Breach in the barrier bar at the mouth of Old Woman Creek estaury following a storm (Charles E. Herdendorf).

Chapter 5. Hydrology

Lake Hydrology

The lower reaches of Old Woman Creek and the estuary are turbid throughout most of the year, owing to the silty nature of the soil and sediment resuspension by wind and lake action. Because of higher-than-average water levels in Lake Erie since the mid-1970s, former marshlands occupying this part of the watershed are now inundated. This condition has resulted in the flooding of approximately 60 hectares (150 acres), extending lake level some 2.1 km (1.3 mi) upstream. Historically, Lake Erie has exhibited extended periods of high and low water levels, which have caused the estuary to alternately be flooded and then to be dewatered. Commensurate with the lowering of water levels in Lake Erie, a trend that began in 1999, much of the once inundated Old Woman Creek estuary can be expected to again develop an extensive emergent vegetation marsh.

Lake-Flooding Potential

Floods within Old Woman Creek estuary can take place from two sources: (1) Lake Erie water entering via the estuary mouth and (2) watershed discharge entering via the main stem of Old Woman Creek and several smaller tributaries. In 1977 the U.S. Army Corps of Engineers (USACE), in conjunction with the Federal Insurance Administration, developed a procedure for establishing flooding potentials for the open coast of Lake Erie using the 1% value from a frequency curve of the maximum instantaneous high level each year. This level is comparable to the storm water level which results from a wind setup superimposed on the undisturbed water level of the lake, but does not include wave runup caused by waves rushing up the beach or a shore structure. Water level records from 1899 to 1974 were used to calculate the flooding potential for 24 reaches of the Lake Erie coast. The coast between Huron and Vermilion, Ohio, including the mouth of Old Woman Creek lies within reach "U." Open-coast flood levels were derived for 10-, 50-, 100-, and 500-year return periods; which represent the highest water levels along the coast that on the average will have a 10%, 2%, 1%, and 0.2%, respectively, chance of being equaled or exceeded in any given year. The predicted elevations for this reach are presented in Table 5.1.

Waves

The largest wind-generated waves on Lake Erie are those produced by large-area (synoptic-scale) circulation features such as extratropical and tropical cyclones (Figure 5.1). Smaller-scale wind phenomena (e.g. individual thunderstorms or squall lines) do not maintain winds over sufficient fetch to generate waves of comparable height. Resio and Vincent (1976) developed a wave hindcast model which predicts significant wave heights for return periods ranging from 5 to 100 years, for 24 grid points off the Lake Erie coast. Grid point "6" lies about 15 km off the barrier beach at Old Woman Creek. Seasonal extreme wave heights for this grid are presented in Table 5.2.

Wind Tides and Seiches

Wind tide or storm surge is a rapid rise in lake level resulting from the forced movement of surface water under the stress of wind. Once the wind has abated, the free oscillation (or sloshing) of the lake's surface is known as a seiche. Wind tide and seiche activity in the vicinity of Old Woman Creek can raise and lower the water level as much as 1 to 2 m (3 to 7 ft) or more in a single storm, but typical daily fluctuations are in the range of 0.1 to 0.2 m (0.3 to 0.7 ft). Seiches are an important factor in producing short-period water level oscillations in Lake Erie and in Old Woman Creek estuary. Owing to the orientation of the lake (longitudinal axis which nearly corresponds to the direction of the prevailing winds), the most common seiche is longitudinal and has a period of approximately 14 hours. Because of the estuary's position on the central basin of Lake Erie, the magnitude of the fluctuations are less pronounced than at the east and west ends of the lake.

Oscillation in lake level may also be set up by elevated atmospheric pressure bearing down upon a particular region of the lake or by a low pressure cell passing over the lake. Once the high or low pressure cell has passed, water either surges back or streams away in the process of reestablishing equilibrium, and exhibits the oscillatory movement of a seiche. A particularly intense cyclonic storm passed over Lake Erie in January 1978, when the lake was significantly ice covered. The low pressure cell crossed the lake

Figure 5.1. Waves from an April 1998 northeast storm batter the Lake Erie shoreline to the west of the Research Reserve (Charles E. Herdendorf).

from south to north near Lorain, Ohio, about 50 km (30 mi) east of the Reserve, inducing a noticeable water level rise (0.2 m or 0.7 ft) of a type that is rare for Lake Erie and usually only seen along the ocean coasts in response to hurricanes (Dingman 1980). The ensuing storm surge produced a 3-m (10-ft) difference in lake level between Old Woman Creek and Buffalo, New York, at the eastern end of the lake. Buffalo was flooded while Lorain reported a severe shortage of water at their treatment plant intake.

BEACH EROSION AND SHORELINE RECESSION

The barrier beach at the mouth of Old Woman Creek has experienced considerable recession in the past several decades. In 1956, the shore of the barrier beach was 220 m north of the U.S. Route 6 bridge (Herdendorf 1963a). By 1990 this distance had been reduced to 137 m. Thus, the center portion of the beach had migrated shoreward a distance of 83 m in the 34-year interval, a recession rate of 2.4 m/yr. During the same period, the length of the barrier beach was reduced from 520 m to 418 m. Hartley (1964) demonstrated that major shore structures, such as harbor jetties at Huron and Vermilion, had trapped large quantities of sand at the expense of the intervening shoreline. Serious beach erosion is evident along the 16.8 km reach between these two harbors, which includes the Old Woman Creek barrier beach. The main agents of beach erosion are wind, lake levels, waves, currents, and ice (U.S. Army Corps of Engineers 1946, 1953; Carter and Guy 1980).

LAKE WATER QUALITY

Lake Erie has undergone major changes in its chemistry and biology over the last 25 years. Nutrient inputs into the lake, particularly from point sources, have diminished (Fuller et al. 1995) and invasions by exotic species, particularly the zebra mussel *Dreissina polymorpha* (Hebert et al. 1991), have changed the ecology of Lake Erie very dramatically. Unfortunately, detailed chemical monitoring in the nearshore zone of Lake Erie over the ice-free periods has not been routinely undertaken for many parameters.

TABLE 5.1. FLOODING POTENTIAL OF THE LAKE ERIE COAST AT OLD WOMAN CREEK MOUTH

Return Period	+ MLS 1929[1] meters	+ MLS 1929[1] feet	+ IGLD 1955[2] meters	+ IGLD 1955[2] feet	+ IGLD 1985[3] meters	+ IGLD 1985[3] feet	+ LWD[4] meters	+ LWD[4] feet	+ Mean[5] meters	+ Mean[5] feet
10-year	175.5	575.9	175.0	574.3	175.2	574.9	1.7	5.7	1.1	3.6
50-year	175.8	576.8	175.3	575.2	175.5	575.8	2.0	6.6	1.4	4.5
100-year	175.9	577.0	175.4	575.4	175.6	576.0	2.1	6.8	1.5	4.7
500-year	176.1	577.6	175.6	576.0	175.7	576.6	2.3	7.4	1.7	5.3

NOTES: 1. Mean Sea Level 1929 (New York City mean tide level)
2. International Great Lakes Datum 1955 (Father Point, Quebec mean water level)
3. International Great Lakes Datum 1985 (Rimouski, Quebec mean water level)
4. Low Water Datum (LWD) = NOAA/USACE Chart Depth:
LWD referred to MLS 1929 = 173.8 m (570.2 feet)
LWD referred to IGLD 1955 = 173.3 m (568.6 feet)
LWD referred to IGLD 1985 = 173.5 m (569.2 feet)
5. Mean Water Level = 0.64 m (2.1 feet) above LWD
6. Ordinary High Water Mark (OHWM) = 1.28 m (4.2 feet) above LWD

Data Source: U.S. Army Corps of Engineers (1977)

TABLE 5.2. ESTIMATES OF EXTREME LAKE ERIE WAVES OFF OLD WOMAN CREEK, OHIO

Return Period	Northwest Storm Height (m)	Northwest Storm Period (sec)	North Storm Height (m)	North Storm Period (sec)	Northeast Storm Height (m)	Northeast Storm Period (sec)
SPRING						
10-year	1.5±0.2	5.6	1.0±0.2	4.6	1.5±0.3	5.7
50-year	2.2±0.2	6.3	1.8±0.3	6.0	2.7±0.4	7.0
100-year	2.5±0.3	6.6	2.1±0.3	6.3	3.2±0.5	7.4
SUMMER						
10-year	1.5±0.2	5.6	1.3±0.3	5.3	1.5±0.5	5.7
50-year	1.9±0.4	6.0	1.7±0.4	5.9	2.3±0.9	6.6
100-year	2.1±0.4	6.2	1.9±0.5	6.1	2.7±1.0	7.0
FALL						
10-year	2.4±0.2	6.5	2.7±0.1	7.0	2.9±0.3	7.2
50-year	3.0±0.2	7.0	3.2±0.2	7.4	4.3±0.5	8.4
100-year	3.3±0.3	7.3	3.4±0.2	7.7	4.8±0.5	8.9
WINTER						
10-year	2.2±0.2	6.3	3.1±0.2	7.4	2.7±0.2	7.0
50-year	3.3±0.3	7.3	4.0±0.3	8.3	3.6±0.3	7.7
100-year	3.7±0.4	7.7	4.4±0.4	8.7	3.9±0.4	8.0

Data Source: U.S. Army Corps of Engineers (Resio and Vincent 1976)

HURON HARBOR WATER QUALITY STUDY

Between April and November 1976, the U.S. Environmental Protection Agency (Gedeon 1977) performed 16 water quality surveys in Lake Erie near the Huron Harbor, Ohio Dike Disposal Facility. A Total of 17 chemical and physical parameters were measured at six lake stations (two background and four near the dike) and one river station. The background stations serve as a useful set of baseline data for nearshore lake conditions in the vicinity of Old Woman Creek estuary, a few years prior to the establishment of the Research Reserve. Measurements were taken 0.5 m below the surface and 0.5 m above the bottom (Table 5.3). Water depths at the two background stations were in the range of 3.0 to 4.0 m. The following section outlines the seasonal water quality trends noted for spring through autumn 1976.

Turbidity and Suspended Solids

Strong northerly winds caused re-suspension of lake bottom sediments as evidenced by high turbidity values obtained in April which were fairly uniform throughout the water column. From May through November turbidity values were relatively low, rarely exceeding 10 JTU. Since there is a direct relationship between turbidity and suspended solids, the seasonal patterns of these two parameters were very similar.

Phosphorus

Ortho-phosphorus constituted about 35% of the total phosphorus present in the water and alone exceeded the Ohio Environmental Protection Agency (EPA) water quality standard for total phosphorus of 25 μgm/l during most of the period from April through July. Ortho-phosphorus represents the most biologically active form of phosphorus dissolved in the lake water. Total phosphorus exceeded the Ohio EPA standards for the entire study period, with the exception of November when the concentration dropped to about 20 μgm/l. Bottom waters exhibited the highest concentrations, most likely the result of releases from the sediments.

Nitrogen

Nitrate-nitrite concentrations were the highest in early April and declined steadily to near zero by mid-September. As the concentration of dissolved oxygen increased in October and November, concentrations of nitrate-nitrite also increased. Ammonia nitrogen was below 0.10 mg/l most of the time and averaged only 0.04 mg/l. However, during the period from April until late June, total inorganic nitrogen (sum of nitrate, nitrite, and ammonia concentrations) exceeded the Ohio EPA standards of 0.30 mg/l for Lake Erie. Total Kjeldahl nitrogen (organic nitrogen) concentrations approximately doubled between mid-April and early August (0.49 to 0.88 mg/l). The early August peak corresponded with the highest water temperature and the optimum period for blue-green algae growth. Following this peak, the concentration of organic nitrogen declined steadily into November.

Chemical Oxygen Demand

Following the high demand values (20-40 mg/l) caused by turbulent lake conditions in early April, the demand values dropped to 10-15 mg/l for most of the summer and autumn. The values for the later half of the year were at or near the maximum limit of 12 mg/l for Ohio EPA water quality standards for nearshore waters of Lake Erie.

Total Iron, Manganese, and Arsenic

During periods of high water turbidity, high total iron concentrations were also observed. Re-suspension of bottom sediments resulting from strong northerly winds appears to have been the major cause of the high values. The average total iron concentration was 873 μg/l. The Ohio EPA standard of 300 μg/l was exceeded a majority of the time, except in late summer when at times values decreased to <200 μg/l. Total manganese followed a similar seasonal pattern as iron, but only exceeded Ohio EPA standards of 50 μg/l in early April. Arsenic was detected at very low levels (<2 μg/l), well below the Ohio EPA standard of 5 μg/l for nearshore waters of central Lake Erie.

Oil and Grease

During April, low concentrations of oil and grease were found in surface and bottom water (1-2 mg/l), which were attributed to decomposing organic matter which was re-suspended by the turbulent lake conditions at the time. For the remainder of the year most values were <1 mg/l.

TABLE 5.3. LAKE ERIE NEARSHORE WATER PROPERTIES IN 1976

	Range	Mean
Turbidity (JTU)		
Surface	4-55	16
Bottom	4-85	19
Suspended Solids (mg/l)		
Surface	5-71	20
Bottom	5-197	29
Ortho-phosphorus (µg/l as P)		
Surface	<5-48	21
Bottom	<5-96	24
Total Phosphorus (µg/l as P)		
Surface	20-120	61
Bottom	<20-300	69
Nitrate + Nitrite (mg/l as N)		
Surface	<0.03-3.01	0.42
Bottom	<0.03-2.98	0.43
Ammonia (mg/l as N)		
Surface	<0.03-0.13	0.04
Bottom	<0.03-0.22	0.04
Total Kjeldahl Nitrogen (mg/l as N)		
Surface	0.26-1.00	0.55
Bottom	0.25-1.58	0.57
Chemical Oxygen Demand (mg/l)		
Surface	5-26	13
Bottom	6-41	14
Iron (µg/l as Fe)		
Surface	185-3,250	793
Bottom	193-5,000	952
Manganese (µg/l as Mn)		
Surface	7-46	20
Bottom	8-170	26
Arsenic (µg/l as As)		
Surface	<2	<2
Bottom	<2	<2
Oil and Grease (mg/l)		
Surface	<1-2	<1
Bottom	<1-1	<1
Temperature (°C)		
Surface	5.7-22.9	14.9
Bottom	5.7-22.8	14.6
Dissolved Oxygen (mg/l)		
Surface	3.2-11.8	7.5
Bottom	3.1-11.5	7.3
Eh (millivolts at 25°C)		
Surface	244-389	298
Bottom	244-424	308
pH (standard units)		
Surface	7.8-8.5	8.2
Bottom	7.8-8.5	8.1
Conductivity (µmhos at 25°C)		
Surface	246-333	280
Bottom	240-315	278
Currents (knots/hr)		
Surface	0.05-0.60	0.27
Bottom	0.08-0.75	0.31

Data Source: U.S. Environmental Protection Agency (Gedeon 1977)

Temperature

Following the typical annual trend, water temperature gradually increased from about 6°C in early April to nearly 23°C in late July and early August. In late summer to autumn, temperatures declined rapidly, reaching about 4°C in early November (Table 5.4).

Dissolved Oxygen

Both surface and bottom dissolved oxygen (DO) concentrations steadily decreased from approximately 10 mg/l in April to about 3 mg/l in mid-September. DO concentrations then rapidly increased to over 11 mg/l by early November as a result of decreasing water temperatures and increased turbulence brought about by more northerly winds (Table 5.4).

Oxidation-Reduction Potential (Eh)

The waters of Lake Erie contained sufficient oxygen to inhibit anaerobic activity. Consequently, Eh values indicated waters of relatively high oxidative potential (i.e. oxidizing bacterial species were more abundant than reducing species).

Hydrogen-ion Concentration (pH)

Lake Erie nearshore waters were slightly alkaline. The values had a narrow range; the most frequently occurring (mode) pH was 8.2.

Conductivity

Specific conductance, the dissolved-ion concentration or mineralization of the lake water as measured by electrical conductivity, was relatively uniform. The background stations averaged 279 μmhos (1 μmhos = 1 μSiemen) which equates to approximately 200 ppm of dissolved solids or a salinity of 0.2% (about 0.57% the salinity of mean sea water).

Currents

Nearshore currents were typically generated by sustained wind, most commonly from a southwesterly direction. The surface currents generally followed the direction of the wind but the bottom currents were more complex, at times opposed to the wind direction, presumably a compensating return flow for the water removed by the surface currents.

TABLE 5.4. TRENDS IN AVERAGE TEMPERATURE AND DISSOLVED OXYGEN OF LAKE ERIE NEARSHORE WATERS IN 1976

Date	Temperature (C°)	Dissolved Oxygen (mg/l)
Apr 5	5.9	9.0
Apr 8	7.6	10.0
Apr 12	7.0	10.2
Apr 15	9.6	10.9
May 17	13.8	9.6
Jun 7	17.8	6.8
Jun 14	21.4	5.6
Jun 21	20.6	7.2
Jul 21	22.4	6.0
Aug 4	22.8	4.0
Sep 8	19.7	7.4
Sep 16	19.8	3.3
Sep 23	16.6	5.0
Sep 30	15.8	4.8
Oct 19	10.8	6.4
Nov 9	4.4	11.6
Mean	14.8	7.4

Data Source: USEPA (Gedeon 1977)

WATER INTAKE STUDIES

Since the 1976 Huron study, no published water quality studies have been conducted in the nearshore zone near the Reserve. However, data from the Sandusky water treatment plant intake (Table 5.5) for the period 1997-2001 shows that locally many of these parameters have not changed significantly over this 25 year period. Chemical parameters measured both at Sandusky and in the nearshore zone of Lake Erie by the Old Woman Creek monitoring program had many similarities during the 1998-2000 period (see Estuary Water Quality section later in this chapter).

