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Dynamic Modeling to Assess Natural Wetlands Treatment of Wastewater in Phnom Penh, Cambodia: Towards an Eco-City Planning Tool

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

Aims: A personal computer version of the Stormwater Management Model (PCSWMM) was applied to seamlessly link urban runoff, sanitary flow, pump station operations, and a natural wastewater treatment wetland in Phnom Penh, Cambodia, as a step towards developing a planning tool that could be used to explore urban development or climate change scenarios.
Study Design: PCSWMM was calibrated with measured flow and water quality data and used to estimate total phosphorus, total nitrogen, detergents, and *E. coli* levels at the outlet of the wastewater treatment wetland for the period May 15 to July 1, 2011.
Place and Duration of Study: Phnom Penh, Cambodia; January, 2011 to March, 2012.
Methodology: In support of model development, a limited water quality sampling program and bathymetric survey were conducted for the sewer and wetland system in both the dry and rainy seasons, 2011. Samples were analyzed for total nitrogen, total phosphorus, detergents, and *E. coli*. Sewer flow was measured continuously at 5 minute intervals to determine sanitary flow characteristics as input to the model and pump operation rules were determined through interviews with the pump operators and analysis of their data log books.
Results: Consistent with past studies, the sampling showed that the wetland was effective in treating municipal waste, particularly with respect to *E. coli* (99% reduction from sewage inputs)

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and detergents (86% reduction from sewage inputs). A lower treatment efficiency was observed for total phosphorus, at around 31%, while the treatment efficiency for total nitrogen was around 71%. The wetland was divided into four zones and PCSWMM was run in continuous mode for the period May 2-July 1, 2011. The mean levels of *E. coli*, detergents, total phosphorus, and total nitrogen estimated by the model for that time period compared favorably with sample results from the field campaign in August, 2011.

Conclusion: The naturally-occurring wetland treatment system in Phnom Penh is effective and fits well with the concepts of green infrastructure and eco-cities. PCSWMM is a useful decision-support and planning tool to explore various development and climate change scenarios in Phnom Penh.

1. INTRODUCTION

Consideration of conservation and the environment is not new in urban planning, but Roseland [1] noted that the concept of "eco-city planning" became more formally established in North America during the mid-1970's with the Urban Ecology group in Berkley, California, and culminating in the First International Eco-City Conference in 1990. Joss [2] suggested that until the mid-2000's, however, there were relatively few concrete examples of true "eco-city planning", but with increasing concerns about climate change and rapid urbanization in the developing world, there has since been a proliferation of eco-city initiatives. Wong et al. [3] provide detailed examples of the global diffusion in eco-city planning and it seems that such planning is becoming embedded within mainstream policy-making. Frequently, the focus of eco-city planning is energy and transportation technologies, land use planning, and empowerment of communities, although water infrastructure, water resource management, and waste management also are included in the eco-city paradigm [2,4]. In parallel with the maturing of eco-city planning concepts, stormwater management through Low Impact Development (LID) (alternately called Sustainable Urban Drainage Systems, SUDS) technologies is becoming part of the urban planning consciousness. Garrison et al. [5] presented case studies of 14 cities in North America that have implemented green infrastructure to help manage stormwater runoff, while Irvine et al. [6] reviewed the extensive LID implementation in Singapore. Technologies including rain gardens, bioretention cells, permeable pavement, rain barrels/cisterns, wetlands (constructed and natural), green roofs, and grassed swales all have a place in the LID philosophy [6,7,8,9,10]. Irvine [11] suggested that LID technology could

help to address climate change adaptation (and mitigation) which would increase urban system resiliency, although considerable research still needs to be done in this area.

Roy [12] underscored the importance of geoinformation technology and modeling support for urban planning when considering climate change, but also noted that such support frequently is not available in developing countries. In fact, although the application of dynamic (i.e. representing time-dependent changes in the system), mathematical modeling in urban drainage design and pollution assessment is well-established in parts of the world and increasingly includes consideration of climate change (e.g. [13,14,15,16,17,18]), such modeling is much less common in most countries of Southeast Asia [19,20,21]. Furthermore, Hansman et al. [22] note that infrastructure design and operation is not solely a technical issue, but the interface between technical and social considerations is poorly understood and inadequately managed at the overall systems level.

