URBAN NONPOINT SOURCE IMPACTS ON A SURFACE WATER SUPPLY

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ABSTRACT

Lake drinking water supplies are particularly vulnerable to nonpoint sources because of cause–effect relationships linking watershed characteristics, nutrient loading, lake eutrophication, treatment plant disturbances, and quality of water supplied to consumers (Walker, 1983). This paper describes results from the first year of an intensive watershed and lake monitoring program undertaken by St. Paul Water Utility, MN. The objectives of the program are: (1) to characterize the limnology of the supply lakes, (2) to quantify major sources of runoff, nutrients, and other pollutants reaching the lakes, and (3) to identify potential control measures for algal-related taste-and-odor problems that have developed in recent years. While diversions from other watersheds account for an average of 85 percent of the flow through the lakes, runoff and nutrient loadings from local watersheds undergoing rapid urban development have become increasingly important. Site-specific and regional data indicate significant effects of urban land uses on runoff and nutrient export. Linked models relate watershed land uses to lake water quality conditions and Water Utility impacts, expressed in terms of the frequency of nuisance-level algal densities and potential costs of chemicals used for taste-and-odor control. The models are used to estimate the impacts of existing and future urban development in the basin on lake water quality conditions and treatment costs.

INTRODUCTION

This paper describes interim results from a diagnostic study of the Vadnais Chain of Lakes, Minnesota, which serves as the water supply for St. Paul. The study has been undertaken by the St. Paul Water Utility to identify causes and corrective measures for taste and odor problems that have occurred with increasing frequency over the past several years. Historical data indicate that taste and odor episodes are generally associated with algal blooms (particularly blue-greens) and lake turnover (Walker, 1985b), as is common for water supplies derived from eutrophic lakes or reservoirs (Lin, 1977). Following is a description of monitoring and modeling efforts to quantify the impacts of local watershed urbanization on existing and future water quality conditions.

ST. PAUL WATER SUPPLY SYSTEM AND MONITORING NETWORK

The Vadnais Lake Watershed (Fig. 1) is a system of 12 interconnected lakes with a drainage area of 6,227 ha (15,381 acres). Morphometric, hydrologic, and water quality characteristics of major lakes in the watershed are summarized in Table 1. Hydrologic data for the 1978–84 period indicate that the Utility diversions account for an average of 85 percent of the inflow to the lake chain (66 percent from the Mississippi River (west) and 19 percent from the Rice Creek Watershed (north)). The remainder of the inflow is attributed to local watershed runoff (9 percent) and direct precipitation on lake surfaces (6 percent). The average withdrawal rate at the Utility's Vadnais Lake intake (the only functional outlet from the watershed) is 187,000 m^3/day (49.4 million gallons/day). The hydraulic residence time of the main lake chain (140 days for Pleasant–Sucker–Vadnais) is essentially determined by the Utility's pumping and withdrawal rates. The Utility throttles back on diversions from the Mississippi during periods of high runoff from the local watershed. Lake level fluctuations are relatively minor.

An intensive monitoring network was established in 1984 at various locations in the Vadnais Lake and Rice Creek Watersheds (Fig. 1). Stations are of three types: six lake stations (sampled biweekly), 22 tributary or diversion stations (sampled weekly or biweekly), and four runoff stations (sampled on a storm event basis using continuous flow monitoring and automated samplers). Under a coop-

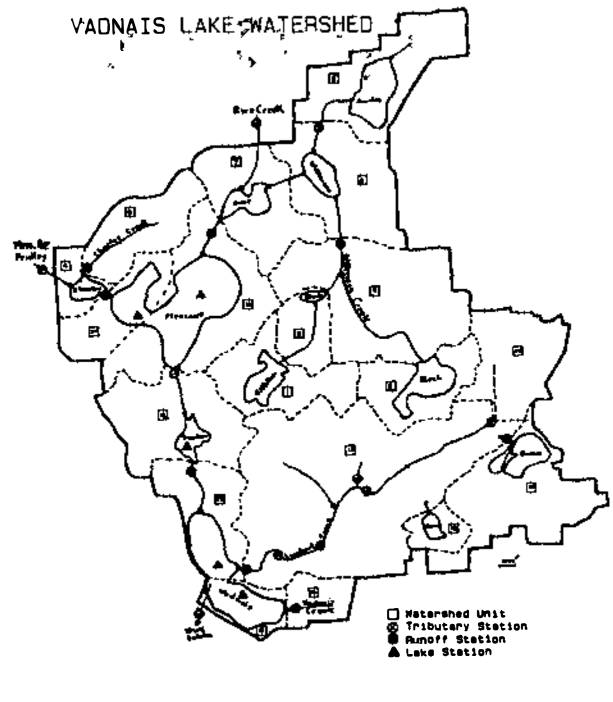


Figure 1.—Vadnais Lake watershed.

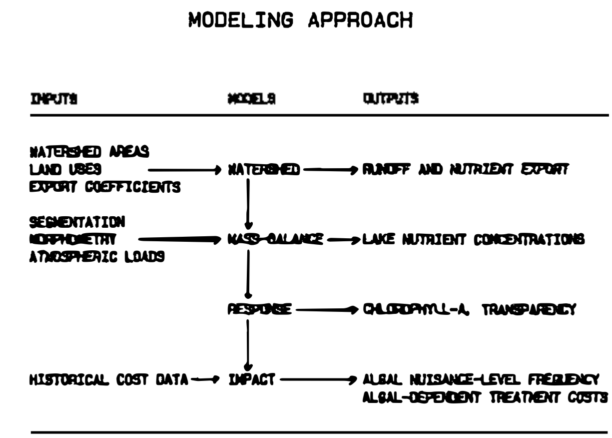


Figure 2.—Modeling approach.

erative arrangement, the U.S. Geological Survey operates the runoff stations and is developing detailed hydrologic simulation models of major subwatersheds.

Water balance calculations for the May–September 1984 period indicate that 86.7 percent of the total inflow to the lake chain was subject to direct flow gauging and quality sampling. The remaining inflows are attributed to ungauged local watershed runoff (4.1 percent) and direct precipitation on lake surfaces (9.2 percent). Monitoring data from 1984 reflect a relatively high runoff period, owing primarily to an 11.4-cm (4.5-in.) rainstorm that occurred in June. May–September total precipitation (60 cm) and local watershed yield (7.6 cm) were both above 1978–84 means for the same months (49 cm and 5.1 cm, respectively). The increased runoff may be attributed to a combination of climatologic factors and changes in land use. Results of 1984 and other historical monitoring activities in the watershed are discussed in an interim report (Walker, 1985b). The study is continuing to provide perspectives on seasonal and year to year variability in watershed loadings and lake conditions.

Overall, land use in the watershed is 32 percent open, 21 percent wetlands, 11 percent lake surfaces, 4 percent agricultural, 12 percent low-density residential (< = 1 unit/acre), and 20 percent urban. Most of the high-density urban development is located in the lower portion of the watershed draining directly into Vadnais Lake, where the Utility's epilimnetic intake is located. The current pace of development is rapid and many open (and, in some cases, unprotected wetland) areas are being converted to high-intensity urban uses. Areas to the north and east of Pleasant Lake are slated primarily for low-density residential development (Ramsey County Soil Water Conservation Distr. 1985).

MODELING APPROACH

To provide a basis for evaluating eutrophication control strategies and future land use scenarios, a mathematical model of the Utility's watershed and lake system is being developed (Fig. 2). The model consists of four components:

1. watershed: estimates runoff and nutrient export from each subwatershed as a function of land use
2. mass balance: routes water, phosphorus, and nitrogen through the stream and lake network to predict lake nutrient concentrations

Table 1.—Lake morphometric, hydrologic, and water quality characteristics.

		Lake				
Variable	Units	Deep	Charley	Pleasant	Sucker	Vadnais
Morphometric and Hydrologic Variables[1]						
Volume	10^6 m^3	0.39	0.22	13.16	0.79	12.56
Surface area	km^2	0.28	0.12	2.45	0.24	1.55
Mean depth	m	1.4	1.8	5.4	3.3	8.1
Maximum depth	m	5.0	6.9	17.8	7.9	16.5
Outflow	10^3 m^3/day	11	165	179	181	196
Residence time	days	35	1.3	74	4.3	64
Water Quality Variables[2]						
Total phosphorus	ppb	136	95	58	58	50
Orthophosphorus	ppb	24	24	<11	<12	<10
Total nitrogen	ppb	2,014	1,228	1,120	1,170	831
Inorganic nitrogen	ppb	156	266	116	165	126
Organic nitrogen	ppb	1,476	962	1,004	1,005	705
Reactive silica	ppm	—	—	2.0	2.1	1.5
Chlorophyll a	ppb	—	—	27	24	19
Secchi depth	m	—	—	1.5	1.4	1.8

[1]Hydrologic conditions for May–September 1984.
[2]Mean concentrations, May–August 1984, Deep Lake and Charley outflows, Others 0–3 m Lake Stations.

3. eutrophication response; predicts mean chlorophyll *a* and transparency in each lake segment as functions of nutrient concentrations

4. utility impact: predicts algal bloom frequency at the Utility's intake and potential economic impacts, based upon equivalent costs of treatment chemicals sensitive to intake algal density or bloom frequency.

This section describes model structure and preliminary calibration based upon monitoring data from May–September 1984. Results are limited by the fact that the early spring runoff period was not monitored. Data from subsequent years will be used to refine the assessment.

A total of 19 subwatersheds, 12 lakes, and 18 mass-balance segments are considered in the model, as illustrated in Figure 1. Mass-balance segments are of two types: stream nodes and lake nodes. Stream nodes collect runoff and nutrient loads from subwatersheds above the lake system and are placed at each of the four runoff monitoring stations (Charley Creek, Wilkenson Creek, Lambert Creek, and Vadnais Creek). Nutrients are assumed to be conservative in the stream nodes. Lake nodes are located in each major lake or lake area. Pleasant and Vadnais Lakes are each subdivided into two segments.

Model computations are performed in three steps: The first step converts land use areas and export coefficients for each subwatershed into stream flows and concentrations required for mass-balance calculations. This is a simple matrix multiplication problem. The second step routes flow and nutrients through the stream and lake network to predict average water quality conditions in each segment using empirical nutrient retention and nutrient/chlorophyll *a* relationships. The third step converts predicted mean chlorophyll *a* concentrations in Vadnais Lake into algal nuisance-level or bloom frequency (percent of the time chlorophyll *a* exceeds 30 ppb). This statistic is a reasonable, predictable surrogate for the frequency of algal-related taste and odor episodes. Potential effects on water treatment costs are also estimated, as described here.

WATERSHED EXPORT MODEL CALIBRATION

Existing land uses in each watershed unit are summarized in Table 2, based upon maps prepared by the Ramsey County Soil and Water Conservation District (1985). Calibration of the watershed model involves estimating runoff and nutrient export coefficients for each land use category, based upon 1984 monitoring and other regional data sets (Oberts, 1983; Payne et al. 1982; Nelson and Brown, 1983). Urban land use is a significant factor contributing to runoff and nutrient export, as illustrated in Figure 3 for 17 regional watersheds with less than 50 percent agricultural land use. Runoff and nutrient export coefficients selected for each land use are summarized in Table 3 and compared with other regional and nationwide estimates.

Export coefficients for agricultural land uses tend to be highly variable because of differences in the types and intensities of agriculture and soil characteristics. Agricultural export coefficients in the lower range of those measured in other watersheds have been selected because agricultural activities in the local watershed are generally of low intensity. Model results are very insensitive to agricultural export coefficients because this land use accounts for only 4 percent of the watershed.

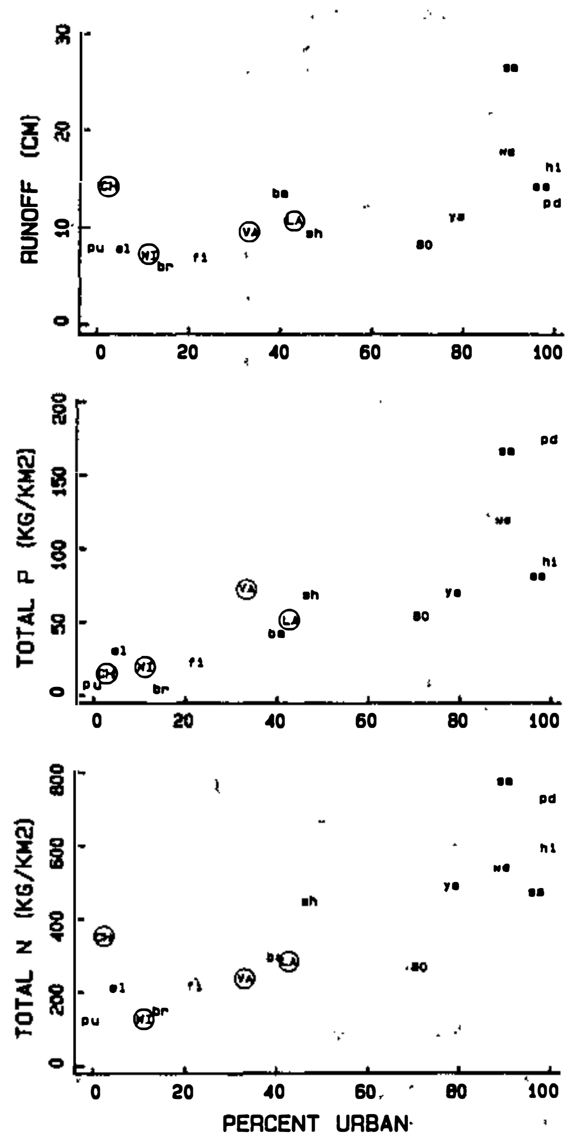
Because of lower use intensity and less impervious area, low-density residential land uses are distinguished from other urban land uses in the export matrix. Regional data analyses indicate that phosphorus export is more strongly correlated with urban land use when low-density areas are excluded. The export estimates for the urban land use category show good agreement with other data sources in Table 3. Estimates for the low-density residential areas are somewhat subjective and may require further investigation.

As applied to the Vadnais Lake watersheds, the estimated export coefficients refer to May–September 1984 conditions. With these coefficients, the total flow, phosphorus, and nitrogen export monitored at the four runoff monitoring stations agree with predicted values to within 10 percent; the predicted water balance on the entire lake

Table 2.—1984 land use breakdown for Vadnais Lake watershed model.

		Watershed Land Uses (Acres)										
ID	**NAME**	R<1	R>1	R–M	CII	AGR	WET	OPEN	HI	LAKE	TOTAL	DEPTH
01	Gilfillan L	0	380	0	0	0	91	132	0	86	689	5.9
02	Black Lake	0	125	0	0	0	61	76	0	15	276	3.3
03	Birch Lake	127	0	6	39	0	21	241	12	138	584	3.6
04	Wilkenson S	120	19	0	62	19	521	774	15	0	1,529	—
05	Amelia Lake	12	60	0	0	310	183	231	0	123	919	3.3
06	Wilkenson L	0	27	11	0	92	272	307	0	120	829	1.6
07	Deep Lake	0	159	0	0	0	213	357	0	63	792	4.6
08	Charley Cr	10	177	8	0	0	264	197	0	0	655	—
09	Charley Lake	0	0	0	13	0	24	130	0	30	197	5.9
10	Pleasant W	0	60	0	68	0	52	141	0	150	471	20.0
11	Pleasant E	0	526	0	0	0	440	76	0	450	1,492	17.1
12	Sucker Lake	120	92	12	19	0	91	410	0	59	803	10.8
13	Gem Lake	5	42	0	0	20	35	67	0	20	188	3.3
14	Goose Lake	387	22	27	166	32	17	151	18	120	939	6.9
15	Lambert Crk	733	128	94	111	87	847	966	42	0	3,007	—
16	Vadnais Crk	83	17	0	4	44	2	105	0	0	255	3.3
17	Vadnais No	79	7	0	0	31	92	386	0	190	784	26.6
18	Vadnais So	0	0	0	0	0	0	97	0	193	290	26.6
19	White Bear	473	0	18	70	0	7	117	0	0	684	—
TOTALS		2,147	1,840	176	551	634	3,231	4,959	87	1,757	15,381	—

Areas rounded to nearest acre (1 acre = .40 ha)
ID = Watershed Unit Number (Fig. 1)
R<1 = Residential < 1 unit/acre
R>1 = Residential >= 1 unit/acre
R–M = Residential, Multi-Unit
CII = Commercial, Industrial, Institutional
AGR = Agricultural
WET = Wetlands & Lake in Upper Watershed, Excluding LAKE
HI = Major Interstate Highways
LAKE = Lake Segment Surface Area at Lower End of Unit
TOTAL = Total Watershed Unit Area
DEPTH = Mean Depth of Lake Segment (Feet)



Legend

Vadnais Lake Watersheds are circled (period = May–September 1984; total precipitation = 60 cm.
Data for other Twin Cities watersheds are from Oberts (1983), Payne et al. (1982), Nelson and Brown (1983) (annual values, 1980 or 1982; total precipitation = 51–68 cm).
Watersheds with >50 percent agricultural land use are excluded.
Sandburg site ("sa") has 70 percent impervious area.
PDQ site ("pd") has construction activity.

Figure 3.—Runoff and nutrient export versus urban land use.

chain is accurate to within 1 percent. Additional monitoring data and model refinements are required to translate the export coefficients to annual estimates and to other hydrologic years. Water balance calculations indicate that local watershed runoff for the 1984 water year was 2.0 times the May–September runoff. Annual nutrient export would probably be less than twice the May–September export because stream nutrient concentrations generally tend to be lower during the October–March period.

