Updated: 4 October 2017

Print version

CEE 577: Surface Water Quality Modeling

Lecture #8

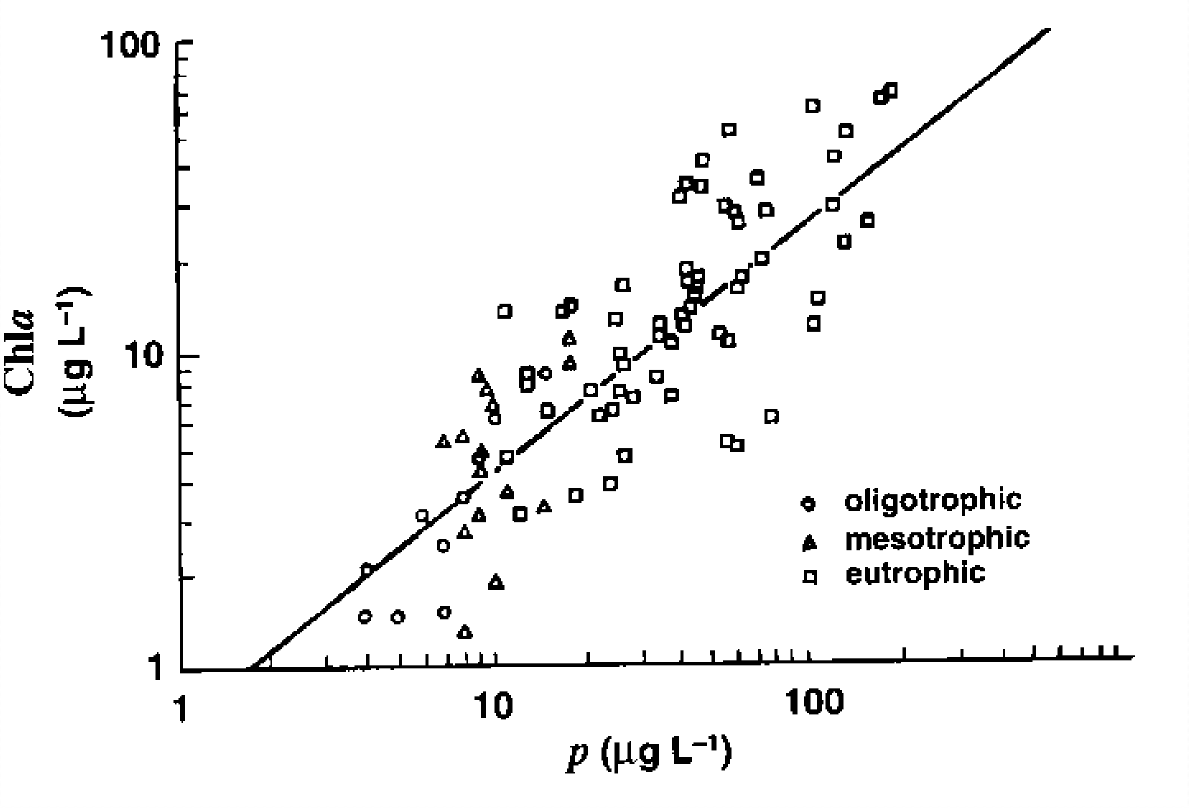
(Simple P models & uncertainty)

Chapra L29 (1st half) & handout

Lake Nutrient Classification

Phosphorus Conc. (mg/L)	Trophic State	Lake Use
<0.010	Oligotrophic	Suitable for water-based recreation and propagation of cold water fisheries, such as trout. Very high clarity and aesthetically pleasing. Excellent as a drinking water source.
0.010 - 0.020	Mesotrophic	Suitable for water-based recreation but often not for cold water fisheries. Clarity less than oligotrophic lake.
0.020 - 0.050	Eutrophic	Reduction in aesthetic properties diminishes overall enjoyment from body contact recreation. Generally very productive for warm water fisheries. High TOC and algal tastes & odors make these waters less desirable as a water supply.
> 0.050	Hyper-eutrophic	A typical "old-aged" lake in advanced succession. Some fisheries, but high levels of sedimentation and algae or macrophyte growth may be diminishing open water surface area. Generally, unsuitable for drinking water supply.

Phosphorus and productivity



Clarity and productivity

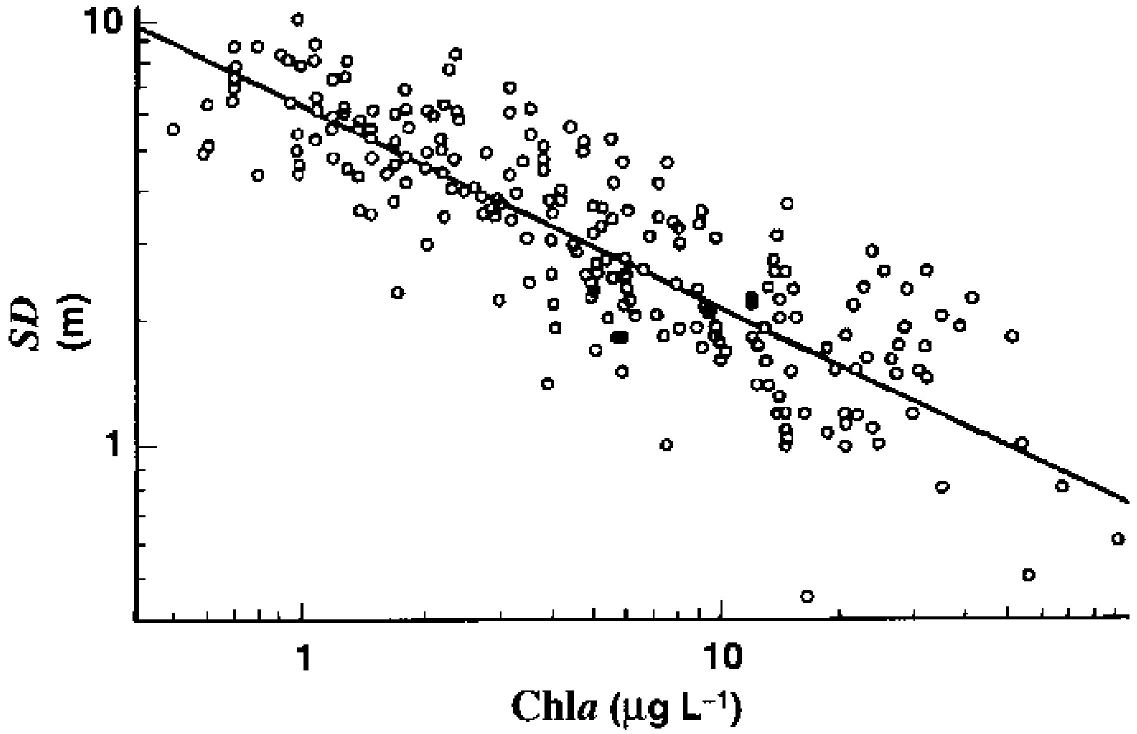


FIGURE 29.6
The relationship between Secchi-disk depth and chlorophyll *a* (from Rast and Lee 1978).

