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TECHNICAL MEMORANDUM

To:	Ed Glaza, Parsons	**Date:**	January 13, 2011
From:	David Glaser, Anchor QEA Wendy Hovel, Anchor QEA	**Project:**	090139-01.17 Task 8
Cc:	Caryn Kiehl-Simpson, Parsons Kevin Russell, Anchor QEA Files		
Re:	Bioturbation depth in the Onondaga Lake cap		

INTRODUCTION

The Onondaga Lake cap performance criteria were developed in part to be protective of benthic invertebrates that will repopulate the habitat layer of the cap. The habitat layer will be at least 12 inches thick. The top 6 inches of this layer is considered to comprise the benthic activity zone or bioturbation layer, which is characterized by generally higher organic carbon content and extensive sediment mixing due to bioturbation.

Literature suggests that exposure of the benthic community may be more heavily weighted toward the surface of the active zone, (i.e., shallower than 6 inches). Because contaminant concentrations within the active zone are anticipated to decrease towards the surface, this means that the estimate of exposure of the biota that is used in the cap modeling is probably conservative. In addition, it is assumed for cap modeling purposes that the organic carbon content will reach 5% to a depth of 6 in. over time through bioturbation, which, based on the evaluation provided herein, is also likely a conservative estimate of the depth to which elevated organic carbon will develop within the cap. The objective of this memo is to evaluate the degree of this conservatism based on a review of published information concerning the depth of benthic activity in aquatic sediments.

BACKGROUND

Most benthic activity is expected to occur near the surface of the sediment bed (Clarke *et al.* 2001). This is expected based on our understanding of the benthic environment. The freshest resource is on the surface: organic matter, the food of the benthos, is deposited on the surface of the sediment bed in the form of phytoplankton cells, macrophytes, and nonliving particulate organic matter from the watershed. In addition, dissolved oxygen is utilized by the invertebrate animals in consuming and degrading the organic matter. Below a thin surface layer, oxygen is no longer available in the sediments. While benthic organisms have several mechanisms by which they can make use of food buried within the deeper anaerobic portions of the sediment bed, the most hospitable environment is at the surface. For example, Kirchner (1975) found that benthic organisms were restricted to depths shallower than about 1 cm below the bottom of the oxidized layer of the sediment in Char Lake, North West Territories, Canada. Boudreau (1994) provided a mechanistic basis for the limited depth of bioturbation: increased bioturbation is correlated with increased organic matter decay; as depth increases within the bed, less labile organic matter is available, and at some point, the energetic cost of burrowing exceeds the benefits of reaching the remaining food. In summary, most activity is expected near the surface, where the freshest organic matter lies, oxygen is available, and the energetic costs of consuming the food are lower.

Infaunal organisms (those that live within the sediment bed) mix the sediments in the course of building tubes, burrowing, feeding and breathing. The depth to which organisms rework sediments (the depth of bioturbation) is an indicator of the depth at which they may be exposed to contaminants within the cap, as well as the depth to which higher levels of organic carbon will develop over time. Bioturbation depth varies (Clarke *et al.* 2001). It is influenced by habitat type (e.g., stream, estuary, lake, ocean, etc.), grain size (Wolfram 1996), oxygen concentration (Newrkla and Wijegoonawardana 1987; McCall 1982), season (Wolfram 1996), species-specific differences (Charbonneau and Hare 1998), feeding behavior (McCall 1982), and organism life stage (Hilsenhoff 1966; Kornijow 1997). Thus, in the following sections, the available literature is evaluated in light of the habitats anticipated in the Onondaga Lake cap, as well as the composition of the benthic community of Onondaga Lake.

ONONDAGA LAKE CONDITIONS

As described above, the particular environmental conditions of the cap will influence the bioturbation depth. The environmental conditions within Onondaga Lake are described below. Their relevance to bioturbation depth is discussed in the next section.

The Onondaga Lake cap will be placed in water depths ranging up to approximately 9 m. The lake is stratified in summer, and anaerobic conditions occur at least part of the summer in water depths deeper than about 9 m. Most of the cap will be in waters that will be oxygenated all or nearly all of the year. Thus, this review focuses primarily on information for the oxygenated littoral zone of temperate lakes.

