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PONDS 3.3 TECHNICAL MEMO

Date: November 2, 2009 (revised)
Re: **Chained Wet Ponds**

The combination of two (or more) wet ponds in series is not directly addressed in the currently proposed methodology (Harper method) for calculating the nutrient removal of a wet pond. A variety of wet pond configurations are possible. Exhibits 1 and 2 below depict two possible chained wet pond configurations.

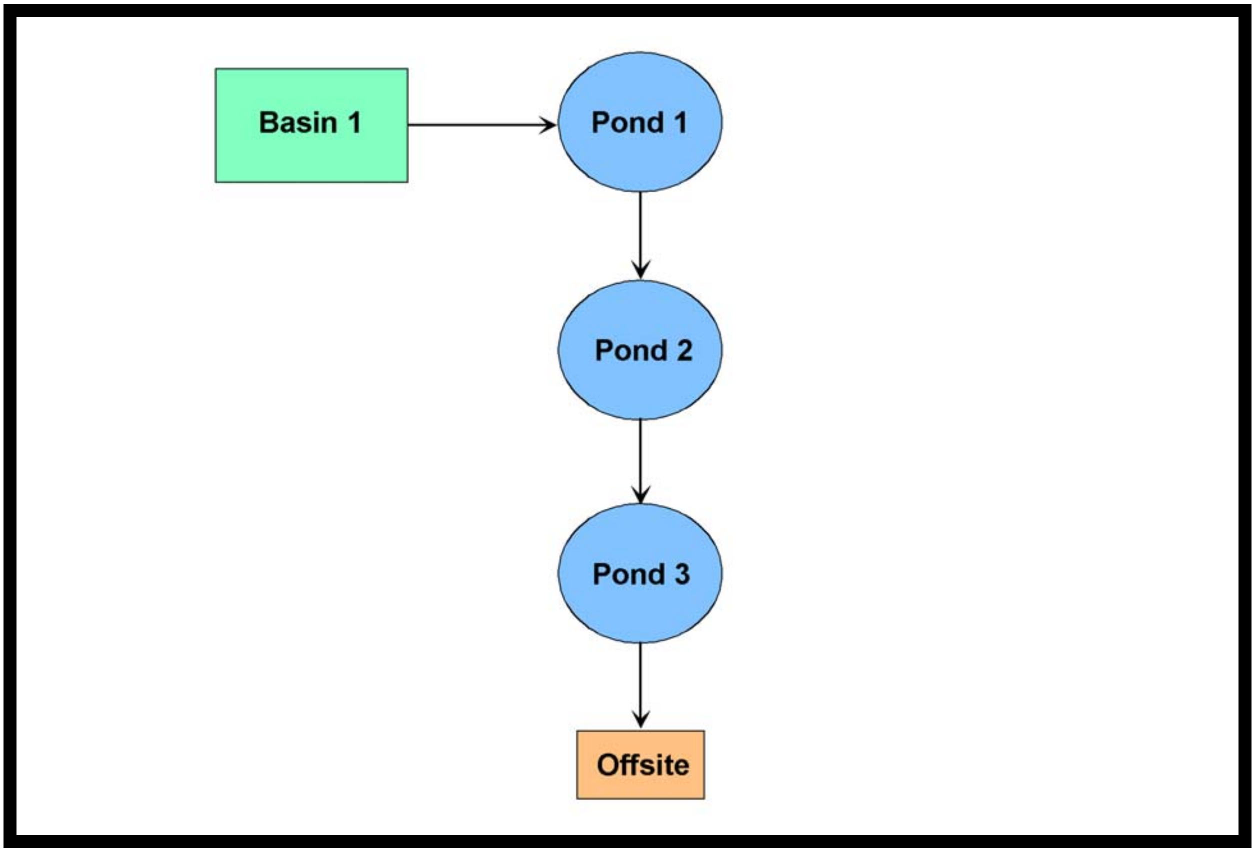

Exhibit 1. Chained wet ponds with single runoff basin

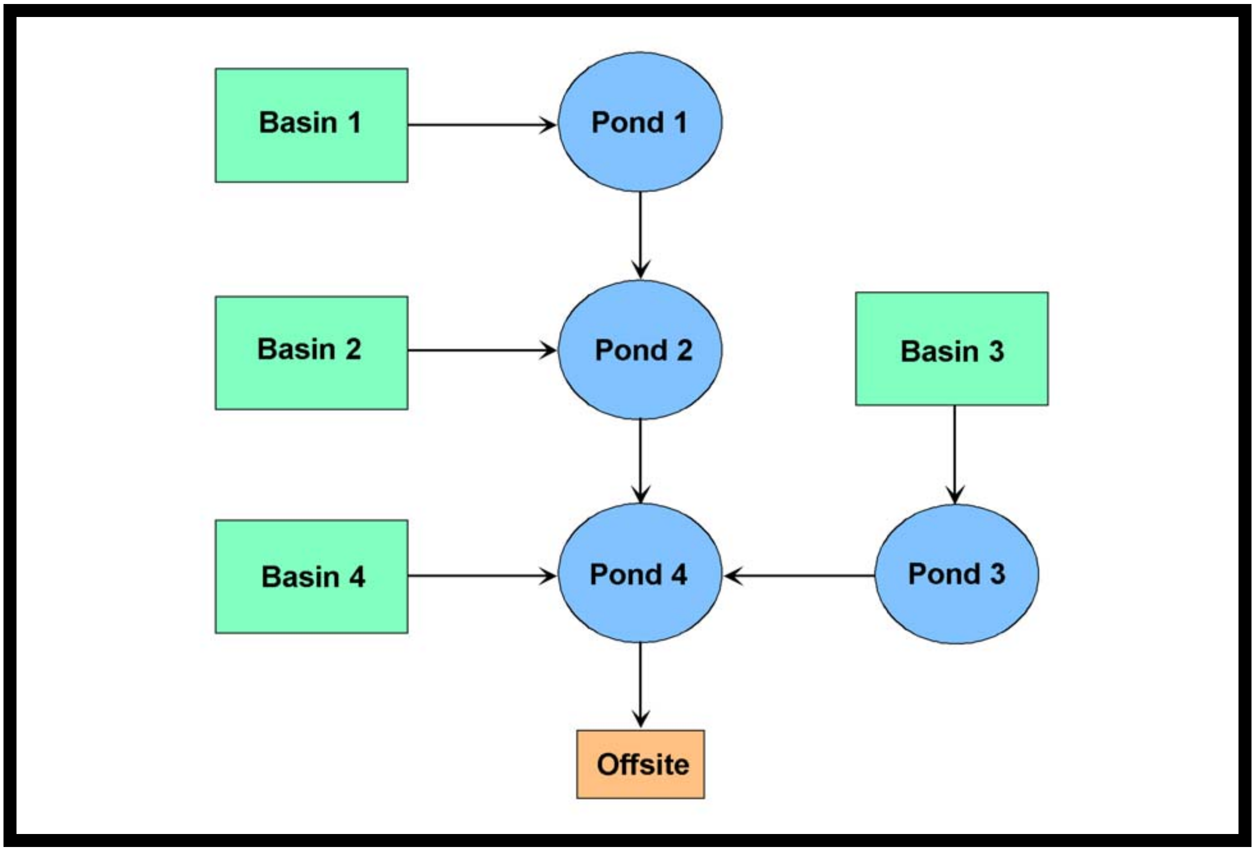

Exhibit 2. Chained wet ponds with multiple basins

When analyzing chained wet ponds it is important to recognize that the removal efficiencies are not compounded from one pond to the next. For example, suppose that Pond 1 has a residence time of 40 days and Pond 2 has a residence time of 50 days. If you considered each pond individually, you would expect the following phosphorous removal efficiencies:

Pond 1, T = 40 days, $E_{p(40)} = 66.5\%$

Pond 2, T = 50 days, $E_{p(50)} = 68.3\ \%$

If the following efficiencies are compounded, then the theoretical removal efficiency for Pond 1 and Pond 2 combined would be calculated as follows:

$$E_{total} = E_1 + (1 - E_1) \times E_2 = 0.665 + (1 - 0.665) * 0.683 = 0.894 = 89.4\%$$

However, this formula is not appropriate for wet ponds in series.

