Development of water and sediment quality management strategies for an urban river basin: a case study in Taiwan

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ABSTRACT

The Love River basin is an important urban river basin in Kaohsiung City, Taiwan. The main cause of the river water quality deterioration is the discharges of municipal wastewaters into the river. In this study, river water analyses, sediment quality investigation, and water quality modeling were conducted to (1) evaluate the impacts of pollutant loadings on Love River and (2) develop basin management strategies. Geo-accumulation index and enrichment factor evaluation indicate that the sediments contained high concentrations of Cu, Zn, Ni, Cr, and Pb. Their concentrations were close to the effect range median implying heavy metals had adverse impacts on aquatics. The WASP (Water Quality Analysis Simulation Program) model was used to perform water quality modeling, and results indicate that sewage discharge from a sewage trench caused significant impairment of river water quality. An on-site aerated gravel-packed contact bed (CB) system was built in the riverside for 10% of river water treatment. The CB system could remove 52% of ammonia nitrogen (NH_3-N) and 64% of biochemical oxygen demand (BOD) from the influents. Modeling results show that an expansion of the CB system for 40% of river water treatment could further reduce NH_3-N and BOD concentrations and improve the water quality.

Key words | aerated gravel-packed contact bed, basin management, sediment, water quality modeling

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INTRODUCTION

Introduction of Love River

The Love River is one of the important urban rivers in Kaohsiung City, Taiwan. It flows across the city center and empties into the Kaohsiung Harbor. The Love River has a length of 16 km with a basin area of approximately 50 km^2. Figure 1 presents the Love River, the on-site aerated gravel-packed contact bed (CB) system, and the major sewage trench (Trench A). The 16-km river originates from the upstream mountainous area and the drainage water from the farmland areas is a major component of the river flow. Trench A is the major sewage trench in the Love River basin, which contributes approximately 24% of the pollutant loadings to the river (Yao *et al.* 2015; Li *et al.* 2016).

The River Pollution Index (RPI) system developed by Environmental Protection Administration in Taiwan (TEPA) has been applied for river water quality evaluation. The RPI index calculation uses four different parameters: biochemical oxygen demand (BOD), suspended solids (SS), dissolved oxygen (DO), and ammonia nitrogen (NH_3-N). Table 1 presents the equation for RPI calculation and four RPI classes (TEPA 2002). Because the sewer hookup rate in the Love River basin is less than 60%, some improperly treated sewage is still discharged to the river, which causes the increased RPI values in Love River. The sewage trenches

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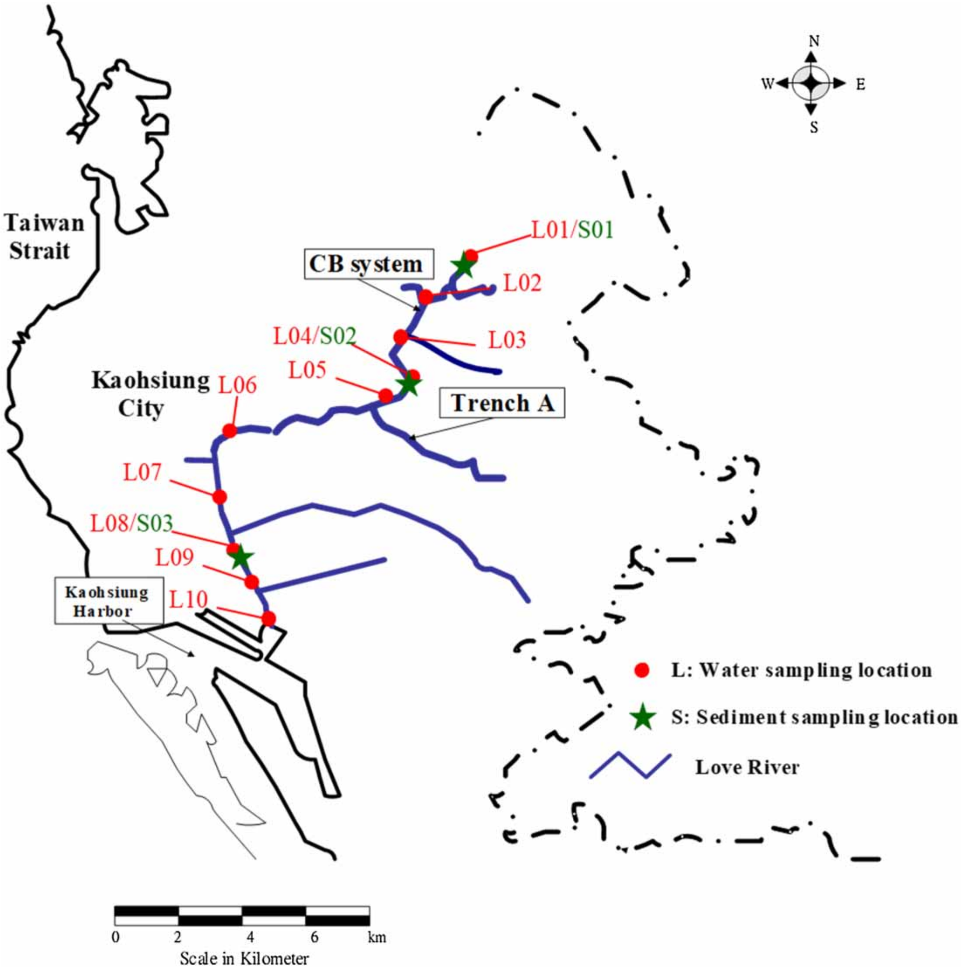

Figure 1 | The Love River, its catchment, and the major sewage trench (Trench A).

