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Spatial Heterogeneity of Water Quality in a Highly Degraded Tropical Freshwater Ecosystem

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Abstract Awareness of environmental heterogeneity in ecosystems is critical for management and conservation. We used the Xochimilco freshwater system to describe the relationship between heterogeneity and human activities. This tropical aquatic ecosystem south of Mexico City is comprised of a network of interconnected canals and lakes that are influenced by agricultural and urban activities. Environmental heterogeneity was characterized by spatially extensive surveys within four regions of Xochimilco during rainy and dry seasons over 2 years. These surveys revealed a heterogeneous system that was shallow (1.1 m, SD = 0.4), warm (17°C, SD = 2.9), well oxygenated (5.0 mg l^{-1}, SD = 3), turbid (45.7 NTU SD = 26.96), and extremely nutrient-rich (NO_3–N = 15.9 mg l^{-1}, SD=13.7; NH_4–N = 2.88 mg l^{-1}, SD = 4.24; and PO_4–P = 8.3 mg l^{-1}, SD = 2.4). Most of the variables were not significantly different between years, but did differ between seasons, suggesting a dynamic system within a span of a year but with a high resilience over longer periods of time. Maps were produced using interpolations to describe distributions of all variables. There was no correlation between individual variables and land use. Consequently, we searched for relationships using all variables together by generating a combined water quality index. Significant differences in the index were apparent among the four regions. Index values also differed within individual region and individual water bodies (e.g., within canals), indicating that Xochimilco has high local heterogeneity. Using this index on a map helped to relate water quality to human activities and provides a simple and clear tool for managers and policymakers.

Keywords Interpolation · Land use · Urban lake · Shallow lake · Xochimilco · Water quality index · Wetlands

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Environmental heterogeneity is closely related to ecosystem pattern and function (George and others 2000; Guo and others 2003). Recently, spatial heterogeneity has been studied in aquatic systems to understand processes in rivers, wetlands, and lakes (Dent and Grim 1999; Comin and others 2001; Robinson and others 2002). Many aquatic systems have spatial heterogeneity based on internal processes (Comin and others 2001). For example, variability in the depth of a lake or water velocity in a river can produce local differences in sediment-water interactions that create spatial heterogeneity in suspended solid and nutrient concentrations.

High spatial heterogeneity increases habitat availability for different organisms (Brown 2003; Dufour and others 2006; Gundale and others 2006), as well as the overall resilience of aquatic ecosystems. High heterogeneity fosters gradual rather than catastrophic changes in zooplankton and phytoplankton populations in response to perturbations (Scheffer and Rinaldi 2000). Managers consider high heterogeneity as a positive attribute because it is directly related to species diversity (Nienhuis and others 2002), although this is not always the case for invertebrates (Brooks and others 2002).

Human activities are capable of modifying patterns in spatial heterogeneity (UNESCO 2006) by changing the water quality of rivers or lakes (Harper 1992; Shivoga and others 2006). For example, human settlements create patchy eutrophication along a water system (Douterelo and others 2004; Kemka and others 2006). Consequently, these changes can modify species distribution (Muhando and others 2002) or sexual selection (Engstroem-Oest and Candolin 2007). Therefore, it is necessary to understand how key ecological variables change across the landscape, in response to both natural complexity and changes in human land use. Analyzing spatial heterogeneity in water quality may help relate the effects of human activities on those limnological variables that are critical for the survival of native organisms.

One of the difficulties in determining heterogeneity in a system is that data collected from single point samples do not explain the behavior of a particular variable in the area surrounding that sampling point. Therefore, the nonsampled areas do not provide information that could be relevant regarding the variables' spatial distribution within the entire system. Interpolation techniques can help fill these gaps between sampling points, which increase the information obtained from specific sites (Matejicek and others 2006). Once variables are interpolated, they can be overlapped, generating a water quality index that may be capable of describing the aquatic system health in a single map. Then it may be possible to use this technique to analyze relationships between spatial heterogeneity, based on a water quality index, and land use (Tveito and others 2005).

The Xochimilco freshwater ecosystem is composed of canals connecting small lakes and a wetland. It is located in the southern portion of Mexico City, the second largest city in the world, with a population of more than 18 million inhabitants (Fig. 1). This ecosystem still hosts 140 species of migratory birds and native species such as the axolotl (*Ambystoma mexicanum*) and crayfish (*Cambarellus montezumae*), both of which are endemic and threatened. This system is a tropical high-altitude water body which produces distinct hydrological and ecological regimes. Water temperature is normally lower and more inconsistent than in a tropical system; thermal variability is due less to seasonal dynamics (as in temperate systems) than to day-night cycles, which can produce temperature fluctuations of >15°C (Zambrano, unpublished data). The hydrological regime at Xochimilco is marked by seasonal change, as the rainy season results in substantial ecosystem expansion due to formation of temporary wetlands that attach to permanent water bodies.

Anthropogenic perturbations have been imposed on this dynamic hydrologic regime, as Xochimilco has one of the longest histories of human management. The contemporary aquatic system is the last remnant of the original aquatic landscape composed of five lakes—Xaltocan, Zumpango, Texcoco, Xochimilco, and Chalco—which covered $\sim$920 km^2 in the Basin of Mexico (DDF 1975). Historically, this ecosystem has been occupied by traditional agriculture in portions of land known as *chinampas*, using aquatic resources and lake sediments for food production. However, 25 years ago, the decline in water quality has caused a shift in agricultural activities to more intensive production in greenhouses (López and others 2006; Méndez 2006). Nowadays Xochimilco is a collage of land uses, ranging from completely urbanized areas (mostly in the southern region) to rural areas (in the central and northern regions), and it is currently threatened by urban growth in the periphery of the Mexico City Metropolitan Area. In 1989 the first attempt at management and restoration of this system generated the Ecological Park (*Parque Ecologico de Xochimilco*; PEX) in the northern region. Also, the complete ecosystem has been part of the UNESCO World Heritage List since 1987 and the International Convention on Wetlands (known as RAMSAR) list since 2004.

To maintain the biodiversity and ecosystem services provided by this aquatic system, conservation and restoration policies must be implemented which consider the high heterogeneity in water quality produced by the regional climate and contrasting land uses. Therefore, the aim of this paper is to create a water quality index, using geographical interpolations to spatially characterize the wetlands, lakes, and channels in this system subject to multiple environmental influences. The broad-scale information produced by this index will help elucidate the spatial influences of different land use types and highlight variation in limnological processes in the whole ecosystem. Together, this information is used to consider the persistence of key aquatic species within this diverse aquatic setting.

Materials and Methods

Sampling

Two sets of samples were collected from a total of 29 canals and 8 lakes in 2000–2001 and 2004. During the 2000–2001 sampling season the whole system was divided into 211 canal sections 250 m in length (Hill 1971). By a simple randomization strategy, 19 sections were selected and the midpoint of each section was georeferenced with a GPS (Garmin GPS12XL) and served as the sampling site for water chemistry. This sampling design provided a representative area to evaluate the general environmental conditions of the entire system. The same sites were sampled twice: in the rainy season (from June to September 2000) and the dry season (from January to May 2001).

A second set of samples was obtained in June to September of 2004 with a different method of selecting sample sites. This selection was based on finding those places necessary to generate an interpolation map. This increased

