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Mass balance of a wastewater loaded canal system: case study of Bangkok

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Abstract A dynamic water quality model was applied in order to investigate self-purification processes in highly loaded canals in the centre of Bangkok, capital city of Thailand. Oxygen production by aquatic plants induces a significant diurnal variation of the dissolved oxygen concentration. The corresponding profiles of heterotrophic growth and BOD_5 concentration demonstrate the limiting impact of oxygen shortage during night time. Both self-purification mechanisms – biological degradation and settling – are considered and water-sediment interactions are calculated. Simulation results and measurement data are summarized by mass balance schemes which offer a telling characterization of the complex system.

Keywords Mass balance; mathematical modeling; oxygen limitation; self-purification; wastewater-loaded canal

Introduction

The surface canal system in the centre of Bangkok faces tropical rain climate and receives high domestic loads as the wastewater collecting and treatment system beginning construction. The city of Bangkok is situated exactly at sea level on a bend of the river Chaopraya about 30 km inland. Mahanak canal is about 11 km long and 20 m wide and receives waste loads up to 11,938 kg BOD_5 d^{-1}. Surface canals are connected to the river by pumping stations and gates. The water exchange between river and canals is controlled by these facilities which create a hydraulic slope (Figure 1). The lateral inflow of pre-clarified wastewater into the canals is diluted by river water in the ratio of about 6 to 1 and the water temperature stays constantly between 29–30°C. The high load together with limited flow leads to oxygen shortage, low water quality and odor problems. Diffusive wastewater flow, lack of water quality data and complex process interactions make it difficult to calculate or improve canal self-purification efficiency without exactly knowing about the mass balances.

Data and methods

Monitoring data from Bangkok Metropolitan Administration (BMA) has been collected between 1997–1998. Dissolved oxygen (DO), pH value, salinity, water level and pumping rate have been monitored hourly.

Water quality parameters such as BOD_5, suspended solids (SS), total Kjeldahl nitrogen (TKN), ammonia, nitrite and nitrate and coliform bacteria have been measured twice a month. Population distribution and infrastructure have been recorded in Geographic Information System by the same organization. Unit load per capita had been investigated by former studies (Thongchai, 1987; JICA, 1990). Most of the data has been prepared in electronic form and analyzed. In the first step, water flow has been calculated from hydraulic data and the removed wastewater fraction has been estimated from the difference between influent and effluent load.

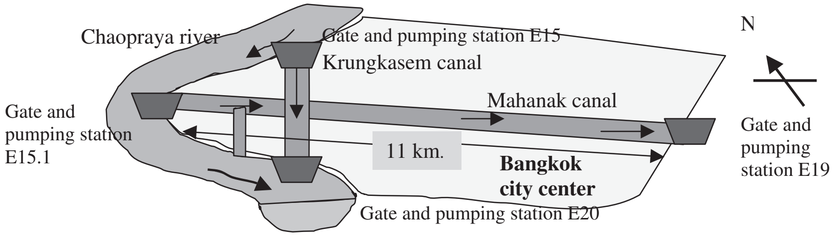

Figure 1 Main canals in Bangkok, showing dominant flow directions and gates to Chaopraya river