Table 1 | Four RPI classes and equation for RPI calculation

Ranks **Items**	**Non-polluted**	**Slightly polluted**	**Moderately polluted**	**Grossly polluted**
BOD_5 (mg/L)	<3.0	3.0–4.9	5.0–15.0	>15
DO (mg/L)	>6.5	4.6–6.5	2.0–4.5	<2.0
NH_3-N (mg/L)	<0.5	0.5–0.99	1.0–3.0	>3.0
SS (mg/L)	<20	20–49	50–100	>100
Score of index (Si)	1	3	6	10
Score of sub-index	<2	2.0–3.0	3.1–6.0	>6.0
Sub-index $= \frac{1}{4}\sum_{i=1}^{4} S_i$				

are combined systems, which collect both sewage and rain water during the rainy days. The discharges of the sewage into the river result in the deterioration of river water quality. Therefore, high concentrations of nutrient and organic pollutants (NH_3-N and BOD) have been observed in river water.

Modeling of river water quality

A water quality model (Water Quality Analysis Simulation Program (WASP)) was applied for Love River water quality modeling. The model was developed by the US Environmental Protection Agency (EPA) to predict and interpret changes of river water quality due to different pollution loadings (Lai *et al.* 2017a). WASP can be used to simulate the river water quality and benthos beneath the water column using a method of finite segmentation (Privette & Smink 2017). The input parameters include the following: initial conditions, model segmentation, simulation and output control, non-point source (NPS) pollution loads, point source pollution loads, boundary concentrations, and advection and dispersive transport variables (Yao *et al.* 2015).

The CB system

The CB system is a wastewater treatment facility using a packed bed filled with gravels for bacterial growth. The system can be classified as an ecological and natural method for wastewater or polluted river water treatment (Lin *et al.* 2015; Birkigt *et al.* 2018). It can be used as an on-site facility and constructed on the river bank for river water treatment (Tu *et al.* 2014). When it is used for river water purification, the water flows into the CB system by gravity or pumping (Carranza-Diaz *et al.* 2014). Aeration is usually used to increase the pollutant (organic contaminant and nutrient) decay rates and treatment efficiency if a river is highly polluted and the hydraulic retention time is short (Wang *et al.* 2015). The water quality modeling was applied in this study to evaluate the contributions of the CB system to river water quality improvement for the Love River. Figure 2 is the schematic diagram of the studied CB system. The inflow rate of the CB was approximately 8,600 m^3/d. The system had an aeration zone with a dimension of 8 m (W) × 24 m (L) × 3 m (H). Gravels (with diameter of 4.5 to 5.5 cm) were packed inside the reactor (with a porosity of 0.38). The hydraulic retention time and aeration rate were 0.2 to 0.3 d and 7 to 10 m^3/min, respectively.

Sediment quality evaluation

Sediments can significantly affect the heavy metals distribution in aquatic environments, and sediments are sinks and sources for heavy metals (Maanan *et al.* 2015; Ma *et al.* 2016; Sulieman *et al.* 2017). Researchers reported that a significant amount of heavy metals are bound to organic matters (OMs) or particles and deposited on the benthic of water bodies (Bhatnagar *et al.* 2013; Rezania *et al.* 2015). Due to the varied physical and chemical characteristics in mineral, OM, and grain size, sediments contain anomalous concentrations of heavy metals (Hou *et al.* 2013; Jiang *et al.* 2014).

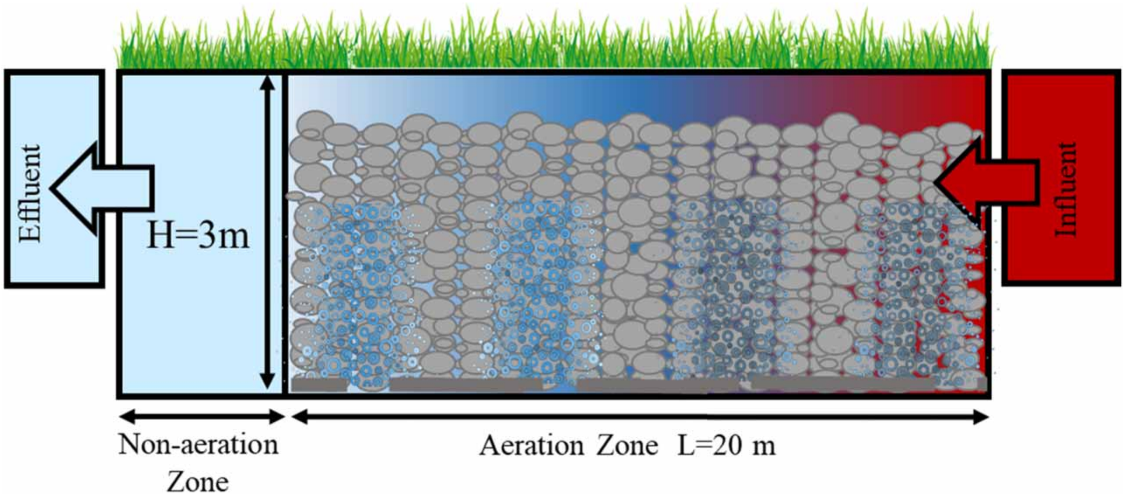

Figure 2 | The layout of the studied CB system.

Statistical approaches (e.g., factor analysis) have been applied to identify the mechanisms which determine the distribution of heavy metal in sediments, and this could help to assign the pollution sources (Dou *et al.* 2013; Luoma 2017). Geochemical procedures are also used to compensate for the composition variation and texture of sediments (Liu *et al.* 2009; Hou *et al.* 2013; Jiang *et al.* 2014). The distinguishing of natural versus anthropogenic contributions of heavy metals and quantification of anthropogenic heavy metals in sediments are indispensable processes for the protection of aquatic systems.

The Love River has a long history of sediment contamination with heavy metals due to the expedient and illegal discharges of industrial wastewaters from the scattered industrial factories in the river basin. This results in the accumulation of heavy metals in sediments, which also causes the deterioration of sediment quality. Thus, sediment sampling and quality evaluation are necessary to develop sediment management strategies.

