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February 22, 1982

Mrs. Cynthia Shanks, Chairman
Surface Water Quality Study Committee
Town Offices
Wayland, MA 01778

Re: Progress Report No. 4 - Diagnostic/Feasibility Study of Dudley Pond

Dear Mrs. Shanks:

The following text and tables present our results for the on-going study of DudleyPond, since the submission of the semi-annual report. In accordance with the scheduling of the study tasks as outlined in our contract, the major focus of this progress report is to present the findings of task no. 6 - "Develop Hydrologic and Nutrient Budget." Jack Rohrer (modeling scientist) prepared the hydrologic budget and preliminary nutrient budget with assistance from Mike Hudson (geologist) and myself. The nutrient budget is still preliminary because we have yet to collect and analyze the second round of storm water samples. We also hope to refine the budget after collecting an additional round of groundwater samples.

You will note that we included a septic system questionnaire, which we hope either the Committee or the Dudley Pond Association will distribute to all homeowners around the Pond. We would like to use the information that would be gathered with this questionnaire to validate and cross check our current phosphorus contributions from septic systems. In order to do this, we propose to use a model developed by CEM (1978) which computes phosphorus inputs, taking into account factors such as; age and usage of the system, distance of the system from shore, percentage of homes using phosphate detergents, etc. We would like to apply this model to Dudley Pond if the Committee and/or Association will handle the leg work involved with distributing, collecting and tabulating the data received. Naturally, we would work closely with you on this task.

Based on our memo of November 24, 1981 and as a result of our recent hydrologic budget and nutrient loading calculations, we feel the following additional groundwater data is still needed at Dudley Pond:

1. Deep Groundwater Quality Data: The 13 well points installed around the pond shoreline are screened in the top 5 feet of the water table. Although care was taken to locate the well points away from shoreline septic systems and known plume locations, we feel the nutrient data obtained from these wells

is indicative of shallow groundwater/septic effluent mixing from septic systems removed from the shoreline. A groundwater sample obtained 15-30 feet below the static water table would answer this question.

2. Water Table Elevations in the NW Area of the Watershed: All available data indicate that groundwater inflow and outflow are significant parameters in the hydrologic budget. Groundwater flows out of the NW portion of the watershed and towards Pod Meadow. The elevation of the groundwater divide on the downslope side of the pond has maximum influence on the interaction of surface water and groundwater (Winter, 1976). No groundwater elevation data is currently available in the NW part of the watershed.

These two concerns could be adequately addressed by intalling a shallow and deep monitor well in the NW portion of the watershed. The deep well would provide a background groundwater sample. The shallow well would be an accurate measure of the static water table in this area. Together, the wells would permit a measure of the vertical hydraulic gradient, further quantifying groundwater inflow and outflow in the watershed. The total estimated cost for observation well installation and sampling (see November 24, 1981 memo) is $1,300.00.

We intend to collect our second round of stormwater samples during a long duration storm event occurring in late March or April. The results of this task will better refine our stormwater nutrient inputs which were very high compared to literature values, and will provide additional data comparing the quality and loadings amongst the different drains, in order to establish priorities for storm water runoff diversion, treatment or other management alternatives.

During the next 6-8 weeks we will be writing the diagnostic study report, presenting and summarizing our data while integrating the available data sources into the report. The feasibility of in-lake management/restoration techniques will be assessed. Watershed management strategies will be examined, however the additional stormwater data will be needed, prior to evaluating and recommending definitive action to reduce nutrient contributions within the Dudley Pond watershed.

Based upon our revised sampling schedule, we anticipate submitting the "draft final report" on or before July 30, 1982.

Feel free to contact me should you have any questions.

Very truly yours,

IEP, Inc.

Gerald N. Smith
Aquatic Biologist

Task 6: Develop Hydrologic and Nutrient Budgets

The baseline morphological characteristics and annual hydrologic budget based on research to date are presented in Table 1. The pond area, volume and watershed area were measured by digital planimetry of Wayland photogrammetric maps and the IEP bathymetric map. The other morphologic parameters (ρ, q_s, T), were derived from the pond volume and discharge data from the hydrologic budget.

