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Phnom Penh Sewer Modelling and Contaminant Load Estimates

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Abstract: A version of the Stormwater Management Model (PCSWMM.NET) was applied to the sewer system of central and south Phnom Penh to model storm event flows. This section of the city is serviced by two main open sewer channels, Trabek and Meanchey, and the surface drainage area for these two channels was divided into 52 sewersheds for modelling purposes. A small (27 mm), medium (76.6 mm, the most representative storm) and large (392 mm, the worst case) storm event was modelled. Model calibration was done through observation of surface flooding locations and velocity measurements in the main sewer channels during the large storm. The model tended to under-predict mean velocity, but at a planning level seems to provide reasonable flow estimates. Storm event contaminant loadings were estimated for the large storm and Cu and Cr loadings were less than, but of the same magnitude, as an entire month of dry weather discharge. The model needs to be further refined by considering certain sewer flow diversions, pumping operations, and linking it to a wetlands model.

Key words: Stormwater management model, combined sewer system, surface flooding, metals loadings, Phnom Penh.

Introduction

Phnom Penh, the capital of Cambodia, is serviced by a combined sewer system that was constructed primarily during the golden age of King Sihanouk's rule in the 1960s. Years of neglect followed by limited maintenance budgets have resulted in a system with significant maintenance problems (Phyrun, 1996; JICA, 1999). JICA (1999) reported that many sewer lines were filled with sediment (mainly from unpaved streets) and solid waste (generated mainly by the neighbourhood inhabitants), such that flow capacity was reduced by between 50 and 90% of design. While the city has attempted to clear the pipes of the sediment and debris, progress has been slow due to budget constraints.

JICA (1999) noted that data showing the present sewer system's features, such as invert levels, longitudinal gradients, manhole locations, condition of the sewer, etc. were not well documented or registered. Furthermore, JICA (1999) took an understandably simple approach to developing runoff and inundation analyses whereby peak urban storm water flows were estimated using the Rational Method, while pipe diameters for new structures were designed using the Manning equation. JICA (1999) reported that between 1986 and 1998 the population of Phnom Penh grew from 581,000 to about 872,000 (the current population is 1.4 million). During this period the city developed with little planning or control, resulting in flooding problems, informal settlement along drainage ways, increased landfill, and poor urban infrastructure (Molyvann, 2003). Furthermore, it is anticipated that by

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2020 the population of the city will be about two million and new construction in the city core and suburbs continues despite the global economic slowdown. It appears that there will be a restructuring of the dense residential areas in the city core, progressive increase in density of the existing suburbs, as well as an expansion of the suburbs and industry (Phnom Penh Municipality, 2005; Englund and Ryttar, 2008). Traditionally, wetlands adjacent to the city have been used as natural wastewater treatment systems for the city, but these wetlands also are under the development process. Development puts more pressure on the drainage and wastewater treatment systems, in particular, during the wet season.

In order to plan for effective urban development, including sustainable wastewater treatment, it is necessary to characterize sewer flow and contaminant loads. Therefore, the objectives of this research are to: (1) establish digital information layers in ArcGIS9.3 to characterize the sewer system of south central Phnom Penh as a prototype for the rest of the city and other urban areas in Cambodia; and (2) apply PCSWMM.NET to estimate the flow rates and contamination loading to the Boeng Cheung Ek treatment wetland from the sewers of south central Phnom Penh.

The intent of this study is to develop analytical tools that can assist or inform urban planners, engineers and water resource experts in making decisions regarding sustainable wastewater treatment and the impact of urban development on wastewater treatment in Phnom Penh. Application of dynamic, graphically-oriented models for sewer analysis and design are not as common in Southeast Asia as in the west (Chaosakul et al., 2009). The proposed modelling approaches for this study (in combination with GIS-based land use assessment) will provide the capability of evaluating different development scenarios and the impact on hydraulic capacity, flooding, contaminant loads, and risk of exposure to water-borne diseases. Furthermore, the Stormwater Management Model can be used to assist with the design work needed for system improvement.

Research Methodology

Data Collection

Primary data collection was done from July 2007 through December 2008. The primary objectives of these efforts were to verify the existing flow direction and diameter of sewers, to geocode the manholes and surface inlets using GPS, and to measure the surface and sewer pipe slope using standard surveying methods. Additionally, flow measurement during storm events was done for the sake of model calibration.

