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Efficiency of Phnom Penh's Natural Wetlands in Treating Wastewater Discharges

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Abstract: Water quality samples were collected in three sewer channels discharging into the Boeng Cheung Ek treatment wetland and at two longitudinal sites within the wetland (mid-point and outlet), principally during the dry season, but also during storm events. YSI datasondes were installed to collect data at 15-minute intervals for dissolved oxygen, turbidity, conductivity, temperature and pH, at two sites in the wetland. Levels of Cu, Cr, Zn, total phosphorus, nitrate, detergents, *E. coli* and total suspended solids entering Boeng Cheung Ek from the three main tributary sewer channels and levels in the outflow from the wetland were compared for the dry season. The difference in mean concentration between inlet and outlet reflected reductions in the range of 44% (nitrate) to 99.97% (*E. coli*), with other parameters fitting within this range. Load reductions also were calculated on a monthly basis. Several contaminants within the sewer channels were significantly diluted by stormwater during individual rain events, although this trend was not observed within the wetland. The YSI data exhibited both interesting daily trends for dissolved oxygen and dry season to rainy season trends in weekly mean values for dissolved oxygen and conductivity.

Key words: Wastewater treatment wetlands, metals, *E. coli*, detergents, dissolved oxygen, Phnom Penh.

Introduction

Phnom Penh, the capital city of Cambodia, has a population of approximately 1.4 million and is growing rapidly at a rate of around 4% annually. Rural to urban migration is one of the major issues facing the city, posing significant social and environmental challenges (Molyvann, 2003; Cambodia Development Resource Institute, 2007). People living in informal housing without adequate services have increased, particularly in the peri-urban areas (Heinonen, 2008).

Phnom Penh is serviced by a combined sewer system of underground concrete and PVC sewer pipes that lead to the main open channels, which are lined either by concrete or packed-earth (e.g. Trabek and Meanchey channels). There are about 160 km of sewer lines in the

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city core including 2.6 km of open channels (JICA, 1999). There is no wastewater treatment plant, so approximately 10 percent of the city's effluent flows directly into the Mekong River without any treatment. The remaining 90 percent is loaded into four natural wetlands around the city for treatment.

There are three wetlands in the south central part of Phnom Penh. The wetland of Boeng Trabek is located within the urban centre of Phnom Penh. Its surface area varies from 35 ha in the dry season to 40 ha in the wet season (BAU, 1997). Muong (2003) reported household wastewater and storm water discharge volumes into this wetland at about 20 million m^3 with a rainfall of 1081 mm in 2002. The wetland of Boeng Tumpun (47.5 ha in the dry season) is located in a suburban area. About 23 million m^3 of household wastewater and storm water was discharged into this wetland in 1998 (Muong, 2000). Industrial effluents also are loaded into this wetland. The wetland of Boeng Cheung Ek is the largest. Its surface area is as large as the centre of Phnom Penh (about 2000 ha) in the wet season and shrinks to 1300 ha in the dry season (Muong, 2000). Effluents from the wetlands of Boeng Trabek and Boeng Tumpun are discharged into this wetland, together with industrial effluents from the surrounding areas. In 2002, the quantity of industrial effluent was estimated at 4.6 million m^3 (based on water consumption), a 14% increase compared with 2001 (MOE, 2003). There are more than 3000 industrial firms in the wetland catchment areas, dealing in battery repair, paint manufacture, zinc and metal products, pulp and paper, textiles, and plastics, and a municipal solid waste landfill that is now full.

Boeng Cheung Ek discharges via an outlet channel to the Bassac river, a distributary of the mainstream Mekong river. During the rainy season, waste continues to enter the wetland from the three sewer channels, but high flows on the Mekong and Bassac rivers force flow *into* the wetland via the same outlet channel. In essence, Boeng Cheung Ek acts as a mini-Tonle Sap pulsing system.

The objective of this study is to provide a baseline assessment of the efficiency of Boeng Cheung Ek in sustainably treating Phnom Penh's waste. It is particularly important to obtain this baseline information as the natural treatment wetlands around the city are being in-filled in preparation for further city development (Becker and Thul, 2009). This baseline assessment can be useful in supporting the development of plans for continued waste treatment.