Objectives

Concern about the deteriorating condition of the river led the government of Kaohsiung City to adopt effective engineering remedies and river management strategies for river water quality improvement. The two main engineering remedies are (1) construction of an on-site CB system located at the upgradient location of the riverbank for river water treatment and (2) construction of an intercepting sewer for the interception of sewage from the two main sewage trenches. The collected sewage is then transported to the wastewater treatment plant for treatment. The major objectives of this study were to: (1) perform the river water quality and sediment sampling and analyses; (2) perform a water quality modeling for water quality simulation; (3) evaluate the effectiveness of the current CB system and CB system expansion on river water quality improvement using the water quality modeling; (4) evaluate the effectiveness of sewage interception on river water quality improvement using the water quality modeling; and (5) evaluate the pollution and toxicity level of sediments.

LITERATURE REVIEW

WASP has been applied to simulate and study the impacts of pollution inputs on water quality in different studies (Lai *et al.* 2013; Knightes *et al.* 2016; Li *et al.* 2016; Bouchard *et al.* 2017; Srinivas & Singh 2018). In this study, NH_3-N and BOD were selected as the water quality indicators for water quality modeling to assess the application of different remedial strategies on water quality improvement for the Love River.

The WASP model has been used for water quality modeling in different rivers and watersheds including the Errer River (Lai *et al.* 2017a), Songhua River (Yu *et al.* 2016), Murderkill River (USEPA 2015), Carp Lake Watershed (Yen *et al.* 2012), Kaoping River (Lai *et al.* 2013, 2017b), Barnegat Bay (Defne *et al.* 2017), and Satilla River (Zheng *et al.* 2004). Researchers applied the WASP model to establish river management strategies and evaluate the effects of river aeration on water quality improvement (Zhu *et al.* 2015). Akomeah *et al.* (2015) used the WASP model to simulate the surface water quality of the upper South Saskatchewan River and satisfactory results were obtained.

The Regional Ocean Modeling System (ROMS) and WASP model coupler was developed by Defne *et al.* (2017) for river water quality modeling. The coupler aggregates hydrodynamic data from ROMS, which are then used as inputs in WASP modeling, and the coupler has been used for eutrophication evaluation (Defne *et al.* 2017). Zheng *et al.* (2004) successfully applied WASP modeling to assess the impact of different physical–chemical and biochemical mechanisms on water quality of the Satilla River estuary located in Georgia, USA. Lai *et al.* (2011) developed an integrated two-model system composed of a multimedia watershed model (Integrated Watershed Management Model) (IWMM) and the WASP model to simulate the impacts of NPS pollution on river water quality. Results from Lai *et al.* (2011) demonstrated that the integral approach could develop a direct linkage between upstream land use changes and downstream water quality. Lai *et al.* (2017b) established a modeling tool with a direct linkage to the water quality index (WQI_5) calculation and the WASP model for pollutant transport modeling. The integrated WQI_5 and WASP system could establish a direct correlation for WQI_5, river flow, and river water quality (Lai *et al.* 2017b).

MATERIALS AND METHODS

Water and sediment sampling and analyses

Ten water sampling stations (L1 to L10) and three sediment sampling stations (S1, S2, and S3) were selected along the Love River from the upstream to downstream sections. Quarterly collected sediment and water samples were analyzed during the investigation period from January 2015 to December 2016.

The factors, which were used for river water sampling station selection, included the following: upgradient and downgradient locations of the discharge points of major sewer or trench systems (including Trench A), upgradient and downgradient locations of the discharge point of the CB system, first grid of the main flow course, and river outfall. Three sediment sampling stations were located in the upstream, mid-stream, and downstream sections of the river.

Hydrological investigation was performed at the sampling stations during flow rate analyses using the TEPA method (NIEA 2004a). Water samples were analyzed for pH, SS, BOD, DO, and NH_3-N analyses. DO and pH were measured in the field. A MP120 pH meter (Mettler Toledo) was used for pH measurements, and a WTW DO meter (Oxi 330) was used for DO measurement. SS, BOD, and NH_3-N were analyzed following the methods in *Standard Methods* (APHA 2005).

Sediment samples (10–20 cm in depth) were analyzed for particle size distribution and concentrations of heavy metals (including Al, Fe, Pb, Cr, Cu, Zn, Ni, Cd, and Mn). Coulter® LS-100 was applied for particle size distribution, and heavy metals were analyzed by inductively coupled plasma-atomic emission spectrometry (NIEA 2004b).

Water quality modeling

In this study, the WASP model was applied for water quality simulation. The inputs of the WASP modeling included locations of inflow and outflow, stream segmentation, hydrological parameters, geological and meteorological conditions, water quality parameters, dispersion coefficient, decay rates, reaeration coefficient, and BOD removal rate. Boundary conditions were established using ambient river water quality data, and model results were compared with observed data for calibration. The upstream and downstream boundaries of the modeling system were set near the river entrance and the outfall (Lai *et al.* (2013, 2017b).