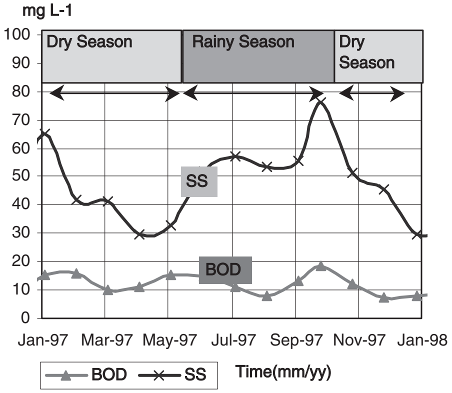

Figure 2 BOD_5 and suspended solids seasonal variation in mg L^{-1}

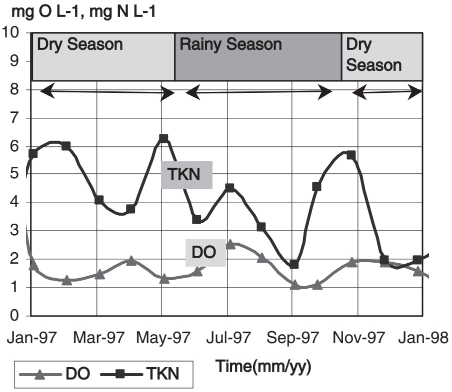

Figure 3 Dissolved oxygen and total Kjeldahl nitrogen seasonal variation in mg L^{-1}

Water quality data are presented in Figures 2 and 3 in unit mg L^{-1} to show seasonal variations. The BOD_5, SS and TKN concentrations dropped twice a year because of high river water inflow from March to April and rainfall between July and September. The peak value of suspended solids occurred in October due to rainfall and high turbidity of river water. Note that average value for BOD_5 is 12 mg L^{-1}, total nitrogen is 3.91 mg N L^{-1}, suspended solids is 47 mg L^{-1} and dissolved oxygen is equal to 1.58 mg L^{-1}.

During the first step of this study basic water quality models (Streeter-Phelps and Monod) have been used in order to investigate the relationships between organic substrate (BOD) and dissolved oxygen concentration (DO) while neglecting conversions of nutrients. Figure 4 presents monthly DO measurement values against corresponding BOD concentrations. Additionally, monthly DO concentrations have been calculated from measured initial DO and BOD concentrations and calibrated degradation and oxygen supply rates by Streeter-Phelps equations ($DO = f(DO_0, BOD_0, k_{deg}, k_{ox})$; Chapra, 1997). Average degradation rate k_{deg} used in point estimation is 1.3 d^{-1} and oxygen supply rate k_{ox} is 1.6 d^{-1}. Linear regression of measured DO concentrations shows a perfect fit with Streeter-Phelps point estimation values (Figure 4).

The BOD removal rates in the canal have been calculated from the difference between organic input and output load related to the input load and the corresponding hydraulic retention time. The retention time ranges between 0.2 and 0.8 days. Resulting removal rates gave the first estimation for the organic degradation and have been plotted versus the actual measured BOD concentration in the canal (Figure 5). This relation was compared to the function for bacterial growth r_g according to Monod

$$r_g = f(BOD, DO) = r_{g,\max} * \frac{BOD}{k_{BOD} + BOD} * \frac{DO}{k_{DO} + DO} \tag{1}$$

where k_{BOD} and k_{DO} are the half-saturation coefficients for organic substrate and dissolved oxygen.

By substitution of substrate BOD from measurement and oxygen DO from regression in Figure 4 into Eq. (1), the maximum growth rate $r_{g,\max}$ was fitted to data by linear least square method (Runge–Kutta fourth order). The maximum growth rate $r_{g,\max}$ is equal to 1.82 d^{-1}. The BOD range that allows highest growth and degradation rates is between 8–18 mg L^{-1}. BOD_5 concentrations exceeding 15–20 mg L^{-1} drive the degradation process towards an oxygen limitation. To investigate this fact in detail, a dynamic modeling tool was employed.

Mahanak canal was defined as river compartments in the AQUASIM simulation software developed by EAWAG, Switzerland (Reichert, 1998). Segment length and calculation time interval have been selected to ensure model stability and accuracy. Initially, the friction slope of the canal (Manning roughness) was calibrated by water level data. The hydrodynamic parameter gained by flow modeling was validated by the transport model in the second calibration step. Since the tides induce regular salinity variations at the canal inflow, the total dissolved solids concentration was interpreted as a natural tracer compound. Time lags between salinity peaks in the influent and effluent flow confirmed the Manning coefficient (0.04 $m^{-1/3}$ s) and the decreasing variation range revealed the diffusion coefficient depending on flow velocity (Wanner *et al*., 1998). Biokinetic conversion processes according to the state of the art of river modeling (Rauch *et al*., 1998) have been implemented into the open structure of the AQUASIM model environment.

