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Pollutant Dynamics of Pond Muck

Historically, most research on stormwater ponds has focused on the movement of pollutants into and out of the pond. This is quite understandable, as knowledge about inputs and outputs of pollutants helps to estimate pollutant removal performance. An impressive amount of input/output monitoring data has been collected: nearly 65 pond monitoring studies have been conducted in the U.S. and Canada.

Most of the monitoring studies have shown that stormwater ponds and wetlands are quite effective in trapping pollutants carried in urban stormwater. Much less is known, however, about the fate of stormwater pollutants once they are trapped in a pond. It is generally assumed that most of the pollutants eventually settle out to the pond bottom and form a muck layer. (The term **muck layer** is used here to distinguish newly-deposited bottom sediments from the older parent soils that formed the original pond bottom.)

The muck layer deepens as the pond ages. Pollutants may remain trapped within the muck layer until the entire layer is excavated during a pond clean-out. In most cases the muck is eventually dewatered, excavated, and applied back to the land surface. Research on bottom sediments in other shallow water systems, however, suggests that the muck layer may not be so inert. Figure 1 illustrates how a given pollutant can follow a number of diverse and complex pathways into and out of the muck layer.

Some runoff pollutants are transformed within the muck layer, while others are decomposed through chemical and microbial processes involved in sediment diagenesis. Indeed, diagenesis is often a key pathway for decomposition of organic matter and some nutrients. Alternatively, pollutants can migrate further below the muck layer and into the original soil profile. In some extreme cases, pollutants can travel into groundwater.

Alternatively, pollutants might enter the food chain while in the muck layer, either through uptake by wetland plants or by bottom feeding fish. Under the right conditions, some pollutants could also be released from the muck into the water column (where they could exit the pond during the next storm).

In this article, we examine the internal dynamics within the muck layer of stormwater ponds, based on an extensive review of research studies on the physical, chemical, and biological nature of the muck layer of over 50 stormwater ponds and wetlands. While it must be admitted that the study of muck is somewhat lacking in glamour, it can have many important implications for the design and operation of stormwater ponds and wetlands. Typical questions include:

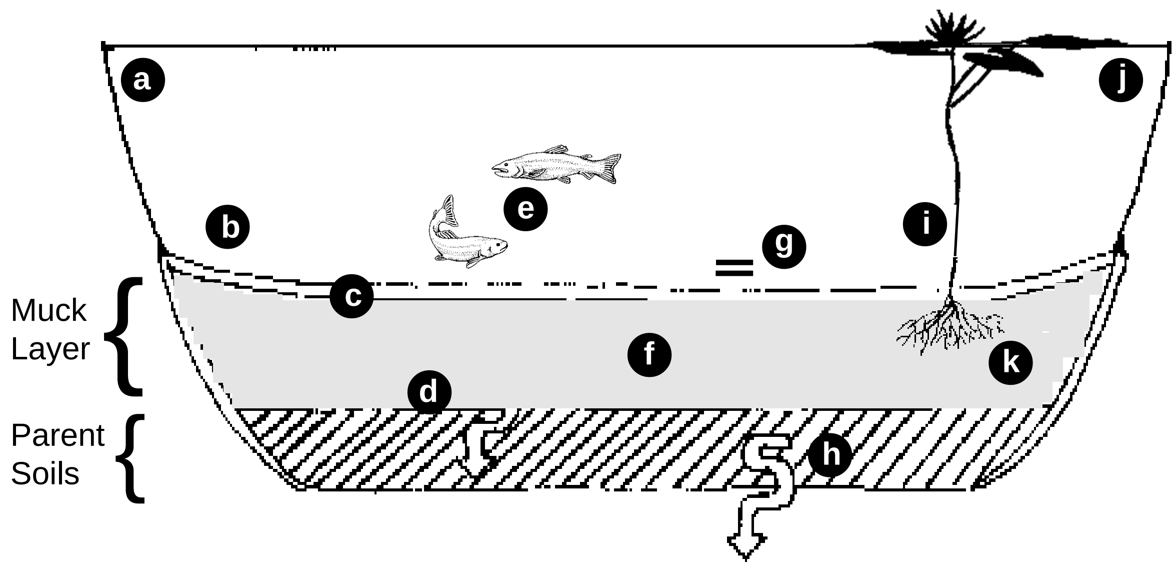
- What is the average deposition rate of muck in ponds?
- After how many years of deposition will muck need to be removed?
- Can the deposition rate be used to calculate the size of the sediment forebay for a pond?
- How tightly are pollutants held in the muck layer?
- Is there any risk that pollutants could be released back into the water column? Or migrate into groundwater supplies? Or enter the aquatic food chain where toxicity might be magnified?
- If pollutants do remain in the muck layer, should muck be considered hazardous or toxic?
- Can muck be safely applied back on the land surface after it is cleaned out from the pond? Or are more exotic and expensive methods needed to safely dispose of muck?
- Finally, the depth of accumulated muck generally represents the long term work of a pond in trapping pollutants. Can the characteristics of pond muck allow us to infer anything about the pollutant removal processes operating in ponds or the land uses that drain to it? Can muck pollutant concentrations "fingerprint" upstream land uses?