The annual hydrologic budget equates the total inflowing and outflowing waters per the equation on Table 1. The annual volumes of watershed and pond precipitation were calcualted by multiplying the average annual depth of precipitation (NOAA, Framingham) by the respective areas. Surface runoff was calculated by taking an areal proportion of a nearby representative station where the discharge has been historically gaged. In this case, the USGS Charles River gaging station at Dover (Charles River Village) due to its proximity to Dudley Pond, its similar surface cover characteristics, and its long (31 year) gaging record. The annual pond evaporation volume was calculated from the regional pond evaporation depth (Chow, 1964 and Higgins and Colonell, 1971) over the Dudley Pond area. Groundwater inflow was calculated by application of the Darcy Equation to four inflow zones as distinguished by groundwater gradient and permeability of the saturated layer. Groundwater outflow was calculated for some pond bottom areas and near shore zones also with the Darcy Equation. Regional well data and IEP test well data were used for establish the groundwater gradients. For the purpose of the hydrologic budget, stream inflow was included in the surface runoff component due to the ephemeral nature of the stream and to its small drainage area. Whereas no definitive stream-gaging program for the outflow has been undertaken, the stream outflow was calculated by solving the budget equation for this unknown parameter. Random field-checking of the outflow with a current meter supports this budgeted value yet continued checking will be required to verify it.

The annual phosphorus budget and trophic state boundary loadings are presented in Table 2. No attempt was made to budget the nitrogen loadings because phosphorus is clearly the limiting nutrient (N:P >15:1) at Dudley Pond based upon the results of our water quality monitoring program conducted during the past summer.

The stormwater runoff phosphorus loading was calculated from the stormwater sampling program (October 1 and 2, 1981) data as a function of the average phosphorus concentration, drainage area, and discharge at each sample station. Our reported (Table 2) annual loading (145.5 kg/gr) from this component, is high in relation to calculated literature (EPA 1980) values which

which range from 26 to 78 kg/yr. Future stormwater sampling will permit a more accurate assessment of this contribution.

The precipitation phosphorus loading was derived from EPA (1980) loading data adjusted for local precipitation depth over the area of the pond.

The pond-wide loading from septic systems was calculated as a function of the number of leachate plumes detected during the shoreline survey and EPA (1980) typical unit koads assuming 50% of shoreline residences use nonphosphate detergent.

The regional groundwater loadings was calculated from the groundwater inflow volume (see Hydrologic Budget) and the background phosphorus concentration (0.03 g/m^3) found in the shoreline well samples.

The trophic state boundaries for Dudley Pond were calculated by methods of three different researchers. All three are well documented and widely used. They all evaluate trophic boundaries as a function of mean pond depth and flushing time, permitting greater phosphorus loadings for deeper ponds with faster flushing time.

As shown by Table 2, the preliminary total annual phosphorus loading of 265.4 kg/yr is significantly higher than the mean mesotrophic/ eutrophic boundary loading of 49.9 kg/yr. Continued study of the components of the budget will permit refinement of the budget.

Additional stormwater sampling will allow a more accurate estimation of the annual runoff loading, as well as locating those subdrainage areas which are the highest contirbutors. Sampling of deeper wells will permit a more accurate estimation of the regional groundwater loading. A survey (by questionnaire) of near-shore residents could provide valuable information on population density and the use of phosphate detergents, thereby refining the estimate of pond-wide septic systems loading. When the final existing budget has been determined, restoration techniques will be evaluated for their effectiveness in either reducing the total phosphorus loading or increasing the permissible loading as indicated by the trophic state boundaries.

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Table 1

Dudley Pond Morphology and Average Annual Hydrologic Budget

Morphology

Watershed Area	$A = 336.1$ acres $= 1.36\ km^2$
Pond Area	$A_o = 90.8$ acres $= 0.367\ km^2$
Pond Volume	$V = 3.651 \times 10^7 ft^3 = 1.034 \times 10^6 m^3$
Average Depth, volumetric	$\bar{z} = 9.23$ ft $= 2.813$ m
Flushing Rate	$\rho = 0.658$/yr
Flushing Time	$T = 1.52$ yr
Areal Water Load	$q_s = 6.068$ ft/yr - 1.850 m/yr