Future refinements to the watershed export model will consider variations in soil type as well as land use. This will require a detailed inventory of soil types and impervious areas in each watershed unit. To provide a basis for estimating year to year variability, runoff and nutrient export coefficients should be tied to measured climatologic factors (precipitation, potential evapotranspiration, and so forth), and long-term stream gauging stations in the region. This will provide a higher resolution tool for evaluating site-specific development impacts and control strategies.

MASS-BALANCE AND EUTROPHICATION–RESPONSE MODEL CALIBRATION

Mass-balance and eutrophication-response calculations are performed using BATHTUB, a generalized computer program designed for application of empirical eutrophication models to segmented lake or reservoir systems (Walker, 1985a). Nutrient retention is predicted using empirical models calibrated to large lake and reservoir data sets. Phosphorus retention is estimated using a second-order decay formulation (Walker, 1984a), based on available phosphorus loading (a weighted sum of ortho- and non-orthophosphorus, with a greater weight on the ortho component). Nitrogen retention is estimated using an empirical formulation developed by Bachman (1980).

Normally, empirical estimates of nutrient retention terms are accurate to within a factor of 2–3, and some adjustment of the effective retention terms in each model segment is required to calibrate simulated nutrient profiles against observed values. In this application, nitrogen and phosphorus sedimentation rates have been reduced by 50 percent in Wilkenson and Deep Lakes to improve agreement between observed and predicted nutrient concentrations in the outflow from Deep Lake. These lakes are relatively shallow and may have more efficient nutrient recycling during the summer than the other lake segments. This adjustment has a minor impact on simulation of nutrient profiles in the main lake chain (Pleasant–Sucker–Vadnais) because the outflow from Deep Lake accounts for only 5.1 percent of the flow, 4.7 percent of the phosphorus, and 6.0 percent of the nitrogen discharged to the main lake chain. The retention models have been used without recalibration in other lake segments.

When a nutrient-balance model is used to predict mixed layer concentrations, the term "retention" refers to loss of nutrients from the mixed layer attributed to direct sedimentation, adsorption, and algal uptake and settling. Significant nutrient accumulation occurs in the hypolimnia of stratified lake segments (Pleasant and Vadnais) during the summer, owing to nutrient release from anoxic sediments and seston. Models of this type are not designed to account for "internal loading" that occurs when the lakes turn over and nutrients are recycled into the mixed layer in the fall. During 1984, this process began during early September in Pleasant Lake and during early October in Vadnais Lake. In calibrating the model network, a May–August averaging period has been used for the observed data to exclude the fall turnover period. The lakes are iron poor, and phosphorus recycled at fall turnover appears to remain in the water column for extended periods. Despite substantial increases in Vadnais Lake's mixed layer orthophosphorus concentrations at fall turnover (from < 10 to 180 ppb), a major algal bloom did not occur, apparently because of unfavorable light, temperature, or mixing regimes. Problems relating to the fall turnover period must be addressed independently of the modeling effort, unless the model structure is refined to account for effects of lake turnover.

Empirical models predict mean, mixed layer chlorophyll *a* and transparency as functions of total phosphorus and total nitrogen concentrations. Nitrogen is included as a chlorophyll *a* predictor because time series data indicate that the lakes approach a nitrogen-limited state during certain periods, although phosphorus is the most important growth-limiting nutrient. The empirical

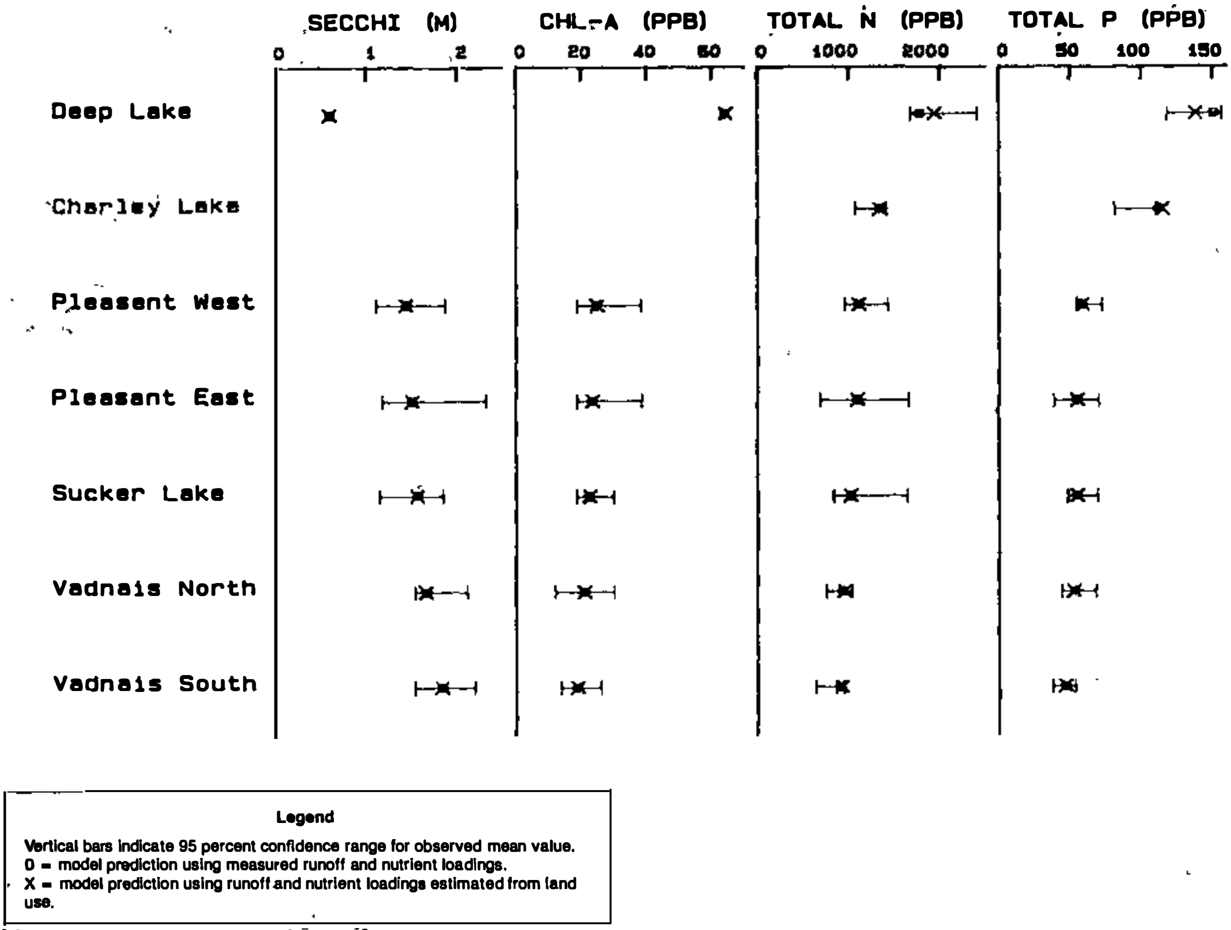


Figure 4.—Observed and predicted trophic state indicators.

Table 3.—Export coefficients selected for Vadnais Lake Watershed model.

Land use	This study[1]	Rice Creek Watershed District (1979)	Ayers et al. (1980)	Reckhow et al. (1980)	Jones & Lee (1982)
Total Phosphorus (kg/km²)					
Low-density residential	50	45			
Urban	120		110	60–110–270[2]	100
Resid. 1 < acre		162			
Multiple units		388			
Commercial/Industrial/Institutional		149			
Agricultural	50				50
Mixed				50–90–140	
Row crops				90–220–550	
Pasture				30–80–270	
Undeveloped	12	34	24	10–20–30	10
Total Nitrogen (kg/km²)					
Low-density residential	200				
Urban	600			400–600–1200	500/250[3]
Agricultural	400				500/200
Mixed				900–1400–2500	
Row crops				400–900–2300	
Pasture				200–400–900	
Undeveloped	100			90–180–230	300/100
Runoff (cm)					
Low-density residential	9				
Urban	16		19		
Agricultural	6				
Undeveloped	7		7.6		

[1]Export coefficients for May–September 1984.
Total precipitation = 60 cm versus annual mean of 74 cm; others average annual values.
[2]Percentiles: 25-50-75 based upon nationwide data summary.
[3]Nitrogen export for Eastern/Western United States.

lake segments. Predictions are shown for two cases: (1) using measured flows and nutrient concentrations at the four runoff-gauging sites, and (2) using values predicted from land use. Runoff and export from ungauged watersheds are predicted from land use in both cases. Effects of errors in the export model are minor, based on the agreement between the two simulations. The vertical bars reflect the approximate 95-percent error bounds for the observed mean concentrations, calculated from the number of sampling dates and interdate variance at each station. Further calibration of the model does not seem appropriate, based upon the fact that predicted concentrations are generally within the observed error bounds.

Table 4 summarizes the water, phosphorus, and nitrogen balances for the entire watershed and for Vadnais Lake alone, based on the calibrated watershed and mass-balance models. Of particular interest is the local watershed loading component, which accounts for 15 percent of the flow, 46 percent of the phosphorus loading, and 23 percent of the nitrogen loading to the entire watershed.

UTILITY IMPACT MODEL CALIBRATION

As a final modeling step, mean chlorophyll *a* concentration at the Utility's Vadnais intake is converted into two measures of impact directly relevant to the Utility's operations: algal nuisance-level frequency and equivalent treatment costs. These relationships are described here.

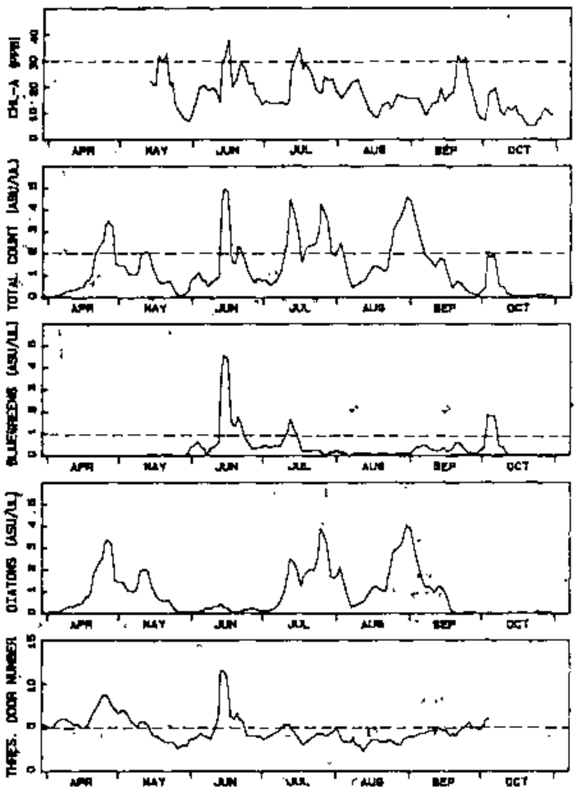
Algal nuisance-level or bloom frequency is defined as the percent of the growing season that chlorophyll *a* concentrations exceed 30 ppb, a reasonable criterion for nuisance-level algal densities, based on 1984 Vadnais intake time series data (Fig. 5) and general literature criteria (Walmsley, 1984; Walker, 1984b). Bloom frequency is computed from mean chlorophyll a using a frequency distribution model described by Walker (1984b). This statistic is a reasonable surrogate for the frequency of algal-related taste and odor episodes. It is limited by the fact that it does not distinguish between diatom and blue-green blooms; the latter are more directly implicated in summer taste and odor problems, although Figure 5 suggests that diatoms may be a factor in the spring.

Table 4.—Mass balances based upon gauged watershed loadings, May–September 1984.

	Drainage Area	Flow		Entire Lake Chain Avail. P		Total N	
Watershed	km²	$10^6 m^3$	%	kg	%	kg	%
Ungauged Local Watersheds							
Amelia Local	3.22	0.22	0.7	123	2.1	747	1.4
Wilkenson Local	2.87	0.20	0.6	75	1.3	432	0.8
Deep Local	2.95	0.22	0.6	76	1.3	360	0.7
Charley Local	0.67	0.05	0.1	19	0.3	93	0.2
Pleasant W Local	1.30	0.12	0.4	74	1.3	292	0.6
Pleasant E Local	4.22	0.34	1.0	158	2.7	635	1.2
Sucker Local	3.01	0.27	0.8	161	2.8	644	1.2
Vadnais N Local	2.41	0.20	0.6	97	1.7	440	0.8
Vadnais S Local	0.39	0.03	0.1	7	0.1	39	0.1
Gauged Local Watersheds							
Charley Creek	2.65	0.38	1.1	36	0.6	933	1.8
Wilkenson South	12.47	0.88	2.6	378	6.5	1598	3.1
Lambert Creek	19.51	2.09	6.2	1420	24.3	5568	10.8
Vadnais Creek	1.03	0.10	0.3	94	1.6	242	0.5
SPWU Diversions							
Fridley	—	25.00	74.2	2970	50.8	34954	67.6
Centerville Wells	—	0.27	0.8	10	0.2	72	0.1
Summary							
Precipitation	5.57	3.34	9.9	152	2.6	4682	9.1
External Inflow	56.71	30.37	90.1	5698	97.4	47048	90.9
Total Inflow	62.28	33.71	100.0	5849	100.0	51730	100.0
Outflow	62.28	30.08	89.2	1418	24.2	27118	52.4
Evaporation	—	3.62	10.8	—	—	—	—
Retention	—	—	—	4431	75.8	24612	47.6

	Drainage Area	Flow		Vadnais Lake only Avail. P		Total N	
Watershed	km²	$10^6 m^3$	%	kg	%	kg	%
Sucker Outflow	37.40	27.76	89.3	1511	47.7	28258	78.8
Vadnais N Local	2.41	0.20	0.6	97	3.0	440	1.2
Vadnais S Local	0.39	0.03	0.1	7	0.2	39	0.1
Lambert Creek	19.51	2.09	6.6	1420	44.8	5568	15.5
Vadnais Creek	1.03	0.10	0.3	94	3.0	242	0.7
Precipitation	1.55	0.92	3.0	42	1.3	1294	3.6
Total inflow	62.28	31.09	100.0	3171	100.0	35840	100.0
Outflow	62.28	30.08	96.8	1418	44.7	27118	75.7
Evaporation	—	1.00	3.1	—	—	—	—
Retention	—	—	—	1752	55.3	8834	24.3

Avail. P = Available Phosphorus Load (Walker, 1984a)
= .33 × Total P + 1.93 × Ortho P, for Lake Inflows
= Total P, for Lake Outflows
Ortho-P/Total P = .57 for Local Watershed Loads



Legend

Three-day moving average of daily measurements at the SPWU Vadnais Lake intake are shown. Dashed lines indicate approximate nuisance-level criteria.

Figure 5.—Time series of algal counts and threshold odor number at the SPWU Vadnais Lake intake, 1984.

Another impact statistic is designed to provide approximate perspectives on potential economic impacts, expressed in terms of chemical treatment costs. Table 5 lists total 1984 Utility costs for chemicals that are directly or indirectly related to intake algal density or nuisance-level frequency. Three chemicals (potassium permanganate, sodium chlorite, and powdered carbon) are used explicitly to control taste and odor problems and account for 75 percent of the total costs. Copper sulfate is applied weekly during the growth season in an attempt to control algal populations in Pleasant, Sucker, and Vadnais Lakes. Chlorine is used as a disinfectant, and higher dosages are required during periods of higher algal densities because of increased chlorine demand attributed to organic materials. Another relatively minor-cost factor, anhydrous ammonia, generates chloramines for disinfection; this treatment has replaced direct chlorination to control trihalomethane production, which is sensitive to source eutrophication (Dorin, 1980; Bernhardt, 1980; Walker, 1983).

If the treatment plant operations were "optimized" to apply these chemicals in exact proportion to their needs based upon intake water quality, then most of the costs (particularly for oxidants and carbon) would be nearly proportional to algal bloom frequency. Chemicals would be used for taste and odor control only when dictated by intake quality. In practice, however, because of the risks and uncertainty involved. The plant is operated in a conservative fashion; certain control chemicals are fed regardless of intake water quality, but dosages are increased during and following taste and odor episodes.

Thus, the actual cost sensitivity is less than that predicted by assuming that chemical costs are proportional to algal bloom frequency. As further studies and experience improve understanding of the cause–effect relationships linking watershed conditions, lake dynamics, intake water quality, treatment plant operations, and taste and odor episodes, the feasibility of optimizing treatment operations and the sensitivity of chemical dosages to intake water quality may increase. The intent of the economic model is to provide an approximate estimate of cost sensitivity. Other cost factors not considered include lake and watershed monitoring, labor for copper sulfate applications, and energy. Algal-dependent costs would increase by more than an order of magnitude if major changes in the treatment process train (addition of ozone or granular activated carbon filtration) were required to solve this problem.

Based on the 1984 chemical costs ($462,266) and nuisance-level frequency at Vadnais South station (14.2 percent), potential chemical costs associated with different nuisance-level frequencies are estimated from:

$$C = 462\ (F^{*}\ /\ 14.2) \qquad (1)$$

where,

C = annual chemical cost for taste and odor control ($1,000)

F^{*} = algal nuisance level frequency (%)

This relationship is linked with the watershed, lake, and chlorophyll *a* frequency distribution models to predict cost sensitivity to watershed development and to variations in diversion water quality. Predicted economic impacts should be interpreted cautiously. Regardless of dosages or cost, the chemical additions do not always effectively control taste and odor problems. The resulting impacts are real (obtained from consumer feedback) but difficult to express in terms of dollars or to otherwise quantify.

URBAN NONPOINT SOURCE IMPACTS

The models described can provide perspectives on the long-term effects of urban watershed development on eutrophication and related water quality conditions in Vadnais Lake. To define the potential range of urban development impacts, three land use scenarios have been simulated:

1. pristine: all existing urban, residential, and agricultural areas converted to open land
2. existing: 1984 land uses
3. developed: all currently undeveloped and agricultural areas (excluding wetlands) converted to urban.