Methods

Manual grab samples for water quality analysis were collected at the middle of Boeng Cheung Ek (i.e. middle site) and the outlet channel (i.e. outlet site) from the wetland in association with the sampling done in the three open sewer channels that discharge into the wetland. Sampling in the Meanchey and Trabek channels was done at an upstream and downstream site along each channel and an additional sewer tributary, the Meanchey channel, that services an industrial area also was sampled. Flow from the Meanchey and Trabek channels is pumped into the wetland past a dyked ring road. The third channel, locally known as the "Iron Bridge" channel, was sampled near the discharge point to the wetland. Greater detail regarding sampling methodology for the sewer sites is provided by Yim et al. (2008). Sample site locations are summarized in Figure 1. Sampling was done between March 30, 2007 and October 25, 2008. Samples were collected in the wetland on 14 dry weather dates during the dry season and three dry weather dates were sampled in the rainy season. Samples also were collected during six storm events between mid-July and mid-October, 2007. The rainy season in Cambodia occurs approximately between May/June and November.

YSI 6920 datasondes were installed in 2007 and 2008 at the outlet site and in the wetland near the Tumpun (Meanchey) pump station (i.e. Meanin site) and recorded water temperature, dissolved oxygen, conductivity, turbidity, and pH at 15-minute time intervals (Figure 1). Flow at the outlet channel was measured using the area-velocity method at the same time that the water quality grab samples were collected. Velocity was measured using a Marsh McBirney Model 2000 Flomate digital meter.

Two injections of Rhodamine WT dye were made along the Iron Bridge channel to measure flow entering the wetland from the west: 0.2 L at 10:12 hrs on Tuesday 31st October, 2007 and 0.5 L at 11:42 hrs on Wednesday 1st November, 2007 at the same location. Turner Designs Cyclops and handheld fluorometers were deployed to determine the temporal concentration distributions at specified sites to the confluence of the Iron Bridge channel.

All water samples were kept on ice in the field and were refrigerated at the Royal University of Phnom Penh (RUPP) Environmental Science Water Chemistry Laboratory prior to analysis. Laboratory analysis was done at the RUPP Water Chemistry Laboratory. The samples were analyzed for *E. coli* using the Coliscan Easy Gel system (Micrology Laboratories, Goshen, IN).

