Bulletin of the Southern California Academy of Sciences

Volume 104 | Issue 1 Article 1

2005

Biological Assessment of Tecate Creek (U.S.–Mexico) with Special Regard to Self-Purification

Volker Lu¨deritz

Frauke Gerlach

Robert Ju¨pner

Jesus Calleros

Jerome Pitt

See next page for additional authors

Recommended Citation

Lu¨deritz, Volker; Gerlach, Frauke; Ju¨pner, Robert; Calleros, Jesus; Pitt, Jerome; and Gersberg, Richard M. (2005) "Biological Assessment of Tecate Creek (U.S.–Mexico) with Special Regard to Self-Purification," *Bulletin of the Southern California Academy of Sciences*: Vol. 104: Iss. 1.
Available at: https://scholar.oxy.edu/scas/vol104/iss1/1

Biological Assessment of Tecate Creek (U.S.–Mexico) with Special Regard to Self-Purification

Authors

Volker Lu¨deritz, Frauke Gerlach, Robert Ju¨pner, Jesus Calleros, Jerome Pitt, and Richard M. Gersberg

Bull. Southern California Acad. Sci.
104(1), 2005, pp. 1–13

Biological Assessment of Tecate Creek (U.S.–Mexico) with Special Regard to Self-Purification

Volker Lüderitz,[1] Frauke Gerlach,[1] Robert Jüpner,[1] Jesus Calleros,[2]
Jerome Pitt,[2] and Richard M. Gersberg[2]*

[1]*University of Applied Sciences Magdeburg, Department of Water Resources Management, Breitscheidstr. 2, D—39114 Magdeburg, Germany*
[2]*San Diego State University, Graduate School of Public Health, 5500 Campanile Drive, San Diego, California 92182/4162, USA*

Abstract.—Macroinvertebrate organisms were sampled at four sites on Tecate Creek (U.S.–Mexico) and quantitatively evaluated using the SIGNAL-w (Stream Invertebrate Grade Number—Average Level-weighted) index. A morphological assessment of the stream structure was also carried out. Bioindication by SIGNAL reflected a very low water quality in the upper three sampled stream reaches, but with a significant improvement by the last site on the Rio Alamar, but only to a grade of critical to high pollution over a flowing distance of 29 km. Levels of BOD and ammonium-N at the Rio Alamar (Toll Bridge) site remained quite high, 56 mg/L and 48 mg/L, respectively. Metal levels also generally decreased as the water flowed downstream to the the Rio Alamar. Despite the fact that Tecate Creek has a quite natural morphological structure, solid inorganic surfaces and aquatic macrophytes (as settlement area) are mostly absent in Tecate Creek. This lack of stable habitats prevents the development of an effective biofilm which would significantly enhance self-purification.

The Tijuana River Watershed (TRW) is a binational watershed on the U.S.–Mexico border, encompassing much of the cities of Tijuana and Tecate in Mexico and portions of the City and County of San Diego in the U.S. The basin contains three surface water reservoirs, various flood control works, and a National Estuarine Sanctuary in the U.S. which is home to several endangered species. For decades, raw and poorly treated sewage from the cities of Tijuana and Tecate, Mexico has flowed into the Tijuana River and across the international border into the United States. Pollution in Mexico has been caused by rapid population growth and urbanization, poor land-use practices, and inadequate sewage treatment and collection facilities in the watershed (Ganster 1996). A fast growing aspect of industry near the border has been the ‘‘maquiladoras.’’ The term ‘‘maquiladora’’ refers to an industry established under a special customs allowance, mostly non-Mexican operations to establish manufacturing plants in Mexico that are allowd to import duty-free raw materials, equipment machinery, and replacement parts (Turner et al. 2003). The maquiladora industry, fueled primarily by foreign investment, has grown faster than the capability of the municipality to deliver services to them. Moreover, the lack of pollution prevention measures for industry and other businesses in Mexico, coupled with a deficiency in proper

