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Effects of Sewage Sludge Disposal on Metal Content in the Sediment and Water of Mitchell Lake, San Antonio, Texas, USA

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Mitchell Lake is located 12 miles south of the City of San Antonio. The lake was dammed near the turn of the 20th century and used as a sludge disposal lagoon for the city of San Antonio from 1901-87. The 600-acre lake, now owned by the San Antonio Water System (SAWS) serves as a natural migratory stopping point in the central migratory flightway for over three hundred species of birds. In collaboration with a Citizens Task Force, SAWS intends to develop Mitchell Lake as an educational and wetlands research field site. However, this will not be possible until the lake is cleaned up to a level that is not considered a human health risk. Currently, the lake is hyper-eutrophic with high pH, low DO, excess nutrient levels, and odiferous algal blooms (SAWS, 2000). Another problem is that Mitchell Lake, being affected by deposition of sewage sludge for many years may contain significantly elevated levels of toxic metals. The metal levels can contribute to noncompliance with the discharge permit issued by TCEQ during wet periods when the lake discharges into the Medina River (SAWS, 2000).

There are several reported studies on metal pollution of water bodies from disposal of sewage sludge. Regnier et al. (1982) reported the presence of a variety of metals, such as cobalt (Co), nickel (Ni), lead (Pb), chromium (Cr), copper (Cu), cadmium (Cd) etc. in sludge-contaminated sediments of Darwent River in UK. The non-biodegradability, toxicity and bioaccumulation of these sediment-borne metals makes the presence of these pollutants of particular concern in discharge systems (Kirk and Lestner, 1984). Alloway et al. (1991) reported that certain physicochemical properties of sewage sludge, most importantly organic matter and Fe/Al/Mn contents govern their metal retention capacities. As a result, certain sludge-impacted sediments may act as a sink or reservoir for toxic metals. Typically, sediment metal concentrations exceed that of the overlying water by 3 to 5 orders of magnitude (Mountouris et al., 2002). It has been noted that, in cases where metal concentrations in the sediments differ significantly from that in overlying water, release of metals from the sediments may occur via upward diffusion (Salomons et al., 1987). Hence, the retention and release of metals from sediment to water can be explained as a function of the geochemical and mineralogical composition of the sediments and also the water chemistry. Water chemistry typically controls the rate of adsorption/desorption of metals to/from the sediment (Alloway et al., 1991).

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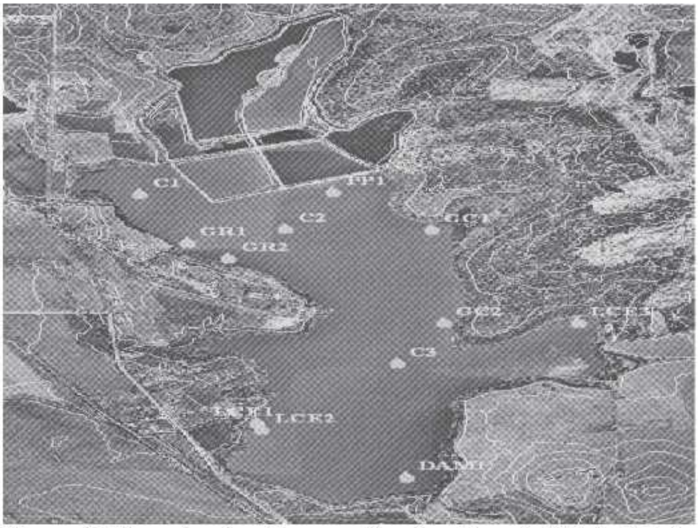

Figure 1. Map showing the sampling locations in Mitchell Lake.

Successful restoration of contaminated water bodies depends on reliable assessment of the source(s) of contaminant flux and the key processes controlling contaminant dynamics within the impacted system. The restoration issue becomes more of a challenge for sludge disposal lagoons, where the metal contents typically do not follow a specific trend because of the indiscriminate method of sludge dumping. The primary objective of this study was to analyze the concentrations and spatial distribution of toxic metals in Mitchell Lake. Sediments and overlaying water samples were collected from 12 sites and were analyzed for 9 "typical" sludge metals (Cd, Co, Cu, Cr, Fe, Mn, Ni, Pb, and Zn). The values obtained were compared to the USEPA guidelines for sediment quality (Ingersoll et al., 2000) and water quality (USEPA, 2005).

