposing links which fold at 90 degrees as they are exposed to the flow of water (Fig. 5). Sites that only fill retain the original chain position, which becomes covered by a layer of sediment. Dynamic scour and fill is when scour occurs first, exposing chain links, followed by burial due to fill; this situation is demonstrated by a chain that is laid over 90 degrees under a layer of sediment. Sites that only had scouring were measured using the exposed chain from the final exposed chain link to the point at which the chain length folded at 90 degrees. Sites with scour chains that were covered by sediment experienced either fill or dynamic scour and fill. To measure this scenario, the final elevation of the stream bed covering the chain was measured first as described above; then, sediment was carefully removed to the depth at which either the top of the chain (indicating a fill-only event) or the point at which the chain was laid over 90 degrees (indicating dynamic scour and fill event) was located. If we determined a dynamic scour and fill event had occurred, chain links were measured the same way as a scouring-only event (described above; Fig. 5).

Total fill during the sampling period was measured by subtracting the initial streambed elevation from the final streambed elevation. Total scour was a direct measurement of the links exposed. Dynamic change, the difference in elevation that may not have been directly measureable during dynamic scour and fill, was calculated by subtracting the scour measurement (or length of chain) from the change in streambed elevation. To better indicate fill or scour events, positive (+) values indicate fill and negative (-) values indicate scour.

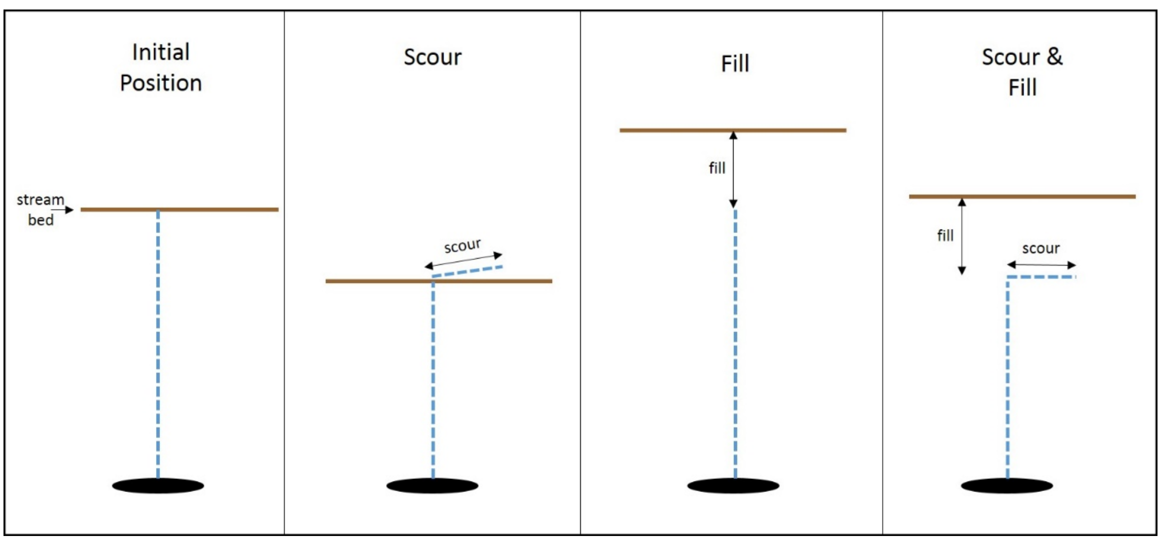

Figure 5. Use of scour chains to measure scour, fill, and dynamic scour and fill of streambed sediment. Arrows indicate points of measurement. Adapted from Bigelow (2003).

Sediment Coring – Sampling and Analysis

Sediment cores were collected using a modified piston coring apparatus (Fisher et al. 1992; Steinman et al. 2004) at all four of the tributary sites on June 26 and at the marsh and alluvial fan on June 20, 2017. The modified piston corer was constructed of a 0.6-m long, ~7-cm inner diameter, 7.6-cm outer diameter polycarbonate tube that was marked in 1-cm increments. The modified corer was positioned vertically at the sediment water interface and was maneuvered into the sediment, with force if necessary, to a depth of ~50 cm. The top and bottom of the core was sealed with a stopper and duct tape. Sediment cores were stored and transported upright on ice back to the lab within a few hours. The number of slices collected from each core was dependent on the total depth of the core. Each core was subsampled into sections that were each 8 cm deep, starting at the top surface of the sediment sample and working downward by extruding the sediment up and out from the core tube, and placing each 8 cm section in separate plastic zip-seal bags, which were refrigerated at 4°C until analysis. Most cores could be subdivided into 4-5 sections, while some sites (i.e., DC-2, DC-3, and M-2) only had only 2-3 sections due to more compact sandy sediment in tributary cores and a high concentration of cattail roots (rhizomes) in the marsh. Sediment in each bag was mixed by hand to a uniform consistency and subsampled for ash-free dry mass (AFDM) and organic matter (OM), with the remaining sample used to measure sediment particle size distribution. Sediment AFDM and OM were determined using gravimetric procedures (i.e., dry for 24 hours at 105˚C, weigh, ash at 550˚C for 4 hours to remove organic substances, re-weigh; APHA 2005). The resulting ashed material was used for sediment TP analysis on a SEAL AQ2 discrete automated analyzer, using 11.0 N H_2SO_4 for P extraction from sediment (USEPA 1993). Sediment particle size was determined by sequential sieving of dried sediment using the following size categories: gravel/cobble (>2 mm), very coarse sand (1-2 mm), coarse sand (0.5-1 mm), medium sand (250-500 µm), fine sand (125-250 µm), very fine sand (62.5-125 µm), and silt/clay (<62.5 µm). A summary of all sampling dates and parameters is presented in Table 2.

Table 2. Summary of sampling events and locations during 2017 sediment investigation study.

Date	Event *(Parameters)*	Tributary				Marsh	Fan
		DC-1A	DC-1B	DC-2	DC-3		
5/25/2017	Transect installation *(Turbidity sensors, scour chain)*	X		X	X		
6/20/2017	Sediment coring *(AFDM, OM, sediment TP, particle size)*					X	X
6/26/2017	Sediment coring *(AFDM, OM, sediment TP, particle size)*	X	X	X	X		
7/19/2017	Baseflow #1 *(water quality, TP, SSC, discharge, bedload)*	X		X	X		
8/10/2017	Storm flow *(water quality, TP, SSC, discharge, bedload)*	X		X	X		
9/12/2017	Baseflow #2 *(water quality, TP, SSC, discharge, bedload, scour chain)*	X		X	X		

Results

Tributary Monitoring

Based on the three discrete sampling events, discharge was much lower during both baseflow and storm flow at the Scholes Creek site (DC-2) than at the other two tributary sampling sites (DC-1 and DC-3; Table 3). The storm event increased stream discharge ~10-fold at all three sites, leading to increased TP concentrations by ~2-4×, increased TP loads by ~10-30×, increased SS loads by 30-60×, and increased bedload at DC-1A and DC-2 but not at DC-3 (Table 4). In contrast, dilution effects from storm runoff resulted in decreasing TDS compared to baseflow at all 3 tributary sites (Table 4). Among the tributary sites, mean TP concentration was highest at DC-2 (Scholes Creek), although the difference among sites was not very large. The higher discharges at DC-1A and DC-3 accounted for the larger TP loads (load = discharge × concentration) at these sites compared to DC-2 (Table 4).

The *in situ* turbidity sensor data (continuous measurements) help fill in data gaps that discrete (individual sampling dates) sampling misses. Turbidity increased rapidly after rain events at all sites; however, the turbidity patterns were quite different among sites (Fig. 6A). In particular, DC-2 behaved out of sync with the other two sites; turbidity at DC-2 spiked to a much greater degree than the other two sites after the June and August rain events as reported by the NOAA precipitation dataset, although the highest measured turbidity spike occurred at DC-3 in early July (Fig. 6A). The sensor at DC-1A malfunctioned between calibrations in August, so that time series portion of DC-1A data was excluded from analysis. Discrete measurements taken with the YSI 6600 showed turbidity increased 10-fold during the storm event when compared to baseflow events (Fig. 6B), although the relative responses of turbidity at each tributary sampling site did not align with the continuous data; for example, discrete sampling in mid-August reveal highest turbidity values at DC-2 (Fig. 6B), but the continuous turbidity data show highest turbidity values at DC-3 (Fig. 6A).

Tributary baseflow SS load averages ranged 0.26-1.32 g/s (Fig. 7A). Baseflow bedload rates varied across three orders of magnitude, with the downstream DC-1A site averaging 0.02 g/s, while mean bedload rates at the two upstream sites DC-2 and DC-3 were calculated at 9.17 and 13.73 g/s, respectively (Fig. 7A, Table 4). All suspended and bedload sediment loads increased during the storm event and the largest measured SS load of 76.66 g/s was observed at DC-3 (Fig. 7B, Table 4). **The main conclusion from these data is that during storm events, the upper reaches of Duck Creek contribute a disproportionately large amount of suspended sediment.**

Sediment rating curves showed that SS load increased with increasing discharge (Fig. 8). Rating curves for discharge and instantaneous bedload rates revealed different results at each site: both DC-1A and DC-2 showed bedload sediment increasing with discharge, although the curves were exponential for DC-1A and logistic (reaching a plateau) at DC-2 (Fig. 9A, B). In contrast, DC-3 showed a strongly negative exponential trend, with a decrease in bedload as discharge increases (Fig. 9C). Given the limited number of observations to generate the rating curves (n=3), these results should be viewed with caution.

Scour chain installations revealed dynamic scour and fill conditions at DC-1A and DC-2 due to the measured scour and the layer of sediment on top of the unburied, exposed chain links. Although DC-3 was buried by sediments, the chain links did not show any measurable scouring, even though the change in streambed elevation does. The differences between streambed initial and final measurements along with chain link length provide evidence of overall scouring at each site (Table 5). Differences in streambed elevation compared to reference points ranged from -0.6 to -4 cm over the 110 day study period, while differences in chain length measured 0.0 to -5.4 cm (Table 5). The calculated dynamic change at sites DC-1A and DC-2 ranged 2.1 to 4-8 cm, respectively (Table 5). Although no scour was indicated by measuring the chain links at DC-3, we observed that the chain was buried under a layer of sediment by the end of the study period. Sediment cover in addition to a negative value for the stream bed elevation still shows a dynamic scour fill event has occurred; however, the scour event may have been too small to cause any links to bend at 90 degrees, but was enough to allow the chain to 'settle' into the sediment enough to obscure it from view. **Overall, these data are consistent with the sediment load data—upstream reaches of Duck Creek are sediment "donors" while the downstream area (DC-1A) is a sediment "recipient".**

Sediment Coring

Percent sediment OM was very low (<10%) at all 4 tributary sites (Fig. 10); among the tributaries, DC-1B had the highest %OM values (Fig. 10D), whereas DC-1A generally had the lowest %OM values (Fig 10B). There was relatively little change in OM with sediment depth at any of the tributary sites, with the greatest variation at DC-1B where OM was greater at the surface sediments than in lower sediments (Fig. 10). TP concentration generally tracks OM values, as organic material either contains P or readily binds to P. Duck Creek sediments behaved similarly; sediment TP was greatest at DC-1B where OM was also greatest (Fig. 10C). The highest TP concentration measured in the tributary sediment was 358 mg/kg at DC-1B in the 8-16 cm deep section; subsurface sections at sites DC-1A, DC-1B, and DC-2 contained higher TP concentrations than their respective surface section (0-8 cm depth), except for DC-3 where the surface section had more TP (Fig. 10). See Appendix Table A1 for more details on OM and TP in the tributary sediments. Overall, these TP concentrations are relatively modest (see below).