---

* Corresponding author: rgersber@mail.sdsu.edu

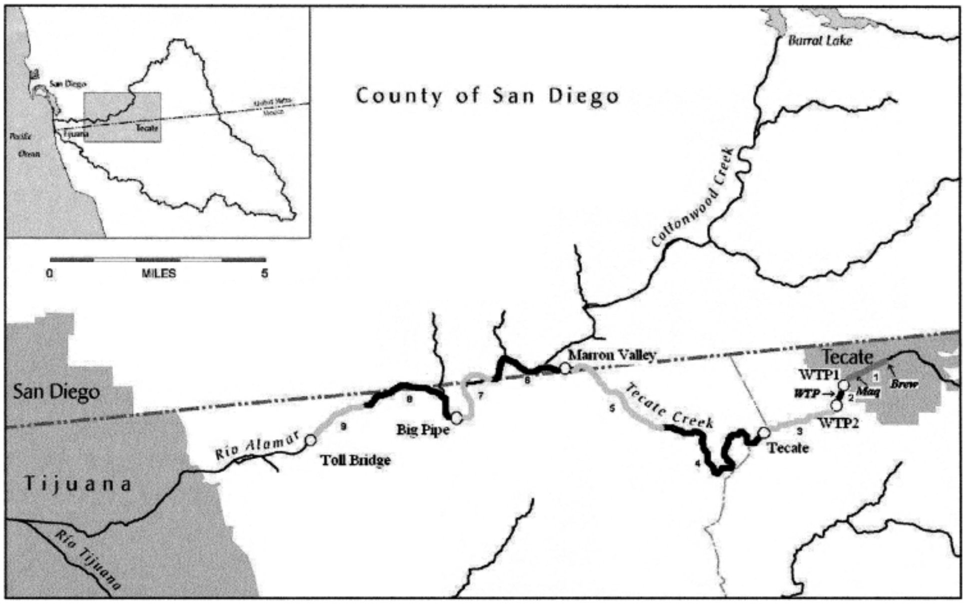

Fig. 1. Map of sampling sites (denoted by open circles) on Tecate Creek and the Alamar River. Shaded (both light and dark) sections of stream segments represent reaches where ecomorphological assessment was made. The location of the discharge from the Tecate Municipal Wastewater Treatment is denoted as ''WTP''. The location of the discharge from the Tecate Beer Brewery and the Tecate maquiladora complex are denoted by ''Brew'' and ''Maq'' respectively. Map adapted from the Tijuana River Watershed GIS database. 2000.

enforcement of existing regulations, has generated pollution that contaminates the tributaries of the Tijuana River and ultimately the Pacific Ocean.

The city of Tecate, Mexico is located in the eastern section of the Tijuana River watershed (Figure 1). In 2000, the population of Tecate was nearly 80,000 persons, with this number expected to increase to around 150,000 by the year 2020 (INEGI 2000). In urban Tecate, major point sources of pollution to Tecate Creek include the discharge of poorly treated sewage from the Tecate Municipal Plant, the discharge of high BOD-containing waters from the Tecate Brewery, and effluent discharge from a maquiladora complex which includes a large metal-working industry and the effluent from a slaughterhouse. Due to these discharges, flow in Tecate Creek occurs throughout the year, even during the summer dry season when the stream would naturally have little or no flow. Downstream, Tecate Creek joins Cottonwood Creek in the U.S. to form the Rio Alamar (Figure 1), which eventually joins the Rio de las Palmas in Mexico to form the Tijuana River. Due to the major point sources of pollution mentioned above, as well as typical urban non-point sources, Tecate Creek may account for a significant part of the loading of a variety of pollutants to the downstream Tijuana River watershed and the Tijuana River Estuarine Research Reserve in the U.S. (Englert et al. 1999; Gersberg et al. 2000; Gersberg et al. 2002).

The purpose of this study was to measure the degree of contamination in Tecate Creek, and the extent to which these contaminants, including heavy metals, organic pollution (BOD and COD), nutrients (N and P), and fecal indicator bacteria, are reduced by self-purification downstream. An additional aim was to perform an integrated biological assessment of Tecate Creek to determine the effects of such pollution on the ecological development potential in this stream. Our overall ecomorphological investigations also allowed an examination of the potential of this stream for restoration efforts that could improve water quality in the Tijuana River watershed.

Materials and Methods

Chemical and Microbiological Assessment

In January and February 2002, water samples were taken four times from five sites on Tecate Creek and the upper Rio Alamar. The sites were: WTP 2 (downstream of the Tecate Municipal Wastewater Treatment Plant), Tecate, Marron Valley, Big Pipe, and Toll Bridge on the Rio Alamar (Figure 1). Sampling was done at each site over a period of one hour, where each sample represented a composite sample of 6 grab samples taken every 10 minutes. Samples were analyzed for dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), the heavy metals cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn), the plant nutrients (nitrogen and phosphorus), and total and fecal coliform bacteria. At an additional site (designated WTP 1, upstream of Tecate Municipal Wastewater Treatment Plant) samples were only analyzed for metals. To be sure that our samples approximate the same parcel of water as it moved downstream, the ‘‘flowing-wave’’-method (Heidenwag et al. 2001) was used. This method involved measuring average flow velocities (Global FP201 Flow Probe) at each of the sites, calculating the average time of flow downstream to each site, and timing the sampling at successive sites to correspond with the flow of water.