The Huron water treatment plant monitors parameters on a daily basis, including pH, alkalinity, and turbidity. Data for the period 2000-2001 is presented in Table 5.6. These data are quite different from those collected during 1998-2000 in the nearshore zone Old Woman Creek. The cause of the difference is unknown, but may be related to the proximity of the Old Woman Creek monitoring site to the lake shore (2 to 5 m from shore, 1 m depth) as compared with the Huron site (400 m offshore, 5 m depth) and the time of day samples were collected. Another factor may be Old Woman Creek discharge at the nearshore station.

TABLE 5.5. LAKE ERIE WATER QUALITY AT SANDUSKY, OHIO WATER INTAKE FOR 1997 TO 2001

Parameter	Range	Mean
Suspended Solids -mg/l	2.5-56	18.5
Total Phosphorus- µg/l P	21-100	39.9
Nitrate + Nitrite- mg/l N	0.12-1.54	0.576
Ammonia- mg/l N	0.025-0.140	0.057
Total Kjeldahl Nitrogen-mg/l	0.02-0.44	0.212
Chemical Oxygen Demand-mg/l	<10	<10
Iron- µg/l	155-1985	820
Manganese- µg/l	18-295	92
Arsenic- µg/l	<2-2.2	<2
pH- Standard Units	8.02-8.22	8.11
Conductivity- µmhos/ cm	259-323	283
Total Alkalinity- mg $CaCO_3$/l	77-92	84.7
Calcium- mg/l	29-38	33
Magnesium- mg/l	8-10	9.5
Chloride- mg/l	12-20.4	15.2
Sodium- mg/l	6-12	8.6
Sulfate-mg/l	18-41	28.1

Data Source: Ohio EPA (courtesy Doug Keller, City of Sandusky Water Treatment Plant)

TABLE 5.6. LAKE ERIE WATER QUALITY AT HURON, OHIO WATER INTAKE FOR 2000 AND 2001

Parameter	Range	Mean
pH- Standard Units	7.2-8.6	7.9
Total Alkalinity- mg $CaCO_3$/l	85-112	98
Turbidity- NTU	0.9-129	15.3

Data Source: City of Huron Water Treatment Plant (courtesy of Ron Marsnic)

ESTUARY HYDROLOGY

Like the oceans, the Great Lakes possess estuarine-like environments in the lower reaches of many tributary streams. Such estuaries are particularly prevalent along the south shore of Lake Erie where crustal rebound, following deglaciation, has resulted in the outlet (Niagara River) rising over 30 m in relation to this shore (Herdendorf 1990). As a result, the lower courses of the southern tributaries have been flooded by the encroaching lake, creating the drowned river mouths typical of estuarine systems.

Coastal wetlands, particularly freshwater estuaries, of the Great Lakes play an important role in mitigating adverse impacts to the lakes by pollutants entering the wetlands from the watersheds and the atmosphere. Here, various chemical, physical, and biological processes transform and trap pollutants, sediments, and nutrients, storing them temporarily or permanently in the wetland. In the absence of wetlands all of these materials would enter the lake directly. Understanding the hydrologic processes which govern the exchange of water between the estuary and lake is fundamental in determining water storage and the flux of materials through these systems.

The mouth of Old Woman Creek has been classified as an estuary because it possesses many features analogous to typical saltwater estuarine systems (Brant and Herdendorf 1972). It is a semi-enclosed body of water that for most of the time has a free connection with the lake. Water exchange in the estuary is primarily driven by wind tides and seiches in Lake Erie and by stream drainage from the catchment. Because of the highly mineralized water from the catchment, a chemical gradient exists between the waters of Lake Erie and Old Woman Creek. Physical features typical of estuaries include the narrow mouth, a barrier beach sheltering the estuary from the lake, perimeter mud flats, and freshwater marshes.

Old Woman Creek drains approximately 69 km^2 (27 mi^2) of primarily agricultural land. The estuary consists of the lower 2.1 km (1.3 mi) of the creek which flows into southwestern Lake Erie. Morphologically the estuary is divided into 3 parts: (1) the upper estuary, or south basin, is comprised of a narrow creek-like channel (which during high water levels spills out over adjacent swampy land) that terminates in a shallow lagoon where a railway causeway constricts drainage, (2) the central or main estuary is a shallow basin cut by a narrow drainage channel along its western margin that terminates where a highway causeway constricts drainage, and (3) a small, elongated lake lagoon that lies between the road causeway and the sandy barrier (Oberlin Beach) that separates the estuary from Lake Erie. For ease of designation, the basins are hereafter referred to as "South," "Main," and "Lake Lagoon," respectively. Table 5.7 presents a comparison of surface area, water volume, and mean depth under several water level conditions for the three basins. The total estuary area (including the upper swamps is about 0.6 km^2 (60 hectares or 150 acres). Bottom sediments in the estuary are unconsolidated muds that are resuspended by wave action to give the estuary water its characteristic turbid appearance. The location and dimensions of the estuary mouth are constantly changing in response to variations in stream flow, currents generated by water level differences between the estuary and the lake, and wave action which modifies the barrier beach. Under certain conditions the beach barrier completely bars off the estuary and the system becomes lacustrine for extended periods. Table 5.8 presents a history of the open conditions of the estuary bar from 1983 to 2000.

HYDROGRAPHIC AND BATHYMETRIC SURVEY

Because only a generalized bathymetric map (Buchanan 1982) and no comprehensive description of the hydrology of Old Woman Creek estuary was available, a hydromorphometric study of the estuary was undertaken in 1990 (Herdendorf and Hume 1991). The objectives of the study were to: (1) map the bathymetry of the estuary, (2) determine the factors controlling temporal variations in the hydrologic characteristics and water storage capacity of the estuary, and (3) examine the role the estuary plays in the exchange of water between the watershed and Lake Erie. Depth soundings were made along 43 transects at nearly 1,000 locations (Figure 5.2). Water levels were monitored during the surveys at a recorder established by the U.S. Geological Survey in the estuary at the lakeshore. Additional information was gained from vertical aerial photographs that had been taken at various water level stages in 1937, 1949, 1950, 1956,

TABLE 5.7. BASINS OF OLD WOMAN CREEK ESTUARY

Basin	Water Level (m + LWD)	Area (m^2)	Volume (m^3)	Mean Depth (m)
South	2.0	194,565	161,404	0.83
	1.0	74,333	28,892	0.39
	0.0	11,800	2,430	0.21
Main	2.0	425,000	578,292	1.36
	1.0	424,375	153,355	0.36
	0.0	3,463	1,672	0.48
	-1.0	1,115	306	0.27
Lake Lagoon	2.0	30,735	36,526	1.19
	1.0	20,752	10,766	0.52
	0.0	2,532	227	0.09

NOTE: Low Water Datum (LWD) = 173.5 m or 569.2 ft (IGLD, 1985) elevation

TABLE 5.8. RECORD OF OPEN CONDITIONS AT THE MOUTH OF OLD WOMAN CREEK ESTUARY

	Days Open																		
Month	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**MEAN(%)**
January	31	31	31	31	31	29	30	31	31	0	31	31	31	31	31	31	14	31	28.2 (91.0)
February	28	29	28	28	28	29	28	28	28	13	28	28	28	29	28	28	19	29	26.9 (95.1)
March	25	31	25	31	31	26	31	31	31	26	31	31	31	31	31	31	31	31	29.8 (96.1)
April	25	30	30	22	26	18	30	24	30	23	30	30	30	30	30	30	30	30	27.7 (92.3)
May	17	31	31	31	5	6	31	29	17	5	31	14	31	31	31	25	12	31	22.7 (73.2)
June	15	29	0	19	29	0	29	0	9	5	23	3	19	30	30	17	0	30	15.9 (53.0)
July	21	9	0	0	31	0	0	4	0	17	8	3	31	13	6	31	15	26	11.9 (38.4)
August	0	0	0	0	12	0	0	23	0	30	0	6	22	0	9	14	0	21	7.6 (24.5)
September	0	0	0	1	0	0	0	21	0	26	0	0	0	18	21	12	0	0	5.5 (18.3)
October	6	0	0	17	0	0	3	25	0	0	0	0	27	26	11	0	0	0	6.4 (20.6)
November	24	0	25	4	13	0	30	16	0	28	3	0	30	11	0	0	23	0	11.5 (38.3)
December	31	28	29	31	29	1	31	31	0	31	26	5	31	31	21	0	25	19	22.2 (71.6)
TOTAL	223	218	199	215	235	109	243	263	146	204	211	151	311	281	249	219	169	248	216.6 (59.3)
% YEAR	61.1	59.7	54.5	58.9	64.4	29.9	66.6	72.1	40.0	55.9	57.8	41.4	85.2	77.0	68.2	60.0	46.3	67.9	59.3

Figure 5.2. Hydrographic survey of a tributary stream within the Research Reserve (Charles E. Herdendorf).

1964, 1968, 1973, 1978, 1979, 1980, 1984, 1985, 1987, and 1989. Morphometric dimensions of the estuary were determined using the methods given in Welsh (1948), Hutchinson (1957), Reid and Wood (1976), Håkanson (1981), Cole (1983), and Wetzel (1983).

The resulting bathymetric map (Figure 5.3) has a contour interval 0.2 m. Each contour line was traced with an electronic planimeter to determine the bounded area, which allowed calculation of the volume of water stored within the estuary for water levels ranging from +2.0 m to -2.0 m LWD. The tabular area and volume calculations are plotted on hypsographic curves (Figures 5.4 and 5.5). Morphometric dimensions are presented in Table 5.9 and definitions and formulas for morphometric parameters are given in Table 5.10.

Examination of the bathymetric map reveals that Old Woman Creek estuary is, in general, a broad shallow water body. When the water level in the estuary is standing at the mean level of Lake Erie (174.1 m IGLD, 1985 or +0.6 m LWD) the average depth of the estuary is only about 0.2 m. During the survey period (October and November 1990) the mean depth of the estuary was nearly 0.4 m.

The south basin, at the upper end of the estuary, is characterized by a relatively deep, stream-like channel flanked by material levees along most of its course (Figures 2.13 and 6.14). A number of small lagoons are found along its left bank (looking downstream) and an extensive lagoon-swamp forest is found between the right levee and an escarpment along the east side of the estuary. The top of the channel levees lies at +1.8 to +2.0 m LWD, while the floor of the swamp forest is about +1.4 to +1.6 m LWD.

The main basin is more lake-like in appearance with a sizable island (Star Island) located near its center (Figures 2.10 to 2.12). The levees continue only at the southern end of this basin. The main basin is surrounded by relatively steep escarpments on all sides, including the island. Into the escarpment, on both the east and west banks, a number of deeply entrenched but shallow coves have been cut by intermittent tributaries. The main channel of this basin follows a course down the eastern side of the estuary. It is only a few tenths of a meter deeper than the generally flat bottom of the remainder of the basin. A minor channel was also detected on the back (western) side of Star Island. Major portions of this basin have a floor

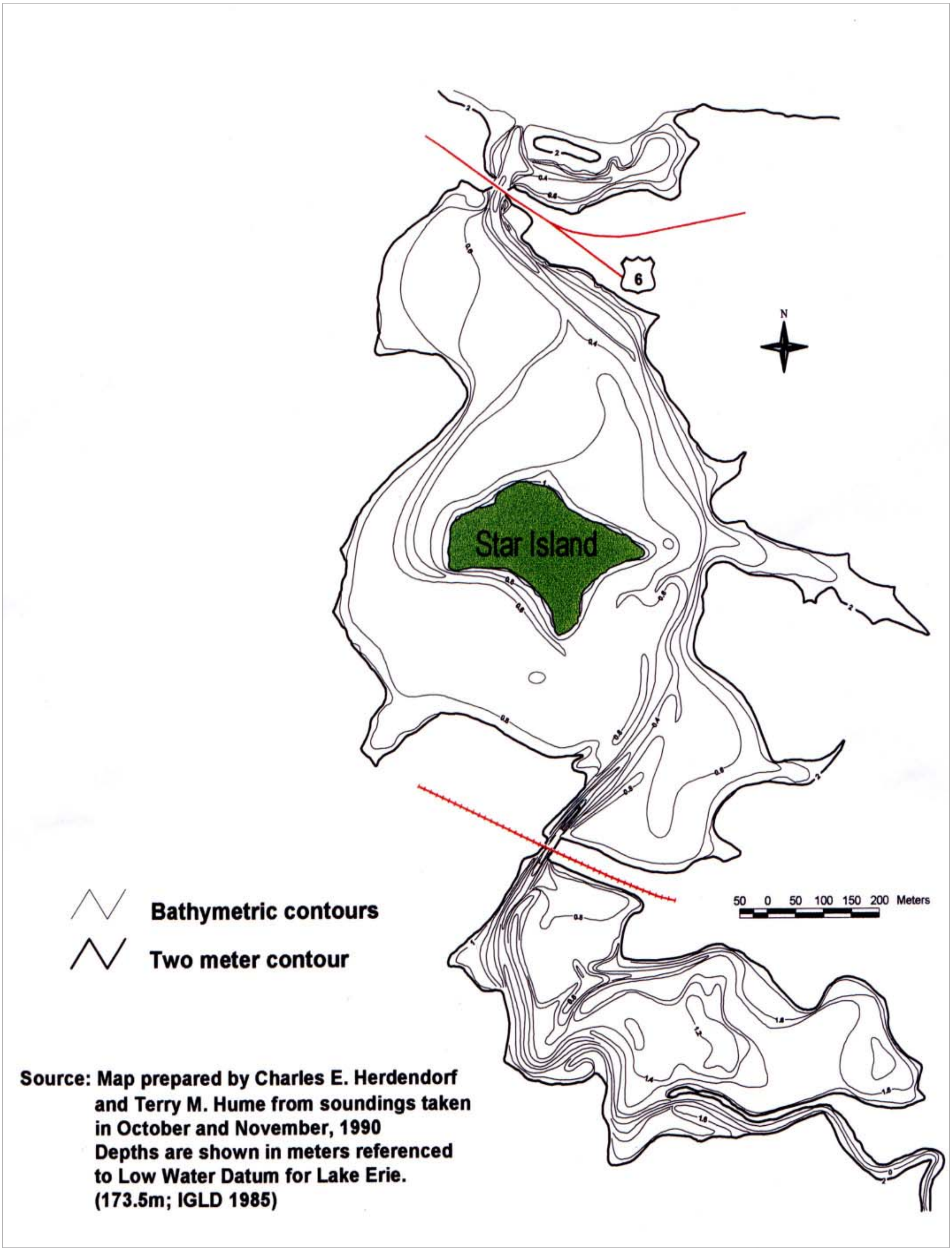

Figure 5.3. Bathymetric map of Old Woman Creek estuary (from Herdendorf and Hume 1991).

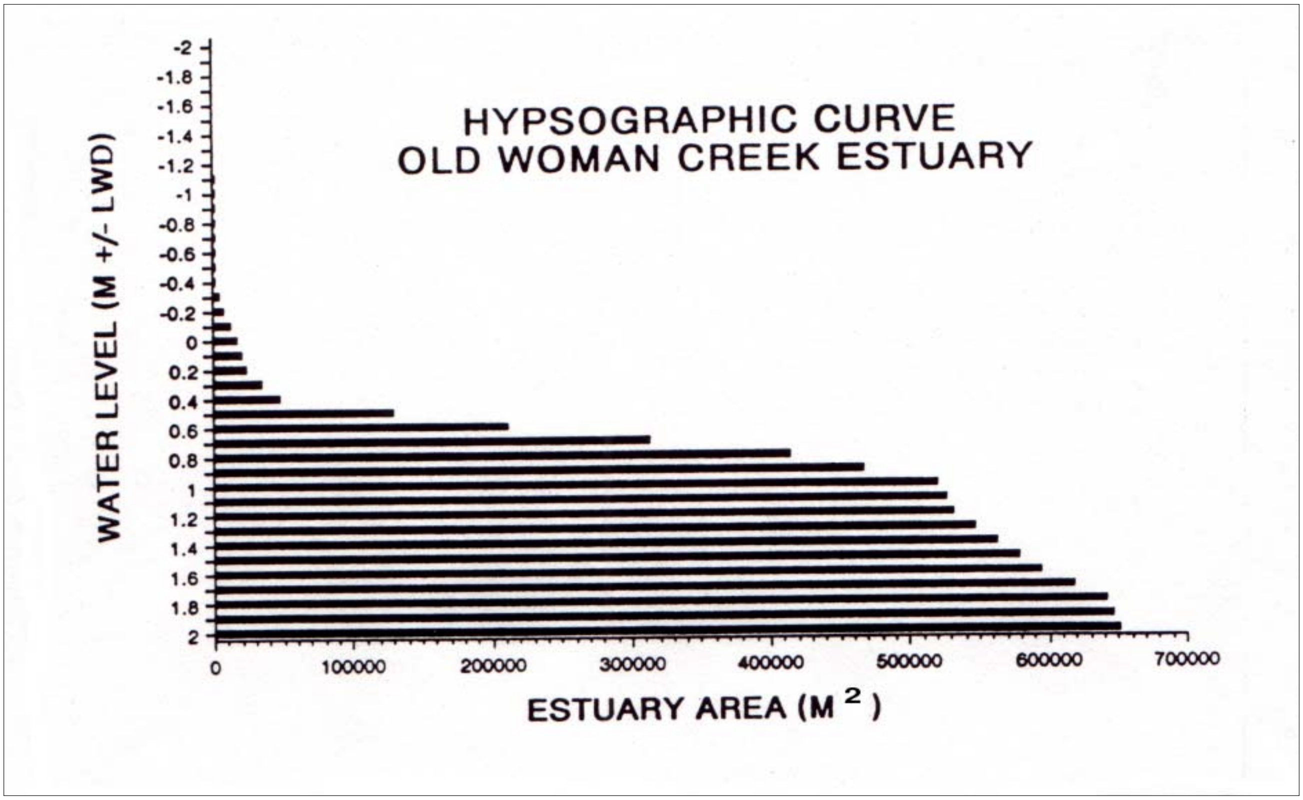

Figure 5.4. Hypsographic curve for Old Woman Creek estuary—area versus depth.