Results and discussion

Dissolved oxygen at the canal outflow has a significant diurnal variation due to plant photosynthesis and anaerobic conditions occur between midnight and sunrise. Figures 6, 7 and 8 demonstrate the correspondence of oxygen variation, heterotrophic growth rate and BOD_5 variation. During day time at oxygen concentrations approaching 3.0 mg L^{-1}, maximum heterotrophic growth rates near 6 g m^{-3} d^{-1} cause a continuous decrease of the BOD_5 concentration until midnight. After all the available oxygen has been consumed, growth drops close to zero and BOD_5 recovers. According to these simulation results about 45% of the total oxygen input is produced by aquatic plants which are the main oxygen source beside oxygen transport from the river and reaeration from the air–water interface (Figure 9).

Saturation and inhibition coefficients used in this study are taken from ASM2 (Henze *et al*., 1995), Chapra (1997) and Cole (1995). In this study, specific nutrient (nitrogen and

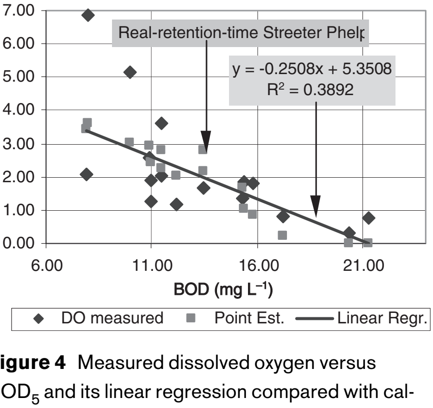

Figure 4 Measured dissolved oxygen versus BOD_5 and its linear regression compared with calculated values from actual retention time (Streeter-Phelps model)

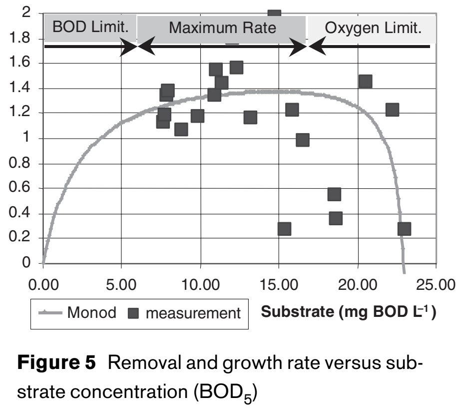

Figure 5 Removal and growth rate versus substrate concentration (BOD_5)

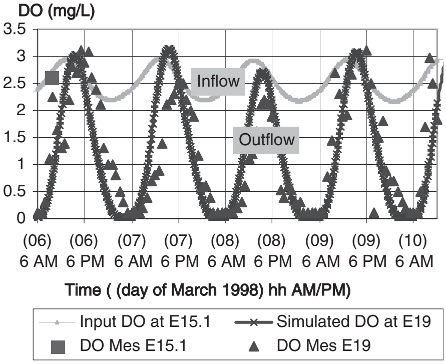

Figure 6 Dissolved oxygen calibration (March 1998)