Samples were analyzed according to the *Standard Methods for the Examination of Water and Wastewater* (APHA 1995). Chemical oxygen demand (COD) which reflects the level of organic carbon, was measured by the reactor digestion method. Biological oxygen demand (BOD) which reflects the level of assimilable organic carbon, was estimated by the 5-day BOD incubation test. The plant nutrients nitrogen and phosphorus were measured by colorimetric methods. Nitrate was analyzed by the cadmium reduction method. Ammonium was measured by the nesslerization method. Phosphorus was measured by the ascorbic acid method. Total coliforms and fecal coliforms were counted according to the most-probable-number method (MPN). For metals analysis, water samples were filtered using cellulose acetate membrane filters (0.45 μm-pore-diameter). Filtrates were acidified to pH 2 with concentrated nitric acid and used directly for Cd, Cr, Cu, Ni, and Pb dissolved metal analysis (APHA 1995). This analysis was performed using a Perkin-Elmer (SIMMA 6000) Graphite Furnace Atomic Absorption Spectrometer (AAS). Zn was analyzed by flame atomic absorption spectrometry using a Buck Scientific flame atomic absorption spectrophotometer (Model 210 VGP). For particulate metal analyses, filters were digested using concentrated nitric acid (APHA 1995). QA/QC included the use of reagent blanks, duplicate samples, recovery of standard concentration, and calibration of standards. Mean percent variation among the duplicates for all metals tested ranged from 2.3%–15.9%. Mean ($n = 3$) sample recoveries from a trace element calibration standard (2709

San Joaquin soil, National Institute of Standards and Technology) ranged from 94.4 to 101.0% for all of the metals tested. Self purification performance was calculated by dividing the pollutant concentration difference (mg/L) or bacterial density (MPN/I00 mL) difference at the first (upstream) and last sampling sites by the flowing distance (km) between them.

Hydrobiological Evaluation

Between October and December 1999, from July till September 2000, and from November 2001 to January 2002, macroinvertebrate organisms were sampled altogether three times in four 100 meter reaches (WTP 2, Tecate, Marron Valley (U.S.), Toll Bridge; see Figure 1) always over a period of one hour. Thereby, all biotope structures (bottom substrate, aquatic plants) were sampled by means of a handnet with a mesh size of 0.5 mm. The organisms were fixed in ethanol (70%) and estimated according to Merrit and Cummins (1996). Biotic Index according to Chessman (1995) was calculated. This calculation is based on the fact that numerous families of macroinvertebrates that are widespread in river systems nearly all over the earth have been awarded sensitivity grades according to their tolerance or intolerance of common types of pollutants as summarized by Chessman (1995). However, in some cases the grades are necessarily a compromise, either because of variation in the sensitivities of species within a family or because some families are sensitive to certain types of pollutants but relatively tolerant to others (Chessman 1995). The index SIGNAL-w (Stream Invertebrate Grade Number—Average Level, weighted by the occurrence) was calculated by multiplicating the grade of each family present by the value to represent its occurrence level (e.g. 1 for only 1 individual, 7 for mass development), summing the products, and dividing by the sum of the occurrence values.

Ecomorphological Assessment

Using the methods of ecomorphological mapping according to Lüderitz et al. (1996) and Heidenwag et al. (2001), the 29 km of the streamcourse of Tecate Creek (and the upper section of the Rio Alamar) were mapped and evaluated in 9 reaches shown in Figure 1.

The following main parameters were registered:

- stream course development
- lengthwise profile
- crosswise profile
- bottom structure
- bank structure
- structure of surroundings

These 6 main parameters are joined by 27 single parameters; an overview is given in Table 1.

The quality of ecomorphology is evaluated by 7 classes of structure grade:

Grade 1: not disturbed, natural morphology
Grade 2: slightly disturbed, unimportant changes which do not influence functionability of the waterbody
Grade 3: moderately disturbed, changes of morphology are obvious and disturb the ecology of the waterbody to a measureable degree

Table 1. Results of Ecomorphological Assessment at selected stream reaches[1] of Tecate Creek/Alamar River.