The nutrient removal provided by a wet pond is a combination of processes, primarily sedimentation, biological uptake, and perhaps some chemical reaction, etc. Of these processes sedimentation is the most significant.

Sedimentation occurs during the initial period of treatment, and is largely responsible for the initial high rate of nutrient removal, as seen in the phosphorous removal efficiency chart in Exhibit 3 below, for example. During the treatment process, sedimentation occurs once (for a given slug of runoff), and will not re-occur simply by routing the runoff volume through additional ponds.

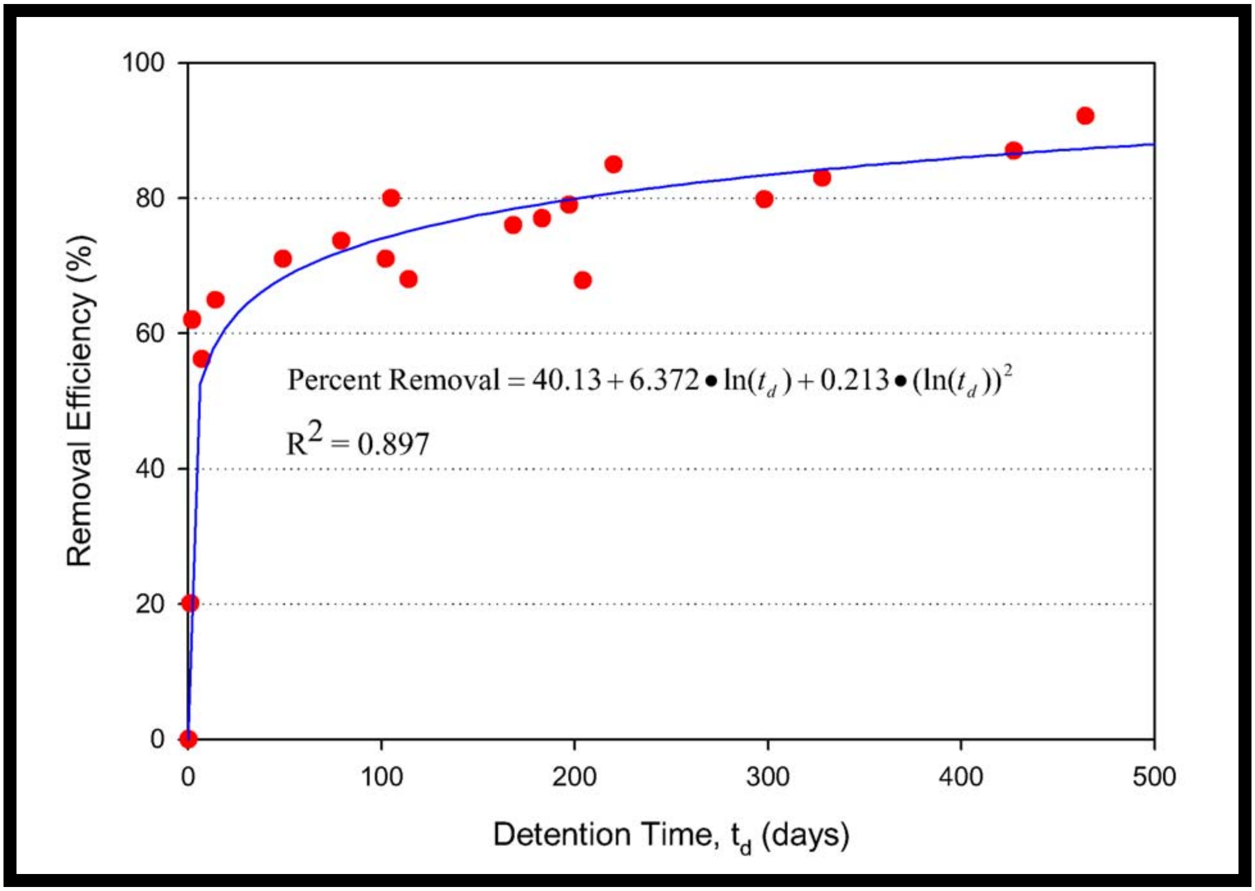

Exhibit 3. Phosphorous removal efficiency over time for a wet pond

Since the removal efficiencies of wet ponds in series can not be compounded due to the role of sedimentation, it is more appropriate to calculate the removal efficiency as a function of the cumulative residence time.