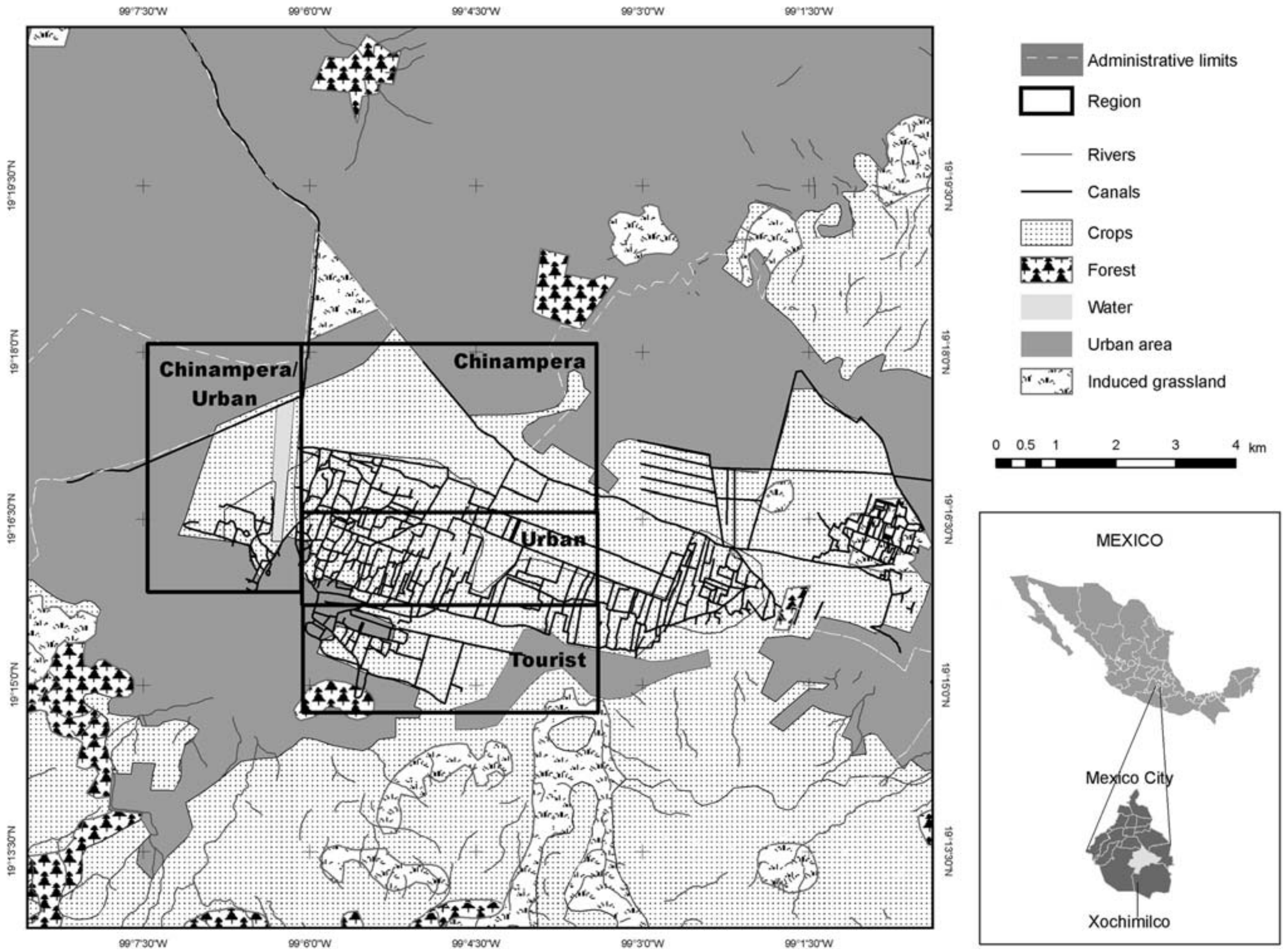

Fig. 1 Map of Xochimilco (light gray) showing the study areas

the number of sampling sites to 59, which included the previous 19. Sites were again georeferenced. Although both sets of samples had different numbers of sampling points, they shared most of the canals and most of the data collection techniques.

In both sets of samples, physicochemical measurements (conductivity as microsvedbergs per centimeter, pH, temperature as degrees centigrade, depth as meters, and dissolved oxygen as milligrams per liter) were done in situ with portable multiparametric equipment (YSI Model 6600). Turbidity was included only in the second set of samples.

Nutrient concentration sampling methods varied for each sampling set. In the first set of samples nitrate and ammonium concentrations in water were analyzed using a Corning electrode. In the second set of samples nutrient concentrations were determined immediately after collection of the water samples with a LaMotte SMART colorimeter. Nitrate was analyzed by zinc reduction, ammonium was obtained by Nesslerization, and phosphate was obtained following the ascorbic acid reduction method (APHA 1998).

Bacteriological Analyses

Bacteriological analyses were conducted during 2001 to characterize the distribution of fecal indicator bacteria. Five hundred-milliliter samples were collected in sterile polypropylene flasks. Water samples were analyzed following standard membrane filtration and incubation procedures (APHA 1998) to enumerate two bacterial types: fecal coliforms, as representative of gram-negative bacteria; and fecal streptococci, as representative of gram-positive bacteria. Membrane filters (0.45-μm cellulose acetate; Millipore MF type HA) were placed on a pad with M-FC for fecal coliforms and K-F agar for fecal streptococci (APHA 1998). For bacterial densities data were normalized with Box-Cox transformations (Sokal and Rohlf 1981). To ascertain the possible origins of bacteriological contamination the index of Geldrich and Kenner (1969) was used. Bacteriological samples were also compared to regulations for water utilized for irrigation purposes, which stipulate a maximum of 1000 CFU/100 ml of fecal coliforms (DDF 1975; Blumenthal and others

2000; DOF 2005). The Mexican water standards for conservation of freshwater aquatic life suggest the same levels (DOF 2004). To analyze fecal contamination origin we used the index of Toranzos and others (2007). A ratio >4 is characteristic of human fecal contamination; between 2 and 4, predominantly of human origin; between 0.7 and 2, predominantly of animal origin; <0.7, suggestive of animal waste. This index has been questioned due to differential die-off kinetics of the two bacterial groups, and the results should be viewed with caution (Toranzos and others 2007). However, it is useful in this case since it gives a general idea of the origin of bacterial contamination.

Physicochemical variables gave information on the living capabilities of organisms, while nutrient concentrations helped to clarify the trophic status of the water system. Finally, bacterial analysis gave information on water contamination and its potential sources.

Interpolation

Interpolation is a technique that converts a unique sample point value to a series of values that covers an area, using information from neighboring stations. To create an interpolated map of water chemistry, it was first necessary to build a polygon of the network morphology of Xochimilco. This network constrained the influence between near sampling points that were not interconnected by water (e.g., two neighborhood sampling points separated by a piece of land). The polygon was built from an aerial photograph (1:5,000 [Instituto de Geografia 2002]) with ESRI Arc View 3.2. Interpolations were generated with data from the second set of samples, using values of dissolved oxygen, turbidity, conductivity, ammonium, nitrate, and phosphate concentrations. Water flow in canals is very slow (<4 m/h), therefore we did not consider it in the interpolations. Interpolations produced a value for each variable on every pixel that represented canal areas within the aquatic system using the inverse distance-weighted interpolation technique with ESRI Arc Map 8.0. We assumed that the influence of one station decreases linearly with the distance between sampled points within 400 m (Dent and Grimm 1999). A power of eight was used to obtain the influence of this distance, giving higher weight to closer neighbors. The power was chosen using smoothness as a decision criterion.

We considered relationships between land use variables and water quality as a potential means of improving our interpolations. Three land use variables were obtained from INEGI (vegetation, human population densities, type of soil). These data were converted in raster format to standardize pixel sizes with ESRI Arc View 3.2. A total of 21 Pearson correlations were performed for the seven physicochemical parameters and three land use categories. Land use variables that were significantly correlated with any of the water quality variables were then considered in the interpolation model.

Ranking from Interpolation Values

To picture which regions have better water quality using data obtained from interpolations, it was necessary to standardize all variables. Therefore, values obtained for every pixel from the interpolations were placed in one of three categories based on the effect of each variable on water quality: (1) "suitable conditions," in which values of every variable were suitable for the survival and reproduction capacities of the native organisms (i.e., DO concentration >3 mg l^{-1}, nutrients at lower concentrations, and turbidity values close to zero); (2) "nonsuitable conditions," in which variables can be suitable for some organisms but not all of them (some of the native fish species would need higher DO concentrations, but other organisms such as amphibians would survive with these concentrations); and (3) "bad conditions," in which most of the native organisms are not able to survive (i.e., toxic concentrations or anoxic conditions). A simple division by three was not always appropriate for categorizing all variables. For instance, the lowest values of oxygen were assigned the highest rank values, while the same category was used for high concentrations of all nutrients and turbidity (Table 1). Although this ranking system can be considered subjective, it provides a broad regional view of water quality within a complex system that is readily understood by nonscientific stakeholders.

Ranking on turbidity was based on (1) clear water, where vertebrates and invertebrate can forage properly; (2) low turbidity, where visual predators experience reduced capability of prey intake; and (3) high turbidity, where visual predator foraging success is reduced almost to zero (Reid and others 1999; De Robertis and others 2003). Dissolved oxygen was divided into anoxic, hypoxic, and sufficient oxygen conditions. Nitrate and ammonium ranks were based on toxic concentrations of each variable (Cheng and Chen 2002; Camargo and others 2004). Since the lowest phosphate concentrations far exceeded any existing trophic status classification system, a modal curve in histogram analysis with number of pixels per value was used to define the ranking categories. This technique was also used for electrical conductivity values, assuming a positive relation between electrical conductivity and pollution (Valsanen and others 1998).