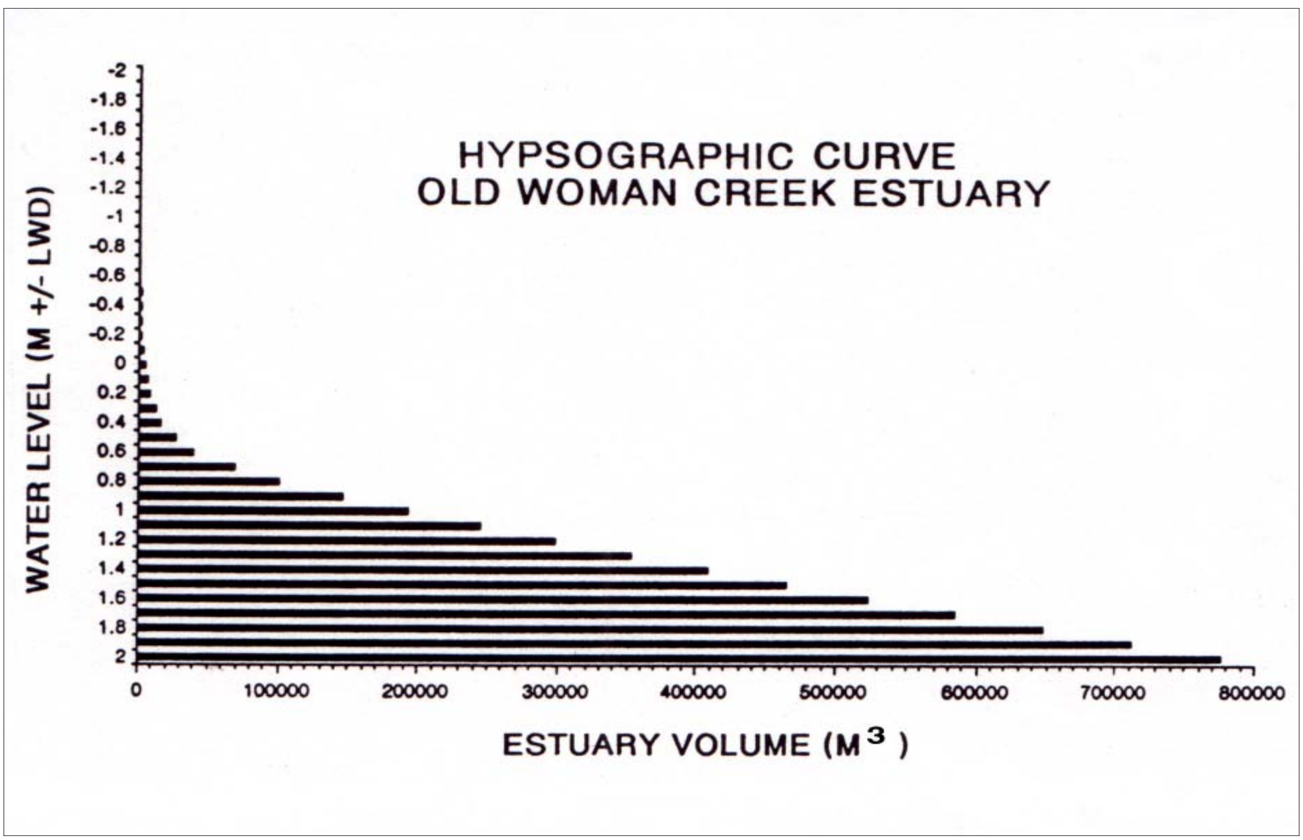

Figure 5.5. Hypsographic curve for Old Woman Creek estuary—volume versus depth.

TABLE 5.9. MORPHOMETRY OF OLD WOMAN CREEK ESTUARY

Parameter	Dimension[1]
MAXIMUM DEPTH (z_m)	2.68 m
South Basin	1.67 m
Main Basin	2.68 m
Lake Lagoon	2.46 m
MEAN DEPTH ($\bar{z}$)	0.37 m
RELATIVE DEPTH (z_r)	0.33%
MAXIMUM LENGTH (l)	2,000 m
MAXIMUM EFFECTIVE LENGTH (l_e)	1,125 m
MAXIMUM BREADTH (b)	670 m
MEAN BREADTH ($\bar{b}$)	260 m
CLOSURE INDEX (CI)	0.02
AREA (A)	519,460 m^2
VOLUME (V)	193,013 m^3
SHORE LENGTH (L)	9,616 m
INSULOSITY (I_n)	7.64% (Star Island)
SHORELINE DEVELOPMENT (D_l)	3.75
VOLUME DEVELOPMENT (D_v)	0.41
ORIENTATION OF MAIN AXIS	335° (N25°W)

SLOPE OF BASIN BETWEEN CONTOURS (S)

1.8 to 2.0 m	8.54%
1.6 to 1.8 m	1.89%
1.4 to 1.6 m	3.33%
1.2 to 1.4 m	2.86%
1.0 to 1.2 m	11.30%
0.8 to 1.0 m	1.79%
0.6 to 0.8 m	0.79%
0.4 to 0.6 m	0.92%
0.2 to 0.4 m	4.95%
0.0 to 0.2 m	12.14%
-0.2 to 0.0 m	5.98%
-0.4 to -0.2 m	8.75%

MEAN SLOPE (s) 1.85%

LENGTH OF CONTOUR LINES (L_z)

2.0 m	9,923 m	-0.2 m	2,892 m
1.8	10,162 m	-0.4	1,918 m
1.6	11,451 m	-0.6	505 m
1.4	10,972 m	-0.8	381 m
1.2	10,090 m	-1.0	235 m
1.0	9,616 m	-1.2	185 m
0.8	9,250 m	-1.4	133 m
0.6	8,298 m	-1.6	30 m
0.4	7,124 m		
0.2	4,258 m		
0.0	3,402 m		

NOTE: 1. Measurements based on estuary water level of +1.0 m LWD (= 174.49 m or 572.48 ft IGLD, 1985)

TABLE 5.10. DEFINITIONS OF HYDROMORPHOMETRIC PARAMETERS

MAXIMUM DEPTH (z_m)

The deepest sounding in m.

MEAN DEPTH ($\bar{z}$)

The relationship between the volume and surface area of a body of water:

$$\bar{z} = \frac{V}{A}$$

$\bar{z}$ = mean depth in m
V = volume in m^3
A = surface area in m^2.

For streams mean depth is defined as:

$$\bar{z} = \frac{a}{w}$$

where,
$\bar{z}$ = mean depth in m
a = cross-sectional area of stream channel in m^2
w = stream width in m.

RELATIVE DEPTH (z_r)

The maximum depth of a lake or estuary expressed as a percentage of the mean diameter:

$$z_r = \frac{50 z_m \sqrt{\pi}}{\sqrt{A}}$$

where,
z_r = relative depth in %
z_m = maximum depth in m
A = surface area in m^2
π = 3.14.

MAXIMUM LENGTH (l)

The length of line connecting the two most remote extremities of a lake (curved for oxbow lakes).

MAXIMUM EFFECTIVE LENGTH (l_e)

The straight line connecting remote extremities along which wind and wave action can occur without land interruption.

MAXIMUM BREADTH (b)

The maximum distance on a lake surface at a right angle to line of maximum length between shores.

MEAN BREADTH ($\bar{b}$)

The mean breadth or width of a body of water is defined by the equation:

$$\bar{b} = \frac{A}{1}$$

where,
$\bar{b}$ = mean breadth in km
A = surface area in km^2
1 = length in km (distance between the farthest points on the shore of a lake or other body of water).

AREA (A)

The surface area, as measured with a planimeter or other means.

ORIENTATION OF MAIN AXIS

The compass directions of line of maximum length in degrees (°).

TABLE 5.10. DEFINITIONS OF PARAMETERS (cont'd)

CLOSURE INDEX (CI)

A dimensionless index of the comparative closure of an embayment, which relates the inlet opening of a bay to the diameter of a semi-circle that has an area equal to that of the embayment:

$$CI = \frac{D}{\sqrt{\frac{2A}{\pi}} \cdot 2}$$

where,
- D = embayment opening in km
- A = area of embayment in km^2
- CI = closure index
- π = 3.14.

Therefore, a perfectly semi-circular bay has an inlet opening exactly equal to the diameter of the semi-circle formed by the area, yielding a closure index of 1.0. Embayments with an index >1.0 are more broadly open and those <1.0 have more constricted inlets.

VOLUME (V)

The total volume of a lake or estuary can be determined by deriving the amount of water contained in each of the strata bounded by depth contours. The volume of a stratum can be calculated by the formula:

$$V_s = \frac{1}{3} (A_1 + A_2 + \sqrt{A_1 \cdot A_2})\, z$$

where,
- V_s = volume of a stratum in m^3
- A_1 = area of the upper surface of a contour stratum in m^2
- A_2 = area of the lower surface of a contour stratum in m^2
- z = depth or contour interval of the stratum in m.

The sum of the volumes of all the strata yields the total volume of the lake.

SHORE LENGTH (L)

The perimeter length of the shoreline in m.

INSULOSITY (I_n)

The percentage of the total area of a lake that is occupied by islands, islets and exposed rocks:

$$I_n = \frac{A_i \cdot 100}{A}$$

where,
- I_n = insulosity in %
- A_i = area of islands in m^2
- A = surface area in m^2.

SHORELINE DEVELOPMENT (D_l)

A quantitative expression derived from the shape of a lake, defined as the ratio of the shoreline length to the length of the circumference of a circle of the same area as the lake:

$$D_l = \frac{L}{2\sqrt{\pi A}}$$

where,
- D_l = shoreline development, a dimensionless index number
- L = length of the shoreline in km
- A = area of lake surface in km^2
- π = 3.14.

Since the ratio is related to a circle, a perfectly round basin would have an index of 1.0. Increasing irregularity of shoreline in the form of embayments and projections results in an increase in the index number.

TABLE 5.10. DEFINITIONS OF PARAMETERS (cont'd)

VOLUME DEVELOPMENT (D_v)
An index to the shape of a lake basin that compares the shape to that of an inverted cone with a height equal to the maximum depth and a base equal to lake's surface area:

$$D_v = \frac{A(\bar{z})}{^1/_3 A(z_m)} = \frac{3\bar{z}}{z_m}$$

where,

D_v = volume development (dimensionless number)
$\bar{z}$ = mean depth of lake in m
z_m = maximum depth of lake in m
A = surface area of lake in m^2.

In a lake with a volume equal to this hypothetical cone, D_v = 1.0; a lake with a relatively greater volume would have an index >1.0; and a basin with a smaller volume than such a cone would have an index <1.0. From the above, it is apparent that the relationship of mean to maximum depth in the case of an ideal conical lake (D_v = 1.0), is 0.333. In the absence of more complete information, this ratio can be used to estimate mean depth from the maximum sounding.

SLOPE OF BASIN BETWEEN CONTOURS (S)
The degree of slope between two adjacent depth contours can be determined if the lengths of the two isobaths and the area enclosed by them are known. The slope (or tangent) is described by the formula:

$$S_{z_1,z_2} = \frac{L_{z_1} + L_{z_2}}{2} \bullet \frac{z_1 - z_2}{A_{z_1} - A_{z_2}} \bullet 100$$

where,

S_{z_1,z_2} = slope between depths z_1 and z_2 in percent (%)
z_1 = depth of first contour in m
z_2 = depth of second contour in m
L_{z_1} = length of first contour line in m
L_{z_2} = length of second contour line in m
A_{z_1} = area enclosed by first contour line in m^2
A_{z_2} = area enclosed by second contour line in m^2.

MEAN SLOPE (s)
An expression of the proximity of bathymetric contours to one another:

$$s = {^1/_n} \left({^1/_2} L_0 + L_2 + L_3 ... + L_{n-1} + {^1/_2} L_n\right) \frac{z_{max}}{A} \bullet 100$$

where,

s = mean slope in percent (%)
L = length of each bathymetric contour line in m
n = total number contours on a bathymetric map, including the shore or zero contour
L_o = length of shore contour in m
L_n = length of deepest contour in m
L_{n-1} = length of next to the deepest contour in m
z_{max} = maximum depth in m
A = surface area of lake in m.

LENGTH OF CONTOUR LINES (L_z)
The linear distance of each contour line in m.

elevation of +0.5 to +0.6 m LWD (water depth of about 0.3 m during the survey). This depth appears to be particularly conducive to the development and dense growth of American water lotus beds (*Nelumbo lutea)*.

The lake lagoon is a small, elongated basin that appears to be the one most altered in recent years (Figure 2.9). It is now a tabular-shaped lagoon, extending in an east-west direction, with its outlet channel along the west side. Aerial photographs taken over the last 50 years show that it was once circular, when the barrier beach forming its north side was more than 100 m farther lakeward (Figures 5.6 and 5.7). The shore recession, resulting primarily from severe northeast storms, has taken place as overtopping waves wash barrier beach sand into the lagoon. The inlet channel through the barrier has also migrated to various positions since 1937.

The three basins are connected by narrow, relatively deep, channels that are the result of causeway constriction at the Conrail bridge (between the south and main basins) and at the U.S. Route 6 bridge (between the main and lake lagoon basins). The southerly channel is about 13 m wide with a maximum depth of -0.85 m LWD, whereas the northerly connecting channel is 18 m wide with a maximum depth of -1.68 m. The latter depth is the deepest sounding in the entire estuary.

Water Levels

Figures 2.4 and 2.5 demonstrate the close correlation of estuary water levels and lake levels when the estuary inlet is open. During October 1989 and June-July 1990, the inlet was barred across, resulting in a considerably higher level in the estuary. As soon as the bar was breached (either by natural process or hand digging) the lake once again controlled the levels in the estuary as demonstrated by the close agreement of the records. Figure 5.8 shows how the lake has a strong (almost 1:1), direct influence on water levels in the estuary up to +1.1 m LWD. At levels higher than this in the estuary no relationship is indicated because the lagoon is barred off and the estuary acts as a lacustrine system.

Daily records of the open (stable) or barred closed (unstable) condition of the estuary mouth have been maintained since 1983 (Table 5.8). During the period 1983 to 1991 the inlet has been open 59% of the time (annual range 30-72%) and closed 41% (annual range 28-70%). Plots of mean daily water levels in Old Woman Creek estuary (such as Figure 2.4) show a marked seasonal trend: late in the year (October-December) the water level in the estuary builds up to >+1.5 m LWD at which stage the barrier is often breached artificially (digging); then December through about May-July the mean water level rises gradually to attain high levels over the summer until it breaches again. When it breaches, a classical "ebb tide delta" is built in Lake Erie off the inlet as sand from the barrier is deposited when velocities in the water exiting the estuary drop below the transport threshold. The rapid water level rise in the estuary in latter part of the year appears to be the result of the damming-effect of the barrier bar. Figures 2.6 and 2.7 indicate that neither precipitation nor runoff from the watershed are sufficient to totally account for the increase in water stored in the estuary in the months prior to the breach. Lake Erie waves, which frequently over top the barrier bar, may also supply a sizable quantity of water to the estuary during storms.

When the inlet is open (about 59% of the time), the primary hydrologic control for Old Woman Creek estuary is the level of adjacent Lake Erie. Both long- and short-term variations in lake level affect water levels in the estuary and thus may affect recent deposition, erosion, and biological processes. Even minor fluctuations in lake level on the order of a few centimeters can have profound effects in the estuary for two reasons: (1) the shallowness of the estuary makes it very responsive to fluctuations in water depth and (2) the elevation of the estuary floor is very near mean lake level.

Lake seiche events can be responsible for alternately exposing and flooding the entire floor of Old Woman Creek estuary. Several factors, however, tend to minimize the effects of seiche events on the long-term deposition of sediment in the estuary. First, many seiche events in Lake Erie are not directly transmitted into the estuary due to closure of the estuary mouth by the barrier bar. During the 17-year period (1983-1999), the mouth of the estuary was closed 41% of the time. If the duration and magnitude of seiche events are high, the likelihood of breaching the interceding barrier beach increases, allowing the estuary water level to fluctuate more directly with the lake. Second, the effects of seiche events in the estuary

Figure 5.6. Opened mouth of Old Woman Creek estuary in May 1949 (ODNR).

Figure 5.7. Closed mouth of Old Woman Creek estuary in July 1949 (Thomas H. Langlois).