Table 5.—St. Paul Water Utility algal-dependent chemical costs for 1984.

Chemical	Annual Cost	Use
Potassium permanganate	$217,661	oxidation of taste and odor compounds
Sodium chlorite	102,102	oxidation of taste and odor compounds
Powdered carbon	27,630	adsorption of taste and odor compounds
Copper sulfate	36,984	lake applications for algal control
Chlorine	61,506	disinfection
Anhydrous ammonia	16,383	disinfection/chloramines
Total	$462,266	

Results are summarized in Table 6 and Figure 6. Because of the nonlinear relationship between mean chlorophyll *a* and nuisance-level frequency, the latter is more sensitive to watershed development. Potential algal-dependent chemical costs are estimated at $159,000, $462,000, and $839,000 per year for the three scenarios, respectively. For a fixed total water demand, pumping requirements from the Mississippi River vary with watershed land use. Table 6 shows that potential pumping cost savings attributed to changes in local runoff volume are generally less than 10 percent of the potential impacts on chemical costs. Despite limitations in the cost estimates, their order of magnitude appears to be significant. The potential costs provide yardsticks for evaluating alternative control measures (best management practices, inlake techniques, etc.) from a cost-effectiveness standpoint.

The nutrient ratio, (N-150)/P, decreases from 19.8 to 15.6 as watershed development increases. This ratio is an approximate indicator of limiting nutrient (N-limited < 8, Transition 8–16, P-limited > 16) (Walker, 1984a). Aside from increasing the total nutrient supply and mean chlorophyll *a* concentration, increased urban runoff may drive the lake system toward a nitrogen-limited state and further promote the growth of nitrogen-fixing blue-greens, which are of greater concern from a taste and odor perspective than are diatoms or green algae.

The fact that a detectable bloom frequency (4.9 percent) remains for the pristine case suggests that the effective nutrient loading from Utility diversions (Mississippi River) may have to be reduced to eliminate taste and odor episodes via nutrient control. As part of the diagnostic study, diversion treatment schemes (nutrient removal or inactivation) and inlake management techniques are being investigated for application to the system, along with watershed management practices.

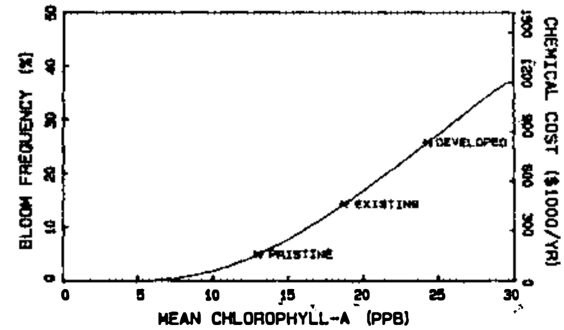


Figure 6.—mean chlorophyll a and bloom frequency for various watershed development scenarios.

Another set of simulations is designed to estimate the marginal impacts of urban development in each watershed unit on lake conditions and potential chemical costs. These simulations involve converting 20 ha (50 acres) of open land in each subwatershed into urban uses. Table 7 lists simulated increases in Vadnais South mean chlorophyll *a*, bloom frequency, and potential chemical costs attributed to development in each watershed unit. While the

Table 6.—Simulated impacts of urban watershed development on Vadnais Lake water quality and potential chemical costs.

Factor	Units	Watershed Development		
		Pristine	Existing	Developed
Mean intake Total P	ppb	32.9	46.7	58.6
Mean intake Total N	ppb	803	920	1064
Mean intake (N–150)/P	—	19.8	16.5	15.6
Mean intake chl. *a*	ppb	13.0	18.7	24.3
Nuisance-level freq.	% > 30	4.9	14.2	25.8
Equiv. chemical cost	$1,000/yr	159	462	839
Pumping cost increase	$1,000/yr	15	0	-26
Net annual cost	$1,000/yr	174	462	813

Table 7.—Marginal impacts of a 50-acre urban development in each watershed unit.

Watershed Unit	Mean Chl. a ppb	Bloom Freq. days	Gross Cost $/yr	Unit Cost $/acre-yr
01 Gillfillan	.005*	0.01*	312	6
02 Black	.011	0.03	687	14
03 Birch	.007	0.02	437	9
04 Wilkenson South	.016	0.05	999	20
05 Amelia	.007	0.02	437	9
06 Wilkenson	.016	0.05	999	20
07 Deep	.022	0.06	1374	27
08 Charley Creek	.030	0.09	1874	37
09 Charley	.030	0.09	1874	37
10 Pleasant West	.033	0.10	2061	41
11 Pleasant East	.035	0.10	2186	44
12 Sucker	.092	0.26	5747	115
13 Gem	.022	0.06	1374	27
14 Goose	.032	0.09	1999	40
15 Lambert Creek	.110	0.32	6871	137
16 Vadnais Creek	.142	0.41	8870	177
17 Vadnais North	.110	0.32	6871	137
18 Vadnais South	.142	0.41	8870	177
19 White Bear	.110	0.32	6871	137

*Simulated increases in mean chlorophyll a and bloom frequency at Vadnais Intake resulting from 50-acre (20 ha) urban development in each watershed unit.
Total watershed area = 15,381 Acres = 6,227 Ha.
Bloom frequency calculated for a 150-day growing season.

simulated increases for an individual development are small and would not be statistically detectable in a monitoring program, the cumulative effects of many developments are of major concern.

The results highlight spatial variations in Vadnais Lake sensitivity to development in specific subwatersheds. Sensitivity ranges over an order of magnitude. As expected, watershed units closest to Vadnais Lake show the greatest sensitivity. Units in the upper extremities of the watershed show lower sensitivity because development impacts are buffered by nutrient retention in upstream lake segments. Expressed per unit of developed area, potential increases in treatment costs attributed to urban development range from \$15–\$437/ha/yr (\$6–\$177/acre/yr). Corresponding cost savings attributed to reduced pumping costs for diversions from the Mississippi River are on the order of \$5/ha/yr (\$2/acre/yr).

CONCLUSIONS

These simulations provide approximate perspectives on long-term impacts of urban watershed development on the St. Paul water supply. The estimates do not reflect potential short-term impacts of construction sites, which have considerably greater runoff and nutrient export potential, as compared with stabilized urban areas. To some extent, dilution afforded by the Utility's diversions from the Mississippi River tends to buffer the lakes from impacts of local watershed development. A water supply without such a significant diversion volume would be expected to show a much higher land use sensitivity.

The assessment of urban impacts is obviously sensitive to the selection of export coefficients for the various land use categories. Refining the assessment will incorporate error analysis concepts (Reckhow and Chapra, 1983). Fortunately, in this case, good site-specific and regional data bases exist for estimating export coefficients.

Additional data collected under the ongoing monitoring program will refine the model structure and impact analysis by considering soil types and year to year variations in diversion water quality and in local runoff quantity and quality. The refined model will evaluate alternative measures for controlling eutrophication and taste and color problems in the St. Paul water supply.

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NONPOINT SOURCE POLLUTION CONTROL FUNDING FOR LAKE RESTORATION: A CASE STUDY AT CARLISLE LAKE

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RICHARD BAINBRIDGE
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ABSTRACT

This paper describes the results of a year-long monitoring program at Carlisle Lake, a small hypereutrophic lake located in southwestern Washington State. The objectives of the study were to assess the current limnology of the lake, to determine and quantify the nutrient sources to the lake, and to make recommendations for possible restoration of the lake and for nutrient control in the watershed. The monitoring has indicated that nonpoint sources associated with dairy and cattle operations contribute most of the extermal nutrient load to the lake. Sponsored by the Washington State Department of Ecology and conducted by the Washington State University Environmental Engineering Department and the USDA Soil Conservation Service, the study of Carlisle Lake illustrates how an interdisciplinary approach may bring together the expertise to deal with nonpoint source pollution problems. Some of the control measures that may be employed in reducing the loading to Carlisle Lake and some nontraditional funding sources and alternatives for these control measures are discussed.

Nonpoint source pollution has been recognized as a major problem in this country. However, the diffuse nature of the pollution has often made abatement and control difficult, not only from a technical standpoint but also from administrative and institutional viewpoints. In many cases, nonpoint source pollution crosses political boundaries and agency jurisdictions. Inclusion of the responsible parties in the decisionmaking process can be essential to the success of a control plan, and the expertise of various groups can be used to strengthen the technical and financial resources brought to bear on the problem.

This has been especially true in the case of Carlisle Lake in western Washington State. By realizing that nonpoint source pollution is a major contributor to the eutrophication of Carlisle Lake, reduction of the nonpoint source pollution has become an integral part of a restoration project for the lake, and has involved personnel and funds from the Washington State University Environmental Engineering Section, the U.S. Department of Agriculture Soil Conservation Service, and the Washington State Department of Ecology. Currently, a Phase I feasibility study of the lake has been completed by the Washington State University Environmental Engineering Section and the Phase II implementation project is being planned. This paper describes some of the findings of the Phase I study and plans for the lake restoration efforts and funding, with emphasis on the interagency cooperative approach taken to solve the technical and financial problems of nonpoint source pollution control.

STUDY AREA AND METHODS

Carlisle Lake is a small (10 ha), shallow (average depth .67 m), hypereutrophic lake located in the town of Onalaska, Lewis County, Washington (Fig. 1). The lake was constructed in about 1910 as a mill pond for what was, at the time, reputed to be the world's largest inland sawmill. The lake was used for log storage and movement until 1942, when mill operations ceased. For many years, the lake was a popular recreational site, providing swimming, fishing, boating, and other activities for local residents. In recent years, water quality has deteriorated significantly. Heavy phytoplankton blooms occur in the summer. These are caused by nonpoint source nutrient enrichment and result in highly turbid water. Large stands of emergent macrophytes have become established and are rapidly filling the lake, compounding the problem. Fish stocked in early spring do not survive past early June because of dissolved oxygen depletion. Recreational use of the lake has almost ceased altogether because of these problems.

The study conducted by Washington State University included the identification and quantification of the sources of pollution contributing to eutrophication in Carlisle Lake, and recommendations for possible restoration options. (The project summary and data cited in this report are to be found in Moore et al. 1985). Examination of the Carlisle Lake watershed showed that dairy and cattle

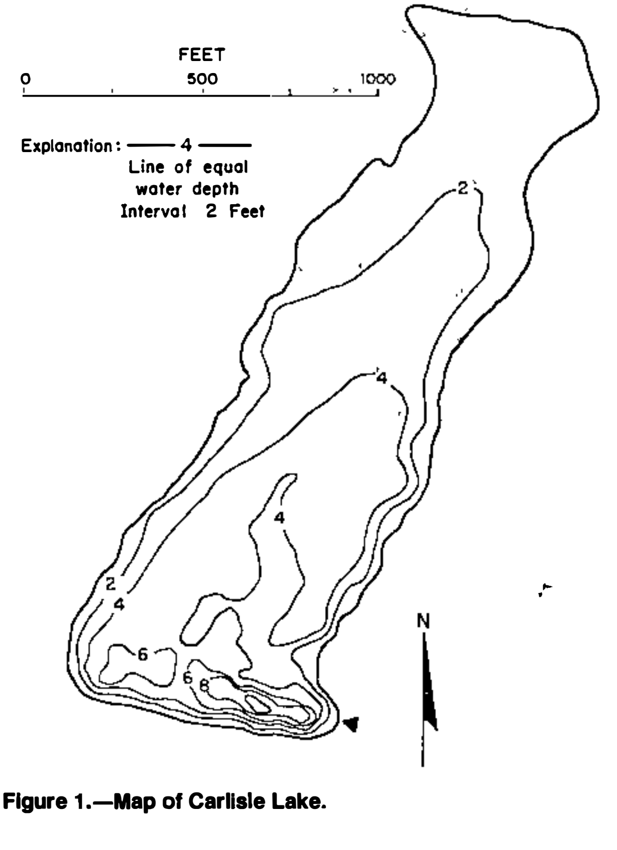

Figure 1.—Map of Carlisle Lake.

operations were the major sources of pollution along the inlet stream.

Monitoring stations were established on the inlet and outlet streams, and samples were taken every 2 weeks, from October 1983 to September 1984, to cover the entire 1983–84 water year. Sampling parameters included stream flow, nitrogen and phosphorus fractions, temperature, dissolved oxygen, conductivity, pH, alkalinity, silicates, and suspended solids. Piezometers were installed around the lake for ground water analysis.

RESULTS AND DISCUSSIONS

The hydraulic budget (Table 1) and the nutrient (phosphorus) budget (Table 2) for the lake were constructed from the data gathered on the inlets and outlet. Nonpoint source pollution associated with the dairy and cattle operations were found to contribute about 75 percent of the total annual phosphorus loading to the lake. The remaining 25 percent of the total phosphorus load resulted from internal nutrient recycling from sediment diffusion and from macrophyte release.

Specific activities and sources that result in nonpoint source pollution include wastewater spray irrigation, wastewater storage lagoon overflow, nutrients leached from wastes deposited in fields, and direct deposition of animal wastes in streams. Although the study was not designed to quantify separately the specific pollution sources, some inferences can be made from the available data.

Figures 2 and 3 show the stream discharge volumes and phosphorus concentrations in the two major inlets, Gheer Creek and the Ditch Inlet. Table 3 shows the seasonal averages for stream discharge and phosphorus loadings for the 1983–84 water year. The discharge and concentrations figures show that an inverse relationship existed between these stream properties throughout most of the study period; that is, as discharge increased, phosphorus concentration decreased, and vice versa. This pattern may have resulted from a relatively constant source of nutrients, so that the phosphorus tended to be diluted during high flows and highly concentrated during low flow periods.

Some exceptions to the general flow and concentration pattern occurred in January 1984, in both inlet streams and, in April/May 1984, in the Ditch Inlet. During these periods, the phosphorus concentration rose as the discharge increased, indicating either a flow-related

Table 1.—Summary hydraulic budget.

	Inlets total	Outlet	Ground water
Oct	507400	−455290	−52110
Nov	2777275	−1233955	−1543320
Dec	1435030	−596550	838480
Jan	2488103	−674725	−1813378
Feb	859544	−1138555	279011
Mar	1083250	−2129901	1046651
Apr	1055821	−1222997	167176
May	995091	−751091	−244000
Jun	306378	−209236	−97142
Jul	64169	−128312	64143
Aug	81450	−123801	42351
Sep	84047	−26194	−57853
Year	11737558	−8690607	−3046951

Note: Ground water estimate includes net rainfall, sheet flow, and ground water. Losses are negative; gains are positive. Flows are in m³.

Table 2.—Summary phosphorus budget.

	Gheer Ck	Ditch	Outlet	Ground water	Sediment
Oct	4.829	32.235	−74.364	−2.606	39.906
Nov	70.398	43.405	−270.078	−77.166	233.441
Dec	46.472	76.534	−76.189	−41.924	−4.893
Jan	160.064	179.51	−89.681	−90.669	−159.224
Feb	22.748	16.269	−96.854	13.951	33.886
Mar	16.799	46.178	−189.012	52.333	73.704
Apr	17.84	15.679	−68.702	8.359	26.824
May	18.121	35.862	−50.429	−39.040	35.486
Jun	17.472	8.567	−21.032	−15.543	10.536
Jul	3.136	1.512	−22.890	3.207	15.035
Aug	6.818	4.072	−19.266	2.118	6.258
Sep	4.996	8.202	−4.331	9.256	0.389
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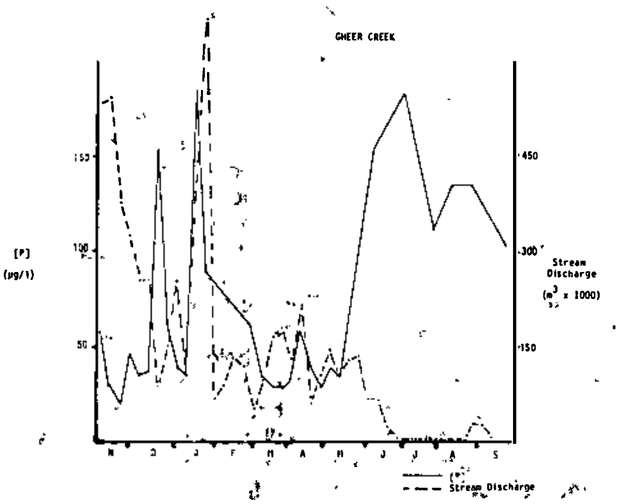

Figure 2.—Gheer Creek discharge and phosphorus concentrations.

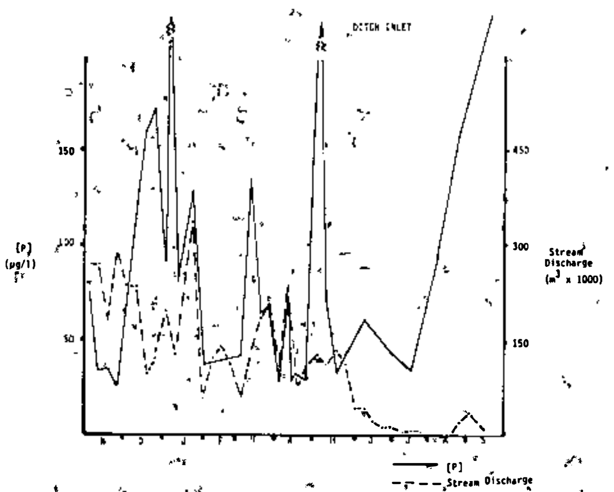

Figure 3.—Ditch Inlet discharge and phosphorus concentrations.