Chapra, pg 541

Oxygen depletion and P

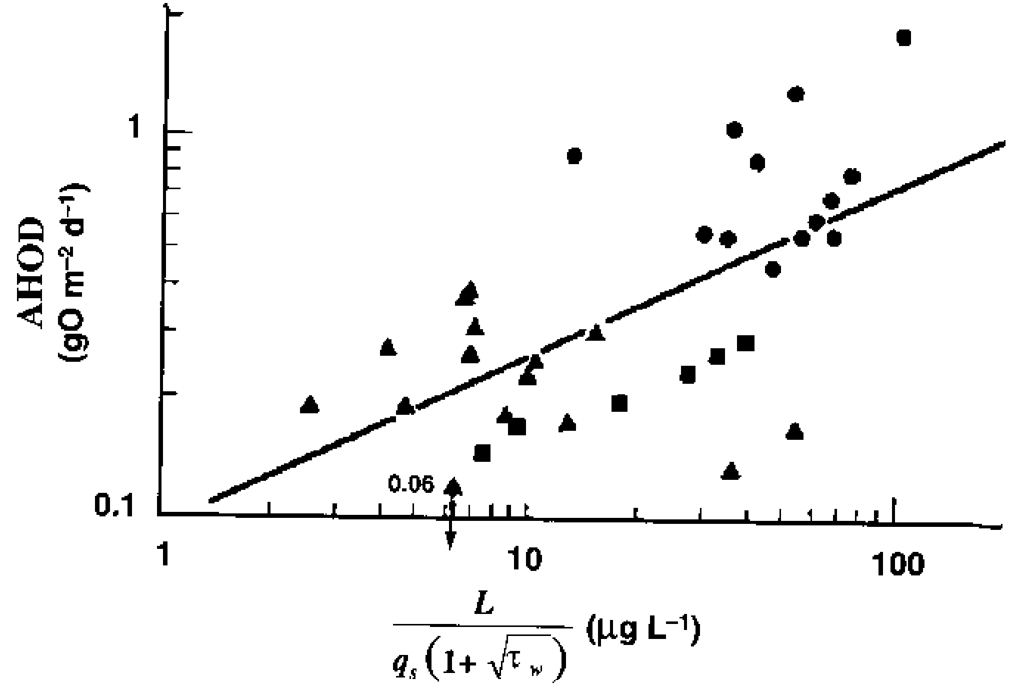
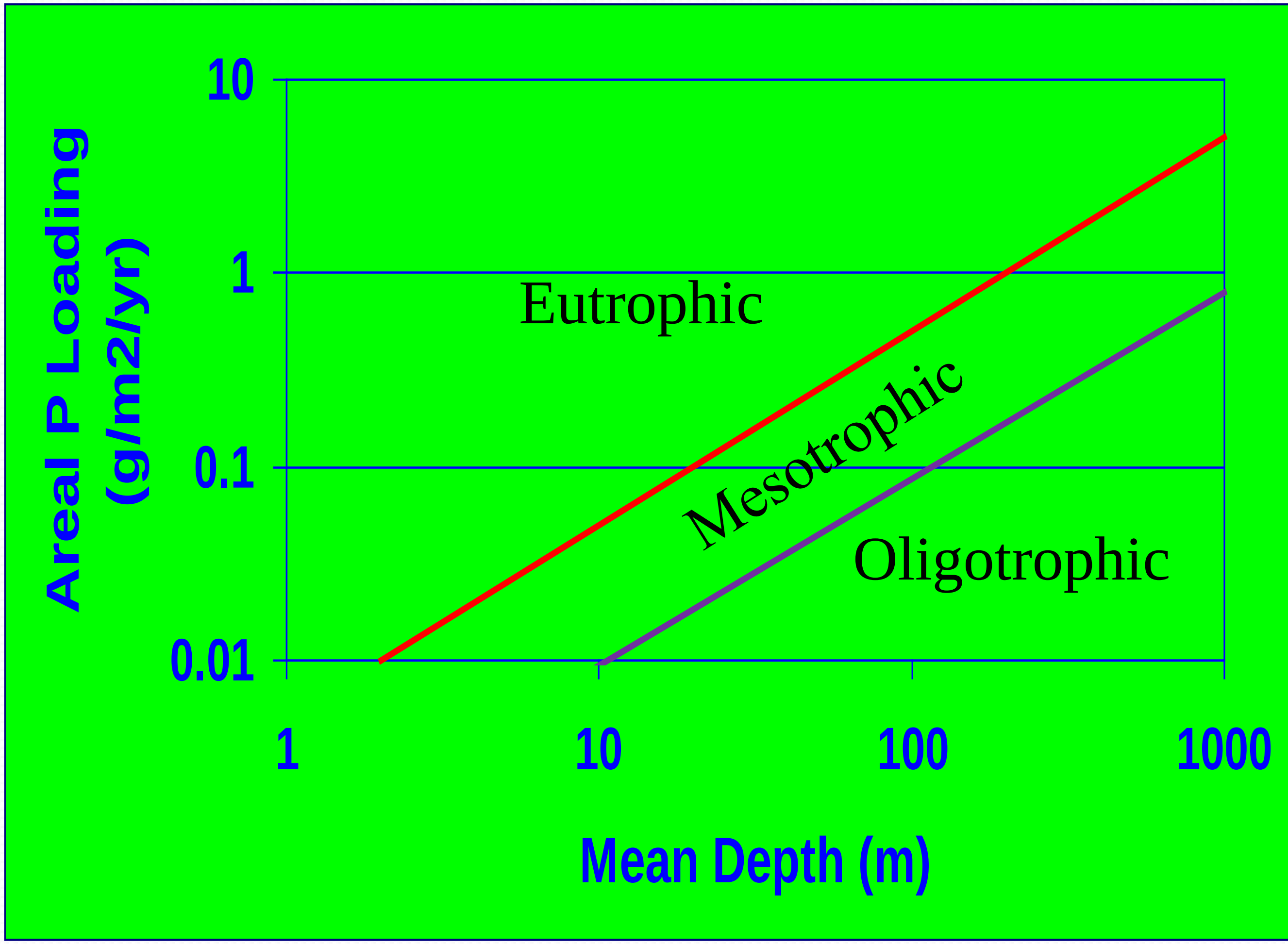


FIGURE 29.8
The relationship between areal hypolimnetic oxygen demand and phosphorus loading (Rast and Lee 1978).

Empirical Modeling

- Vollenweider's phosphorus loading plot
- P=fn(L/Z)
- refer to Chapra, pg. 535



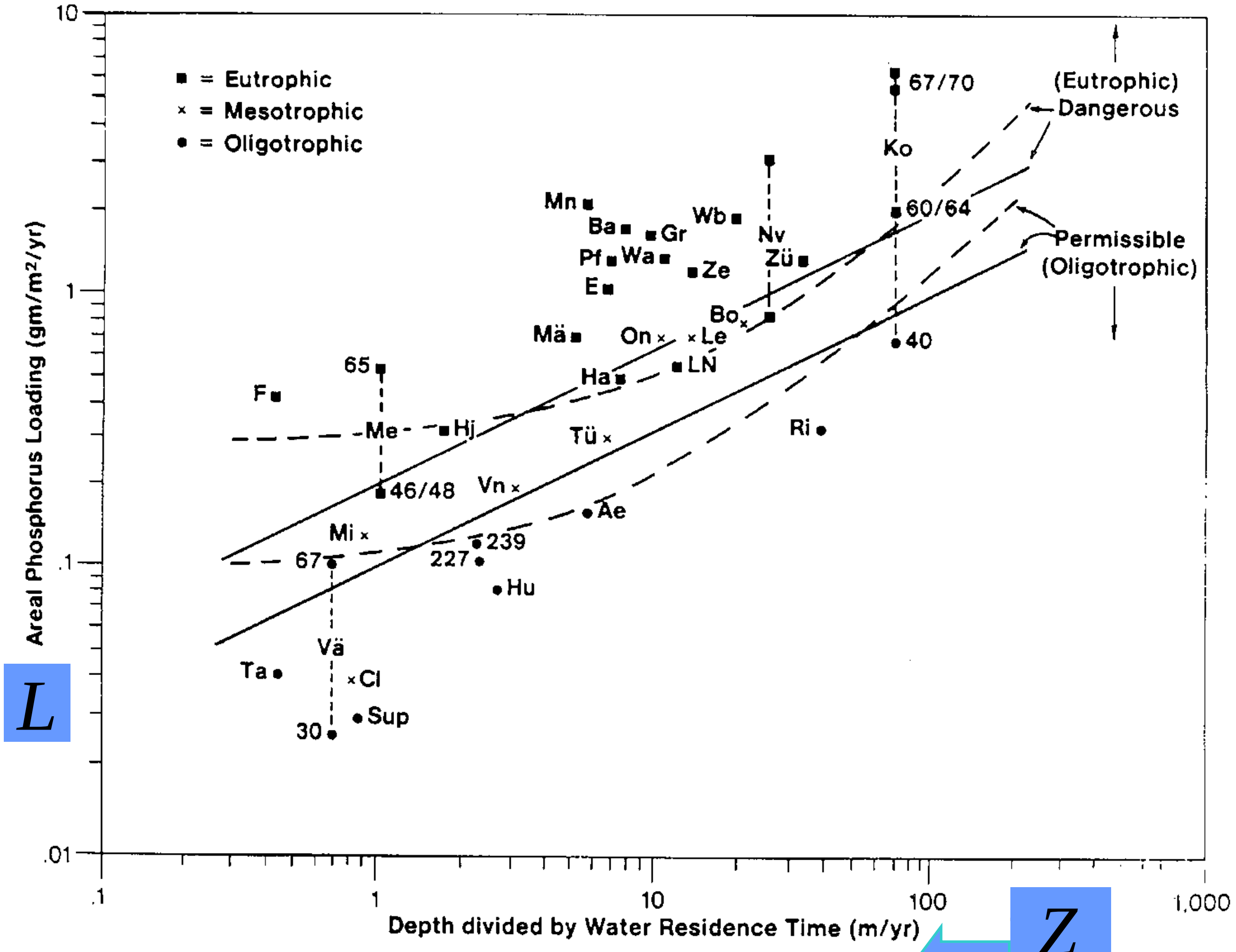
Depth is H or Z

Total Maximum Daily Load (TMDL)

- See lecture #38, extra topic
- Definition (from DEP Website):
  - *"A TMDL is the greatest amount of a pollutant that a waterbody can accept and still meet water quality standards for protecting public health and maintaining the designated beneficial uses of those waters for drinking, swimming, recreation, and fishing. A TMDL is implemented by specifying how much of that pollutant can come from point, nonpoint, and natural sources."*
    - *"The TMDL provisions require states to identify and list waterbodies that are threatened or not meeting water quality standards despite controls on point source discharges."*
- For MA studies see DEP website
  - http://www.mass.gov/eea/agencies/massdep/water/watersheds/total-maximum-daily-loads-tmdls.html

Empirical P Models (cont.)

- Vollenweider modifies earlier model for effects of flushing
- x-axis is equivalent to hydraulic overflow rate, Q/A_s.



L

$\frac{Z}{\tau_w}$

Simple Lake P Model

- This model is based on a simple mass balance with terms for loading (W), settling, and outflow. There is no spatial, or temporal resolution

$$V\frac{dP}{dt} = W - v_s P A_s - QP$$

- Dividing both sides by the surface area (A_s) gives:

$$H\frac{dP}{dt} = L - v_s P - q_s P$$

- where, H is the lake depth, L is the areal loading (W/A_s) and q_s is the overflow rate (Q/A_s). At steady state ($dP/dt = 0$), the solution becomes:

$$P = \frac{L}{v_s + q_s}$$

Simple Lake P Model (cont.)