Percent OM values in marsh sediments were much greater than in the tributary sediments (Fig. 11, Table 6). Among the 5 marsh sites, %OM tended to decline with sediment depth, although M-1 had anomalously low %OM values at the surface (Fig. 11B). Site M-5 had the lowest %OM values (Fig. 11J). Surface (0-8 cm depth) sediment TP ranged from 741 to 6092 mg/kg, considerably greater than surface sediment TP in the tributaries (Table 6). Sediment TP slightly decreased with increasing sediment depth, as bottom (24-32 cm depth) sediments ranged from 88 to 1114 mg/kg (Fig. 11). See Appendix Table A2 for more details on OM and TP in the marsh sediments.

Percent OM values in sediment along the alluvial fan sampling transect were intermediate between tributaries and marsh (Fig. 12, Table 6). Percent OM in the surface layer (0-8 cm depth) was greatest at sites located further from the mouth of Duck Creek (F-1 and F-2) and decreased with increasing sediment depth, whereas fan sites located nearest to Duck Creek (F-4 and F-3) had lower %OM values that generally increased with increasing sediment depth (Fig. 12). Similar to %OM, sediment TP concentrations were intermediate between tributaries and marsh (Fig. 12, Table 6) and among fan sampling locations, almost exactly mimicked the patterns observed for their corresponding %OM (Fig. 12). See Appendix Table A3 for more details on OM and TP in the alluvial fan sediments.

To summarize the sediment results, both mean %OM and sediment TP values at all depths were lowest in the tributary cores, highest in marsh cores, and intermediate at the alluvial fan cores (Fig. 13, Table 6). We compared the mean surface sediment TP concentrations from the sites in the Duck Creek watershed with sediment TP concentrations from other west Michigan waterbodies. Results indicate that the Duck Creek watershed sediment TP concentrations fall within or below the range generated from the previously sampled habitats (Fig. 14). The much higher Duck Lake marsh sediment TP concentration (Figs. 11, 14) is skewed by the high TP concentration (>6000 mg/kg, dry wt) in core M-1; even if this data point is removed, and the mean marsh TP concentration is reduced to 1289 (±421) mg/kg, the value still leaves the Duck Lake marsh sediment TP concentration well within the range of other local waterbodies (Fig. 14).

Sediment particle size distribution from the tributary sites mostly contained medium sand (250-500 µm) and fine sand (125-250 µm) size classes (Fig. 15). DC-1A and DC-2 contained higher percentages of larger sediment particles, especially of the cobble/gravel (>2 mm) and coarse sand (0.5-1 mm) size classes (Fig. 15). Conversely, DC-1B and DC-3 contained a mixture of smaller sediment particles of medium (250-500 µm) and fine sand (125-250 µm) size classes (Fig. 15). DC-1A shows a variety of particle size distribution influenced by the upstream sites, with all sediment fraction sizes represented, although by comparison it is lacking the large quantities of the fine sand and silt/clay found at DC-1B, which is the closest in proximity (Fig. 15).

Sediment particle size distribution in the marsh varied greatly from the creek, with silt/clay (<63 µm) sediments constituting a large percentage of 4 of the 5 cores at all observed sediment core depths (Fig. 16). Whereas creek coring sites are subject to constant flow, marsh coring sites are surrounded by vegetation, which reduces stream flow velocity, allowing sediment particles to settle out of the water column and thereby increasing sediment retention. Smaller sediment particles are typically first to enter into the water column and last to settle out, which likely explains the relatively high abundance of silt/clay sediment fraction in the marsh. Interestingly, site M-5 has a very different size fraction distribution when compared to other marsh cores even though sites M-4 and M-5 are geographically the closest of any two marsh sites (Fig. 2). M-5 is most similar to alluvial fan core F-4 (Fig. 17), the closest fan core located to where Duck Creek enters into Duck Lake (Fig. 2).

Cores sampled along the alluvial fan showed the influence of Duck Creek's flow regime, as sediment size fraction varied with distance from the mouth of Duck Creek, with sediment closer to Duck Creek (F-4) being predominantly medium sand (250-500 µm) and sediment sampled furthest away from Duck Creek (F-1) dominated by silt/clay <63 µm), with F-2 and F-3 following the gradient between the two transect endpoints (Fig. 17).This again exemplifies that as water from the stream begins to slow when entering Duck Lake, the larger sediment particles settle out first whereas the smaller fractions settle last. See Appendix Tables A4-6 for more details on particle size distributions in the tributary, marsh, and alluvial fan sediments, respectively.

Table 3: Mean (±SD) summary of general water quality parameters and stream discharge at Duck Creek tributary sites. N = number of total samples, Temp. = temperature, DO = dissolved oxygen, SpCond = specific conductance, ORP = oxidation-reduction potential, and Q = discharge. NA = not applicable.

Flow	Site	N	Temp. (°C)	DO (mg/L)	DO (%)	SpCond (µS/cm)	ORP (mV)	Q (m^3/s)
Base (7/19 & 9/12)	DC-1A	2	15.35 (4.26)	7.48 (1.63)	74.05 (9.40)	282 (14)	369.95 (33.87)	0.32 (0.16)
	DC-2	2	13.40 (2.60)	10.10 (0.53)	96.55 (0.49)	224 (14	375.45 (24.40)	0.03 (0.02)
	DC-3	2	15.92 (2.84)	10.03 (0.64)	101.25 (0.35)	292 (15)	382.95 (17.32)	0.22 (0.08)
Storm (8/10)	DC-1A	1	17.69 (NA)	6.79 (NA)	71.3 (NA)	162 (NA)	499.50 (NA)	1.62 (NA)
	DC-2	1	16.7 (NA)	7.86 (NA)	80.9 (NA)	148 (NA)	512.50 (NA)	0.34 (NA)
	DC-3	1	16.46 (NA)	8.16 (NA)	83.5 (NA)	177 (NA)	515.30 (NA)	1.91 (NA)

Table 4: Mean (±SD) summary of total phosphorus (TP) in water and sediment-related water quality parameters at Duck Creek watershed sites. N = number of total samples, SS Load = suspended sediment load and TDS = total dissolved solids. NA = not applicable.

Flow	Site	N	TP (µg/L)	TP Load (mg/s)	SS Load (g/s)	Bedload (g/s)	TDS (mg/L)	Turbidity (NTU)
Base (7/19 & 9/12)	DC-1A	2	11 (5)	3.88 (3.46)	0.82 (0.29)	0.02 (0.00)	184 (9)	4.0 (1.6)
	DC-2	2	17 (13)	0.72 (0.81)	0.26 (0.29)	9.17 (3.54)	146 (9)	5.0 (5.4)
	DC-3	2	15 (8)	3.60 (2.88)	1.32 (1.04)	13.73 (8.36)	190 (9)	3.0 (1.8)
Storm (8/10)	DC-1A	1	28 (NA)	46.00 (NA)	22.93 (NA)	1.50 (NA)	105 (NA)	9.1 (NA)
	DC-2	1	66 (NA)	22.10 (NA)	14.30 (NA)	23.91 (NA)	96 (NA)	25.0 (NA)
	DC-3	1	56 (NA)	107.45 (NA)	76.66 (NA)	2.29 (NA)	115 (NA)	20.3 (NA)

Table 5. Streambed elevation and scour chain measurements with calculated fill or scour rates during the 110 day Duck Creek tributary sampling period. Fill is shown as a positive value (adding sediment) and scour as a negative value (removing sediment). Dynamic change is a calculated value difference between the scour measurement (chain length) and change in streambed elevation and represents change that may not have been directly measureable between sampling events (Fig. 5).

Site	Measured Change (cm)		Dynamic Change (cm)
	Streambed	Chain	
DC-1A	-0.6	-5.4	4.8
DC-2	-0.9	-3.0	2.1
DC-3	-4.0	0.0	-4.0