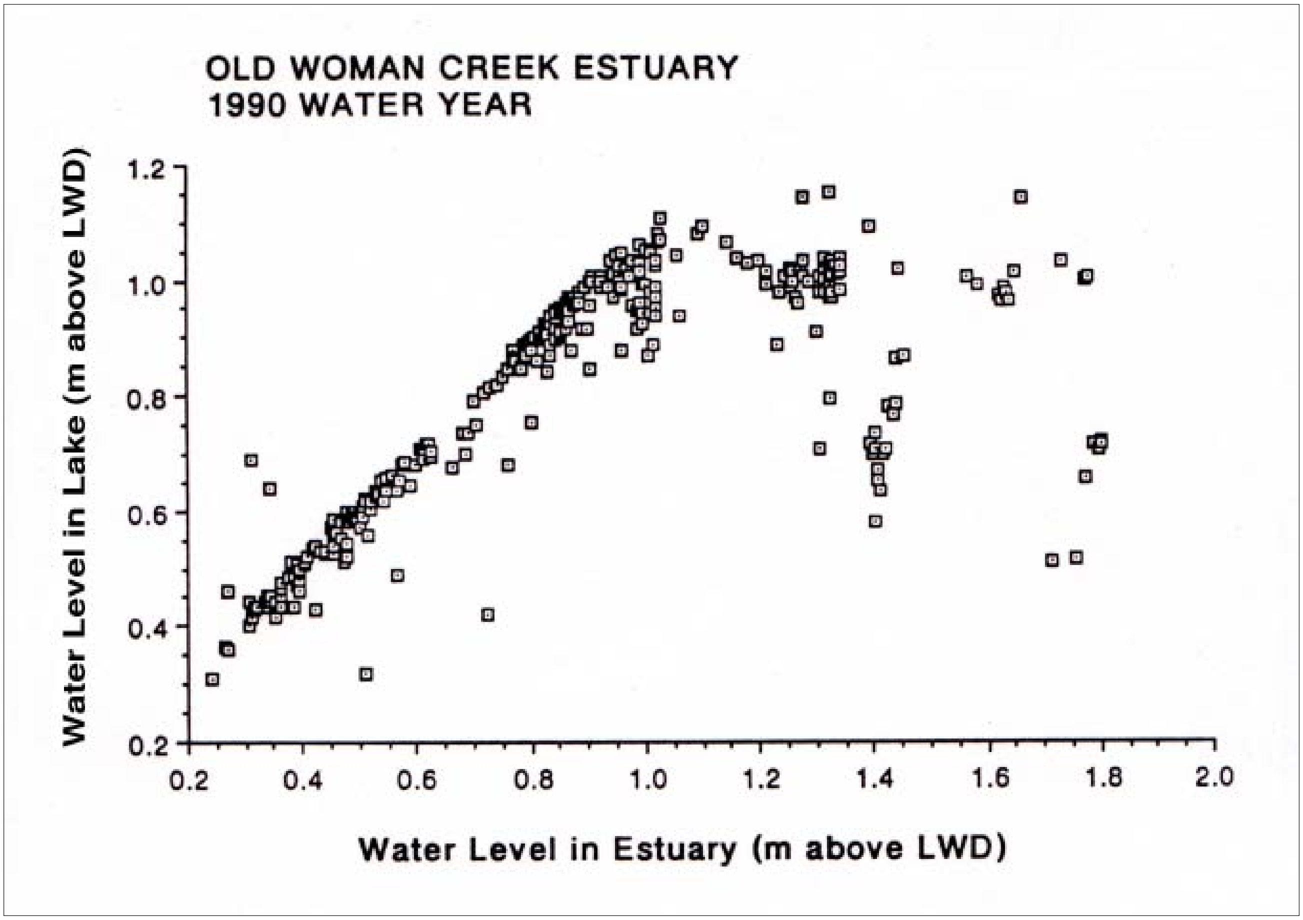

Figure 5.8. Correlation of Lake Erie and Old Woman Creek estuary water levels.

are limited by other factors. The duration of a seiche event is short (generally less than a 14-hour period). Further, the magnitude of the water-level fluctuations transmitted into the estuary may not be sufficient to generate flow through the estuary channel capable of disturbing sediments previously deposited. Finally, there may not be an influx of texturally different sediment to record the event. Despite these minimizing factors, Buchanan (1982) concluded that seiches are responsible for some of the erosional unconformities observed in the sediment record and may have provided opportunities for wind-generated wave action in the estuary to resuspend deposited sediment.

Table 5.11 presents the long term mean (1918 to 1996), maximum, and minimum monthly water levels for Lake Erie. These data show that the elevation of Lake Erie has a range of 1.6 m from the lowest levels recorded in the mid-1930s to the highest levels recorded in the mid-1980s. On a month-to-month basis, the lake tends to be lowest in winter and highest in late spring or early summer. The water budget for Lake Erie is composed of a number of factors which contribute to either inflow, outflow, or change in the amount of water stored in the lake.

Inflow Factors

- inflow from the Detroit River (80%)
- precipitation fall on the lake surface (11%)
- runoff from rivers in the lake basin (9%)

Outflow Factors

- outflow through Niagara River (88%)
- evaporation from the lake surface (8%)
- outflow via Welland Canal diversion (3%)
- consumptive use of water from lake (1%)

The difference between the inflow and the outflow is the change in storage, which in turn changes lake levels. Because of high spring runoff and low

TABLE 5.11. LAKE ERIE WATER LEVELS

	Maximum					Minimum					Mean			
	IGLD 1985		LWD		Year	IGLD 1985		LWD		Year	IGLD 1985		LWD	
	meters	feet	meters	feet		meters	feet	meters	feet		meters	feet	meters	feet
January	174.86	573.69	1.37	4.49	1987	173.21	568.27	-0.28	-0.93	1935	173.98	570.80	0.49	1.60
February	174.78	573.43	1.29	4.23	1987	173.18	568.18	-0.31	-1.02	1936	173.97	570.77	0.48	1.57
March	174.88	573.75	1.39	4.55	1986	173.20	568.24	-0.29	-0.96	1934	174.05	571.03	0.56	1.83
April	174.98	574.08	1.49	4.88	1985	173.38	568.83	-0.11	-0.37	1934	174.21	571.56	0.72	2.36
May	174.97	574.05	1.48	4.85	1986	173.44	569.03	-0.05	-0.17	1934	174.29	571.82	0.80	2.62
June	175.04	574.28	1.55	5.08	1986	173.45	569.06	-0.04	-0.14	1934	174.32	571.92	0.83	2.72
July	175.03	574.25	1.54	5.05	1986	173.45	569.06	-0.04	-0.14	1934	174.31	571.88	0.82	2.68
August	174.94	573.95	1.45	4.75	1986	173.43	569.00	-0.06	-0.20	1934	174.24	571.65	0.75	2.45
September	174.83	573.59	1.34	4.39	1986	173.38	568.83	-0.11	-0.37	1934	174.16	571.39	0.67	2.19
October	174.94	573.95	1.45	4.75	1986	173.30	568.57	-0.19	-0.63	1934	174.06	571.06	0.57	1.86
November	174.85	573.65	1.36	4.45	1986	173.20	568.24	-0.29	-0.96	1934	173.99	570.83	0.50	1.63
December	174.90	573.82	1.41	4.62	1986	173.19	568.21	-0.30	-0.99	1934	173.98	570.80	0.49	1.60
MEAN	174.92	573.84	1.43	4.67		173.32	568.63	-0.17	-0.57		174.13	571.29	0.64	2.09

Period of Record: 1918-1996

Data Source: U.S. Army Corps of Engineers, Detroit, MI, *Monthly Bulletin of Lake Levels for the Great Lakes* evaporation, storage of water in Lake Erie is highest in the spring. Levels are lowest in the fall and winter due to high evaporation and low runoff (Bolsenga and Herdendorf 1993).

Precipitation on the Lake Erie watershed contributes approximately the same amount of water into the lake as precipitation falling directly on the surface of the lake, however the watershed has a much larger surface area. Thus, if all the water that fell on the watershed ran into the lake, the runoff would contribute three times as much as precipitation over the lake. However, only about one-third of the rain falling on the watershed makes its way to the lake. The rest is lost to the air by evaporation from the soil or by transpiration from plants.

WATER STORAGE CAPACITY

In addition to size, depth, and configuration of the estuary, variations in lake level—attributable to regional climatic factors such as precipitation, evaporation, and runoff—are significant considerations when calculating the water storage capacity of the Old Woman Creek estuary. A model presented by Matisoff and Eaker (1989,1992) suggests the following flux rates for some of the hydrological factors influencing water storage in the estuary.

Flux Factors

- precipitation = 0.01 m^3/sec
- groundwater advection =0.00 – 0.07 m^3/sec
- seepage discharge (barrier beach) = 0.01 m^3/sec

They reported groundwater discharge velocities along the barrier sandbar, as calculated from seepage measurements, ranging from -0.007 m/day (recharge to estuary from Lake Erie) to 1.8 m/d (discharge to Lake Erie). Seepage measurements in the southern portion of the estuary ranged in velocity from 0 to 0.38 m/day into the estuary. These data yield flux calculations for groundwater advection to the estuary of near zero to 0.07 m^3/sec and a seepage discharge flux of near zero to 0.61 m^3/sec.

Mitsch, et al. (1989) devised a water budget for Old Woman Creek estuary using a catchment area of 68.6 km^2. They estimated the following water input and export fluxes for the estuary.

Inputs

- surface inflow = 0.18 m^3/sec
- precipitation = 0.01 m^3/sec

Exports

- evapotranspiration = 0.02 m^3/sec
- estuary discharge = 0.17 m^3/sec

Their surface inflow is equivalent to 0.0026 m^3/sec/km^2. This value compares favorably with Sandusky River inflow to Sandusky Bay at 0.0022 m^3/sec/km^2 and Portage River inflow to its estuary at 0.0017 m^3/sec/km^2 (Youngquist 1966). These estimates were made for the period March 1 through September 30, 1988. During this period, the water level in the estuary increased slightly, at a rate of about 700 m^3/day which accounts for the difference between inputs and exports.

Buchanan (1982) surveyed Old Woman Creek estuary in 1977 and calculated the average water depth at 0.3 m (water elevation = 174.4 m IGLD 1985 or +0.9 m LWD). He estimated the total volume of water in the estuary to be 113,000 to 127,000 m^3. A more detailed bathymetric survey by Herdendorf and Hume (1991) found that under same water level condition the estuary would hold approximately 146,500 m^3 of water.

Water storage in Old Woman Creek estuary is a function of the morphometry of the basins and the water level in the estuary. The water level, in turn, is primarily controlled by Lake Erie levels (when the inlet channel is open) or by catchment hydrologic factors (when the inlet is barred across). Typically the inlet is unstable (barred) over 41% of the time. The hydrologic factors which have a significant influence on water levels in the estuary include: (1) precipitation, (2) runoff, (3) evaporation, (4) groundwater advection, (5) seepage through the barrier bar and (6) wave overtopping of the bar. When the water level in the estuary is standing at the mean level for Lake Erie (+0.6 m LWD) the area and the volume of the estuary are 211,000 km^2 and 38,600 km^3, respectively.

WATERSHED DISCHARGE

Buchanan (1982), using a drainage basin area of 69.5 km^2, estimated the average discharge into the estuary at 0.43 m^3/sec or 0.006 m^3/sec/km^2. Based on an average concentration of suspended sediment of 0.1 g/l, he estimated that about 0.6 g/m^3/sec of sediment enter the estuary. Within the estuary he found the average concentration of suspended sediment to be only 0.02 g/l or equivalent to 2.4 tons. Buchanan's estimates permit a retention time calculation of 7.3 days for water in the estuary based on precipitation records (Table 4.4). This value compares favorably with a flushing rate calculation of 8.5 days based on the water budget presented by Mitsch et al. (1989) and the estuary volume obtained by Herdendorf and Hume (1991). By extrapolating a surface inflow coefficient from the Sandusky River basin (0.002 m^3/sec/km^2), one obtains an average discharge rate of 0.15 m^3/sec for Old Woman Creek estuary which is equivalent to a flushing rate of 11.2 days.

Woods (1987) studied Old Woman Creek under storm conditions and measured a maximum discharge from Old Woman Creek to the estuary of 4.3 m^3/sec and a maximum sediment transport to the estuary of 411 g/sec for a brief period. He found that high discharges were not necessarily associated with high sediment concentrations. Land use activities, such as field preparation in the spring and cropping in the fall, heavily affected sediment concentrations in Old Woman Creek.

Worthy (1980) constructed a hydrograph for predicting runoff in the Old Woman Creek drainage basin. He used a watershed area of 78.7 km^2, an average drainage area slope equal to 4.85 m/km, and a basin length of 14.2 km. From the hydrograph he determined that a storm of 6 hours in duration and 1.73 inches of rainfall would yield a peak discharge of 18.3 m^3/sec. The peak discharge would occur in the creek 4.2 hours following the storm. Such a storm has a 5-year return period for the Old Woman Creek watershed.

Worthy (1980) concluded that the supply of sediment from the watershed does not have a significant effect on the stability of Old Woman Creek inlet. He found that the sediment being transported through the estuary was largely silt-and-clay-sized material, whereas the barrier beach is composed of medium sand, derived from erosion of adjacent lake bluffs. Using data from the Sandusky River watershed (50 km to the east), he extrapolated average suspended sediment load of 0.64 tons/day for Old Woman Creek. Thus, about 234 tons of sediment are transported to the estuary annually. He speculated that seiche activity keeps the estuary agitated and the sediment suspended so that the bulk of this material is carried through the inlet during periods of high flow when the inlet is stable (mouth open).

ESTUARY WATER QUALITY

Water quality monitoring has been conducted in Old Woman Creek Estuary since the early 1980s. The complete data records for this monitoring program are available at the Ohio Center for Coastal Wetlands Study located within the Old Woman Creek State Nature Preserve and National Estuarine Research Reserve. Currently this data is being assembled for publication as Old Woman Creek Technical Report No. 16, which will also be Contribution No. 6 to this Site Profile.

The means and ranges of the monitored parameters are presented in the following tables: Table 5.12 (Old Woman Creek at N & W Railroad bridge, Figure 1.6), Table 5.13 (upper Old Woman Creek estuary at Darrow Road bridge, Figure 1.4), Table 5.14 (lower Old Woman Creek estuary at mouth), and Table 5.15 (adjacent nearshore Lake Erie). The three year periods represent conditions at the inception of the monitoring program at Old Woman Creek (1981-1983), conditions during the last period of high water conditions at the estuary (1995-1997), and conditions during falling lake water levels (1998-2000). Figures 5.9 through 5.12 compare temperature, turbidity, soluble reactive phosphorus, and nitrate measurements in the estuary from the early 1980s with values for the late 1990s.

There were distinct differences between various chemical parameter means between the periods 1981 to 1983 and 1995 to 1997, particularly nitrate and silicate, but not for soluble reactive phosphorus (Figures 5.11 and 5.12). Despite these apparent differences, there was no statistical difference due to the very wide range of measured values during each of the two periods. These changes in water quality do not appear to be related to changing land use practices, but rather a consequence of either stagnation or free flow when the mouth of the estuary is either open or barred across, particularly during the summer months (Klarer 1999). In the 1981 to 1983 period, the mouth was closed during much of the summer, the result of diminished rainfall in the watershed. This decreased

TABLE 5.12. WATER QUALITY IN THE LOWER REACH OF OLD WOMAN CREEK AT THE N & W RAILROAD BRIDGE FOR THREE TIME PERIODS

Parameter		1981-1983	1995-1997	1998-2000
Temperature- ($^{\circ}C$)	mean	11.4	13.7	15.4
	range	-2.0-25.0	0.4-24.6	0.7-24.5
Dissolved Oxygen-mg/l	mean	9.5	8.9	7.7
	range	1.8-15.0	4.4-14.4	2.6-15.1
Specific Conductivity-µmhos/cm	mean	706	613	636
	range	389-1191	403-1117	317-1074
pH- Standard Units	mean	7.92	7.87	7.79
	range	7.50-8.45	7.52-8.55	7.11-8.62
Total Alkalinity-mg $CaCO_3$/l	mean	130	146	143
	range	64-238	93-207	60-212
Turbidity- NTU	mean	23.6	23.5	29.9
	range	2.4-150	2.9-300	1.6-354
Soluble Reactive Phosphorus-µg P/l	mean	31.4	28.9	41.5
	range	1.5-129.9	1.4-103.8	0.0-468.2
Total Phosphorus-µg P/l	mean	Not tested	115.2	122.1
	range	Not tested	13-707	4-571
Nitrate-mgN/l	mean	1.918	2.652	3.168
	range	0.012-7.578	0.0-6.354	0.008-15.153
Nitrite-µg N/l	mean	25.8	23.4	21.7
	range	1.0-191.9	1.6-129.7	0.0-196.7
Ammonia-mgN/l	mean	0.155	0.147	0.089
	range	0.001-1.472	0.008-0.840	0.015-0.526
Chloride-mgCl/l	mean	64.4	50.0	58.7
	range	27.8-129.0	19.0-129.6	15.3-130.4
Sulfate-mgSO_4/l	mean	65.7	65.9	63.4
	range	31.8-123.3	37.6 –154.3	22.5-128.9
Calcium-mg/l	mean	83.2	62.1	70.4
	range	45.0-158.3	37.2-104.2	33.4-159.8
Magnesium-mg/l	mean	18.1	16.1	17.6
	range	3.5-53.0	7.4-28.0	9.5-32.0
Sodium-mg/l	mean	31.8	30.9	37.6
	range	16.4-63.6	14.4-72.5	11.7-114.0
Potassium-mg/l	mean	6.0	6.4	7.1
	range	3.3-10.5	2.7-24.9	3.5-16.8
Iron- mg/l	mean	0.99	1.57	1.12
	range	0.04-2.99	0.18-34.10	0.17-11.22
Silicate- mgSi/l	mean	2.476	6.173	6.409
	range	0.286-10.427	1.404-9.492	1.610-12.652