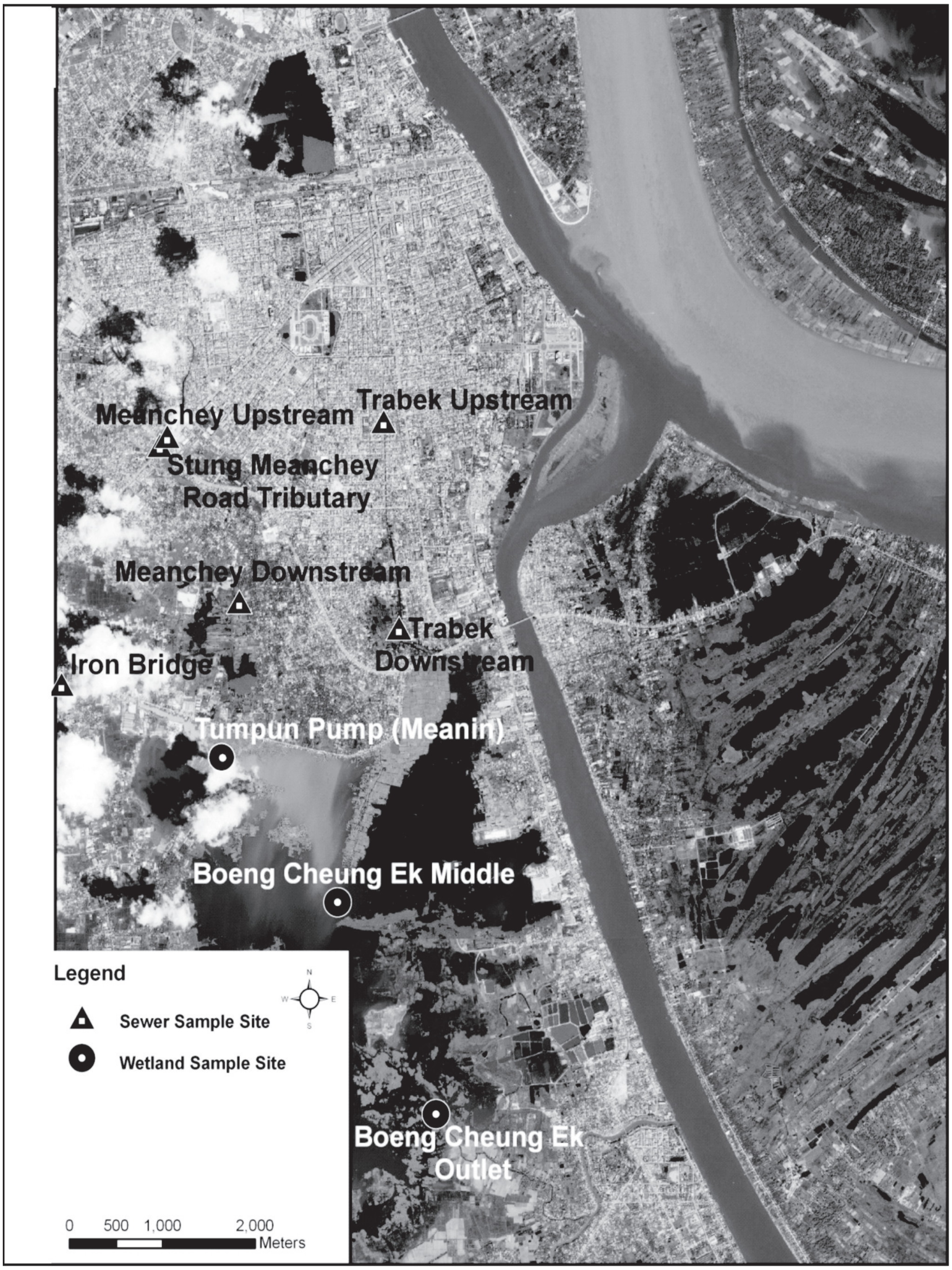

Figure 1: Sample site locations.

Nitrate, total phosphorus, Cu, Cr and Zn were analyzed using a Hanna Instruments C-200 multiparameter photometer. Detergents (anionic surfactants) were analyzed using the methylene blue active substances method from Chemetrics, Inc. (Claverton, VA) in which anionic detergents react with methylene blue to form a blue coloured complex that is extracted into an immiscible solvent. The intensity of the colour reaction is determined using a visual standards scale. Total suspended solids (TSS) concentrations were determined gravimetrically using glass fibre filters with a nominal pore size of 0.7 μm. The analytical methodologies were selected as being robust, providing reproducible results, and technologically appropriate (Deutsch and Busby, 2000; Krueger et al., 2004; Kummu et al., 2007; Irvine et al., 2009).

Results and Discussion

Dry Weather Water Quality

The majority of dry weather samples were collected during the dry season. As noted above, water from the Bassac river enters Boeng Cheung Ek through the outlet during the rainy season. Because of this added complexity, the dry weather samples from the dry season (*n*=14) were analyzed separately from the dry weather, rainy season (*n*=3) samples. The data set was strongest for the dry weather, dry season conditions and because these conditions persist the majority of the time, this became the focus of the treatment efficiency calculations.

Example results for the middle and outlet sites are presented and compared with the results from the Meanchey and Trabek sewer channels (Figures 2 through 6). Relatively few samples have been collected from the Phnom Penh sewers in the past. JICA (1999) collected water samples at six sewer locations twice during the dry season and twice during the rainy season. Analytes included fecal coliform, dissolved oxygen, turbidity, conductivity, pH, COD, and BOD, but metal levels were not reported. Fecal coliform levels in the sewers ranged between 3600 and 4,600,000 cfu per 100 mL. The JICA (1999) data are consistent with our *E. coli* results as shown in Figure 5, for the Trabek, Meanchey, and Iron Bridge sites.