Figure 3 presents the grids for the main flow course of the Love River. The input data for the water quality modeling contained the following: locations of outflow and inflow, stream segmentation, hydrological data, dispersion coefficient, decay rates, BOD removal rate, water quality parameters, geological and meteorological conditions,

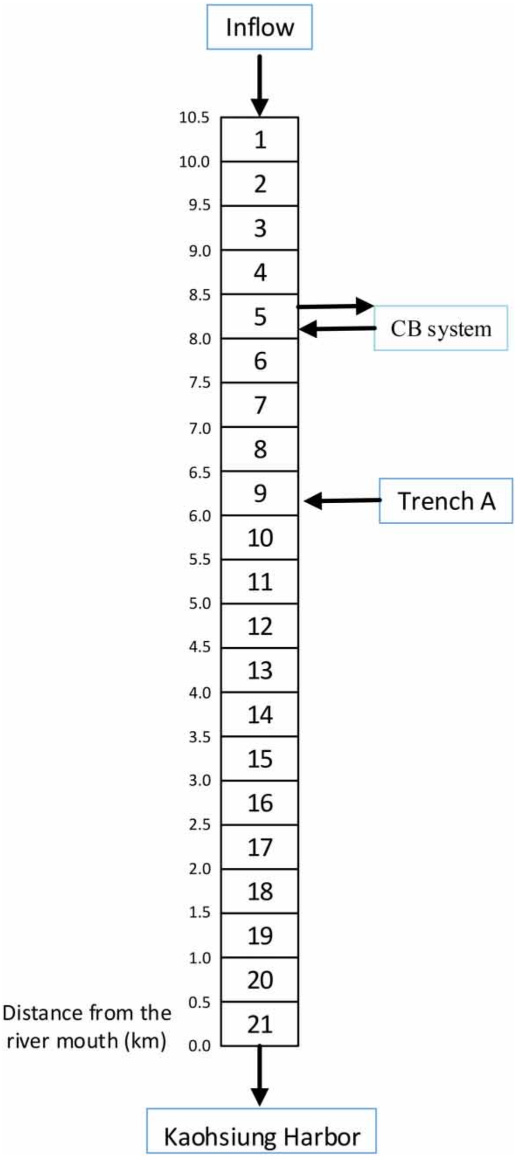

Figure 3 | Model grids for the Love River.

benthal oxygen demand, and reaeration coefficient. The WASP modeling was used for model construction and a time step of 1 second was used. The mass balance equation used in this study was described in Lai *et al.* (2013, 2017b). The calibrated model was applied to (1) assess the effectiveness of the current CB system and CB system expansion on river water quality improvement and (2) assess the effectiveness of sewage interception on river water quality improvement. Table 2 shows the values of input parameters for the WASP modeling.

Sediment quality analyses

The enrichment factor (EF), sediment quality guidelines (SQGs), and geo-accumulation index (I_{geo}) were applied to assess the quality of Love River sediments. The pollution

Table 2 | Parameters used in the WASP modeling process

Description	Parameter	Range	Fixed or estimated by calibration
Denitrification			
Denitrification rate constant	K20C	–	0.03
Denitrification rate temperature constant	K20T	–	1.04
Half saturation constant for denitrification	KNO3	–	0.01
Nitrification			
Nitrification rate constant	K12C	0.05–0.15	0.05
Nitrification rate temperature constant	K12T	1.08–1.20	1.04
Half saturation constant for nitrification	KNIT	–	0.01
BOD			
Oxidation of BOD rate constant	KDC	0.05–0.3	0.15
Oxidation of BOD rate temperature constant	KDT	–	1.04
BOD half-saturation constant	KBOD	–	0.4
Phytoplankton			
Phytoplankton growth rate constant	K1C	1.4–2.6	2.01
Phytoplankton growth rate temperature constant	K1T	0.98–1.072	1.066
Algal respiration rate constant	K1RC	0.05–0.35	0.008
Algal respiration rate temperature constant	K1RT	1.045–1.1	1.08
Phytoplankton death rate constant	K1D	0.02–0.1	0.11
Zooplankton grazing rate	K1G	–	0.80
Oxygen to carbon rate	OCRB	–	2.67
Phosphorus to carbon rate	PCRB	–	0.028
Nitrogen to carbon rate	NCRB	–	0.200
Fraction of dead and respired phytoplankton			
Fraction of ON from algal death	FON	0.25–0.5	0.3
Fraction of OP from algal death	FOP	–	0.3
ON			
Mineralization of dissolved ON rate constant	K71C	0.02–0.2	0.03
Mineralization of dissolved ON rate temperature constant	K71T	1.02–1.3	1.04
OP			
Mineralization of dissolved OP rate constant	K83C	0.01–0.4	0.03
Mineralization of dissolved OP rate temperature constant	K83T	1.045–1.2	1.04

ON, organic nitrogen; OP, organic phosphorus.

level of sediments was screened and assessed by comparison with SQGs (Hasan *et al.* 2013). SQGs assessed the contamination level to which the chemical status in sediments might have adverse impact on organisms in aquatic environments, and were used to interpret the sediment quality (Chen *et al.* 2007; Hasan *et al.* 2013). Two sets of SQGs, which were developed to assess the freshwater ecosystems, were used to evaluate the impacts of trace elements in sediments on ecoenvironments in this study (MacDonald *et al.* 2000): (1) the ratio of effect range low (ERL) to effect range median (ERM) and (2) the ratio of threshold effect level (TEL) to probable effect level (PEL) (MacDonald *et al.* 2000).

The I_{geo} and EF values were calculated to determine the sediment pollution level. EF is the actual contamination extent in sediments, and it is also used to (1) evaluate the degree of sedimentation pollution and (2) differentiate the metal source between natural and anthropogenic occurrence (Hu *et al.* 2011; Luoma 2017).

In aquatic sediments, Al and Fe are inert elements and they are applied as the normalizer to determine the EF values (Chen *et al.* 2015). Because Al has less active chemical features in sediments with geochemical conditions' variation, Al was used as the normalizer metal in this study (Whiteley & Pearce 2003; Soto-Jiménez & Páez-Osuna 2008).

The equations used for EF calculation and the ranking system are described in Chen *et al.* (2007) and Amin *et al.* (2009). Al is the normalizing element, and the baseline values for X_{crust} are as follows: 3.6% for Fe, 6.9% for Al, 127 μg/g for Zn, 0.2 μg/g for Cd, 32 μg/g for Cu, 71 μg/g for Cr, and 16 μ/g for Pb.