The habitat layer of the cap will generally consist of sand and/or gravel. Over time, the upper 6 in. of the habitat layer are assumed to reach an organic carbon content averaging about 5% via natural processes, which is consistent with current conditions.

The current benthic community of the lake is typical of temperate eutrophic lakes, consisting predominantly of oligochaetes, chironomids and amphipods (OCDWEP 2006; Honeywell 2008). It is anticipated that a similar community will reestablish itself after cap placement.

OVERALL BIOTURBATION DEPTH

U.S. Environmental Protection Agency (EPA; 2002) surveyed aquatic biologists from several research facilities around the Great Lakes to evaluate bioturbation depth in caps. The survey described two hypothetical cap designs under shallow water conditions typical of the Great Lakes; one with a cap surface of medium to fine sand, and the other with a sand cap armored with gravel-sized stone. EPA concluded:

> *The surveyed researchers generally agreed that the most likely benthic organisms to colonize a sand cap in the Great Lakes would be Chironomids (midges) and Oligochaetes (worms). One researcher indicated that Spaerids (fingernail clams), Trichopteran larvae and nematodes might also colonize the sand cap. The armored cap would attract a greater diversity of macroinvertebrates than the sand cap, including those that attach to surfaces (including Zebra mussels) or inhabit the larger interstitial spaces. As the interstices of the gravel are filled with "new" sediments, the benthos would likely become dominated by Oligochaetes and Chironomids.*
>
> *While some organisms indigenous to the Great Lakes can burrow 10-40 cm in soft silt or clay sediments, most of the researchers surveyed felt that bioturbation in a sand cap would be limited to the top 5-10 cm. The presence of armor stone should inhibit colonization by deep-burrowing benthic organisms.*

The community described above is generally similar to the current community of Onondaga Lake, and therefore likely to be similar to the community that will colonize the Onondaga Lake cap. In addition, the Onondaga Lake cap will be sandy, similar to the sand cap described in the EPA study. Thus, EPA's conclusion that the depth of bioturbation is likely to be limited to the top 5 to 10 cm is appropriate for Onondaga Lake as well.

Boudreau (1994, 1998) summarized bioturbation data for a large number of marine studies and estimated a world-wide mean bioturbation depth of 9.8 cm. Teal *et al.* (2008) updated this study and calculated an overall average marine bioturbation depth 5.8 cm. Freshwater mixing depths are likely similar to or less than marine depths (Clarke *et al.* 2001, Table 1; Adriens *et al.* 2009), suggesting that these marine averages are generally appropriate and possibly conservative estimates for freshwater environments.

EPA (2006) reviewed literature pertaining to bioturbation depths for the Housatonic River PCB Superfund site. They concluded that mixed layer depths likely range from 4 cm in the relatively coarse-grained areas to 10 cm in the fine-grained backwater areas with organic carbon contents of approximately 10% to 15%. In comparison, Onondaga Lake surface sediments currently exhibit organic carbon contents that average 5%, which would be consistent with a mixed depth that is on the lower end of the range used in the Housatonic River.

Reible (2008) presented a distribution of freshwater bioturbation layer thicknesses (based on work by Thoms *et al.* 1995). The median was 4.8 cm, and the 90th percentile was approximately 10 cm.

The sandy nature of the cap suggests that all or most of the Onondaga Lake cap is likely to be on the low end of estimates presented above: EPA (2002) concluded that deeper burrowing occurs in silt and clay; Wolfram (1996) found that In Neusiedler See, Austria, penetration of chironomid species was restricted to areas of soft mud; and finally, the tubificid oligochaetes, which typically feed in the top 2 to 8 cm (McCall 1982), prefer fine-grained mud to sand (McCall and Tevesz 1982.

In summary, the depth over which benthic activity occurs is generally considered to range from about 5 to 10 cm. The bioturbation depth in the Onondaga Lake cap is likely to lie towards the low end of this range.