- Based on data from 47 northern temperate lakes included in EPA's National Eutrophication Survey, the settling velocity (in m/yr) was found to be an empirical function of the overflow rate[1]:

$$v_s = 11.6 + 0.2 q_s$$

- so substituting this into the steady state model above, we get:

$$P = \frac{L}{11.6 + 1.2 q_s}$$

[1] From: Reckhow, 1979 [JWPCF 51(8)2123-2128] "Uncertainty Analysis Applied to Vollenweider's Phosphorus Loading Criterion"

Simple Lake P Model (cont.)

$$P = \frac{L}{11.6 + 1.2 q_s}$$

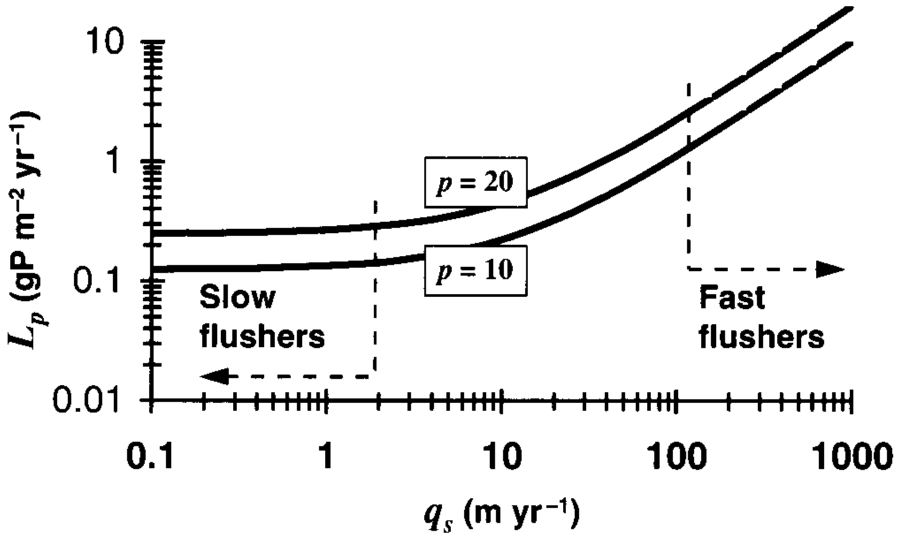
- where:
  - P = mean annual total phosphorus concentration (g-P/m^3 or mg-P/L)
  - L = mean annual areal phosphorus loading (g-P/m^2-yr)
  - q_s = mean annual areal water loading or overflow rate (m/yr) = Q/A_s
- This model was developed from lakes with the following characteristics
  - phosphorus concentrations in the range of 0.004-0.135 mg/L
  - phosphorus loadings of 0.07-31.4 g-P/m^2-yr
  - overflow rates of 0.75-187 m/yr.
- It should not be used for lakes whose characteristics are outside of this range.

Simple Lake P Model (cont.)

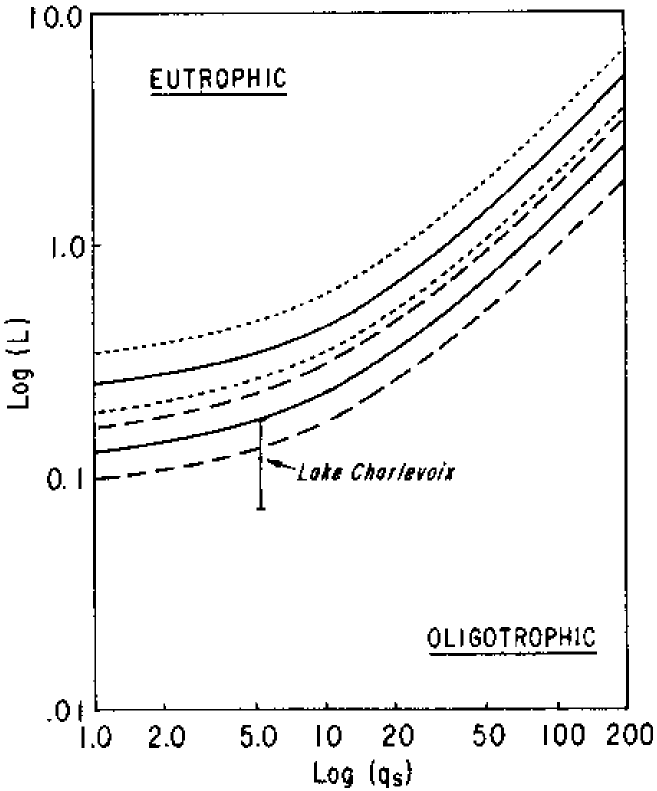
- When used properly, the log transform of the model has an estimated error (s_{mlog}) of 0.128. This value was determined from comparison of observed and predicted phosphorus concentrations in the 47 lakes. Therefore, considering error, the model can be written as:

$$L = \left(11.6 + 1.2 q_s\right)\left[10^{\log(P) \pm s_{m\log}}\right]$$

Modeling Perspectives



From Chapra (pg 538)



from: Reckhow, 1979

Determination of Areal Water Loading (overflow rate)

- $q_s = Q/A_s$
- If Q is not directly measurable from inflow or outflow, then it can be estimated from:
  - $Q = (A_d \times r) + (A_s \times Pr)$

where:

q_s = areal water loading (m/yr)

Q = inflow water volume to lake (m^3/yr)

A_d = watershed area (land surface) (m^2)

A_s = lake surface (m^2)

r = total annual unit runoff (m/yr)

Pr = mean annual net precipitation (m/yr)

Data Collection

- Determine total drainage area (A_d) from a GIS database, or USGS maps, using a polar planimeter, or cut paper with squares.
- Estimate the surface area of the lake (A_s). This may also be done by GIS or planimetry using a USGS map, or the cut paper method.
- Estimate annual runoff (r) which is usually expressed in meters/year. This information is generally available from the USGS.
- Determine average annual net precipitation (P_r), also expressed as meters/year. This information can usually be obtained from the USGS or the US Weather Service.

Determination of Areal Loading with Uncertainty

- Total phosphorus mass loading (W) as proposed by Reckhow et al. (1980):
  - $W = (Ec_f \text{ x } Area_f) + (Ec_{ag} \text{ x } Area_{ag}) + (Ec_u \text{ x } Area_u) + (Ec_a \text{ x } A_s) + (Ec_{st} \text{ x } \#\text{capita-yrs x } [1\text{-S.R.}]) + PSI$

where:

Ec_f = export coefficient for forest land (kg/ha-yr)

Ec_{ag} = export coefficient for agricultural land (kg/ha-yr)

Ec_u = export coefficient for urban area (kg/ha-yr)

Ec_a = export coefficient for atmospheric input (kg/ha-yr)

Ec_{st} = export coefficient to septic systems impacting the lake (kg/(capita-yr)-yr)

$Area_f$ = area[1] of forested land (ha)

$Area_{ag}$ = area of agricultural land (ha)

$Area_u$ = area of urban land (ha)

A_s = surface area of lake (ha)

#capita-yrs number of capita-years in watershed serviced by septic tank impacting the lake

S.R. = soil retention coefficient (dimensionless)

PSI = point source input (kg/yr)

Data Collection

- Estimate land use drainage areas (forested, agricultural, urban).
  - This information may be available from:
    - local planning agencies
    - otherwise it may be obtained from GIS data.
  - For future projections, high and low estimates are needed for assessment of uncertainty
- Choose Export Coefficients for each category.
  - Ranges should be selected for the major sources (often all but precipitation).
    - Choice depends on characteristics of watershed as compared to those previously studied, for which there already exists export coefficients. Other factors may play a role such as the use of phosphate detergents (will impact E_{cst}).

General P Export Coefficients

- From Reckhow et al. 1980

Source	Symbol	Units	High	Mid-range	Low
Agricultural	Ec_{ag}	kg/(ha-yr)	3.0	0.4-1.7	0.10
Forest	Ec_{f}	kg/(ha-yr)	0.45	0.15-0.3	0.02
Precipitation	Ec_{a}	kg/(ha-yr)	0.60	0.20-0.50	0.15
Urban	Ec_{u}	kg/(ha-yr)	5.0	0.8-3.0	0.50
Input to septic tanks	Ec_{st}	kg/(capita-yr)	1.8	0.4-0.9	0.3

- Mattson & Isaac (1999)
  - Argue that MA may have a lower P export than the US average

Septic System Calculations

- Estimate SR:
  - This is a number between 0 and 1 that indicates how well the soil and associated plants take up phosphorus. When it is low more of the phosphorus reaches the lake. Factors to consider include:
    - phosphorus adsorption capacity
    - natural drainage
    - permeability
    - slope
- Estimate number of capita-years on septic systems impacting lake
  - This requires some judgment, but usually a strip of about 20-200 m wide surrounding the lake is considered the zone of influence. All septic systems within this zone would be counted in the following calculation:

Data Collection (cont.)

Total # of capita-years = average # of persons per living unit X # days spent at unit per year /360 X # of living units within zone of influence

- Estimate Point source inputs: possibly from NPDES permits

- Now determine high, low and most likely estimates of W using above equation. These are obtained from high, low and most likely estimates of the various input parameters (note that the low value of S.R. should go with the high estimate of W, and vice versa).

Determine areal loading (L)

- From these three estimates of W, calculate the high, most likely and low estimates for annual areal phosphorus loading
  - $L = W/A_s$
- Evaluate the three estimates of phosphorus concentration

$$P = \frac{L}{11.6 + 1.2 q_s}$$

Estimate Prediction Uncertainty (sT)

- This requires that the model error be appropriately combined with the uncertainty inherent in the model terms. This is done on log transforms of the model results, using standard error propagation techniques.
  - Model Error
    - positive and negative model errors are calculated separately and not presumed equal.

    - sm+ = antilog[logPml + smlog] - Pml
    - sm- = antilog[logPml - smlog] - Pml

  - Error in Model Terms
    - sL+ = (P(high) - P(ml))/2
    - sL- = (P(ml) - P(low))/2