Table 3.—Practices eligible for cost-sharing under the Agricultural conservation Program (Soil Conserv. Serv. 1984)

Prevention of soil loss from water and wind erosion.
- Permanent vegetative cover establishment
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source(s) or an activity that was occurring during these times and not during others. Substantial nutrient loading occurred during these periods (Table 2).

The January peak flows were the highest of the water year and occurred at the end of a 3-month period of high rainfall and stream flows. As stated, both inlet streams experienced increases in nutrient concentration and loading associated with the January peak discharges. It is possible that the high rainfall caused increased leaching of nutrients, but such increased leaching usually occurs at the onset of the high flow periods. This was not the case in the Carlisle Lake watershed. The more likely source of the increased nutrients was overflow from dairy wastewater lagoons. The lagoons are used to hold water to be recycled from milk parlor and feed lot cleaning. The lagoons may have been full by January because of high levels of rainfall, and the continued rainfall in January—especially some high precipitation storm events—combined with the washwater flows probably caused the lagoons to overflow during this period.

The April/May high-loading period for the Ditch Inlet has, we believe, a different but related cause. Manure spreading of lagoon water is employed by the dairy to fertilize some of the pastures, but it is used primarily to control the water levels in the recycling lagoons. Manure spreading was performed on fields draining into the Ditch Inlet. This practice probably accounted for the phosphorus increase in the Ditch Inlet during the spring.

From the evidence discussed and from other data collected during the study, we can characterize the nonpoint pollution sources that result in nutrient enrichment to the inlet streams and to Carlisle Lake. Nutrients leached from manure in the pastures adjacent to the streams and from manure deposited directly in the streams seem to provide a relatively constant source of loading. Manure spreading and lagoon overflow are intermittent sources that contribute spike loadings, especially during high rainfall and stream flow periods.

Controlling the pollution sources to Carlisle Lake will be the goal of the Phase II project. Dredging will be required to remove the sediments and macrophytes to deepen the lake and reduce the internal nutrient loading. In the watershed, pollution-control measures will be aimed at reducing or eliminating the nutrients from animal wastes that reach the inlets. The amount of nutrient reduction needed in the watershed was estimated using a phosphorus model which has been found to yield reasonably accurate predictions of phosphorus concentrations in western lakes (Mahamah and Bhagat, 1982). A Vollenweider-type analysis was used to predict trophic state in the lake following restoration with various phosphorus loadings and stream discharges (Vollenweider, 1975). The model results are presented in Figure 4. Permissible loading is defined as that loading which will result in an average annual phosphorus concentration of 10 μg/L or less. Dangerous loadings will result in average annual phosphorus concentrations of 20 μg/L or greater. The model predicts that a nutrient-loading reduction of approximately 85–90 percent would be required to maintain acceptable water quality in the lake after the restoration is completed.

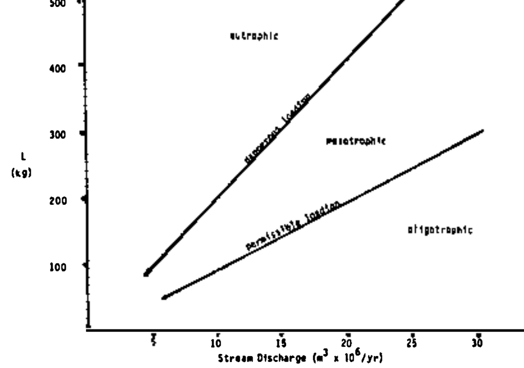

Figure 4.—Carlisle Lake trophic status predicted by the Walker model.

The watershed control measures include creating additional lagoons to increase water storage, so that overflow can be eliminated. The additional storage capacity should give the dairy more flexibility in its management and reduce the need to use wastewater spray irrigation to control the lagoon water levels. The wastewater spray irrigation should be allowed only at distances of 30 m or greater from the streams to allow for nutrient attenuation by the vegetation and soils. In addition, the wastewater spray irrigation will be moved from fields with soils of poorly drained Lacamas clay to fields with the well-drained Cinebar sandy soils.

A vegetated buffer zone will be established around the streams, which will be fenced to prohibit direct access by animals. Many of the pastures have high water tables, and overland sheet flow occurs during most of the year. The sheet flow picks up nutrients from the fields and allows for little nutrient attenuation by the vegetation or soils. Drain tiles will be installed to improve drainage in these fields, to prevent sheet flow, and provide for nutrient attenuation.

The technical aspects of the proposed pollution control plan were worked out with the cooperation and help of personnel from Washington State University, the Soil Conservation Service, and the Department of Ecology, working with local farmers, concerned citizens, and public service groups from the Carlisle Lake area. It is clear that close cooperation among these groups will be necessary to secure the resources needed to put the plan into effect.

Funding for the many lake restoration projects in Washington is provided by the State from Referendum 39 funds. Referendum 39 established a lake restoration program that is administered by the State Department of Ecology. The program funds qualified restoration projects, with 75 percent of funds provided by the State and 25 percent by local sources. In the case of Carlisle Lake, the Lewis County Soil Conservation District has taken the lead for raising local contributions. The costs of the Phase II implementation project at Carlisle Lake are estimated to be about $300,000. This requires about $75,000 in local matching funds. Because Onalaska has a small population base, local matching at this level poses a problem. However, the Department of Ecology allows for inclusion of in-kind services as part of the local match. Approximately 50 percent of the local match is still required to be in cash outlays, but a lower percentage is allowed in certain cases.

The in-kind services provision of Referendum 39 may be a distinct boon for nonpoint source pollution control associated with lake restoration projects, because of the nature of nonpoint sources. Nonpoint source pollution is often associated with small operations that have limited cash resources. The sources are frequently located in rural areas with low population densities and a low tax-revenue base. However, these operators will often own or have access to heavy equipment that can be used for services required in a restoration project, services which would otherwise have to be purchased as part of the project. For example, backhoes, a common farm implement, can be used to dig lagoons, clear channels, or dig drain tile ditches. The farmer must provide the labor, machinery, and fuel, but the work can be credited to the project for operations were the major sources of pollution along the inlet stream.

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Mar	16.799	46.176	-189.012	52.333	73.704
Apr	17.84	15.679	-68.702	8.359	26.824
May	18.121	35.862	-50.429	-39.040	35.486
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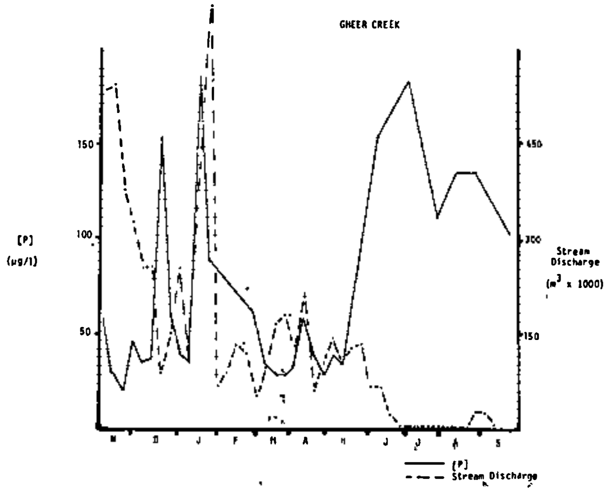

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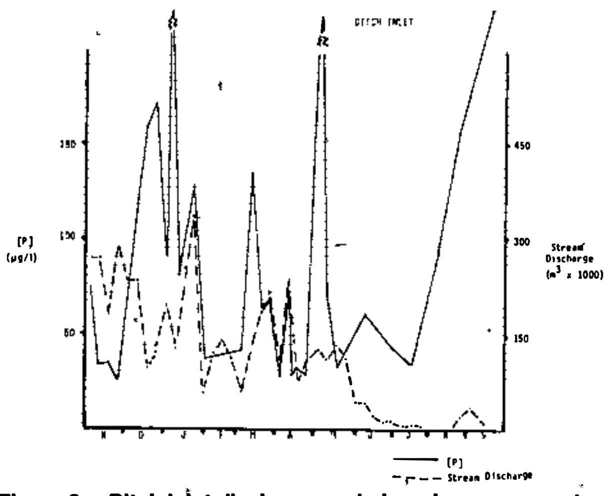

Figure 3.—Ditch Inlet discharge and phosphorus concentrations.

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- Forest tree stand improvement

source(s) or an activity that was occurring during these times and not during others. Substantial nutrient loading occurred during these periods (Table 2).

The January peak flows were the highest of the water year and occurred at the end of a 3-month period of high rainfall and stream flows. As stated, both inlet streams experienced increases in nutrient concentration and loading associated with the January peak discharges. It is possible that the high rainfall caused increased leaching of nutrients, but such increased leaching usually occurs at the onset of the high flow periods. This was not the case in the Carlisle Lake watershed. The more likely source of the increased nutrients was overflow from dairy wastewater lagoons. The lagoons are used to hold water to be recycled from milk parlor and feed lot cleaning. The lagoons may have been full by January because of high levels of rainfall, and the continued rainfall in January—especially some high precipitation storm events—combined with the washwater flows probably caused the lagoons to overflow during this period.

The April/May high-loading period for the Ditch Inlet has, we believe, a different but related cause. Manure spreading of lagoon water is employed by the dairy to fertilize some of the pastures, but it is used primarily to control the water levels in the recycling lagoons. Manure spreading was performed on fields draining into the Ditch Inlet. This practice probably accounted for the phosphorus increase in the Ditch Inlet during the spring.

From the evidence discussed and from other data collected during the study, we can characterize the nonpoint pollution sources that result in nutrient enrichment to the inlet streams and to Carlisle Lake. Nutrients leached from manure in the pastures adjacent to the streams and from manure deposited directly in the streams seem to provide a relatively constant source of loading. Manure spreading and lagoon overflow are intermittent sources that contribute spike loadings, especially during high rainfall and stream flow periods.

Controlling the pollution sources to Carlisle Lake will be the goal of the Phase II project. Dredging will be required to remove the sediments and macrophytes to deepen the lake and reduce the internal nutrient loading. In the watershed, pollution-control measures will be aimed at reducing or eliminating the nutrients from animal wastes that reach the inlets. The amount of nutrient reduction needed in the watershed was estimated using a phosphorus model which has been found to yield reasonably accurate predictions of phosphorus concentrations in western lakes (Mahamah and Bhagat, 1982). A Vollenweider-type analysis was used to predict trophic state in the lake following restoration with various phosphorus loadings and stream discharges (Vollenweider, 1975). The model results are presented in Figure 4. Permissible loading is defined as that loading which will result in an average annual phosphorus concentration of 10 μg/L or less. Dangerous loadings will result in average annual phosphorus concentrations of 20 μg/L or greater. The model predicts that a nutrient-loading reduction of approximately 85–90 percent would be required to maintain acceptable water quality in the lake after the restoration is completed.

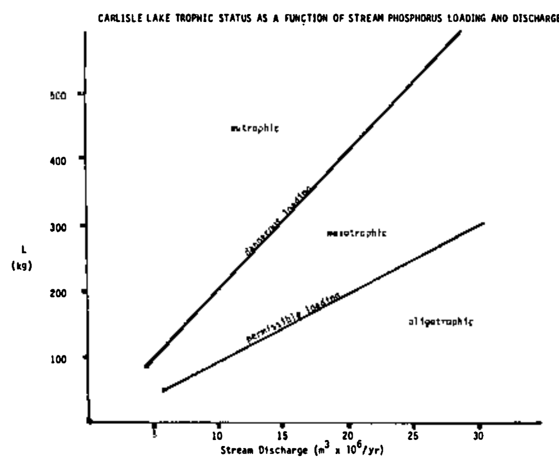

Figure 4.—Carlisle Lake trophic status predicted by the Walker model.

The watershed control measures include creating additional lagoons to increase water storage, so that overflow can be eliminated. The additional storage capacity should give the dairy more flexibility in its management and reduce the need to use wastewater spray irrigation to control the lagoon water levels. The wastewater spray irrigation should be allowed only at distances of 30 m or greater from the streams to allow for nutrient attenuation by the vegetation and soils. In addition, the wastewater spray irrigation will be moved from fields with soils of poorly drained Lacamas clay to fields with the well-drained Cinebar sandy soils.

A vegetated buffer zone will be established around the streams, which will be fenced to prohibit direct access by animals. Many of the pastures have high water tables, and overland sheet flow occurs during most of the year. The sheet flow picks up nutrients from the fields and allows for little nutrient attenuation by the vegetation or soils. Drain tiles will be installed to improve drainage in these fields, to prevent sheet flow, and provide for nutrient attenuation.

The technical aspects of the proposed pollution control plan were worked out with the cooperation and help of personnel from Washington State University, the Soil Conservation Service, and the Department of Ecology, working with local farmers, concerned citizens, and public service groups from the Carlisle Lake area. It is clear that close cooperation among these groups will be necessary to secure the resources needed to put the plan into effect.

Funding for the many lake restoration projects in Washington is provided by the State from Referendum 39 funds. Referendum 39 established a lake restoration program that is administered by the State Department of Ecology. The program funds qualified restoration projects, with 75 percent of funds provided by the State and 25 percent by local sources. In the case of Carlisle Lake, the Lewis County Soil Conservation District has taken the lead for raising local contributions. The costs of the Phase II implementation project at Carlisle Lake are estimated to be about $300,000. This requires about $75,000 in local matching funds. Because Onalaska has a small population base, local matching at this level poses a problem. However, the Department of Ecology allows for inclusion of in-kind services as part of the local match. Approximately 50 percent of the local match is still required to be in cash outlays, but a lower percentage is allowed in certain cases.

The in-kind services provision of Referendum 39 may be a distinct boon for nonpoint source pollution control associated with lake restoration projects, because of the nature of nonpoint sources. Nonpoint source pollution is often associated with small operations that have limited cash resources. The sources are frequently located in rural areas with low population densities and a low tax-revenue base. However, these operators will often own or have access to heavy equipment that can be used for services required in a restoration project, services which would otherwise have to be purchased as part of the project. For example, backhoes, a common farm implement, can be used to dig lagoons, clear channels, or dig drain tile ditches. The farmer must provide the labor, machinery, and fuel, but the work can be credited to the project for part of the local match at the market price for comparable services.

Even with credit for labor for the in-kind services, local expense requirements can still be substantial. Some of the control measures for nonpoint source pollution control may actually improve production for dairies or farms. This may possibly disqualify them from direct Referendum 39 funds under provisions that prohibit public funding for private improvements. There is some ambiguity in the provisions, but the cost to an individual farm, dairy, or range operation can be large if even moderate pollution control measures are required. These problems have suggested the use of the Agricultural Conservation Program, administered by the Soil Conservation Service.

The Agricultural Conservation Program provides some cost-sharing funding to individual farms for implementation of practices that result in soil conservation, pollution abatement, or forestry practices. The practices eligible for cost-sharing must meet specifications of the Soil Conservation Service and the State Department of Natural Resources. As one of the stated aims of the program is to encourage public benefits, especially the goal of "preventing or abating pollution and other environmental degradation," linking the ACP with a public lake restoration project should provide impetus for favorable deposition of the application. Table 3 contains a list of the types of practices eligible for cost-sharing under the ACP. Many of these eligible activities are practices for eliminating or abating nonpoint source pollution.

In conclusion, the Carlisle Lake Phase II restoration implementation project is in the planning stages. Cooperation among personnel from the involved agencies has led to the unification of some diverse funding sources into a cohesive program for abatement of a specific nonpoint source pollution problem. Similar cooperative approaches in other areas may be required to secure the funds and technical resources to control nonpoint source pollution.

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WHY SCOFIELD RESERVOIR IS EUTROPHIC: EFFECTS OF NONPOINT SOURCE POLLUTANTS ON A WATER SUPPLY RESERVOIR IN UTAH

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ABSTRACT

Studies since 1979 have classified Scofield Reservoir as mesoeutrophic or eutrophic. The principal pollutants are nutrients, trace metals, and sediments associated with nonpoint sources, such as construction of roads and mine portals, domestic waste disposal, animal grazing, and natural deposits of rock containing phosphate. Blooms of blue-green algae, which have resulted in fishkills, have corresponded to years of decreased inflow. Biota populations during wet years were quite diverse, with only minimal numbers of undesirable blue-green algae. During 1981, however, the minimum usable water storage decreased to 31 percent of the 25-year average and blue-green algae blooms resulted in serious fishkills. Concentrations of mercury in the water in Scofield Reservoir have caused concern for water users, but none of the concentrations has exceeded revised State standards. The mercury originates from coal particles within the drainage basin, and most of it is bound as silicate in the reservoir sediments and is not readily soluble. Several management practices have been implemented to decrease nonpoint source pollution. Among these are an improved waste disposal station for recreational vehicles, a containerized waste system for fish cleaning, and streambank stabilization.

OBJECTIVES OF THE INVESTIGATION

Extensive research on Scofield Reservoir in central Utah has been conducted during the last few years by the Utah Division of Environmental Health and the U.S. Geological Survey. The objectives of the State studies were to quantify nonpoint sources of nutrients entering the reservoir, determine the trophic conditions, and identify possible restoration methods. The Geological Survey, in cooperation with the Bureau of Land Management, was interested primarily in determining the effects on the reservoir of coal mining within the drainage basin. Eutrophic conditions, large sediment loads, and trace metal contamination were problems anticipated prior to the start of the studies. Because of differences in objectives and the period of study, there was little duplication of effort, and complementary data bases were compiled.

