Preliminary identification of watershed management strategies for the Houjing river in Taiwan

C. E. Lin, C. M. Kao, C. J. Jou, Y. C. Lai, C. Y. Wu and S. H. Liang

ABSTRACT

The Houjing River watershed is one of the three major river watersheds in the Kaohsiung City, Taiwan. Based on the recent water quality analysis, the Houjing River is heavily polluted. Both point and non-point source (NPS) pollutants are the major causes of the poor water quality in the Houjing River. Investigation results demonstrate that the main point pollution sources included municipal, agricultural, and industrial wastewaters. In this study, land use identification in the Houjing River watershed was performed by integrating the skills of geographic information system (GIS) and global positioning system (GPS). Results show that the major land-use patterns in the upper catchment of the Houjing River watershed were farmlands, and land-use patterns in the mid to lower catchment were residential and industrial areas. An integrated watershed management model (IWMM) and Enhanced Stream Water Quality Model (QUAL2K) were applied for the hydrology and water quality modeling, watershed management, and carrying capacity calculation. Modeling results show that the calculated NH_3-N carrying capacity of the Houjing River was only 31 kg/day. Thus, more than 10,518 kg/day of NH_3-N needs to be reduced to meet the proposed water quality standard (0.3 mg/L). To improve the river water quality, the following remedial strategies have been developed to minimize the impacts of NPS and point source pollution on the river water quality: (1) application of BMPs [e.g. source (fertilizer) reduction, construction of grassy buffer zone, and land use management] for NPS pollution control; (2) application of river management scenarios (e.g. construction of the intercepting and sewer systems) for point source pollution control; (3) institutional control (enforcement of the industrial wastewater discharge standards), and (4) application of on-site wastewater treatment systems for the polishment of treated wastewater for water reuse.

Key words | best management practice (BMP), carrying capacity, multimedia modeling, non-point source (NPS) pollution, water quality modeling, watershed management

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INTRODUCTION

The Houjing River is 21 km long, and drains a catchment of more than 77 km^2. It flows through the northern part of the Kaohsiung City, and empties into the Taiwan Strait. The Houjing River watershed is one of the three major river watersheds in the Kaohsiung City. Figure 1 shows the Houjing River, its catchment, and two major reaches (Dashe and Renwu Creeks), which flow through the Dashe and Renwu Industrial Parks, respectively. The two creeks merge at the Si-Chingpu Landfill located at the lower catchment of the watershed.

Taiwan Environmental Protection Administration (TEPA) has developed a five-part (A to E) classification system for the major river systems in Taiwan based on the purpose of water usage and degree of protection for each stream section (TEPA 1999; TEPA 2000). Table 1 presents the water quality criteria for the five classes. Recent water

doi: 10.2166/wst.2010.460

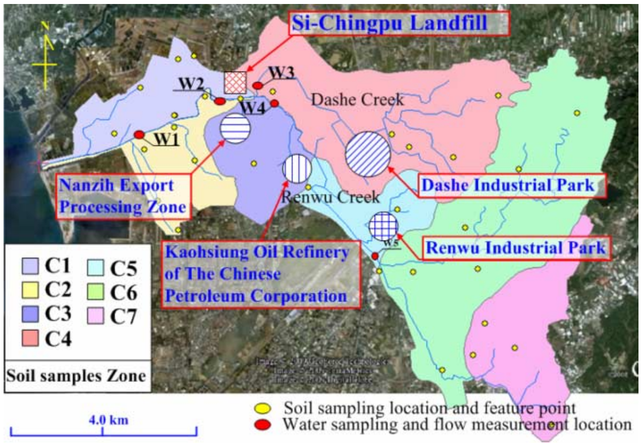

Figure 1 | Houjing river watershed showing the Houjing river, major reaches, feature points, and soil and water sampling locations.

quality analyses by Kaohsiung Environmental Protection Bureau and Kaohsiung Sewer Engineering Department indicate that the Houjing River is heavily polluted (KEPB 2006; KSD 2007). The concentrations of some major water quality indicators [e.g. dissolved oxygen (DO), biochemical oxygen demand (BOD), suspended solid (SS), ammonia-nitrogen (NH_3-N), total phosphorus (TP), and total coliform (TC)] could not meet any of the standards listed in the five-part system. Although no certain class has been assigned to the Houjing River, the Government of Kaohsiung City has temporarily chosen Classes E and C as the short-term and long-term remediation goals for the water quality standards of the Houjing River, respectively.