Takeuchi et al. (2005) reported the results for 15 sewer samples collected from around the city during the dry season (December, 1997). The means of the results reported by Takeuchi et al. (2005) were as follows: anionic surfactant (detergents) – 8.2 mg/L; total phosphorus – 5.6 mg/L; Cr – 9.4 µg/L; and Cu – 33 µg/L. The mean total phosphorus results from Takeuchi et al. (2005) are similar to our results (Figure 4), while the anionic surfactant, Cr and Cu levels reported by the earlier study are lower. Between 1997 and 2008 there was a general increase in industrial activity in Cambodia (focussing in Phnom Penh) particularly in the textile and garment industries (National Institute of Statistics, 2006). Given the limited data and differences in analytical methodologies, comparisons between studies must be viewed with caution. However, the increase in anionic surfactant levels in sewage certainly is consistent with increasing textile and garment industry activity.

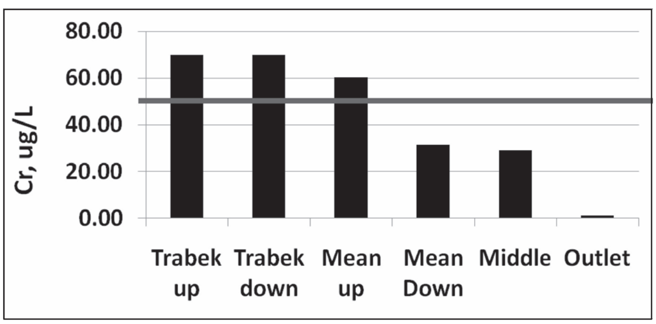

Figure 2: Mean concentrations for Cr. The Cambodian effluent standard for protected public water areas is 50 µg/L (shown by horizontal bar). "up" refers to the upstream sites and "down" refers to downstream sites. "Mean" in the x-axis refers to the Meanchey sites.

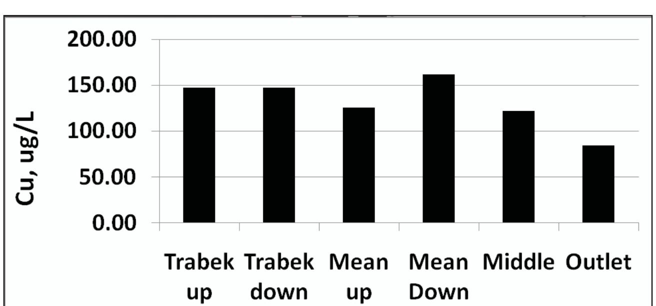

Figure 3: Mean concentrations for Cu. The Cambodian effluent standard for protected public water areas is 200 µg/L.

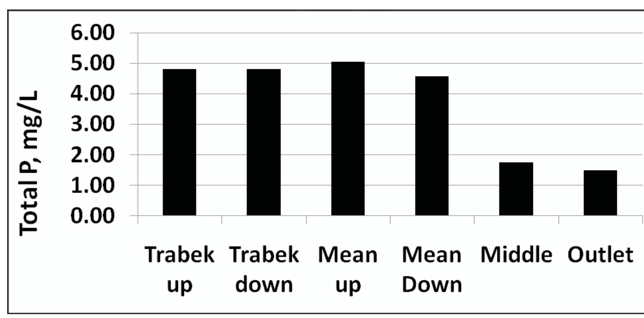

Figure 4: Mean concentrations for total phosphorus.

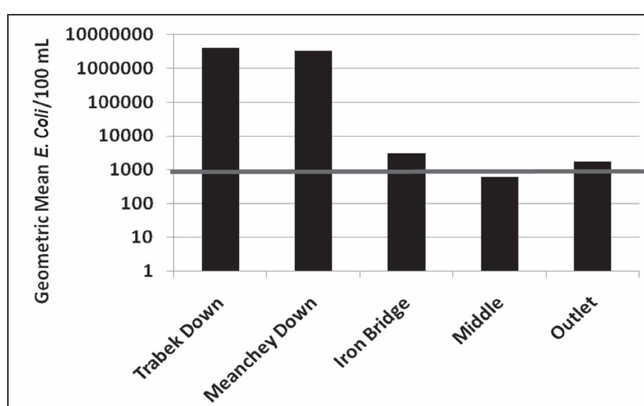

Figure 5: Geometric mean *E. coli*/100 mL. WHO standard, unrestricted irrigation for crops eaten raw - 1,000 E. coli/100 mL (shown by horizontal bar).