DESCRIPTION OF THE AREA

Scofield Reservoir, at an elevation of about 2,320 m in central Utah (Fig. 1), was formed in 1926 and enlarged in 1945 by dams on the Price River. Usable capacity of the reservoir is 81 hm^3 and maximum depth is 14 m. The drainage basin for the reservoir is 400 km^2 and is primarily mountainous, with elevations ranging from 2,312 to 3,183 m. The drainage basin contains large coal deposits and the area has been mined since the late 1800's. The major source of inflow to the reservoir is Fish Creek, which contributed 72 percent of the total inflow during the 1980 water year. Minor inflows were from Mud Creek (16 percent), and Lost and Pondtown Creeks and from precipitation (12 percent). Agricultural use of the basin is limited to grazing of sheep (15,000 head) and cattle (5,000 head). Ninety-three percent of the drainage basin is forest or range land.

The reservoir supplies water for domestic use to 20,000 people downstream, and it provides recreational opportunities for about 70,000 visitors per year. There are 1,100 recreational camping or cabin units on the shores. Sanitary facilities for the camps, cabins, and the town of Scofield (200 people) are limited to pit privies and septic tanks.

ALGAL BLOOMS AND FISHKILLS

Periodic data for algal populations and blooms are available since 1975. Colonies of objectionable blue-green algae were identified in the reservoir in 1975, but their numbers did not reach bloom proportions, most likely because of increased tributary flow and high water in the reservoir. During most wet years, algal populations are quite diverse, with few blooms of blue-green algae. Considerable data on the algal community have been collected since 1981, and this may be summarized by examining the fluctuations of two blue-green algae, *Aphanizomenon flos-aquae* and *Anabaena flos-aquae*, and the diatom *Stephanodiscus minutula*, which are good indicators of eutrophication in reservoirs in Utah. The density of these blue-green algae and the percentage of the diatom (relative to all diatoms) are plotted in Figure 2 for 1981–84. Although both groups of organisms are indicators of eutrophication, their densities typically are inverse. Increased densities of the blue-green algae indicate blooms during August 1981 and October 1982. Possible bloom conditions for the diatom are indicated during early August 1981, September 1981, and August 1983. The phytoplankton bloom in August–September 1981, resulted in a considerable fishkill. The bloom of blue-green algae in October 1982 did not result in a major fishkill, because water storage had reached an historic high in June and was still relatively high during October. Similarly, the diatom bloom of August 1983 occurred at a time when the water storage historically was very large.

Fishkills in Scofield Reservoir have been reported during 6 years since 1960, and most were associated with small discharges from the principal inflowing stream or decreased reservoir water storage (Table 1). During most years, Fish Creek contributes about 70 percent of the annual inflow to the reservoir. The Utah Division of Wildlife Resources (Donaldson, 1984) has found that fishkills occur in years when the annual value for mean daily discharge of Fish Creek is less than 1.13 m^3/sec. This observation has been verified by all data since 1960, with the exception of data from 1963 and 1966. In 1963, the flow from Fish Creek decreased to 63 percent of the 25-year average daily flow of 1.5 m^3/sec, and the minimum water storage in the reservoir was only 52 percent of the 25-year average. The flushing rate (total inflow divided by Price River outflow) in 1963 was about 1, which may have prevented a fishkill. During 1966, the average daily flow of Fish Creek was 67 percent of the 25-year average, but

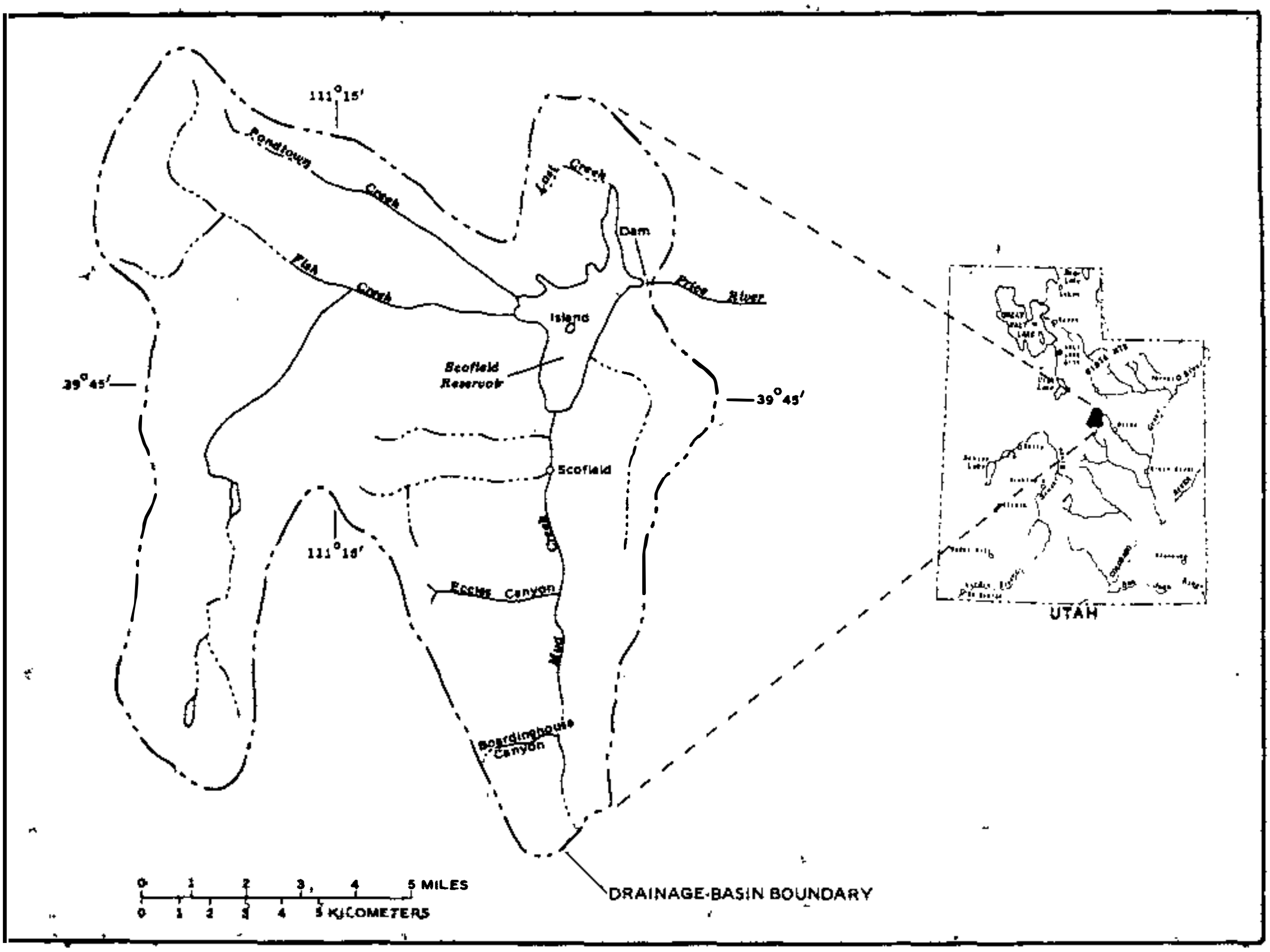

Figure 1.—Location of Scofield Reservoir and associated streams.

minimum water storage in the reservoir was 143 percent of the average.

Analysis of published (Waddell et al. 1983; Denton et al. 1983) and calculated water budgets since 1960 indicate that fishkills occur 80 percent of the time the annual flushing rate for the reservoir is less than 0.85. No fishkills have been reported during years when the flushing rate was greater than 1.1. It is likely that fishkills result from a combination of environmental factors that are intensified by decreased tributary inflow. These factors are large populations of blue-green algae that release biological toxins, oxygen demands resulting from respiration and decomposition of algal populations, increased rate of warming of lake water, and increased volume of the anaerobic hypolimnion.

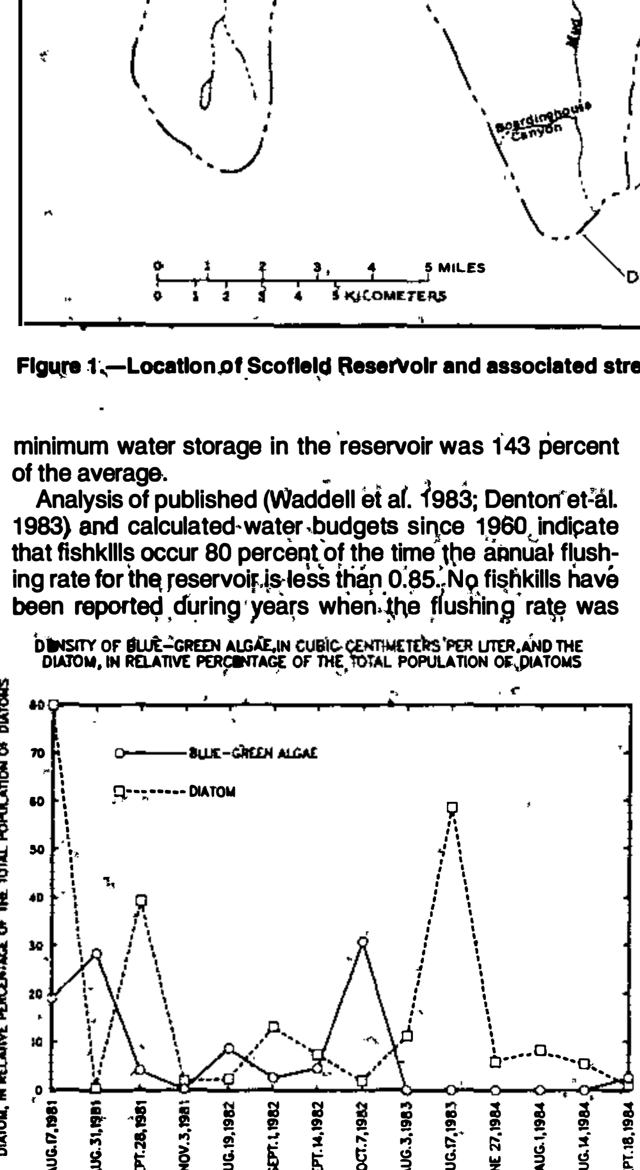

Figure 2.—Fluctuations of the blue- reen algae *Anabaena flos-aquae*, *Aphanizomenon flos-aquae*, and the diatom *Stephanodiscus minutula* in Scofield Reservoir, 1981–84.

Considerable reservoir data were collected before and after the 1981 summer fishkill (Utah Dep. of Health, 1984), which indicate the relationship between total reservoir water storage and the actual volume of fish-habitable water (Fig. 3). Total water storage began decreasing in June, and during August it decreased 15 percent. The volume of fish-habitable water containing a minimum dissolved oxygen concentration of 5.5 mg/L, which is sufficient to support a fishery, decreased at about the same rate until August. During the first half of August, the habitable water decreased about 60 percent. This was caused by an expansion of the anaerobic hypolimnion and decreased volume of total storage, which greatly decreased the living area for fish and resulted in an estimated fishkill of 200,000.

TROPHIC STATE OF THE RESERVOIR

Because of recurring algal blooms and large concentrations of nutrients, Scofield Reservoir has been classified as eutrophic (Denton, 1980) to meso-eutrophic (Waddell et al. 1983; Denton et al. 1983). Data collected by the U.S. Geological Survey since 1979 indicate that 47 percent of all measurements of total phosphorus in the epilimnion

Table 1.—Fishkills and minimum water storage in Scofield Reservoir, ratio of inflow to outflow, and discharge of Fish Creek.

Water year	Type and time of fishkill	Minimum useable water storage (thousands of cm³)	Percentage of 25-year average minimum storage	Total inflow / Total outflow	Mean daily discharge of Fish Creek (m³/sec)
1960	major summerkill	2,070	7	0.95	0.88
1961	major winterkill	680	2	1.09	.42
1972	minor summerkill	24,040	80	.74	.91
1976	minor summerkill	38,350	127	.84	1.01
1977	major summerkill	21,840	73	.49	.29
1981	major summerkill	9,390	31	.73	.89

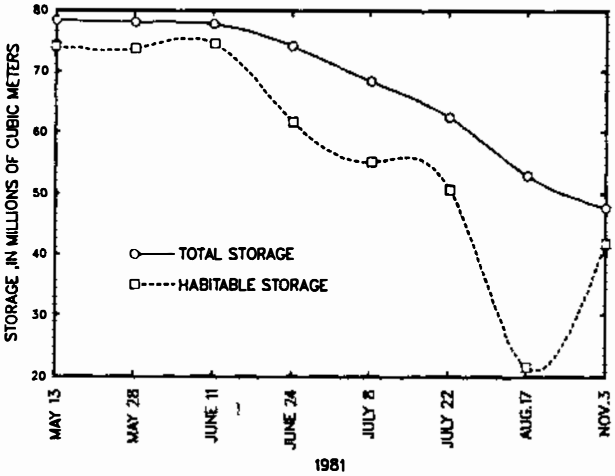

Figure 3.—Total and fish-habitable water stored in Scofield Reservoir during the 1981 fishkill.

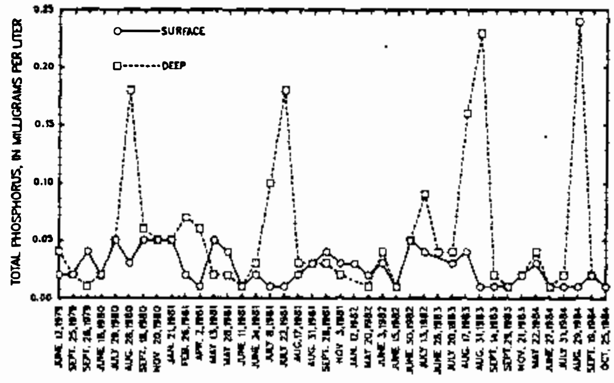

Figure 4.—Total phosphorus in surface and deep water in Scofield Reservoir, 1979–84.

and 69 percent of phosphorus measurements in the hypolimnion have exceeded the Utah water quality standard of 0.025 mg/L. The seasonal cycling of total phosphorus, using data collected by the Utah Division of Environmental Health and the U.S. Geological Survey, is shown in Figure 4. Phosphorus concentrations typically increase in the hypolimnion during winter stratification because of release from the sediments in the reservoir. During turnover in May or June, concentrations generally decrease in the hypolimnion and increase in the epilimnion. The increase in algal and bacterial populations during the summer, coupled with increased stratification and development of an anaerobic hypolimnion, decreases the phosphorus concentration in the epilimnion. In July or August, when summer stratification is at a maximum, release of phosphorus from the anaerobic sediments results in large concentrations in the hypolimnion. During fall turnover, in late August or September, the phosphorus accumulated in the hypolimnion is released to the overlying waters and surface concentrations of phosphorus typically increase. It is during the August–September turnover that recycled phosphorus is made available to the blue-green algae and late summer blooms can occur.

Denton et al. (1983) reported that ratios of nitrogen to phosphorus mostly were greater than 15 during 1981, indicating phosphorus limitation of algal populations. During 1982, ratios in the spring indicated phosphorus limitation and summer ratios generally identified a nitrogen limitation. Bioassay tests of algal growth potential indicated that on June 27, 1984, when the ratio of nitrogen to phosphorus in the reservoir water was 43 to 1, the water was primarily phosphorus limited. Additions of small concentrations of nitrogen (as nitrate), as well as phosphorus (as orthophosphate), however, stimulated nearly four times as much algal growth as phosphorus alone. On July 31, 1984, when the nitrogen-to-phosphorus ratio was 40 to 1, the addition of nitrogen as well as phosphorus to the test algae resulted in nearly 17 times the growth of phosphorus alone. By Sept. 19, the ratio was 50 to 1, but the addition of nitrogen resulted in only a twofold increase in algal mass when compared with the addition of phosphorus alone. It is likely that phosphorus is limiting during most years, particularly when large populations of blue-green algae, such as *Aphanizomenon* and *Anabaena*, are present, because such algae are capable of fixing atmospheric nitrogen into a form available to organisms.

SOURCES OF NUTRIENTS

Because of basin slopes of 0.38 in Boardinghouse and Eccles Canyons, and the construction of extensive roads and coal mine portals in Eccles Canyon, large quantities of sediment are transported into Mud Creek and then into Scofield Reservoir. Suspended-sediment loads in Mud Creek during July–September storms averaged 18,000 kg during 1983–84. Loads during thunderstorms in spring were believed to be even larger. Soils in the Mud and Fish Creek drainages contain considerable quantities of naturally occurring phosphorus. Soils collected in Boardinghouse and Eccles Canyons during 1984 contained 300–500 mg of total phosphorus per kilogram. Suspended stream sediments from the Fish Creek drainage were reported to contain 440–900 mg of total phosphorus per kilogram, with biologically available phosphorus averaging about 49 percent (Denton et al. 1983).

Considerable loads of nitrogen and phosphorus are discharged to the reservoir by Mud and Fish Creeks, the major inflowing streams to Scofield Reservoir (Table 2). Loads of nitrogen and phosphorus increased considerably during 1984 compared with 1983, although the total inflow to the reservoir was nearly the same. The distribution of loads also changed considerably during 1984, showing a greater proportion of nutrients, relative to the discharge, entering from the Fish Creek drainage. During 1980 and 1983, the proportion of total nutrient loads, relative to discharge, was greater for the Mud Creek drainage. The increased loads in Mud Creek during 1984 may be due, in part, to increased construction in the Eccles Canyon. There is no evidence to explain the increased loads during 1984 in Fish Creek.

Clyde et al. (1981) reported that wells in the Scofield area yielded water with an average phosphorus concentration of 170 µg/L, except in several of the subdivisions adjacent to the lake. In these areas, the water from several shallow wells contained mean total phosphorus concentrations greater than 1,400 µg/L. Relatively large concentrations of nitrate nitrogen also were common in the same wells, with concentrations ranging from 1,000 to 14,000 µg/L. Contamination of the ground water by disposal of domestic waste was suspected.