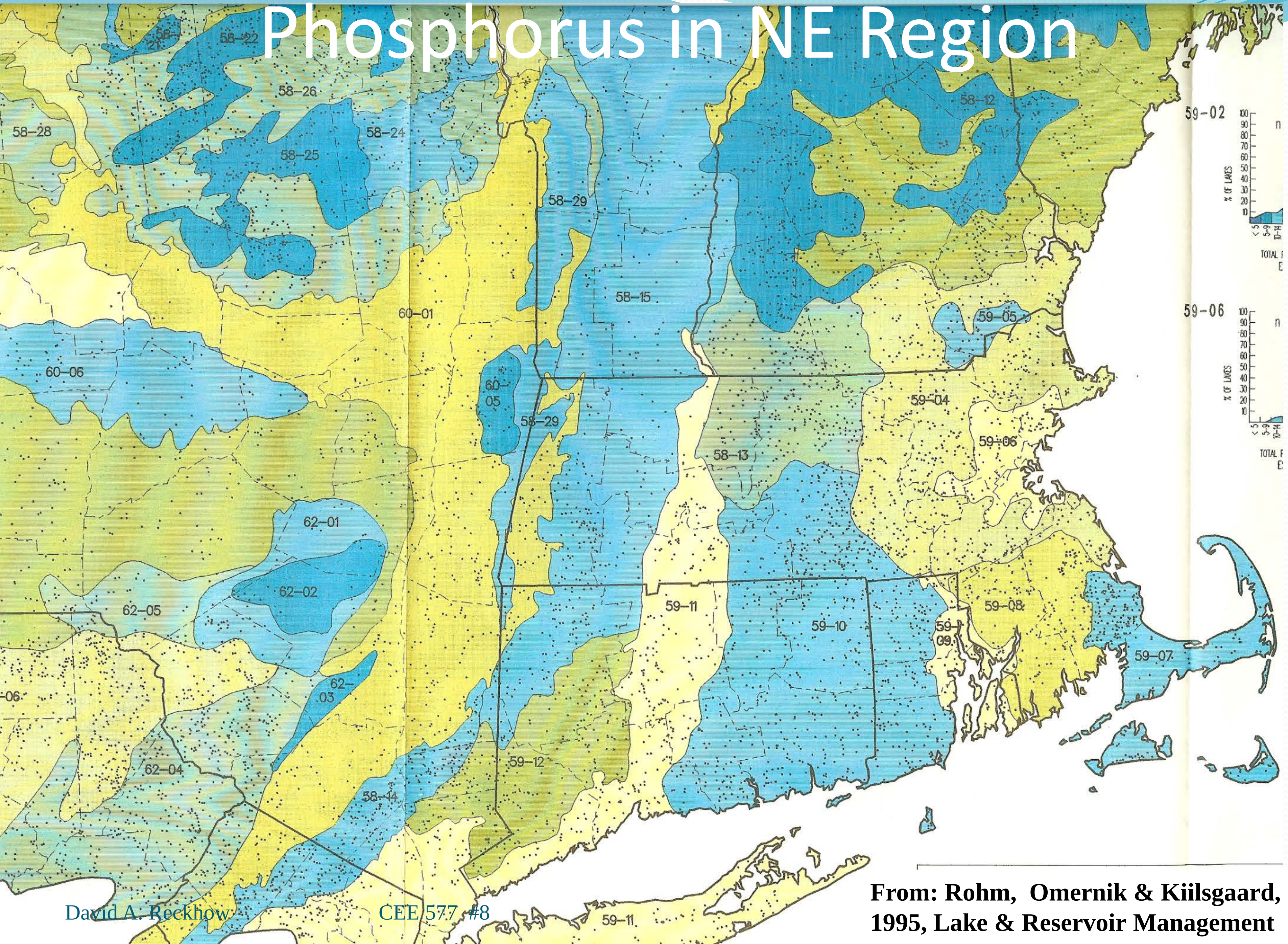
Confidence Intervals

- **Overall Error**
  - $s_{T+} = [(s_{m+})^2 + (s_{L+})^2]^{0.5}$
  - $s_{T-} = [(s_{m-})^2 + (s_{L-})^2]^{0.5}$
- **Confidence Intervals**
  - The intervals are 55% for 1 prediction error, and 90% for 2 (based on a modification of the Chebyshev inequality).

55% confidence interval: $(P_{(ml)} - s_{T-}) < P < (P_{(ml)} + s_{T+})$

90% confidence interval: $(P_{(ml)} - 2s_{T-}) < P < (P_{(ml)} + 2s_{T+})$

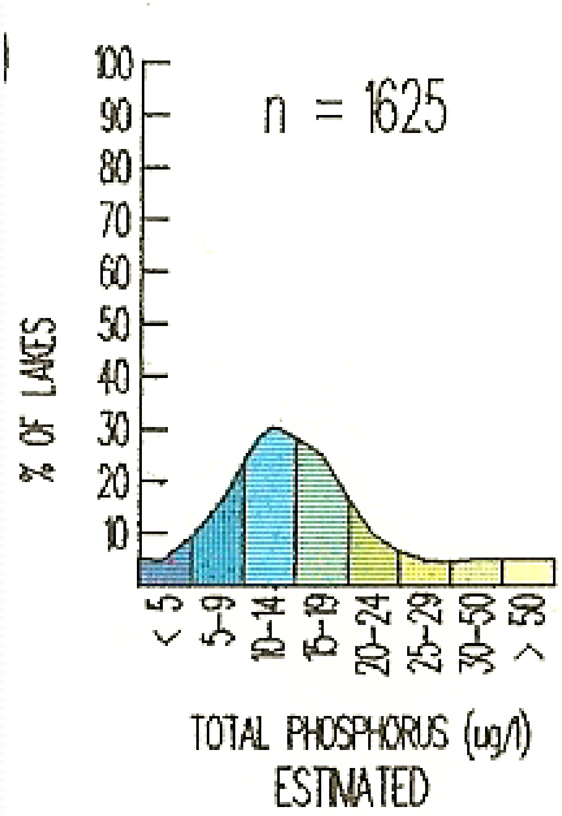
Phosphorus in NE Region



From: Rohm, Omernik & Kiilsgaard, 1995, Lake & Reservoir Management

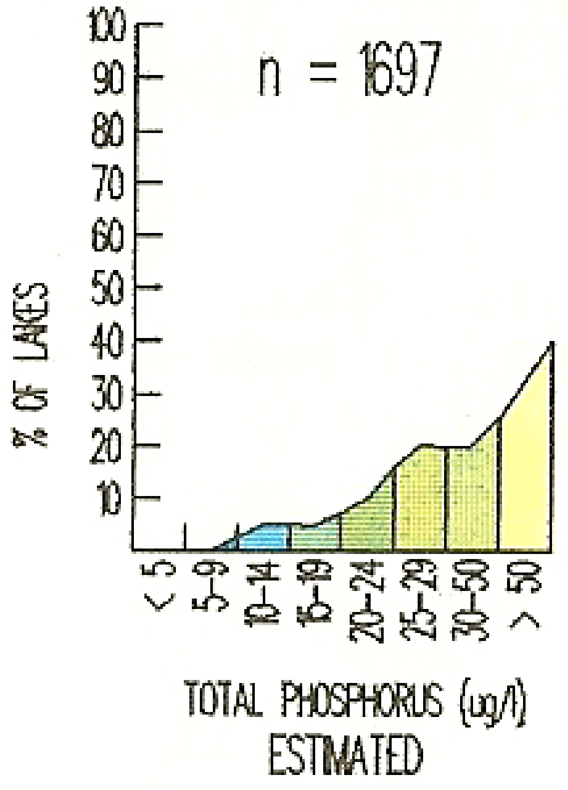
Regional P Description I

- 59-10
  - Most lakes are small and shallow with many being human-made. Landforms predominantly comprise numerous low relief hills rising above the general level of outwash plains.   Glacial till is derived from gneiss, schist, and granite. LULC is a mix of central hardwood forest and cropland/pasture. The lack of reliable lake P data in MA coupled with the increased urban/industrial presence of south-central MA makes estimates of patterns of P in the northern part of this region difficult.



Regional P Description II

- 59-11
  - Mostly high phosphorus values. The region encompasses metropolitan NY, the highly urbanized coastal margin of CT and the CT River Valley. Lakes in this region are typically small., shallow, and Human-made. Landscape associations that might affect lake total-P values in the urbanized half of this region are masked by impacts brought on by extensive coverage of residential, commercial and industrial land use. In the CT River Valley, P values are elevated due to intensive agriculture practiced throughout the valley. The estimated P distribution is shifted somewhat to lower classes to reflect the expectation of lower P for water bodies located on the margins of the valley.