The I_{geo} was used in this study to calculate and determine the metal contamination in sediments by comparing sediment concentrations with preindustrial levels (Muller 1979). I_{geo} could also be used as a reference to assess the extent of metal contamination in sediments. The equation used for I_{geo} calculation is described in Muller (1979), Gonzalez-Macias *et al.* (2006), and Hu *et al.* (2011).

The following seven-class ranking system is to define the pollution extent of sediments (Gonzalez-Macias *et al.* 2006): $I_{geo} > 5$ (Class 6) indicates very strongly polluted; $I_{geo} = 4$–5 (Class 5) indicates strongly to very strongly polluted; $I_{geo} =$ 3–4 (Class 4) indicates strongly polluted; $I_{geo} = 2$–3 (Class 3) indicates moderately to strongly polluted; $I_{geo} = 1$–2 (Class 2) indicates moderately polluted; $I_{geo} = 0$–1 (Class 1) indicates unpolluted to moderately polluted; and $I_{geo} < 0$ (Class 0) indicates unpolluted.

RESULTS AND DISCUSSION

Water quality analysis and modeling

Table 3 shows the averaged results of flow rate and water quality analyses for the Love River. Hydrological

Table 3 | Averaged results of flow rate and water quality analyses

Station	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**L9**	**L10**
pH	7.63	7.56	7.35	7.62	7.51	7.66	7.75	7.64	7.82	7.80
EC (ms/cm)	0.75	1.70	2.73	10.70	10.83	12.82	39.50	35.91	36.42	36.86
Temperature (°C)	27.5	27.63	28.2	27.9	28.11	28.43	29.68	29.54	29.33	29.4
DO (mg/L)	3.52	3.67	3.61	4.63	4.28	5.43	4.81	6.12	6.20	6.38
COD (mg/L)	24.32	24.55	35.57	37.45	32.88	27.57	27.45	26.26	21.40	23.81
BOD (mg/L)	8.59	12.94	8.90	14.23	12.85	10.34	6.65	9.98	6.43	7.62
SS (mg/L)	20.42	7.84	11.32	10.25	12.40	12.53	28.67	14.32	18.24	12.62
NH_3-N (mg/L)	4.20	5.94	4.57	4.82	4.75	4.50	1.52	2.85	1.89	2.25
TP (mg/L)	0.68	0.96	0.90	0.67	0.62	0.54	0.40	0.38	0.42	0.37
Flow rate (m^3/s)	0.25	1.08	1.89	4.98	5.82	6.68	11.13	15.42	16.22	17.83
Sub-index (RPI)	6.25	5.75	5.75	5	5.75	5	4.5	4	4	4
Water quality	MP	SP	SP	SP	SP	SP	SP	SP	SP	SP

MP, moderately polluted; SP, slightly polluted.

investigation results reveal that flow rates increased along the Love River flow course. This implies that the NPS pollutant loadings from the farmland area in the upstream catchment caused higher concentrations of nutrients (e.g., TP, NH_3-N). Results from the mid-stream locations show higher BOD concentrations, and this could be because of the discharges of domestic wastewater into the river causing the deterioration of river water quality. Because some of the domestic sewage was transported to the wastewater treatment plant via the intercepting sewers, the organic and nutrient pollutant loadings to the Love River is reduced (Long 2006). Because the intercepting sewers stop the sewage collection during the rainstorms, increased organic and nutrient loadings to river water are sometimes observed.

Part of the upper catchment is agricultural areas, and thus, soil erosion could cause the increase in nutrient and SS concentrations in the upstream section. This suggests that NPS pollution would be the cause of the impaired water quality in the upstream section. Moreover, the discharges of domestic wastewater into the river could result in worsened water quality in the mid-stream of the river. The pollutants from the discharged wastewater would accumulate onto the sediments, resulting in the impairment of the sediments.

In this study, RPI values were calculated using the averaged results (Table 3). Results indicate that NH_3-N and BOD made significant contributions to the RPI levels. Because farmland drainage water was the major component of the river water, higher NH_3-N concentrations were observed in the upstream river section. In the mid-stream section, domestic wastewater was discharged into the river, thus, BOD concentrations were relatively higher in the mid-stream section. Therefore, NH_3-N and BOD were the key factors in up- and mid-stream sections of the Love River for RPI determination. Because the downstream section of the river was in the estuary zone, increased DO concentrations and decreased organic, nutrient, and SS concentrations were observed due to the dilution effect of the sea water. Moreover, higher DO concentrations were observed in the mid- and downstream sections, which would affect the RPI calculation.

Figure 4 shows the measured and simulated water quality results for BOD and NH_3-N. Results indicate that the modeling results had a good match with the observed data. The loadings of BOD and NH_3-N were affected by the inputs of sewage into the river. Results indicate that increases in BOD, NH_3-N, and SS concentrations were observed in mid-stream water sampling stations. Thus, decreased RPI value was observed in the downstream section near the river mouth.