PHOSPHORUS IN LAKE SEDIMENTS

Selective chemical extraction of phosphorus from sediments in Scofield Reservoir by Messer and Ihnat (1983) indicated that nearly 200 mg of phosphorus per kilogram of sediment were potentially available for biological uptake. Although the quantity of phosphorus in the sediments is quite large, the actual quantity released is small because of the large concentrations of iron in the sediments. The phosphorus is in the form of iron-oxide gels, which release phosphorus when the iron in the gel is reduced to the ferrous form during anaerobic periods of stratification.

Release rates of available orthophosphorus from intact sediment cores were determined under aerobic and anaerobic conditions by the authors. Some differences in release rates depended on the sampling location of the core. Under anaerobic conditions at a typical hypolimnion temperature of 15°C, however, phosphorus release generally peaked within 15 days, at a rate of about 2 mg/m^2 per day and decreased to about 1.3 mg/m^2 per day for the remaining 17 days of the experiment. Under aerobic conditions, at a typical epilimnion temperature of 20°C, the maximum release rates were about 0.6 mg/m^2 per day, decreasing to about 0.3 mg/m^2 per day after 28 days. These rates are slightly less than those reported for Deer Creek Reservoir (75 km to the northwest) by Messer and Ihnat (1983).

The quantity of orthophosphorus released from the sediments during summer stratification was calculated using data obtained during 1983. The reservoir was stratified from the end of July to the end of September, about 70 days. During this time, water covering about 380 ha was anaerobic. Using a release rate of 1.3 mg/m^2 per day, a total of 360 kg of phosphorus could have been released from the sediments to the hypolimnetic water. This indicates that phosphorus release from anaerobic lake sediments is of minor importance when compared with loads of total phosphorus entering from streams (Table 2).

TRACE METALS

The presence of an active mining industry and large sediment loads created by construction of road and mine portals in the basin indicated that trace metals may be a pollution problem in the reservoir. Prior to November 1984, the State water quality standards for the protection of aquatic wildlife did not incorporate water hardness into the allowable concentrations for trace metals. Because of the accumulation of literature indicating that trace metal toxicity to aquatic wildlife is dependent on water hardness, trace metal standards were revised to less stringent concentrations. This necessitated revisions in the interpretation of the effects of trace metals on Scofield Reservoir, particularly for mercury, which had been identified previously as a potential pollutant problem (Clyde et al. 1981). Under the old standards, 39 of 46 analyses for total mercury in reservoir waters indicated concentrations in excess of State standards of 0.05 µg/L. The mean of all the violations was 0.17 µg/L. Under the revised standard of 1 µg/L, none of the samples exceeded the standard. Analyses of fish tissue also indicated the existence of small concentrations of mercury in the reservoir waters, but the concentrations were considerably less than the allowable limit for edible fish (Denton et al. 1983). The small concentrations of mercury probably originate from coal particles transported into the reservoir. The composition of coal in the area indicates that the mercury content may be as large as 0.25 part per million by weight (Smith, 1981).

Manganese and zinc are the only other trace metals that are potential pollutants in the reservoir. The standards of the U.S. Environmental Protection Agency (1976) for a public water supply prohibit exceeding a total manganese concentration of 50 µg/L. During periods of stratification, concentrations of total manganese may range from 500 to 700 µg/L in the anoxic hypolimnion in Scofield Reservoir. The concentrations increase considerably in the hypolimnion during summer stratification and abruptly decrease during spring and late summer turnover. It is during these turnover periods that the concentrations increase in the epilimnion because of mixing with hypolimnetic water enriched with manganese. Concentrations of manganese in the epilimnion rarely exceeded the standard during 1979–82, but during the late summer turnover in 1983 and 1984, near-surface concentrations tended to range from 80 to 120 µg/L. Total, and to a lesser extent, dissolved iron concentrations were similar in magnitude to those of total manganese during periods of stratification and mixing.

Concentrations of total zinc in the reservoir occasionally exceed 150 µg/L but the dissolved form rarely exceeds the State standard of 50 µg/L. Some cycling of both forms of zinc occurs in the surface and bottom waters, but it does not conform to well-defined periods of stratification and mixing as is the case with manganese.

EXTRACTIONS FROM SEDIMENT CORES

Sediment cores were collected at five sites in the reservoir, radioisotope methods were used to determine sedimentation rates, and chemical extractions were performed (Skei and Paus, 1979) to provide an estimate of the ease with which trace metals may be removed from the sediment. In general, isotope-dating methods indicated that sedimentation rates within the reservoir were

Table 2.—Loads of nitrogen and phosphorus entering Scofield Reservoir in gauged streams during 1980, 1983, and 1984 water years. Numbers in parentheses are the percent of total.

	Water year								
	1980			1983			1984		
	Inflow (million m^3)	Dissolved nitrogen (MT)	Total phosphorus (MT)	Inflow (million m^3)	Dissolved nitrogen (MT)	Total phosphorus (MT)	Inflow (million m^3)	Dissolved nitrogen (MT)	Total phosphorus (MT)
Fish Creek	74.9 (82)	57 (79)	4.0 (71)	100.9 (81)	37 (79)	15 (73)	96.6 (78)	110 (81)	79 (86)
Mud Creek	16.2 (18)	15 (21)	1.6 (29)	23.9 (19)	10 (21)	5 (27)	27.5 (22)	25 (19)	13 (14)
Total	91.1	72	5.6	124.8	47	20	124.1	123	92

not uniform. Sedimentation rates near the major sources of inflow could not be determined accurately, but they were believed to be greater than rates in the central part of the reservoir. Sediments accumulating in the shallow areas periodically move toward the center of the lake, where the sedimentation rate is about 1 cm per year. An even smaller rate of deposition, 0.3 cm per year, has been determined for an area near the dam, where the velocity of the current is slowest.

Concentrations of arsenic, cadmium, and cobalt in all cores were very small, and these elements primarily were present in a tightly bound form. Copper concentrations in the sediments ranged from 15 to 20 μg/g. Most of the copper was present in the nonsilica fraction, most likely tightly bound to clays or in sulfide compounds. The quantity of copper potentially available to the biota was usually about 5 μg/g. Concentrations of manganese at most sites showed a gradual decrease from the sediment surface to the bottom of the 20–40 cm core. Concentrations of total manganese varied from 400 to 700 μg/g in the surface segments and decreased about one-third in the bottom segments of the core. This is a typical pattern for manganese in lake sediments. The oxidized forms of manganese are deposited in the sediments and gradually buried. As oxygen is excluded from the cores and reducing conditions are established, the oxides are reduced and made soluble, releasing manganese with a +2 valence which migrates upward in the pore water (Skei and Paus, 1979).

Mercury concentrations in the sediments generally were less than 0.02 μg/g, particularly in the shallow, recently deposited alluvium from Mud and Fish Creeks. Sediments from deeper sites had considerably larger concentrations of mercury, with a maximum concentration of 6 μg/g. At sites where concentrations were larger, the concentrations were present in the least soluble (silicate) form. Concentrations in a biologically available form did not exceed 0.02 μg/g, and they generally were present in concentrations less than 0.01 μg/g.

CONTROL OF EUTROPHICATION THROUGH MANAGEMENT

The State of Utah has proposed several management practices for controlling nonpoint and point sources of nutrients (Denton et al. 1983). These methods consist of integrating public education programs with physical, chemical, and biological management practices to decrease the rate of eutrophication and restore reservoir quality. These practices may be categorized as lakeshore and reservoir management.

Lakeshore management would decrease the quantity of sewage-associated nutrients entering the lake from nonpoint sources, such as holding tanks and leach fields. It would prohibit the installation of additional sewage-holding tanks in subdivisions around the lake shore, require sanitary dump stations for recreational vehicle parks, and require centralized septic tanks with drain fields located far from the lake shore in several subdivisions. Extensive wetlands would be created near the mouth of Mud Creek, which would be managed to preclude animal grazing and to encourage plant growth so as to decrease nutrient concentrations in the inflowing water. The plant growth would be periodically harvested and removed from the area. Willows planted along the creek drainage area near the reservoir would stabilize stream banks. The wetlands proposal could not be funded, and it has been temporarily suspended from consideration.

Reservoir management is designed to decrease the effects of eutrophication by controlling nutrients after they reach the reservoir. Fishery practices, such as no-limit or commercial fishing, would decrease the nutrient load caused by chemical treatment periodically used to control rough fish. Fish cleaning, with return of the entrails to the reservoir, is estimated to contribute more than 180 kg of phosphorus annually (Denton et al. 1983). Prohibition of fish cleaning on the reservoir and along the shore, and construction of fish-cleaning stations in the camping areas would decrease this source of nutrients. Public education and more restroom facilities would be used to decrease waste disposal by boaters. Other water management practices considered but rejected as being too costly or in conflict with water users included: alum treatment to precipitate phosphorus, followed by fly ash addition to seal the nutrients in the sediment ($160–$600 per hectare); aerators to decrease anaerobic conditions under which phosphorus leaches from the sediments ($6,000–$12,000 annually); dredging to remove sediment ($1,000 per hectare); installation of a large pipe, which would allow hypolimnetic water to be discharged during the summer (more than $43,000); water drawdown during midsummer to encourage complete water mixing and prevent formation of an anoxic hypolimnion.

Several practices had been implemented by 1985. An improved waste disposal system for recreational vehicles and a containerized fish-cleaning station with grinder and waste system connections are in use at the State park campground. Posting of antipollution signs has increased public awareness, and the channel has been stabilized along the downstream reach of Mud Creek. Subsequent monitoring and study is planned by the State to determine the effectiveness of these control practices.

All lakes are different, and the effect of nonpoint source pollutants cannot be predicted unless the chemistry and biology of each lake are understood. Management practices to control eutrophication need to be deferred until the dynamics of specific lake systems are fully known.

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TROPHIC STATE RESPONSE TO NONPOINT POLLUTION CONTROL: APPLICATION OF COUPLED MICROCOMPUTER MODELS TO THE GREAT LAKES

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ABSTRACT

Phosphorus loading from the Fox River (Wisconsin) produces a gradient in trophic state along the major axis of Green Bay (Lake Michigan) ranging from hypereutrophic to oligotrophic. Water quality problems associated with the gradient include high turbidity, excessive algal growth, and dissolved oxygen depletion. The Fox River contributes 78 percent of the tributary total phosphorus load to Green Bay; more than half of that load originates from nonpoint sources. A unit area load (UAL) based microcomputer model is used to generate estimates of nonpoint total phosphorus loads as a function of land use and soil texture in the Fox River watershed. Phosphorus loads are input to a water quality microcomputer model which calculates the total phosphorus and chlorophyll concentrations, water transparency, and trophic state corresponding to that load. Changes in water quality and trophic state are examined under existing conditions and two hypothetical land use scenarios: 100 percent woodland and 100 percent high tillage cropland. The basin is well suited to such a demonstration because of the dominance of the cropland land use classification (65 percent of total basin land acreage). Water quality and trophic state changes associated with the two hypothetical scenarios are dramatic, demonstrating the utility of the approach in providing a basinwide overview of the potential impact of nonpoint management programs in the watershed.

POINT AND NONPOINT POLLUTANT SOURCES

Deterioration in the water quality of the Great Lakes and concommitant changes in the biota of that system have paralleled the cultural development of the region (Beeton, 1970). Long-term alterations in land use from a primarily forested condition to intensive urban and agricultural uses have played an important role in the water quality degradation process (Int. Joint Comm., 1980). One manifestation of cultural development in the basin is accelerated eutrophication of these waters resulting from point and nonpoint loads of plant nutrients and oxygen-demanding materials.

Actions taken in response to the Federal Water Pollution Control Act Amendments of 1972 (P.L. 92-500), the Municipal Wastewater Treatment Construction Grant Amendments of 1981 (P.L. 97-117), and establishment of the National Pollution Discharge Elimination System (NPDES, Sec. 402 of P.L. 92-500) have reduced point source loads of conventional pollutants to the Nation's waters.

The 1978 Great Lakes Water Quality Agreement established phosphorus target loads designed to maintain or improve the trophic status of the Great Lakes' waters. Point source phosphorus management strategies (e.g., upgraded treatment, effluent limitations, detergent phosphorus ban) have reduced phosphorus loads to the Great Lakes. Hartig and Horvath (1982) concluded that reductions in taste and odor problems and decreased chlorophyll levels in Saginaw Bay (Lake Huron) occurred at least partly in response to improved treatment efficiencies and the Michigan phosphorus detergent ban. Bierman et al. (1984) reported, however, that almost half of the observed loading reduction to Saginaw Bay was caused by altered nonpoint contributions associated with decreased tributary flow.

Nonpoint source loads of phosphorus are important across the basin. The Pollution from Land Use Reference Group (PLUARG) reported that contributions of phosphorus from land use sources in 1976 accounted for one-half of the total load to Lakes Superior, Huron, and Erie, and one-third of the total load to Lakes Michigan and Ontario (Int. Joint Comm., 1980). Nonpoint sources of pollution differ from point sources in that they represent the cumulative effect of a large number of diffuse sources that are difficult to identify, monitor, and control.

MANAGEMENT OF NONPOINT POLLUTION

During the last decade, comprehensive studies of water-quality degradation in the Great Lakes and their major embayments have led to increased concern over the significance of nonpoint sources of pollution as contributors to deteriorating conditions (Great Lakes Basin Comm., 1981; PLUARG, 1978; U.S. Army Corps Eng., 1982). This concern is evidenced at all levels of government: at the international level through the U.S./Canadian Great Lakes Water Quality Agreement, at the national level through the Rural Clean Water Program and the Nationwide Urban Runoff Program, and at the State level through the Wisconsin Nonpoint Source Water Pollution Abatement Program.

Mathematical models play a critical role in the water quality management process by linking stated water quality objectives with the treatment or control options required to meet those objectives (Thomann, 1972). As the state of the art has advanced, mathematical models have been more extensively used to gain insight into the dynamics of water quality degradation, and models are relied on to forecast the impact of reduced contaminant stress. The development of areawide water quality management plans in response to Section 208 of P.L. 92-500 has extended the potential role of models within the planning process.

The need for quantification of the role of nonpoint sources of pollution (rural and urban runoff) in determining surface water quality has led to the development of mathematical models of varying degrees of complexity and sophistication (SWMM, Huber et al. 1975; STORM, U.S. Army Corp. Eng., 1975; CREAMS, Knisel, 1980; and ANSWERS, Beasely and Huggins, 1980). Models such as these have the capability of estimating pollutant loads corresponding to land use, soil classification, and climatological conditions. Successful implementation of a water quality management plan requires that the impact of those loads on the system under study be quantified as well. This manuscript demonstrates the application of coupled microcomputer models for a preliminary analysis of nonpoint pollutant loading and water quality response within a drainage of interest. Responses in trophic state and water quality conditions are demonstrated using the lower Fox River–Green Bay drainage (Wisconsin, Lake Michigan) as an example.

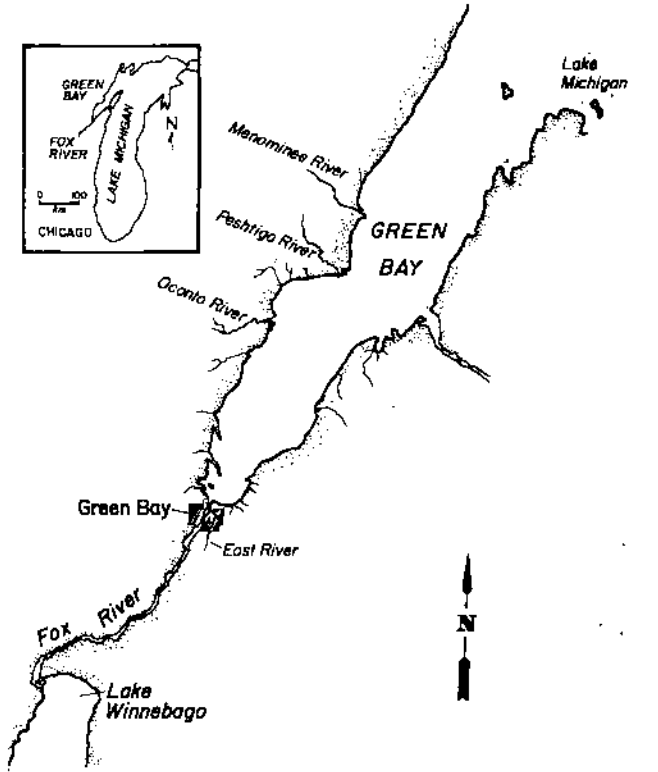

Figure 1.—Major morphological features of the Green Bay–Lower Fox River system and their location with respect to Lake Michigan.

THE GREEN BAY SYSTEM

Green Bay is a large gulf located in the northwest corner of Lake Michigan (Fig. 1). The bay is approximately 160 km long and 22 km wide, has a mean depth of 15.8 m, a volume of 67 km^3, and a hydraulic retention time of 6 years (Mortimer, 1978). For many years, industrial (pulp and paper) and municipal discharges of oxygen-demanding substances and plant nutrients have contributed to severe dissolved oxygen depletion in the lower Fox River and extreme southern Green Bay (Wis. State Comm. Water Pollut., 1939; Epstein et al. 1974). Reductions in municipal and industrial pollutant discharges over the past decade have led to improved water quality conditions in the river and lower bay. Significant residual water quality problems related to agricultural runoff (high turbidity) and point and nonpoint sources of phosphorus (excessive algal growth and reduced water clarity) remain. Hypolimnetic oxygen depletion in Green Bay at sites far removed from point source discharges of organic material occurs, apparently in response to secondary enrichment (e.g., eutrophication).