Tipping bucket rain gauges were installed at three locations (Royal University of Phnom Penh (RUPP), Mennonite Central Committee (MCC) office and east Phnom Penh (near the waterfront) to record all rainfall for the period from May to December 2008 (Figure 1). The rainfall data were further analyzed to choose the most suitable events for input to PCSWMM.NET.

Figure 1: Study area, including rain gauge locations.

Secondary data were obtained from various institutions, agencies, and ministries as well as the literature (e.g. James et al., 2005). The existing catchments and drainage network categorized by the Department of Public Work and Transport (2007), and the sewer modelling report from the Municipality of Phnom Penh (2004) were collected and used as the baseline information for data processing.

Data Processing

The surface runoff from each sewershed is routed to a single point within the sewershed. To estimate the surface flow rate, the existing catchments (Boeng Salang (Meanchey) and Trabek, Figure 1) were further sub-divided into smaller sub-catchments by directly digitizing boundaries on Ikonos satellite images (1 m resolution). Through the combination of the findings from the field work, the satellite imagery, and ArcGIS9.3, several parameters were quantified including subcatchment area, width, pervious and impervious area. Sewer lines for the model input were drawn based on the existing sewer network lines. Additionally, the rainfall data from MCC were adopted for the data input preparation for the model since this location seemed to provide the most reliable results.

Model Operation and Calibration

PCSWMM.NET was applied to predict the overall picture of flooding and flow rate for the selected catchments. The output from each sub-catchment (sewershed) became the input for the modelled sewer pipe or channel. In addition to this, three different storm events (small, medium and large) were selected and run with the model.

The flow velocities measured at various locations in the sewers were applied for model calibration to ensure that the model produced reliable outputs. Field observation (location of surface flooding) during heavy rain also was used an indicator for this purpose. This required the field teams to travel through the city by moto during rain events to record time and location of surface flooding.

Contaminant Loading Estimation

The mean concentrations of five parameters (Cu, Cr, nitrate, Zn and total phosphorus) reported by Yim et al. (2008) were selected for the estimation of contaminant load. The total flow volume (Q) was determined from the model's output itself. The calculation of contaminant loading at the end point of each channel was estimated using a simple volumetric approach which is frequently used in sewer studies (e.g. Marsalek and Ng, 1989; Marsalek, 1990; Irvine et al., 1993, 1998, 2005). The equation is given as $L = Q \times C$, where L is contaminant mass load (mg), Q is total flow volume for the period of concern (L) and C is contaminant concentration (mg/L).

Results and Discussion

Sub-Catchment Identification

Sub-catchment identification was one of the most difficult tasks to complete and needed to be assessed carefully to optimize calibration effort and accuracy of model output. A total of 52 sub-catchments (sewersheds) were digitized for both Meanchey and Trabek catchments (Figure 2). It was concluded that this number of sub-catchments provided enough detail to adequately characterize the variable surface types of the different neighbourhoods and not be too numerous to be onerous for calibration.

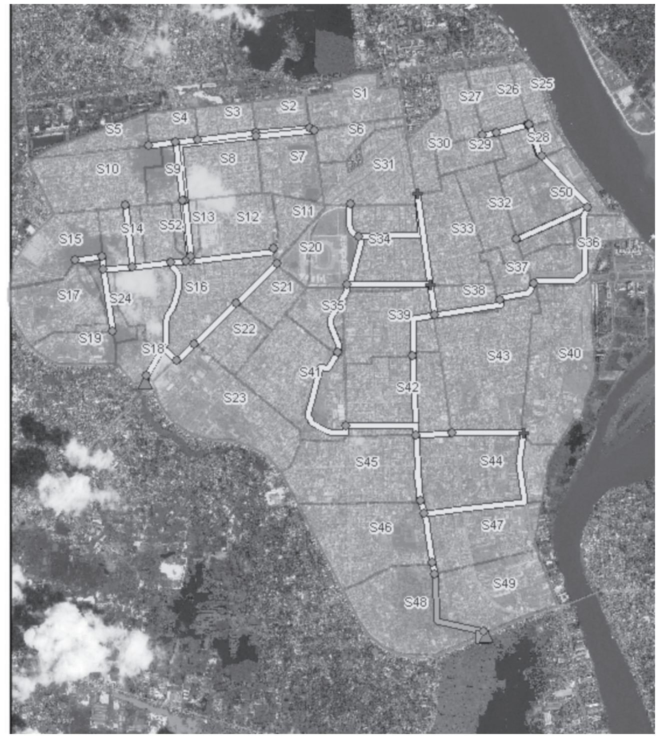

Figure 2: Digitized sub-catchments, conduits and nodes used in the modelling effort.