Table 1: Dry weather, dry season treatment efficiencies for Boeng Cheung Ek

	Cr μg/L	*Cu μg/L*	*Nitrate** mg/L*	*Tot. P, mg/L*	*Zn mg/L*	*Detergents mg/L*	*TSS mg/L*	*E. coli/100 mL*
Input*	28.9	205.2	4.2	4.7	0.6	6.2	48.8	5631692
Outlet	3.27	93.16	2.37	1.35	0.65	0.87	24.62	1741
% Reduction	–89	–55	–44	–71	+7	–86	–50	–99.97

* Flow-weighted mean concentration for the Trabek, Meanchey and Iron Bridge sites;
** Nitrate is nitrate-nitrogen, for nitrate as NO_3^- numbers must be multiplied by 4.43.

Table 2: Summary of treatment efficiencies for wetlands located worldwide, as reported in literature

Pollutant	*Treatment efficiency (%)*	*Source water that was treated*	*Reference*
TSS	45-85	Stormwater	Cappiella et al., 2008
Total phosphorus	15-75	Stormwater	Cappiella et al., 2008
Total nitrogen	0-55	Stormwater	Cappiella et al., 2008
Total Zn	30-70	Stormwater	Cappiella et al., 2008
Total Cu	20-65	Stormwater	Cappiella et al., 2008
Total Pb	14-51	Stormwater	Nu Hoai et al., 1998
TSS	25-86	Stormwater	Nu Hoai et al., 1998
Total Zn	13	Stormwater	Scholes et al., 1998
Total Cd	25-53	Stormwater	Scholes et al., 1998
Total Pb	65-(+180)	Stormwater	Scholes et al., 1998
Total Cu	68-(+171)	Stormwater	Scholes et al., 1998
Total Ni	48-52	Stormwater	Scholes et al., 1998
Total Cr	43-51	Stormwater	Scholes et al., 1998
Ionic Cu	53	Stormwater	Rochfort et al., 1997
TSS	47	Stormwater	Rochfort et al., 1997
Particle-bound Zn	57	Stormwater	Walker and Hurl, 2002
Particle-bound Pb	71	Stormwater	Walker and Hurl, 2002
Particle-bound Cu	48	Stormwater	Walker and Hurl, 2002
Particle-bound Cr	0	Stormwater	Walker and Hurl, 2002
Particle-bound As	(+150)	Stormwater	Walker and Hurl, 2002
Total Cu	80	Stormwater and Process water	Nelson et al., 2004
Total Hg	80	Stormwater and Process water	Nelson et al., 2004
Total Pb	83	Stormwater and Process water	Nelson et al., 2004
TSS	86	Sanitary waste	U.S. EPA, 2000
BOD_5	96	Sanitary waste	U.S. EPA, 2000
Fecal coliform	90	Sanitary waste	Quinonez-Diaz et al., 2001
Nitrogen	30-50	Sanitary waste	Kivaisi, 2001
Phosphorus	20-60	Sanitary waste	Kivaisi, 2001
Indicator bacteria	60-99	Sanitary waste	Kivaisi, 2001

Table 3: Example monthly mass loadings (kg), dry weather dry season for Boeng Cheung Ek

	Cr	*Cu*	*Nitrate***	*Tot. P*	*Zn*	*Detergents*	*TSS*
Trabek down	71.4	235.4	9149.2	7511.3	1033.8	17217.1	74329.9
Mean down	42.0	209.8	7185	4866.2	462.3	11328.7	78425.6
Iron bridge	29.0	567.7	4483.6	10846.1	1471.7	2268	87921.8
Total input	142.4	1012.9	20817.8	23223.6	2967.7	30813.8	240677.3
Outlet	10.3	293	7449.6	4235.2	2033	2750.9	77426.9
Difference (Retained)*	132.2	719.9	13368.2	18988.4	934.7	28062.9	163250.4

* Retained means this mass of material was trapped within Boeng Cheung Ek for the month;
** Nitrate is nitrate-nitrogen, for nitrate as NO_3^- numbers must be multiplied by 4.43.