Phnom Penh, the capital city of Cambodia (population 1.5 million in 2009), is serviced by a combined sewer system and the sewage and stormwater is pumped to natural wetlands for treatment before it flows to the Mekong River system [23]. A natural wetland system potentially can provide effective wastewater treatment, collectively with environmental and economic benefits that include reduced energy use, reduced use of chemicals, no fixed (or sunk) costs, and essentially no maintenance costs. As such, a natural wetland system is consistent with eco-city philosophy. A recent study for Phnom Penh applied a personal computer version of the Stormwater Management Model (PCSWMM) to estimate contaminant loads in the sewer system

for a range of storm intensities and suggested that the Boeng Cheung Ek wetland was effective in treating municipal waste [21,24,25]. Some aspects of one of the major catchment areas, Stung Meanchey, required update, but more importantly, the earlier model did not represent pump station operations nor did it explicitly consider contaminant fate within the wetland. Wetland treatment efficiency assessment most simply was based on the difference between input and output contaminant concentrations and some simple loading calculations [21]. While PCSWMM appears to be a promising tool for decision-making and design purposes under current conditions and projected changes related to urban development and climatic shifts, additional sampling and model refinement to include pump station operations and explicitly consider wetland treatment were needed to fully realize the model's potential.

This study therefore aimed to expand the existing PCSWMM model for Phnom Penh to explicitly consider pump station operations, flow and contaminant routing through the Boeng Cheung Ek wetland. It also provides better insights to contaminant treatment within the Boeng Cheung Ek wetland using total nitrogen and phosphorus, *E. coli* and detergents as indicators. The application of PCSWMM to the Phnom Penh sewer and wetland treatment system will demonstrate that dynamic modeling can be usefully implemented for planning in a developing country. Ultimately, it is hoped PCSWMM can be one tool that can help to bridge the gap between technical and social issues in infrastructure design noted by Hansman et al. [22].

2. MATERIALS AND METHODS

2.1 Model Development

PCSWMM (running the U.S. EPA SWMM5 engine) was used to seamlessly connect the modeled sewer flows from central and south Phnom Penh (Meanchey and Trabek catchments) with the pump station (Trabek and Tumpun) operations, and then route the flow and contaminants through the Boeng Cheung Ek treatment wetland. The earlier work reported by Sothea et al. [25] for the subcatchment and sewer network parameterization was used as the starting point for the model refinement in this study (see Fig. 1). The dynamic wave routing

option was chosen rather than the kinematic wave option to reduce flow and water quality continuity error. Dynamic wave routing includes a term for momentum and therefore represents pumping and surcharging conditions more accurately. PCSWMM routing calculations were done at a 1 second time interval, with output reporting done every 10 minutes as well as averaging over the entire simulation period. Variable data reporting times provide flexibility for design or planning work. The observed pump operation data for storm events in 2011 were retrieved from pumping log books kept by the staff of the Tumpun and Trabek pump stations. Furthermore, the rules of pump operation used for PCSWMM were determined through discussions with the pump operators where it was determined that the pumps are operated manually, depending on the observed water levels at the stations. The Trabek station has 8 pumps, each with a capacity of 1 m^3/s, while the Tumpun station, which drains the Meanchey sewershed, has 5 pumps, each with a capacity of 3 m^3/s. The pump operators at the Tumpun station indicated that even during the largest storms historically only 4 pumps are run at a time for a total operational capacity of 12 m^3/s and the model therefore reflects this as the maximum capacity. The pumps were represented using the inline option in PCSWMM and the general pump curves are shown in Figs. 2 and 3.

The Boeng Cheung Ek wetland varies in surface area between 1,300 ha in the dry season and 2,000 ha in the rainy season. Because of the large size, it was decided to divide the wetland into four zones for modeling purposes. Zones 1 and 2 directly receive the pumped input from the Trabek and Tumpun stations, respectively (Fig. 1). Zone 3 represents the narrower middle part of the wetland, while Zone 4 includes the outlet towards the Bassac River at Ta Khmao. The rate of change of storage in the wetland was calculated in PCSWMM using the standard level-surface routing (or Puls Method) that required input of depth/area data pairs based on the bathymetry measurements described in Section 2.2 and GIS analysis of satellite images for each zone. PCSWMM determined the depth-volume relationship by averaging the surface area between adjacent values of depth, multiplying by the difference in depth, and adding the incremental volume to the accumulated total. A fuller description of the Puls Method, with worked examples, is provided by James et al. [26].

Pollutant routing through the wetland was done using a complete mixing approach:

$$C_2 = \frac{C_1 V_1 + \frac{(C_1^I I_1 + C_2^I I_2)}{2}\Delta t - \frac{C_1 O_1}{2}\Delta t - \frac{K C_1 V_1}{2}\Delta t}{V_2\left(1 + \frac{K\Delta t}{2}\right) + \frac{O_2}{2}\Delta t} \qquad (1)$$

where V is reservoir volume, C is effluent and wetland pollutant concentration, C^I is influent pollutant concentration, subscripts 1 and 2 represent the beginning and end of the calculation time step, respectively, I is inflow rate, O is outflow rate, $\otimes$t is the time step, and K is a decay coefficient, or the rate constant(1/day). The product of K and Δt was represented by R (the removal fraction) and ultimately R was used as a calibration coefficient in the model.