The two main sewer lines identified for modelling were the Meanchey and Trabek open sewer channels. Each modelled sewer line was combined by a series of connected pipes and nodes in the sub-catchments where nodes were identified depending upon the flow direction of water. The endpoints of the model were defined as C50 (Meanchey) and C56 (Trabek), both at locations near the pump stations. Pump station operation was not modelled in this study, but should be included in future work.

Storm Events

Three storm events, hereafter denoted as the small, medium and large storms, were processed for the model operation (Figure 3). The selection of different levels of rainfall was done to predict and visualize the different level of flow rate and flooding associated with the given storm event. The largest rainfall on 20th July, 2008 reached 392 mm (it was a worst case for the city) over a period of one hour and half, whereas the medium rainfall was on 15th August, 2008 and had a depth of 76.6 mm over a three-hour precipitation time. The small event had a total rainfall depth of 27 mm over a period of one hour and occurred on 14th September 2008. A probability analysis of daily rainfall from the Phnom Penh International Airport (2001-2005) showed the data to be

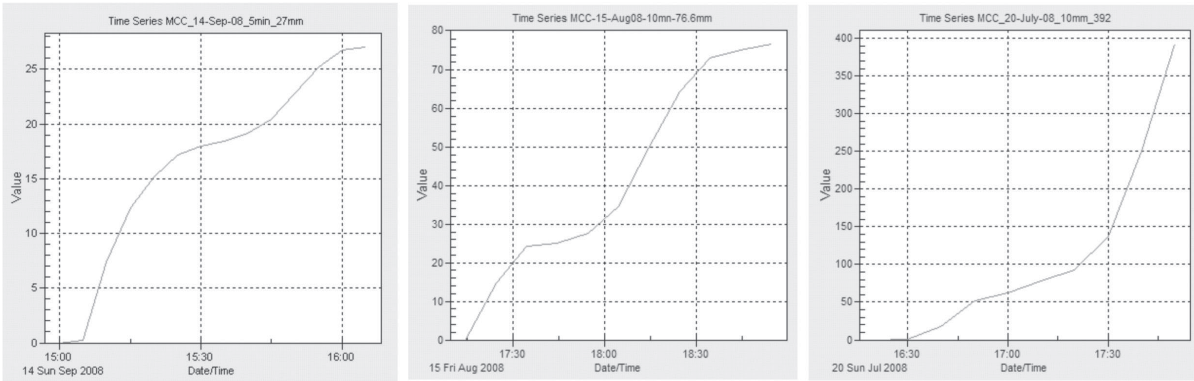

Figure 3: Selected rainfall events (mm) used for model input with small storm (left), medium storm (middle), and large storm (right).

well represented by the Inverse Gaussian distribution and that the probabilities of exceedance for the small, medium, and large storms were 10%, 2.8% and 0.0002%, respectively.

Model Results

Surface Run-off

The greatest peak run-off for all sub-catchments occurred at sub-catchment S43 reaching 183.3 m^3/s, 16.6 m^3/s, and 1.8 m^3/s for the simulation of the large, medium and small storm events, respectively. The lowest peak run-off for all sub-catchments was estimated for sub-catchment S13 at values of 10.8 m^3/s, 1.10 m^3/s, and 0.21 m^3/s for the large, medium and small storm events, respectively. A complete result from the model simulation for peak run-off is illustrated in Figure 4. The results from the model show that the sub-catchments (for instance, S39, S41, S43 and S44) having a larger area and greater width resulting in higher run-off rates.

Flooding Level and Duration

The maximum flooding overflows (surface flooding) for the sub-catchments are presented in Figure 5. The level of flooding varied from one junction to another due to the properties of the nodes and the maximum peak flooding overflow at J47 was estimated as 266.45 m^3/s, 104.94 m^3/s, and 9 m^3/s, resulting from the simulation of the large, medium and small storms, respectively.