To answer these questions, we reviewed bottom sediment chemistry data from 37 wet ponds, 11 detention basins, and two wetland systems, as reported by 14 different researchers. Although the studies covered a broad geographic range, almost 50% of the sites were located in Florida or the Mid-Atlantic states. Analysis was restricted to mean dry weight concentrations of the surface sediments that comprise the muck layer (usually the top five centimeters). The stormwater ponds ranged in age from three to 25 years.

The Nature of Pond Muck

The muck layer can be easily distinguished from the parent soils that comprise the pond's original bottom.

Figure 1: A Field Guide to the Muck Layer



Pond muck represents a long term repository for the pollutants trapped within a stormwater pond. A pollutant, however, can take many different pathways through the mucklayer, as shown in the diagram above.

a **Pollutant inflow.** Sediment, nutrients, trace metals, and hydrocarbons enter the pond during each storm. The total pollutant load delivered to the pond depends to some degree on land use. Some evidence exists that metal and hydrocarbon loads are significantly greater from watersheds draining roads or industrial areas.

b **Sediment Deposition.** A steady rain of sediment particles, attached pollutants, and algal detritus forms the muck layer over time. Field measurements indicate that the muck layer grows from 0.1 to 1 inch per year, with greater deposition noted near the inlet.

c **Muck Microlayer.** The uppermost layer of muck represents the recently deposited sediments and pollutants. Consequently, it is very high in organic matter and constantly worked over by microbes, worms and other organisms.

d **Downward Migration.** Most pollutants are tightly bound to sediment particles and remain fixed within the muck layer. Other pollutants can migrate downward into the subsoil via pore spaces between sediment particles.

e **Fish Bio-magnification.** Bottom feeding fish that dwell in larger ponds, such as carp and catfish, ingest detritus from the muck layer. Not much is known about pollutants accumulating in their tissues over time.

f **Sediment Diagenesis.** Organic matter and nutrients are gradually reduced and decomposed over time in the muck layer through a process known as sediment diagenesis. Diagenesis is a key pollutant removal pathway that combines physical, chemical, and biological processes within the sediment to slowly break down organic matter, in the presence or absence of oxygen.

g **Phosphorus Release.** In the summer, low oxygen levels near the bottom of pond can induce a “burp” of soluble phosphorus, ammonia, or methane back into the water column. The potential for this phenomena is greatest in deeper ponds in warmer latitudes.

h **Groundwater Migration.** Pollutants not tightly bound to the pond muck can migrate downward through sediment pore spaces and ultimately reach the water table. Soluble pollutants, such as chloride and nitrate, are the most mobile and have been reported to migrate outward from ponds into groundwater at modest levels. Most monitoring studies, however, reveal little if any risk of groundwater contamination from stormwater pond muck.