Hydrologic Budget

Inflow = Outflow

$$P_p + Q_i + R + GW_i = Q_o + Ev + GW_o$$

		$10^6\ ft^3/yr$
Total Watershed Precipitation	P	= 52.8
Surface Runoff	R	= 18.9
Precipitation on Pond	P_p	= 14.1
Pond Evaporation	E_v	= 8.9
Groundwater Inflow	GW_i	= 6.0
Groundwater Outflow	GW_o	= 5.8
Stream Inflow	Q_i	= 0.0
Stream Outflow	Q_o	= 24.3

Table 2. Dud_ey Pond Annual Phosphorus Budget and Trophic State Boundaries

Preliminary Phosphorus Budget

Source	Annual Loading (kg/yr)
Stormwater runoff	147.5
Precipitation (on pond)	9.9
Septic Systems	102.9
Regional Groundwater	5.1
Total	265.4

Trophic State

Researcher/Method	Oligotrophic/mesotrophic boundary loading (kg/yr)	Mesotrophic/eutrophic boundary loading (kg/yr
Vollenweider (1976)	15.2	30.4
Dillon Rigler	37.8	75.6
Reckhow (1979)	21.8	43.7
Mean	24.9	49.9

DUDLEY POND - SHORELINE RESIDENTS QUESTIONNAIRE

1. OCCUPANCY
   - A. AVERAGE JUNE - SEPTEMBER NUMBER PERSONS ___________
   - B. AVERAGE OCTOBER - MAY NUMBER PERSONS___________

2. FACILITIES

   (Please state your quantity of each type)

   - A. SHOWERS/BATHTUBS ___________
   - B. TOILETS ___________
   - C. DISHWASHERS ___________
   - D. CLOTHES WASHERS ___________
   - E. GARBAGE DISPOSALS ___________

3. DETERGENTS

   (Please state the brand and type of detergent you use for)

   - A. DISHWASHER ___________________________
   - B. CLOTHESWASHER_________________________

4. SEWERAGE SYSTEM

   TYPE OF DISPOSAL SYSTEM _______________________ AGE_____ YEARS

   IF SEPTIC TANK, METAL _____ CONCRETE _____VOLUME _____ GALLONS

   DATE OF LAST PUMPING _______________ PROBLEMS ___________________

   ____

   DATE OF LAST REPAIR OR REPLACEMENT ______________________________

   TYPE OF SOIL ________________________ WATER TABLE DEPTH ________

PLEASE SKETCH YOUR SYSTEM ON THE BACK OF THIS QUESTIONNAIRE, SHOWING: LAKE SHORE, HOUSE, ROAD, WELL, SEPTIC TANKS, CESS POOLS, COLLECTION TANKS, PUMPS, LEACH FIELDS, PIPE LINES, ETC. INDICATE APPROXIMATE DISTANCE BETWEEN LEACH FIELDS AND LAKE SHORE. SHOW CONNECTIONS TO ANY OTHER DWELLINGS THAT MIGHT BE ON THE SAME SYSTEM AND INDICATE WHETHER YOU HAVE DIFFERENT SYSTEMS FOR WASH WASTES AND HUMAN WASTES, OR WHETHER YOU HAVE A BACKUP SYSTEM (SEE SAMPLE SKETCH).

Dudley Pond - Morphologic Data Calculation

Volume (from bathymetry)

depth interval feet	A_1 acres	A_2 acres	V $ft^3 \times 10^6$
0-2	90.80	85.09	7.662
2-4	85.09	78.15	7.111
4-6	78.15	67.37	6.339
6-8	67.37	35.37	4.475
8-10	35.37	22.97	2.541
10-12	22.97	18.16	1.792
12-14	18.16	15.53	1.468
14-16	15.53	13.45	1.262
16-18	13.45	11.60	1.091
18-20	11.60	9.76	0.930
20-22	9.76	7.06	0.733
22-24	7.06	4.60	0.508
24-26	4.60	2.13	0.293
26-28	2.13	0	0.093
Total			3.651×10^7 ft3

A_{shed} = 336.1 acres = 1.36 km^2

A_0 = 90.8 acres = 0.367 km^2

$\bar{z}$ = V/A_0 = $3.651 \times 10^7 / 3.955 \times 10^6$ = 9.23 ft = 2.813 m

ρ = Q/V = $2.4 \times 10^7 / 3.651 \times 10^7$ = 0.658/yr

T = $1/\rho$ = 1.52 years

q_s = Q/A_0 = $2.4 \times 10^7 / 3.955 \times 10^6$ = 6.068 ft/yr = 1.850 m/yr.