2.2 Data Collection and Processing

Rainfall data to drive the PCSWMM model were taken from a tipping bucket rain gauge installed on Street 432 (11.541870º N, 104.920084º E) in subcatchment S44 (Fig. 1). Dry weather flow rate data were collected at 5 minute intervals using a Hach Sigma 910 area-velocity meter installed at node J33 (11.543744º N, 104.920219º E) from March 25-31, 2011. This site, on Mao Tse Tung Blvd., was selected because it represents a relatively large, mixed land use contributing area, flow in the pipe was free from backwater effects and not affected by any adjacent lateral connections, ease of access, and relative security. Although limited, we believe this to be the first measurement of its kind in Cambodia. Through these data, dry weather flow rates for the Trabek and Meanchey catchments were estimated and a time pattern of dry weather inflow was calculated. Evaporation from the wetland was estimated using Meyer's formula, as described by Visoth et al. [21].

Wetland depth was determined manually from small, traditional wooden canoes across 8 transects (Zone 1 with 3 transects, Zone 2 with 3 transects, Zone 3 with 1 transect, and Zone 4 with 1 transect). Fig. 4 shows the general location of the transects. The measurements were done once in the dry season (March 27-28, 2011) and once in the rainy season (August 2-3, 2011). For each of the rainy and dry season efforts, 76 depth measurements were taken and it was to these data that the wetland hydraulics of the model were primarily calibrated. The modeled flow in the sewer system was based on the earlier calibrations done by Sothea et al. [25]

with some additional velocity measurements in September, 2011 for verification. Modeled flow also was checked against the measured outflow rates from the wetland reported by Visoth et al. [21].

Sampling for water quality was done at the same time as the depth measurements, although due to budget constraints not as many locations were sampled, with 36 samples for *E. coli* and detergents, and 20 samples for total phosphorus and nitrogen being taken in each of the dry and rainy seasons. Samples also were collected on the same dates at the pump stations to characterize influent water quality and at the outlet of the wetland to characterize effluent quality. Grab samples for E. coli and detergents were collected in 20 mL clean plastic bottles, approximately 10 cm below the surface. The bottles were new and provided by Micrology Labs (http://www.micrologylabs.com/Home), Goshen, IN, the supplier of the E. coli media. The bottles were rinsed three times with water from the sample site, before final collection, to minimize possible contamination. The samples were immediately placed on ice and were processed in the lab within a maximum of 8 hours after collection. The samples for total phosphorus and total nitrogen were collected in separate 500 mL clean plastic bottles, approximately 10 cm below the surface. These bottles also were rinsed three times with the water from the sample site, before final collection. After collection, the samples immediately were preserved with H_2SO_4 to pH<2, and placed on ice.

Coliscan Easygel from Micrology Labs (http://www.micrologylabs.com/Home), Goshen, IN, was used to determine *E. coli* levels. Briefly, a new, sealed, sterile plastic pipette was used to withdraw 1 mL of sample from the 20 mL sample bottle in the field and the sample was dispensed into the Coliscan Easygel growth medium contained within individual plastic vials. Each vial was gently swirled to distribute the inoculum and then placed on ice in the field, along with the 20 mL sample bottle. The medium/inoculum mix was plated immediately upon return to the Environmental Science Department Laboratory at Royal University of Phnom Penh. The poured samples were incubated at room temperature for 48 hours and after this period all purple colonies were counted as *E. coli*. In a comparison between Coliscan tests and standard membrane filtration (done at a New York State Health Department certified lab), Irvine et al. [27]

reported a correlation of 0.98 (n=21) over a range of 0 to 120,000 cfu/100 mL.

Detergents were measured using a CHEMetrics, Inc. (www.chemetrics.com) visual test kit that employs the methylene blue active substances method in which anionic detergents react with methylene blue to form a blue coloured complex that is extracted into an immiscible organic solvent. Results are expressed in mg/L as linear alkylbenzene sulfonate (LAS) equivalent weight 325. The intensity of the coloured reaction was determined using a graduated colour comparator having divisions of 0, 0.25, 0.50, 0.75, 1.0, 1.5, 2.0, and 3.0 mg/L. Samples were not filtered prior to analysis, but were diluted and re-analysed if the levels initially were reported as 3.0 mg/L. Detergents are a particularly good marker for garment and textile industry activities, which are prevalent in Phnom Penh [25].