Main parameter	Individual parameters at different mapping sites	1	2	3	4	5	6	7	8	9	Average
1. Stream course development	Course bending	4	4	3	2	2	2	2	3	3	3
	Bending erosion	4	3	3	3	1	1	2	2	2	2
	Lengthwise banks	3	2	2	2	1	1	2	2	1	2
	Special course structures	2	2	1	1	1	1	1	1	1	1
	Average	3	3	2	2	1	1	2	2	2	2
2. Lengthwise profile	Crosswise constructions	3	1	1	1	1	1	1	1	1	1
	Backwater	2	1	1	1	1	1	1	1	1	1
	Piping	1	1	1	1	1	1	1	1	1	1
	Crosswise banks	2	3	2	1	2	2	2	2	2	2
	Current diversity	3	1	2	2	2	2	1	1	1	2
	Depth variation	2	2	2	2	1	1	2	2	2	2
	Average	2	2	2	1	1	1	1	1	1	1
3. Crosswise profile	Type of profile	2	2	3	1	1	1	1	1	1	1
	Depth of profile	1	2	3	1	1	1	2	1	1	2
	Bank erosion	3	2	3	1	1	1	2	1	1	2
	Width variety	3	3	3	2	1	1	2	2	2	2
	Culverts	7	1	7	1	1	1	1	1	4	3
	Average	3	2	4	1	1	1	2	1	2	2
4. Bottom structure	Bottom substrate	5	5	6	5	2	3	3	2	3	4
	River bottom protection structures	1	1	1	1	1	1	1	1	1	1
	Special natural bottom structures	3	1	3	3	2	1	1	1	1	2
	Substrate diversity	5	4	5	4	3	2	3	2	2	3
	Average	4	2	3	3	2	2	2	2	2	2
5. Bank structure	Bank trees	3	2	2	1	1	2	1	1	2	2
	Bank vegetation	3	2	3	2	1	2	2	1	2	2
	Bank paving	1	1	1	1	1	1	1	1	1	1
	Special natural bank structures	4	2	2	1	2	3	3	2	3	2
	Average	3	2	2	1	1	2	2	1	2	2
6. Surroundings	Area use	4	2	4	2	2	2	2	1	2	2
	Protection zones	4	2	3	2	2	2	2	1	2	2
	Adverse Structures	6	5	6	2	2	1	5	2	4	4
	Average	5	3	4	2	2	2	3	1	3	3
Final evaluation		3	2	3	2	1	2	2	1	2	2

[1] Stream reaches sampled and designated here 1–9 are shown on map (Figure 1).

Table 2. Land use characterization of Tecate Creek/Alamar River sub-basin drainage area downstream of urban Tecate, Mexico.[1]

Description	Hectares	Percent area
Commercial	36.70	0.31
Dispersed residential	95.11	0.80
Disturbed/under construction	358.48	3.01
Extractive industry	51.74	0.43
Improved pasture	55.90	0.47
Industrial	52.83	0.44
Institutional	13.46	0.11
Non-developed	10,197.70	85.58
Open grazeable land	536.20	4.50
Recreation	130.60	1.10
Residential	113.44	0.95
Row crops	91.33	0.77
Transportation	142.85	1.20
Tree crops	34.72	0.29
Water body	4.65	0.04
Total Area in Acres	11,915.79	100.00

[1] Tijuana River Watershed GIS database 2000.

Grade 4: clearly disturbed, waterbody shows a clear distance from natural status, is straightened and lined to a degree up to 50%
Grade 5: markedly disturbed, straightening and lining reach a percentage of 100
Grade 6: heavily disturbed, natural dynamics are avoided by bank pavement and lining
Grade 7: excessively disturbed, channelization is complete

Morphological assessment was done by comparing undisturbed stream reaches upstreams of Tecate (reference reaches) with the mapped sites.

Results

Tecate Creek has quite natural morphological structures, almost without typical problems like lining, straightening, and bank paving (Table 1). Expressed as a meander valley river and braided system, it shows a flat type of profile with a natural course with meanders and lengthwise banks, as well as a relatively high current diversity and depth variation. It generally has natural bank vegetation consisting of loose trees and shrubs. There are no dams or backwaters (and few culverts) on Tecate Creek. Downstream of Tecate, there are no adverse structures or any intensive landuses (Table 2). Indeed, downstream of urban Tecate, 90% of the land area that drains into Tecate Creek or the upper Alamar River, is either undeveloped or open grazable land, with industrial, commercial, and residential land uses (combined) only comprising less than 2% of the area (Table 2) (Tijuana River Watershed GIS database 2000). This data supports our visual observation that there are no major pollutant sources downstream of urban Tecate that would confound our analysis of self-purification efficiencies.

On the other hand, the substrate of Tecate Creek is very uniform (gravel partially filled with sewage sludges) and the river is oversaturated with these sediments (braided system). Solid surfaces are very rare, and biofilms that play an

Table 3. Settlement of representative sites on Tecate Creek/Alamar River with macroinvertebrates used for SIGNAL-w calculation.

Sample site	Family (genus species)	Sensitivity grade	Occurrence	SIGNAL-w
WTP2	*Psychodidae* (*Psychoda* sp.)	2	4	1.5 (excessively polluted)
	Culicidae	2	2	
	Chironomidae	1	2	
	Tubificidae (*Tubifex tubifex*)	1	4	
Tecate	*Psychodidae* (*Psychoda* sp.)	2	2	1.7 (excessively polluted)
	Chironomidae (*Chironomus* spp.)	1	1	
	Stratiomyidae	2	1	
	Ceratopogonidae	6	1	
	Tubificidae (*Tubifex tubifex*)	1	7	
Marron Valley	*Psychodidae* (*Psychoda* sp.)	2	2	2.1 (heavily polluted)
	Chironomidae (*Chironomus* spp.)	1	3	
	Ceratopogonidae	6	1	
	Tabanidae	5	1	
	Coenagrionidae (*Agria* sp.)	7	1	
	Tubificidae (*Tubifex tubifex*)	1	7	
Toll Bridge	*Psychodidae* (*Psychoda* sp.)	2	2	3.1 (critically polluted)
	Chironomidae (*Chironomus* spp.)	1	2	
	Tabanidae (*Chrysops* sp.)	5	1	
	Simulidae (*Simulium venustum*)	5	1	
	Coenagrionidae (*Ischnura* sp. *Argia* sp.)	7	2	
	Aeshnidae (Anax sp.)	6	1	
	Belostomatidae (*Belostoma* sp.)	5	1	
	Dytiscidae (*Rhantus* sp.)	5	1	
	Gammaridae	6	1	
	Tubificidae	1	7	