Hydrologic Budget

Precipitation

annual P (NOAA, Framingham) = 43.28 in/yr

P areal volume = $\left(\frac{43.28 \text{ in}}{12 \text{ in/ft}}\right)$(336.1 acres) 43560 ft²/acre

$P = 5.28 \times 10^7$ ft³/yr

Surface Runoff

Charles River average $Q = 293$ ft³/sec [USGS HA554]

$A = 184$ mi²

$Q_{unitized} = 293/184 = 1.59$ CSM

Dudley Pond Shed $A = 336.1$ acres

$A_0 = 90.8$ acres

$R = (336.1 - 90.8)(1.59)/640$ acres/mi²

$= 0.60$ ft³/sec

$= 1.89 \times 10^7$ ft³/yr

Precipitation on Pond

$P_{pond} = 43.28$ in (90.8 acres)(43560 ft²/acre)(12 in/ft)

$P_p = 1.427 \times 10^7$ ft³/yr

Pond Evaporation

Central Mass Evaporation = 27 in (Chow)

$Ev = 27(90.8)(43560)/12$

$Ev = 8.90 \times 10^6$ ft³/yr

Groundwater Inflow:

$$GW_I = Q = KIA \quad \text{(Darcys Law)}$$

where Q = Groundwater Discharge (gallons per day)
K = Permeability (gpd/ft^2)
I = Hydraulic Gradient (ft/ft)
A = Cross-sectional area (ft^2)

Zone 1: Eastern shoreline

K_1 = 400 gpd/ft^2 (OW1 Boring Log)

$I_1 = \frac{153.0 - 149.1}{1200'} = .0032$ (Winter, 1976 Karnauskas, 1978)

A_1 = (20' deep)(2400' wide) = 48,000 ft^2

Q_1 = 61,440 gpd

Zone 2: Southern shoreline

K_2 = 50 gpd/ft^2 (TW1 boring log)

$I_2 = \frac{154.0 - 149.1}{1900'} = .0026$

A_2 = (20' deep)(2000' wide) = 40,000 ft^2

Q_2 = 5,200 gpd

Zone 3: Northern shoreline

K_3 = 400 gpd/ft^2 (Nelson, 1974)

I_3 = .0032 (assumed)

A_3 = (20' deep)(1600' wide) = 32,000 ft^2

Q_3 = 40,960 gpd

Groundwater Inflow (cont'd):

Zone 4: Western shoreline

K_4 = 400 gpd/ft^2 (based on several test well logs)

I_4 = .0017 (assumed) (Winter, 1976; Karfort, 1981; Fortin, 1980)

A_4 = (7.5' deep)(3000' wide)

Q_4 = 15,300 gpd

$GW_I = Q_t = Q_1 + Q_2 + Q_3 + Q_4$

= 61,440 + 5,200 + 40,960 + 15,300 = 122,900 gpd

Groundwater Outflow:

Zone 1: Bottom of Western Half

K_1 = 1 gpd/ft^2 (Cervione, 1972; for sand + muck sediments)

I_1 = −0.11 (Well point data; McBride, 1975)

A_1 = ½ (1680)(1280) = 1,075,200 ft^2

Q_1 = 118,272 gpd

GW_O = 118,272 gpd

Stream Inflow - budget as runoff

Stream Outflow -

budget equation for Q_o

$Q_o = P_p + Q_i + R + GW_i - E_r - GW_o$

$= (14.1 + 0.0 + 18.9 + 6.0 - 8.9 - 5.8)\, 10^6\ ft^3/yr$

$Q_o = 24.3 \times 10^6\ ft^3/yr$

Nutrient (Phosphorus) Budget

Stormwater Runoff Load

sampling program October 1 and 2, 1981

$Q_{shed} = (1.59\ ft^3/sec \cdot mi^2)(mi^2/640\ acres)(3.15 \times 10^7\ sec/yr)$
$= 78,345\ ft^3/yr \cdot acre$

annual load per sub-drainage area $L_i = \bar{P}_i A_i (2.2187)$ (conversion)

sample station #	average phosphorus concentration (mg/l) $\bar{P}_i$	sub-drainage area (acres) A_i	sub-drainage area load (kg/yr) L_i
3	0.04	1.74	0.154
4	0.16	13.98	4.96
5	0.64	5.14	7.30
6	1.70	2.90	10.94
7	0.70	1.15	1.79
8	0.17	31.50	11.88
9	0.19	0.15	0.063
11	0.12	2.68	0.714
12	0.10	5.75	1.28
sampled storm drain total		64.99	39.08