MATERIALS AND METHODS

Sediment samples were collected from 12 locations (Figure 1) in May 2003, from the top 10 cm of the substrate. The sample sites were chosen as follows: GR1 and GR2 are next to the San Antonio Police Academy Gun Range; GC1 and GC2 are next to the Mission Del Lago golf course; PP1 is next to the polder pond used for holding the sludge; Dam1 is just north of the dam that discharges excess water of the lake to the downstream Medina River; LCE1 and LCE2 are on the East and West ends of a pipeline that discharges effluent from the nearby Leon Creek Wastewater Treatment Facility; C1, C2, and C3 are at the center of the lake traveling from North to South (Figure 1). Collected samples were dried at 105°C, homogenized, and passed through a 2 mm sieve prior to being characterized for the various physicochemical properties (see Branom and Sarkar, 2004). Porewater samples were extracted from the sediments by centrifugation and filtering following standard protocols. Water samples directly overlying the sediment surface were collected with a water sampler. Total concentrations of Cd, Co, Cu,

Table 1. Metal concentrations in the sediment (ppm) in comparison with the EPA sediment quality limits (SQL).

SITE	Cd	Co	Cu	Cr	Fe	Mn	Ni	Pb	Zn
C1	**28.4**	14.5	151	**731**	3183	226	16.0	**893**	159
C2	**4.64**	17.0	8.3	**172**	5014	252	13.6	**173**	81.1
C3	**9.01**	15.9	11.0	**281**	4395	234	12.8	**299**	138
LCE1	**8.53**	18.0	25.6	**292**	330	425	10.5	**239**	152
LCE2	**108**	16.5	28.7	**276**	2679	388	6.02	**257**	142
LCE3	**108**	19.4	16.7	**188**	252	400	5.12	**134**	74.7
GC1	**109**	17.6	29.0	**323**	385	218	4.14	**387**	204
GC2	**108**	12.7	33.9	**163**	79.1	94.5	**56.3**	53.0	40.2
PP	**109**	20.3	41.0	**585**	3720	197	6.01	**551**	216
Dam	**109**	22.1	41.1	**524**	378	257	**98.4**	**380**	183
GR1	**108**	21.8	9.4	**269**	312	173	**72.4**	**94.8**	53.0
GR2	**108**	25.7	13.2	**338**	421	182	**81.8**	**156**	62.1
SQL	3.53	N/A	197	90	N/A	N/A	36	91.3	315

Data represent mean of three replicates. Metal concentrations in bold are above the SQL. N/A = Not Available.

Cr, Fe, Ni, Mn, Pb, and Zn in the sediments were measured by a Perkin Elmer PE 700 Atomic Absorption Spectrometer (AAS) after acid digestion of the samples following USEPA Method 3050B (USEPA, 1996). Porewater and overlying water samples were filtered and analyzed for the target metals by flame-AAS. All analyses were carried out in triplicates and the mean values are reported. Replicates had to fall within 95-105% to be considered acceptable. Recoveries of 90-110% of spikes and external standards were considered acceptable. Analyses that did not satisfy these QA/QC protocols were reanalyzed.

RESULTS AND DISCUSSION

Total concentrations of metals in sediments are reported in Table 1. Concentrations of metals in sludge impacted sediments were compared to the sediment quality limits (SQL) established by the USEPA (Ingersoll et al., 2000). Such guidelines are based on potential negative effects of metal contents on the growth and distribution of flora and fauna in the impacted water bodies.

Mitchell Lake sediments were typically elevated in the majority of the metals (Table 1). Although present in relatively high concentrations, Co, Cu, Fe, Mn, and Zn were still below the SQL at all the sampling sites, and hence, are not expected to pose any serious toxicity problem under the prevailing conditions. However, Ni concentrations were 2 to 3 fold higher than the acceptable SQL at four sampling sites in the lake, with the highest concentration at the Dam site (nearly 3 fold higher than the SQL). Cr was highly elevated at all sites in the lake, 2 to 8 times higher than the SQL. The highest Cr concentration was at center of the Lake (northernmost site - C1), which was 8 times higher than the SQL. Pb was elevated