$T_{total} = T_1 + T_2 + T_3 \ldots$

The removal efficiency is then calculated from the cumulative residence time. For example, the combined phosphorous removal efficiency of Pond 1 and Pond 2 (for the example on the previous page) is determined as follows:

T_1 = 40 days, T_2 = 50 days, T_{total} = 90 days
$E_{p(90)}$ = 73.1%

Note that the resulting efficiency (73.1%) is considerably less than would be obtained by compounding the efficiencies (89.4%)

The simple example shown in Exhibit 1 is notable because the same volume of runoff passes through each pond, i.e., the offsite discharge from Pond 3 equals the runoff volume generated in Basin 1. However, this is not true for the more general case shown in Exhibit 2. In Exhibit 2, the total volume of runoff passing through a particular pond increases the more downgradient the pond is. For example, Pond 1 must accommodate the flow generated in Basin 1, whereas Pond 2 must accommodate the flow generated from Basin 1 plus the flow generated from Basin 2, and this will impact the required pond volume necessary to ensure that the assumed residence time is provided.

To illustrate this, suppose that two ponds are chained together, and each pond has the same residence time (say 50 days) and each pond receives the same volume of runoff from its contiguous runoff basin (say 73 acre-ft/yr).

The residence time for a given pond is defined as follows:

Residence Time = (Permanent Pool Volume) / (Annual Flow Volume)
Residence Time = (Permanent Pool Volume) / (Upgradient Flow + Runoff)

or

Permanent Pool Volume = (Residence Time) * (Upgradient Flow + Runoff)

Using this formula, the required permanent pool volume for Pond 1 is:

V_1 = (50 days * 1 yr/365 days) * (0 + 73 ac-ft/yr) = 10 ac-ft

For Pond 2, the runoff from Basin 1 becomes the upgradient flow to Pond 2, and the required permanent pool volume for Pond 2 is:

V2 = (50 days * 1 yr/365 days) * (73 + 73 ac-ft/yr) = 20 ac-ft

All else being equal, the required permanent pool volume will continue to proportionally increase the more downgradient the pond is in the chain.

Example Problem

Given the series of chained wet ponds as shown in Exhibit 4 below, calculate the overall efficiency for the pond system and determine the required pond properties (permanent pool volume and anoxic depth, etc.)

For convenience, we will solve for phosphorous only in this example.

The annual runoff volume and phosphorous load from each basin are listed in Table 1 below, along with the residence time for each of the ponds.

Table 1. Basin and Pond Parameters			
Basin Parameters			
Basin Number	Basin 1	Basin 2	Basin 3
Annual Runoff Volume (ac-ft/yr)	51.82	101.78	137.05
Annual phosphorous load (kg/yr)	22.05	43.31	58.32
Pond Parameters			
Pond Number	Pond 1	Pond 2	Pond 3
Residence Time (days)	76	98	52