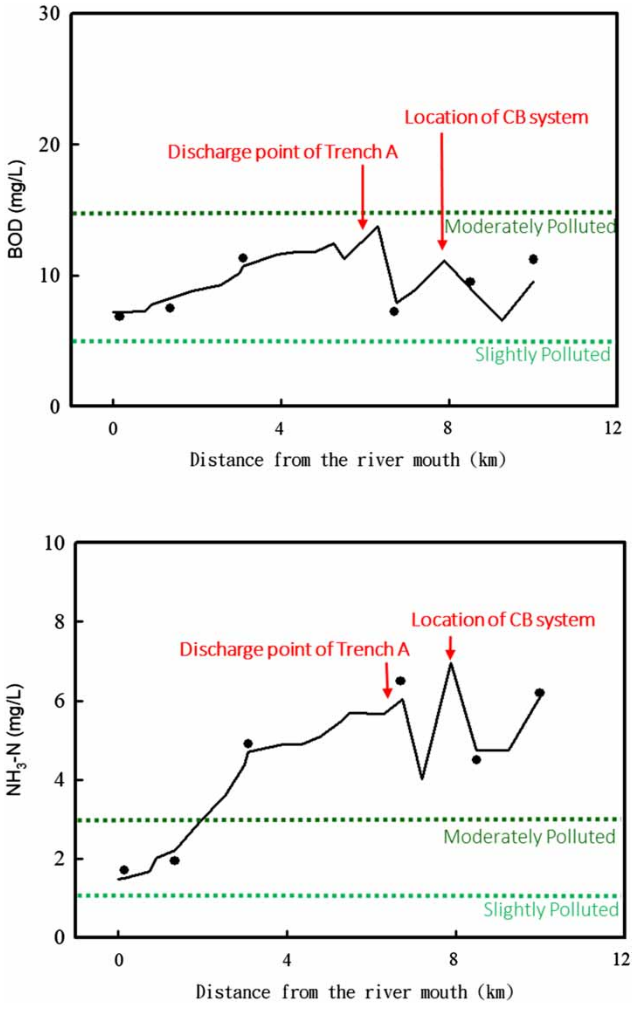

Figure 4 | Measured and simulated water quality results for BOD and NH_3-N in the Love River.

Effects of on-site CB system application on river water quality improvement

Currently, the on-site CB system is used to treat approximately 10% of the river water. Results from the influent and effluent water quality analyses show that approximately

64 and 52% of BOD and NH_3-N could be removed via the CB system. The treated water was then discharged back to the river after treatment. To further improve the water quality, water quality modeling was performed to evaluate the effects of CB system expansion (increased river water pumping from 10 to 20 and 40%) on river water quality improvement.

Figure 5 shows the simulated BOD and NH_3-N results with application of the CB system for river water treatment. Results indicate that the water quality was significantly improved with the application of the CB system for 10% of the river treatment. Results also show that the water quality could be further improved if 20 or 40% of the river water could be pumped into the expanded CB system for treatment (Figure 5). However, due to the discharges of domestic wastewater from other sewage trenches, increased NH_3-N and BOD concentrations were observed in sections located downgradient of the CB system. Results imply that the construction of intercepting sewers is necessary in the mid-stream sections of the river to effectively control the river water quality.

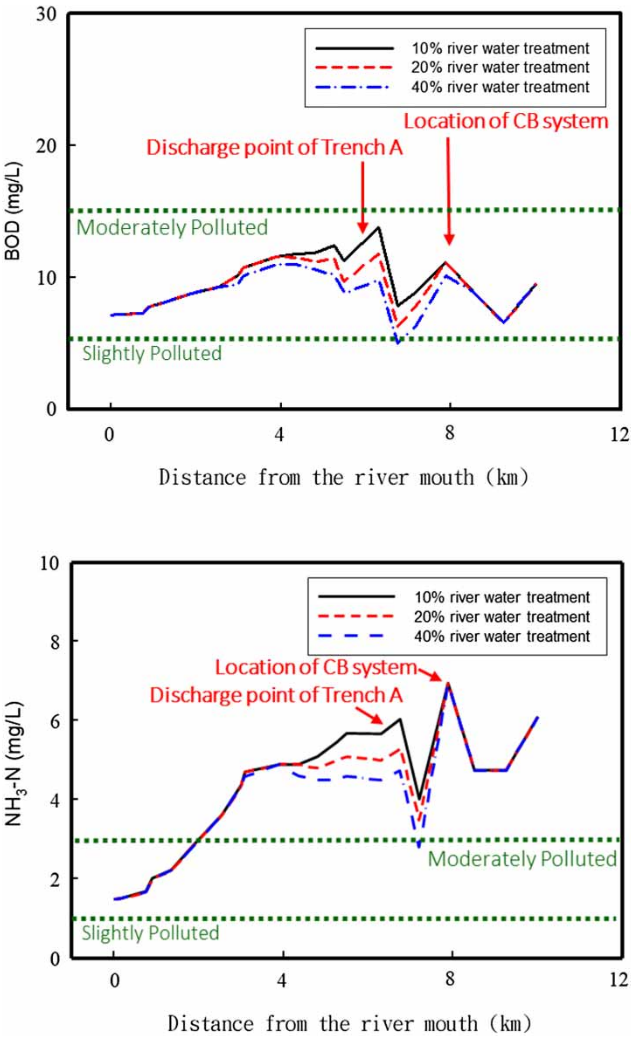

Figure 5 | The simulated BOD and NH_3-N results with the application of expanded CB system for river water treatment.

Effects of sewage interception on river water quality improvement

The sewage from the Trench A system is currently intercepted and transported to the wastewater treatment plant directly without discharging into the river during the sunny days. Because sewage trenches are combined systems, which collect both sewage and rainwater, part of the sewage is still discharged into the river from Trench A during rainstorms or wet days. In this study, the water quality modeling was applied to evaluate the effectiveness of sewage interception from Trench A on water quality improvement. The WASP modeling was used to assess the variation of water quality with the application of 100, 50, and 20% of sewage interception. The modeling results could be used to establish optimal river management strategies.

Figure 6 shows the water quality modeling results for BOD and NH_3-N without sewage discharge and with 100, 50, and 20% of sewage discharges from Trench A into the river. Results show that the discharge of sewage water from Trench A resulted in significant deterioration of river water quality. BOD and NH_3-N concentrations in river water were higher than 25 and 14 mg/L, respectively, if 100% of sewage was discharged into the river without interception. Because the Love River is an urban river with a short length and low carrying capacity, sewage discharge into the river would cause an abrupt jump of contaminant concentrations in the river, and this would also cause an adverse impact on the river environment and ecosystem. Thus, a complete sewage interception from the sewage trenches is required. Moreover, construction of a separate sewer system should be a long-term management strategy for the Love River basin management.