outstanding role in self-purification can develop only poorly due to this fact, and because of the friction between sediment particles which leads to a lack of stable habitats. Microscopic observation showed that very thin biofilms formed by filamentous bacteria and algae only existed on about 10% of the gravel surface.

Bioindication by SIGNAL-w reflects a very low water quality with index values of 1.5 to 2.1 in the upper three sampled stream reaches at WTP 2, Tecate, Marron Valley (Table 3). By the last site (Toll Bridge) on the Rio Alamar, there was significant improvement, but even here the index value of 3.1 represented a system still critically polluted (Table 3). Macroinvertebrate settlement at all sites is dominated by those Diptera larvae and Tubificidae which do not demand a high water quality; their high abundances indicate a polysaprobic status (i.e. a very high organic load).

Sampling for this study was all conducted under dry weather (baseflow) conditions when Tecate Creek was polluted to a very high degree with organic substances, plant nutrients, heavy metals, and fecal indicator bacteria (Table 4, Figures 2–7). With regard to self-purification, we found only a poor performance concerning organic substances and nutrients. Over a distance of 29 km (from site WTP 2 to the Toll Bridge on the Rio Alamar), BOD decreased only by 53% (2.14 mg/L km), COD by 84% (14.31 mg/L km), ammonium by only 4% (0.07 mg/L km), and total P by 51% (0.32 mg/L km). However, even this modest reduction

Table 4. Self-purification of Tecate Creek/Alamar River over a distance of 29 km as measured at 5 sampling sites.

Parameter	Units	WTP 2	Tecate	Marron Valley	Big Pipe	Toll Bridge
BOD	(mg/L) ± Std	118 ± 15	133 ± 12	47 ± 10	27 ± 8	56 ± 7
COD	(mg/L) ± Std	492 ± 68	379 ± 5	177 ± 29	122 ± 23	77 ± 28
DO-saturation	(%) ± Std	48 ± 11	23 ± 13	71 ± 6	65 ± 4	59 ± 7
NH4+-N	(mg/L) ± Std	50.3 ± 3.3	55.3 ± 6.2	58.0 ± 2.5	53.8 ± 4.8	48.3 ± 2.4
TP	(mg/L) ± Std	17.9 ± 3.6	15.0 ± 2.8	10.4 ± 1.2	9.1 ± 0.7	8.7 ± 1.0
Total coliforms	(MPN/100 mL) × 1000 ± Std	3650 ± 1909	2900 ± 2500	2600 ± 565	950 ± 212	465 ± 245
Fecal coliforms	(MPN/100 mL) × 1000 ± Std	2000 ± 425	650 ± 26	215 ± 120	180 ± 56	6 ± 3
Flow	(L/s) ± Std	191 ± 31	171 ± 28	213 ± 42	181 ± 17	187 ± 22

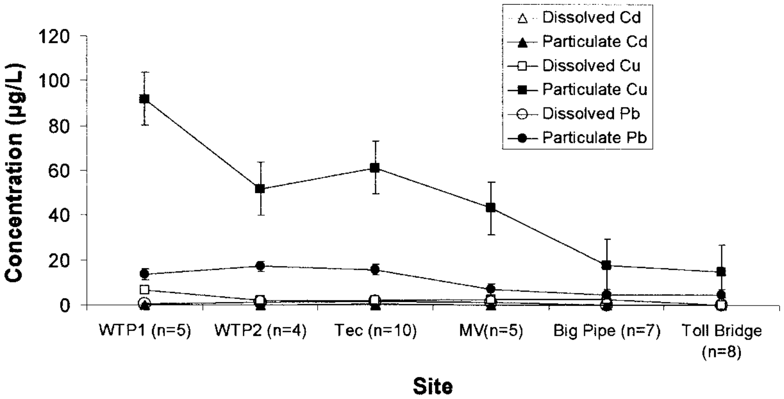

Fig. 2. Levels of dissolved and particulate cadmium (Cd), copper (Cu) and lead (Pb) in Tecate Creek/Alamar River; n denotes the number of samples taken at each site. Levels of disolved Cd are so low (<0.15 µg/L) that they do not show in the this figure.

of the organic and nutrient loads could be responsible for the appearance of some higher-demanding macroinvertebrate organisms especially at the last site on the Rio Alamar (Table 3).