Table 4: Mean storm event vs. dry weather (dry season) concentrations

	Cr μg/L	*Cu μg/L*	*Nitrate** mg/L*	*Tot. P, mg/L*	*Zn mg/L*	*Detergents mg/L*	*TSS mg/L*	*E. coli/100 mL**
				Storm Event				
Middle	33.17	124	4.9	1.45	0.40	0.67	51	11,749
Outlet	1	205	0.65	0.9	0.54	4.8	28	2187
				Storm Event				
Middle	29.21	122	1.70	1.75	1.17	1.66	36	611
Outlet	1.17	84.8	2.48	1.49	0.63	1.01	24	1741

* E. coli is geometric mean;
** Nitrate is nitrate-nitrogen, for nitrate as NO_3^- numbers must be multiplied by 4.43.

The first step to calculate the treatment efficiency for Boeng Cheung Ek was to determine a flow-weighted mean concentration for the three input sites, Trabek Down(stream), Mean Down(stream), and Iron Bridge. The flow weighting was based on the mean flow from the Trabek and Tumpun (Meanchey) pump stations for February, 2007 (as reported by the Ministry of Public Works and Transportation, City of Phnom Penh) and the dye testing for the Iron Bridge site. February, 2007, was selected for the flow weighting calculations because February is a month that is firmly in the dry season and a review of the pump station flow data indicated that minimal impact from storms was observed for this month. The flow for Trabek was 0.59 m^3s^{-1}, for Tumpun was 0.45 m^3s^{-1}, and for Iron Bridge was 1.0 m^3s^{-1}. Results of the treatment efficiency calculations are shown in Table 1. It is worth noting that the result for Zn was particularly affected by a high concentration recorded at the Outlet on 20/4/08. The concentration on 20/4/08 was about eight times higher than the mean of the remaining sample dates. Despite this possible anomaly, the 20/4/08 data point was retained in the analysis.

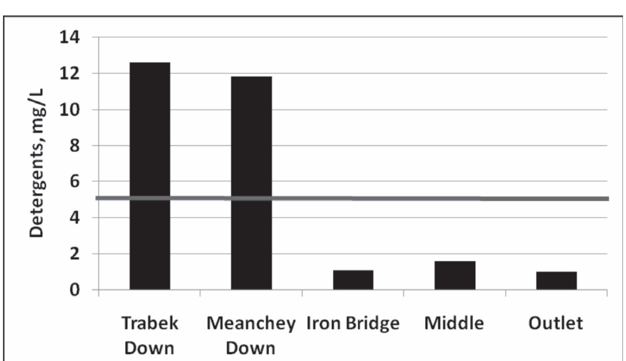

Figure 6: Mean detergents concentrations. The Cambodian effluent standard for protected public water areas is 5 mg/L (shown by horizontal bar).

The treatment efficiency results shown in Table 1 are quite good. For comparison purposes, results from other studies for both stormwater and sanitary wastes are summarized in Table 2. The treatment efficiencies for Boeng Cheung Ek tend to be in the mid- to higher-end of the range of the efficiences reported in Table 2.

Some of the data (e.g. Figures 4, 5 and 6) suggested that while the wetland was providing treatment, there was little difference in many of the quality parameters between the middle and outlet sites. Irvine et al. (2008) conducted more intensive sampling (up to 58 samples) on two different dates in locations that focussed on the area near the Trabek pump station. In analyzing *E. coli* and detergents only, it was found that much of the treatment was being done in association with the dense morning glory (*Ipomoea aquatic*) and water mimosa (*Neptunia oleracea*) fields within 350 m of the input to the wetland. Dye testing confirmed the path of flow through these vegetation fields and it appeared that filtration by these plants was providing particularly effective treatment. Slight increases in *E. coli* and detergent levels away from the morning glory/water mimosa and in open water areas was observed to occur in association with local, peri-urban community inputs (Irvine et al., 2008). Anh et al. (2007) found that morning glory in the Boeng Cheung Ek wetland was highly contaminated with fecal pathogens, which lends support to the idea of the filtering effect of the vegetation. Furthermore, Anh et al. (2007) reported at 2-3 log reduction of thermotolerant coliforms between water samples collected at the Tumpun and Trabek pump stations and the outlet of Boeng Cheung Ek, a finding consistent with our study.