TABLE 5.13. WATER QUALITY IN THE UPPER REACH OF OLD WOMAN CREEK ESTUARY AT DARROW ROAD BRIDGE FOR THREE TIME PERIODS

Parameter		1981-1983	1995-1997	1998-2000
Temperature- (°C)	mean	12.84	14.7	16.6
	range	-1.5-28	0.2-26.3	0.8-27.1
Dissolved Oxygen-mg/l	mean	8.63	8.46	7.07
	range	0.66-16.8	4.26-13.11	1.8-14.79
Specific Conductivity-µmhos/cm	mean	624	584	600
	range	346-1099	384-1023	298-929
pH- Standard Units	mean	7.91	7.83	7.78
	range	7.50-9.25	7.53-8.43	7.46-8.14
Total Alkalinity-mg $CaCO_3$/l	mean	131	150	146
	range	64-233	88-218	58-231
Turbidity- NTU	mean	30.1	29.2	47.5
	range	3.7-170	5.0-290	22-519
Soluble Reactive Phosphorus-µg P/l	mean	23.7	29.1	22.8
	range	0.4-121.8	1.7-120.1	0.0-206
Total Phosphorus-µg P/l	mean	Not tested	183.5	130.6
	range	Not tested	41-640	19-691
Nitrate-mgN/l	mean	1.890	2.585	3.110
	range	0.020-7.862	0.001-6.754	0.0-13.467
Nitrite-µg N/l	mean	41.7	30.6	34.7
	range	1.32-742.7	1.8-160.5	0-269.6
Ammonia-mgN/l	mean	0.176	0.204	0.118
	range	0.0-1.303	0.009-1.531	0.226-0.616
Chloride-mgCl/l	mean	57.99	43.2	49.3
	range	24.2-113.0	17.6-117.0	15.0-107.8
Sulfate-mgSO_4/l	mean	60.4	59.4	54.8
	range	30.6-98.3	30.4-150.4	21.8-124.9
Calcium-mg/l	mean	81.8	61.5	67.6
	range	49-140	40.9-102.7	31.2-120.7
Magnesium-mg/l	mean	17.9	16.1	17.0
	range	4.4-54.0	6.2-28.6	9.3-31.7
Sodium-mg/l	mean	30.2	27.7	31.9
	range	11.9-65.7	14.4-62.7	9.9-71.7
Potassium-mg/l	mean	6.2	6.5	6.9
	range	3.0-11.7	2.8-20.3	3.6-16.95
Iron- mg/l	mean	0.96	1.70	1.74
	range	0.04-3.25	0.31-23.3	0.22-9.35
Silicate- mgSi/l	mean	2.65	6.45	6.00
	range	0.310-8.87	2.00-10.21	1.22-10.17

TABLE 5.14. WATER QUALITY IN THE LOWER REACH OF OLD WOMAN CREEK ESTUARY AT THE MOUTH FOR THREE TIME PERIODS

Parameter		1981-1983	1995-1997	1998-2000
Temperature- (°C)	mean	13.0	16.0	18.2
	range	-3-32	0.2-28.6	1.9-29.7
Dissolved Oxygen-mg/l	mean	9.3	8.7	6.69
	range	3.6-15.0	2.5-13.4	2.68-15.64
Specific Conductivity-μmhos/cm	mean	431	397	448
	range	250-1096	263-524	268-771
pH- Standard Units	mean	8.03	7.97	7.89
	range	7.45-8.90	7.46-8.64	7.50-8.61
Total Alkalinity-mg $CaCO_3$/l	mean	112	118	126
	range	57-230	84.1-193	84-202
Turbidity- NTU	mean	32	30	53
	range	4-99	6.7-78	3.3-279
Soluble Reactive Phosphorus-μg P/l	mean	12.0	15.7	9.9
	range	0.0-89.2	1.7-100.8	0.0-98.7
Total Phosphorus-μg P/l	mean	Not tested	214	152
	range	Not tested	39-1232	21-357
Nitrate-mgN/l	mean	1.159	1.119	1.209
	range	0.009-28.594	0.0-5.271	0.0-8.564
Nitrite-μg N/l	mean	24.6	27.8	23.3
	range	0.6-144.6	0.8-152.8	0.11-99.0
Ammonia-mgN/l	mean	0.189	0.315	0.168
	range	0.001-1.149	0.009-1.745	0.019-1.073
Chloride-mgCl/l	mean	30.6	23.3	30.0
	range	10.7-112.5	12.0-37.8	8.3-77.3
Sulfate-mgSO_4/l	mean	29.8	31.3	33.9
	range	11.2-78.0	11.1-62.6	16.7-112.7
Calcium-mg/l	mean	59.1	43.2	49.8
	range	36.0-116.3	27.3-64.6	26.5-85.9
Magnesium-mg/l	mean	12.4	11.3	13.5
	range	3.2-37.0	6.0-16.0	8.2-28.9
Sodium-mg/l	mean	17.2	16.1	19.9
	range	8.1-37.7	9.3-24.0	7.8-57.6
Potassium-mg/l	mean	3.8	4.6	5.3
	range	0.2-7.6	1.8-8.7	2.2-13.1
Iron- mg/l	mean	1.13	1.51	1.86
	range	0.02-5.60	0.32-7.11	0.22-9.50
Silicate- mgSi/l	mean	1.075	3.187	2.935
	range	0.025-4.031	0.320-8.340	0.0-9.550

TABLE 5.15. WATER QUALITY IN NEARSHORE LAKE ERIE OFF OLD WOMAN CREEK ESTUARY MOUTH FOR THREE TIME PERIODS

Parameter		1981-1983	1995-1997	1998-2000
Temperature- (°C)	mean	13.9	15.9	17.1
	range	-5 to 28	.8 to 27.3	2.3-26.5
Dissolved Oxygen-mg/l	mean	9.5	9.3	9.0
	range	3.4 to 14.5	4.9 to 14.1	6.5-14.5
Specific Conductivity- µmhos/cm	mean	313	286	297
	range	250-607	248-348	252-534
pH- Standard Units	mean	8.24	8.13	8.18
	range	7.75 to 8.72	7.78 to 8.64	7.8-8.75
Total Alkalinity-mg $CaCO_3$ /l	mean	90.5	90.2	89
	range	49 to 134	76 to 103	77-114
Turbidity- NTU	mean	25	18.3	30
	range	1 to 79	2.2 to 70	1.2-242
Soluble Reactive Phosphorus-µg P/l	mean	8.4	11.1	10.3
	range	0.0 to 45	0.7 to 35.4	0.0-221.3
Total Phosphorus-µg P/l	mean	Not determined	100	68
	range	Not determined	21 to 366	14-396
Nitrate-mgN/l	mean	0.392	0.666	0.753
	range	0.0 to 2.333	0.0 to 3.606	0.0-6.342
Nitrite-µg N/l	mean	12.8	11.7	10.2
	range	1 to 52.7	3.8 to 28.2	0.9-35.8
Ammonia-mgN/l	mean	0.106	0.146	0.071
	range	0.0 to .715	.001 to .884	0.007-0.603
Chloride-mgCl/l	mean	16.5	13.9	14.4
	range	4.6 to 65.9	8.9 to 22.2	3.2-60.2
Sulfate-mgSO_4/l	mean	19.4	22.0	22.5
	range	10.5 to 49.1	14.4 to 37.9	13.8-51.8
Calcium-mg/l	mean	43.1	32.7	33.4
	range	24.2 to 82.5	26.9 to 42.4	20.7-50.5
Magnesium-mg/l	mean	10.4	8.1	9.5
	range	2.0 to 25.5	3.4 to 13.1	7.1-15.1
Sodium-mg/l	mean	12.2	10.9	10.7
	range	8.0 to 32.7	7.8 to 15.3	7.6-24.7
Potassium-mg/l	mean	2.6	3.2	3.5
	range	1.7 to 6.2	2.1 to 6.2	2.0-18.2
Iron- mg/l	mean	0.75	0.76	1.12
	range	0.01 to 4.09	0.07 to 3.29	0.04-9.4
Silicate- mgSi/l	mean	0.510	1.530	1.320
	range	0.041 to 3.659	0.002 to 3.606	0.034-8.169

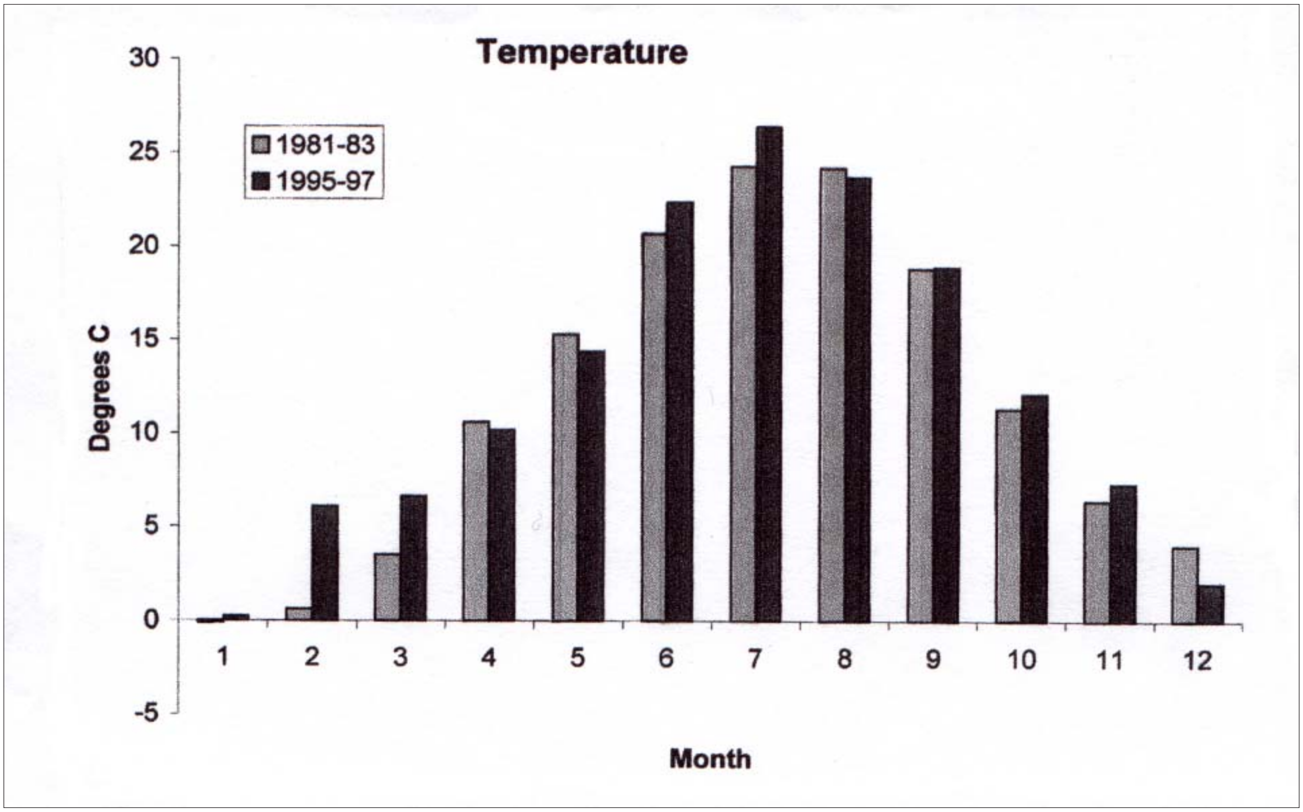

Figure 5.9. Trends in temperature for Old Woman Creek estuary.

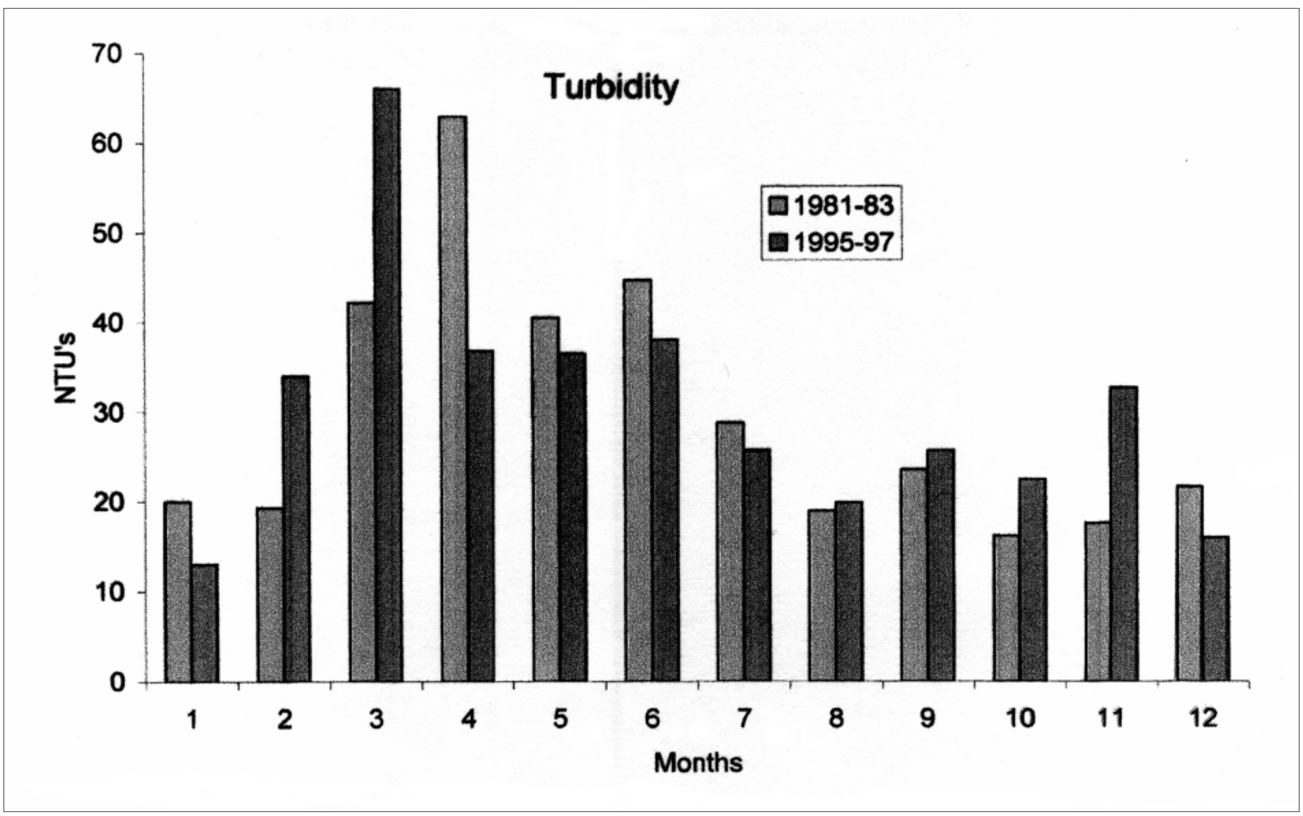

Figure 5.10. Trends in turbidity for Old Woman Creek estuary.

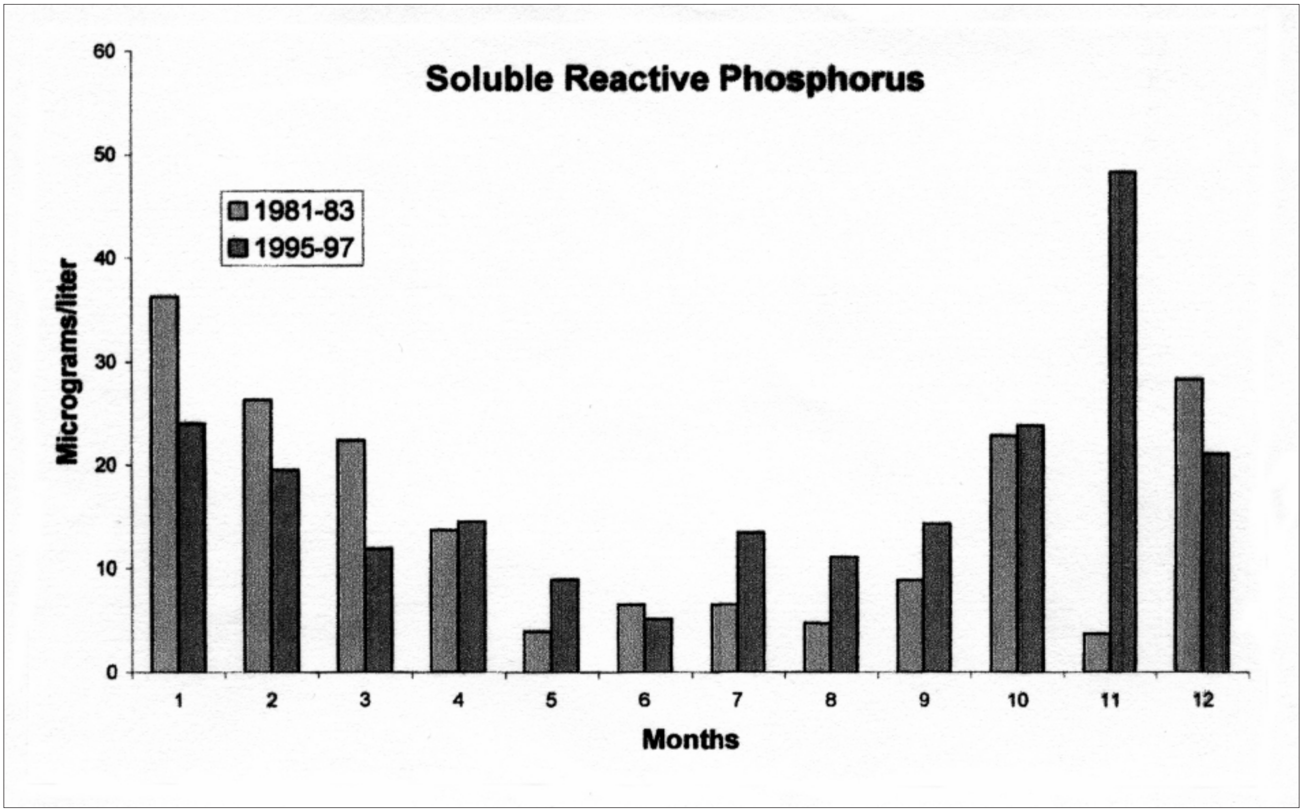

Figure 5.11. Trends in soluble reactive phosphorus concentrations for Old Woman Creek estuary.