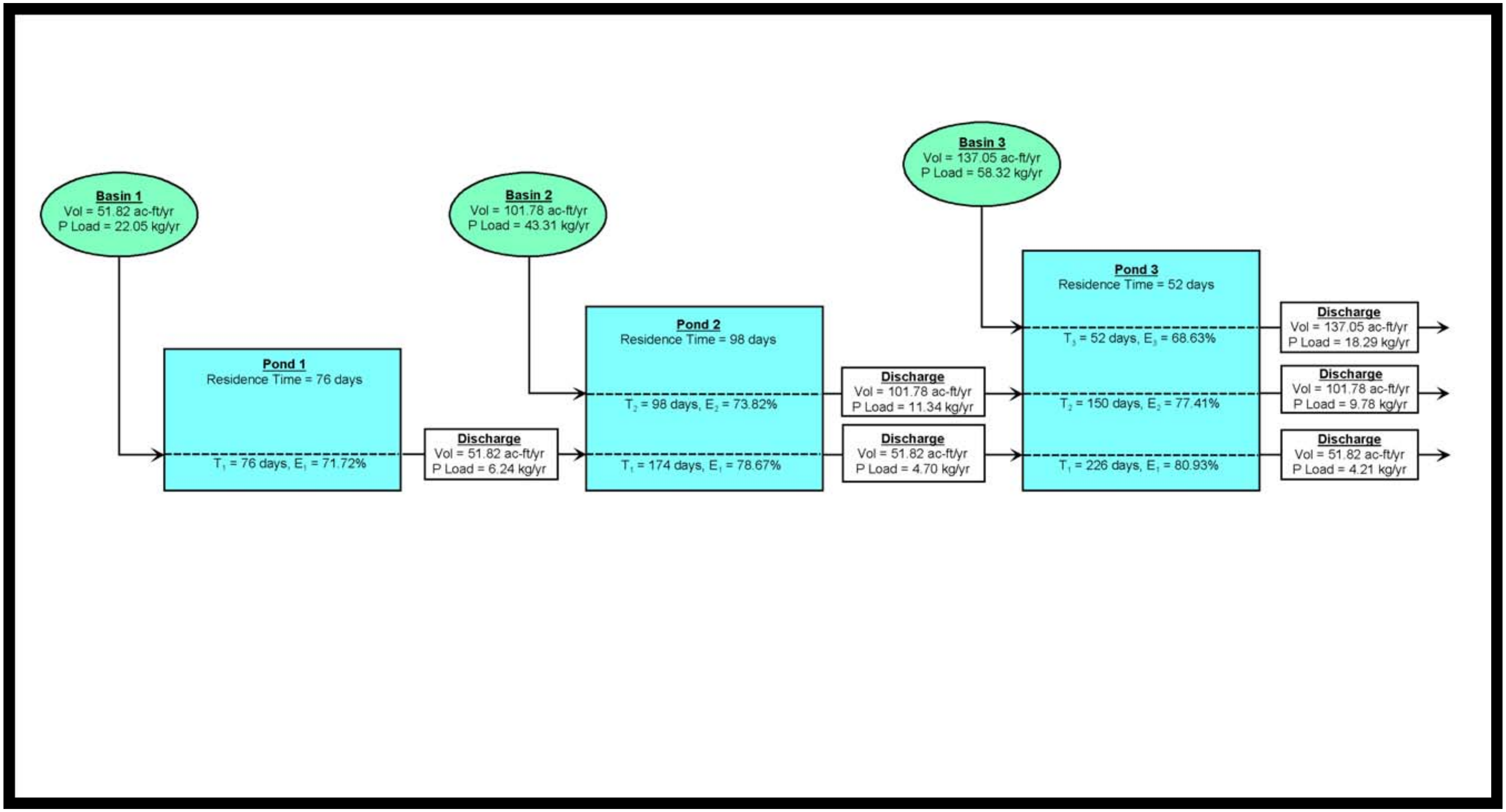

Exhibit 4. Nodal diagram for example problem

Table 2. Phosphorous Discharge Through Chained Wet Ponds										
Individual Residence Time		Runoff from Basin 1			Runoff from Basin 2			Runoff from Basin 3		
Pond	T (days)	Total Residence Time (days)	Efficiency (%)	Discharged Mass (kg)	Total Residence Time (days)	Efficiency (%)	Discharged Mass (kg)	Total Residence Time (days)	Efficiency (%)	Discharged Mass (kg)
		0		**22.05**	0		**43.31**	0		**58.3**
Pond 1	76	76	71.7	6.24	--	--	--	--	--	--
Pond 2	98	174	78.7	4.70	98	73.8	11.34	--	--	--
Pond 3	52	226	80.9	**4.21**	150	77.4	**9.78**	52	68.6	**18.29**
Total Phosphorous In = 22.05 + 43.31 + 58.3 = 123.68										
Total Phosphorous Out = 4.21 + 9.78 + 18.26 = 32.28										
Efficiency = (123.68 - 32.28) / 123.68 x 100 = 73.9%										