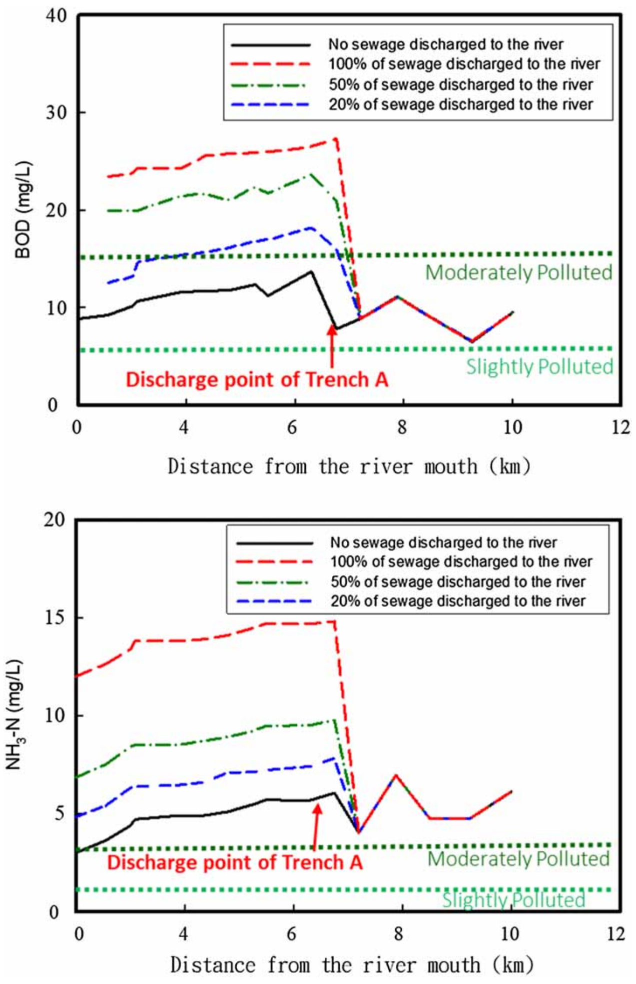

Figure 6 | The simulated water quality results for NH_3-N and BOD after the application of 100, 50, and 20% of sewage interception from Trench A.

Sediment quality analyses

Results indicate that sediments with fine and coarse grains were found in samples collected from downstream and upstream locations, respectively. This could be because the high flows caused the sand transport and deposition. Thus, sands and silts were the main components of upstream and downstream sediment samples, respectively. Moreover, organic pollutant discharges from domestic sewers caused an increase in OM contents in S2 (ranged from 0.56 to 5.16%).

Table 4 shows the concentrations of heavy metals in sediments. Results show that Zn concentrations ranged from 49.9 to 59.4% and Cu concentrations ranged from 13.6 to 21.2%. Results also indicate that high concentrations of Zn and Cu were observed in sediments located in downstream sections. Moreover, wider concentration (mg/kg) variations were found for other metals: Cr, 18.3–93.0; Cd, 0.45–0.59; Ni, 14.1–32.7; Pb, 4.9–31.0; Cu, 42.5–67.3; Zn, 100.0–213.0; Hg, 0.01–0.08; and As, 1.2–2.1 mg/kg.

The heavy metals Cd, Cr, Pb, Zn, and As had the highest measurements at S2, and the highest concentration for Cu was observed in S1 samples. Moreover, S3 samples had higher Ni and Hg concentrations. Results show that concentrations of Cd, Cu, Pb, and Zn had a similar trend of evolution along the main flow course. Heavy metal concentrations for all samples were higher than the world average levels for surface rock exposed to average and weathering sediment concentrations (Amin *et al.* 2009). The maximum concentrations of Cd, Cr, Pb, Cu, and Zn were 0.59, 93, 31.0, 67.3, and 213 mg/kg, which were higher than the world average concentrations by 3, 1.3, 1.9, 2.1, and 1.7 times, respectively. Moreover, higher concentrations of Cr, Pb, and Zn were observed in S2 samples, which could be due to the discharges of wastewater from the sewers.

Results indicate that the concentrations for Cd were below the ERL (5 mg/kg) and ERM (9 mg/kg) values for all samples. However, concentrations for Zn in most samples were higher than the ERL value. Concentrations for Cr in most samples were below the ERL value, and only S2 had concentrations which were higher than the ERL value. The toxic unit (TU), ratio of the determined concentration of PEL value, was determined to normalize the heavy metal toxicity.

The potential acute toxicity of heavy metal could be determined as the sum of the TUs. The calculated TU values are presented in Figure 7. The TUs for heavy metals in the Love River decreased in the order of Ni > Zn > Cr > Cu > Pb > Cd > Hg > As. Compared to other heavy metals, Cr had higher TU values in S2 samples, and Ni and Zn had higher TU values in S1 and S3 samples.

The TUs for heavy metals in sediment samples decreased in the order of S2 > S1 > S3. Results show that higher heavy metal concentrations were observed in S2 samples with acute toxicity. Results imply that heavy metals had key roles in TU values in the Love River. Results indicate that sediments around the S2 region should be effectively managed, and dredging of polluted sediments are required to improve the sediment quality.