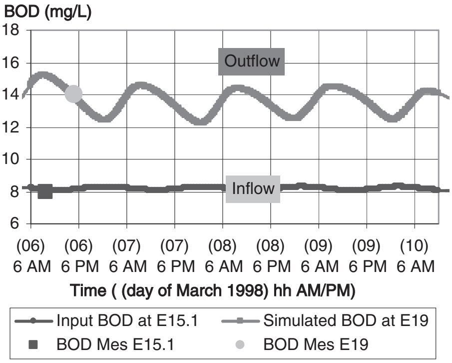

Figure 7 Biological oxygen demand calibration

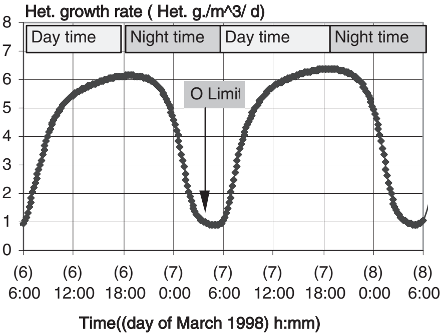

Figure 8 Heterotrophic growth rate

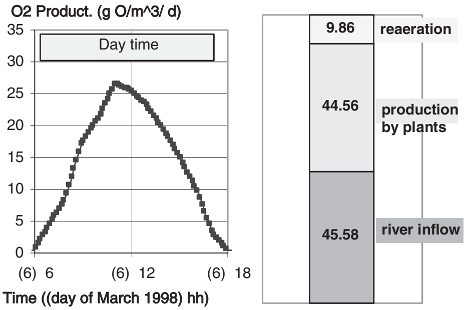

Figure 9 Oxygen production rate by aquatic plants in absolute numbers and in comparison with other sources

phosphorus) concentrations are found to be higher than half saturation value all the time. Delayed decrease of DO after sunset indicates a limiting influence of phosphorus which is confirmed by the model performance (Figure 6) and the agreement with measurement values of 0.2 mg total-P L^{-1} on the average. The nitrogen demand for the building up of biomass is completely saturated at a mean concentration of 3.7 mg TKN L^{-1}.

The results from model calibration have been used to calculate the internal mass balance of the considered system – i.e. canal water with biomass and the sediment – and the mass flow from and to the boundaries (river, wastewater flow, atmosphere). Figure 10 shows the mass balance of oxygen from free oxygen and nitrate that can be used as oxygen sources for growth and respiration (aerobic and anoxic). These amounts are presented in unit kg O_2 d^{-1} and percent of total oxygen input and do not include oxygen bonded in organic substances. Sediment and water interaction has been involved in the model, about 5% of the oxygen input is required for oxidation of methane and ammonia released from sediment layer. Mass balance of organic carbon based on BOD_5 calculation is presented in Figure 11 in unit kg C d^{-1} and percent of total received load. 10% of the organic input load is biologically oxidized to CO_2, about 1% is converted to methane and about 7% is accumulated in the canal sediment. The canal sediment layer needs about 7 years to build up its 60 cm thickness according to the actual dredging intervals. To sum up the self-purification efficiency of the canal including biodegradation and settling achieves only 18.5% of the input load during the dry season. During the rainy season oxygen transport from the river and the rain water increases significantly and self-purification exceeds 60%.