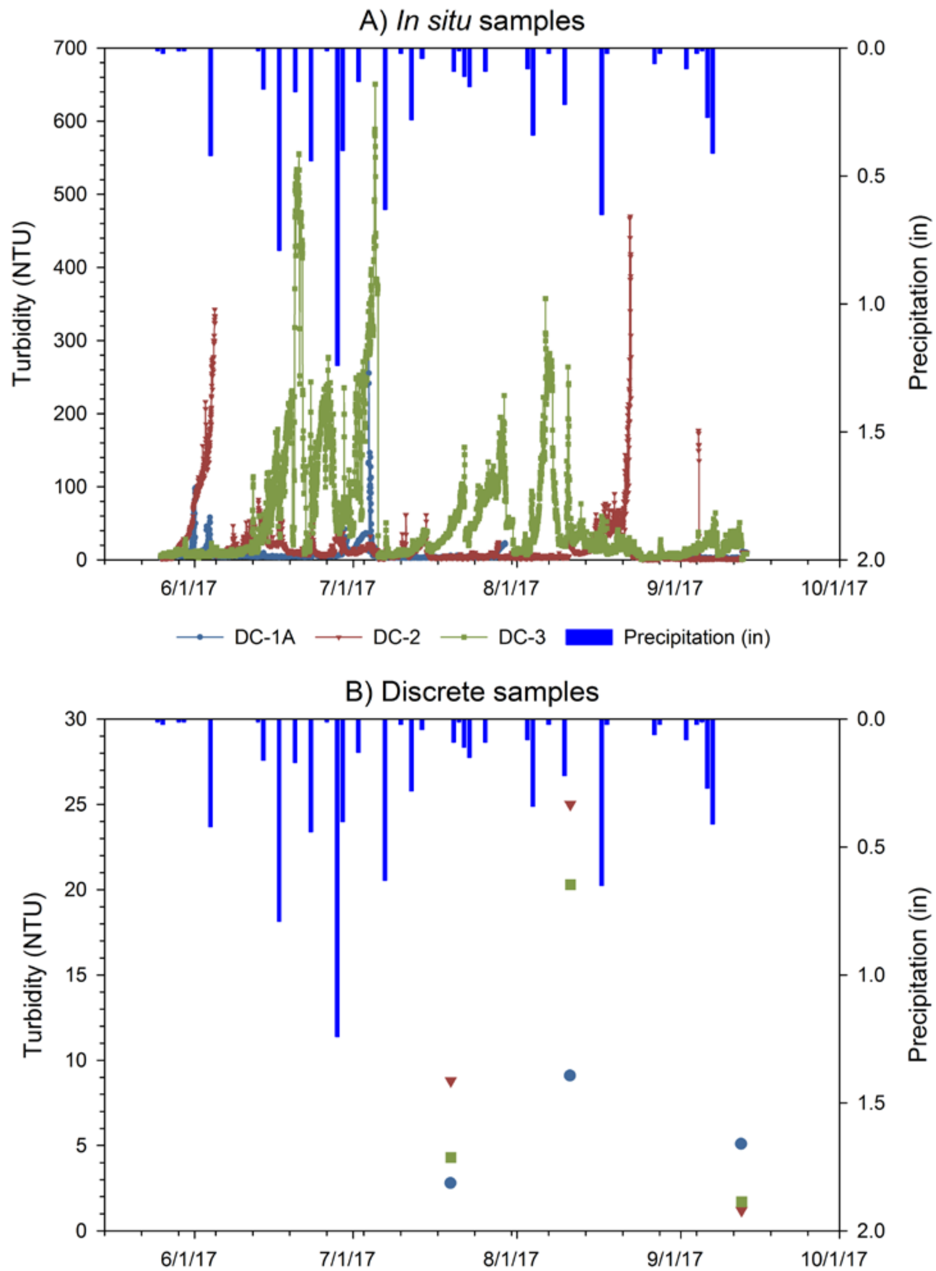

Figure 6. Daily precipitation (blue vertical bars extending down from top x-axis) and turbidity during 2017 sampling at the Duck Creek tributary sites. (A) Turbidity data (extending up from bottom x-axis) were collected continuously every 30 minutes via *in situ* Cyclops sensors. DC-1A data from 7/29 to 8/24 is excluded due to a sensor malfunction. (B) Discrete turbidity measurements taken during two base (7/19 & 9/12) and one storm flow (8/10) event with YSI 6600. Precipitation data are from the National Climatic Data Center (2017; NOAA). Note different scales for turbidity on the y-axes in panels. Legend between A and B applies to both panels.

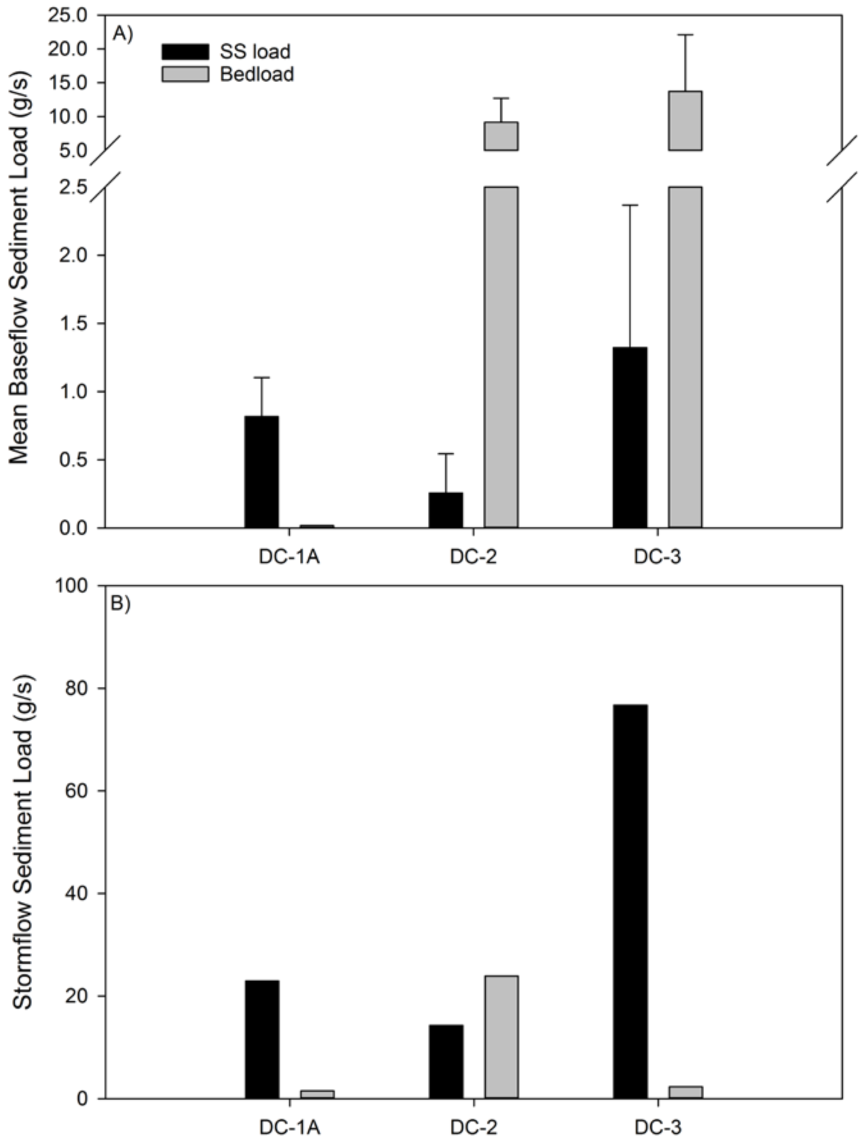

Figure 7. Calculated mean suspended sediment (SS) and bed loads (g/s) at Duck Creek watershed sites during baseflow (A, n=2) and storm flow conditions (B, n=1). Note that Y-axis scales differ between panels and that A has a broken Y-axis with a changing scale on either side of the break. Legend in A also applies to B. Error bars represent standard deviation.

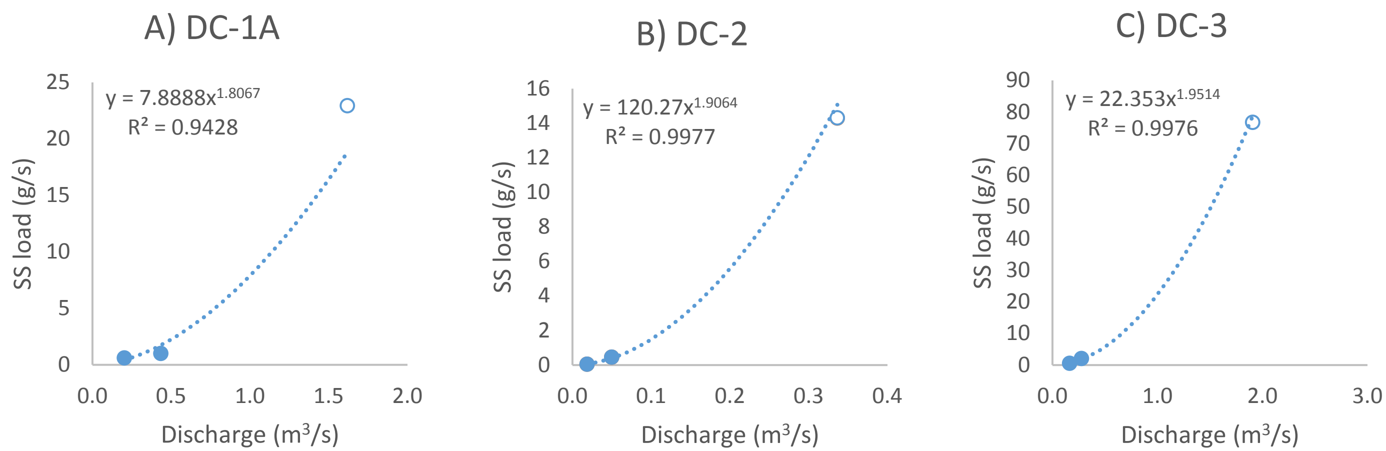

Figure 8. Suspended sediment rating curves. Solid circles represent baseflow samples; open circles represent storm flow conditions. SS load = suspended sediment load.

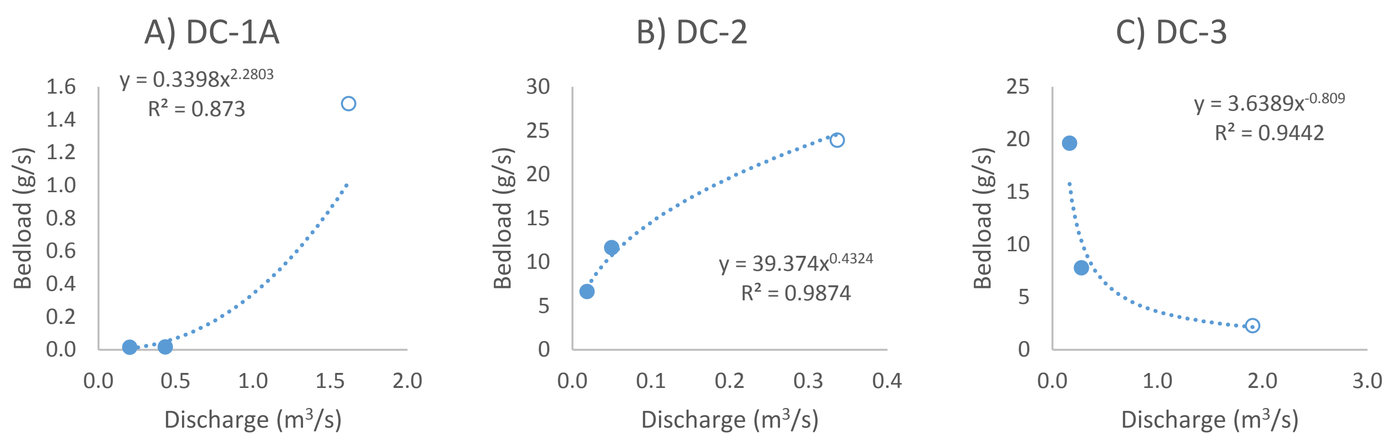

Figure 9. Bedload sediment rating curves. Solid circles represent baseflow samples; open circles represent storm flow conditions.