Analysis of Seasons and Years

To compare differences among variables between seasons and years, we standardized the data into two different sets of samples. The information obtained from the second set of

Table 1 Values for categorization of physicochemical data (see Methods)

Category	DO (mg l^{-1})	Turbidity (NTU)	Conductivity (μS cm^{-1})	NO_3–N (mg l^{-1})	NH_4–N (mg l^{-1})	PO_4–P (mg l^{-1})
1	0–1	0–40	0–65	0–5	0–1	0–3
2	1.1–3	41–70	66–93	5.1–10	1.1–1.6	3.1–7
3	>3.1	>71	>94	>10.1	>1.7	>7.2

Note: DO, dissolved oxygen. Category levels: 1 = more suitable conditions; 2 = less suitable conditions; 3 = bad conditions

samples was reduced to the 19 canals used in the first set of samples by averaging all values within each canal. Information obtained outside these canals was not used for this analysis. Using each canal as a unit, a paired *t*-test was used to identify differences between temporal changes (dry vs. wet season and between years) from the two data sets. To avoid Type I statistical error in making multiple comparisons of canals in this test, we used the Bonferroni adjustment.

Analysis of Regions

We divided the sampled area into four regions according to different human activities using satellite imagery and field observations (Fig. 1).

A. The *chinampera* region has 10 canals and 1 lake. This region supports traditional agricultural production in small square islands called *chinampas*. Production is less intensive and the area is not used for human settlement. The Xochimilco Ecological Park (PEX) is located within this region and contains an artificial wetland. Canals situated in the northeast of the region receive water from the rest of the system and sewage outflow toward the deep drainage system of Mexico City.
B. The *urban* region has seven canals and four lakes. This region has experienced legal and illegal urban development and intensive cropping systems based on greenhouses. Consequently, this region corresponds to a transition state between urbanized *chinampas* and modern agriculture, which relies on pesticides and chemical fertilizers.
C. The *tourist* region has six canals and two lakes. Economic activities of this region rely on tourism and intensive cropping systems. This region has been semiurbanized for a long time, but the rapid greenhouse development has promoted human settlements without any urban planning by the local or federal government.
D. The *chinampera/urban* region has six canals and one lake. This region also maintains the *chinampas* technique for production, but part of this region is immersed in an urban matrix. The network of canals is connected to the rest of the system by only one canal, possibly working as a bottleneck, reducing the water exchange with the other regions.

The first set of samples did not cover the complete study area, and therefore we only used the second set of samples to identify differences among the four regions. ANOVAs were used to find differences among the regions using interpolated data.

Results

General Description

Results demonstrate that Xochimilco is a heterogeneous shallow (<2.2-m maximum depth) aquatic system (Table 2). As a subtropical system >2200 meters above sea level (masl), temperatures were slightly lower during the dry season (but never below 11°C) compared to the rainy season (never <16°C), and the maximum was close to 20°C in both seasons. Turbidity varied from sites with virtually complete transparency (*Puente de Urrutia*) to highly turbid canals (*Paso del Aguila*). pH was circumneutral and slightly skewed to basic (between 6.8 and 8). Although canals in general are adequately oxygenated, anoxic conditions were present in some areas. Bacteriological results obtained in the first set of samples revealed contamination in 90% of the samples and high bacteriological counts were attributable to human and animal origin, as shown by the fecal coliforms/fecal enterococci index (Table 3).

Differences Between Years and Seasons

Depth differences between years were observed (shallower in the 2004 wet season compared to both seasons in 2001). Dissolved oxygen showed limited seasonality, with lower concentrations in the wet season, but it also differed between years. Other variables that showed a seasonal pattern included temperature and ammonium, with higher values during the dry season; electrical conductivity, with higher values in the wet season; and pH, with lower values in the wet season. Nitrate did not differ between seasons or years (Table 4).

Coliforms had significantly higher abundances in the dry season, while enterococci did not show any significant differences (Fig. 2). Bacteriological counts suggest a critical

Table 2 Average values for the sampled channels in both seasons

Canal	Depth (m)			Temperature (°C)			pH			Dissolved oxygen (mg l^{-1})		
	2000–2001		2004	2000–2001		2004	2000–2001		2004	2000–2001		2004
	Dry	Wet	Wet	Dry	Wet	Wet	Dry	Wet	Wet	Dry	Wet	Wet
Almoloya	0.76	0.70	0.60	18.80	11.20	20.86	7.02	8.61	7.72	1.40	11.00	4.19
Apatlaco	1.83	1.45	0.90	21.40	15.50	20.66	7.53	7.66	8.21	7.00	7.80	7.32
Atizapa	1.44	1.08	0.60	21.80	16.00	21.80	7.52	8.21	7.52	4.60	9.47	5.17
Cerca Draga	0.80	2.05	1.20	19.80	18.40	21.68	6.91	7.18	7.40	4.00	5.80	4.10
Compuerta	2.10	1.90	1.60	19.70	17.60	21.11	6.74	7.77	7.33	3.40	2.40	2.14
Comunidad	1.20	0.50	0.50	19.25	12.80	20.25	7.21	8.01	7.75	2.15	7.50	5.39
Costetexpa	1.10	1.07	0.60	19.20	15.30	19.68	6.97	6.79	7.24	1.00	1.80	1.59
Cuemanco	1.70	1.10	0.70	20.60	18.10	21.63	8.80	8.99	8.42	7.40	9.60	9.30
El Bordo	1.03	1.60	0.90	19.80	12.40	22.24	7.73	8.89	9.37	4.60	7.40	5.45
Japon	1.32	1.50	1.30	20.90	13.00	22.85	7.62	8.65	8.57	7.60	11.00	9.78
Nativitas	1.44	1.10	1.50	18.60	18.90	20.61	7.33	7.32	7.23	2.00	5.40	1.91
Paso de Aguila	1.08	1.00	0.60	19.02	14.30	22.45	6.88	8.34	8.19	1.40	11.00	8.92
Pizocoxpa	1.70	1.80	0.70	21.65	16.45	20.59	6.91	7.47	7.34	3.10	3.00	2.79
San Diego	1.10	0.40	0.90	20.00	15.60	19.46	7.30	7.38	7.26	0.80	3.40	4.51
Seminario	1.30	1.10	1.40	19.90	15.30	20.66	7.00	7.25	7.34	3.80	2.40	3.11
Tezhuillo	1.15	1.00	0.70	19.70	15.30	22.38	6.91	7.36	8.51	3.20	4.20	9.96
Tlilac	1.20	0.70	0.60	21.40	13.30	21.38	7.51	8.10	7.62	5.20	9.80	4.47
Urrutia	1.87	1.82	1.00	20.20	16.30	16.17	7.38	8.18	6.97	0.60	3.20	0.07
Xaltocan	1.00	1.00	0.50	20.00	17.30	20.83	6.82	6.69	7.87	5.40	9.00	6.18
Average	1.32	1.20	0.88	20.09	15.42	20.91	7.27	7.83	7.78	3.61	6.59	5.07
SD	0.37	0.48	0.35	0.97	2.16	1.47	0.48	0.68	0.62	2.22	3.29	2.91

Canal	Conductivity (μS cm^{-1})			NO_3–N (mg l^{-1})			NH_4–N (mg l^{-1})			Turbidity (NTU)	PO_4–P (mg l^{-1})
	2000–2001		2004	2000–2001		2004	2000–2001		2004	2004	2004
	Dry	Wet	Wet	Dry	Wet	Wet	Dry	Wet	Wet	Wet	Wet
Almoloya	939.0	713.0	704.0	29.12	0.62	5.76	4.57	5.73	2.32	50.30	10.20
Apatlaco	905.0	729.0	914.0	6.50	35.06	21.00	0.12	2.65	1.96	49.80	8.13
Atizapa	757.3	938.0	631.0	17.53	7.78	25.96	0.16	20.95	0.23	57.90	8.15
Cerca Draga	683.0	779.0	729.0	0.90	0.83	16.72	2.19	1.70	1.84	29.70	10.60
Compuerta	941.0	608.0	668.0	35.30	0.63	16.72	2.19	2.69	0.62	33.50	7.10
Comunidad	1360.5	715.0	693.0	14.52	13.74	2.77	2.43	3.16	0.31	52.40	10.20
Costetexpa	701.0	378.0	643.0	n.d	n.d	n.d	n.d	n.d	n.d	24.70	n.d
Cuemanco	467.0	791.0	716.0	2.50	6.76	12.85	0.17	1.81	0.61	26.90	8.60
El Bordo	1077.0	762.0	535.0	4.05	15.74	2.51	0.45	1.24	0.22	78.20	1.08
Japon	1035.0	710.0	706.0	46.31	34.56	7.92	1.93	0.02	1.24	33.30	6.70
Nativitas	985.0	678.0	672.0	36.27	0.60	60.00	1.00	11.48	1.60	21.00	10.80
Paso de Aguila	989.0	702.0	784.0	32.70	20.46	6.20	2.53	12.31	2.50	68.00	10.10
Pizocoxpa	633.5	724.0	664.0	22.90	29.38	11.44	0.41	0.87	2.34	49.00	8.40
San Diego	797.0	627.0	655.0	17.09	43.65	12.67	0.65	0.03	1.79	14.30	8.90
Seminario	688.0	850.0	757.0	6.72	9.43	7.74	1.52	16.95	1.61	25.00	11.10
Tezhuillo	783.0	706.0	805.0	5.20	15.52	8.18	0.04	11.48	1.91	44.90	7.60
Tlilac	1189.0	738.0	677.0	9.90	44.93	5.06	0.09	5.73	0.53	103.00	6.30
Urrutia	1127.0	740.0	943.0	16.31	14.48	8.93	0.68	2.78	1.56	6.10	9.20
Xaltocan	638.0	745.0	757.0	15.72	4.21	11.35	1.00	7.55	1.27	101.00	6.20

