PERSPECTIVES ON NONPOINT SOURCE POLLUTION

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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-

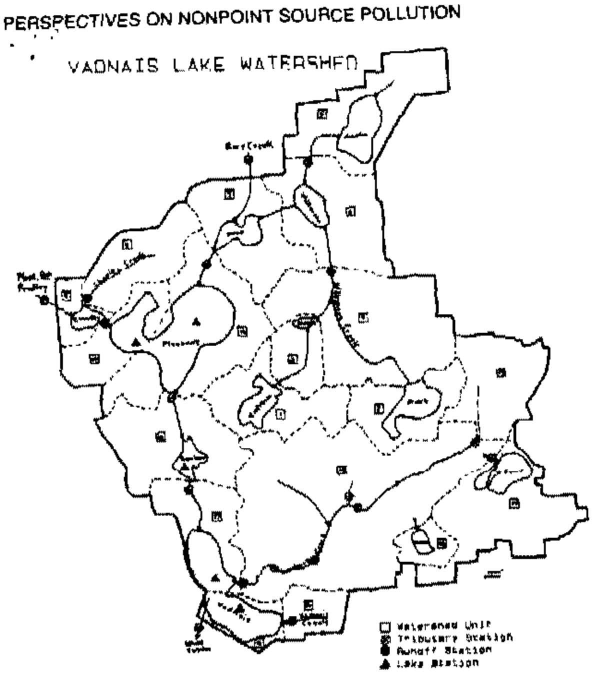


Figure 1.—Vadnais Lake watershed.

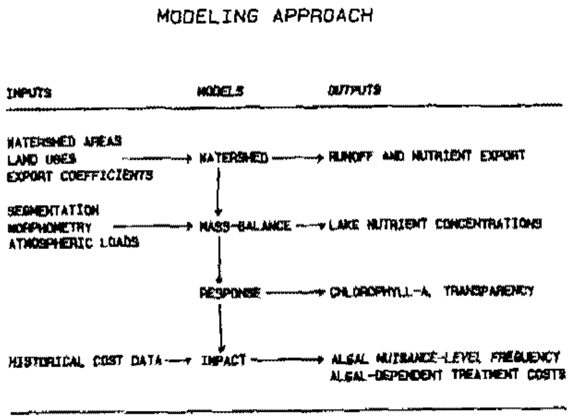


Figure 2.—Modeling approach.

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.

Variable	Units	Lake 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.

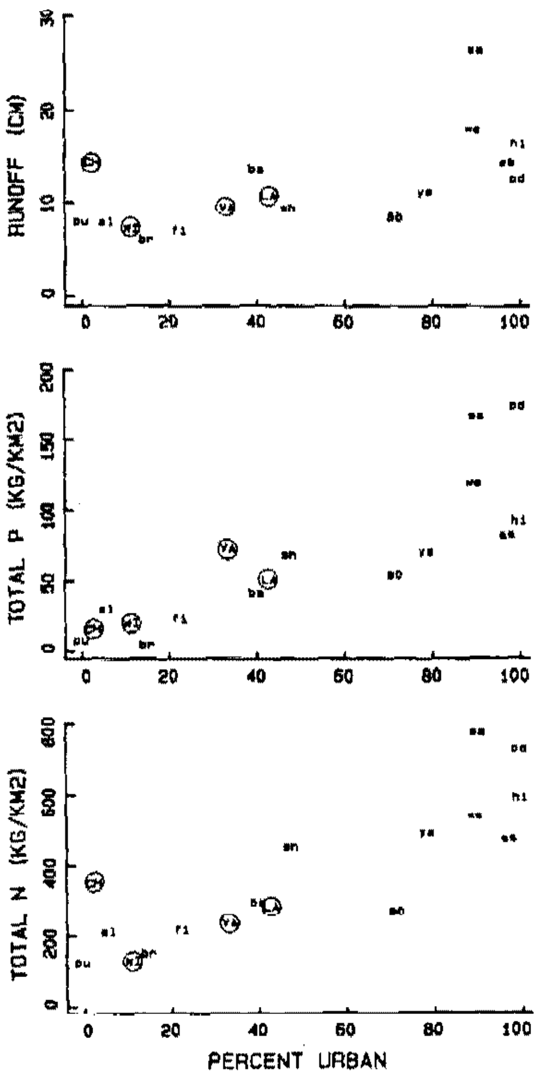
Because of lower use intensity and less impervious area, low-density residential land uses are distinguished from other urban land uses in the export matrix. Regional data analyses indicate that phosphorus export is more strongly correlated with urban land use when low-density areas are excluded. The 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	986	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.