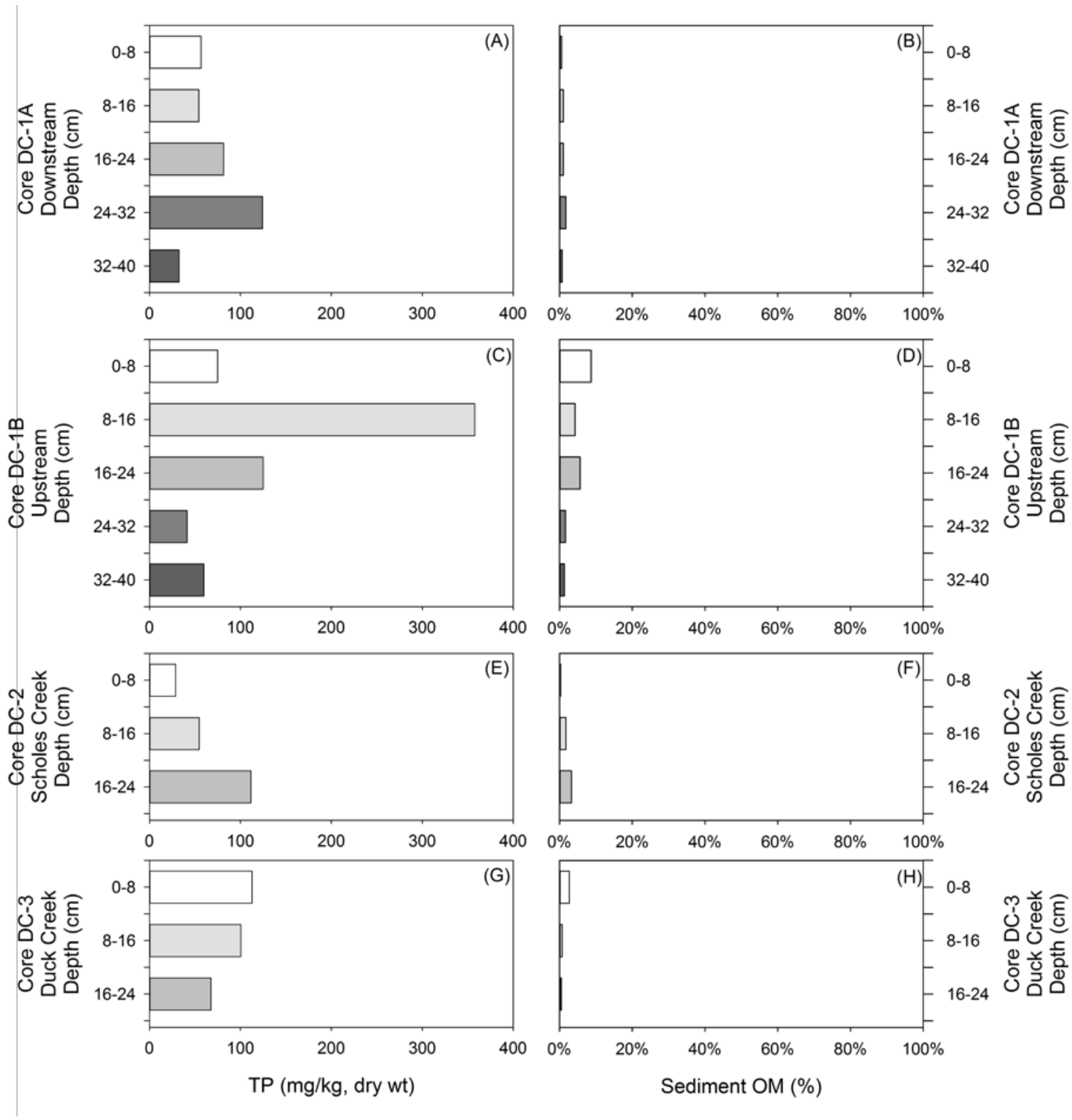

Figure 10. Sediment total phosphorus (TP; mg/kg, dry weight) and organic matter (%) in Duck Creek watershed tributary sediment cores at depth. Bars are color coded by depth, with colors becoming darker as depth increases. Note that Core DC-1A and DC-1B (panels A-D) have longer y-axes depths than other creek sediment cores.

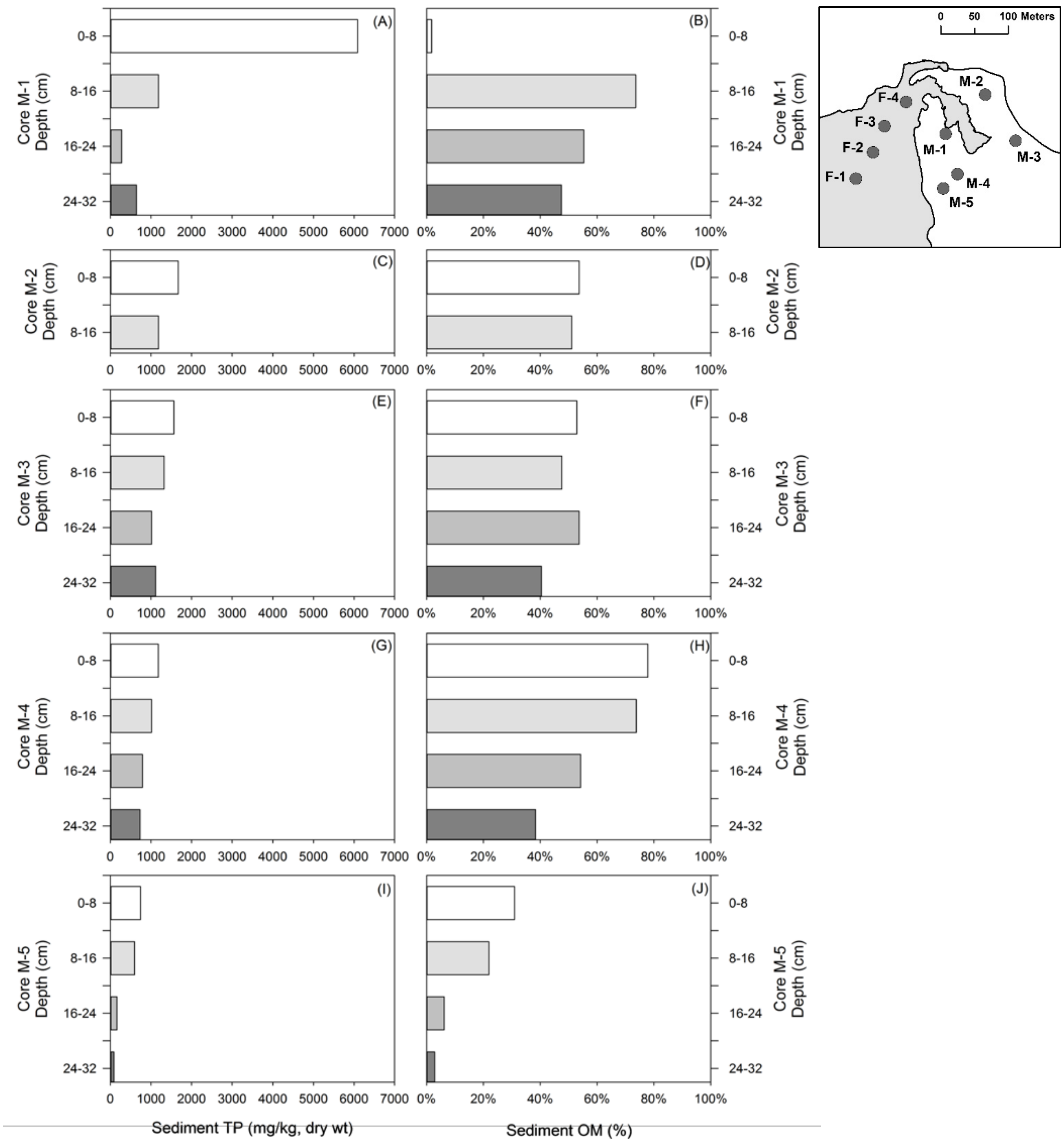

Figure 11. Sediment total phosphorus (TP; mg/kg, dry weight) and organic matter (%) in marsh sediment cores at depth. Bars are color coded by depth, with colors becoming darker as depth increases. Note that Core M-2 (panels C, D) has a shorter y-axis depth than other marsh sediment cores. An inset from the site map (Fig. 2) is provided for reference.

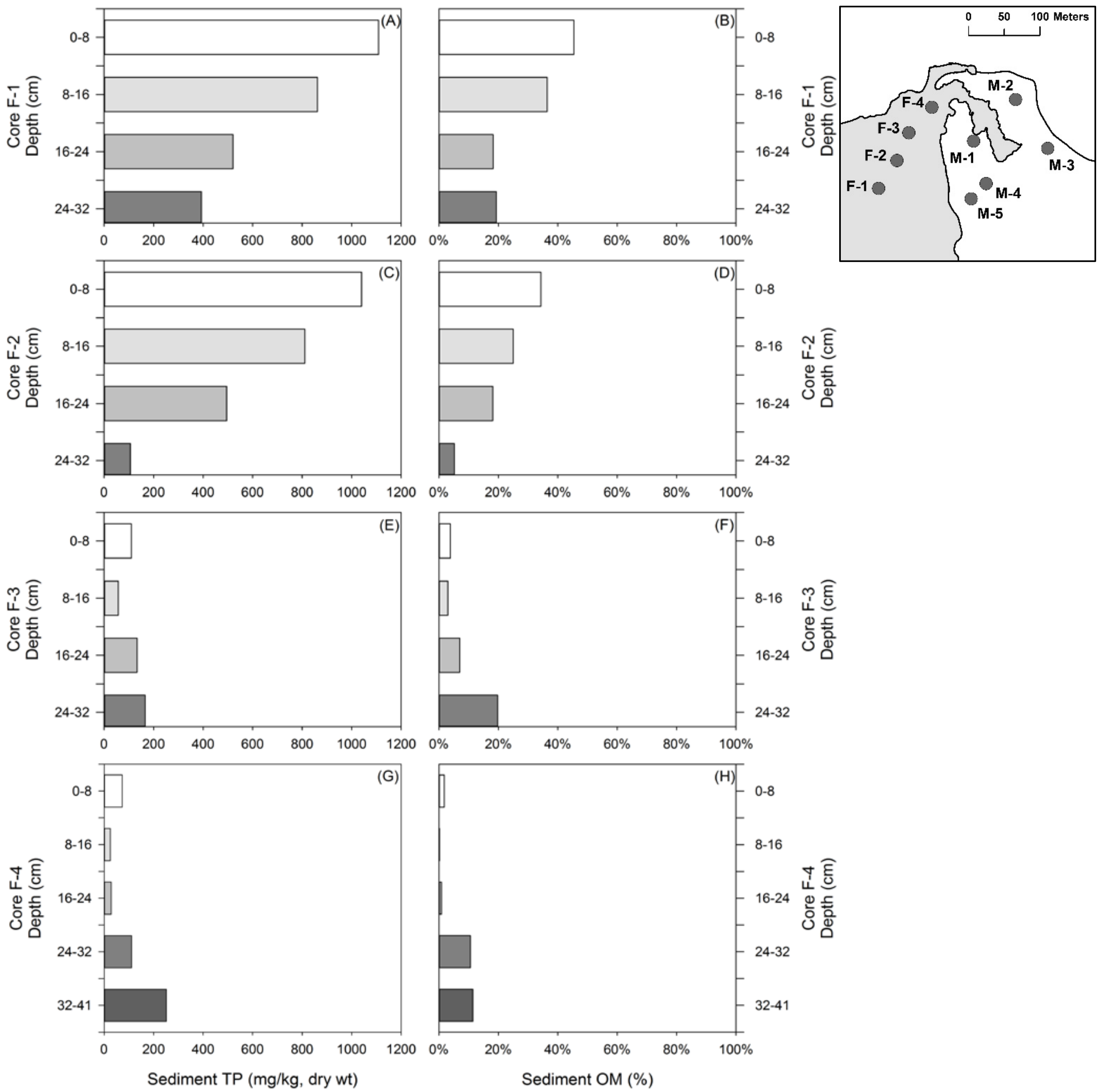

Figure 12. Sediment total phosphorus (TP; mg/kg, dry weight) in Duck Lake alluvial fan sediment cores at depth. Bars are color coded by depth, with colors becoming darker as depth increases. Note that Core F-4 (panels G, H) has a greater y-axis depth than other alluvial fan sediment cores. An inset from the site map (Fig. 2) is provided for reference.

Table 6. Mean (±SD) sediment total phosphorus (TP; mg/kg, dry weight) and organic matter (%) by depth in sediment cores sampled in Duck Creek tributaries, Duck Lake marsh, and alluvial fan. N = total number of core depth sections included in mean, NA = not applicable, ND = no data. No cores collected in the marsh extended beyond the 24-32 cm depth.