Strong longitudinal gradients in trophic status are set up along the major axis of the bay as a result of phosphorus loaded from the Fox River. Hypereutrophic conditions exist in the southernmost region near the Fox River mouth, while oligotrophic conditions prevail in the northern reaches near the junction with Lake Michigan. The Fox River, is the single greatest hydrologic and pollutant source for Green Bay, contributing 45 percent of the annual tributary flow and 78 percent of the annual tributary phosphorus load (Roznowski and Auer, 1984). The lower Fox River drainage basin is highly agricultural: nonpoint sources (Lake Winnebago and urban and rural runoff) accounted for 55 percent of the annual Fox River total phosphorus discharge to Green Bay in 1970–71 (Sager and Wiersma, 1975). That nonpoint fraction has probably increased with upgraded point source treatment efficiencies in the basin achieved over the past 15 years. For example, Roznowski and Auer (1984) calculated that the Green Bay Metropolitan Sewerage District contributes only 3 percent of the total annual Fox River total phosphorus load.

OBJECTIVE AND APPROACH

The objective of this paper is to demonstrate the application of coupled, interactive, microcomputer models in evaluating the sensitivity of the system to changes in land use patterns. A unit area load (UAL)-based microcomputer model is used to generate estimates of nonpoint total phosphorus loading as a function of land use and soil texture distributions. Loads calculated by the nonpoint model drive a steady-state water quality model that describes the spatial distribution of phosphorus within the system. Corresponding water quality conditions and trophic levels may be assigned through the use of water quality and trophic state indices. When costs are provided for various levels of land use management, the coupled models provide an overview of the cost effectiveness, as well as the remedial impact of nonpoint pollution control scenarios.

THE NONPOINT LOADING MODEL

The microcomputer model used to calculate average annual total phosphorus loadings from nonpoint sources within a drainage basin uses a unit area load approach. The model assumes that the total phosphorus load resulting from surface runoff at a given site is characteristic of the predominant land use and soil texture of the area. The

UAL (mass of phosphorus per unit area per unit time) reflects nonpoint loadings for an "average" year of wetness.

To evaluate the annual nonpoint source total phosphorus loading, the area under study is divided into a set of subbasins or subwatersheds representing the major hydrologic units within the system. A matrix is constructed for each subbasin to reflect all possible combinations of land use and soil texture—each of which has a characteristic UAL. The area associated with each point on the land use–soil texture matrix (e.g., hectares of fine textured cropland) is multiplied by the appropriate UAL (e.g., kgP per hectare per year) to yield the site-specific phosphorus load (kgP per year). Contributions for each point on the land use–soil texture matrix are summed across the subbasin and then subbasin totals are added to yield the annual nonpoint phosphorus load for the drainage; the procedure is summarized in Figure 2.

For purposes of this demonstration, the lower Fox River watershed is divided into three subbasins: Lower Fox River, Lake Winnebago, and River-Lakes (Fig. 3). Information on land use and soil classifications within the watershed were obtained from the Fox Valley Water Quality Planning Agency and Soil Conservation Service offices for the five-county area that constitutes the Fox River watershed. Eight land use classifications were considered, with cropland predominating in all subbasins. High tillage cropland (complete soil inversion) was not differentiated from low tillage cropland (noninversion soil conditioning); for demonstration purposes, it was assumed that high and low tillage cropland practices are equally represented in each subbasin. Soil classifications were grouped into three major soil texture categories: coarse, medium, and fine; fine soils predominated in all subbasins. Major land uses and soil textures are summarized in Figure 3.

The nonpoint source total phosphorus contribution for each land use–soil texture combination is calculated using UALs derived from studies of systems having similar climatological, land use, and soil texture conditions (see Heidtke et al. 1985). The UALs applied in this demonstration (Table 1) are intended to represent annual total phosphorus contributions from surface runoff events within the lower Fox River watershed during an average year of total precipitation. Contributions from interflow–baseflow are not included in the UAL values, but are treated as constant at a rate of 0.02 kgP/ha per year over the entire watershed. The reader is referred to Heidtke et al. (1985) for additional details on the nonpoint source microcomputer model.

THE WATER QUALITY MODEL

The water quality microcomputer model is a steady-state, mass balance model for phosphorus (Auer and Canale, 1985). The model quantifies phosphorus sources (tributary loads) and sinks (net settling, mass transport) and calculates the steady-state, summer average phosphorus concentration for each of 12 model cells oriented along the major (northeast/southwest) axis of Green Bay. Tributary loads (annual average and summer average) used in model calibration and verification were calculated from tributary monitoring data, USGS flow information, and point source discharge permit reports (Roznowski and Auer, 1984). Net settling losses are estimated from measured sedimentation rates and the phosphorus content of the sediments and overlying water. Mass transport (dispersion) is quantified by calibration to cell-specific, summer average chloride concentrations. Model output is a profile of steady-state phosphorus concentration in Green Bay as a function of distance from the Fox River mouth.

NONPOINT SOURCE MODEL

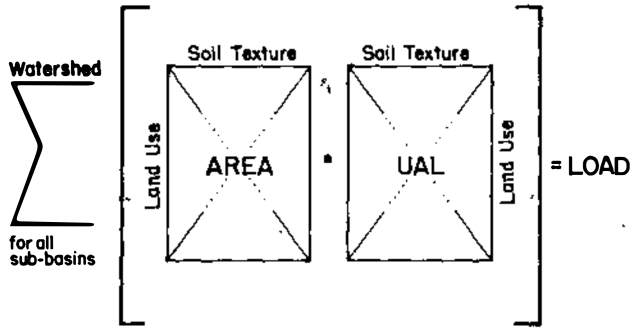

Figure 2.—Schematic for the nonpoint model calculation procedure.

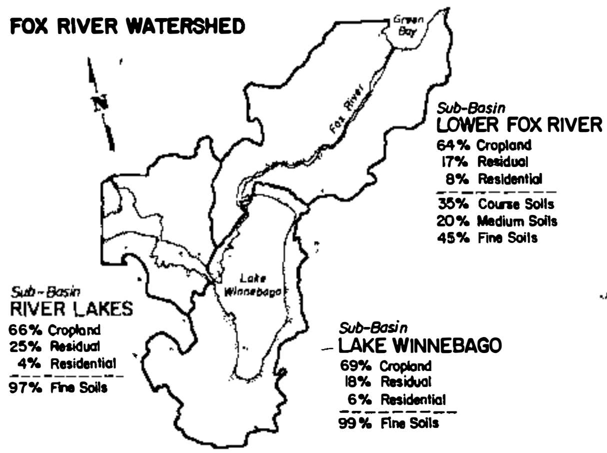

Figure 3.—Land use, soil texture, and major subbasins of the Lower Fox River watershed. Residual land use classification includes woodlands, wetlands, and pasture.

Table 1.—Total phosphorus UAL matrix (kgP/ha · year).

	Soil Texture		
Land Use	**Coarse**	**Medium**	**Fine**
Residential	0.06	0.13	0.18
High tillage cropland	0.55	0.74	0.92
Low tillage cropland	0.22	0.29	0.37
Pasture	0.06	0.07	0.09
Woodland/residual	—	0.02	0.04

Empirically derived trophic state and water quality indices are used to evaluate water quality conditions for each model cell. Relationships published by Dillon and Rigler (1975) are used to estimate water clarity (Secchi disk transparency) and chlorophyll concentration from steady-state phosphorus levels. Chlorophyll levels reflect the phytoplankton standing crop and will respond to phosphorus loading reductions in phosphorus-limited systems (see Bierman et al. 1984). Secchi disk transparency is influenced by dissolved color, chlorophyll, and suspended particulate matter and will respond to phosphorus loading reductions where phytoplankton play a dominant role in light extinction. Secchi disk transparency is closely tied to the public perception of water quality (Shapiro et al. 1975) and thus provides useful input for cost benefit analyses. Trophic state is evaluated in a similar fashion using the criteria of Chapra and Dobson (1981) where a total phosphorus concentration, <11.0 μgP/L, indicates oligotrophy, the range 11.0–21.7 μgP/L indicates mesotrophy, and >21.7 μgP/L indicates eutrophy. The Chapra and Dobson trophic classification may be also used to estimate hypo-

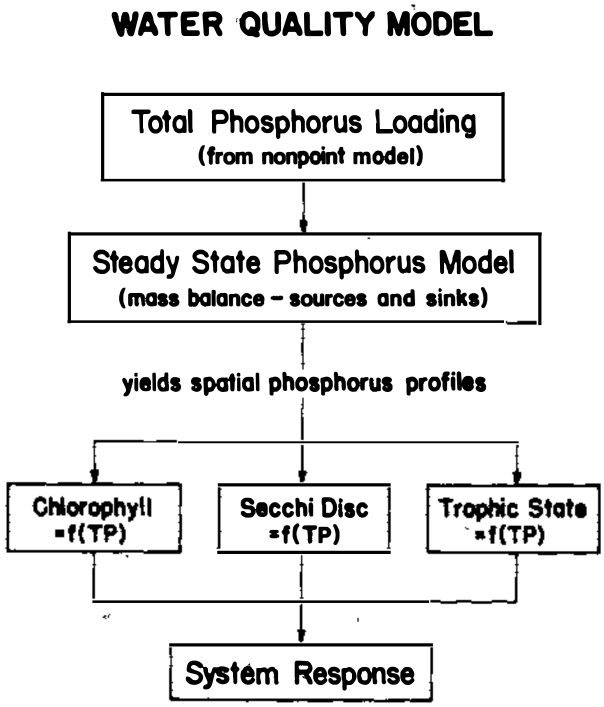

Figure 4.—Schematic for linking nonpoint and water quality models to generate information on response in water quality and trophic state.

Table 2.—Annual average and summer total phosphorus loads.

Land Use Scenario	Annual Average Load (kgP/day)	Summer Average Load (kgP/day)
Baseline	2361	959
100% woodland	252	102
100% high tillage	4591	1865

limnetic oxygen depletion rates. Linkages between nonpoint phosphorus loads, the steady-state model and trophic state and water quality indices are illustrated in Figure 4.

NONPOINT MODEL OUTPUT AND HYPOTHETICAL MANAGEMENT SCENARIOS

The annual average nonpoint total phosphorus loading for the lower Fox River under existing land use conditions, as calculated by the nonpoint source model, is 2,361 kgP/day. This value agrees well with estimates for point plus nonpoint loads reported by Roznowski and Auer (1984: 2,174 kgP/day) and Sager and Wiersma (1975: 2,008 kgP/day). The measured summer average total phosphorus load for the Fox River is 959 kgP/day (Auer and Canale, 1985); loads calculated by the nonpoint model are normalized to summer average levels for input to the water quality model using the ratio of annual average to summer average loads (959/2,361 = 0.406).

The nonpoint source microcomputer model is used to estimate the average annual total phosphorus loads for the Fox River for baseline (= existing) conditions and two hypothetical land use scenarios: 100 percent woodland and 100 percent high tillage cropland. The annual average total phosphorus loads and the normalized summer average loads for the three scenarios are presented in Table 2. The baseline scenario represents existing conditions, the woodland scenario, a best case condition and the high tillage scenario, a worst case condition. These test cases are not intended to characterize specific land use trends within the basin, but rather represent a range of conditions that demonstrate the value of the model in obtaining a rapid, macroscopic estimate of nonpoint loadings and corresponding trophic state. The test cases further demonstrate the model's utility for examining water quality improvements resulting from remedial actions within the watershed.

TROPHIC STATE AND WATER QUALITY RESPONSE

Summer average total phosphorus loads for each land use scenario are input to the steady-state mass balance model and used to calculate corresponding spatial distributions for phosphorus in Green Bay. Figure 5 illustrates spatial patterns for total phosphorus, chlorophyll, Secchi disk transparency, and trophic state for each land use scenario. Total phosphorus concentrations in Green Bay range from 117 to 10 μgP/L under the baseline scenario, 12 to 8 μgP/L under the woodland scenario, and 191–11 μgP/L under the high tillage scenario. When compared with baseline conditions, the worst case, high tillage scenario results in a transparency reduction of approximately 1 m over much of the bay; actual conditions may be worse over the first 15–20 km of the gradient because of increased suspended sediment load and the shallow nature of that part of the system. Chlorophyll levels increase by 2–5 μg/L in the mid- and outer-bay regions and by 20–50 μg/L near the river mouth. Chlorophyll increases near the river mouth may be overestimated because of nutrient saturation and reduced light penetration (self-shading). The best case, woodland scenario generates striking improvements over existing water quality conditions throughout the bay. An increase in Secchi disk transparency of 2–3 m and a reduction in chlorophyll of 1–5 μg/L are characteristic of much of Green Bay. Again, the shallow nature of the extreme southern portion of the bay may lead to an overestimate of water clarity and chlorophyll levels.

Under baseline conditions, the four southernmost model cells (approximately 20 km) are classified as eutrophic, the mid-bay region as mesotrophic, and the outer reaches as oligotrophic. The most dramatic change in trophic status is that for the best case woodland scenario where oligotrophic conditions prevail over the entire length of the bay. Output from this scenario may offer an indication of trophic conditions in the bay prior to cultural development. Under the worse case, high tillage scenario, eutrophic conditions persist for approximately 65 km out into the bay and overlay regions most susceptible to hypolimnetic oxygen depletion.

An example of the impact of land use changes on dissolved oxygen depletion may be developed using the Thienemann Index as presented in Equation 17 of Chapra and Dobson (1981). Volumetric oxygen depletion rates, calculated for an initial hypolimnetic oxygen concentration of 11 mg/L and a duration of stratification of 4 months, would yield anaerobic conditions in 2.2–4.4 months for eutrophic waters, 4.4–8.8 months for mesotrophic waters, and >8.8 months for oligotrophic waters. The portion of Green Bay classified as eutrophic under baseline conditions is shallow and does not permanently stratify; thus, severe dissolved oxygen depletion is rare in that region. The trophic state pattern under the high tillage scenario extends eutrophic conditions over a substantial portion of the bay that does thermally stratify. For the 3–4 months' stratification period characteristic of Green Bay, this region could experience severe hypolimnetic oxygen depletion.

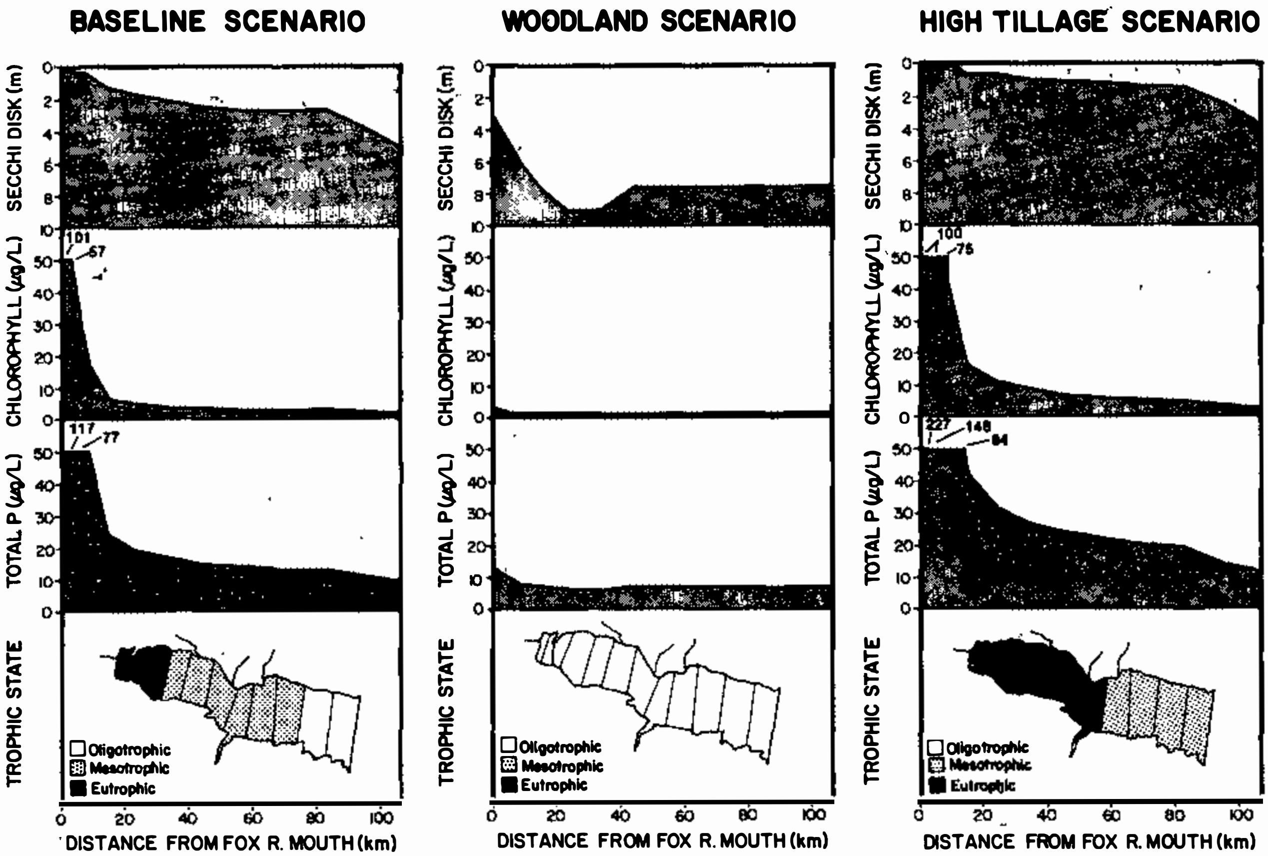

Figure 5.—Examples of water quality model output for three hypothetical land use scenarios: (a) baseline (existing) conditions, (b) 100 percent woodland, and (c) 100 percent high tillage cropland.