1 - Calculate the removal efficiency

First, consider the runoff originating from Basin 1:

The total residence time for runoff originating in Basin 1 before discharging offsite is:

$T = T_1 + T_2 + T_3 = 76 + 98 + 52 \text{ days} = 226 \text{ days}$

The phosphorous removal efficiency for a residence time of 226 days is 80.93%.

The mass of phosphorous discharged offsite, origination in Basin 1 is therefore:

$P_{discharge} = 22.05 \text{ kg/yr} * (1 - 0.8093) = 4.21 \text{ kg/yr}$

Next, consider the runoff originating from Basin 2:

The total residence time for runoff originating in Basin 2 before discharging offsite is:

$T = T_2 + T_3 = 98 + 52 \text{ days} = 150 \text{ days}$

The phosphorous removal efficiency for a residence time of 150 days is 77.41%.

The mass of phosphorous discharged offsite which originates in Basin 2 is therefore:

$P_{discharge} = 43.31 \text{ kg/yr} * (1 - 0.7741) = 9.78 \text{ kg/yr}$

Then, consider the runoff originating from Basin 3:

The total residence time for runoff originating in Basin 2 before discharging offsite is:

$T = T_3 = 52 \text{ days}$

The phosphorous removal efficiency for a residence time of 52 days is 68.63%.

The mass of phosphorous discharged offsite which originates in Basin 2 is therefore:

$P_{discharge} = 58.32 \text{ kg/yr} * (1 - 0.6863) = 18.29 \text{ kg/yr}$

The overall phosphorous removal efficiency is calculated as:

$$E_{total} = (P_{in} - P_{out}) / P_{in}$$

where

$$P_{in} = 22.05 + 73.31 + 58.32 = 123.68 \text{ kg/yr}$$

$$P_{out} = 4.21 + 9.78 + 18.29 = 32.28 \text{ kg/yr}$$

Therefore

$$E_{total} = (123.68 - 32.28) / 123.68 = 0.7390 = 73.9\ \%$$

2 - Calculate the required permanent pool volume

The permanent pool volume is calculated based on the specified residence time for a given pond and the total volume of water that passes through that pond (annually). The total volume is the combined volume of upgradient flow plus runoff from contiguous basins. The permanent pool volume is calculated as follows:

$$V_{pool} = (\text{Residence Time}) * (\text{Upgradient Flow} + \text{Runoff})$$

For Pond 1, the upgradient inflow is zero and the annual runoff volume from Basin 1 is 51.82 acre-ft/yr, so the required permanent pool volume is as follows:

$$V_{pool} = (76 \text{ days}) * (0 + 51.82 \text{ ac-ft/yr}) * (1 \text{ yr}/365 \text{ days}) = 10.79 \text{ ac-ft}$$

For Pond 2, the upgradient discharge from Pond 1 is 51.82 ac-ft/yr and the runoff volume from Basin 2 is 101.78 ac-ft/yr, so the required permanent pool volume is as follows:

$$V_{pool} = (98 \text{ days}) * (51.82 + 101.78 \text{ ac-ft/yr}) * (1 \text{ yr}/365 \text{ days}) = 41.24 \text{ ac-ft}$$

For Pond 3, the upgradient discharge from Pond 2 is 153.60 ac-ft/yr (51.82 ac-ft/yr from Basin 1 and 101.78 ac-ft/yr from Basin 2) and the runoff volume from Basin 3 is 137.05 ac-ft/yr, so the required permanent pool volume is as follows:

$$V_{pool} = (52 \text{ days}) * (51.82 + 101.78 + 137.05 \text{ ac-ft/yr}) * (1 \text{ yr}/365 \text{ days}) = 41.41 \text{ ac-ft}$$