Table 2 continued

	Conductivity (µS cm^{-1})			NO_3–N (mg l^{-1})			NH_4–N (mg l^{-1})			Turbidity (NTU)	PO_4–P (mg l^{-1})
	2000–2001		2004	2000–2001		2004	2000–2001		2004	2004	2004
	Dry	Wet	Wet	Dry	Wet	Wet	Dry	Wet	Wet	Wet	Wet
Average	878.7	717.5	718.6	17.75	16.58	13.54	1.23	6.06	1.36	45.74	8.30
SD	224.8	109.7	95.7	13.36	14.92	13.15	1.21	6.15	0.76	26.96	2.38

Note: Wet: samples obtained in wet season. Dry: samples obtained in dry season. Turbidity and PO_4 were sampled only in the 2004 season

Table 3 Percentage of contaminated samples by animal or human origin, following Torranzos and others (2007)

Region	Canals sampled	Fecal contamination origin	
		Animal (%)	Human (%)
Chinampera	30	87	13
Urban	25	68	32
Tourist	14	50	50
Chinampera/urban	2	50	50

Table 4 Paired *t*-test for sampled canal (see Table 2)

Variable	Season/year	*t* value	*P*
Depth	Dry 2001 vs. wet 2001	1.12	n.s.
	Wet 2001 vs. wet 2004	4.70	<0.01
	Dry 2001 vs. wet 2004	3.29	<0.01
Temperature	Dry 2001 vs. wet 2001	8.79	<0.01
	Wet 2001 vs. wet 2004	−2.11	n.s.
	Dry 2001 vs. wet 2004	−8.46	<0.01
Conductivity	Dry 2001 vs. wet 2001	2.74	n.s.
	Wet 2001 vs. wet 2004	2.89	<0.01
	Dry 2001 vs. wet 2004	−0.03	n.s.
Dissolved oxygen	Dry 2001 vs. wet 2001	−4.34	<0.01
	Wet 2001 vs. wet 2004	−2.60	n.s.
	Dry 2001 vs. wet 2004	2.44	n.s.
pH	Dry 2001 vs. wet 2001	−4.74	<0.01
	Wet 2001 vs. wet 2004	−3.73	<0.01
	Dry 2001 vs. wet 2004	0.36	n.s.
NO_3–N	Dry 2001 vs. wet 2001	0.25	n.s.
	Wet 2001 vs. wet 2004	1.12	n.s.
	Dry 2001 vs. wet 2004	0.57	n.s.
NH_4–N	Dry 2001 vs. wet 2001	−3.19	<0.01
	Wet 2001 vs. wet 2004	−0.44	n.s.
	Dry 2001 vs. wet 2004	3.17	<0.01

Note: n.s., not significant

period during the dry season, as 72% of the samples had bacterial counts higher than the WHO and Mexican standards recommended for irrigation water. During the rainy season, only 43% of the samples exceeded these standards, and bacteria from human sources were reduced to 27% in all samples, leaving higher proportions to animal origins.

Spatial Variation

There were no significant correlations between land use and water quality, as the highest correlation coefficient (r) was <0.43. Variable interpolations demonstrated variability at relatively small spatial scales within canals (see the Appendix). Turbidity values were generally higher in the northern and western areas, while high-conductivity waters were distributed in the western and central areas. Oxygen had a relatively homogeneous distribution (values >3 mg l^{-1}), except in the southern and western areas, where canals were anoxic. Phosphate concentration was higher in the central-western region, ammonium was higher in the central and western areas, and nitrate was highest in the southern region.

The *chinampera* region was significantly more turbid (75.7 NTU on average) than the other regions (urban = 40.5, tourist = 47.2 and *chinampera*/urban = 46.0) (see Fig. 3). Ammonium (average [avg] = 1.9 mg l^{-1}) and bacterial counts (avg = 10.3 tranformed Box-Cox) were significantly higher in the urban region than in the other three regions (ammonium avg—*chinampera* = 0.9 mg l^{-1}, tourist = 1.5 mg l^{-1}, and *chinampera*/urban = 1.33 mg l^{-1}; bacterial count avg—*chinampera* = 2.8, tourist = 7.5, transformed Box-Cox). The tourist region had the highest nitrate concentration (avg = 22.2 mg l^{-1}, vs *chinampera* = 7.7 mg l^{-1}, urban = 10.0 mg l^{-1}, and *chinampera*/urban = 6.9 mg l^{-1}). Finally, the *chinampera*/urban region had the highest conductivity (avg = 1.0 µS cm^{-1}) (Fig. 3). There were no significant differences in DO (avg: *chinampera* = 6.8 mg l^{-1}, urban = 5.8 mg l^{-1}, tourist = 3.4 mg l^{-1}, *chinampera*/urban = 3.9 mg l^{-1}) and phosphate (avg: *chinampera* = 7.2 mg l^{-1}, urban = 9.3 mg l^{-1}, tourist = 8.0 mg l^{-1}, *chinampera*/urban = 10.4 mg l^{-1}) among regions.

Ranks of Physicochemical Variables

Categorical ranks of physicochemical data demonstrated that most canals had intermediate water quality (lighter areas in Fig. 4). Very few canals were in bad condition

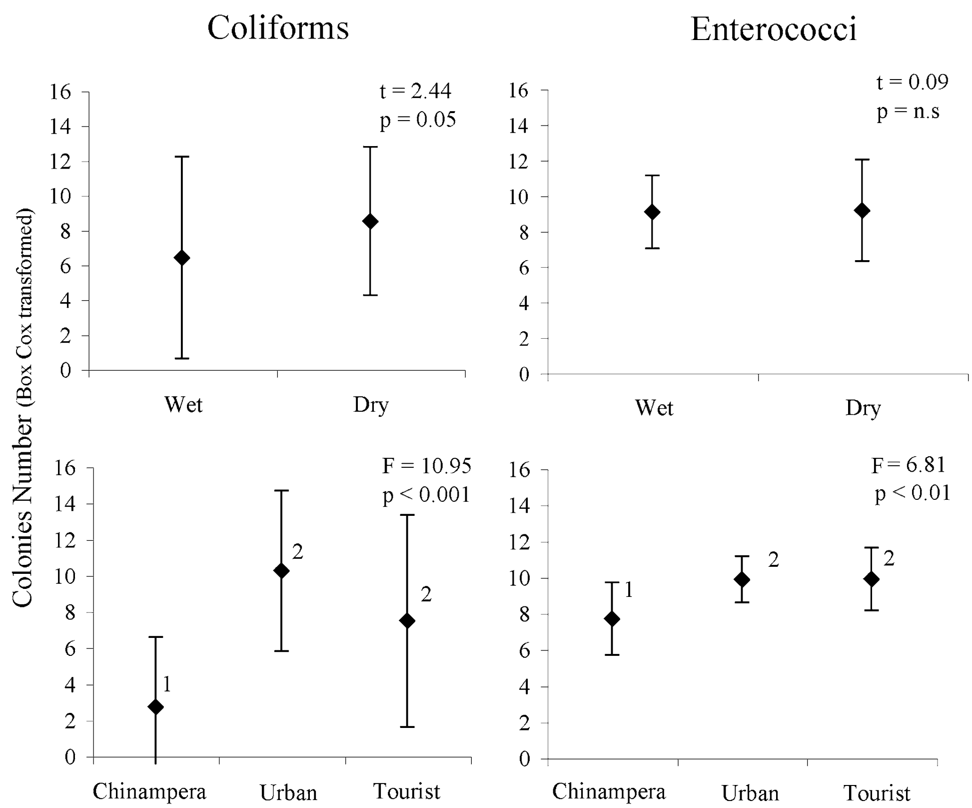

Fig. 2 Average bacteriological densities for two seasons, using a Box-Cox transformation. Different numbers (1 and 2) in region comparison indicate significant differences in Tukey multiple-comparison tests