Table 4 | Heavy metal concentrations in surface sediments of Love River

	Concentration (mg kg^{-1})								
	Cd	Cr	Ni	Pb	Cu	Zn	Hg	As	Fe
S1	0.45	31.4	21.3	16.9	67.3	203.0	0.01	1.2	42,068
S2	0.59	93.0	14.1	31.0	55.5	213.0	0.02	2.1	36,934
S3	0.53	18.3	32.7	4.9	42.5	100.0	0.08	1.3	38,532
Mean	0.52	47.57	22.7	17.6	55.1	172.0	0.04	1.53	39,175
World average[a]	0.2	72	–	16	32	127	–	–	
Sediments average	0.17	–	52	19	33	95	–	–	41,000
ERL[b]	5	80	30	35	70	120	0.15	8.2	
ERM[b]	9	145	50	110	390	270	0.71	70.0	
TEL[b]	0.596	37.3	18	35	35.7	123	–	7.2	
PEL[b]	3.53	90	36	91.3	197	315	0.7	41.6	
Enrichment factor, EF									
EF S1	2.58	0.43	0.40	0.87	1.99	2.08			
EF S2	3.85	1.43	0.30	1.81	1.87	2.49			
EF S3	3.32	0.27	0.67	0.27	1.37	1.12			
Geo-accumulation index, I_{geo}									
I_{geo} S1	0.82	−1.78	−1.87	−0.75	0.44	0.51			
I_{geo} S2	1.21	−0.22	−2.47	0.12	0.17	0.58			
I_{geo} S3	1.06	−2.56	−1.25	−2.54	−0.22	−0.51			

[a] Amin *et al.* (2009); Chen *et al.* (2015).
[b] MacDonald *et al.* (2000); Pekey *et al.* (2004).

Results show that the EF values for Cd, Cr, Cu, Ni, Pb, and Zn ranged from 2.58 to 3.85, 0.43 to 1.43, 1.37 to 1.99, 0.3 to 0.67, 0.27 to 1.81, and 1.12 to 2.49, respectively. Significant anthropogenic contributions could result in the high EF values.

The mean I_{geo} values for heavy metals were 1.03 for Cd, −1.52 for Cr, 0.13 for Cu, −1.86 for Ni, −1.06 for Pb, and 0.19 for Zn. The I_{geo} for Cd varied between 0.82 and 1.21, allocating it in the I_{geo} classes 1–2. Cd was determined as moderately polluted with a moderate level of EF and I_{geo} class of 3.25. The I_{geo} value for Zn ranged from −0.51 to 0.58 and the I_{geo} class was 0–1. This indicates that Zn was at a slightly contaminated level. I_{geo} and EF results for heavy metal evaluation demonstrate that EF and I_{geo} were in the order of Cd > Zn > Cu > Pb > Cd > Cr > Ni. The high EF and I_{geo} values for Cd and Zn imply that the wastewater discharges caused the significant pollution of Cd and Zn.

CONCLUSIONS

In this study, water and sediment sampling and analyses were performed for the Love River. Because the WASP model has been successfully applied for river water quality simulation worldwide, it was constructed and used for the development of management strategies for river water quality improvement of the Love River. Results from water quality and sediment analyses and water quality modeling show that the Love River was slightly to moderately polluted. Higher NH_3-N concentrations were observed in the upstream section due to the discharges of drainage water from the farmlands in the upper catchment. Results also show that higher BOD concentrations were detected in the mid-stream section due to the discharges of domestic wastewaters into the river from sewer systems. Therefore, NH_3-N and BOD were the key factors in up- and mid-stream sections of the Love River for RPI determination.

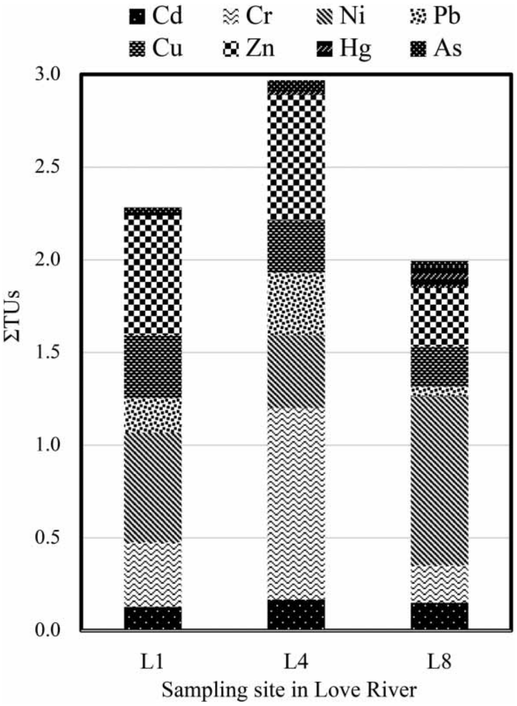

Figure 7 | Estimated sum of the toxic units (ΣTUs) in Love River sediments.

Performance evaluation of the CB system shows that approximately 64 and 52% of BOD and NH_3-N could be removed through the system. This indicates that the CB system played an important role in river water quality improvement. The following remedial strategies have been developed to prevent adverse impacts of wastewater discharges on the river water quality of the Love River: (1) construction of the intercepting and separate sewer systems for sewage interception from sewage trench and (2) expansion of the on-site CB system for river water treatment. Results from SQGs' assessment indicate that relatively high concentrations of Cu, Zn, Ni, Cr, and Pb were observed in sediments. The SQGs for Zn, Ni, and Cr in sediments exceeded the toxic effect range. The PEL, ERM, EF, and I_{geo} values also reveal that the sediments were polluted by heavy metals (e.g., Cd, Cr, Ni, Pb, Cu, Zn, Hg, and As). Zn, Ni, and Cr made significant contributions to sediment contamination, which accounted for 13.3–25%, 13.3–33.3%, and 8.3–36.7% of the total toxicity of sediments. Results imply that the sediments would threaten the ecosystem and surrounding environments. Thus, effective pollution control strategies including sediment dredging and excavation should be applied for sediment quality improvement. Results from this study also suggest that a complementary approach that integrates EF, I_{geo}, and sediment standard criteria should be conducted to provide a more thorough assessment of the fate and transport of heavy metals in sediment environments.

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