Samples for total phosphorus and total nitrogen were refrigerated upon delivery to the Environmental Science Laboratory at Royal University of Phnom and were analyzed within a maximum hold time of 28 days. Total phosphorus was determined using Standard Method 4500 P [28] and quantified with a Helios Omega UV-VIS. Total nitrogen was determined using Standard Method 4500 N and quantified using manual titration.
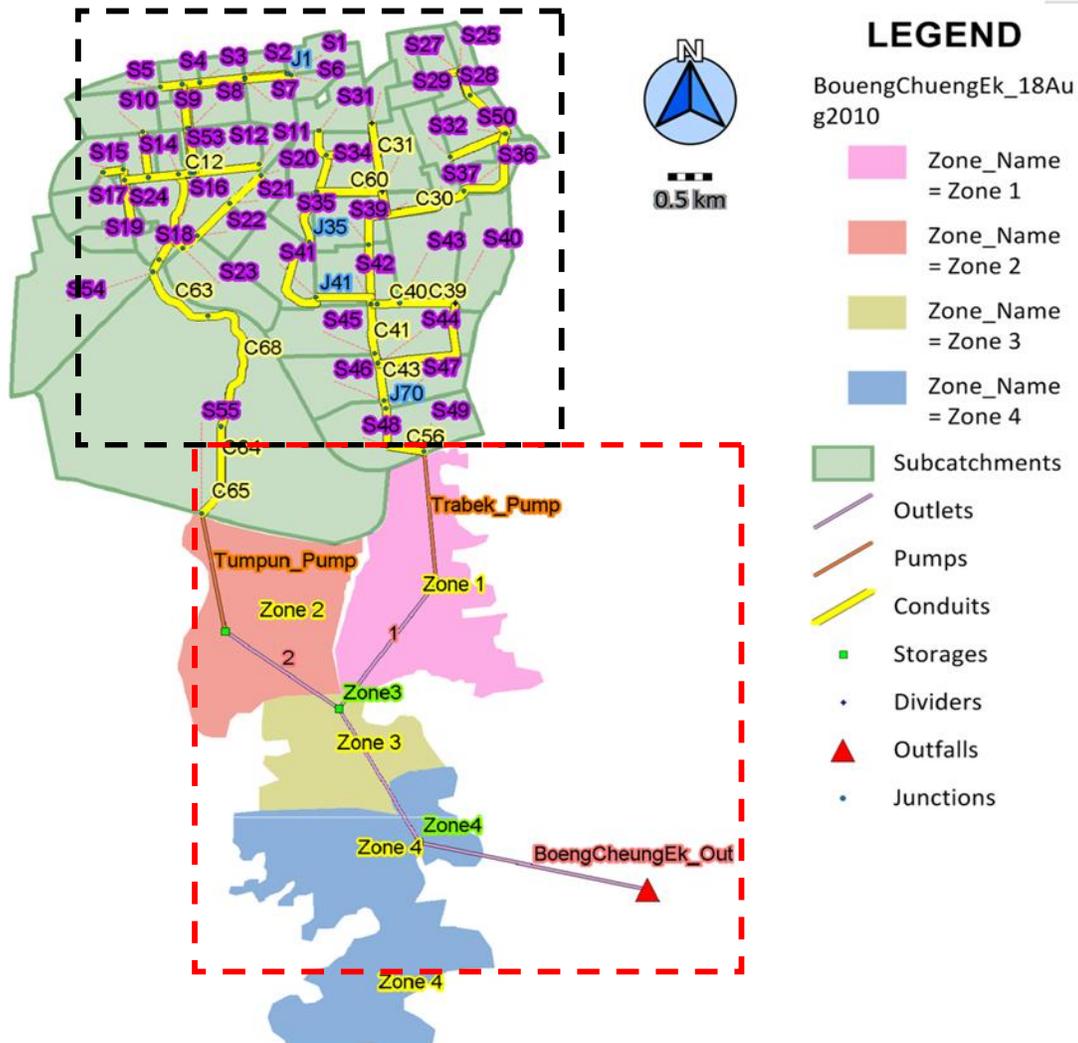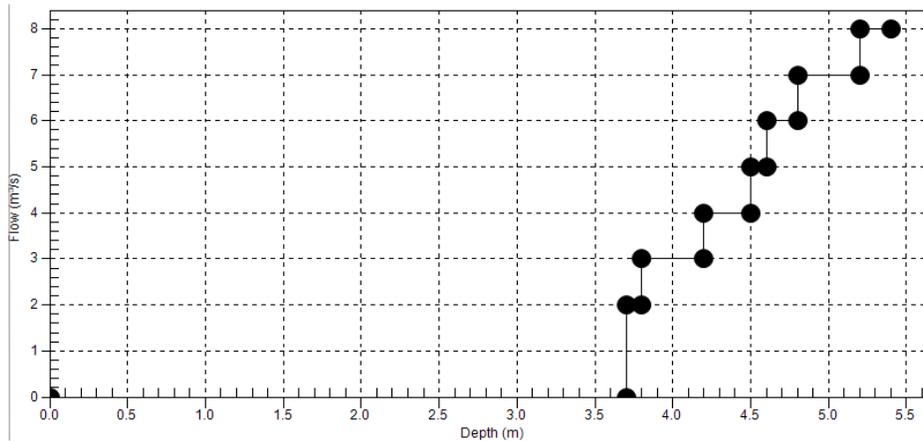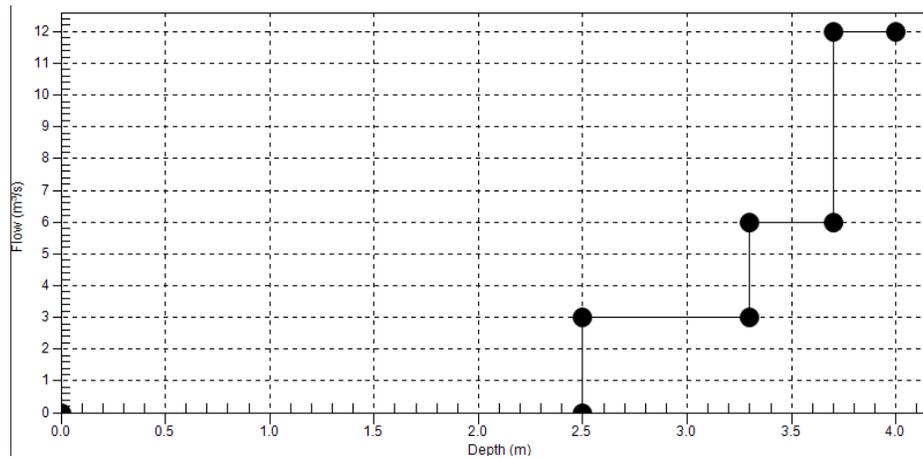