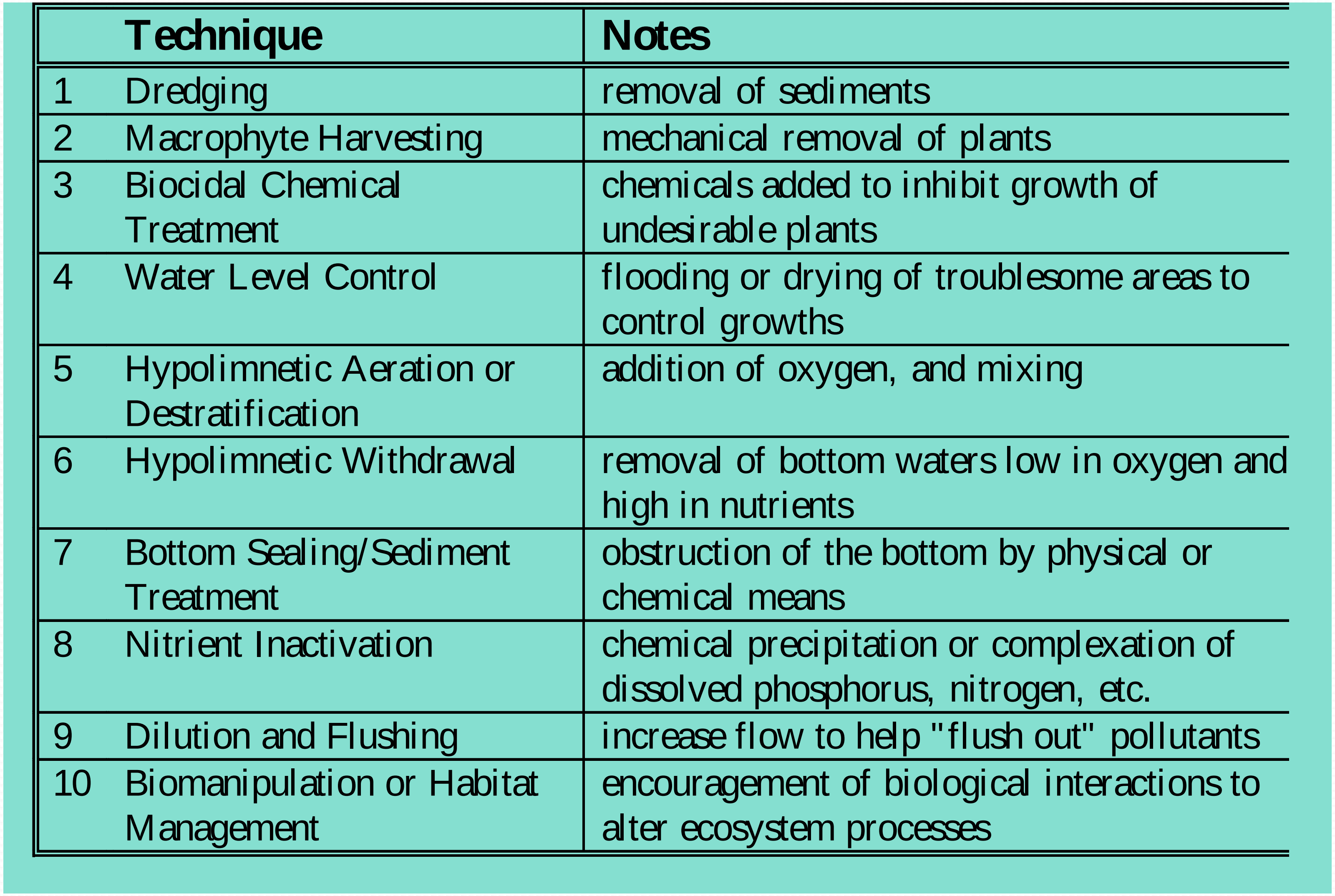


Mattson & Isaac approach

- Generalized model
  - $W = (Ec_f \text{ x } Area_f) + (Ec_r \text{ x } Area_r) + (Ec_u \text{ x } (Area_u)^{0.5}) + (Ec_a \text{ x } A_s) + (Ec_{st} \text{ x } \#septics)$
- Model calibrated in terms of hectares
  - $W\ (kg/yr) = 0.13(Area_f) + 0.3*(Area_r) + 14*(Area_u)^2 + 0.5*(\#\ septics)$
  - Note that: $Area_r$ = rural area
  - 1 hectare = 2.47 acres = 10,000 m^2
- Based on 16 MA lakes,
  - Error for W is estimated at ±36%

From: *"Calibration of Phosphorus Export Coefficients for Total Maximum Daily Loads of Massachusetts Lakes"* M.D. Mattson & R.A. Isaac, J. Lake & Reservoir Mgmt., 15(3)209-219.

In-lake Management

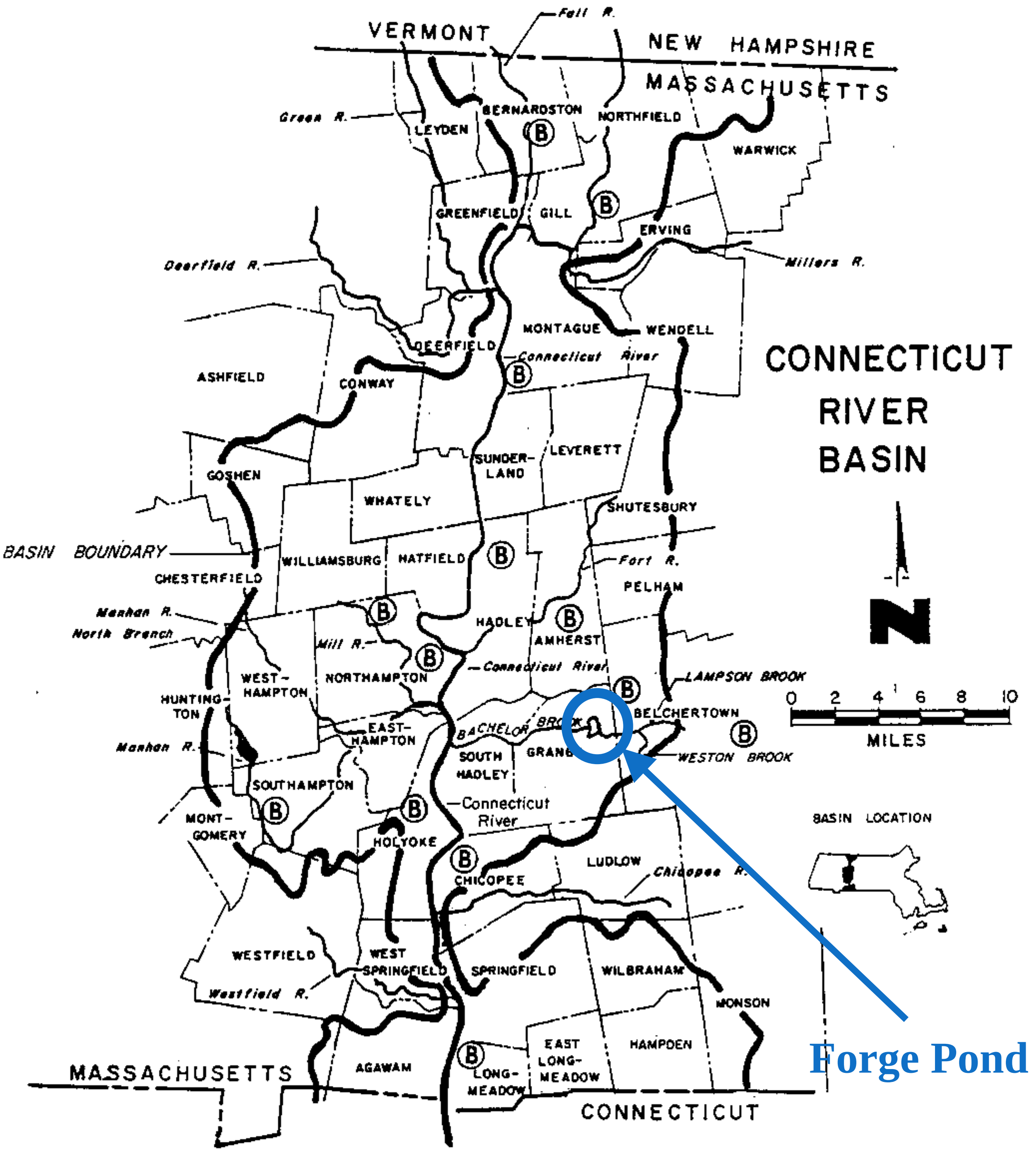


	Technique	Notes
1	Dredging	removal of sediments
2	Macrophyte Harvesting	mechanical removal of plants
3	Biocidal Chemical Treatment	chemicals added to inhibit growth of undesirable plants
4	Water Level Control	flooding or drying of troublesome areas to control growths
5	Hypolimnetic Aeration or Destratification	addition of oxygen, and mixing
6	Hypolimnetic Withdrawal	removal of bottom waters low in oxygen and high in nutrients
7	Bottom Sealing/Sediment Treatment	obstruction of the bottom by physical or chemical means
8	Nitrient Inactivation	chemical precipitation or complexation of dissolved phosphorus, nitrogen, etc.
9	Dilution and Flushing	increase flow to help "flush out" pollutants
10	Biomanipulation or Habitat Management	encouragement of biological interactions to alter ecosystem processes

Watershed Management

	Technique	Notes
1	Zoning/Land Use Planning	Management of land use
2	Stormwater/Wastewater Diversion	re-routing of wastewater flows
3	Detention Basin Use and Maintenance	increase time of travel for polluted waters so natural purification processes act
4	Sanitary Sewers	installation of community-level collection syst
5	Maintenance and Upgrade of On-site Treatment Systems	better operation & performance of home septi systems, etc.
6	Agricultural Best Management Practices	use of improved techniques in forestry, anima crop science
7	Bank and slope stabilization	erosion control to reduce sediment and associa loadings
8	Increased street sweeping	frequent washing and removal of urban runof contaminants
9	Behavioral Modifications	
	a. use of Non-phosphate detergents	eliminates source of P
	b. eliminate garbage grinders	reduces general organic loading
	c. minimize lawn fertilization	reduces nutrient loading
	d. restrict motorboat activity	reduce turbulence and sediment resuspension
	e. eliminate illegal dumping	reduce a wide range of conventional and toxi inputs

Forge Pond


CONNECTICUT RIVER BASIN
VERMONT
NEW HAMPSHIRE
MASSACHUSETTS
CONNECTICUT
Fall R.
Green R.
Deerfield R.
Millers R.
Connecticut River
Fort R.
Manhan R.
North Branch
Mill R.
LAMPSON BROOK
BACHELOR BROOK
WESTON BROOK
Chicopee R.
Westfield R.
BASIN BOUNDARY
LEYDEN
BERNARDSTON
NORTHFIELD
WARWICK
GREENFIELD
GILL
ERVING
MONTAGUE
WENDELL
DEERFIELD
ASHFIELD
CONWAY
SUNDERLAND
LEVERETT
GOSHEN
WHATELY
SHUTESBURY
WILLIAMSBURG
HATFIELD
CHESTERFIELD
PELHAM
HADLEY
AMHERST
WESTHAMPTON
NORTHAMPTON
HUNTINGTON
EASTHAMPTON
BELCHERTOWN
SOUTH HADLEY
GRANBY
SOUTHAMPTON
MONTGOMERY
HOLYOKE
CHICOPEE
LUDLOW
WESTFIELD
WEST SPRINGFIELD
SPRINGFIELD
WILBRAHAM
MONSON
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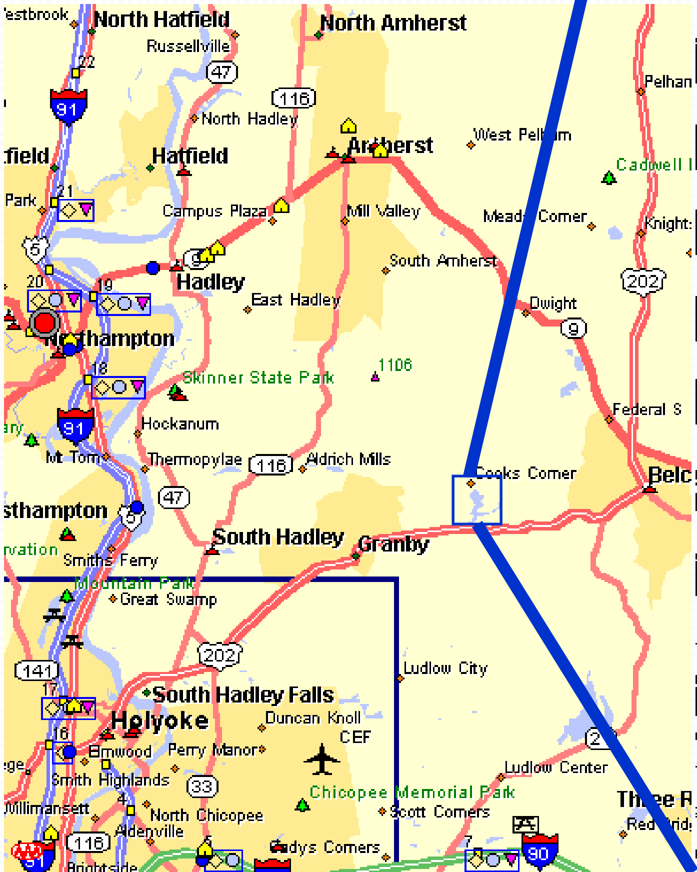
MILES
BASIN LOCATION
Forge Pond