	N			Mean Sediment TP (±SD)			Mean Sediment OM (±SD)		
Depth (cm)	**Creek**	**Marsh**	**Fan**	**Creek**	**Marsh**	**Fan**	**Creek**	**Marsh**	**Fan**
0-8	4	5	4	68 (35)	2249 (2179)	582 (568)	3% (4%)	43% (29%)	21% (22%)
8-16	4	5	4	142 (146)	1059 (282)	439 (460)	2% (2%)	54% (22%)	16% (18%)
16-24	4	4	4	96 (26)	561 (409)	294 (250)	3% (2%)	42% (24%)	11% (9%)
24-32	2	4	4	83 (59)	643 (423)	194 (135)	2% (0%)	32% (20%)	14% (7%)
32-41	2	0	1	46 (19)	ND (NA)	251 (NA)	1% (0%)	ND (NA)	11% (NA)

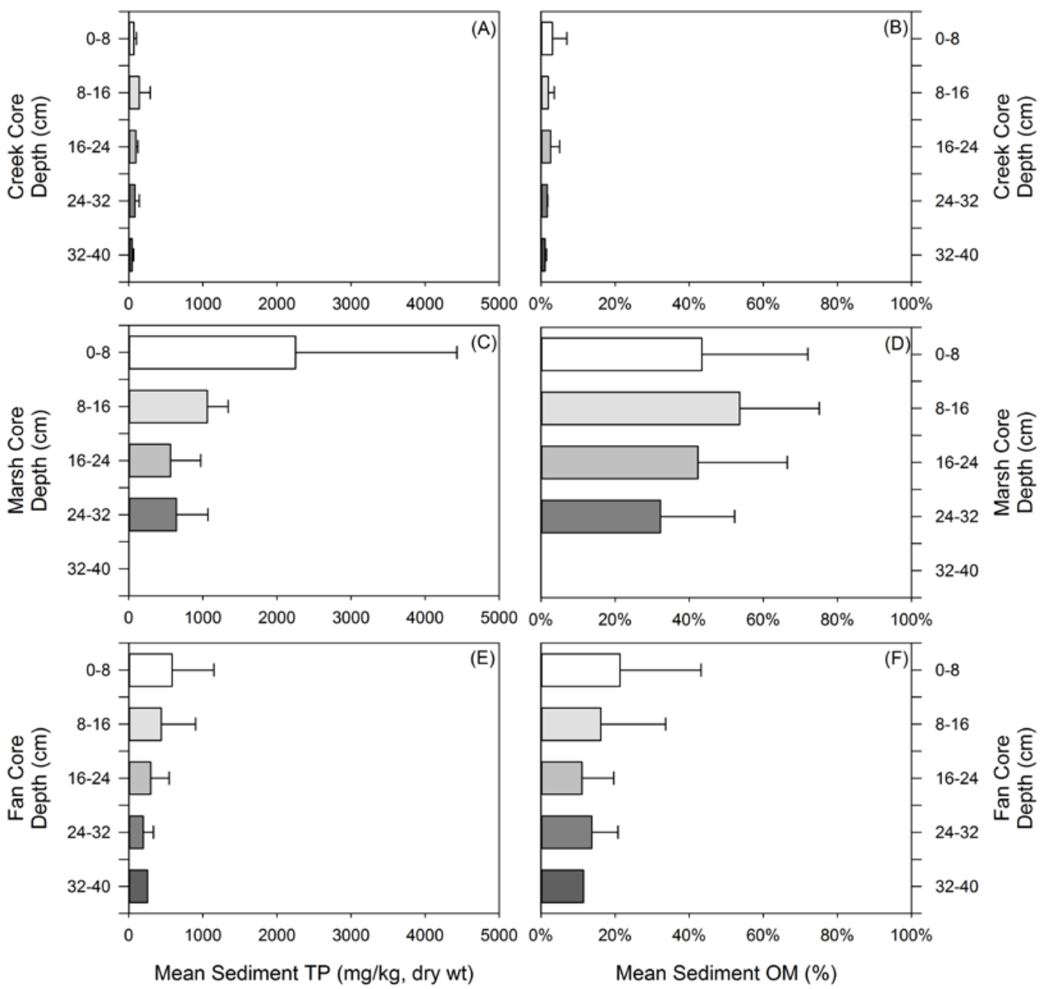

Figure 13. Mean sediment total phosphorus (TP) (mg/kg, dry weight) and organic matter (%) by depth in sediment cores sampled in Duck Lake alluvial fan (A, B), marsh (C, D), and Duck Creek watershed (E, F). Bars are color coded by depth, with colors becoming darker as depth increases. Error bars represent standard deviation.

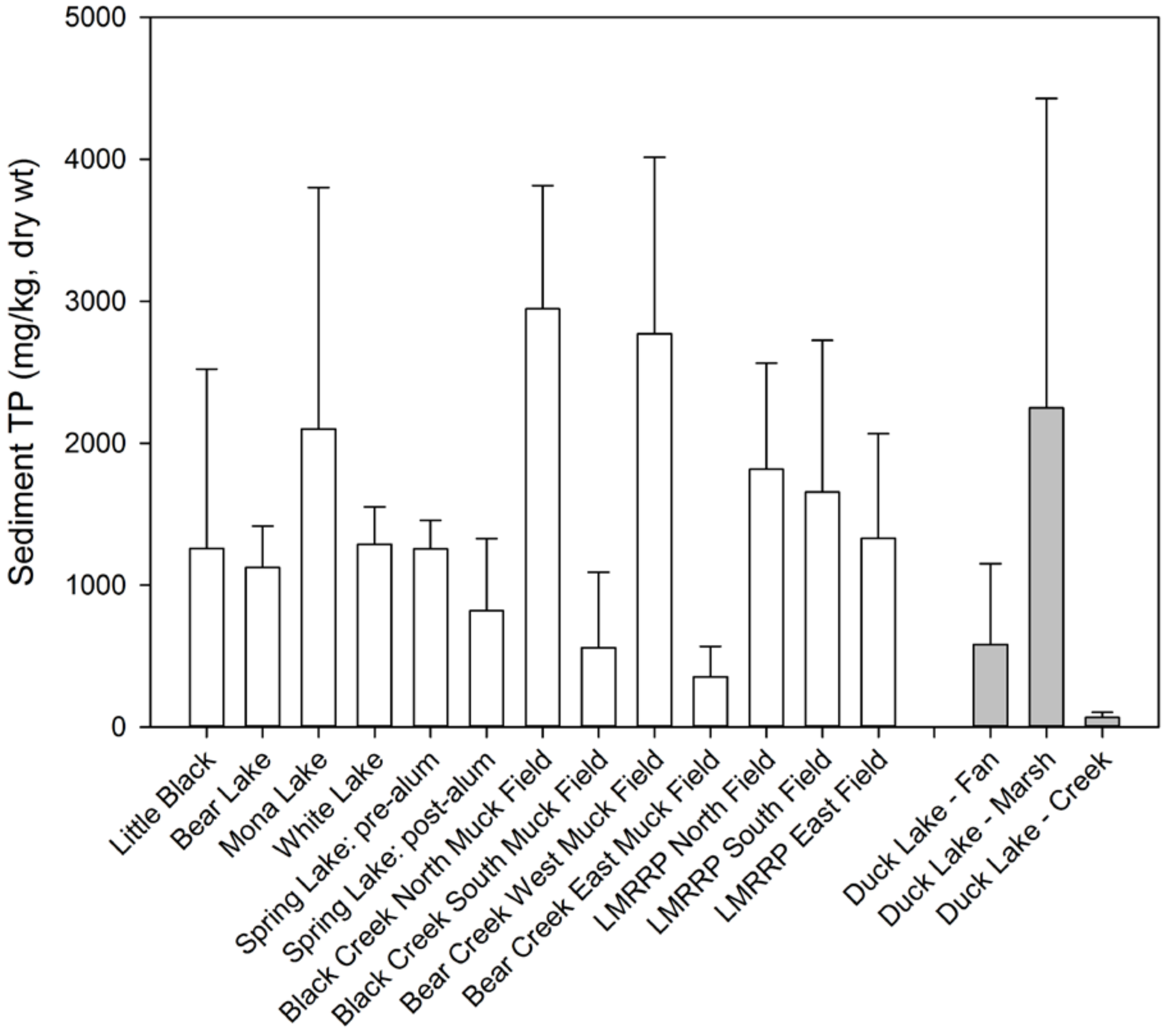

Figure 14. Mean near-surface (0-8 cm) sediment total phosphorus (TP) measured in Duck Lake alluvial fan, marsh, and Duck Creek tributaries compared to other west Michigan waterbodies. Note that mean surface sediment TP in Duck Lake - Marsh cores is heavily influenced by a single core (M-5 at 6092 mg/kg, dry weight), while the remaining marsh cores had a smaller range of TP concentrations at surface depth (741-1668 mg/kg, dry weight; Table 6). Error bars represent standard deviation.

Sources: Little Black Lake: Steinman et al. 2011; Mona Lake: Steinman et al. 2009; White Lake: Steinman et al. 2008a; Spring Lake pre-alum: Steinman et al. 2004; Spring Lake post-alum: Steinman and Ogdahl 2008; Bear Lake: unpublished data; Black Creek muck fields: Steinman and Ogdahl 2011; Bear Creek: Steinman and Ogdahl 2013; Lower Muskegon River Reconnection Project (LMRRP) pre-restoration surface sediments: Steinman et al. 2017.