BIOTURBATION DEPTH – RELATIVE ACTIVITY WITHIN THE ACTIVE LAYER

Benthic activity is expected to be greater closer to the surface. Studies are available that provide information that aids in refining the the estimated depth to which most activity will occur within the cap. Studies in which bioturbation was assessed in habitats similar to the Onondaga Lake cap (i.e., lakes, temperate climate, oxygenated water column) are summarized below.

The measured depth of bioturbation of relevant species in the littoral zone of temperate lakes is shown in Table 1 below. The greatest activity of invertebrates generally occurs to a depth of 3 to 5 cm. For example:

- More than 90% of benthic invertebrates, including a large proportion of tubificid oligochaetes, were distributed in the top 5 cm of sediment from three habitats within Eau Galle Lake, Wisconsin (Beckett *et al.* 1992; Figure 1).
- In a laboratory study of burrowing behavior, the average burrowing depth of benthic infauna in Lake St. Joseph, Québec over a 3-day period in autumn ranged from 1.3 cm

to 7 cm; however, excluding *Hexagenia limbata*, a species not found in Onondaga Lake by OCDWEP (2005), the mean burrowing depth of relevant species was 1.3 to 5 cm (Charbonneau and Hare 1998; Figure 2).

- Milbrink (1968) sampled benthic invertebrates from Lake Mälaren, Sweden and found that more than 86% of organisms common to Onondaga Lake (i.e., chironomid larvae and oligochaetes) and greater than 72% of all benthic species inhabited the top 4 cm of sediment (Figure 3).
- Finally, in a study conducted in a stream, Ford (1962) found that 79% of chironomid larvae were found in the first 2.5 cm and 98% in the top 5 cm of mud.

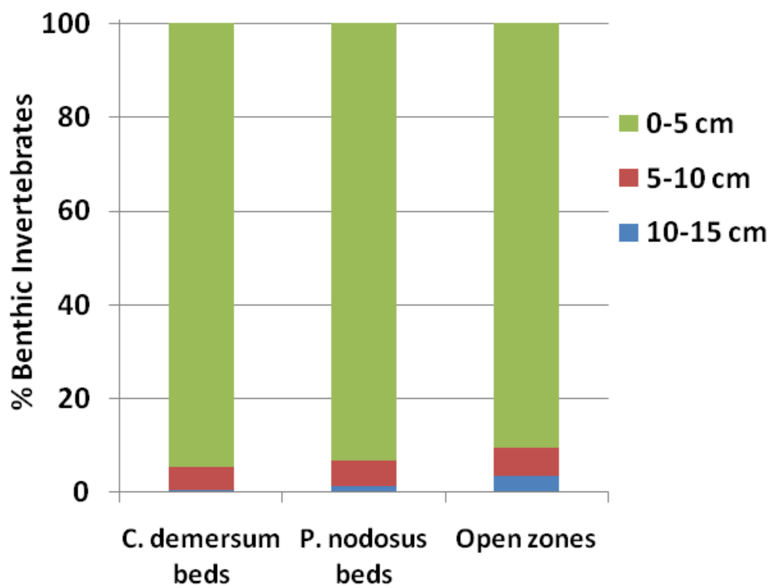

Figure 1
Percent of Benthic Invertebrates Found in Three Depth Fractions within Three Habitat Types (Ceratophyllum demersum beds, Potomageton nodosus beds, and open zones) in Eau Galle Lake, Wisconsin (created from: Beckett *et al.* 1992)