3 - Estimate the anoxic depth for each pond

For Pond 1, the anoxic depth is calculated as follows:

- Annual mass of unremoved phosphorus, i.e, the mass of phosphorous discharged from the pond:

  P_u = 6.24 kg/yr (see exhibit 4)

- Mean phosphorous concentration in pond, i.e., the annual mass of unremoved phosphorous (P_u) divided by the dilution volume, where the dilution volume is the total volume passing through the pond ($V_{through}$) plus the permanent pool volume (V_{pool}):

  $p_{avg} = P_u / (V_{through} + V_{pool})$

  p_{avg} = (6.24 kg) / (51.82 acre-ft + 10.79 ac-ft) = 80.79 ug/l

- Chlorophyll-a concentration:

  $Chlor_a = e^{[1.058 * \ln(pavg) - 0.934]}$
  $= e^{[1.058 * \ln(80.79) - 0.934]} = 40.96 \text{ mg/m}^3$

- Estimated Secchi disk depth:

  $D_s = (24.2386 + 0.3041 * Chlor_a) / (6.0632 + Chlor_a)$
  $= (24.2386 + 0.3041 * 40.96) / (6.0632 + 40.96)$
  = 0.780 m
  = 2.56 ft

- Estimated anoxic depth

  $D_{anox} = 3.035 * D_s + 0.02164 * Chlor_a - 0.004979 * p_{avg}$
  $= 0.035 *0.780 + 0.02164 * 40.96 - 0.004979 * 80.79$
  = 2.85 m
  = 9.36 ft

For Pond 2, the anoxic depth is calculated as follows:

- Annual mass of unremoved phosphorus:

  P_u = 4.70 + 11.34 = 16.04 kg/yr (see Exhibit 4)

- Mean phosphorous concentration in pond:

  p_{avg} = (16.04 kg) / (51.82 + 101.78 + 41.24 ac-ft) = 66.7 ug/l

- Chlorophyll-a concentration:

  $$Chlor_a = e^{[1.058 * \ln(pavg) - 0.934]}$$
  $$= e^{[1.058 * \ln(66.7) - 0.934]} = 33.44 \text{ mg/m}^3$$

- Estimated Secchi disk depth:

  $$D_s = (24.2386 + 0.3041 * Chlor_a) / (6.0632 + Chlor_a)$$
  $$= (24.2386 + 0.3041 * 33.44) / (6.0632 + 33.44)$$
  $$= 0.871 \text{ m}$$
  $$= 2.86 \text{ ft}$$

- Estimated anoxic depth

  $$D_{anox} = 3.035 * D_s + 0.02164 * Chlor_a - 0.004979 * p_{avg}$$
  $$= 0.035 * 0.871 + 0.02164 * 33.44 - 0.004979 * 66.7$$
  $$= 3.04 \text{ m}$$
  $$= 9.96 \text{ ft}$$

For Pond 3, the anoxic depth is calculated as follows:

- Annual mass of unremoved phosphorus:

  P_u = 4.21 + 9.78 + 18.29 = 32.28 kg/yr

- Mean phosphorous concentration in pond:

  p_{avg} = (32.28 kg) / (51.82 + 101.78 + 137.05 + 41.41 ac-ft) = 78.8 ug/l

- Chlorophyll-a concentration:

  $Chlor_a = e^{[1.058 * \ln(pavg) - 0.934]}$
  $= e^{[1.058 * \ln(78.8) - 0.934]}$ = 38.89 mg/^{M3}

- Estimated Secchi disk depth:

  D_s = (24.2386 + 0.3041 * $Chlor_a$) / (6.0632 + $Chlor_a$)
  = (24.2386 + 0.3041 * 38.89) / (6.0632 + 38.89)
  = 0.802 m
  = 2.63 ft

- Estimated anoxic depth

  D_{anox} = 3.035 * D_s + 0.02164 * $Chlor_a$ - 0.004979 * p_{avg}
  = 0.035 * 0.802 + 0.02164 * 38.89 - 0.004979 * 78.8
  = 2.88 m
  = 9.46 ft