i **Wetland Plant Uptake.** The roots of wetland plants take up both nutrients and metals from the muck layer and transport them upward to tubers, stems, and leaves. At the end of the growing season, this above-ground plant matter often dies off. Some of the nutrients are released back into the pond, while others settle back to the muck layer as detritus.

j **Pollutant Export from the Pond.** Pollutants remaining in the pond’s water column will often flush out during the next storm event. Consequently, any pollutants that were released from the muck layer back into the water column may exit as well, thereby reducing the long term pollutant removal performance of the pond.

k **Sediment Clean-outs.** The ultimate removal of stormwater pollutants is accomplished when the muck layer is excavated from the pond and applied back on the land. This operation may need to be conducted every 25 to 50 years, depending on whether the pond has a forebay. Based on existing data and sediment quality criteria, pond muck does not usually constitute a toxicity hazard.

Distinguishing features include the following:

- **Very "soupy" texture** — 57% moisture; number of studies reporting (N) = 15
- **Distinctive grey to black color**
- **High organic matter content** — nearly 6% volatile suspended solids on average (N=16)
- **Low density** (about 1.3 gms/cm) (Dorman *et al.*, 1989)
- **Poorly-sorted sands and silts dominating the muck layer**

Deposition of Muck

Muck essentially represents the bulk of all sediments and pollutants that have been historically trapped within a pond (excepting those that are microbially broken down into gaseous forms or those pollutants that migrate below the pond). Therefore, the long term deposition rate of the muck layer is of great interest.

The annual deposition rate can be easily calculated if the age of the pond and the depth of the muck layer are known. The depth of the muck layer is relatively easy to estimate in the field, due to its unique physical characteristics. Annual muck deposition rates on the order of 0.1 to 1.0 inch per year have been reported for a series of ponds in Florida (Yousef *et al.*, 1991). These rates compare favorably with other pond sedimentation rates calculated at 0.5 inches/yr (Galli, 1993) and 0.8 inches/yr (Schueler, 1994) utilizing different techniques.

The deposition rate of muck is not always the same throughout a pond, however. The greatest rates tend to be observed near the inlets of wet ponds, and to some extent, the outlets of detention basins (Grizzard *et al.*, 1983). In addition, muck deposition rates increase sharply for ponds that are small in relation to the contributing watershed areas and for ponds that located directly in streams (Galli, 1993).

Nutrient Content of Pond Muck

As might be expected, the muck layer is highly enriched with nutrients (Table 1). Phosphorus concentration for the 23 studies reviewed averaged 583 mg/kg (range 110 to 1,936 mg/kg, N=23). Nearly all the nitrogen found in pond muck is organic in nature, with a mean concentration of 2,931 mg/kg (range 219 to 11,200, N=20). Nitrate is present in extremely small quantities, which may indicate that some denitrification is occurring in the sediments, or perhaps merely that less nitrate is initially trapped in muck.

In the entire pond data set, the nitrogen to phosphorus (N:P) ratio of the muck layer averages about five to one, whereas the average N:P ratio for incoming stormwater runoff is typically around seven to one. This lower N:P ratio is not unexpected. Ponds are generally more effective in trapping phosphorus than nitrogen and the decay rate for nitrogen in the muck layer is generally thought to be more rapid than for phosphorus (Avinmelich *et al.*, 1984).

Researchers have expressed concern that phosphorus trapped in the muck layer might be released back into the water column, particularly when oxygen levels are low in the summer. A number of investigators have observed hypoxic and even anoxic conditions near the muck layer in ponds as shallow as five feet deep (Galli, 1993; Yousef *et al.*, 1990).

An intriguing suggestion for possible sediment phosphorus release is evident in a handful of Florida ponds (Table 1). These ponds had unusually high N:P ratios of the muck layer, often in excess of 10 to one. One explanation for the apparent depletion of phosphorus in the muck layer would be the mobilization and release of phosphorus from recurring anoxia over many years.