The flooding duration for each junction also was computed by the model. The average flooding duration for the large, medium and small storms were 87, 46, and 9 minutes, respectively (Figure 6). Examples of floods occurring during the large storm are illustrated in Figure 7. There are several points to be discussed in this

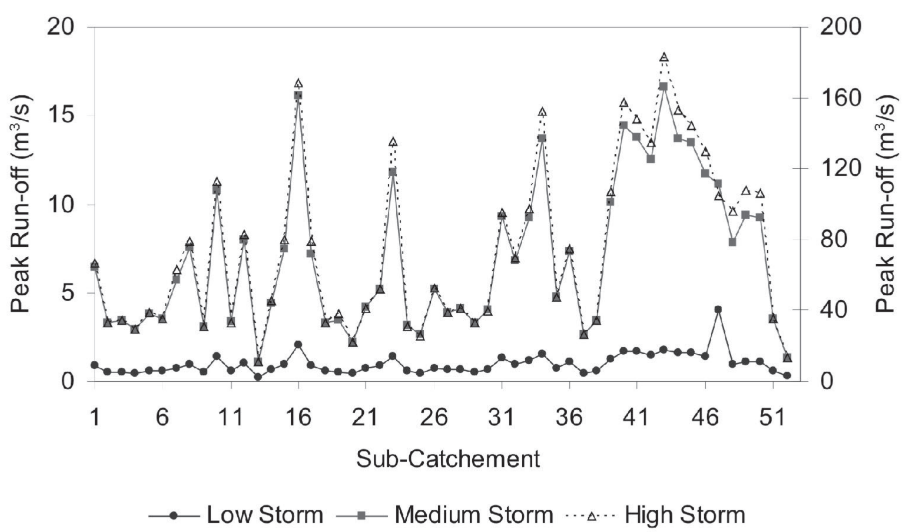

Figure 4: Peak run-off from sub-catchments for the three different sized storm events. The low (small) and medium storm run-off rates correspond to the left y-axis and the high (large) storm run-off rates correspond to the right y-axis.

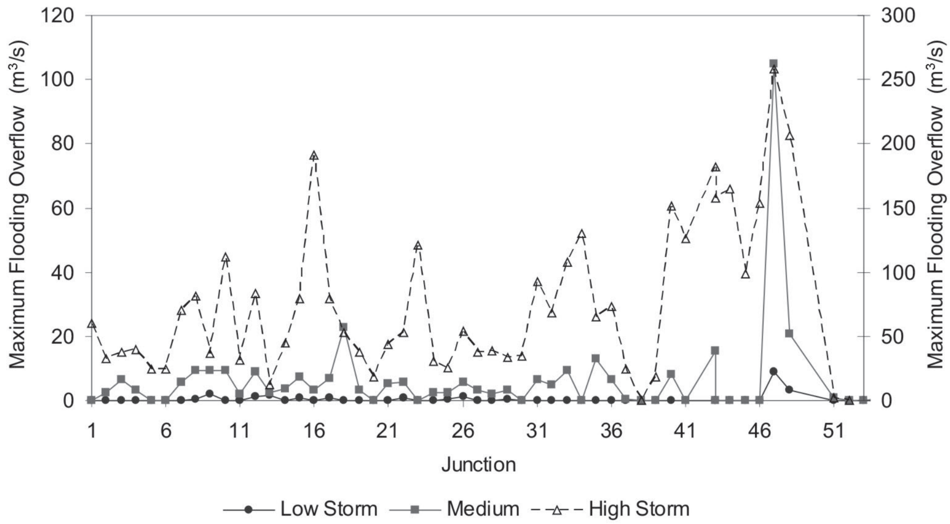

Figure 5: Maximum flooding overflow (surface flooding) for the three different sized storm events. The low (small) and medium storm flooding rates correspond to the left y-axis and the high (large) storm flooding rates correspond to the right y-axis.

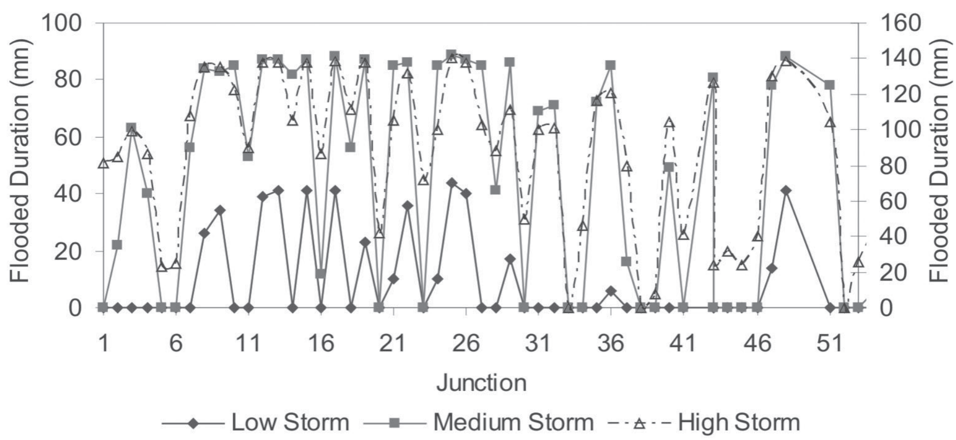

Figure 6: Flooding duration for the three different sized storm events. The low (small) and medium storm flooding durations correspond to the left y-axis and the high (large) storm flooding durations correspond to the right y-axis.