An example monthly mass loading also was calculated for illustrative purpose using a simple volumetric approach where the loading was the product of a typical flow volume and representative concentration. The inputs from the three major locations, Trabek, Meanchey and Iron Bridge, were calculated and are presented separately in the case of loadings. Flow for the Trabek and Meanchey sites represented the monthly flow for February, 2007 (a dry period in the dry season), while flow for the Iron Bridge site was based on the dye testing. Results of the mass loading calculations are summarized in Table 3.

Dry Weather Hydrologic Characteristics

The volumetric determinations clearly are important to the calculation of the loadings in Table 3. A planning level check on the volumetric determinations proceeded as follows, assuming the month of February, 2007 (fully a dry weather period), to the extent possible:

Flow input to Boeng Cheung Ek

Trabek Channel: 0.59 m^3s^{-1}; Meanchey Channel: 0.45 m^3s^{-1} (Trabek and Meanchey based on pump station data); Iron Bridge Channel: 1.0 m^3s^{-1} (based on dye testing).

Total: 2.04 m^3s^{-1}

Evaporation from Boeng Cheung Ek

Estimated using Meyer's formula (after Patra, 2000):

$$E = \left(1 + \frac{U}{16}\right) \times 0.36 \times (e_s - e_a)$$

where E is evaporation in mm/day; U is elevation-adjusted wind velocity; e_s is saturation vapour pressure at the water surface and e_a is saturation vapour pressure of the air, at a specific temperature. Saturation vapour pressure at the water surface depends on surface water temperature (Patra, 2000, Table 4), values of which (mean = 28.8 ^{o}C; standard deviation = 0.8 ^{o}C) were obtained from YSI measurements at 38 locations on the wetland in February, 2007. Wind velocity for the city was only available for the International School site, downtown Phnom Penh for March, 2005 (elevation-adjusted value of 5.42 km/hr). The value for e_a is determined as $e_s \times$ relative humidity (relative humidity data for March, 2005, International School of Phnom Penh).

Total: 0.97 m^3s^{-1}

Outflow from Boeng Cheung Ek

Average from flow measurements at outlet site: 1.3 m^3s^{-1}

The total measured/estimated outputs (outflow+ evaporation) were 2.27 m^3s^{-1} while the measured/ estimated inputs were 2.04 m^3s^{-1}. Data were not available for water level elevation to estimate change in storage, but at this time of year it is likely that outputs slightly exceed inputs and water levels would be falling. Groundwater inputs and outputs were assumed negligible at this time of year. At a planning level it can be concluded that the hydrologic measurements/estimates were consistent and accurate.

Storm Event vs. Dry Weather

More limited data were available for storm events, with a sample collected in each of six storms at the middle and outlet sites. The mean values (geometric mean in the case of *E. coli*) are summarized in Table 4 for both dry weather (dry season) and storm event samples. In general, there is relatively little difference in the dry weather and storm event characteristics. The absence of a clear storm event vs. dry weather trend may be due to the combined factors of limited storm data and the size of the wetland that masks short term, event-based inputs. This was not the case for the sewer channel samples. Yim et al. (2008) showed that for the Trabek Upstream site, Cr, detergents and nitrates were significantly greater (α=0.05) in the dry weather than in the storm event samples and for the Meanchey Upstream site, detergents, *E. coli* and total phosphorus were significantly greater (α=0.05) in the dry weather than in the storm event samples. In general, it appears that sewage-related parameters (nitrates, total phosphorus and *E. coli*) and detergents (sourced from industrial effluents) were diluted in the sewers by stormwater runoff. Takeuchi et al. (2005) also found higher levels of total nitrogen, total phosphorus and detergents in dry weather samples as compared to rainy season samples.

Some of the increases in concentration observed between the middle and outlet sites may have resulted from local inputs by the peri-urban community, as noted above. The levels of total phosphorus in Boeng Cheung Ek during both dry weather and storm event periods (Table 4) place it well within the eutrophic category (Irvine and Murphy, 2009).