Still, most of the more Northern ponds, as well as many Southern ones, appear to retain most of the phosphorus deposited in the muck layer. For example, phosphorus levels in the muck layer are 2.5 to 10 times higher than the soils underlying the pond bottom. Also, muck layer phosphorus levels do not normally show a decrease as ponds grow older.

Trace Metal Content of the Muck Layer

The muck layer of stormwater ponds is heavily enriched with trace metals. This phenomenon is consistent with reported performance data (Table 2). Trace metal levels are typically five to 30 times higher in the muck layer, compared to parent soils. Trace metal levels in the muck layer also follow a consistent pattern and distribution, (zinc > lead >> chromium = nickel = copper > cadmium).

This pattern is nearly identical to their reported concentrations monitored in urban stormwater runoff. It also suggests that rarely monitored (or detected) trace metals, such as chromium, copper, nickel, and possibly cadmium, are actually trapped by stormwater ponds. The muck layers of older ponds often contain more lead than zinc, whereas in younger ponds the converse is true. This may reflect the gradual introduction of lead-free fuels over the last decade, with the consequent reduction in lead loadings delivered to the younger ponds.

The trace metal content of the muck layer happens to be directly influenced by the type of land use that drains to it (Table 3). Muck layers in stormwater ponds that drain residential areas had the lightest metal enrichment. Commercial sites were subject to slightly greater enrichment, particularly for copper, lead, and zinc. Ponds that primarily served roads and highways were highly enriched with metals, presumably due to the influence of automotive loading sources (e.g., cadmium, copper, lead, nickel, and chromium).

Table 1: Characteristics of the Muck Layer in Wet Stormwater Ponds (mg/kg Dry Weight Unless Otherwise Noted)

Location	Land Use	% Moisture	% Volatile Suspended Solids	Total Kjeldahl Nitrogen	Total Phosphorus	Nitrogen to Phosphorus Ratio	Hydro-carbons
FL	Road	63	7.1	5180	510	10:1	
FL	Road	77	10.2	4140	301	14:1	
FL	Road	50	9.7	3110	1116	3:1	
FL	Road	60	6.8	1130	100	11:1	
FL	Road	52	6.5	2290	270	9:1	
FL	Road	62	4.5	1440	370	4:1	
FL	Road	65	4.8	2070	480	4:1	
FL	Road	60	4.3	2110	110	20:1	
FL	Road	76	10.4	11200	420	26:1	
FL	Residential	33	2.4	889	292 #	3:1	
FL	Road	64		2306 *	3863	0.6:1	
FL	Residential		6.4	624	619	1:1	
FL	Residential		1.1	256	389	0.7:1	
FL	Commercial		4.1	5026	1936	3:1	
FL	Road				1100		
VA	Residential		4.3	828	232	4:1	
NZ	Industrial			2471	995	3:1	12892
NZ	Residential			5681	1053	5:1	2087
MN	Residential	70	9.5		405		
MN	Residential	32	4.8		606		
MN	Road	51		3271	695	5:1	
CT	Road	32		219	499	0.4:1	
MD	Institutional			11000	917	12:1	474
	MEANS	**57**	**6.0**	**2931**	**583**	**5:1**	

* = Total Nitrogen
# = May have been influenced by fuel spill

Although the sample size was small (N=2), industrial catchments had, by far and away, the greatest level of trace metal enrichment in the muck layer of any land use. Clearly, further monitoring of heavily industrial catchments is warranted to confirm if muck enrichment represents a problem.

Most trace metals are very tightly fixed in the muck layer and do not migrate more than a few inches into the soil profile. Many researchers have examined soil cores to determine the distribution of trace metal concentration with depth. A consistent pattern is noted. Trace metal levels are at their maximum at the top of the surface layer, and then decline exponentially with depth. Eventually they reach normal background levels within 12 to 18 inches below the pond. Representative sediment metal profiles are shown in Figure 2.

Although the muck layer is highly enriched with metals, it should not be considered an especially toxic or hazardous material. For example, none of over 400 muck layer samples from any of the 50 ponds sites examined in this study exceeded current EPA's land application criteria for metals (Giesy and Hoke, 1991) (Table 2). In fact, metal levels in the muck layer are usually less than 10 times higher than the national mean for agricultural soils in the U.S. (Holmgren *et al.*, 1993) (Table 4).