SUMMARY

Coupled microcomputer models for nonpoint source phosphorus loads and water quality are used to evaluate the sensitivity of water quality conditions and trophic state to changes in land use in the watershed. The approach is demonstrated for three land use scenarios in the Fox River–Green Bay drainage, a highly agricultural watershed in Wisconsin. The demonstration compares water quality and trophic state for loads representing best and worst case scenarios (woodland and high tillage cropland). Water quality response was dramatic in both cases because of the significant load from agricultural sources under the baseline and high tillage scenarios. The exercise demonstrates the utility of a coupled microcomputer model for nonpoint pollutant loads and water quality as an interactive, user-friendly planning and management tool.

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A PROJECT TO MANAGE AGRICULTURE WASTES HAS IMPROVED THE QUALITY OF VERMONT'S LAKE PARKER

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ABSTRACT

Lake Parker's quality declined in the 1970's. This 83 ha (206 acre), northeastern Vermont Lake suffered from weeds, algae, and bacteria growths. Trout fishing and recreation were no longer an attraction. The Vermont Department of Water Resources determined that the lake's problems were caused by excessive phosphorous and bacteria loads from the 11 dairy farms in the watershed. The town of Glover and other sponsors joined with the Soil Conservation Service to implement a Resource Conservation and Development Project. Eight of the 11 farms had critical waste management problems. All eight participated in the project. Treatment included proper utilization and disposal of wastes through manure storage, barnyard runoff control, and milkhouse waste management. The project was started in January 1981 and completed in June 1982. In 1983 and 1984 Lake Parker has improved markedly.

Pollution and eutrophication of lakes and ponds is a major problem in Vermont. In its water quality management planning, Vermont has recognized agriculture as the single most significant nonpoint source of nutrients and other pollutants reaching many of these waters.

Vermont completed its original State Water Quality Plan for Controlling Agricultural Pollution in 1978. The plan provides a priority list of lake and pond watersheds for project assistance. The State of Vermont, the USDA, and local sponsors have been successful in jointly implementing agricultural nonpoint source management projects in eight of the priority watersheds. The Lake Parker Resource Conservation and Development Measure is one of these and provides the focus for this report.

The Lake Parker Measure is particularly noteworthy because it was requested, planned, funded, designed, and installed in 2 years; it demonstrates the cooperation needed among Federal, State, and local entities and landowners to expedite such a project; and it quickly improved lake water quality.

LAKE PARKER AND ITS WATERSHED

Lake Parker is a glacially formed water body at 44° 40′ north latitude nestled in the steep, rolling hills of Orleans County in northeastern Vermont (Fig. 1). Table 1 provides a summary of the lake and watershed features.

Two perennial streams flow eastward into the lake. Of the 11 dairy farms within the drainage area, two are only partially in the area. The lake shoreline includes 110 seasonal or year-round cottages. Table 2 summarizes land use in the watershed.

The town of Glover (population 790), lakeshore residents (seasonal population 350), nearby communities, and Vermont tourists and fishermen all have used Lake Parker extensively for recreation.

The lake has supported both cold- and warmwater fish in the past, including brown, lake, and rainbow trout; smallmouth bass; pickerel; and yellow perch. The trout fishery has declined in the past decade.

The predominant soil association in the watershed is Buckland–Cabot. These silt loams are poorly drained to moderately well drained. They are glacial tills and often have a hardpan (U.S. Department of Agriculture, 1980).

Climate strongly influences activities in the area. Winter low temperatures of −40°C and summer highs of 32°C are common. Average annual precipitation is 109 cm (30 percent as snow) and runoff is 61 cm. Average flushing rate for the lake is about once every 6.4 months (Vermont Agency of Environmental Conservation, 1980).

WATER QUALITY PROBLEMS IN THE LAKE

Weeds were documented as a threat to the lake as early as 1966, when the Vermont Department of Fish and Wildlife surveyed a fishery and noted extensive growths of aquatic plants, especially *Eloden* (Vermont Agency of Environ. Conserv. 1974). At that time, the Department cited the possibility that agricultural runoff was stimulating the plant growth.

By the 1970's weed growth had become worse, particularly near the stream inlets. Dominant species were *Potamogeton richardsonii, Eloden canandensis, Chara vulgaris,* and *Potamogeton anplifolus* (Warren, 1985). Weed growth was so dense that motor boats could not negotiate much of the area shallower than 3 m. The weeds served as a refuge for yellow perch, rock bass, and stunted bait fish from the larger predators—trout and bass. Decaying weeds consumed dissolved oxygen, especially in the deeper lake segments.

The Lake Parker Association has conducted a weed harvesting program since the early 1970's. In 1980 the weed problem became so severe that the Association was able to gain assistance from the Vermont Department of Water Resources to purchase and operate a weed harvester. Since 1980, the Department of Water Resources and the Association have spent over $32,600 and countless hours of volunteer time trying to control the weeds through a harvesting and disposal program (Garrison, 1984, 1985).

Shoreline and town residents were alarmed by the changing character of the lake. It was no longer aesthetically pleasing. Boating and fishing were not up to par.

The Department's water quality testing (Table 3) showed reason for concern. Though years of data are necessary to draw reasonable conclusions on water quality trends, a key parameter, mean springtime total phosphorus, seemed to be on the increase as did algal density (chlorophyll *a*) prior to 1982. Bacteria were not a widespread problem throughout the lake, but high fecal coliform counts were observed on the west side of the lake between the two perennial stream inlets. The decaying plant material and other organic sediments entering the lake have consumed available dissolved oxygen (DO). Deeper portions of the lake (below 7 m), where the trout tend to congregate during July and August, were found to have inadequate levels (less than 5 mg/L) of dissolved

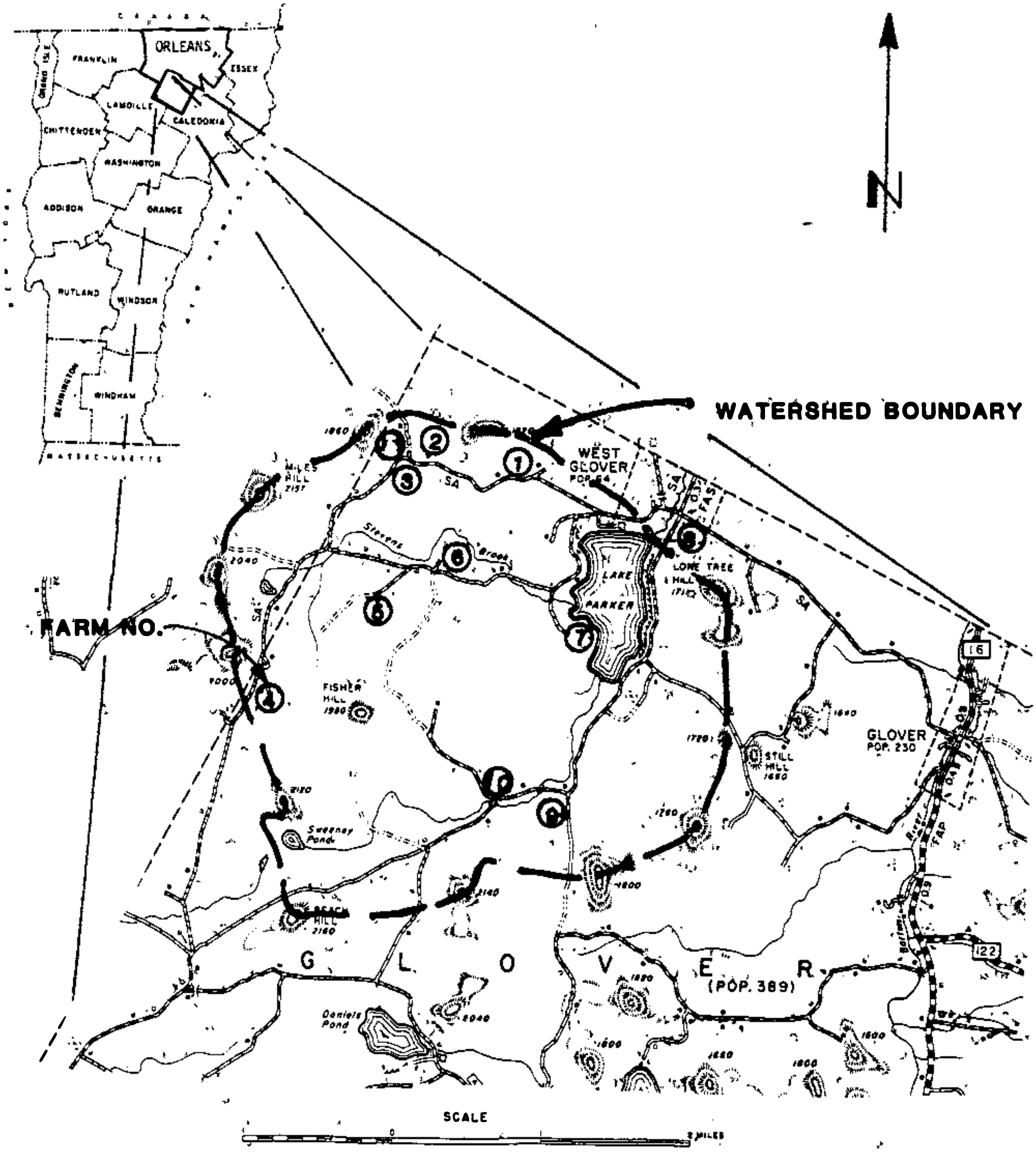

Figure 1.—A location map of the lake and watershed.

Table 1.—Selected physical features of Lake Parker and its watershed.

Feature	**Size** Metric	(U.S. Customary)
Normal lake surface	83.0 ha	206 ac
Normal lake level	396.0 m	1,299 ft NGVD
Major axis	1,677.0 m	5,500 ft
Minor axis	854.0 m	2,800 ft
Maximum depth	12.8 m	42 ft
Mean depth	8.5 m	28 ft
Normal lake volume	7,154,200.0 m³	5,800 ac–ft
Shoreline length	4,880.0 m	16,000 ft
Watershed area	2,125.0 ha	5,250 ac
Highest watershed elevation	658.5 m	2,160 ft NGVD

Source: Vt. Agency of Environ. Conserv. 1974.

Table 2.—Land use of the Lake Parker watershed.

Type	Size		Percent of
	Hectares	Acres	Total
Pasture and hayland	971	2,400	45.7
Cropland in rotation	24	60	1.1
Mixed hardwoods and conifers	903	2,230	42.5
Water surfaces	89	220	4.2
Residential	45	110	2.1
Road surface	57	140	2.7
Other	36	90	1.7
Totals	2,125	5,250	100.0

oxygen. In 1974, five of six DO samples in this depth range were under 5 mg/L DO. This, along with the inaccessibility of prey to fish because of dense weed growth, may partially explain the decline of the trout fishery during the 1970's.

AGRICULTURAL NONPOINT SOURCES

A 1980 study by the Orleans County Natural Resources Conservation District for the Department of Water Resources found that soil erosion was not a significant nonpoint source (Orleans County Nat. Resour. Conservation Dist. 1980). Instead it found that agricultural waste runoff from 8 of the 11 farms was reaching water courses leading to the lake. The town of Glover diverted runoff from one of three other farms to preclude this waste from entering the lake. Selected characteristics of the eight farms with significant runoff are provided in Table 4.

Several reasons accounted for the farm runoff problems: barns, feedlots, barnyards, manure stacks, and milking center waste outfalls were located close to streams (most within 60 m); the landscape is steep and includes stream gradients (fast and flushing runoff); winter manure storage space was inadequate, resulting in winter spreading and improper stacking; and above-site drainage was not diverted, allowing quantities of clean water to mix with and carry wastes away to the streams.

In developing the Rural Clean Water Program Measure plan, the watershed's agriculture was estimated to contribute 85 percent (4,310 kg annually) of the total phosphorus load to the lake. Studies by the Lake Parker Association and the Department of Water Resources found that lake contamination from human wastes and other cultural activities was not a problem. Therefore, agricultural runoff management was key to reducing total phosphorus loads to the lake (Dunbar, 1983).

PROJECT DEVELOPMENT AND INSTALLATION

The Resource Conservation and Development program provides technical and financial assistance to accelerate resource development and environmental protection in multicounty areas. Local sponsors plan, implement, operate, and maintain projects in cooperation with USDA's Soil Conservation Service.

In August 1980, the Soil Conservation Service (SCS) received an application for assistance to control agriculture-related pollutants in the Lake Parker watershed. Sponsors were the Northern Vermont Resource Conservation and Development Council, Orleans County Natural Resources Conservation District, and the town of Glover. The Soil Conservation Service developed a plan to improve agricultural waste management on eight farms. The plan called for negotiating voluntary long-term contracts (3–10 years) with the farmers. This plan was unique to the Resource Conservation and Development program in that the federally assisted long-term contracts were to be locally administered by the town of Glover. The farmers would install, operate, and maintain proper waste management practices in return for cost-share and technical assistance.

In all, the planned waste management systems included 427 m of diversions, 0.8 ha of waterways, 0.8 ha of filter strips, 305 m of fencing, and eight waste storage structures. The plan estimated these could be installed for $178,950, with $131,720 cost-share and $32,720 technical and administrative assistance through SCS's Resource Conservation and Development program. The measure was funded in February 1981.

Farmers favored the measure. They recognized that their operations could cause problems. They liked the idea of a voluntary rather than a regulatory program. They appreciated the technical expertise available to help them develop efficient waste management systems on their farms. The Soil Conservation Service planned, surveyed, and designed practices for each of the farms in the early part of 1981. All eight farmers undertook long-term contracts. By July 1982, all the practices were installed and operating on all eight farms (Dunbar, 1983). Table 5 summarizes the project.

The construction cost for the project amounted to $162,750. Of this, SCS cost-shared $108,800. The farmers now operate and maintain their practices, following operation and maintenance plans prepared for them as a part of the long-term contract. The Orleans County Natural Resources Conservation District and the Soil Conservation Service provide followup assistance as needs arise.

Project implementation was successful because of the cooperation of the farmers, the town of Glover, the Orleans County District, Lake Parker Association, the Department of Water Resources, and the Soil Conservation Service.

LAKE PARKER NOW

Two summers have passed since the Lake Parker Measure was completed. A longer period of evaluation will be needed to establish trends of the lake's response to the waste management. So far, indications have been promising.

From the Lake Parker Association's viewpoint the project has been highly successful. Leo Millette, who heads the lake's weed harvesting program, maintains that "manure management has really helped—you can see the difference in the lake." In July of 1983 and 1984, little weed cutting was needed, in comparison with prior years. Weeds still require harvesting in August. Gerald Anderson, president of the Lake Parker Association, has lived by the lake for 9 years. Anderson claims that the Lake has improved "drastically" since the project. In fact, the association will request the Department of Fish and Wildlife's assistance in restocking the lake with trout. Department of Water Resources officials also are pleased with the lake's response so far.

Water quality data available for the lake in 1983 and 1984 (Table 3) show that averages for summer chlorophyll *a* and Secchi disk transparency values were about the same as in earlier years (Warren, 1985). However, springtime total phosphorus concentrations are declining (Vt. Agency Environ. Conserv. 1978–1983).

The lake's aquatic weed growth appears to be diminishing. Plankton activities may be less sensitive or respond more slowly to the declining concentrations of total phosphorus. The presence of nuisance bacteria needs further evaluation but is not perceived to be a problem. Recycling of various forms of phosphorus from the lake's sediments

Table 3.—Selected water quality data from testing of Lake Parker by the Vermont Department of Water Resources.

Parameter	Unit	74	77	78	79	80	81	82	83	84	Remarks
		Dates 19—									
Mean summer total phosphorus	μg/l	44	—	—	—	—	—	—	—	—	Spring value not available
Mean spring total phosphorus	μg/l	—	14	10	16	20	21	17	15	12	
Summer average chlorophyll a	μg/l	—	4.8	—	6.1	7.2	5.9	5.2	5.6	5.8	
Summer average Secchi disk transparency	m	—	3.5	—	3.3	3.7	3.2	4.0	4.2	3.6	
Fecal coliform	count per 100ml	700	None Available								high of observations. Range 8–700 at various locations
Dissolved oxygen (percent observations below 5 mg/l at or more than mean depth)	%	42	None Available								

Source: Vt. Dept. Water Resources.

Table 4.—Animal and waste management characteristics of eight Lake Parker watershed farms.

Farm No.	Animal Units	Annual manure tons	Cropland receiving manure acres	Milkhouse effluent could enter watercourse	Barnyard runoff to watercourse
1	80	1,440	55	Yes	Yes
2	68	1,225	68	Yes	No
4	60	1,080	110	Yes	Yes
5	77	1,385	70	Yes	No
6	80	1,440	84	Yes	No
7	80	1,440	99	Yes	Yes
9	65	1,170	80	Yes	Yes
10	65	1,170	80	Yes	No
Totals	575	10,350	646	—	—

Table 5.—Lake Parker resource conservation and development (RC&D)—practices installed.

Practice	Type	Quantity	Unit	Total Cost $
Waste storage structure	Rein. concrete	2	no.	60,170
Waste storage structure	Timber wall	4	no.	75,180
Waste storage pond	Earth	2	no.	19,460
Waste utilization	—	8	no.	
Diversion	Grassed	185 (607)	m (ft)	840
Milking center absorption trench and grass filter	—	6	no.	4,300
Grass filter strip	—	0.7 (1.8)	ha (ac)	310
Farm road relocation	—	1	no	750
Heavy use area protection	Barnyard	1	no.	1,740
Total				162,750

should not pose a critical problem because only minor amounts of sediment reach the lake and because the lake is flushed rapidly.

CONCLUSION

The Lake Parker Measure is an example of what can be done through a program of voluntary participation. Government agencies at various levels and the local citizenry participated. All farmers with significant on-farm nonpoint sources participated. Lake users are already pleased with the results. Continued monitoring is needed to establish long-term water quality trends.

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