Fig. 1. The PCSWMM model setup. The previously existing component is enclosed by the black dashed box while the newly developed component is enclosed by the red dashed line

Fig. 2. Pump curve of Trabek station programmed in PCSWMM, showing forebay depth at which individual pumps are turned on

Fig. 3. Pump curve of Tumpun station programmed in PCSWMM, showing forebay depth at which individual pumps are turned on

3. RESULTS AND DISCUSSION

3.1 Rain Data

The recorded rainfall data for the period May 2-July 1, 2011 were binned into 10 minute time steps to drive the PCSWMM model. This period represents the early rainy season, which is a time when flow in the wetland is not yet influenced by a freshwater pulse entering from the Bassac River at the outlet of the wetland. A total of 362 mm of rainfall were recorded for the modeled period, with two events having peak rainfall intensities of 48 mm/hr.
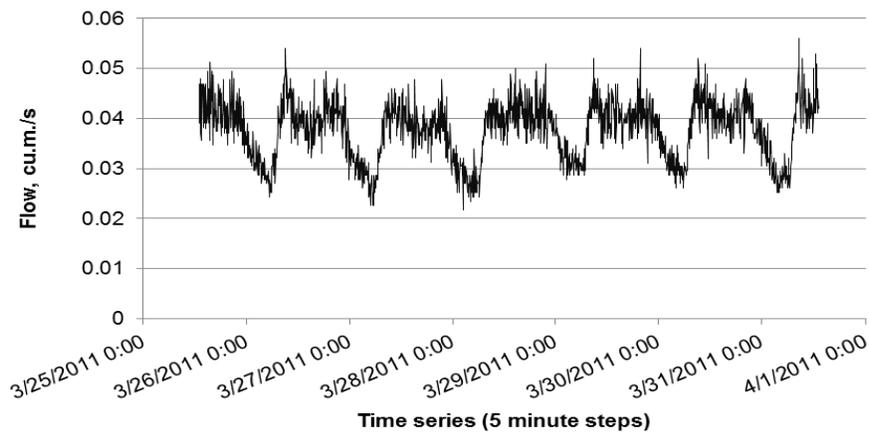
3.2 Dry Weather Flow