YSI Results

A very interesting diurnal pattern in dissolved oxygen consistently emerged at the outlet site, an example of which is shown in Figure 7. There was little observed diurnal variation near the sewage discharge (Meanin site), probably because the wetland metabolism had not started to work so close to the pump station. However, the swing in dissolved oxygen at the outlet is a good indicator of the changing balances between system photosynthesis and respiration (Ansa-Asare et al., 1999; Williams, 2000; Wang et al., 2003; Mulholland et al., 2005). A more thorough approach to modelling this diurnal pattern and relating it to wetland metabolism is warranted.

The weekly mean data for dissolved oxygen and conductivity at the outlet site also showed an interesting trend, as illustrated in Figure 8. During the period April through early August, 2007, the dissolved oxygen levels were fairly low and conductivity was fairly high, representing a dominant input of sewage during the dry season. During the rainy season, early August to late November, 2007, the dissolved oxygen levels rose at the outlet and conductivity dropped, as the freshwater pulse from the Bassac river continuously entered the wetland at the outlet end. Dissolved oxygen levels again dropped and conductivity increased from December, 2007 through February, 2008 with the onset of the dry season and the increasingly strong sewage signal.

Conclusion

Boeng Cheung Ek is effectively reducing pollutant loads in Phnom Penh's wastewater before it reaches the Bassac river during the dry season. The complexity of treatment during the rainy season, when sewage continues to enter at one end of the wetland and a freshwater pulse enters at the other end, could not be evaluated. It is expected, however, that this condition would increase residence time and treatment efficiency.

Although much of the treatment may be done before the wastewater reaches the mid-point of the wetland, this does not mean the wetland could be filled in without impact. The larger wetland provides storage for storm water pumped from the city to avoid flooding, as well as socioeconomic benefits (fishing, aquatic crops) for the peri-urban community living on the wetland.

Not surprisingly, the wetland is eutrophic and exhibits a strong diurnal pattern in dissolved oxygen that reflects the metabolism of the system. The metabolism dynamics should be studied in more detail and the dissolved oxygen pattern modelled.

A fuller assessment of wetland treatment performance, including modelling, optimization scenarios, socio-economic benefits, and health impacts should be completed before the wetland is irreparably altered and an important, sustainable means of water treatment is lost.

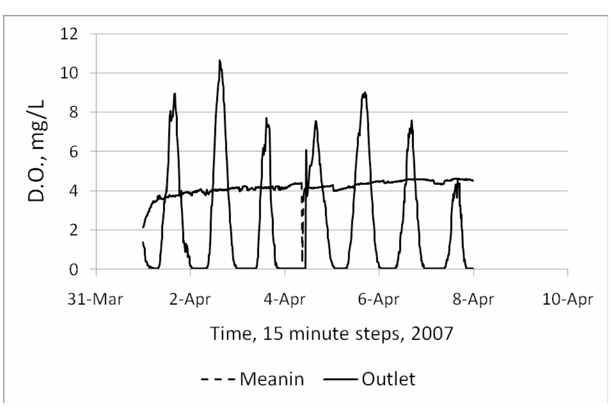

Figure 7: Dissolved oxygen levels in Boeng Cheung Ek near the Meanchey (Tumpun) pump station (Meanin) and at the outlet site.

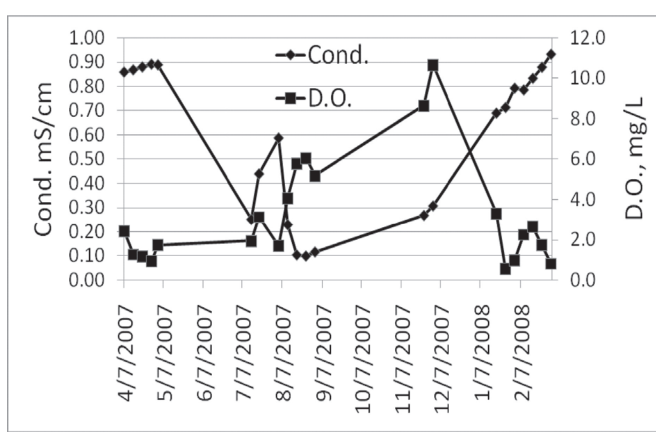

Figure 8: Weekly mean conductivity and dissolved oxygen, outlet site.

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