Nitrification seems to be nearly totally absent, probably because of the high organic carbon levels in the water which leads to the dominance of heterotrophic bacteria and suppresses the development of nitrifying organisms (Table 4). Meanwhile, the decrease of total coliform densities remains moderate, with an 87% (110×10^3 MPN/100 mL km) removal efficiency; while fecal coliforms are reduced (69×10^3 MPN/100 mL km) with a rather high efficiency of 99.7%.

For most metals, there was a significant loss of the particulate (as well as the dissolved) fraction, as the water moved downstream in Tecate Creek to the Rio Alamar (Figures 2–3). Surprisingly, for Cu, Cr, and Ni, the highest levels observed among all of the sampled sites was actually at WTP1 (this site upstream of the discharge point for the Tecate Municipal Wastewater Treatment Plant), where levels of these metals were 98, 345, and 518 µg/L, respectively. It should be

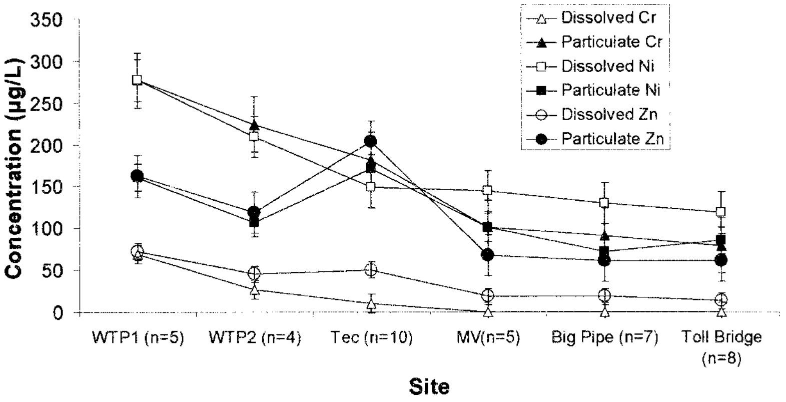

Fig. 3. Levels of dissolved and particulate chromium (Cr), nickel (Ni) and zinc (Pb) in Tecate Creek/Alamar River; n denotes the number of samples taken at each site.

noted here that this site (WTP1) lies just downstream of the point source discharge of water from a maquiladora (industrial) complex which includes a rather large metal-working facility. On three separate occasions in 2002, we sampled both upstream and downstream of the Wastewater Treatment Plant at WTP1 and WTP 2, respectively, and on one occasion, upstream and downstream of this specific maquiladora discharge point to Tecate Creek. The results of these analyses showed that the discharge from this industrial complex was a significant contributor to Tecate Creek's downstream metal contamination, and explained why observed levels were actually higher upstream of the Tecate Wastewater Treatment Plant for many of the metals we measured. Metal levels then generally decreased as the water moved downstream to the Toll Bridge site on the Rio Alamar, with total metal reduction efficiencies at the Toll Bridge (compared with WTP 2 upstream of the city of Tecate) of 71% for Cu, 60% for Cr, 76% for Pb, 40% for Ni, and 54% for Zn (Figures 2–3).

Discussion

Self-purification is a process which may allow the preservation of the ecological balance in a stream despite the presence of municipal sewage discharges upstream. It provides a unique set of advantages to clean-up polluted water streams: It acts very fast, does not require any chemical additions, acts instantly at the whole body of water at the site, works all the year around and can result in substantial decrease in contaminants concentration (Spellman 1996). Self-purification can be described as the sum of all physical, chemical, and biological processes by which the quantity of pollution in a stream is decreased. This self-purification results from mineralization of organic substances, nitrification-denitrification, sedimentation, and assimilation, as well as from dilution and mixing processes (Heidenwag et al. 2001).

Tecate Creek is excessively polluted with organic substances, plant nutrients, and fecal indicator bacteria because it receives the discharge of poorly-treated municipal sewage, brewery effluent, and industrial effluents containing heavy metals. The SIGNAL-w index (based on the occurrence of macroinvertebrate species) indicates an improvement from a grade of excessively polluted to only a grade of critically polluted over a flowing distance of 29 km to the downstream Rio Alamar site at Toll Bridge (Table 3), and this is confirmed by the results of chemical analyses (Table 4). Excessive pollution in this case, allows only the survival of the most tolerant macroinvertebrate species (most of them Diptera), while under conditions of critical pollution, more demanding organisms (e.g. Coleoptera, Odonata) can exist at least seasonally.