The dry weather flow measured at node J33 clearly exhibited daily variation related to anthropogenic activity (Fig. 5). Generally, the flow started to decrease between 22:10 and 22:50 and dropped to a minimum level between 05:30 and 08:30, increasing after that time. Flow on Sunday (March 27, 2011) was slightly lower than the other days measured, but further monitoring is required to confirm this as a consistent trend. The average dry weather flow per hectare was calculated as the average observed flow rate divided by the catchment area of the measured node. Thus, the average flow rate per hectare was 0.000234 m^3/s (0.0375 m^3/s/160 ha). Based on this result, the total dry weather inflows of the Trabek and Meanchey catchments applied in the model were 0.255496 m^3/s and 0.349257 m^3/s respectively.
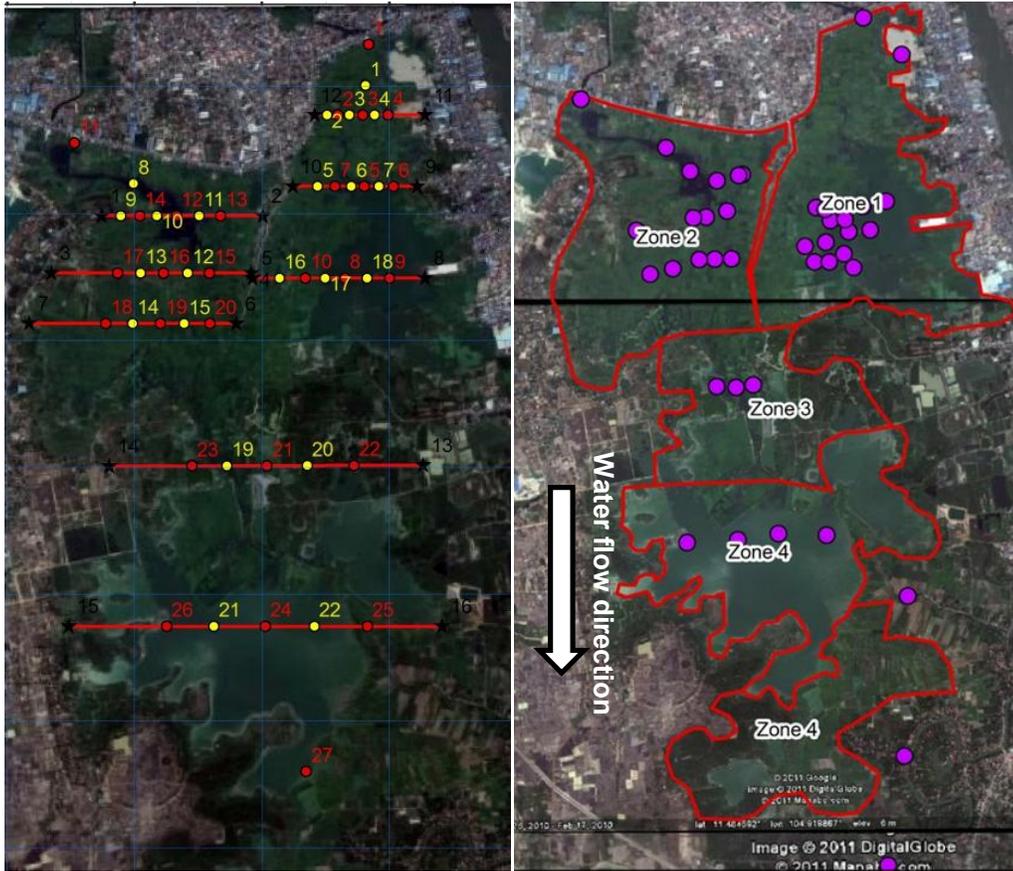
Fig. 4. Pre-determined transects for sampling sites (Left) and actual sampling sites (purple dots) for *E. coli* and detergents in Boeng Cheung Ek (Right). The difference between the pre-determined and actual sites was due to access to the water and ability to manually maneuver a small traditional wooden boat during the sampling process

Fig. 5. Dry weather flow in node J33 from March 25-31, 2011

The time pattern multiplier of dry weather flow at node J33, illustrating the cycle of anthropogenic activities calculated from the dry weather flow data (Fig. 5) is shown in Fig. 6. The temporal multipliers in Fig. 6 were used in PCSWMM to distribute total flow through the day.

3.3 Wetland Bathymetry

Results of the bathymetric surveys in Boeng Cheung Ek for the dry and rainy seasons are summarized in Table 1. The mean water depth for the entire wetland in the dry and rainy season surveys was 0.8 m and 3.1 m, respectively. Among the four modeled zones, Zone 3 is noticeably the deepest with an average depth in the dry season of about 1.2 m and 3.7 m in the rainy season.

3.4 Water Quality

The water quality results are summarized in Table 2. Not surprisingly, contaminant levels were highest at the pump stations, which would represent the sewage input to the wetland. Levels generally decreased moving towards the outlet from the pump stations to Zones 1/2, then Zone 3, Zone 4 and the outlet. The exception to this general trend is that *E. coli* increased slightly at the outlet site. The Wetland Outlet site (Table 2) actually is a channel connecting the wetland to a tributary of the Bassac River. Both formal and informal housing areas directly discharge sanitary waste to the channel, which may account for the slight increase in *E. coli* at this site. There also seems to be a general trend (although not for all parameters at all sites) towards lower levels in the rainy season than in the dry season. This suggests that the high volume of stormwater runoff from the city, associated with the rainy season, dilutes contaminant levels. The dilution from the city stormwater runoff in the rainy season can be enhanced by a freshwater pulse coming into the wetland from the Bassac River. The water quality findings in general are consistent with those reported by Visoth et al. [21] for sampling done in

2007 and 2008, although the total phosphorus treatment efficiency was lower in this study. Vuong et al. [29] similarly noted that the wetland was effective in reducing thermotolerant coliforms between inlet and outlet.