Total watershed runoff load $= \Sigma L_i \left(\frac{A_{shed} - A_o}{\Sigma A_i}\right)$

$L = 39.08 \left(\frac{336.1 - 90.8}{64.99}\right)$

$L = 147.5\ kg/yr$

Precipitation (on pond) Load

annual loading factor = 25 kg/km² yr (EPA 1980)
Dudley load = $25(43\text{ in}/40\text{ in})(0.367\text{ km}^2)$
= 9.9 kg/yr

Septic Load (from shoreline survey)

28 active plumes detected
assume 3.5 people/house
50% usage of phosphate detergent

annual loading factors (EPA, 1980)
with phosphate detergent = 1.6 kg/capita yr
non-phosphate detergent = 0.5 kg/capita yr

annual septic load = $3.5(0.5)[1.6(28)+0.5(28)]$
= 102.9 kg/yr

Regional Groundwater Load

$GW_i = 1.70 \times 10^5\ m^3/yr$
assume lowest well samples typical of background groundwater. Range: 0.02 to 0.04 mg/l
use: 0.03 mg/l

annual groundwater load = $1.70 \times 10^5 (0.03)/1000$ g/kg
= 5.1 kg/yr.

Trophic State Evaluation

Vollenweider (1976)

$$L = P q_s \left(1 + \sqrt{\bar{z}/q_s}\right)$$

$q_s = 1.850$ m/yr

$\bar{z} = 2.813$ m

$P_{oligotrophic/mesotrophic} = 0.01$ mg/l (EPA)

$P_{mesotrophic/eutrophic} = 0.02$ mg/l (EPA)

$$L_{oligotrophic/mesotrophic} = 0.01(1.850)\left(1 + \sqrt{2.813/1.850}\right)$$
$$= 0.0413 \text{ gm/m}^2\text{yr}\left(1\text{kg}/1000\text{g}\right)\left(3.676 \times 10^5 \text{m}^2\right)$$
$$= 15.2 \text{ kg/yr}$$

$$L_{mesotrophic/eutrophic} = 2\left(L_{o/m}\right)$$
$$= 0.0826 \text{ gm/m}^2\text{yr}$$
$$= 30.4 \text{ kg/yr}$$

Dillon - Rigler

$$L = \frac{PQ}{1-R_{KD}}$$

$$R_{KD} = 0.426\, e^{(-0.271\, z/t)} + 0.574\, e^{(-0.00949\, z/t)}$$

$$= 0.426\, e^{(-0.271)(1.85)} + 0.574\, e^{(-0.00949)(1.85)}$$

$$= 0.82$$

$Q = 6.8 \times 10^5\ m^3/yr$

$P_{oligo/meso} = 0.01\ mg/l$ (EPA)

$P_{meso/eutro} = 0.02\ mg/l$ (EPA)

$$L_{oligo/meso} = \frac{0.01(6.8 \times 10^5)}{(1-0.82)} = 3.78 \times 10^4\ g/yr = 37.8\ kg/yr$$

$$L_{meso/eutro} = 0.02/0.01\ (37.8) = 75.6\ kg/yr$$

Reckhow (1979)

$$L = P\left[\frac{18z}{10+z} + 1.05\left(\frac{z}{T}\right)e^{0.012\, z/T}\right]$$

all parameters previously defined

$$L_{oligo/meso} = 0.01\left[\frac{18(2.813)}{10+2.813} + 1.05(1.85)e^{0.012(1.85)}\right]$$

$$L_{oligo/meso} = 0.059 \ g/m^2\,yr \ (3.674 \times 10^5 m^2)/1000 g/kg$$

$$= 21.8 \ kg/yr$$

$$L_{meso/eutro} = 0.02/0.01 \ (21.8) = 43.7 \ kg/yr$$