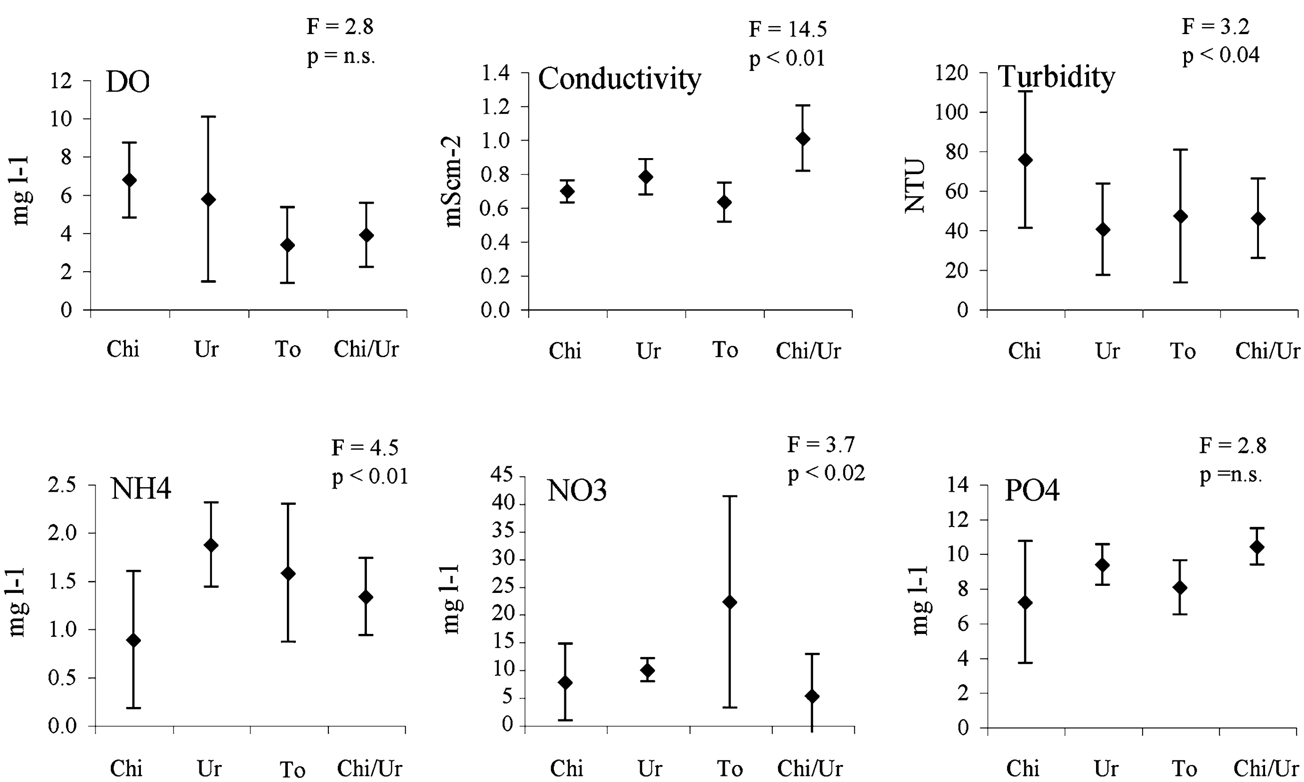

Fig. 3 Average of the variables in the four regions with standard deviation (see Fig. 2). Letters over the variable indicate significant differences in Tukey multiple-comparison tests. Chi, *Chinampera*; Ur, urban; To, tourist

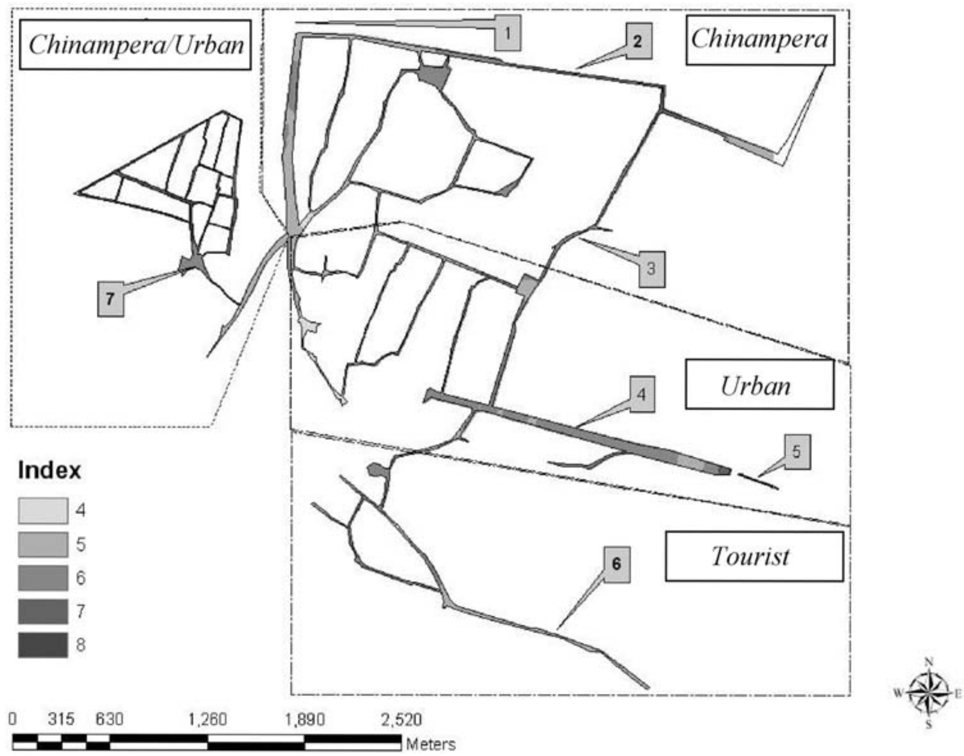

Fig. 4 Sum of the physicochemical variables to produce a partial quality index (see Methods and Table 1). Lower values in the index give best water quality conditions. (1) Ecological Park (PEX); (2) *El Bordo* canal; (3) *Paso del Aguil*a canal; (4) *Apatlaco* canal; (5) *Puente de Urrutia* canal; (6) *Santa Cruz* canal; (7) *Laguna del Toro* lake

(darker areasin Fig. 4). Based on these variables, the central region (urban) and the southern region (tourist) had better water conditions. In contrast, the poorest water quality conditions were present in the western region (*chinampera/*urban). Electrical conductivity and turbidity were elevated in most regions, therefore they were responsible for high index values.

Ranking Nutrient Variables

The sum of nutrient values showed lower quality conditions in the central (urban) and southern (tourist) region, while better quality conditions were distributed in the north (*chinampera*) (Fig. 5). All of the variables seemed to have equal influence on the sum of all ranked nutrient variables. Most places with higher bacterial counts, and therefore poor water quality, also had elevated nutrient concentrations.

Ranking all Variables

Ranked data from all variables in the map showed a mosaic of suitable and poor (inadequate) water quality conditions (Fig. 6). Canals classified as less suitable and bad were concentrated in the tourist region. The *chinampera* region had the lowest total index values, suggesting that this is the best water quality region, followed by the *chinampera/* urban region. The other two areas had lower quality conditions, the worst being the urban region, followed by the southern tourist region. Urban and tourist regions were mainly influenced by high nutrient conditions, whereas the *chinampera/*urban region had scores were influenced mainly by physicochemical conditions (Table 5).

Discussion

On average, nutrient concentrations are extremely high in the Xochimilco ecosystem compared to other natural systems. The lowest phosphorous value is higher than any value classification for a hypereutrophic system; average nitrate and ammonium concentrations exceeded maximum concentrations observed in agricultural streams and rivers in the Midwestern United States (Goolsby and Battaglin 1999; Stanley and Maxted 2008) and far exceed he WHO drinking water recommendation of 10 mg N/L. These high nutrient concentrations are clearly the consequence of the substantial human influence that has persisted for many years. High bacterial count values are also an indicator of this ecosystem deterioration. The fact that human fecal forms can represent as much as 50% of the total counts suggests a substantial influence of domestic sewage on the water quality.