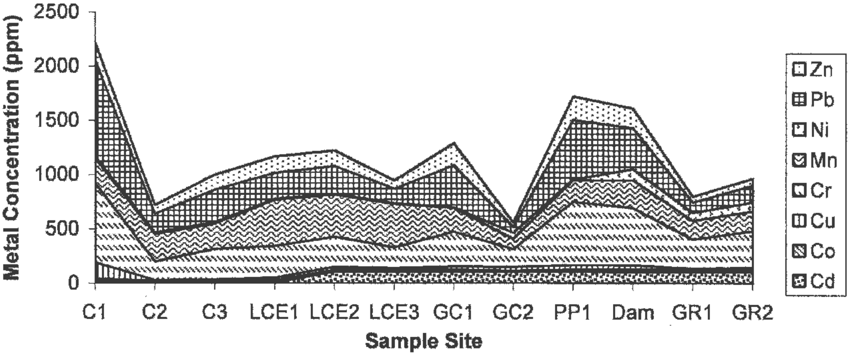

Figure 2. Spatial distribution of metals in the sediments of Mitchell Lake.

at 11 out of the 12 sampling sites. The highest concentration of Pb was also observed at the C1 site, 10 times the SQL. Among the nine metals investigated, Cd had the highest concentration to SQL ratio in the sediments, approximately 27X higher than the acceptable limit (3.53 ppm) in 8 out of the 12 sampling sites.

Analysis of total metal distribution in the lake sediment showed highest concentrations of Cd, Co, Cr, Cu, Ni, and Pb at the polder pond (PP) site and the C1 site (Figure 2). The sludge was originally dumped in the holding (polder) pond; hence, sediment metal concentrations were expected to be high at the PP site. The high concentration of metals at the C1 site (central part of the lake), which is down-gradient to the PP site can be attributed to the overflow of ponder pond. Sediment samples collected from the Dam site were typically characterized by high metal concentrations. The dam is in the southernmost part of the lake, characterized by its gentle slope relative to the other sampling stations at the center of the lake. This natural contour gradient may be responsible for deposition of metal-enriched sediments at the Dam site. High concentration of metals at the Dam site is of substantial environmental concern as this is the only outflow site in the lake. Under high precipitation conditions, the dam allows the water to flow from Mitchell Lake into the downstream Medina River.

Metal concentrations in the porewater were extremely low as compared to that in sediments (Table 2). Porewater data was compared with the USEPA water quality guidelines (USEPA, 2005) in terms of maximum allowable concentrations (MAC) in surface waters. Among the nine metals studied, Mn, Ni, and Zn were typically below the detection limit of AAS (Table 2). Co, Cu, and Fe were detected in the sediment porewater, but their concentrations were below the MAC limits. Cr concentration in the deepest locations (along the center) of the lake was 2X higher than the MAC. Cd and Pb concentrations in the porewater were significantly higher than the MAC levels and corresponded to the high sediment metal concentrations. Cd was elevated at all sampling locations; the concentrations were 6-10 fold higher than the acceptable limit. Pb was also elevated at all locations in

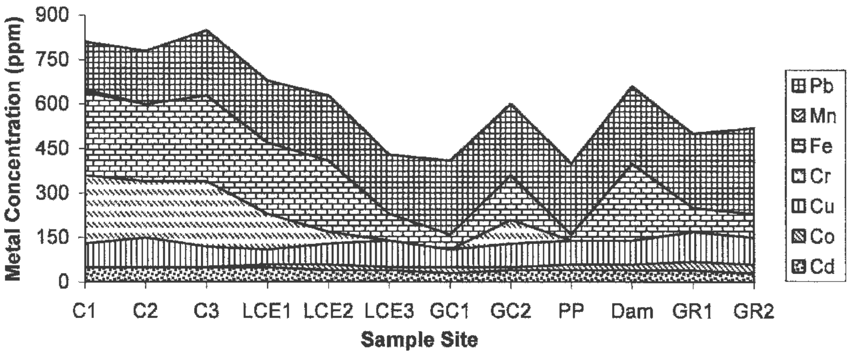

Figure 3. Spatial allocation of metals in porewater of Mitchell Lake sediments.

Table 2. Porewater metal concentrations (ppb) compared to the maximum allowable concentrations (MAC) in surface water.