Figure 7: Surface flooding in Phnom Penh during the large storm event.

section since there were some junctions that the model suggested were experiencing flooding overflow even though in reality this did not happen, and other junctions for which flooding was predicted, but not at the magnitude observed. The possible factors contributing to model error are: (1) the diversion of flow along the modelled sewer lines was not considered at some locations, although it may occur; (2) the impact of sediment accumulation is unknown; (3) pumping activities at Trabek and Meanchey outlets were excluded; (4) the informal water releasing practices to the natural ponds and reservoirs nearby were not taken into account; and (5) possible inaccurate representation of diameter of sewer pipe.

Model Evaluation

It is important to evaluate model output to ensure that the model is producing a logical, reliable and acceptable output. For this project, in addition to observed surface flooding patterns, it was possible to compare the measured flow velocity with the modelled velocity at a limited number of locations. The flow velocity measurements recorded at Trabek Up (C37) and Trabek Down (C56) during the storm event on 21st July, 2007 were selected for the calibration (Table 1). The comparison in Table 1 indicated that the velocity from the model is lower than the actual measurement. The discrepancy between measured and modelling results may be due, in particular, because the pump station operation was not modelled. Pump capacity for the Tumpun (Meanchey) pump station is 15 m^3/s and 8 m^3/s at the Trabek pump station.

Based on the comparisons between observed and modelled surface flooding patterns and measured and modelled flow velocity it can be concluded that the results from model simulation were acceptable and reasonable at a planning level. Therefore, the outputs from the model can be used as a tool or baseline for urban planners, decision-makers and other concerned agencies in assessing future drainage and sewage treatment options.

Contaminant Load Estimation

The contaminant load estimation at Trabek Down (C56) and Meanchey Up (C50) sites were computed based on the available concentration data obtained from Yim et al. (2008). The contaminant loading estimation is summarized in Table 2. The nutrient concentrations at the Meanchey Up (C50) site generally were higher than at the Trabek Down (C56) site during storm events, which resulted in higher loading rates (Table 2). It also is interesting to note that the Cr and Cu loadings at the Trabek Down site (Table 2) were less, but of a similar magnitude, as the dry weather flow loadings of an entire month reported by Visoth et al. (2010). The nitrate and total phosphorus loadings from the large event are much less than the monthly dry weather flow loadings reported by Visoth et al. (2010) (8-13% of the monthly loading), primarily because of concentration dilution for the storm (Yim et al., 2008).

Conclusions and Recommendations

PCSWMM.NET was successfully applied to provide planning level estimates of urban runoff and combined sewer flows, together with contaminant loadings, for central and south Phnom Penh, Cambodia. The model has good potential for use as a decision-making tool in urban drainage design work, as well as to assess sustainable sanitation options to support future

Table 1: Comparison between actual and modelled flow velocity

Conduit's Location	*Actual Flow Velocity (m/s)*	*Modelled Flow Velocity (m/s)*	*Differences (%)*
Trabek Up (C37)	5.9	4.6	22
Trabek Down (C56)	10.5	8.35	20.5

Table 2: Contamination mass loading (kg)

	Mass Loading (kg)				
Location	*Cr*	*Cu*	*Zn*	*Nitrate*	*Total Phosphorous*
Meanchey Up	16.57	104.02	133.99	2,327.29	881.55
Trabek Down	16.44	115.67	3,572.10	1,190.70	623.70

development of the city. Rivard et al. (2006) note that stormwater management in tropical countries poses some specific challenges not encountered in temperate climates, particularly in relation to rainfall data, surface flooding, debris and sediment, and design criteria. They caution that urban stormwater control measures for tropical countries must consider region-specific issues that prevent the direct use of approaches routinely used in temperate climates. This issue can be seen particularly with respect to surface flooding in Phnom Penh. As such, it will be important to refine the PCSWMM.NET model in the future, through collection of additional rainfall, runoff, and pollutant data. The operation of the major pump stations also needs to be included in the future. Nonetheless, this was a good first step in establishing urban stormwater modelling principles in Cambodia. Future modelling efforts also must extend to include technical training workshops for government line agencies and dissemination of results to the public.

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