At first glance, this poor self-purification seems to be surprising because of a more or lesser natural stream morphology, relative good oxygen supply, and high water temperatures which should stimulate metabolism of bacteria. It should be noted here that temperature effects on self-purification were not investigated here, since other seasonal effects (e.g. flow rate, sunlight) complicate such an analysis. In a former study about Harz mountain streams in Germany (Heidenwag et al. 2001), we were able to show that self-purification concerning ammonium, phosphorus, organic substances, and bacteria can reach a rate up to 80% over a distance of only 2 or 3 kilometers in case of a natural stream morphology. Purification rates measured (118 mg/L km for COD; 45 mg/L km for BOD_5; 14 mg/L km for ammonia; 1.9 mg/L km for phosphorus) were one order of magnitude higher than in case of the Tecate Creek/Rio Alamar rates. However, these rates were only attained by a stream with a good ecomorphological structure, providing a high number of stable habitats with well developed biofilms, that contain aerobic layers for degradation of organic substances and nitrification (and also anaerobic layers for denitrification). Mikhailovski and Fisenko (2000) found under such conditions a still more rapid self-purification of a stream in the Toronto area. Unfortunately, rates for self-purification of streams in the southwestern United States have not been reported, since in this region sewage discharged to streams and rivers is at least secondary quality (and usually tertiary treated).

Horn (1992) and Horn and Hempel (1996), emphasize the outstanding role of biofilms in self-purification and especially in nitrification and denitrification. For this, bottom structure is the determining factor. Frey (2001) found that an increase of roughness leads to the strongest impacts on reduction rates and oxygen supply caused by the increment of flow duration and substrate surface for degradative and nitrifying bacteria. In Tecate Creek, the lack of appreciable nitrification activity is probably caused by the scarcity of these biofilms, as well as by the dominance of heterotrophic organisms that exist because of the high load of organic substances in the stream. Typically, in sewage-dominated effluents, nitrification does not occur until BOD levels become very low (Brehm and Meijering 1990; Jancarkova et al. 1997).

In Tecate Creek, solid inorganic surfaces are mostly absent, as are aquatic macrophytes. In lowland streams in Germany, self-purification performances remain lower than in mountain streams (Heidenwag et al. 2001), but macrophytes in such lowland streams can have there a comparable function as stones and rock debris in upland brooks, because their surface can be settled by periphyton. In Tecate Creek, there were only a few stable habitats, such as big rocks and bars covered with macrophytes, observed on the stream bottom. Even in the case of a (near)-pristine morphological structure, the features of a braided system like Tecate Creek, can set limits on the occurrence of such stable habitats on the stream bed because the sediment is constantly shifting in a natural manner. The resulting friction of the bottom substrate caused by the transposition of sediment in this braided system, may be responsible for the disturbed or missing biofilms.

The toxicity of metals may also strongly disturb the biotic community in streams (Schönborn 1992). The concentrations of heavy metals found in Tecate Creek are higher (except in the case of Cd) than those levels in freshwater found in natural streams all over the world (Schönborn 1992). However, our calculations (taking into account site-specific hardness values) show that for nearly all metals (except Ni), levels in Tecate Creek/Rio Alamar never exceeded either the CCC (criterion continuous concentration) which is a four-day average concentration chronic limit for metal pollutants in freshwater, or the CMC (criterion maximum concentration), a short-term concentration acute limit for metal pollutants not to be exceeded. Both of these water quality criteria provide for the protection of aquatic life from acute and chronic toxicity to animals and plants, and from bioconcentration by aquatic organisms (U.S. Environmental Protection Agency 2000). Even in the case of Ni, which was significantly elevated due to the discharge from a metal-working industrial plant upstream of the WTP2 site on Tecate Creek, the CMC value (1.51 mg/L) was never exceeded, and self purification lowered Ni levels, such that ambient water quality criteria were met (at all times tested) at all sites downstream of Marron Valley. Therefore, at least with regard to the metals we analyzed, toxicity effects to resident species would not be expected.

Conclusions

Our overall analysis shows that while little water quality benefit may be achieved by enhancing the ecomorphological status of Tecate Creek, the introduction of coarse material could help to enhance self-purification. The most immediate improvement in water quality status could be achieved by controlling the discharge of organic pollution from the waste treatment plant and the brewery. This could be done by means of technical sewage treatment systems or with subsurface flow constructed wetlands which are cheaper and more stable in function (Lüderitz et al. 2001). In the nearly unsettled area between Tecate and Tijuana a cascade of such wetlands consisting of relatively coarse and stable material could be constructed with moderate efforts. Further research and development is going on to estimate the necessary dimensions of such systems. Self-purification can support such activities but it would not be able to replace them.

Acknowledgments

Financial support was provided by the California State Water Resources Control Board (Agreement No. 00-246-190-0), and the Southwest Center for Environmental Research and Policy and United States Environmental Protection Agency (Subcontract Q00744). Financial assistance for travel to research site by German investigators was supported by the San Diego State University Foundation (Sponsored Project Support Fund 260201). We also thank Walter Hayhow for his valuable technical support.