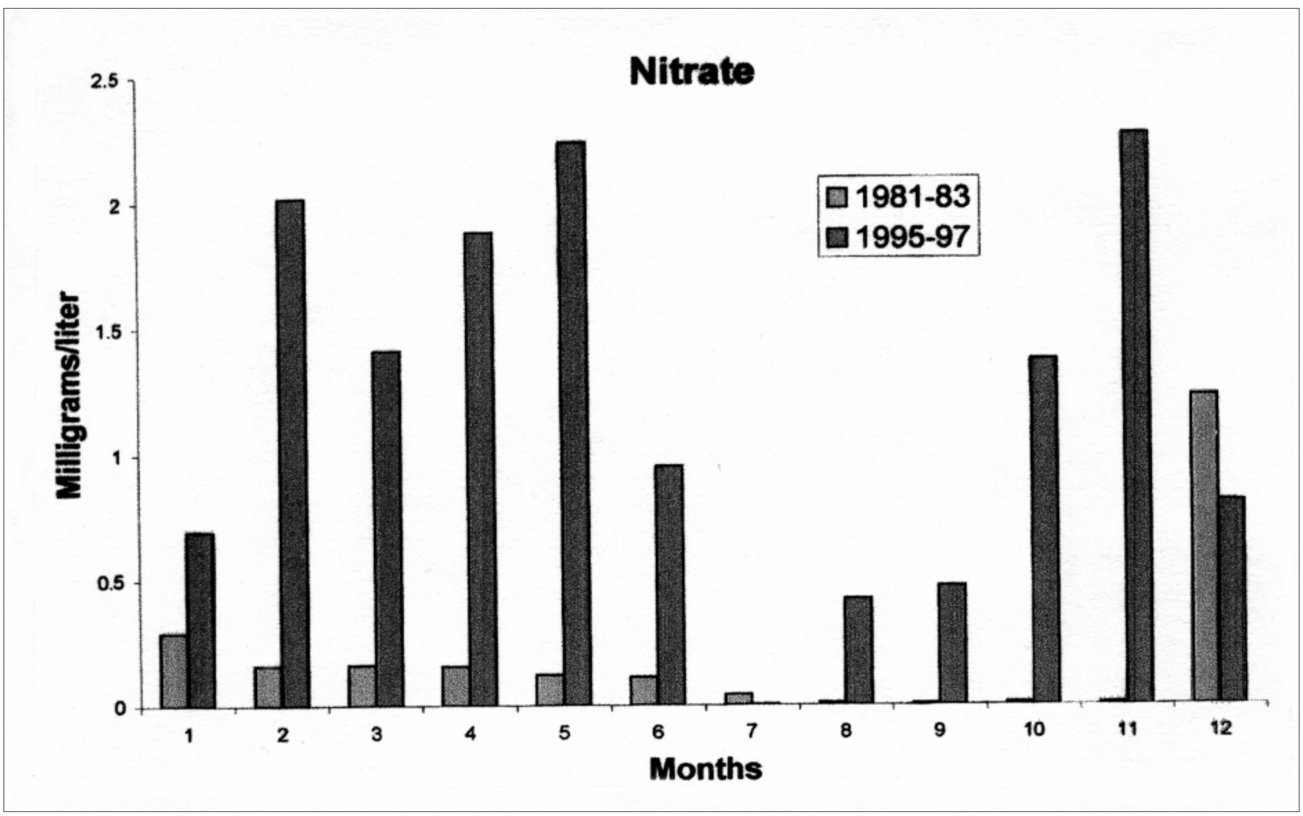

Figure 5.12. Trends in nitrate concentrations for Old Woman Creek estuary.

rainfall resulted in the transport of nutrients of lower concentrations into the estuary. With decreased rainfall, the input of groundwater—which remains fairly constant during most conditions—became more significant. The concentrations of chemicals associated with groundwater inflow, such as calcium, increased. The changes in the chemical composition of the estuary related to declining Lake Erie water levels (1995 to 1997 verses 1998 to 2000) do not appear to be as great as those associated with the opening (1995 to 1997) and closing (1981 to 1983) of the estuary mouth.

The addition of automated data loggers to the monitoring program in 1995 resulted in a more detailed understanding of the daily, weekly, and monthly changes in the chemistry and biology of the estuary. Figure 5.13 is an example of the diurnal fluctuations in oxygen levels that are now being recorded.

ESTUARY MIXING

Several investigations have demonstrated the encroachment of Lake Erie water into coastal estuaries and the subsequent mixing of lake and tributary water. Herdendorf (1965) noted a fourfold decrease in specific conductance of Cuyahoga River water in its estuary as it mixed with and was diluted by lake water. Schroeder and Collier (1966), also studying the Cuyahoga water quality, found that colder and less mineralized lake water intruded under warmer and more contaminated river water. They concluded that the extent of the intrusion was affected by seiches, wind, and fluctuations in both streamflow and lake level. Surveys and water level comparisons showed similar characteristics in the Maumee River estuary with distinct intrusions of lake water that mixed with river water for 10 km upstream (Herdendorf 1970). Current

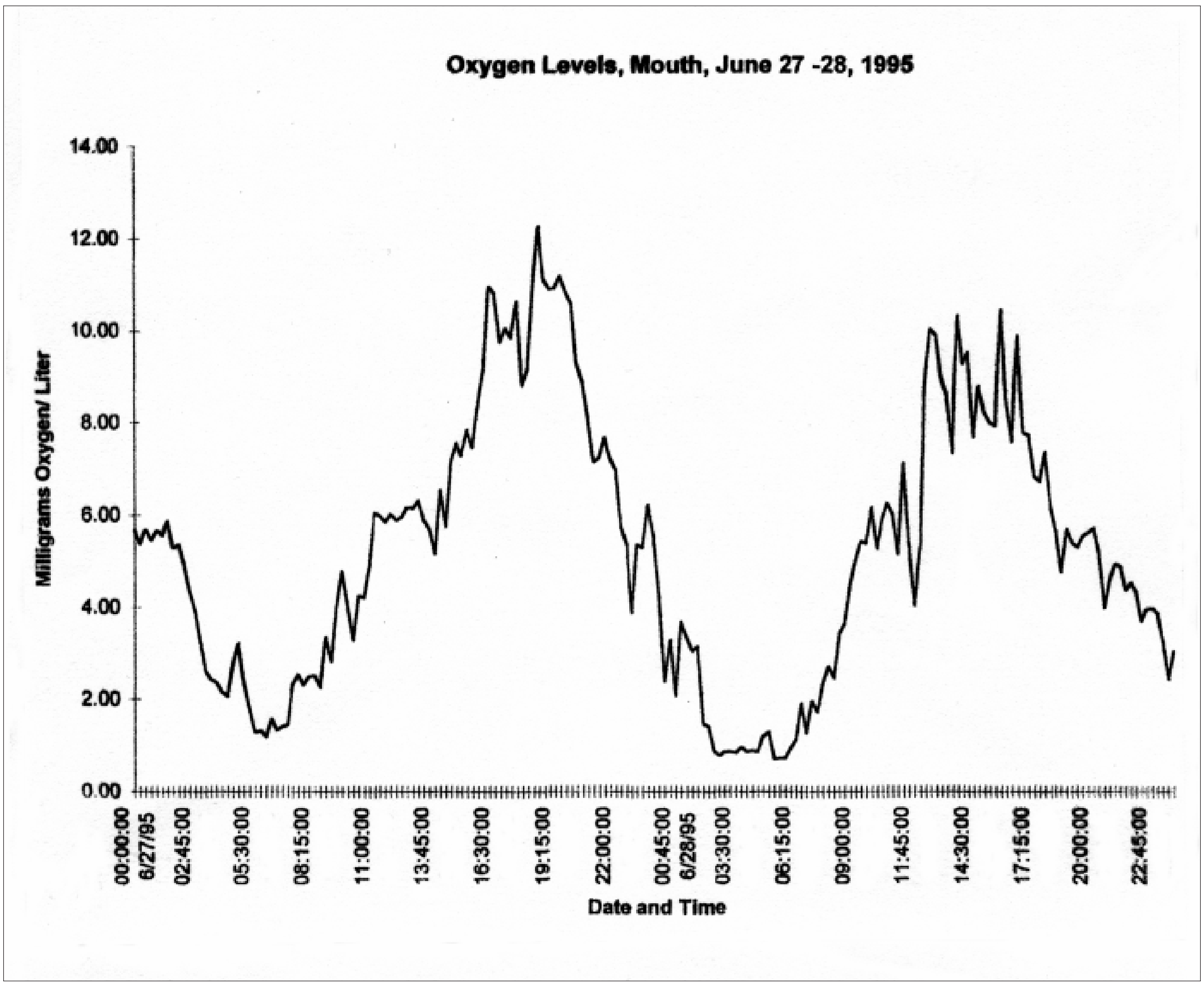

Figure 5.13. Example of dissolved oxygen monitoring in Old Woman Creek estuary.

measurements mid-way along the estuary yielded an upstream flow at all depths under the stress of a 25 km/hr wind from the northeast. Bedford (1989) contrasted transport mechanisms in Lake Erie tributaries to those operating in marine estuaries and concluded that although there is negligible propagation of lunar-solar driven tidal waves, there are transport analogies within Lake Erie estuaries associated with meteorologically induced water level fluctuations and chemical gradients. Krieger (1993) developed a method for estimating fluxes of materials from estuarine wetlands into Lake Erie using Old Woman Creek as a demonstration example. The method requires frequent measurements of atmospheric deposition, precipitation, evaporation, upstream tributary discharge, estuary water level changes, and water chemistry at upstream and downstream locations, as well as a knowledge of estuary depth-area and depth-volume relationships.

ESTUARY AS A CHEMICAL SINK AND TRANSFORMER

Klarer and Millie (1989) studied the role of the Old Woman Creek estuary in ameliorating storm water that passed through it. Storm water caused one of three possible changes in the concentration of individual chemical species. Possibility 1— if a chemical was fairly insoluble or bound to the sediment, then its concentration went up with the input of the surface runoff phase of storm water, as did orthophosphate (Figure 5.14). Maximum water inflow and maximum sediment input (turbidity) is associated with this surface runoff phase (Baker 1984). Possibility 2—if the chemical was soluble, it percolated into the ground and entered the creek with the interflow, after the initial influx of the sediment-rich storm water. Nitrate (Figure 5.14) followed this pattern. Possibility 3—if a chemical entered the creek at a constant rate, such as in groundwater, the concentration of this chemical decreased with the influx of storm water. For example, calcium displayed this pattern of distribution during storm runoff events (Figure 5.14).

Inflow-outflow ratios of chemical concentrations were used to estimate the estuary's relative effectiveness in modifying water passing through it (Klarer and Millie 1989). The results showed that 12 to 60% of the metals and 35 to 80% of the biologically-important nutrients were retained within the estuary. They attributed the amelioration of storm-water quality to sedimentation, biological uptake, and geochemical processes. Similarly, Heath (1986) determined that water leaving Old Woman Creek estuary had a 77% lower concentration of soluble reactive phosphorus than water entering the estuary, while Klarer (1988) found that nitrate and silicate concentrations were reduced 42% and 49%, respectively. In another study of Old Woman Creek estuary, Reeder and Mitsch (1989a) found that conductivity, turbidity, and total suspended solids generally had the highest concentrations at the upstream inflow, then decreased as much as sevenfold as the water transited the estuary.

Krieger (2001) has shown that Old Woman Creek estuary receives chemically-laden water from its tributaries and that the estuary's wetlands function as sink and transformer of most incoming materials and thereby substantially reducing the impact of those materials on the chemistry and biology of the receiving water body, Lake Erie**.** Figure 5.15 presents a model that demonstrates the processes involved. Water carries dissolved and particulate materials into the estuary via several pathways in: (1) surface runoff from the watershed, (2) intrusions of lake water during seiches and storm surges, (3) direct precipitation, (4) groundwater flow, and (5) wind-borne dry deposition. Water and associated materials are exported from the estuary via: (1) outflow to the lake, (2) groundwater seepage at the barrier bar, and (3) evaporation and volatilization. Biota, such as fish and waterfowl, may also provide important routes of materials input and export for the estuary. In his 3-year study, Krieger (2001) measured the major nutrients and agricultural pollutants entering and leaving the estuary. Table 5.16 presents the monthly averages of several water quality parameters for the 1990 water year (October 1989 through September 1990). He found that phosphorus and nitrate/nitrite nitrogen showed significant reduction as water passed through the estuary (Table 5.17). Of 12 herbicides analyzed, only four (alachlor, atrazine, metolachlor, and metribuzin) were consistently detected, and their concentrations were substantially lower at the outlet than upstream.

Krieger (2001) noted that both the ammonia and total Kjeldahl nitrogen loads leaving the estuary were greater than those entering, thus suggesting that ammonification may be a major process within the estuary. Wickstrom (1988) also reported elevated ammonia concentrations in the water flowing out of the estuary. When analyzing total nitrogen loading data

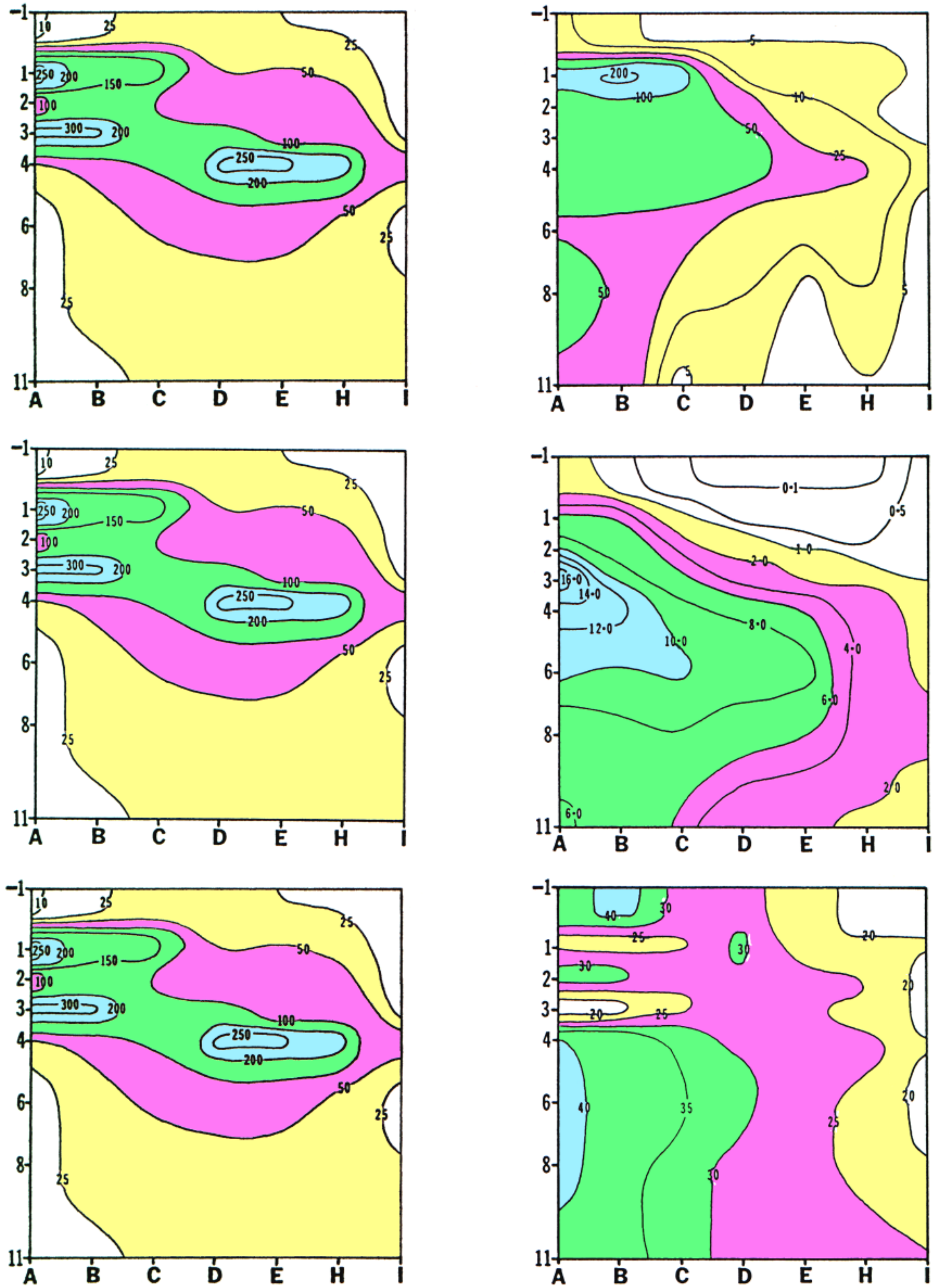

Figure 5.14. Impact of storm water passage on the concentration of selected chemicals in Old Woman Creek estuary.