Spatial Heterogeneity

The transition in measured values between traditional land use and periurban development is noticeable in spatial patterns present along the canals. Turbid, but with low nutrient concentrations, canals in the *chinampera* region

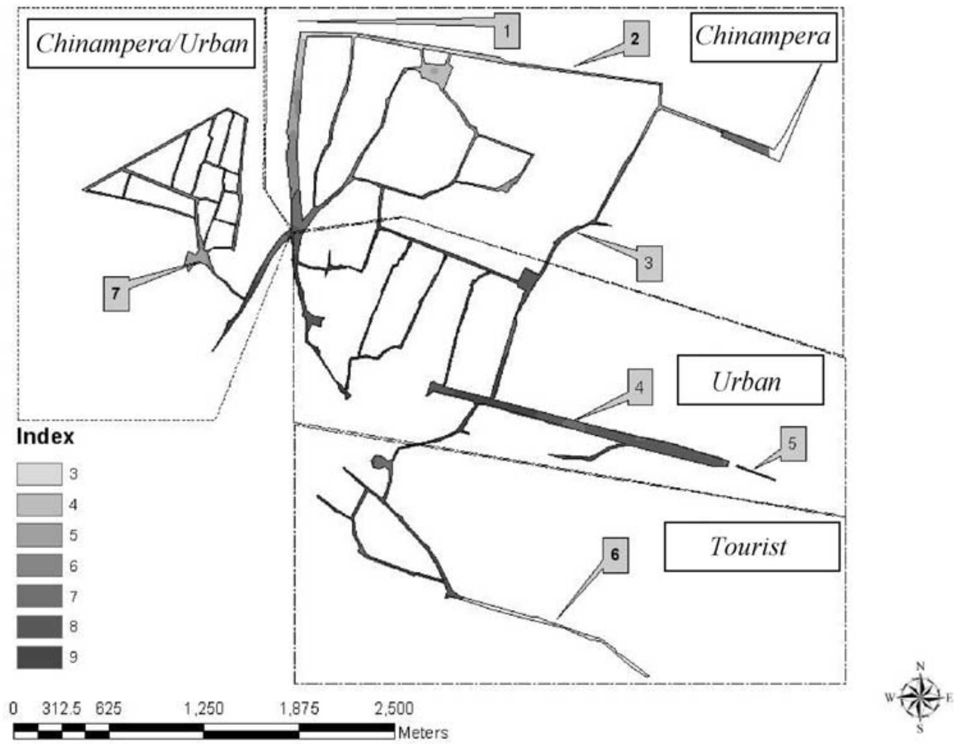

Fig. 5 Sum of the nutrient variables to get the water quality index (see Methods and Table 1). Lower values in the index give the best water quality conditions. (1) Ecological Park (PEX); (2) *El Bordo* canal; (3) *Paso del Aguil*a canal; (4) *Apatlaco* canal; (5) *Puente de Urrutia* canal; (6) *Santa Cruz* canal; (7) *Laguna del Toro* lake

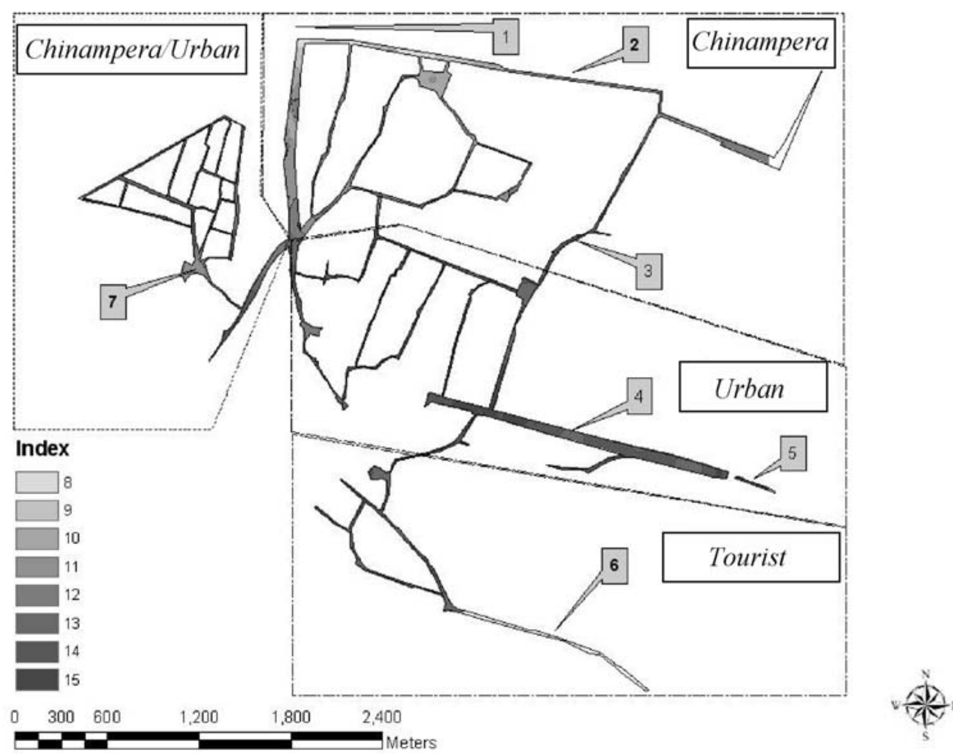

Fig. 6 Sum of the nutrients and physicochemical variables together (see methods and Table 1). Lower values in the index gives best water quality conditions. (1) Ecological Park (PEX); (2) *El Bordo* canal; (3) *Paso del Aguil*a canal; (4) *Apatlaco* canal; (5) *Puente de Urrutia* canal; (6) *Santa Cruz* canal; (7) *Laguna del Toro* lake

contrast with those in the neighboring urban region, which has a lower turbidity and higher nutrient concentrations. These variables maintained their values in the two study seasons, suggesting that permanent factors such as land use have a local influence on the water quality in each region.

Land use is not the only possible cause of water quality heterogeneity; physical barriers can play a role in this variability. For example, in the *chinampera*/urban region, substantial hydrologic isolation could determine its physicochemical character of high conductivity and phosphate concentration.

Table 5 Regional average (avg) for each variable using data obtained from the interpolation

Region	DO (mg l^{-1})		Turbidity (NTU)		Conductivity (μS cm^{-1})		NO_3–N (mg l^{-1})		NH_4–N (mg l^{-1})		PO_4–P (mg l^{-1})	
	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg	SD
Chinampera	6.78	2.30	68.90	29.79	0.70	0.08	6.97	3.67	0.77	0.50	6.32	3.00
Urban	7.13	2.99	45.58	21.72	0.85	0.10	9.64	3.67	1.97	0.31	8.84	1.03
Tourist	2.86	1.07	39.57	19.49	0.67	0.03	23.42	14.58	1.28	0.34	7.93	1.24
Chinampera/urban	3.72	1.21	49.49	14.24	1.02	0.13	3.03	4.50	1.22	0.27	10.04	0.90

High nutrient concentrations in a shallow system with an average temperature close to 19°C throughout the year (unpublished data) allow for high rates of primary production. Such high productivity can be associated with a variety of different biogeochemical and food web dynamics (Mallin and others 2006), producing many paths of energy flow within a small-scale area. For example, high productivity increases water turbidity, which can modify the food web reliance on benthic to pelagic organisms within a few hundred meters (Zambrano and others 2008). Therefore, an analysis based on point samples would create difficulties in interpretation, and a broader-scale framework is necessary for understanding the limnological dynamic within this system.

Interpolation Technique

Interpolations helped to generate a two-dimensional picture of water chemical dynamics in the Xochimilco freshwater system. These interpolations can shed light on both pattern and process in this intricate aquatic system. Different interpolation methods were considered here. The lack of relationship between physicochemical variables and land use variables indicated the presence of other factors affecting water quality at smaller spatial scales (e.g., heavy boat traffic, nontreated sewage discharges, and strong localized agriculture and urban influences). Therefore, it was not possible to use extrapolation of land use variables to predict water quality. Also, a Krigging method was tested but required more data to produce reliable results (Kravchenko 2003). The inverse distance-weighted method used here is simpler than others, but the interpolation method used was based on the assumption that there is a linear relationship among sampling points for all chemical variables, as shown by Dent and Grimm (1999). Therefore, this method seems to be accurate enough to achieve our goal of developing a general pattern for this complicated system.

Water Quality Index

Generating an index based on environmental and biological variables, such as the Index of Biological Integrity, has been a common practice for evaluating ecosystem health (Wang and others 2001). In a wider analysis, it is possible to obtain information using all variables together to generate a composite value. This is particularly useful in systems in which variables are not related and therefore each individual variable cannot fully represent ecosystem status. For example, high nutrient concentrations do not necessarily result in large algal populations in shallow systems (Zambrano and others 2001). Food web factors such as top-down control (Carpenter and others 1985) could generate a stable clear-water system with high nutrient concentrations (Scheffer and others 2001). Consequently, different variables apart from nutrient concentrations must be considered to understand the trophic status (Strobl and others 2007). In Xochimilco, the oxygen concentration is sufficient to support resident biota in the whole ecosystem, but there are regions in which ammonium concentrations are often at levels considered toxic for fish (Wetzel 2001). A single index value that incorporates all these variables can be a simple, effective means of providing qualitative information about overall water suitability.