Literature Cited

American Public Health Assiciation (APHA). 1995. Standard Methods for the Examination of Water and Wastewater, 19th Edition. Washington, DC.

Brehm, J., and M.P.D. Meijering. 1990. Fließgewaesserkunde. Einfuehrung indie Limnologie der Quellen, Baeche und Fluesse. Biologische Arbeitsbuecher 36. Quelle & Meyer Verlag, Heidelberg, Germany.

Chessman, B.C. 1995. Rapid assessment of rivers using macroinvertebrates: A procedure based on habitat—Specific sampling, family level and a biotic index. Australian J. Ecol. 20: 122–129.

Englert, P., C. Brown, C. Placchi, and R.M. Gersberg. 1999. Geographic information system (GIS) characterization of metal loading in the binational Tijuana River watershed. J. Borderlands Studies. 14: 81–91.

Frey, W. 2001. The effects of structural improvements on the water quality and the self-purification capacity of a running water by the example of the Oster (Saarland, Germany). Deutsche Gesellschaft für Limnologie, Tagungsbericht 2001.

Ganster, P. 1996. Environmental issues of the California-Baja California border region, Institute for Regional Studies of the Californias, San Diego State University, San Diego, CA.

Gersberg, R.M., C. Brown, V. Zambrano, K. Worthington, and D. Weis. 2000. Quality of urban runoff in the Tijuana River watershed. pp. 31–45 *in* P. Westerhoff (ed.), Water Issues Along the United States and Mexico Border, SCERP Monograph Series (no.2), Southwest Center for Environmental Research and Policy.

Gersberg, R.M., J. Pitt, D. Weis, D. and D. Yorkey. 2002. Characterizing in-Stream metal loading in the Tijuana River watershed. Proceedings of the Water Environment Federation Specialty Conference on National TMDL Science and Policy, Phoenix, AZ. November 13–16, 2002.

Heidenwag, I., U. Langheinrich, and V. Lüderitz. 2001. Self-purification in upland and lowland Streams. Acta Hydrochim. Hydrobiol. 29: 22–33.

Horn, H. 1992. Simultane nitrifikation und denitrifikation in einem hetero-/autotrophen biofilm unter berücksichtigung der sauerstoffprofile. GWF Gas- und Wasserfach: Wasser-Abwasser 133: 287–292.

Horn, H., and D.C. Hempel. 1996. Modellierung von substratumsatz und stofftransport in biofilmsystemen. GWF Gas- und Wasserfach: Wasser-Abwasser 137: 293–301.

Instituto Naciaonal de Estadística, Geografia e Informática (INEGI). 2000. XII. Censo de poblacio´n y vivienda. Aguascalientes:INEGI.

Jancarkova, I., T.A. Larsen, and W. Gujer. 1997. Distribution of nitrifying bacteria in a shallow stream. Wat. Sci. Technol. 36: 161–166.

Lüderitz, V., J. Gläser, A. Kieschnik, and E. Dörge. 1996. Anwendung und weiterentwicklung ökomorphologischer kartierungs- und bewertungsverfahren an der selke und ihren nebengewässern (Sachsen-Anhalt). Arch. für Naturschutz und Landschaftsforschung 35: 15–31.

Lüderitz, V., E. Eckert, M. Lange-Weber, and R.M. Gersberg. 2001. Nutrient removal efficiency and resource economics of vertical flow and horizontal flow constructed wetlands. Ecological Engineering 18: 157–171.

Merritt, R.W., and K.W. Cummins. 1996. An Introduction to the Aquatic Insects of North America. Kendall/Hunt Publishing, Dubuque, Iowa. Company, 3rd edition.

Mikhailovski, V., and A.I. Fisenko. 2000. The physical-chemical mechanism of water stream self-purification. Working paper, Los Alamos National Laboratory (available at http://arXiv.org)

Schönborn, W. 1992. Fließgewässerbiologie.—Gustav Fischer Verlag Jena, Stuttgart, Germany.

Spellman, F. 1996. Stream ecology and self-purification: An introduction for wastewater. Technomic Pub Co.

Tijuana River Watershed GIS database. 2000. Department of Geography, San Diego State University. typhoon.sdsu.edu/facilities/data/clearinghouse/trw.html. June 15, 2004.

Turner, C., E. Hamlyn, and O.I. Hernandez. 2003. The challenge of balancing water supply and demand in the Paso del Norte. pp. 185–248 *in* S. Michel (ed.), Border Environment, Binational Water Management Planning. Scerp Monograph Series, no. 8. San Diego State University Press, San Diego, CA.

U.S. Environmental Protection Agency. 2000. Water Quality Standards: Establishment of numeric criteria for priority toxic pollutants for the state of California. Federal Register 65 (97):31682–31719.

Accepted for publication 16 September 2004.