3.5 PCSWMM Modeling

Normally with a modeling exercise, one data set is used for model calibration and a second data set is used for validation. Unfortunately, due to budget constraints and the challenges associated with field efforts in a developing country, an extensive field program was not possible and only enough data were collected for model calibration. Dry weather flow concentrations input to the PCSWMM Pollutant Editor were an average of the Tumpun and Trabek Station rainy season values from Table 2. Similarly, an Event Mean Concentration (EMC) approach was used to model wet weather contaminant loadings and concentrations. The EMC value used for each subcatchment depended on which pump station it contributed to and the EMC values were based on the Tumpun and Trabek Station rainy season values in Table 2. The simple removal fraction option was used to model pollutant treatment for each zone, with average removal fraction (R) values being 0.16, 0.05, 0.25, and 0.29 for total nitrogen, total phosphorus, detergents, and E. coli, respectively. PCSWMM provided a report at 10 minute time steps, but for comparison purposes, the results of the water quality modeling effort were averaged and are shown in Fig. 7. To allow for model start-up in representing the large treatment wetland, the data in Fig. 7 were averaged for the period 15 May to 1 July, 2011 rather than from 2 May.
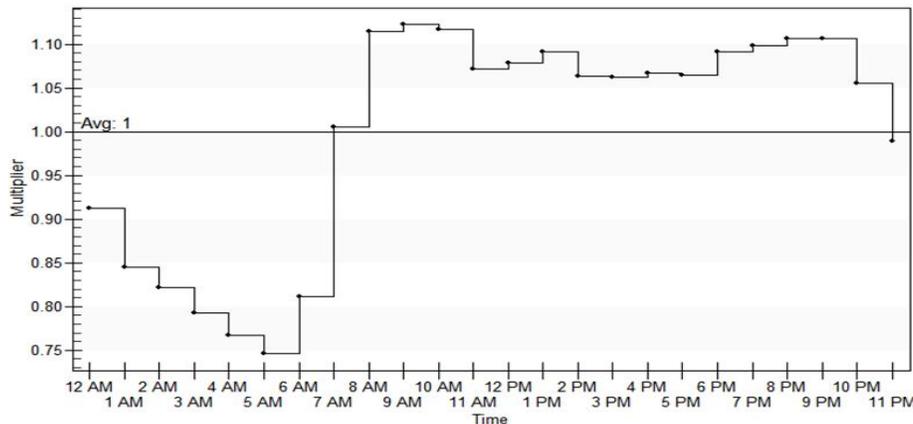

**Fig. 6. Time pattern multiplier of dry weather inflow at J33 for 24 hours**

Table 1. Characteristics for the water depths in different zones of Boeng Cheung Ek

Water depth (m)	Zone 1		Zone 2		Zone 3		Zone 4		Overall	
	Dry (n=22)	Rainy (n=22)	Dry (n=30)	Rainy (n=30)	Dry (n=7)	Rainy (n=7)	Dry (n=17)	Rainy (n=17)	Dry (n=76)	Rainy (n=76)
Mean	0.85	2.92	0.70	2.91	1.22	3.70	0.70	3.49	0.79	3.11
Standard deviation	0.33	0.48	0.40	0.74	0.63	0.63	0.32	0.42	0.41	0.66
Minimum	0.25	2.10	0.10	1.81	0.32	2.80	0.19	2.79	0.10	1.81
Maximum	1.51	4.01	1.47	4.04	1.87	4.35	1.16	4.16	1.87	4.35