SITE	**Cd**	**Co**	**Cu**	**Cr**	**Fe**	**Mn**	**Ni**	**Pb**	**Zn**
C1	**50**	N/D	80	**230**	280	10	N/D	**160**	N/D
C2	**50**	N/D	100	**190**	260	N/D	N/D	**180**	N/D
C3	**50**	N/D	70	**220**	290	N/D	N/D	**220**	N/D
LCE1	**50**	10	50	**120**	240	N/D	N/D	**210**	N/D
LCE2	**40**	20	70	40	240	N/D	N/D	**220**	N/D
LCE3	**40**	10	90	N/D	90	N/D	N/D	**200**	N/D
GC1	**30**	20	60	N/D	50	N/D	N/D	**250**	N/D
GC2	**40**	10	80	80	150	N/D	N/D	**240**	N/D
PP	**40**	20	80	N/D	20	N/D	N/D	**240**	N/D
Dam	**40**	20	80	N/D	260	N/D	N/D	**260**	N/D
GR1	**40**	30	100	N/D	80	N/D	N/D	**250**	N/D
GR2	**30**	30	90	N/D	80	N/D	N/D	**290**	N/D
MAC	5	50	1300	100	300	50	610	15	740

Data represent mean of three replicates. Values in bold are higher than the MAC. N/D = Not detected.

the lake at concentrations typically 100 - 200X higher than the MAC limit. The highest concentration of Pb was obtained from the porewater extracted from the sediment collected from sampling station GR2 near the San Antonio Police Academy gun range. This was expected because of the daily occurrence of stray bullets hitting the lake water at times of firing practice.

Spatial distribution of the porewater metals is shown in Figure 3. Metal concentrations were highest in the porewater extracted from sediments collected from the deepest locations in the lake. Porewater metal concentrations roughly mimicked the sediment metal concentrations, and similar to the lake sediments, the Dam site had relatively high concentrations of several metals. As porewater metals have the potential to be released from the sediments under conditions of disequilibrium, the Dam site is a point of concern because of the possibility of lake water contaminating downstream Medina River.

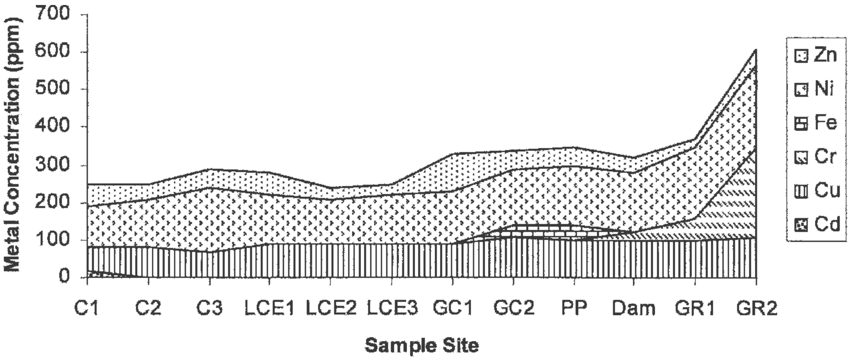

Figure 4. Spatial distribution of metals in Mitchell Lake water.

Table 3. Metal concentrations in the overlying water (ppb) in comparison with MAC in surface water.

SITE	**Cd**	**Co**	**Cu**	**Cr**	**Fe**	**Mn**	**Ni**	**Pb**	**Zn**
C1	**20**	N/D	60	N/D	N/D	N/D	110	N/D	60
C2	N/D	N/D	80	N/D	N/D	N/D	130	N/D	40
C3	N/D	N/D	70	N/D	N/D	N/D	170	N/D	50
LCE1	N/D	N/D	90	N/D	N/D	N/D	130	N/D	60
LCE2	N/D	N/D	90	N/D	N/D	N/D	120	N/D	30
LCE3	N/D	N/D	90	N/D	N/D	N/D	130	N/D	30
GC1	N/D	N/D	90	N/D	N/D	N/D	140	N/D	100
GC2	N/D	N/D	110	N/D	30	N/D	150	N/D	50
PP	N/D	N/D	100	N/D	40	N/D	160	N/D	50
Dam	N/D	N/D	100	20	N/D	N/D	160	N/D	40
GR1	N/D	N/D	100	60	N/D	N/D	190	N/D	20
GR2	N/D	N/D	110	**240**	N/D	N/D	220	N/D	40
MAC	5	50	1300	100	300	50	610	15	740

Data represent mean of three replicates. Values in bold are higher than the MAC. N/D = Not detected.