Of perhaps greater interest is whether soluble metals can easily leach from the muck layer where they could exert a biological or groundwater impact. The capacity for metals to leach from sediments is measured by EPA's Toxicity Characteristics Leaching Procedure (TCLP). The TCLP test, or a slight variant, has been applied by four different investigators to pond muck (Dewberry and Davis, 1990; Harper, 1988; Yousef *et al.*, 1990, 1991) with much the same result—usually less than 5% of the bulk metal concentration is susceptible to leaching.

In general, cadmium and zinc exhibited the greatest potential for leaching (usually less than 10%) while copper and lead showed little or no leaching potential. Moreover, leachate concentrations seldom exceeded the mean metal concentrations reported for urban stormwater runoff.

Table 2: Trace Metal Content in the Muck Layer of 50 Stormwater Ponds and Wetlands (mg/kg dry weight)

Practice	Location	Land Use	Cadmium	Copper	Lead	Zinc	Nickel	Chromium
WP	FL	Residential	4.8	13	38.2	35.7	10.8	4.8
WP13	VA	Mix	3.2		45.3			25
WP	VA	Residential	0.8	17.2	48	78	12.2	
WP	NZ	Industrial		173	578	3171		
WP	NZ	Commercial		18.2	48.9	146		
WP9	FL	Road	15	28	374	161	52	61
WP	MD	Institutional	12	130	202	904		120
WP	MN	Residential			32.9			
WP	MN	Residential			17.0			
WP	OR	Institutional		60.2				
WP	CT	Road	0.4	19	39	53		13
WP	FL	Road	ND	13	125	105		31
WP	MN	Road	ND	57	139	261		51
WP	FL	Road	6	49	620	250		20
WP	FL	Residential	1.5	7	11	6	3	6
WP	FL	Residential	0.6	2	12	11	4	12
WP	FL	Commercial	2.7	6	42	103	6	11
SM	MN	Residential			82			
SM	MN	Residential			56			
DPSM	MD	Industrial	12	140	400	1098		
EDP	MD	Residential	0.4	8	223	45		
DP	VA	Commercial	1.7	30	748	202		
DP8	VA	Residential	3.0		50		30	
EPA land application criteria			380	3300	1600	8600	990	3100

KEY: WP = Wet pond; SM = Shallow marsh; DPSM = Detention basin with shallow marsh; DP = Detention basin; EPA = Maximum metal limits for land application

Hydrocarbon Content in Muck

One aspect of the muck layer that has yet to be well explored is the potential for hydrocarbons and PAH contamination. The limited data on hydrocarbon levels in the muck layer (Table 1) are a cause for some concern, particularly at an Auckland, New Zealand industrial site. Gavens *et al*. (1982) reported that the concentration of total PAH and aliphatic hydrocarbons in the muck layer of a 120 year old London basin were three and 10 times greater, respectively, than the basal sediments. Only limited biodegradation of the hydrocarbons trapped in the muck appeared to have occurred in the basin in recent years. Yousef (1994) on the other hand, reports that hydrocarbons were rarely detected in the muck of Florida ponds.