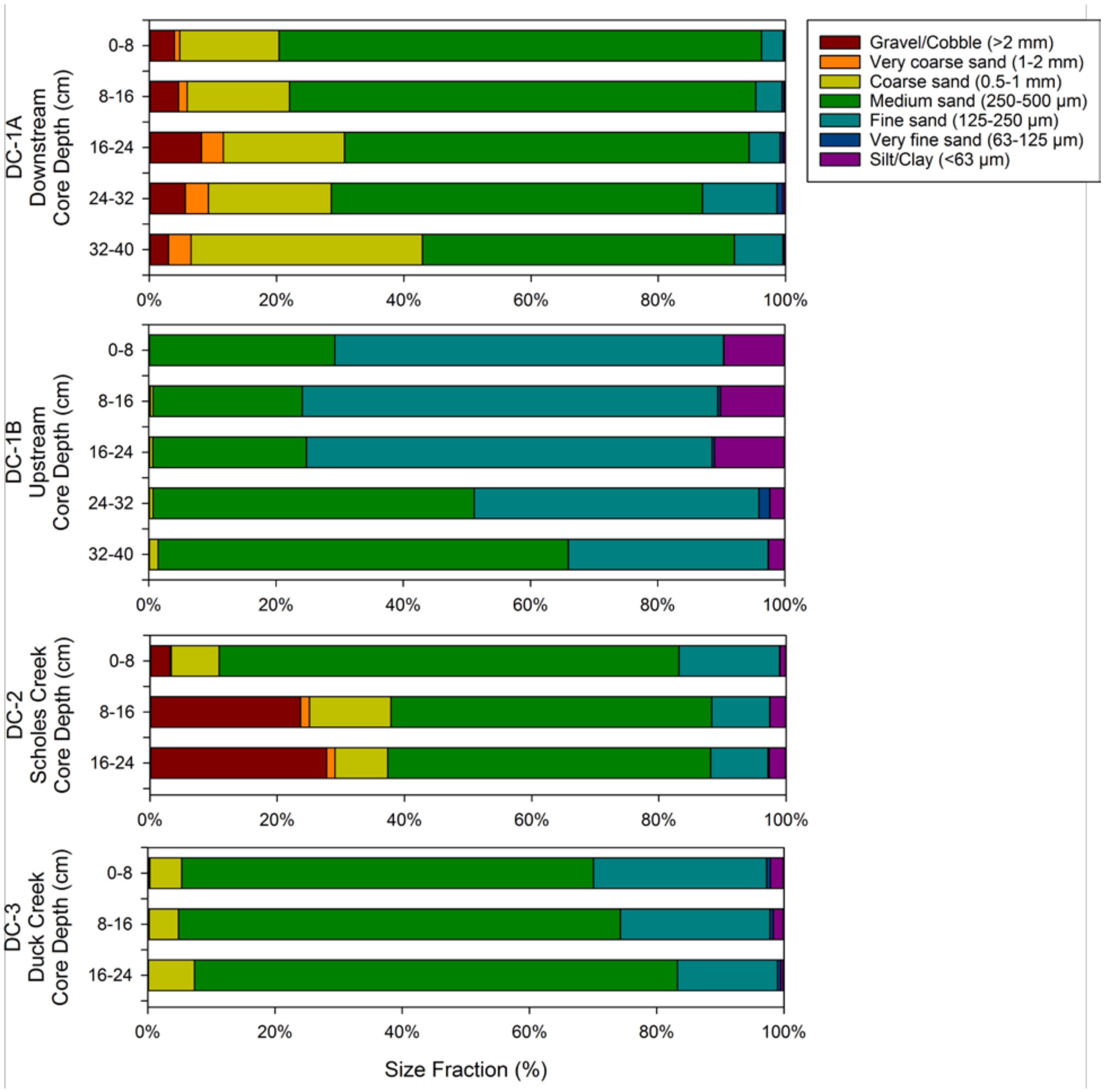

Figure 15. Sediment particle size fractions at depth from cores sampled from tributaries throughout the Duck Creek watershed (Fig. 2).

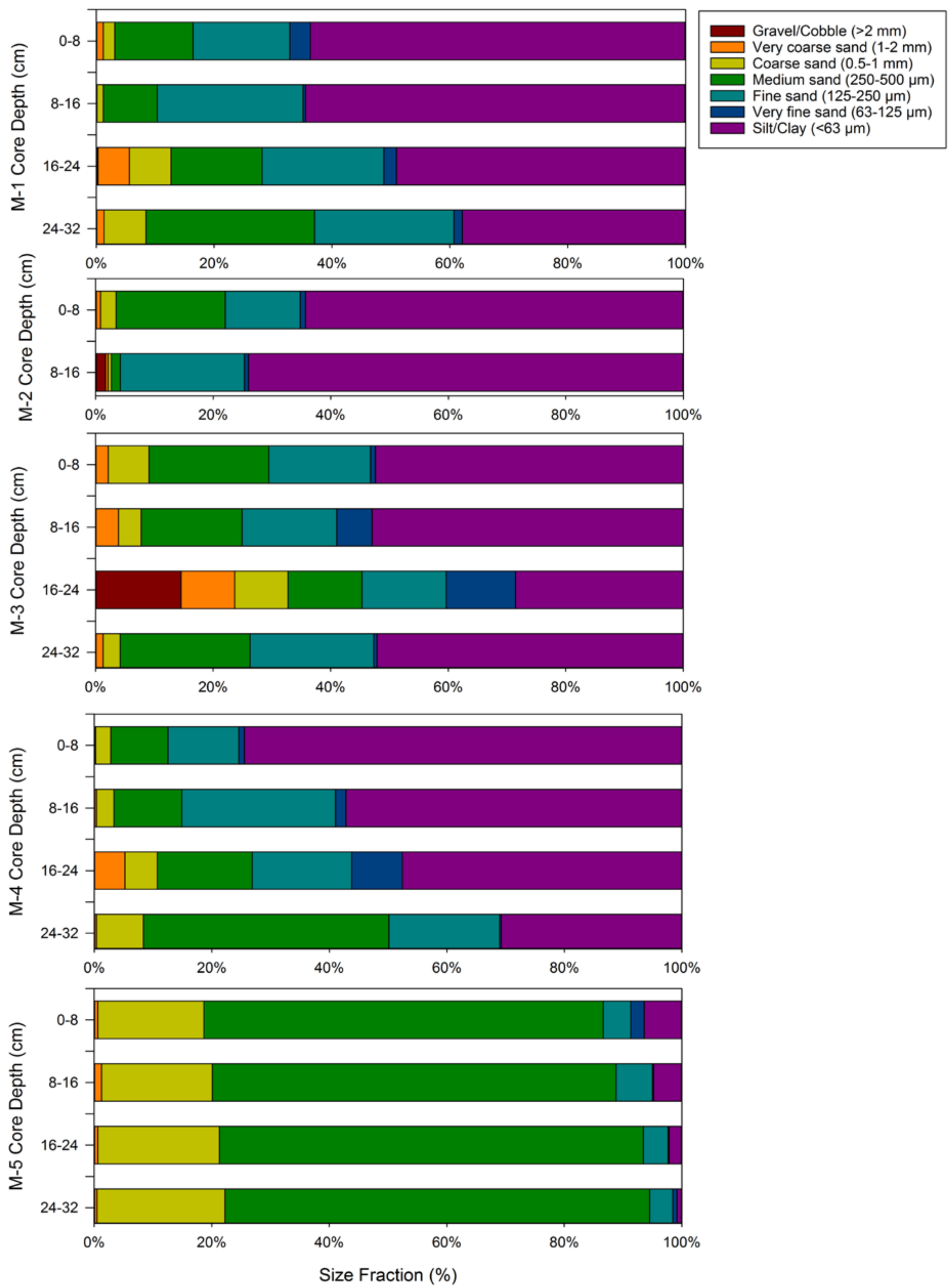

Figure 16. Sediment particle size fractions at depth from cores sampled in the cattail marsh where Duck Creek enters Duck Lake (Fig. 2).

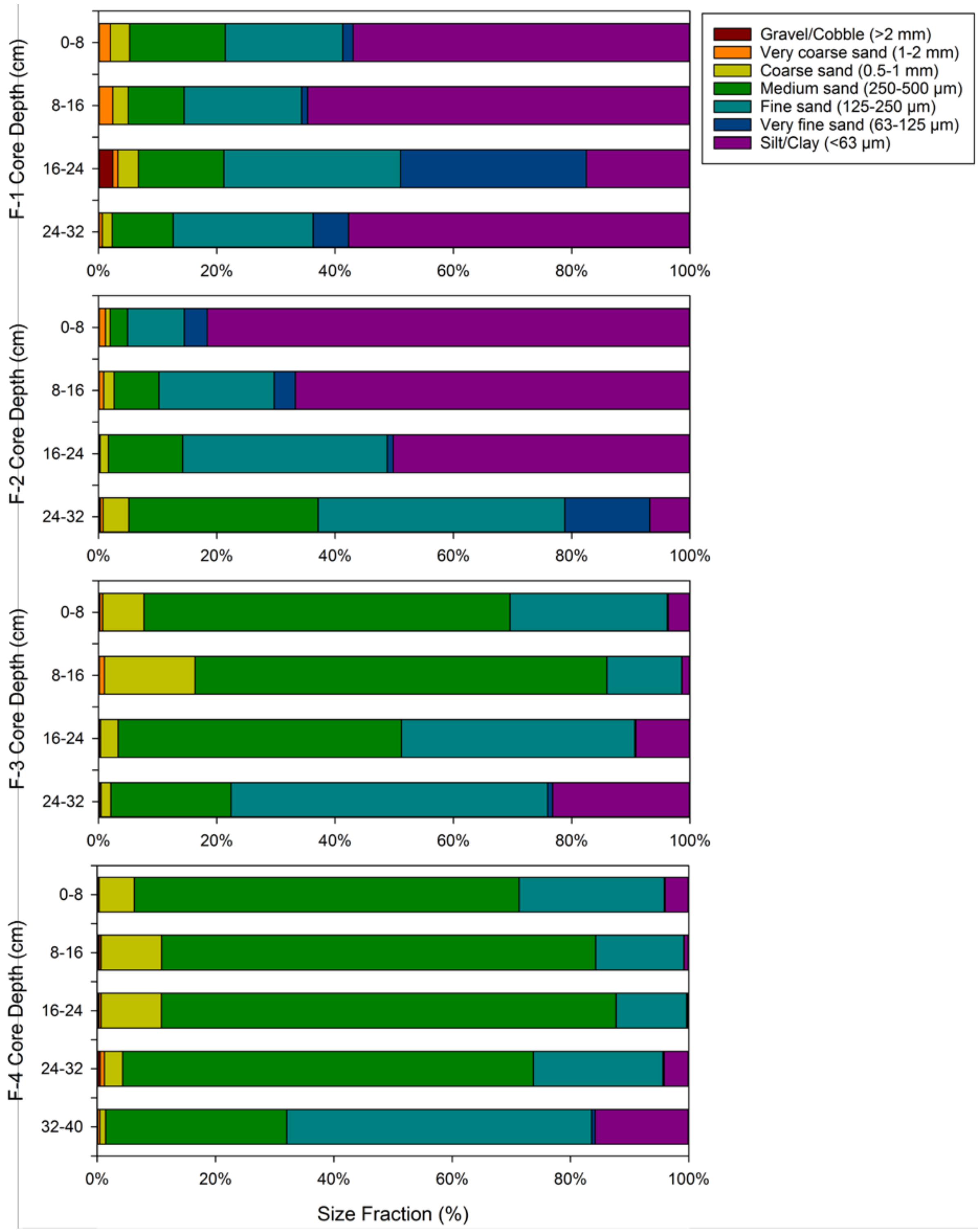

Figure 17. Sediment particle size fractions at depth from cores sampled in the alluvial fan where Duck Creek enters Duck Lake. Fan cores were sampled from equally spaced locations along a transect from the eastern area of Duck Lake (F-1) to the mouth of Duck Creek (F-4) (Fig. 2).

Discussion

While our sampling regime was limited, our findings identified three topics that warrant further discussion and, potentially, future watershed restoration projects: TP load in the Duck Creek watershed; rates of sediment movement throughout the tributaries during storm flow and particle size distribution; and high concentrations of sediment TP in the Duck Lake marsh and alluvial fan. Finally, sediment particle size distribution in the vicinity of Nestrom Road bridge over Duck Creek is examined at the request of watershed residents.