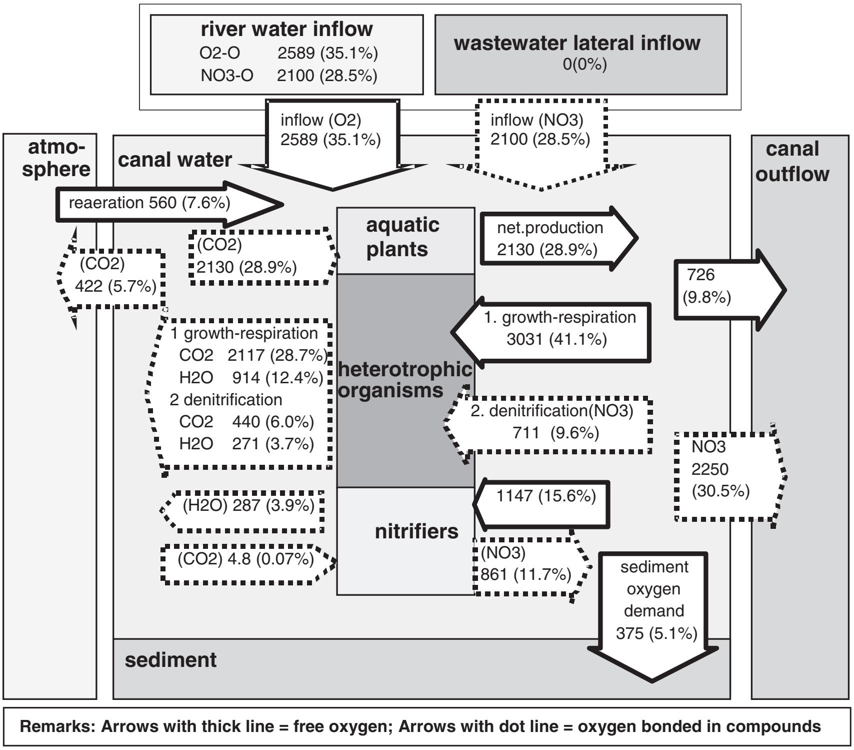

Figure 10 Mass balance of oxygen in the canal system of Bangkok, March 1998 (in unit kg O d^{-1} and percent of total oxygen input, oxygen bonded in organic substances is not included)

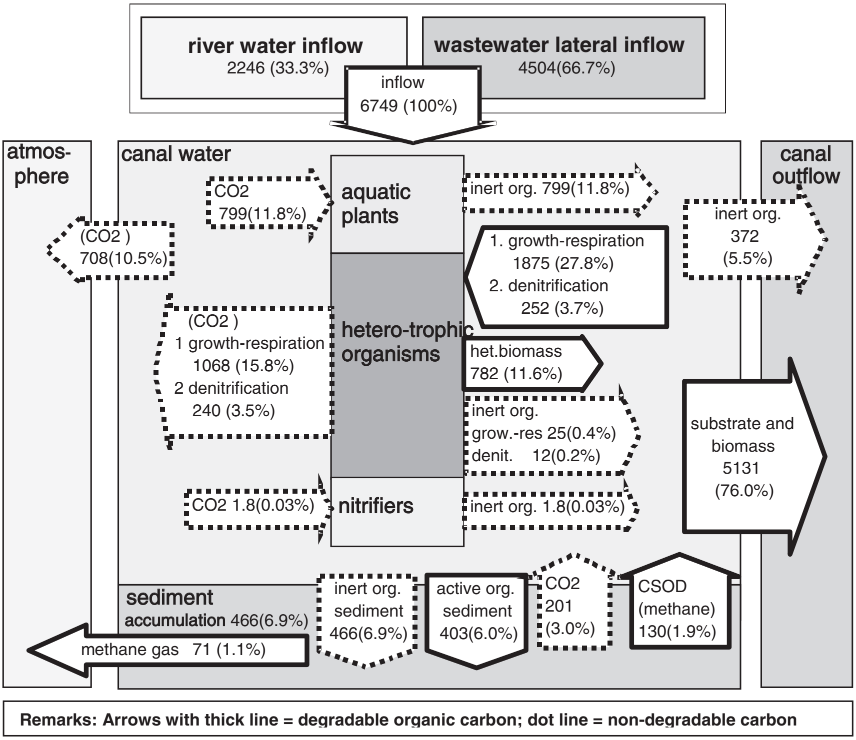

Figure 11 Mass balance of organic carbon and its degradation products in the canal system of Bangkok, March 1998 (in unit kg C d^{-1} and percent of total input calculated from the BOD load)

Conclusions

Oxygen has been identified as the limiting factor of the degradation of organic compounds in the canals of Bangkok. During the dry season almost half of the consumed oxygen is produced by aquatic plants causing a significant diurnal variation with a lack of oxygen between midnight and sunrise. The oxygen mass balance illustrates the symbiotic O_2 and CO_2 supply of aquatic plants and microbial organisms whereas a competitive relation concerns light extinction by suspended solids and phosphorus uptake. The alternation of aerobic and anaerobic conditions improves the biological phosphorus elimination and reduces phosphorus concentration close to a limiting range and a N/P ratio of 20 – an interesting aspect for further investigations.

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