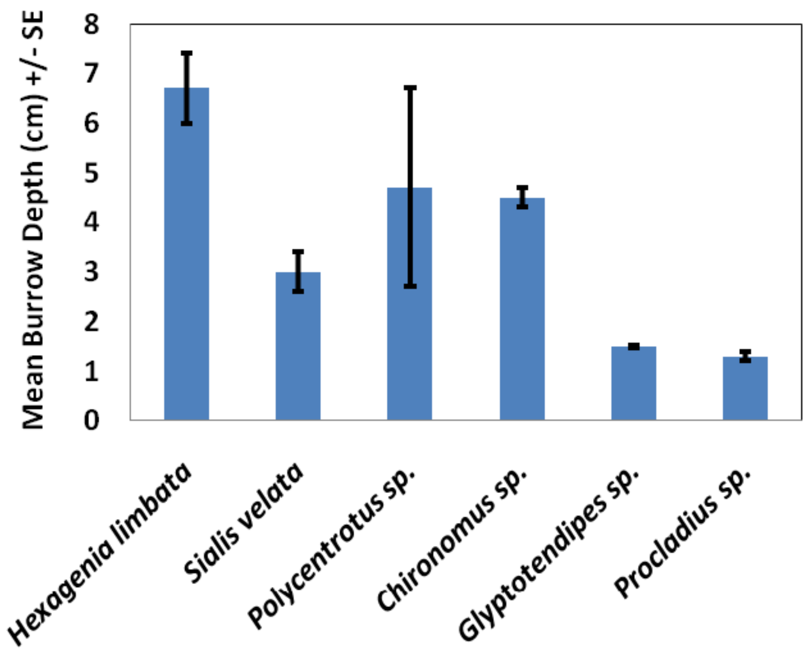

Figure 2

Mean Burrowing Depth of Benthic Infauna in Lake St. Joseph, Québec over a 3-day period in Autumn (created from: Charbonneau and Hare 1998)

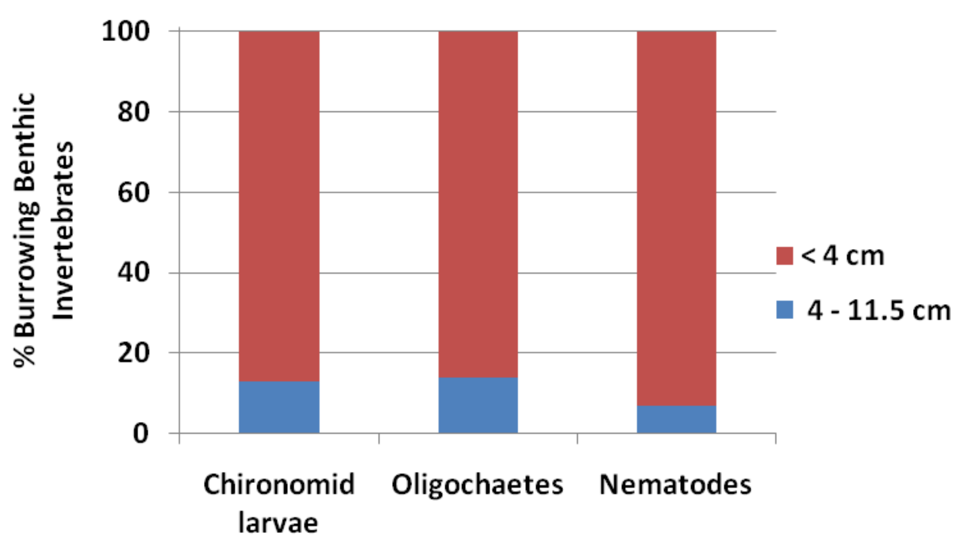

Figure 3

Percent of burrowing benthic invertebrates from Lake Mälaren, Sweden found above and below 4 cm in the sediment (created from Milbrink 1968)

Oligochaetes were found to be quite abundant outside the Metro outfall (Ecologic 2006). While oligochaetes such as *Tubifex tubifex* have been shown to burrow to 16 cm or deeper, most of their feeding and sediment reworking occurs within the top 3 to 6 cm (Rogaar 1980). Another oligochaete commonly found in Onondaga Lake, *Limnodrilus hoffmeisteri* (EcoLogic 2006), has been shown to prefer burrowing within the top 2 cm (67%), with 87% of the organisms found within the top 6 cm under normal oxygen concentrations (Fisher and Beeton 1975). In laboratory microcosms, White *et al.* (1987) found that the particle-feeding oligochaete *Stylodrilus heringianus* fed to a depth of about 5 cm at the highest organism densities (>100,000 per m^2). Density was correlated with the depth of maximum feeding. For comparison, the density of oligochaetes measured by OCDWEP (2005) in the lake sediments near the Metro outfall was less than this, approximately 68,000 per m^2.