Duck Creek Watershed TP Load

Excess runoff of TP is a known stressor in west Michigan, often resulting in algal blooms (Steinman et al. 2004, 2008). In the Duck Creek watershed, upstream of DC-3 (the furthest downstream reach of the upper sub-watershed of Duck Creek), TP concentrations during baseflow ranged between 10 and 20 µg/L but increased 3-6× during storm flow (Table 3). A previous study in the Duck Creek watershed defined the upper sub-watershed of Duck Creek as a potential source of P using PLOAD, a storm water pollution loading model developed by the U.S. Environmental Protection Agency (USEPA), based on land cover change from 1998 to 2009. PLOAD estimated TP load (TP concentration × discharge) ranged from ~2.20 to 11.23 mg/s in the upper Duck Creek area (MCD 2012). Our site of DC-3 fell within that range during baseflow, but was a ~30x higher during the storm event we captured. Our results suggest that P concentrations are not unusually excessive in the Duck Lake watershed, but that there would be likely benefits in reducing P loads.

The P within the Duck Lake watershed is most likely coming from nonpoint sources, such as excess fertilizers on land, stormwater runoff, and septage, which are difficult to measure and control (Carpenter et al. 1998). With some of the changes to land use (MCD 2012) one possible source of P input could be from existing septic systems throughout the watershed. Silver Lake in Oceana County, MI found that septic systems could contribute up to ~22% of P into a creek (Brennan 2016). While the density of homes is much less in this watershed than around Silver Lake, there may be value in assessing subsurface inputs to Duck Creek. Clearly, more P is moving during storm events, so management activities to reduce either water movement (e.g., implementing water retention best management practices in critical areas) or P concentrations (septage maintenance and treatment for subsurface inputs; wetland restoration and creation for surface inputs) in upper Duck Creek would be beneficial.

Storm Flow Sediment Movement Rates

At the three tributary sites, we observed increases in suspended and streambed sediment loads during storm flow; however, these instantaneous sediment measurements, although limited spatially and temporally, appear to be within acceptable ranges. Total suspended solid (TSS) guidelines used by the State of Michigan in developing total maximum daily limits (TMDLs) for watersheds incorporate the following 4-part scale (MDEQ 2005, Alabaster 1972):

Optimum	≤ 25 mg/L
Good to Moderate	>25 to 80 mg/L
Less than Moderate	>80 to 400 mg/L
Poor	>400 mg/L

TSS and SSC are similar, but not directly interchangeable measurements, and SSC tends to be a larger value when paired with TSS in a given sample (Gray et al. 2000). The SSC samples collected in this study and used to calculate SS load, ranging ~2-9 mg/L at baseflow and ~14-43 mg/L at storm flow (data not shown), are potentially overestimates of TSS at these sampling times and suggest that suspended solids in Duck Creek are in Optimum or Good to Moderate range. These results may vary seasonally or even temporally within the timeframe of a single storm system as it moves through the watershed. This becomes apparent when looking at the turbidity data from the *in situ* sensors. Although NTU and TSS units are not directly comparable, it is clear that more particles are coming from DC-3 than the other tributary sites during this study (Fig. 6). Our observations in this study for DC-3 followed the PLOAD model, reiterating once again that the upper Duck Creek sub-watershed is the primary source of sediment (MCD 2012). Best management practices identified in the previous section also could benefit sediment reduction, as P often attaches to sediment—reducing one often results in the reduction of the other.

Sediment TP in Duck Marsh and Alluvial Fan

From 1978 to 2009 the Duck Lake watershed has seen an 87% increase in developed land (MCD 2012), although the overall percentage of developed land is very small (~1.2%; Fig. 3). The urbanization of landscapes is known to degrade ecological conditions in their respective watersheds and this "urban stream syndrome" can be detected even on small scales in lightly urbanized areas (Walsh et al. 2005, Halstead et al. 2014). Symptoms of urban stream syndrome can include increased nutrient concentrations among others, which may be linked to the high sediment TP concentrations observed at the Duck Lake marsh. Tributary site sediment samples contained low mean sediment TP; however, the Duck Lake marsh has high concentrations of sediment TP and is within range of other local west Michigan waterbodies that are sites of previous and current environmental restoration efforts (Fig. 14). Typically, wetlands can serve as a sink for P via sorption to sediments and biotic uptake from the algae, plants, and microbial communities (Steinman and Ogdahl 2013). Without more detailed research on P fate and movement in these sediments, it is not possible to know if the phosphorus is being retained or released from the sediment, or if the P is biologically available or in a non-bioavailable form. Additional studies could resolve this issue; alternatively, removal of this sediment (perhaps by dredging) may be a proactive strategy, assuming the change in topography doesn't significantly impact flow patterns of Duck Creek entering Duck Lake.

Sediment Particle Size Analysis

In addition to sediment-related concerns with regard to ecosystem health, some watershed residents have expressed concerns that sediment may be accumulating in undesirable quantity, resulting in streambeds too shallow for boat navigation in Duck Creek just upstream of Duck Lake. In addition, the streambanks were becoming more characteristically 'mucky' sediment rather than the predominantly sandy sediments they remember from previous decades (C. Mitenbuler, personal communication). Residents also hypothesized that the construction of the bridge crossing of Nestrom Road over Duck Creek may be a source of the fine, mucky sediments seen in the lower area of Duck Creek and Duck Lake with sediments being inadvertently introduced during bridge construction in the same timeframe as a historic 1986 flood (L. Knopf, personal communication).

From our tributary sediment cores at sites downstream (DC-1A) and upstream (DC-1B) of the bridge, we found that the high percentage of fine particles (<63 μm) present in upstream samples were absent in the area directly downstream of the bridge (Fig. 15, Appendix Table A4), but were present in cores in the Duck Lake alluvial fan closest to Duck Creek (Fig. 17, Appendix Table A6). Since only one core was taken from each site, we may have been unable to capture some of the sediment deposition that clearly is moving through DC-1A to the alluvial fan, or may be deposited on streambanks and/or in the marsh during high flow. DC-1A is wide and slow-moving during baseflow and the increased storm flow stream discharge and dynamic scour and fill indicated by the DC-1A scour chain supports the idea that sediment is moving through this site, although based on our data it is likely that the source of sediment is much further upstream. Hence, any impact the bridge may be having is likely to be very localized.

Conclusions

Our analyses of physical and chemical water quality parameters, including TP and sediment movement in both the water column and streambed, did not identify any one "smoking gun" responsible for sediment-related impairments in the Duck Lake watershed. Rather, we were able to isolate the upper reaches of the watershed as the areas that contribute the most P and sediment to Duck Lake. With respect to restoration, we provide the following recommendations, noting that they are based on a limited data set, given time and budget constraints:

- The upper Duck Creek tributary, upstream of DC-3, is a likely source of P and sediment loads, especially during storm flow. Hence, restoration efforts to implement water retention structures (created wetlands; green swales; rain gardens) in key areas of impervious pavement are recommended. These initiatives will have the added benefit of retaining phosphorus as well.
- Septic systems, both domestic and industrial, may be contributing phosphorus to the watershed through shallow subsurface flow paths. Hence, an educational campaign is recommended to inform citizens of the need to maintain septic systems on a regular basis.
- The Duck Lake marsh may be close to reaching its phosphorus retention capacity based on the high concentration of sediment TP compared to both the overall watershed and other local west Michigan waterbodies. Further study to determine if the marsh is a source or sink of P may be useful; alternatively, removing the sediment P may provide a more long-term solution, although until it is determined how much P leaves the marsh sediment, the cost-benefit ratio of this action cannot be estimated.
- There is no clear evidence that the sediment in the vicinity of the bridge crossing at Nestrom Road is the sole source of sediment being deposited in and around the mouth of Duck Creek. We recommend no action in this region at this time.

Acknowledgements

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References

Alabaster, J.S. 1972. Suspended Solids and Fisheries. Proceedings of the Royal Society of London, Series B 180:395-406.

APHA (American Public Health Association). 2005. Standard Methods for the Examination of Water and Waste Water, 21st ed., American Public Health Association. Washington, DC.

Asselman, N. E. M. (2000). Fitting and interpretation of sediment rating curves. Journal of Hydrology, 234, 228-248.

Bigelow, P. E. (2003). Scour, fill, and salmon spawning in a northern California coastal stream. Master's Thesis, Humboldt State University, Arcata, CA

Brennan, A.K., Hoard, C.J., Duris, J.W., Ogdahl, M.E., and Steinman, A.D. 2015. Water quality and hydrology of Silver Lake, Oceana County, Michigan, with emphasis on lake response to nutrient loading, 2012–14. U.S. Geological Survey Scientific Investigations Report 2015–5158, 75 p. http://dx.doi.org/10.3133/sir20155158.

Carpenter, S. R.; Caraco, N. F.; Correll, D. L.; Howarth, R. W.; Sharpley, A. N.; Smith, V. H. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 1998, 8 (3), 559−568.

Chu, X. & Steinman, A. D. 2009. Combined event and continuous hydrologic modeling with HEC-HMS. ASCE Journal of Irrigation and Drainage Engineering, 135, 119-124.

Fisher, M.M., M. Brenner, and K.R. Reddy. 1992. A simple, inexpensive piston corer for collecting undisturbed sediment/water interface profiles. J. Paleolimnol. 7: 157–161.

Francy, D.S., A.M Gifford, and R.A. Darner. 2003. Escherichia coli at Ohio bathing beaches--Distribution, sources, wastewater indicators, and predictive modeling. USGS Water-Resources Investigations Report No. 02-4285.

Gray, J.R., G. D. Glysson, L.M. Turcios, and G.E. Schwarz. Comparability of suspended-sediment concentration and total suspended solids data. U.S. Geological Survey, Water-Resources Investigations Report 00-4191, Reston, VA. 2000.

Halstead, J. A., S. Kliman, C.W. Berheide, A. Chaucer, & A. Cock-Esteb. 2014. Urban stream syndrome in a small, lightly developed watershed: a statistical analysis of water chemistry parameters, land use patterns, and natural sources. Environmental monitoring and assessment, 186(6), 3391-3414.Kovalenko, K.E., S.M. Thomaz, and D.M Warfe. 2012. Habitat complexity: approaches and future directions. Hydrobiologia 685: 1-17.

MCD (Muskegon Conservation District) and Annis Water Resources Institute. 2012. Duck Creek Watershed Management Plan.

Michigan Department of Environmental Quality Water Bureau. 2005. Total Maximum Daily Load for Biota for the Bass River, Ottawa County. http://www.michigan.gov/documents/deq/wrd-swas-tmdl-bass-biota_450909_7.pdf.

Muskegon County Board of Commissioners. 2006. Amendment to ordinance no. 2006-329 to ban fertilizer containing phosphorus in Muskegon County. Publish date: November 8, 2006. http://www.co.muskegon.mi.us/boardofcommissioners/ordinances/phosphorus_ordinance.pdf

Olsson, T.I. and P.G. Persson. 1986. Effects of gravel size and peat material concentrations on embryo survival and alevin emergence of brown trout, Salmo trutta L. Hydrobiologia 135: 9–14.

Rantz, S. E., and others. 1982. Measurement and computation of streamflow: U.S. Geological Survey water-supply paper 2175, 2 v., 631 p.