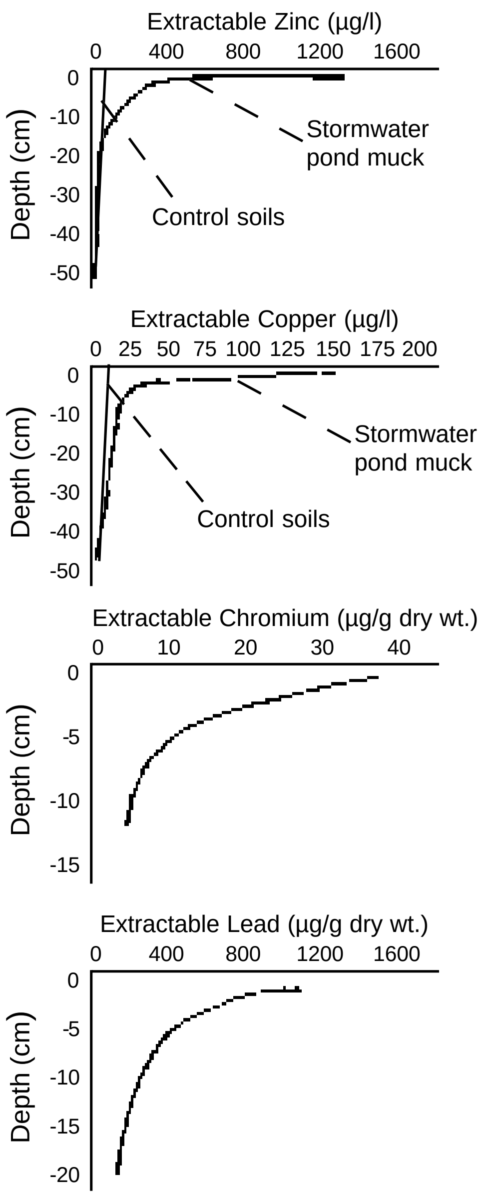
Aquatic Community

A soupy substrate, high pollutant load, and periodically low oxygen level render the muck layer a rather poor habitat for aquatic life. Macroinvertebrate sampling conducted by Yousef *et al.* (1990) and Galli (1988) indicate that the muck layer community has poor diversity and characteristics of high pollution stress. Chironomid and tubificid worms comprised over 90% of all organisms counted in a Florida pond muck layer, and dipteran midge larvae constituted 95% of all organisms collected in the muck layer of a Maryland pond. While the diversity of the community is extremely low, the benthic population can become very dense at certain times of the year. This is not surprising, given that extensive microbe population that uses the highly organic muck layer as an attractive food source.

Table 3: The Effect of Land Use on Trace Metal Concentrations in the Muck Layer (mg/kg)

Land Use	No. of Sites	Cadmium	Copper	Lead	Zinc	Nickel	Chromium
Residential	18	2	9.4	44	35	831	
Commercial	5	2	18	214	150	6	22
Road	13	11	30	330	163	52	51
Industrial	2	—	157	489	2135	—	—

Figure 2: Metal Profiles With Depth (Grizzard *et al*., 1983; Yousef *et al*., 1991)



Comparison of Pond Muck to Sediments Trapped in Other Stormwater Practices

How does pond muck compare to the sediments trapped in other stormwater practices? Table 4 shows that the metal content of the muck layer of wet ponds and stormwater wetlands is quite similar to concentrations seen in the soils of "dry" detention basins. The metal content of pond muck and grassed swale soils are also quite similar in most respects, although swale soils tend to have about twice as much phosphorus and lead as their pond counterparts. Sediments trapped within the filter bed and sedimentation chamber of sand filters also appear to be generally comparable to pond muck, although only one sand filter has been sampled to date (Shaver, 1991).

The one stormwater treatment practice that sharply departs from this pattern is the oil grit separator (OGS). The metal content of trapped sediment within OGSs is five to 20 times higher than other stormwater practices, particularly if the OGS drains a gas station (Schueler and Shepp, 1993). Hydrocarbon and priority pollutant levels in OGS sediments are also much higher.

This condition reflects the fact that OGSs often exclusively serve hydrocarbon hotspots and are designed to trap lighter fractions of oil (Schueler, 1994). It is doubtful that metal and hydrocarbon levels in pond muck could approach the level seen in OGSs, since they typically drain larger watersheds that dilute the influence of individual hydrocarbon hotspots.

Implications for Pond Design and Maintenance

An understanding of the dynamics of the pond muck layer has many implications for the design and maintenance of stormwater ponds.