Table 2. Water quality at different locations of Boeng Cheung Ek wetland

	Average total phosphorus (mg/L)		Average total nitrogen (mg/L)		Average detergent (mg/L)		Average *E. coli* (cfu/100 mL)	
	Dry season	Rainy season	Dry season	Rainy season	Dry season	Rainy season	Dry season	Rainy season
Tumpun St.	10.65 (n=1)	9.22 (n=1)	54.57 (n=1)	30.80 (n=1)	7.50 (n=1)	5.00 (n=1)	3984000 (n=1)	2285625 (n=1)
Trabek St.	14.02 (n=1)	9.64 (n=1)	44.94 (n=1)	33.04 (n=1)	2.50[*] (n=1)	7.50 (n=1)	39600[*] (n=1)	970312 (n=1)
Zone 1	10.79±1.93 (n=7)	7.09±0.97 (n=7)	32.42±4.49 (n=6)	16.47±3.07 (n=6)	1.03±0.54 (n=14)	0.73±0.40 (n=14)	46778±76945 (n=14)	5287±3178 (n=14)
Zone 2	12.88±2.23 (n=8)	7.27±1.01 (n=8)	35.60±11.12 (n=8)	19.89±5.01 (n=8)	3.67±1.36 (n=12)	2.69±0.89 (n=10)	72988±109426 (n=12)	108495±300932 (n=10)
Zone 3	7.85±1.15 (n=2)	8.90±2.08 (n=2)	23.94±21.39 (n=2)	17.29±0.89 (n=2)	0.92±0.14 (n=3)	0.50±0.14 (n=3)	2900±1452 (n=3)	1377±1452 (n=3)
Zone 4	6.51±0.31 (n=2)	5.35±0.56 (n=2)	26.06±0.62 (n=2)	7.63±1.88 (n=2)	0.25±0.01 (n=4)	0.31±0.31 (n=4)	100±115 (n=4)	269±311 (n=4)
Wetland outlet	8.54±0.95 (n=3)	1.08±1.01 (n=3)	14.39±2.75 (n=3)	3.78±3.53 (n=3)	0.33±0.14 (n=3)	0.17±0.14 (n=3)	3300±2254 (n=3)	19800±317968 (n=3)

[*]*Flagged as low, but a second analysis confirmed the detergents result*
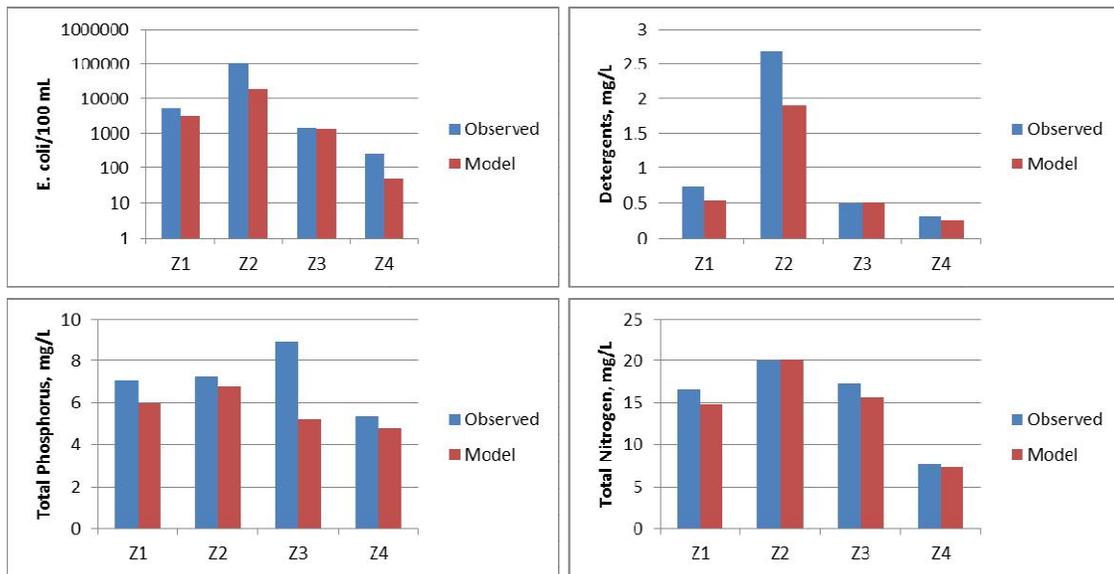
Fig. 7. Modeled mean values in each wetland zone for the period May 15-July 1, 2011. The observed values are for the rainy season data from Table 2, for comparison purposes

The comparison shown in Fig. 7 does not warrant a rigorous model fit analysis since the observed values only reflect the single sample campaign of August, 2011 (rainy season). However, for planning purposes, PCSWMM appears generally capable of replicating observed water quality. The *E. coli* and detergents values in Zone 2 and total phosphorus in Zone 3 were underestimated by the model. The higher observed values may reflect localized inputs to the wetland from the surrounding peri-urban community that are not captured by the model, or the need to better define the hydrodynamics and residence time in these zones.

4. CONCLUSION

This study confirms earlier work [21,24,25,29] that Boeng Cheung Ek can be regarded as an effective natural wastewater treatment system and fits well with the concepts of green infrastructure and eco-cities. PCSWMM was linked so that the entire system, from urban runoff to routing through the wetland can now be used as a planning tool. Within the PCSWMM framework, of course, questions remain including issues of more rigorous calibration and validation, better investigation of wetland bathymetry, and more explicit representation of pollutant treatment within the wetland than the simple removal fraction approach. Nonetheless, it would be possible to use the model described

herein to investigate issues related to wetland infilling due to urban expansion (including treatment issues and surface flooding within the city) as well as the potential impact of climate change on treatment and surface flooding.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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