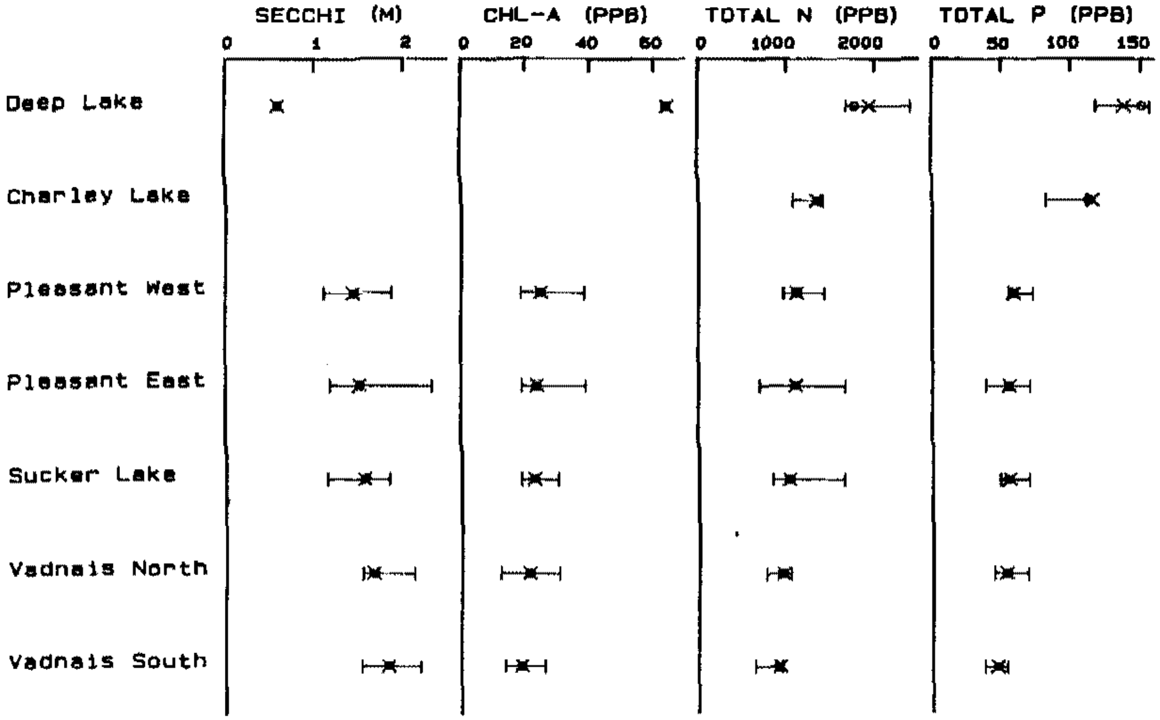
MASS-BALANCE AND EUTROPHICATION-RESPONSE MODEL CALIBRATION

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



Legend

Vertical bars indicate 95 percent confidence range for observed mean value
0 = model prediction using measured runoff and nutrient loadings.
X = model prediction using runoff and nutrient loadings estimated from land use.

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		102			
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.

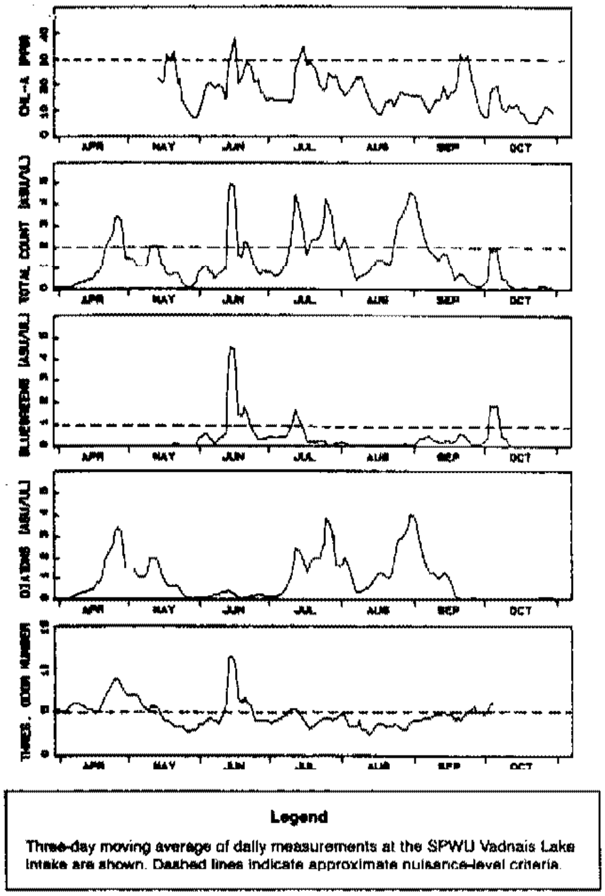
Algal nuisance-level or bloom frequency is defined as the percent of the growing season that chlorophyll *a* concentrations exceed 30 ppb, a reasonable criterion for nuisance-level algal densities, based on 1984 Vadnais intake time series data (Fig. 5) and general literature criteria (Walmsley, 1984; 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			Entire Lake Chain			
	Area	······· Flow ·······		···· Avail. P ····		······ Total N ······	
Watershed	**km^2**	**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	0.86	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			Vadnais Lake only			
	Area	······· Flow ·······		···· Avail. P ····		······ Total N ······	
Watershed	**km^2**	**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



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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.

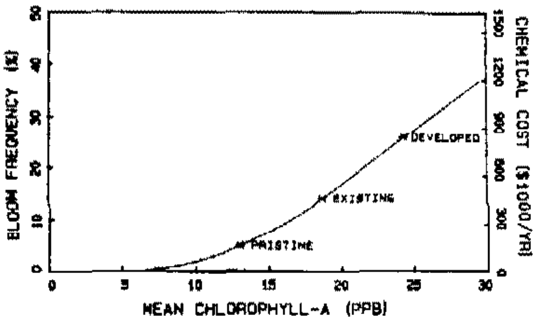

Figure 6.—mean chlorophyll a and bloom frequency for various watershed development scenarios.

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.

		Watershed Development		
Factor	**Units**	**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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