Pond Clean-out Frequency

Based on observed muck deposition rates, stormwater ponds should require sediment clean-out on a 15 to 25 year cycle (Schueler, 1994; Yousef *et al.*, 1991). For

Table 4: Comparative Metals Concentration in Stormwater Practice Sediments (mg/kg) Dry Weight

Practice	No. of Observations	Cadmium	Copper	Lead	Zinc	Nickel	Chromium
Wet pond	38	6.4	24.5	160	299	38	36
Detention Basin	11	4	59	161	448		30
Grassed swale	8	1.9	27	420	202	13	30
Oil grit separator	13	14	210	320	504		284
Oil grit separator [A]	4	36	788	1198	6785		350
Sand filter	1	1.3	43	81	182	30	30
Sand filter [B]	1	4.6	71	171	418	49	52
Agricultural soils[C]	3000	0.28	30	12	56	24	
Resid. yards	9	0.1	5	13	9		

A = Oil Grit Separator, serving gas stations B = Sand filter with sedimentation chamber
C = Holmgren *et al*., 1993

example, using a 0.5 inch/year muck deposition rate, and assuming that the muck consolidates over time as it deepens, up to 15 to 25% of pond depth can be lost over a 25 year period. The loss of capacity would be faster if construction occurs in the contributing watershed over this time period.

Most ponds are now designed with a forebay to capture sediments. A common forebay sizing criteria is that it constitutes at least 10% of the total pool volume. Based on a 0.5 inch/yr muck deposition rate, and the *untested* assumption that a forebay traps 50% of all muck deposited in the pond, the forebay could lose 25% of its capacity within five to seven years. At the same time, the sediment removal frequency for the main pool might be extended to about 50 years. These calculations assume that turbulence in the forebay does not cause muck to be resuspended and exported to the main pool. To meet this critical assumption, the forebay must be reasonably deep (four to six feet) and have exit velocities no greater than one foot/second at the maximum design inflow.

The Proper Disposal of Muck

All of the available evidence strongly argues that pond muck does not constitute a hazardous or toxic material. Thus it can be safely land-applied with appropriate techniques to contain any leachate as it dewaters. The high organic matter and nutrient content of pond muck might even make it useful as a soil amendment. Chemical testing of pond muck prior to land application is probably not needed for most residential and commercial sites, given the consistent pattern in the distribution of pond data reviewed in this paper.

Greater care should probably be exercised when disposing of pond muck from industrial sites and perhaps some heavily travelled highways. Although only a few industrial sites have been sampled to date, the data suggests these sites may pose a risk. In addition, there is a much greater chance of pollutant spills, leaks, or illegal discharges occurring in a pond over the 20 or 25 year time span in between clean-outs. It would seem prudent, therefore, to require prior testing at selected industrial and roadway ponds to reduce this risk.

Further Research Into the Muck Layer

While our emerging understanding about the muck layer is probably sufficient to make reasonably good management decisions regarding clean-outs and disposal, further research on muck layer dynamics is needed in several areas.

- Ponds need to be sampled to verify the deposition rate of muck over a broader range of geographic and regional conditions. Based on this data a predictive model of muck deposition rates could be developed to help practitioners who design and maintain ponds.
- Much more data needs to be collected concerning the accumulation of hydrocarbons and PAHs in the muck layer, particularly in ponds draining roads and industrial sites. Further testing of the muck layer for these compounds would give managers greater confidence about the proper method for muck disposal, as well as providing inferences about how well stormwater ponds can trap these key pollutants.
- The significance of muck layer phosphorus release as a factor in reducing the long term pollutant removal performance of a stormwater pond remain an open question. Perhaps direct, in-situ measurements of phosphorus flux in a stormwater pond, such as those used for many years in estuarine studies, could help resolve this issue.
- So far, few researches have explored the possible risk of pollutant bio-magnification in the muck layer, either by wetland plant uptake or by bottom feeding fish. A systematic sampling program to define pollutant levels in plant and animal tissue in a large population of stormwater ponds and wetlands would help assess the nature of this risk. Such a survey would also provide helpful guidance to designers on the issue of whether efforts should be made to attract wildlife to these systems.

—TRS

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