Metal concentrations in the overlying water columns were much lower compared to the sediments and even the porewater (Table 3). Among the nine metals studied, Co, Mn, and Pb were not detected in the overlying water at any of the sampling stations, while Fe was detected only at two places, namely the PP and the GC2 sites at concentrations well below the MAC limits. Cd was detected only at one site (C1) at a concentration 4 times higher than the MAC. Cr was detected at three sites at concentrations below the acceptable limit except for the GR2 site where its concentration was 3 times higher than the MAC. Cu, Ni and Zn were detected in water collected from all the sampling stations; however, their concentrations were well below the MAC limits.

Spatial distribution of metals in the overlying water is shown in Figure 4. Compared to the profiles obtained for sediments and porewater, metal concentrations in lake water was relatively uniform, except for the sampling sites near the San Antonio Police Academy gun range, where Ni and Zn concentrations were the highest. However, even in the GR sites, water soluble Pb was not detected, although that part of Mitchell Lake gets regular input of Pb via bullets entering the water system. This is because of the high carbonate and phosphate contents of the lake water (Branom and Sarkar, 2004), which tends to precipitate Pb in the form of stable Pb compounds, which then become a part of the sediment Pb pool. Relatively high metal concentrations were detected in water samples at the polder pond, which correspond to the high sediment metal concentrations at the PP site. At other locations, the highly alkaline and reducing conditions of the water appear to be buffering the release of heavy metals from the sediments. In general, the relatively uniform distribution of metals in the lake water indicates a well-mixed system. Mitchell Lake gets regular input of water in the form of effluent discharge from the nearby Leon Creek recycling facility, which helps to maintain a uniform water level all throughout the year, thereby not subjecting the lake system to periodic wet/dry conditions. Such variant physical conditions could have been detrimental to the water quality of the lake by promoting chemical disequilibrium, potentially releasing the otherwise stable sediment-bound metals.

It is well documented that metals in lacustrine systems can be remobilized and redistributed between the sediments, porewater, and the overlying water columns. Tomson et al. (2003) studied the fate of metals in several lake sediments in New York, Oklahoma, and Louisiana and concluded that the adsorption of Cd, Pb, and Zn on the sediments was reversible. Tsai et al. (2003) observed that metals from river sediments remobilized to become a part of porewater at the sediment/water interface. Results from such investigations support the hypothesis that sediment metal concentrations can be considered a major determinant of sediment quality.

The results of this study indicate that concentrations and spatial distribution of metals in Mitchell Lake sediments have been affected by the indiscriminate and long-term disposal of sewage sludge. Generally, the physico-chemical characteristics and the mineralogical composition of the sediments (data not shown) seemed to be controlling the retention/release characteristics of metals in the lake system. The majority of the metals were largely immobilized at the sediment/water interface, thereby preventing them from being released to the overlying water column. This is because of high pH conditions and the high concentrations of fines (silt and clay) in the sediments, which provide room for metal retention, owing to their typically large specific surface area. Retention of metals in the sediments was further augmented by the abundance of amorphous Fe and Al oxides (Branom and Sarkar, 2004), a strong scavenger of metals in aquatic systems. However, elevated levels of Cd, Cr, and Pb in the lake sediments as well as in the porewater are indicative of the potential for future release of these metals to the lake ecosystem. Furthermore, the metals in Mitchell Lake sediments typically followed a downgradient distribution pattern because of gravitational transport to the deeper portions of the lake. The metals bound to these sediments, which are gradually becoming saturated with increasing porespace loading have the greatest potential of becoming bioavailable due to any sudden shift in chemical equilibrium of the lake aquatic system. Therefore, caution needs to exercised while designing (and implementing) a reclamation plan for Mitchell Lake water, which is a stated priority of SAWS, the current owner of the lake. Any major physical disturbance (such as sediment dredging or cutting) caused by the remediation effort may severely affect the chemical equilibrium of the system, thereby causing re-dissolution of the metals currently bound to the sediments at the solid/water interface. Century-long disposal of sewage sludge has had a tremendous effect on the lake ecosystem, particularly in terms of metal concentrations in the sediments. Distribution and dynamics of these metals in the lake ecosystem should be taken into account while developing an appropriate remediation plan to improve Mitchell Lake water quality.

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