Steinman, A.D., X. Chu, and M. Ogdahl. 2009. Spatial and temporal variability of internal and external phosphorus loads in an urbanizing watershed. Aquatic Ecology 43: 1-18.

Steinman, A.D., R. Rediske, and K.R. Reddy. 2004. The reduction of internal phosphorus loading using alum in Spring Lake, Michigan. Journal of Environmental Quality 33: 2040-2048.

Steinman, A.D., M. Ogdahl, R. Rediske, C.R. Ruetz III, B.A. Biddanda, and L. Nemeth. 2008. Current status and trends in Muskegon Lake, Michigan. J. Great Lakes Res. 34: 169-188.

Steinman, A.D. and M. Ogdahl. 2008. Ecological effects after an alum treatment in Spring Lake, Michigan. Journal of Environmental Quality 37:22-29.

Steinman, A.D., and M.E. Ogdahl. 2011. Does converting agricultural fields to wetlands retain or release phosphorus? J. No. Am. Benthol. Soc. 30: 820-830.

Steinman, A.D., M.E. Ogdahl, and C.R. Ruetz III. 2011. An environmental assessment of a small shallow lake (Little Black Lake, MI) threatened by urbanization. Environmental Monitoring and Assessment 173: 193-209.

Steinman, A.D. and M.E. Ogdahl. 2013. Muskegon lake AOC habitat restoration design: Bear Lake hydrologic reconnection/wetland restoration. Final Project Report. National Oceanic and Atmospheric Administration. http://www.gvsu.edu/cms4/asset/DFC9A03B-95B4-19D5-F96AB46C60F3F345/bear_muck_final_report_final.pdf

Steinman, A.D. and M E. Ogdahl. 2015. TMDL reevaluation: reconciling phosphorus load reductions in a eutrophic lake. Lake and Reservoir Management 31: 115-126.

Steinman, A.D., M.C. Hassett, M. Oudsema, and S.K. Hamilton. 2017. Lower Muskegon River Reconnection Project Pre-Restoration Monitoring Report. https://www.gvsu.edu/cms4/asset/DFC9A03B-95B4-19D5-F96AB46C60F3F345/bosma_pre-restoration_report_may2017.pdf

Towns, G.L. Duck Lake. Michigan Department of Natural Resources. Status of the fishery Resource Report 92-11, 1992.

U.S. Environmental Protection Agency (USEPA). 1983. Method for the chemical analysis of water and wastes, EPA 600/4-79-020. Environmental Monitoring and Support Laboratory, Cincinnati, OH.

U.S. Environmental Protection Agency (USEPA). 1993. Methods for Chemical Analysis of Inorganic Substances in Environmental Samples. EPA- 600/4-79R-93-020/100.

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan II, R. P. 2005. The urban stream syndrome: current knowledge and the search for a cure. Journal of the North American Benthological Society, 24(3), 706-723.

Wood, P.J. and P.D. Armitage. 1997. Biological effects of fine sediment in the lotic environment. Environmental Management 21: 203-217.

Appendix

Table A1. Tributary sediment core sample physicochemical features and sediment particle size fraction, organized by depth. AFDM = ash-free dry mass, OM = organic matter, and TP = total phosphorus. The first row of depth data from every core is highlighted to maintain readability.

Core ID	Depth (cm)	Dry Mass (g)	AFDM (g)	OM (%)	Sediment TP (mg/kg, dry wt)
DC-1A	0-8	369.88	367.93	0.53%	57
	8-16	208.70	206.57	1.02%	54
	16-24	223.60	221.29	1.03%	81
	24-32	224.29	220.38	1.74%	124
	32-40	375.99	373.36	0.70%	33
DC-1B	0-8	120.77	110.25	8.71%	75
	8-16	253.59	242.74	4.28%	358
	16-24	222.79	210.15	5.67%	125
	24-32	168.26	165.47	1.66%	41
	32-40	337.84	333.32	1.34%	60
DC-2	0-8	368.19	367.05	0.31%	29
	8-16	366.90	360.40	1.77%	55
	16-24	169.50	163.94	3.28%	111
DC-3	0-8	190.60	185.51	2.67%	113
	8-16	192.21	190.81	0.73%	101
	16-24	202.23	201.31	0.45%	68

Table A2. Marsh sediment core sample physicochemical features and sediment particle size fraction, organized by depth. AFDM = ash-free dry mass, OM = organic matter, and TP = total phosphorus. The first row of depth data from every core is highlighted to maintain readability.

Core ID	Depth (cm)	Dry Mass (g)	AFDM (g)	OM (%)	Sediment TP (mg/kg, dry wt)
M-1	0-8	224.29	220.38	1.74%	6092
	8-16	28.60	7.55	73.60%	1186
	16-24	32.66	14.59	55.33%	276
	24-32	30.07	15.80	47.46%	639
M-2	0-8	31.05	14.38	53.69%	1668
	8-16	40.00	19.56	51.10%	1184
M-3	0-8	36.65	17.25	52.93%	1564
	8-16	44.66	23.37	47.67%	1319
	16-24	37.41	17.32	53.70%	1018
	24-32	39.76	23.68	40.44%	1114
M-4	0-8	19.50	4.31	77.90%	1182
	8-16	21.78	5.70	73.83%	1013
	16-24	28.64	13.10	54.26%	789
	24-32	49.93	30.77	38.37%	729
M-5	0-8	47.48	32.78	30.96%	741
	8-16	75.73	59.11	21.95%	594
	16-24	208.24	195.29	6.22%	160
	24-32	162.86	158.20	2.86%	88

Table A3. Fan sediment core sample physicochemical features and sediment particle size fraction, organized by depth. AFDM = ash-free dry mass, OM = organic matter, and TP = total phosphorus. The first row of depth data from every core is highlighted to maintain readability.

Core ID	Depth (cm)	Dry Mass (g)	AFDM (g)	OM (%)	Sediment TP (mg/kg, dry wt)
F-1	0-8	24.37	13.30	45.42%	1108
	8-16	35.04	22.27	36.44%	862
	16-24	80.96	66.20	18.23%	520
	24-32	75.55	60.96	19.31%	393
F-2	0-8	40.56	26.64	34.32%	1040
	8-16	62.51	46.88	25.00%	811
	16-24	87.69	71.79	18.13%	495
	24-32	125.70	119.21	5.16%	106
F-3	0-8	258.24	248.32	3.84%	110
	8-16	310.22	301.02	2.97%	57
	16-24	212.86	197.98	6.99%	133
	24-32	192.33	154.33	19.76%	166
F-4	0-8	371.56	365.00	1.77%	73
	8-16	350.83	350.24	0.17%	25
	16-24	206.74	204.98	0.85%	29
	24-32	159.22	142.32	10.61%	111
	32-41	133.76	118.39	11.49%	251

Table A4. Tributary sediment core particle size fractions, organized by depth. The first row of depth data from every core is highlighted to maintain readability.

		% Size Fraction						
Core ID	**Depth (cm)**	**>2 mm (gravel/ cobble)**	**1-2 mm (very coarse sand)**	**0.5-1 mm (coarse sand)**	**250-500 µm (fine sand)**	**125-500 µm (very fine sand)**	**62.5-125 µm (silt/ clay)**	**<62.5 µm**
DC-1A	0-8	4%	1%	16%	76%	3%	0%	0%
	8-16	5%	1%	16%	73%	4%	0%	0%
	16-24	8%	3%	19%	64%	5%	0%	0%
	24-32	6%	4%	19%	58%	12%	1%	0%
	32-40	3%	4%	36%	49%	8%	0%	0%
DC-1B	0-8	0%	0%	0%	29%	61%	0%	10%
	8-16	0%	0%	0%	23%	65%	0%	10%
	16-24	0%	0%	1%	24%	64%	0%	11%
	24-32	0%	0%	1%	50%	45%	2%	2%
	32-40	0%	0%	1%	65%	31%	0%	3%
DC-2	0-8	3%	0%	8%	72%	16%	0%	1%
	8-16	24%	1%	13%	50%	9%	0%	3%
	16-24	28%	1%	8%	51%	9%	0%	3%
DC-3	0-8	0%	0%	5%	65%	27%	1%	2%
	8-16	0%	0%	5%	69%	24%	1%	2%
	16-24	0%	0%	7%	76%	16%	1%	1%

Table A5. Marsh sediment core particle size fractions, organized by depth. The first row of depth data from every core is highlighted to maintain readability.

		% Size Fraction						
Core ID	**Depth (cm)**	**>2 mm**	**1-2 mm**	**0.5-1 mm**	**250-500 µm**	**125-500 µm**	**62.5-125 µm**	**<62.5 µm**
M-1	0-8	0%	1%	2%	13%	16%	4%	64%
	8-16	0%	0%	1%	9%	25%	0%	65%
	16-24	0%	5%	7%	15%	21%	2%	49%
	24-32	0%	1%	7%	29%	24%	1%	38%
M-2	0-8	0%	1%	3%	19%	13%	1%	64%
	8-16	2%	0%	1%	2%	21%	1%	74%
M-3	0-8	0%	2%	7%	20%	17%	1%	52%
	8-16	0%	4%	4%	17%	16%	6%	53%
	16-24	15%	9%	9%	13%	14%	12%	29%
	24-32	0%	1%	3%	22%	21%	1%	52%
M-4	0-8	0%	0%	3%	10%	12%	1%	74%
	8-16	0%	0%	3%	12%	26%	2%	57%
	16-24	0%	5%	6%	16%	17%	9%	48%
	24-32	0%	0%	8%	42%	19%	0%	31%
M-5	0-8	0%	1%	18%	68%	5%	2%	6%
	8-16	0%	1%	19%	69%	6%	0%	5%
	16-24	0%	1%	21%	72%	4%	0%	2%
	24-32	0%	0%	22%	72%	4%	1%	1%

Table A6. Fan sediment core particle size fractions, organized by depth. The first row of depth data from every core is highlighted to maintain readability.

		% Size Fraction						
Core ID	**Depth (cm)**	**>2 mm**	**1-2 mm**	**0.5-1 mm**	**250-500 µm**	**125-500 µm**	**62.5-125 µm**	**<62.5 µm**
F1	0-8	0%	2%	3%	16%	20%	2%	57%
	8-16	0%	2%	3%	9%	20%	1%	65%
	16-24	2%	1%	3%	14%	30%	31%	18%
	24-32	0%	1%	2%	10%	24%	6%	58%
F2	0-8	0%	1%	1%	3%	10%	4%	82%
	8-16	0%	1%	2%	8%	19%	4%	67%
	16-24	0%	0%	1%	13%	35%	1%	50%
	24-32	0%	0%	4%	32%	42%	14%	7%
F3	0-8	0%	0%	7%	62%	27%	0%	4%
	8-16	0%	1%	15%	70%	13%	0%	1%
	16-24	0%	0%	3%	48%	39%	0%	9%
	24-32	0%	0%	2%	20%	54%	1%	23%
F4	0-8	0%	0%	6%	65%	25%	0%	4%
	8-16	0%	0%	10%	73%	15%	0%	1%
	16-24	0%	0%	10%	77%	12%	0%	0%
	24-32	0%	1%	3%	69%	22%	0%	4%
	32-41	0%	0%	1%	31%	52%	1%	16%