Because it is not possible to add data that have different unit scales, ranking different variables allowed us to sum the categories for each variable and derive a map of more suitable, less suitable, and bad conditions. The categorization also helps to simplify a description of the spatial conditions. While the ranking reduces the opportunity to understand the dynamics and processes driving each variable, the information is easier to interpret and use for resource managers and other stakeholders. Since the index gives spatial information within a map, it is possible to visualize specific activities in regions and relate them to water quality. For instance, the effect of an industrial corridor on water quality in the surrounding regions and its consequences on organisms' distribution or human health in the neighborhood can easily be visualized using this simple, spatially explicit index method.

We were able to use this index to describe the water quality of a complex ecosystem such as Xochimilco and relate it to human activities. The *chinampera* region has the highest water quality values, but they are not homogeneous, improving in the northern part closer to the PEX and being reduced along the urban region border. Index values can be related to its proximity to the artificial wetland in the reserve area and to the traditional (low nutrient) agriculture activity. This is also complemented by measures of low bacteriological density. The second-best-preserved area, *chinampera/*urban, also includes the *chinampas* farming technique, but the urban matrix in which it is immersed possibly reduces its water quality index values, which are higher in areas away from human settlements such as Laguna del Toro. The second-worst conditions lie in the tourist region, which has been urbanized, but has also experienced rapid greenhouse development, which may increase nutrient concentrations (mainly nitrate) (López and others 2006; Méndez 2006), in the northern area. The urban region, with the lowest ranking values, has been exposed to sewage going directly to canals (personal observation), a product of intensive illegal urban development and greenhouses that are spread throughout the entire region. This results in homogeneous, low water quality values in all the canals and lakes. It also may explain the high ammonium values in most canals, which are further exacerbated by added agrochemicals and manure from cattle and pigs produced by nonregulated agricultural activities. Higher bacterial densities in the water also match this information.

The index also makes it possible to identify those variables that have the greatest influence on water quality within each region. By separating each standardized variable on a map (see the Appendix), it is possible to weight their contribution to the final results. In this case, the sum of all nutrients seems to determine most of the areas with higher index values. Within nutrient concentrations, it is also possible to evaluate which elements produce spatial heterogeneity. Here, even when phosphate caused high index values in three of the four areas, ammonium and nitrate were responsible for differences among regions in the final calculation. Inverse patterns arise from the spatial variation of these two nitrogen forms. While ammonium was the major determinant of the sum ranks for the central area, nitrate was the key variable in the southern area.

This index is also useful when analyzing species distribution patterns. The group of variables that we used to form our water quality index is related to the survival capacity of aquatic biota in the system. High heterogeneity in water quality may produce local differences in the survival capacity of both native and exotic organisms (Contreras 2006). A species' distribution may be restricted to isolated areas of suitable water quality (personal observation). Furthermore, food web structure may differ dramatically among regions because of distinct biogeochemical processes associated with contrasting water quality (Zambrano and others 2008). Therefore, future research must try to clarify the consequences of spatial heterogeneity in water quality for native species in Xochimilco. Such an analysis may suggest areas more suitable for aquatic restoration and conservation of native organisms such as the axolotl and native fish based on increasing patch size and connectivity of areas with sufficient water quality.

Conclusions

Human influence is capable of modifying the water quality of freshwater environments in different regions, producing aquatic ecosystems with pronounced small-scale spatial heterogeneity. Such heterogeneity makes point-based data more difficult to understand. The sum of the water quality ranks index has been a useful approach for comparing conditions among different regions within a complex, interconnected ecosystem with many activities and variables that influence its dynamics. These variables are related to diverse ecological, economic, agricultural, and social issues, and therefore there are multiple causes of water quality changes in each region. An index representing the status of the water quality spatially is intended to allow decision makers to relate ecosystem health to human activities.

Despite the fact that Xochimilco is listed in RAMSAR and UNESCO World Heritage, its water quality is remarkably poor, and it clearly needs active management to allow persistence of native species and human use of the water. Information provided by this index can generate possibilities for a better management strategy of the entire water system. Some of these actions seem quite obvious, such as prohibiting the discharge of wastewater without adequate treatment. But other activities present more difficult management challenges, such as the influence of agricultural nutrients on the aquatic ecosystem. Traditional agriculture methods seem to be extremely efficient and possibly have limited ecological effects on the system. However, to increase the use of these agricultural practices, they must be linked to economic incentives to make them feasible. We hope that this type of approach will assist decision makers in managing and sustaining the ecosystem.

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Appendix

Geographical Interpolation of Each Abiotic Variable Within Xochimilco Canals and Lakes Fig A1.

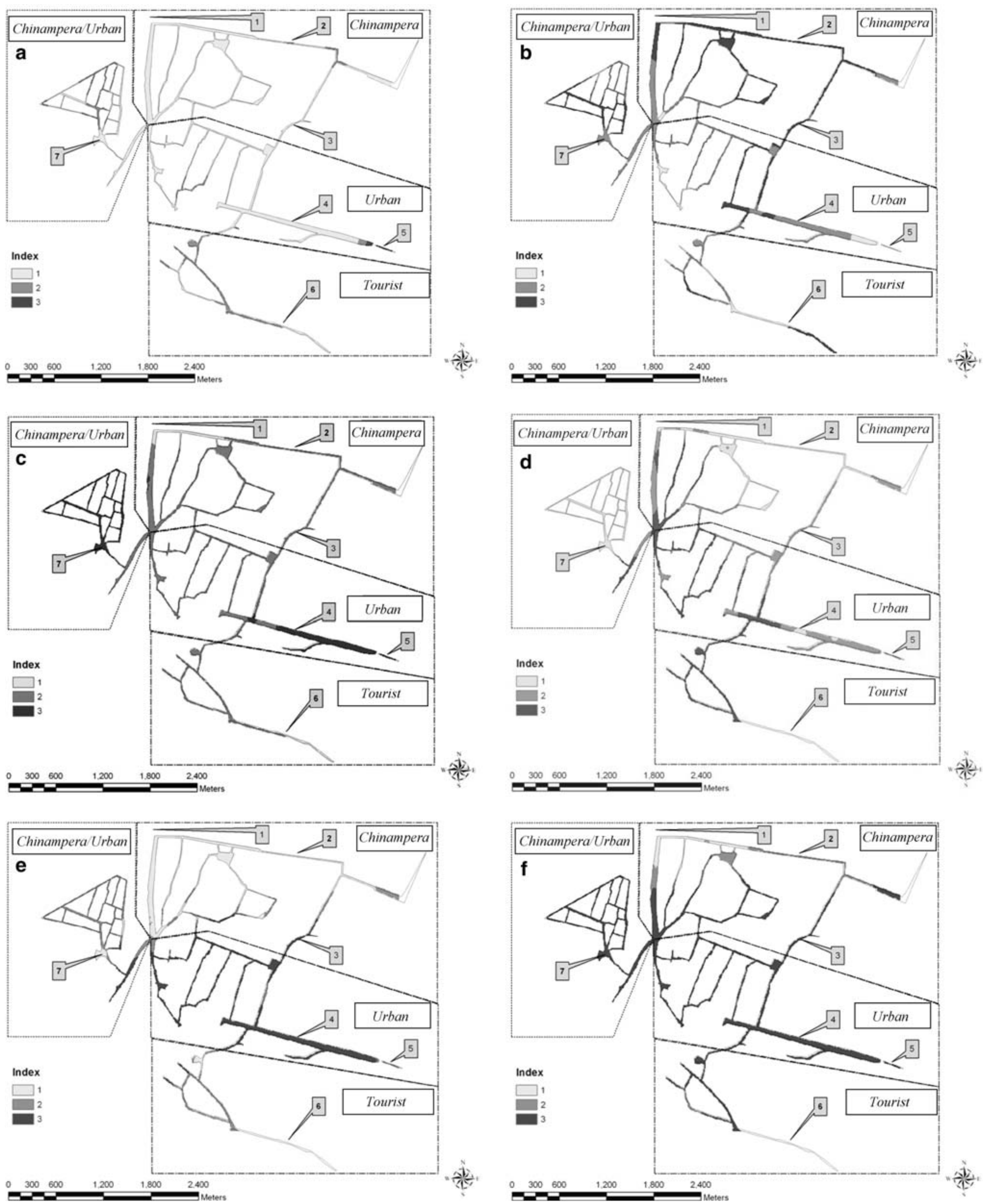

Fig. A1 Interpolations from physicochemical and nutrient variables, using the index built based on more suitable to less suitable categories. Higher values (darker regions on the map) give less suitable conditions of the water quality based on each variable: (**a**) dissolved oxygen; (**b**) turbidity; (**c**) electrical conductivity; (**d**) nitrate concentration; (**e**) ammonium concentration; (**f**) phosphate concentration. Numbers relate to the name of the canals or areas: (1) ecological park (PEX); (2) *El Bordo* canal; (3) *Paso del Aguil*a canal; (4) *Apatlaco* canal; (5) *Puente de Urrutia* canal; (6) *Santa Cruz* canal; (7) *Laguna del Toro* lake