NOTE: Turbidity (NTU), on the left side of the diagram, represents the passage of storm water; right side—soluble reactive phosphorus (upper), nitrate (center), calcium (bottom). Vertical scale on each graph is day after rainfall event; horizontal scale is sampling sites from above the estuary (A) to nearshore Lake Erie (I).

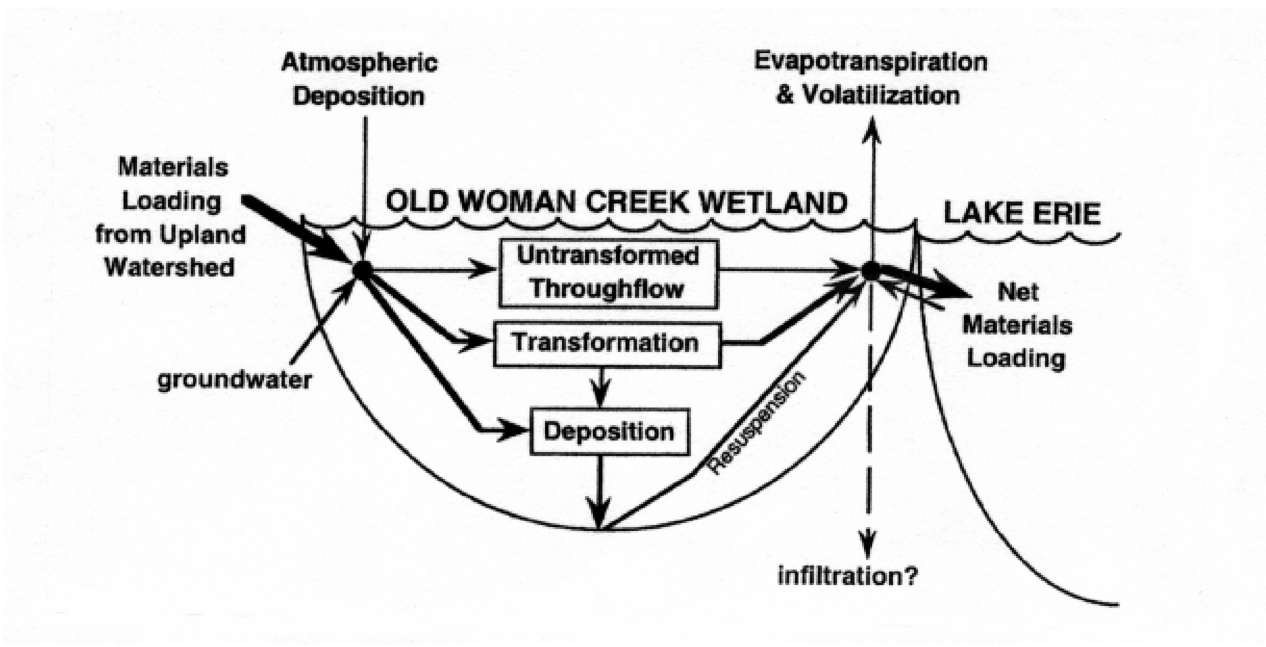

Figure 5.15. Conceptual model of materials fluxes in Old Woman Creek estuary wetlands (Krieger 2001).

(nitrate/nitrite and total Kjeldahl nitrogen) for water year 1990, Krieger found that about 14% of the nitrogen that flowed into the estuary did not enter Lake Erie (Table 5.17). Tomaszek et al. (1997) measured denitrification rates in the Old Woman Creek estuary sediments. The rates they reported support the hypothesis that the denitrification process could be a major sink for nitrogen in this estuary. Lavrentyev et al. (1998) examined the nitrogen dynamics of the microbial plankton communities. Although they were unable to estimate ammonia cycling rates, because of large ammonium concentrations in the water from storm runoff during their sampling periods, their preliminary data suggest that ammonium recycling in these plankton communities may be significant, particularly during periods of summer-stagnation.

An average nitrogen:phosphorus (N:P) ratio of 29.67 suggested that the phytoplankters in the estuary were P-limited (Heath 1992a,b). However, there was no evidence of P-limitations in the nutrient enrichment studies of Heath (1987). In addition, phosphatase specific activity, an indicator of P-limitation, also remained low during the study period. Heath (1987,1992a,b) reported that there was some evidence that N-availability may, on occasion, be limiting; but, he felt that light probably was the most important limiting factor for the phytoplankton in the estuary .

Organic pollution, including agricultural pesticides, in the Great Lakes is a growing major concern (Brody et al. 1998). The role of the estuary in mitigating organic pollution, particularly herbicides and pesticides has been examined by Chin et al. (1998), Everett et al. (1999), and Miller and Chin (2002). Their work has demonstrated the role of nitrates and naturally-occurring organic matter in serving as photosensitizers to enhance the photolytic breakdown of the pesticide carbaryl and the herbicide alachlor, both widely used agrochemicals in the midwest. The present authors anticipate that wetland areas such as Old Woman Creek estuary may play a significant role in the mitigation of this pesticide problem.

Marine estuaries have been found to be important in improving the quality of riverine water flowing through them to the ocean (Kennedy 1984). Physical, geochemical, and biochemical processes are all important in removing both suspended and dissolved chemicals from the water in these estuaries. Physical and geochemical processes are usually most effective in the area of the upper estuary, termed the "turbidity maximum," where suspended sediment concentrations are much higher than in surrounding waters (Schubel and Pritchard 1986). Biochemical processes are most evident in the lower estuary, because this is the area of greatest biological activity (Sharp et al. 1984).

TABLE 5.16. OLD WOMAN CREEK AND ESTUARY WATER QUALITY: 1990 WATER YEAR

	Oct	Nov	Dec	Jan	Feb	Mar
Water Discharge (m^3/s)						
Old Woman Creek	0.15	0.61	0.13	2.40	2.13	0.19
Estuary	0.24	0.61	0.13	2.08	2.64	0.15
Conductivity (µmhos at 25°C)						
Old Woman Creek	831	744	855	667	542	631
Estuary	536	585	847	646	504	428
Total Suspended Solids (mg/l)						
Old Woman Creek	12.8	19.6	2.3	23.0	37.1	8.1
Estuary	45.5	115.2	29.2	62.1	72.7	66.2
Chloride (mg/l as Cl^-)						
Old Woman Creek	96.3	72.2	85.1	60.5	46.1	53.7
Estuary	45.2	48.5	81.4	58.6	41.5	30.2
Soluble Reactive Phosphorus (µg/l as P)						
Old Woman Creek	16	14	10	9	14	4
Estuary	7	7	10	5	11	4
Total Phosphorus (µg/l as P)						
Old Woman Creek	71	90	30	77	100	28
Estuary	150	191	76	107	133	83
Nitrate + Nitrite (mg/l as N)						
Old Woman Creek	3.93	3.86	3.94	7.23	5.93	4.25
Estuary	0.37	2.44	3.94	6.63	5.28	2.39
Ammonia (mg/l as N)						
Old Woman Creek	1.17	0.48	0.51	0.19	0.13	0.15
Estuary	0.20	0.39	0.51	0.24	0.05	0.11
Total Kjeldahl Nitrogen (mg/l as N)						
Old Woman Creek	1.81	1.12	1.00	0.84	0.81	0.66
Estuary	1.52	1.51	1.29	0.99	0.96	0.75
Soluble Reactive Silica (mg/l as SiO_2)						
Old Woman Creek	5.98	7.51	6.84	7.96	7.15	4.74
Estuary	3.98	6.19	5.87	7.51	6.29	3.40

Data Source: Krieger (2001)

TABLE 5.16. OLD WOMAN CREEK AND ESTUARY WATER QUALITY: 1990 WATER YEAR (cont'd)

	Apr	May	Jun	Jul	Aug	Sep	Mean
Water Discharge (m^3/s)							
Old Woman Creek	1.25	0.82	0.04	0.20	0.08	0.74	0.71
Estuary	1.28	0.77	0.00	0.18	0.05	0.59	0.71
Conductivity (µmhos at 25°C)							
Old Woman Creek	586	584	708	714	639	640	678
Estuary	496	391	520	512	354	381	517
Total Suspended Solids (mg/l)							
Old Woman Creek	30.7	71.3	19.2	25.1	29.4	37.1	26.3
Estuary	116.7	126.9	75.2	67.9	52.9	64.7	74.6
Chloride (mg/l as Cl^-)							
Old Woman Creek	45.9	42.9	70.3	70.3	63.2	54.6	63.4
Estuary	35.2	22.6	38.6	38.7	20.8	22.1	40.3
Soluble Reactive Phosphorus (µg/l as P)							
Old Woman Creek	8	9	11	13	16	30	12.8
Estuary	7	4	3	4	5	8	6.3
Total Phosphorus (mg/l as P)							
Old Woman Creek	57	130	63	70	98	183	83.1
Estuary	157	174	230	184	143	170	149.8
Nitrate + Nitrite (mg/l as N)							
Old Woman Creek	4.20	5.56	2.53	7.05	1.65	3.48	4.47
Estuary	3.16	2.85	0.41	0.92	0.42	1.00	2.48
Ammonia (mg/l as N)							
Old Woman Creek	0.13	0.16	0.06	0.08	0.10	0.12	0.27
Estuary	0.19	0.22	0.15	0.24	0.14	0.16	0.22
Total Kjeldahl Nitrogen (mg/l as N)							
Old Woman Creek	0.82	1.12	0.67	0.74	0.80	0.93	0.89
Estuary	1.22	1.38	1.49	1.66	1.16	1.19	1.26
Soluble Reactive Silica (mg/l as SiO_2)							
Old Woman Creek	4.63	5.26	5.11	7.30	7.50	8.43	6.53
Estuary	4.37	2.94	0.98	1.41	2.48	4.34	4.15

Data Source: Krieger (2001)

TABLE 5.17. COMPARISON OF MATERIALS LOADING FROM TRIBUTARIES TO OLD WOMAN CREEK ESTUARY WITH DISCHARGE FROM THE ESTUARY TO LAKE ERIE: 1990 WATER YEAR

Component	To OWC Estuary	To Lake Erie	Retained in Estuary
Water Discharge	22.5×10^6 m^3	22.4×10^6 m^3	0.3 %
Total Suspended Solids	2.70×10^6 kg	3.01×10^6 kg	-11.5 %[1]
Chloride (Cl^-)	0.97×10^6 kg	1.00×10^6 kg	-3.0 %[2]
Total Phosphorus (P)	5,831 kg	3,867 kg	33.5 %
Soluble Reactive Phosphorus (P)	521 kg	283 kg	45.7 %
Nitrite/Nitrate Nitrogen (NO_{2+3}-N)	136,733 kg	107,610 kg	21.3 %
Ammonia Nitrogen (NH_3-N)	3,255 kg	6,234 kg	-91.8 %[3]
Total Kjeldahl Nitrogen (organic N)	30,123 kg	35,093 kg	-16.5 %[4]
Soluble Reactive Silica (SiO_2)	154,104 kg	145,121 kg	5.8 %

NOTES:

1. Total suspended solids load increased during passage through the estuary, although most inorganic particles settle out of the water column upon entering the estuary, because plankton is produced throughout the estuary and upon export more than compensates for the sedimentation loss.

2. A small increase in the amount of chloride exported from the estuary may reflect the use of salt for ice control on the bridges crossing the estuary and groundwater contributions within the estuary.

3, 4. More ammonia and organic nitrogen left the estuary than entered, with the net export enlarged by storms, which may reflect the release of transformed nitrite/nitrate nitrogen to ammonia and organic compounds by storm-induced resuspension of anaerobic, organic-rich sediment of the estuary.

Data Source: Krieger (2001)

The general physical, geochemical, and biological pollution reduction processes are similar in both marine estuaries and Old Woman Creek estuary (Klarer 1988). However, unlike marine estuaries, there is no specific “turbidity maximum” in the upper part of the estuary. In Old Woman Creek, the lower estuary may partially serve as this “turbidity maximum.” Here, the estuary is very shallow and has a very high surface area to volume ratio. Even moderate winds re-suspend the bottom sediments, creating high turbidity areas which facilitate these physical and geochemical processes. Like marine estuaries, biological activity is highest in the lower estuary of Old Woman Creek.

WATERSHED HYDROLOGY

Streams tributary to Lake Erie, such as Old Woman Creek above its estuary, are characterized by a continual downstream movement of water, dissolved substances, and suspended particles, as well as bedload sediments during periods of high flow. These components are derived primarily from the stream’s watershed—the total land area (69 km^2) draining into the channel of Old Woman Creek. Hence, the hydrological, chemical, and biological characteristics of Old Woman Creek reflect the climate, geology, and vegetational cover of the watershed along with the human land use activities within the drainage basin.

Water in the channel of streams originates from: (1) direct precipitation, (2) overland or sheet runoff, and (3) subsurface flow (Wetzel and Likens 1979). When water is added to the surface of the watershed's soil at a rate that exceeds the soil's infiltration capacity, it runs overland as sheet flow. Overland runoff plus water that soaks into the soil and flows laterally to the stream channel are the main components of peak flow or floods. Permeable soils tend to become saturated with water below a certain depth. The surface of this saturated zone is known as the water table; water in the soil above the water table is termed vadose water, while that below is called groundwater. During the dryer portions of the year, groundwater provides a relatively stable base flow component in Old Woman Creek.

Stream Order

The Horton-Strahler method of ordering the tributaries to a stream (Horton 1945, Strahler 1952) provides a way of analyzing the bifurcations of a stream and comparing the complexity of one watershed to another. In this method each headwater or finger-tip tributary (including ephemeral and intermittent streams) is designated as the first order. Two first-order tributaries combine to produce a second-order tributary, two second-order tributaries produce a third, and so on. Only the union of two tributaries of equal order can produce a higher order, thus the order of the trunk stream is not changed below the confluence with a stream of lower order. Generally, the diversity and abundance of aquatic organisms in a stream increases as its order increases. Table 5.18 gives a summary of stream orders for Old Woman Creek. At its estuary, Old Woman Creek is an fourth-order tributary to Lake Erie.

Surface Drainage Area

The network of tributaries in the Old Woman Creek watershed forms a dendritic (tree-like) drainage pattern (Figure 5.16). The boundaries of the drainage basin were determined from surface features (topographic divides) depicted on U.S. Geological Survey topographic maps, soils maps, and aerial photographs. The total surface drainage area is 69 km^2. The drainage density for the watershed (total stream length/area of drainage basin) is 1.1 km/km^2.

Subsurface Drainage Area

Subsurface flow may have different boundaries (phreatic divides), particularly in areas underlain with soluble or permeable deposits (Wetzel and Likens 1979). This is the case for Old Woman Creek where the subsurface drainage basin is dramatically larger than the surface watershed by virtue of a major glacially buried valley that underlies the estuary and extends over 70 km to the south. Preglacial bedrock topography was used to define the boundaries of the subsurface drainage basin (Figure 5.17). This yields a potential subsurface drainage area of approximately 2,500 km^2. Because the bedrock floor of the preglacial valley lies some 40 m below the bed of the estuary, it is likely that much of the groundwater flow in the buried valley is beneath the creek channel and therefore does not influence the hydrologic regime of Old Woman Creek. However, if the elevation of the deepest part of the channel in the estuary is extended laterally until bedrock is encountered, a more reasonable estimate is obtained for a subsurface drainage area that interacts with Old Woman Creek estuary. This effective subsurface drainage area is approximately 100 km^2.