Forge Pond



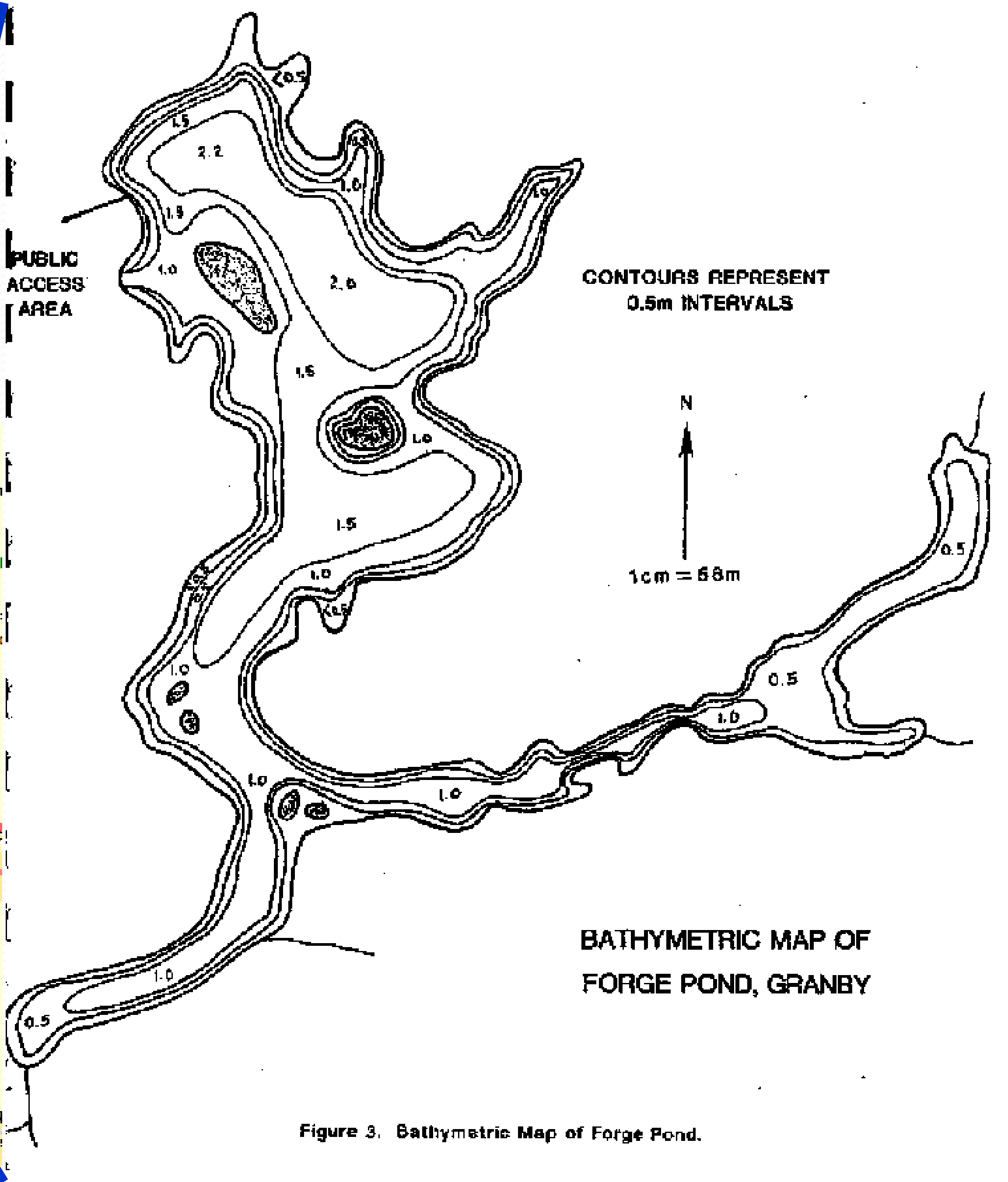
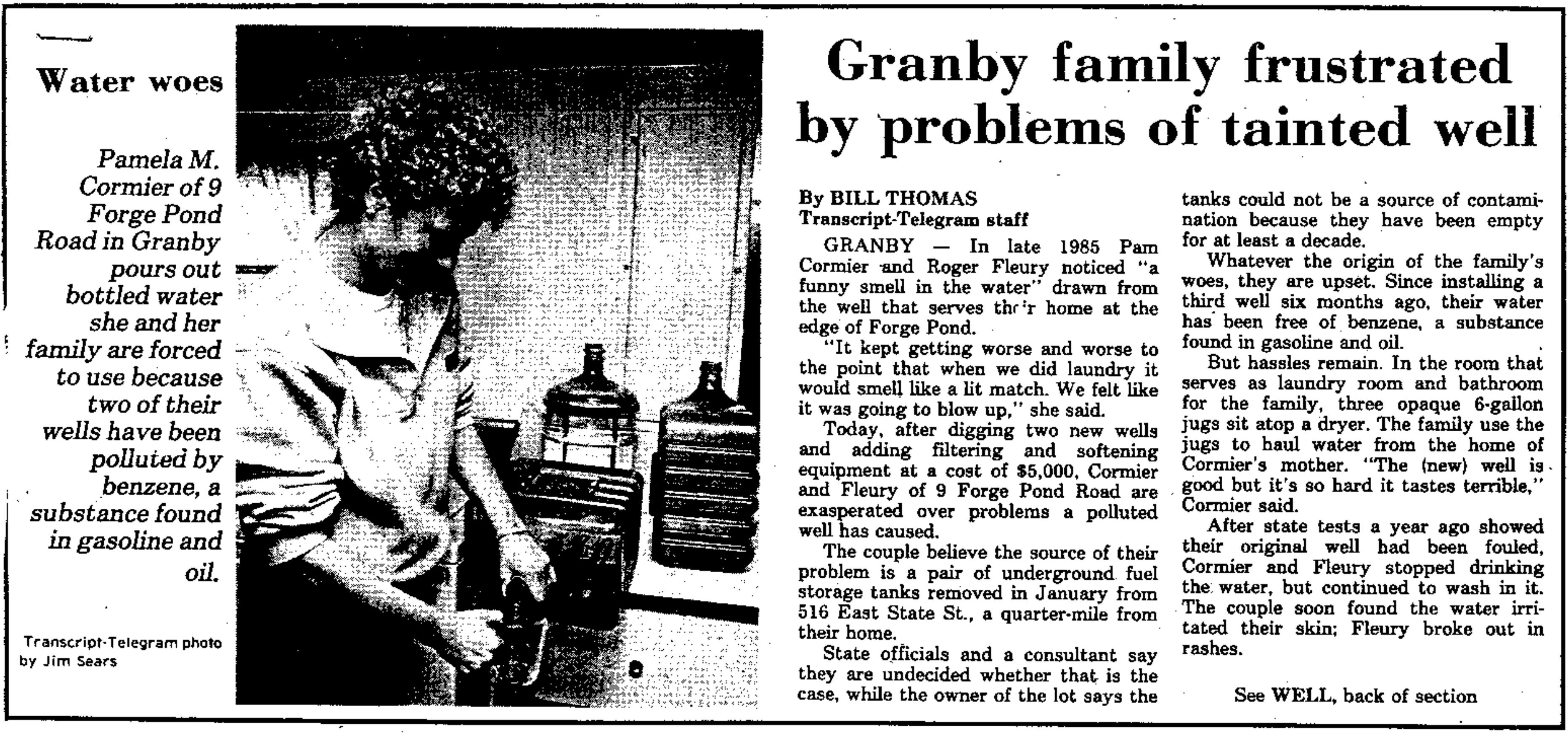


Figure 3. Bathymetric Map of Forge Pond.



Water woes

Pamela M. Cormier of 9 Forge Pond Road in Granby pours out bottled water she and her family are forced to use because two of their wells have been polluted by benzene, a substance found in gasoline and oil.

Transcript-Telegram photo by Jim Sears

Granby family frustrated by problems of tainted well

By BILL THOMAS
Transcript-Telegram staff

GRANBY — In late 1985 Pam Cormier and Roger Fleury noticed "a funny smell in the water" drawn from the well that serves their home at the edge of Forge Pond.

"It kept getting worse and worse to the point that when we did laundry it would smell like a lit match. We felt like it was going to blow up," she said.

Today, after digging two new wells and adding filtering and softening equipment at a cost of $5,000, Cormier and Fleury of 9 Forge Pond Road are exasperated over problems a polluted well has caused.

The couple believe the source of their problem is a pair of underground fuel storage tanks removed in January from 516 East State St., a quarter-mile from their home.

State officials and a consultant say they are undecided whether that is the case, while the owner of the lot says the tanks could not be a source of contamination because they have been empty for at least a decade.

Whatever the origin of the family's woes, they are upset. Since installing a third well six months ago, their water has been free of benzene, a substance found in gasoline and oil.