References

APHA, American Water Works Association, Water Environment Federation (1998) Standard methods for the examination of water and wastewater, 20th edn. APHA, Washington, DC

Blumenthal UJ, Mara DD, Peasey A, Ruiz-Palacios G, Stott R (2000) Guidelines for the microbiological quality of treated wastewater used in agriculture: recommendations for revising WHO guidelines. Bulletin of the World Health Organization 78:1104–1116

Brooks SS, Palmer MA, Cardinale BJ, Swan CM, Ribblett S (2002) Assessing stream ecosystem rehabilitation: limitations of community structure data. Restoration Ecology 10:156–168

Brown BL (2003) Spatial heterogeneity reduces temporal variability in stream insect communities. Ecology Letters 6:316–325

Camargo JA, Alonso A, Salamanca A (2004) Nitrate toxicity to aquatic animals: a review with new data for freshwater invertebrates. Chemosphere 58:1255–1267

Carpenter S, Kitchell J, Hodgson JR (1985) Cascading trophic interactions in a lake productivity. Bioscience 35:634–639

Cheng S-Y, Chen J-C (2002) Study on the oxyhemocyanin, deoxyhemocyanin, oxygen affinity and acid-base balance of *Marsupenaeus japonicus* following exposure to combined elevated nitrite and nitrate. Aquatic Toxicology 61:181–193

Comin FA, Romero JA, Hernandez O, Menendez M (2001) Restoration of wetlands from abandoned rice fields for nutrient removal, and biological community and landscape diversity. Restoration Ecology 9:201–208

Contreras REAV (2006) Distribución potencial del *Ambystoma mexicanum* en los canales de la zona chinampera de Xochimilco. Universidad Nacional Autonoma de Mexico, Mexico, DF

DDF (Departamento del Distrito Federal) (1975) Memoria de las obras del sistema de drenaje profundo del Distrito Federal. Talleres Gráficos de la Nación

Dent CL, Grimm NB (1999) Spatial heterogeneity of streamwater nutrient concentrations over successional time. Ecology 80:2283–2298

De Robertis A, Ryer HC, Veloza A, Brodeur RD (2003) Differential effects of turbidity on prey consumption of piscivorous and planktivorous fish. Canadian Journal of Fisheries and Aquatic Sciences 60:1517–1526

DOF (Departamento del Distrito Federal) (2004) Ley Federal de Derechos. Disposiciones aplicables en materia de aguas nacionales. GDF, México

DOF (Departamento del Distrito Federal) (2005) Capitulo VIII Agua. Ley Federal de Derechos, México, DF, pp 183–190

Douterelo I, Perona E, Mateo P (2004) Use of cyanobacteria to assess water quality in running waters. Environmental Pollution 127:377–384

Dufour A, Gadallah F, Wagner HH, Guisan A, Buttler A (2006) Plant species richness and environmental heterogeneity in a mountain landscape: effects of variability and spatial configuration. Ecography 29:573–584

Engstroem-Oest J, Candolin U (2007) Human-induced water turbidity alters selection on sexual displays in sticklebacks. Behavioral Ecology 18:393–398

Geldrich E, Kenner BA (1969) Comments on fecal streptococci in stream pollution. Journal of Water Pollution Control Federation 41:336–341

George DG, Talling JF, Rigg E (2000) Factors influencing the temporal coherence of five lakes in the English Lake District. Freshwater Biology 43:449–461

Goolsby DA, Battaglin WA (1999) Long-term changes in the concentration and flux of nitrogen in the Mississippi River Basin, USA. Hydrological Processes 15:1209–1222

Gundale MJ, Metlen KL, Fiedler CE, DeLuca TH (2006) Nitrogen spatial heterogeneity influences diversity following restoration in a ponderosa pine forest, Montana. Ecological Applications 16:479–489

Guo Z, Li Y, Gan Y (2003) Spatial pattern of ecosystem function and ecosystem conservation. Environmental Management 32:682–692

Harper D (1992) Eutrophication of freshwaters. Principles, problems and restoration. Chapman and Hall, New York

Hill B (1971) Principles of medical statistics. Oxford University Press, New York

Instituto de Geografia, Universidad Nacional Autónoma de México (2002) Fotomosaico escala 1:5000. Mexico

Kemka N, Njine T, Togouet SHZ, Menbohan SF, Nola M, Monkiedje A, Niyitegeka D, Compere P (2006) Eutrophication of lakes in urbanized areas: the case of Yaounde Municipal Lake in Cameroon, Central Africa. Lakes & Reservoirs: Research and Management 11:47–55

Kravchenko AN (2003) Influence of spatial structure on accuracy of interpolation methods. Soil Science Society of American Journal 67:1564–1571

López A, Guerrero M, Hernández C, Aguilar A (2006) Rehabilitación de la zona chinampera. In: Carballo C (ed) Xochimilco. Un proceso de gestión participativa. GDF-UNESCO, México, pp 201–218

Mallin MA, Johnson VL, Ensign SH, MacPherson TA (2006) Factors contributing to hypoxia in rivers, lakes, and streams. Limnology and Oceanography 51:690–701

Matejicek L, Engst P, Janour Z (2006) A GIS-based approach to spatio-temporal analysis of environmental pollution in urban areas: a case study of Pragues environment extended by LIDAR data. Ecological Modelling 199:261–277

Muhando CA, Kuguru BL, Wagner GM, Mbije NE, Oehman MC (2002) Environmental effects on the distribution of Corallimorpharians in Tanzania. Ambio 31:558–561

Méndez A (2006) Rehabilitación de la zona chinampera. In: Carballo C (ed) Xochimilco. Un proceso de gestión participativa. GDF-UNESCO, México, pp 219–221

Nienhuis P, Bakker J, Grootjans A, Gulati R, de Jonge V (2002) The state of the art of aquatic and semi-aquatic ecological restoration projects in the Netherlands. Hydrobiologia 478:219–233

Reid SM, Fox M, Whillans T (1999) Influence of turbidity on piscivory in largemouth bass (*Microptherus salmoides*). Canadian Journal of Fisheries and Aquatic Sciences 56:1362–1369

Robinson CT, Tockner K, Ward JV (2002) The fauna of dynamic riverine landscapes. Freshwater Biology 47:661–677

Scheffer M, Rinaldi S (2000) Minimal models of top-down control of phytoplankton. Freshwater Biology 45:265–283

Scheffer M, Carpenter S, Foley RJA, Walker B (2001) Catastrophic shifts in ecosystems. Nature 413:591–596

Shivoga WA, Muchiri M, Kibichi S, Odanga J, Miller SN, Baldyga TJ, Maina-Gichaba C (2006) Impacts of upland land use on downstream water quality in River Njoro Watershed, Kenya. In: Proceedings of the 11th International Conference and the Conservation and Management of Lakes, vol II, pp 472–476, 31 October to 4 November. Nairobi, Kenya

Sokal RR, Rohlf FJ (1981) Biometry. The principles and practice of statistics in biological research. W.H. Freeman, New York

Strobl RO, Forte F, Pennetta L (2007) Application of artificial neural networks for classifying lake eutrophication status. Lakes & Reservoirs: Research and Management 12:15–25

Stanley E H, Maxted JT (2008) Changes in the dissolved nitrogen pool across land cover gradients in Wisconsin streams. Ecological Applications 18:1579–1590

Toranzos GA, McFeters GA, Borrego JJ, Savill AM (2007) Detection of microorganisms in environmental freshwaters and drinking waters. In: Hurst CJ, Crawford RL, Garland JL, Lipson DA,

Mills AL, Stetzenbach LD (eds) Manual of environmental microbiology. ASM Press, Washington, DC, pp 249–264
Tveito OE, Bjorad I, Skjelvag AO, Une BA (2005) A GIS-base agro-ecological decision system based on gridded climatology. Meterological Application 12:57–68
UNESCO (2006) Water, a shared responsibility. Bergham Books, New York
Valsanen U, Misund A, Chekushin V (1998) Ecogeochemical investigation: stream water quality as an indicator of pollution in the border areas of Finland, Norway and Russia. Water Air and Soil Pollution 104:205–219
Wang LZ, Lyons J, Kanehl P (2001) Impacts of urbanization on stream habitat and fish across multiple spatial scales. Environmental Management 28:255–266
Wetzel R (2001) Limnology. Lake and river ecosystems. Academic Press, San Diego, CA
Zambrano L, Scheffer M, Martinez-Ramos M (2001) Catastrophic response of lakes to benthivorous fish introduction. Oikos 94:344–350
Zambrano L, Valiente E, Vander Zanden MJ (2008) Spatial variation in food web structure of a highly heterogeneous freshwater system: role of nutrient enrichment and species introductions (submitted for publication)