Table 1
Bioturbation Depth of Species in the Littoral Zone of Temperate Lakes

Reference	Location	Finding
Beckett *et al.* (1992)	• Eau Galle Lake, WI • Littoral zone (3 habitats)	• Evaluated benthic invertebrates (i.e., tubificid oligochaetes, chironomids, nematodes, gastropods, etc.) in 5 cm horizons within three habitat types. • 90 % to 94.5% of total invertebrates were found in top 5 cm.
Charbonneau and Hare (1998)	• Lake St. Joseph, Québec	• Evaluated mean depth of burrowing aquatic insects from several orders (i.e., Diptera, Ephemeroptera, Megaloptera, Trichoptera) in sediment in the laboratory. • Mean burrowing depth for *Chironomus* spp. In muddy sediments was 5 cm and burrowing depth ranged from 1.3 to 5 cm for species relevant to Onondaga Lake (i.e., for *Procladius* sp. and *Polycentropus* sp., respectively).
Hilsenhoff (1966)	• Lake Winnebago, WI	• Evaluated maximum depth of feeding larvae of *Chironomus plumosus* • "The tubes of the second- and third-instar larvae are at or just beneath the mud-water interface. The fourth-instar larvae, especially the older, construct very deep, U-shaped tubes, some of which extend 8 cm below the surface of the mud."

Reference	Location	Finding
Kornijow (1997)	• Lake Little Mere, England	• The mean depth of *Chironomus plumosus* larvae of varying life-stages was evaluated in field enclosures with varying plant densities. • The greatest proportion of larvae assess were in the mid-size range (5 – 15 mm). • Mid-sized (5 – 15 mm) larvae were most abundant at depths of 0-5 cm while larger larvae (>15 mm) were most abundant at 5-10 cm depths. • The lake bottom consisted of peat covered by loose mud of about 20–25 cm thickness. (The presence of mud suggests that burrowing may be deeper in this environment than in Onondaga Lake.)
Milbrink (1968)	• Lake Mälaren, Sweden sampled in central basin (32 m)	• Evaluated the abundance of benthic invertebrates in the water column and sediment. • Mesotrophic lake, according to Milbrink (1999); oxygen concentration in overlying water unknown • More than 86%, 87%, and 93% of oligochaetes, chironomids and nematodes, respectively, were found within the top 4 cm.
Wolfram (1996)	• Neusiedler See, Austria	• Evaluated the spatial (vertical and horizontal) distribution of chironomids. • "Most species preferred the uppermost sediment layer and a penetration into the sediment was restricted to the soft mud areas near the reed belt." • The littoral zone of the lake was dominated by chironomids • The fourth instar larvae of the chironomid *Tanypus punctipennis* were found in the upper 3 cm in summer; however, in February of 1991 they demonstrated a peak abundance between 3 and 5 cm below surface with a maximal depth of 12 cm.

CONCLUSIONS

The depth over which benthic infaunal communities mix sediments within the littoral zone of lakes is generally considered to range from 5 to 10 cm. Bioturbation within the Onondaga Lake cap is likely to be on the lower end of this range, due to the sandy nature of the cap.

Within this bioturbation zone, the majority of benthic activity is anticipated to occur even closer to the surface. In part, this is based on habitat quality: food is deposited on the surface from above. Furthermore, oxygen diffuses into the sediment bed from above, and the density of organisms is generally greatest within the oxidized sediment layer. Published studies indicate that the activity of benthic organisms inhabiting the littoral zone of temperate lakes has been found to be greatest in the top 3 to 5 cm. Based on these results, 6 inches is a conservative estimate of the depth to which benthic organisms will be exposed to contaminants within the cap and the depth to which elevated levels of organic carbon will develop over time due to bioturbation.

Taking all of this information into account, a reasonable estimate of the depth within the Onondaga Lake cap to which most of the benthic activity is expected to occur is likely to be less than 5 to 10 cm, probably in the range of 3 to 5 cm.

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