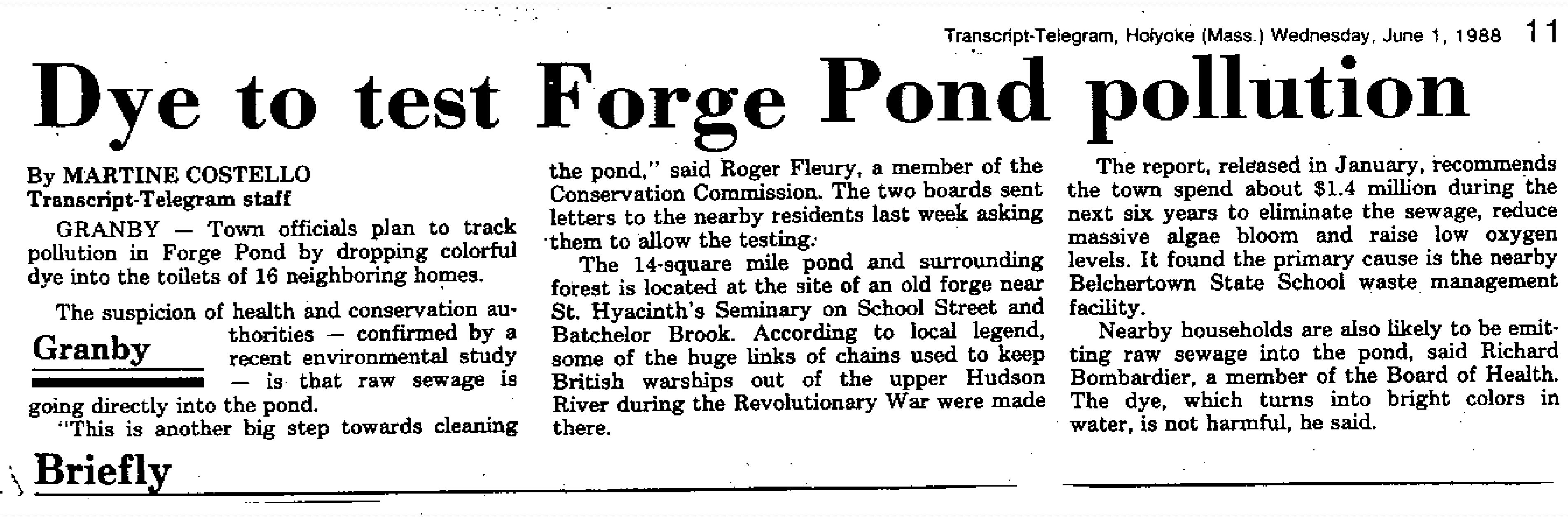
But hassles remain. In the room that serves as laundry room and bathroom for the family, three opaque 6-gallon jugs sit atop a dryer. The family use the jugs to haul water from the home of Cormier's mother. "The (new) well is good but it's so hard it tastes terrible," Cormier said.

After state tests a year ago showed their original well had been fouled, Cormier and Fleury stopped drinking the water, but continued to wash in it. The couple soon found the water irritated their skin; Fleury broke out in rashes.

See WELL, back of section

HTT 11/12/87

Holyoke Transcript-Telegram



Transcript-Telegram, Holyoke (Mass.) Wednesday, June 1, 1988 11

Dye to test Forge Pond pollution

By MARTINE COSTELLO
Transcript-Telegram staff

GRANBY — Town officials plan to track pollution in Forge Pond by dropping colorful dye into the toilets of 16 neighboring homes.

Granby

The suspicion of health and conservation authorities — confirmed by a recent environmental study — is that raw sewage is going directly into the pond.

"This is another big step towards cleaning the pond," said Roger Fleury, a member of the Conservation Commission. The two boards sent letters to the nearby residents last week asking them to allow the testing.

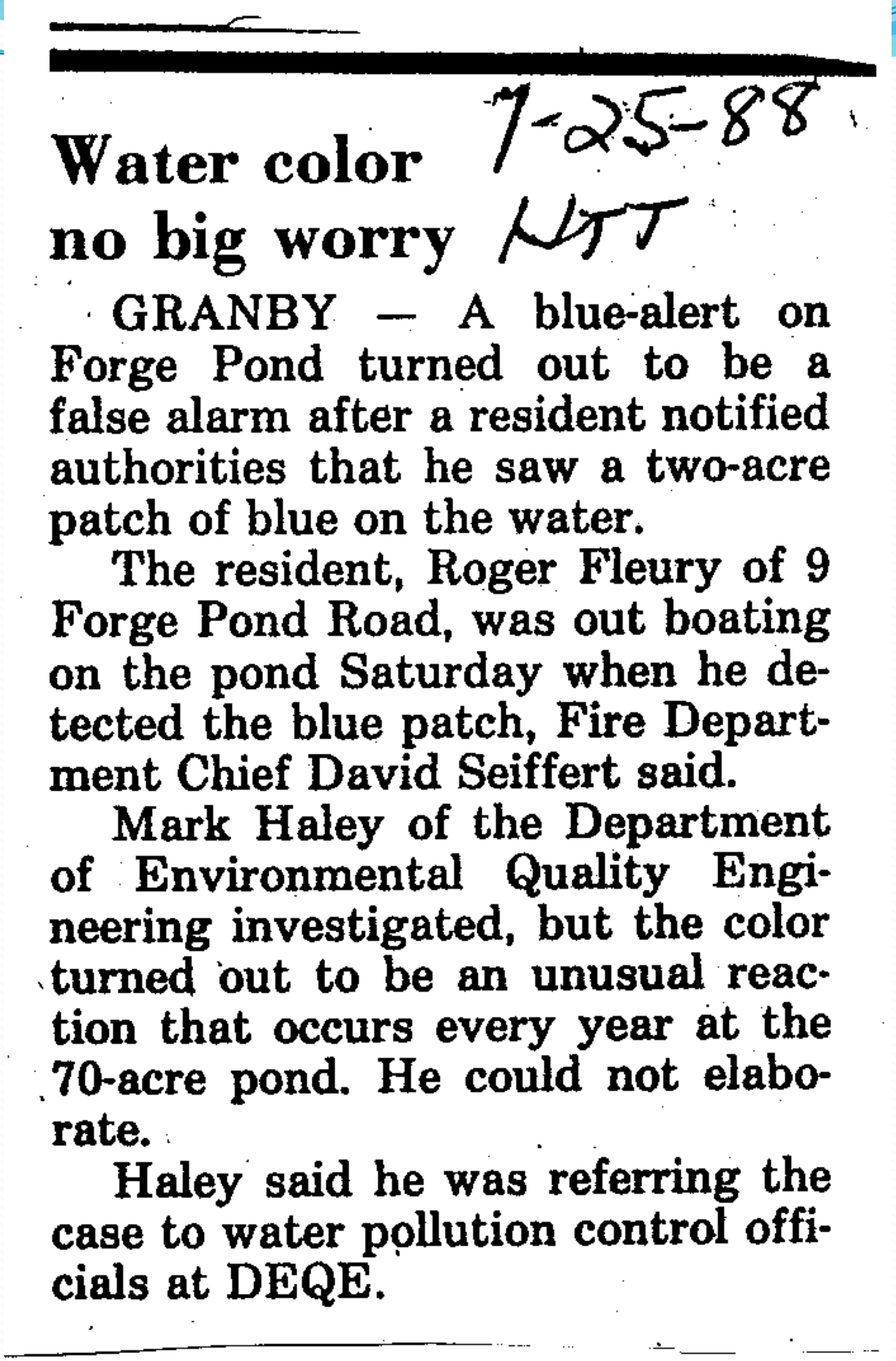
The 14-square mile pond and surrounding forest is located at the site of an old forge near St. Hyacinth's Seminary on School Street and Batchelor Brook. According to local legend, some of the huge links of chains used to keep British warships out of the upper Hudson River during the Revolutionary War were made there.

The report, released in January, recommends the town spend about $1.4 million during the next six years to eliminate the sewage, reduce massive algae bloom and raise low oxygen levels. It found the primary cause is the nearby Belchertown State School waste management facility.

Nearby households are also likely to be emitting raw sewage into the pond, said Richard Bombardier, a member of the Board of Health. The dye, which turns into bright colors in water, is not harmful, he said.

Briefly

Holyoke Transcript-Telegram



7-25-88

Water color no big worry

HTT

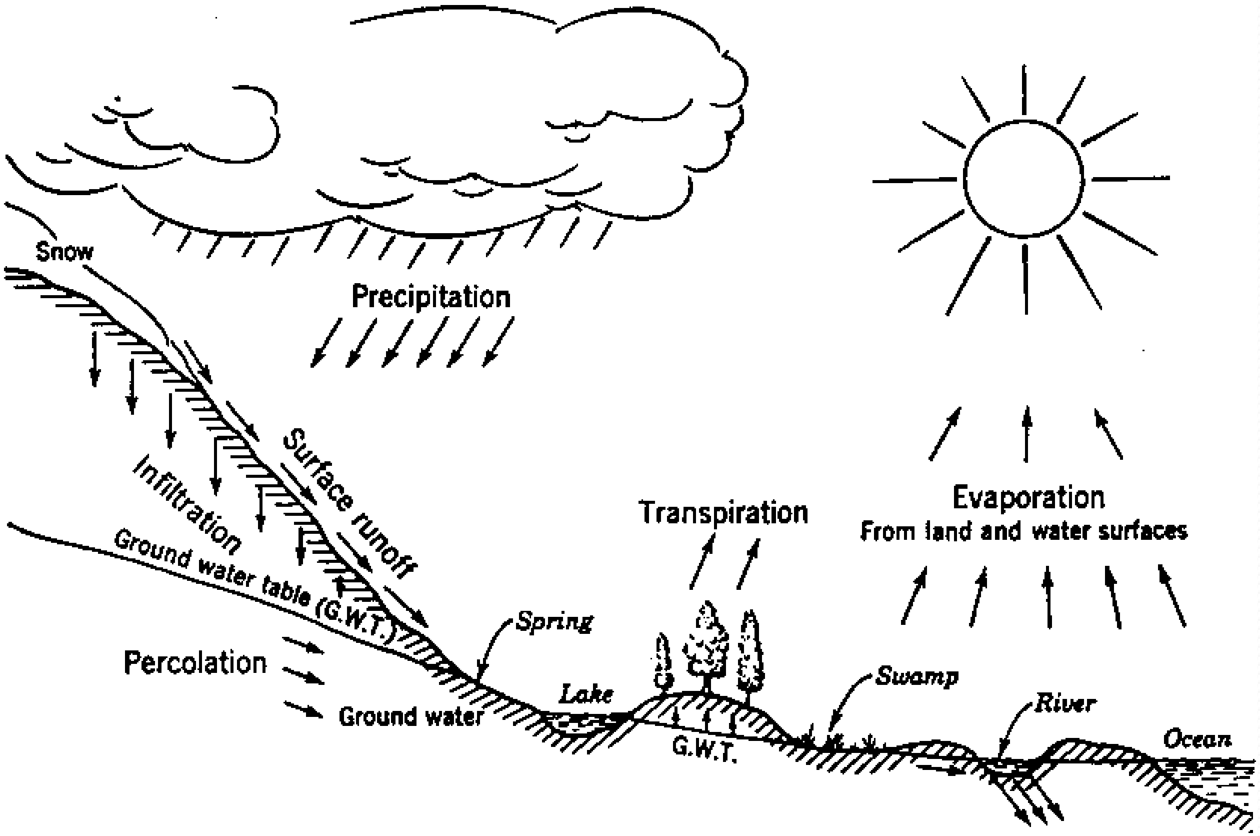
GRANBY — A blue-alert on Forge Pond turned out to be a false alarm after a resident notified authorities that he saw a two-acre patch of blue on the water.