TABLE 5.18. STREAM ORDERS FOR OLD WOMAN CREEK TRIBUTARIES

Order	Number	Mean Length (km)	Total Length (km)
1st	28	1.4	42.0
2nd	6	3.1	18.2
3rd	2	4.8	9.5
4th	1	5.3	5.3
Total	37	2.0	75.0

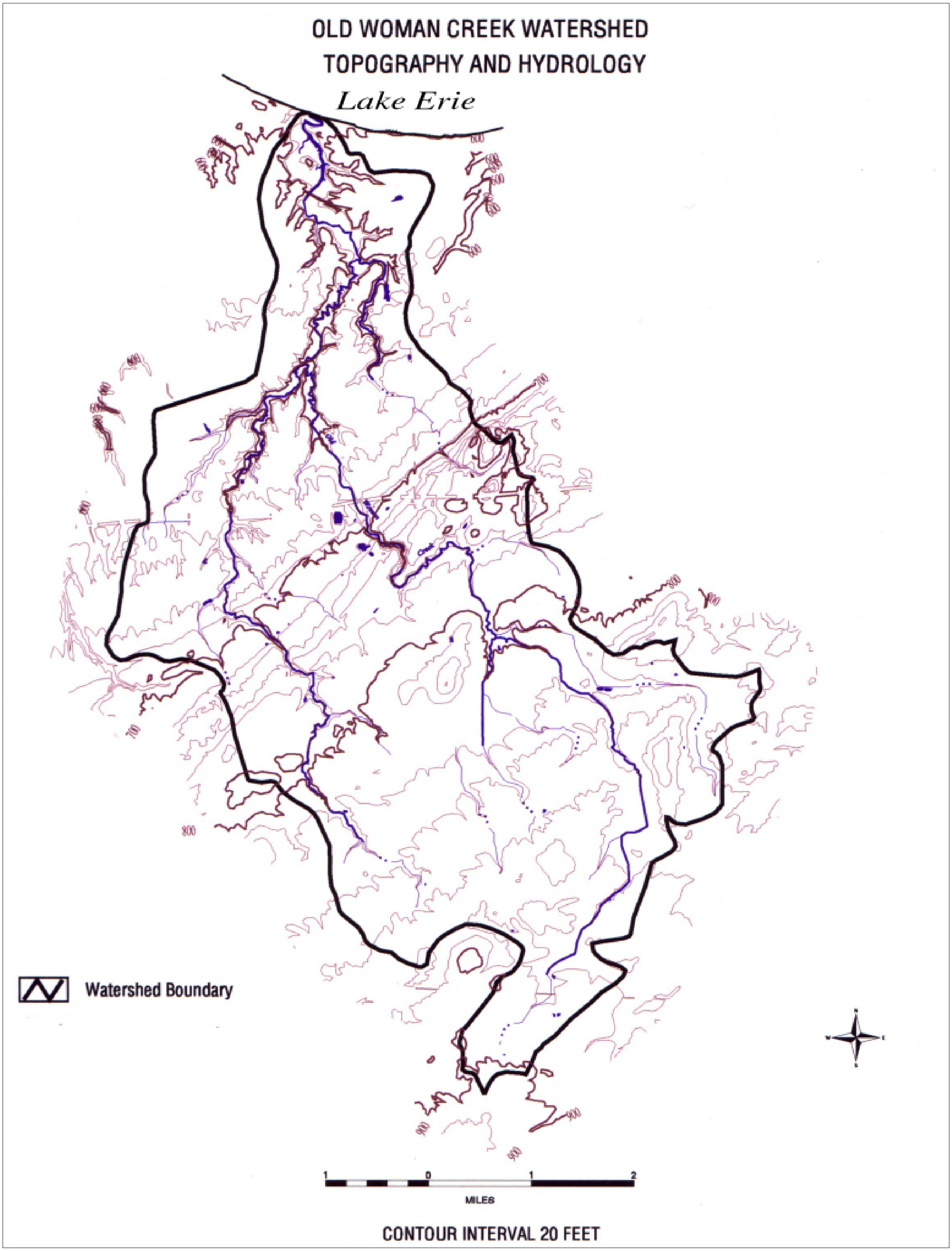

Figure 5.16. Surface drainage pattern of Old Woman Creek watershed.

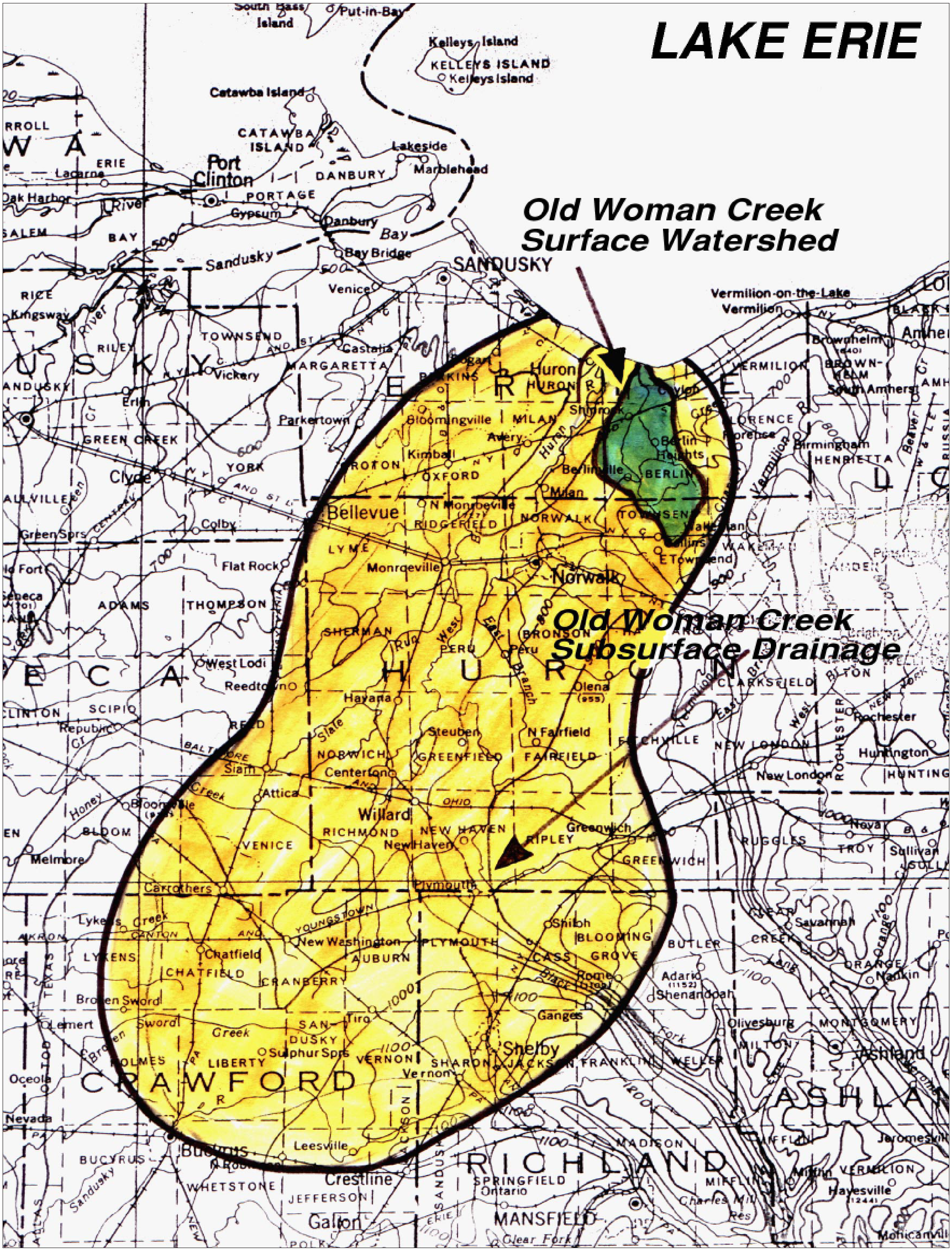

Figure 5.17. Subsurface drainage area for Old Woman Creek estuary.

GROUNDWATER

The geological formations beneath the surface of the Earth play an important role in the occurrence and development of groundwater. When rainwater strikes the ground, a portion flows across the surface of the land as "runoff" into streams and drains. The remainder seeps downward into the ground where it is temporarily stored. Water is contained in numerous openings, pore spaces, cracks, crevices between rocks, joints, bedding planes, fractures, or voids in the rock. These openings are usually interconnected, thereby permitting the movement of water from one opening to another. The quantity of groundwater in the watershed depends upon the size and number of these openings. The shape and the degree to which these openings are interconnected governs the amount of water available to wells. For this reason, wide variations in groundwater conditions are found because the geology differs in various locations in the watershed (Figure 5.18).

The amount of annual rainfall and temperature are the major climatic factors affecting the groundwater supply in any particular area. Recharge to aquifers is supplied directly or indirectly by precipitation, depending on the season of occurrence, its intensity, and whether it occurs as rain or snow. In the spring as the growing season starts, melted snow and rain usually result in large additions to the groundwater supply. However, layers of ice, or frost on the ground, can delay infiltration when thawing occurs. Under these conditions, water from snowmelt and early spring rains may be lost by quick surface runoff. In the fall of the year after the end of the growing season, when evaporation losses are reduced by cooler weather, substantial rises in groundwater levels usually occur from rainfall.

Groundwater Hydrology

Within Old Woman Creek watershed groundwater is present in pore spaces in sandstone, in joints and fractures in shale, and between the grains of sand and gravel. Groundwater supplies wells, keeps streams flowing during dry periods, and saturates certain soils to sustain wetland vegetation. Groundwater yields in the watershed (Figure 5.18) can be classified into three zones (Stein 1962a,b). In the vicinity of the estuary, from the lakeshore south to Ohio Route 2, yields are relatively high at 25 to 100 gallons per minute (about 100 to 400 l/min). Groundwater is developed from several lenses of sand and gravel interbedded in thick layers of clay. The preglacial valley that trends to the southwest under the Reserve has been penetrated by water wells drilled to 38 m without reaching bedrock. Such wells generally stop in sand and gravel lenses which are good producers of groundwater. From Ohio Route 2 south to Berlin Heights and then southwest to the Huron County line, groundwater yields are poor at less than 5 gallons per minute (<20 l/min). Surface material in this zone is glacial drift, composed predominantly of clay, underlain by shale and some thin sandstone. Wells developed in the upper weathered portion of the bedrock yield an average of 3 gallons per minute. The remainder of Old Woman Creek watershed south of Berlin Heights and into Townsend Township of Huron County has moderate groundwater yields ranging from 5 to 25 gallons per minute (about 20 to 100 l/min). In this zone sandstone and shale bedrock is covered with an average of 12 m of glacial drift. Sandstone typically yields 5 to 20 gallons per minute (about 20 to 75 l/min) at depths up to 40 m.

Groundwater Quality

Walker (1986) and Hartzell (1986) reported the quality of groundwater in Erie and Huron Counties from test wells in the vicinity of Old Woman Creek watershed. Wells Erie-C and Huron-B are located in the buried preglacial valley that trends to the southwest from the present mouth of Old Woman Creek, while wells Erie-D and -E are in sandstone and shale terrain, respectively (Table 5.19). Wells developed in the Ohio Shale have the lowest yield and the poorest quality, while sand and gravel lenses in the buried valley have the best yield, but not necessarily the best quality.

The Ohio Department of Natural Resources, Division of Water has determined that the lower valley of Old Woman Creek (surrounding the estuary) has the highest potential for groundwater pollution while, the higher ground portions of the watershed (remote from the estuary) have the lowest potential (Figure 5.19). This situation appears to be related to pollutants from agricultural sources that have a greater potential for infiltrating the groundwater in the quiescent estuary as compared to the more rapidly flowing upstream surface waters.

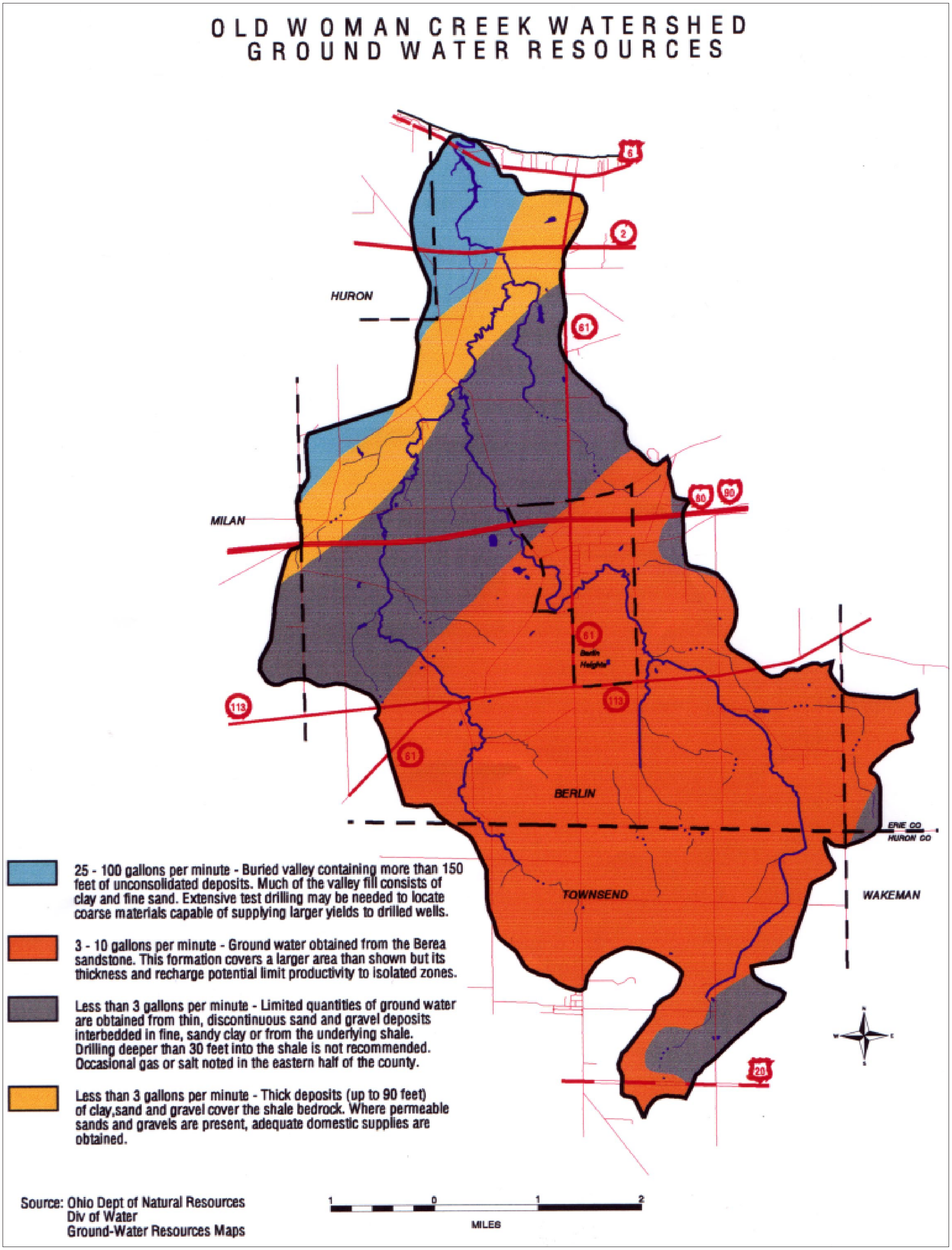

Figure 5.18. Groundwater resources of Old Woman Creek watershed.

TABLE 5.19. GROUNDWATER QUALITY OF THE WATERSHED

Parameter	Erie-C	Erie-D	Erie-E	Huron-B
Location (Twp)	Milan	Berlin	Florence	Willard
Depth	45.0	30.0	21.0	12.0
Aquifer	sand&gravel	sandstone	shale	sand&gravel
Iron (Fe mg/l)	1.3	0.9	1.1	0.8
Calcium (Ca mg/l)	82.0	86.0	8.2	78.0
Sodium (Na mg/l)	30.0	21.0	479.0	17.0
Chloride (Cl mg/l)	0.6	10.0	134.0	27.0
Fluoride (Fl mg/l)	0.4	0.2	0.8	0.2
Sulfate (SO_4 mg/l)	68.0	72.0	188.0	134.0
Hydrogen sulfide (H_2S)	—	—	trace	—
Dissolved solids (mg/l)	—	328.0	1230.0	—
Hardness ($CaCO_3$ mg/l)	282.0	301.0	32.0	—
pH	7.5	6.8	8.0	7.9
Yield (gpm)	250	5	1	490

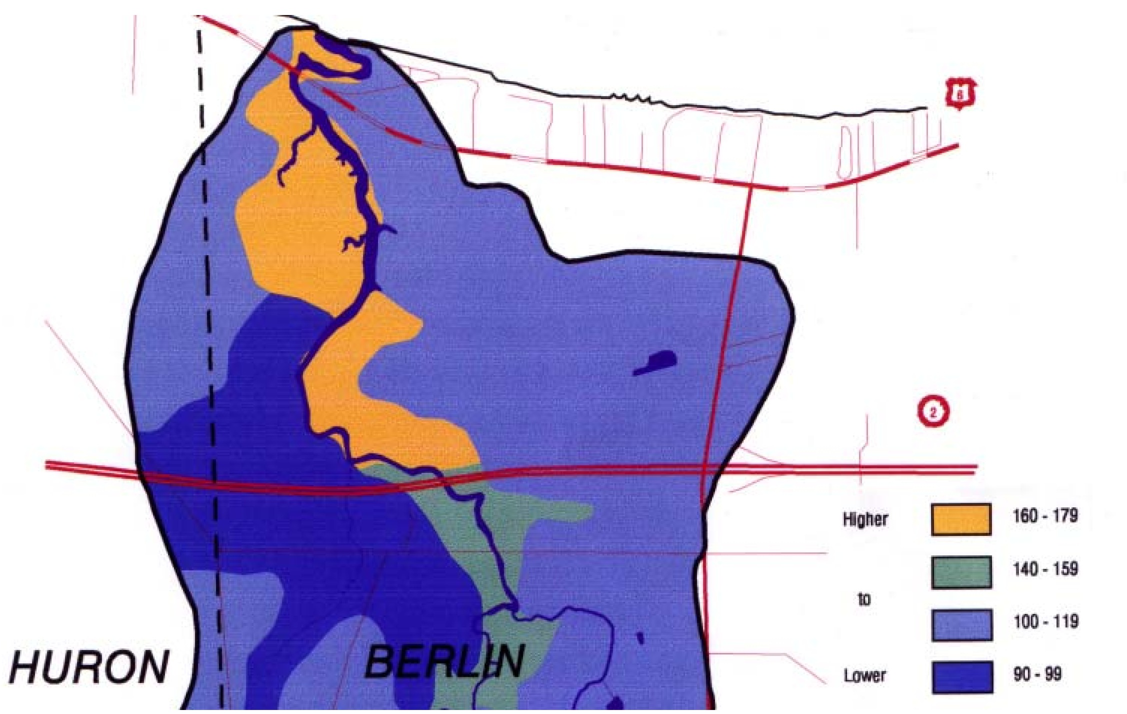

Figure 5.19. Groundwater pollution potential of the lower Old Woman Creek watershed (ODNR).