The resident, Roger Fleury of 9 Forge Pond Road, was out boating on the pond Saturday when he detected the blue patch, Fire Department Chief David Seiffert said.

Mark Haley of the Department of Environmental Quality Engineering investigated, but the color turned out to be an unusual reaction that occurs every year at the 70-acre pond. He could not elaborate.

Haley said he was referring the case to water pollution control officials at DEQE.

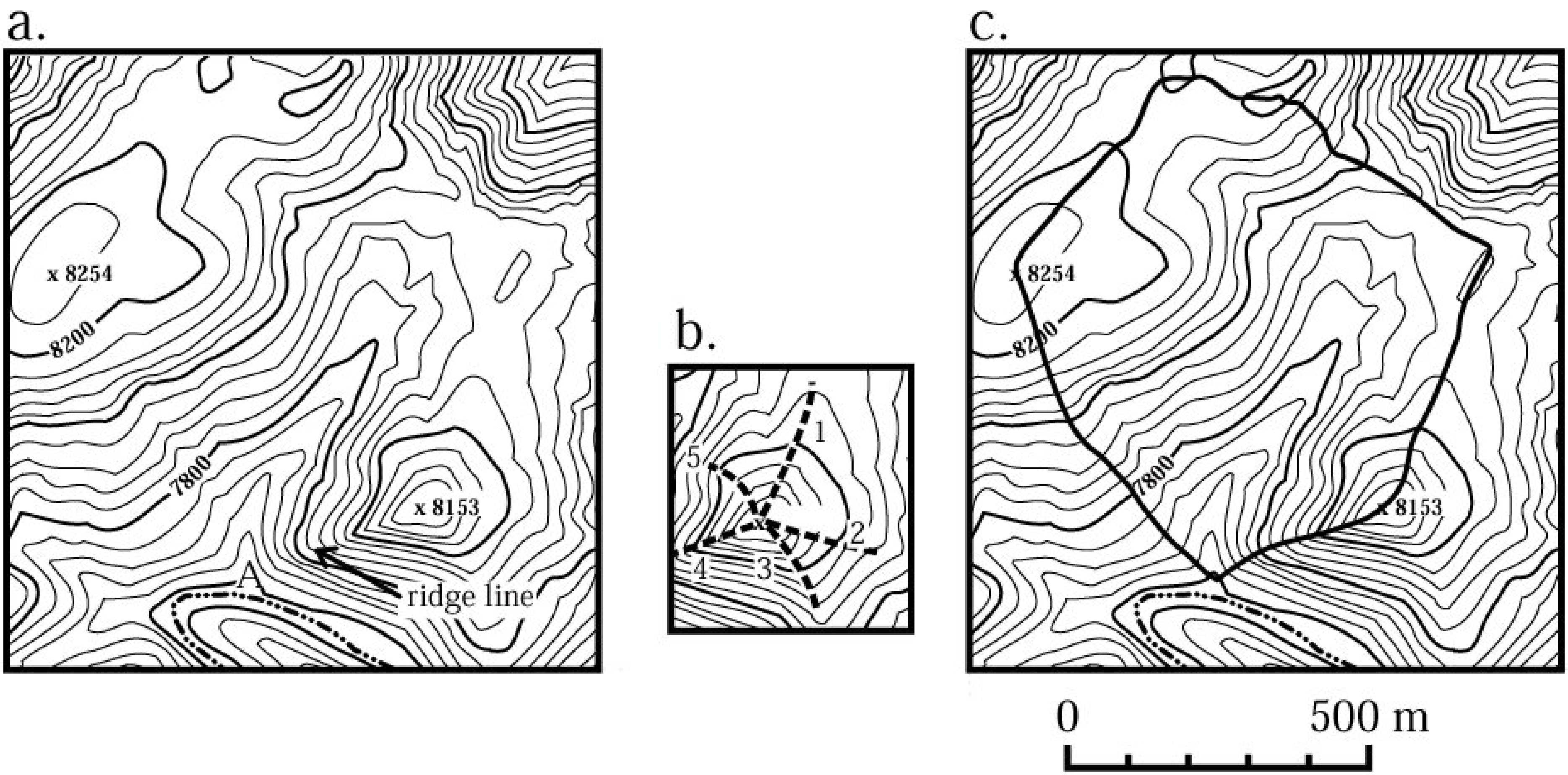
Holyoke Transcript-Telegram



From Water Supply & Wastewater Removal, by Fair Geyer & Okun

Thanks to Colorado State U., ER454 website: http://www.cnr.colostate.edu/class_info/er454/lab4/morph.html

Mapping drainage basins



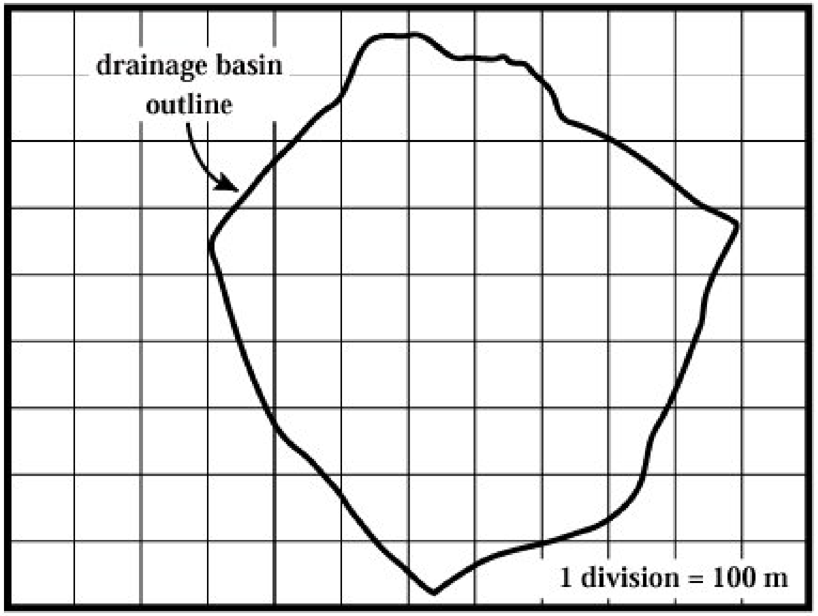
From: Colorado State U., ER454 website: http://www.cnr.colostate.edu/class_info/er454/lab4/morph.html

Basin Delineation (cont.)

- Consider Figure 1a and suppose we wish to draw a line enclosing the drainage basin of the stream whose mouth lies at ‘A'. Beginning at the mouth we can proceed to the east or west. Notice that to the east a narrow ridge rises toward a peak. Runoff on the west side of the ridge will flow through the mouth at "A" whereas water to the east will flow down a hillside and into another stream. The ridge line is a obvious drainage divide, therefore we can begin drawing our perimeter line by tracing its crest. After reaching the peak, you should follow once again follow a ridge. Ridges are most easily recognized as a series of bent contour lines whose apex point *downhill*. Note that five ridges converge at the peak (Figure 1b). Choosing the correct ridge is simply a matter of determining which ridge sheds water into the stream of interest *and* a different stream. Of the 5 ridges in Figure 1b, ridge 4 has already been chosen as a drainage divide. Water shed by ridge 5 will flow into two different basins, but both of these basins ultimately drain to "A". Ridges 2 and 3 separate basins that do not drain to "A". Thus, we find that ridge 1 marks the eastern side of the drainage basin. Tracing the rest of the perimeter is now a matter of choosing the correct ridges (Figure 1c).

From: Colorado State U., ER454 website: http://www.cnr.colostate.edu/class_info/er454/lab4/morph.html

Basins (cont.)



- **Figure 2:** Measuring drainage basin area by counting grid intersections. In this case, each intersection would represent 10,000m^2. The area of this basin is therefore 4,518,528ft^2, 0.162mi^2, 420,000m^2, or 0.42km^2.

From: Colorado State U., ER454 website: http://www.cnr.colostate.edu/class_info/er454/lab4/morph.html

Basins (cont.)

- **To measure area, one would ideally use a digitizer and simply trace the outline of a given basin. This procedure is as accurate as the digitizer and its user. Alternate means include overlaying a basin outline on a sheet of squares or dots. By counting the squares, intersections, or dots, each of which represents a given area, one can determine the area of a basin with modest accuracy. We will estimate basin area using graph paper with 10 divisions per inch. Furthermore, we will count the number of line intersections within a given basin (see Figure 2). We will assume that each intersection represents an area equivalent to a 1/10" by 1/10" square. Using this method, the area of the basin in Figure 2 is calculated as 0.42 km^2. We can cross-check this value using a digitizing tablet. Doing so yields an area of 0.425 km^2. The grid intersection method yielded a fair approximation of the area, but is entirely less satisfactory when areas are small relative to the fineness of the grid.**

- To next lecture