Previous results demonstrated that non-point source (NPS) pollution is one of the major causes for the impairment of the upstream water quality of Houjing River. Since the agricultural drainage water is the main component of the Houjing River inflow in the upstream area, NPS pollutants from the upstream farmland also caused the increase of nutrient levels in the river. However, the municipal and industrial wastewaters are the main water pollution sources in the mid and downstream sections of the Houjing River. Currently, the percent of sewer system connection in the Houjing River watershed is less than 35%. Part of the domestic wastewater is discharged into the river without proper treatment. Moreover, there are more than 95 registered industrial factories that discharge their wastewaters into the Houjing River. Illegal or expedient discharges are sometimes practiced feeding polluted industrial flows into the river. Thus, the Houjing River has a long history of higher BOD, NH_3-N, and TP concentrations due to the inadequate discharges of domestic, agricultural, and industrial wastewaters into the river.

Water quality improvement and watershed management have encountered a new challenge with regards to both technical and managerial requirements. In this study, the main objectives include (1) investigate and identify the current contributions of point and non-point source pollutants to the Houjing River pollution, (2) perform the land use identification and construct the watershed geographical information system (GIS) to effectively manage the watershed, (3) perform water quality and soils sampling and analyses, (4) apply multimedia models for NPS pollution evaluation and water quality simulation, (5) perform water quality simulation and carrying capacity calculation, and (6) evaluate the effectiveness of the applied remedial strategies on watershed management and water quality improvement.

In this study, the integrated watershed management model (IWMM) developed by Systech Engineering, Inc.

Table 1 | The five-part (A–E) classification system for the major rivers in Taiwan

Water Quality Item	Class A	Class B	Class C	Class D	Class E
Dissolved oxygen (DO) (mg/L)	≥6.5	≥5.5	≥4.5	≥3.0	≥2.0
Biochemical oxygen demand (BOD) (mg/L)	<1	<2	<4	–*	–
Ammonia-nitrogen (NH_3-N) (mg/L)	<0.1	<0.3	<0.3	–	–
Suspended solid (SS) (mg/L)	<25	<25	<40	<100	No suspended matters and no grease
Total phosphorus (TP) (mg/L)	<0.02	<0.05	–	–	–
Total coliform (TC) (cfu/100 mL)	<50	<5,000	<10,000	–	–

*No criteria.

(USA) was applied for simulating hydrology and water quality, and developing NPS pollution control strategies for the Houjing River watershed (Chen 2003). Moreover, the Enhanced Stream Water Quality Model (QUAL2K) developed by US Environmental Protection Agency (US EPA) was selected as the water quality-planning tool to perform the water quality evaluation and watershed management, as well as the carrying capacity calculation. The IWMM model includes five major components: air and canopy, land surface and subsurface, mountain stream, river and estuary, and reservoir/lake. The output of the model includes water temperature, pH, total alkalinity, nutrients, sediments, organic carbon, dissolved oxygen, algae, and sulfate, etc. The IWMM model is an ideal multimedia model that contains components including a global atmosphere module, a land module, a human impact module, a canopy module, and a global ocean module. Those modules can be linked and managed by a graphic user-interface (Chen 2003; Yang *et al.* 2006). The enhanced stream water quality model (QUAL2K) is a river and stream water quality model, and it is a modernized version of the QUAL2E model (Brown & Barnwell 1987; Park & Lee 2002; Ennet *et al.* 2008).

MATERIALS AND METHODS

Land use classification

To establish the basic database for land cover within the watershed of the Houjing River and detect the geographical location of the studied area based on the Thematic Mapper^{TM} coordinates, SPOT multi-spectral images and GIS themes need to be overlaid. The SPOT has high resolution visible imagery, which included three bands with 10-m resolution color mode and 5-m resolution panchromatic mode. The entire analysis for land use identification and classification in the watershed of the Houjing River watershed was designed based on a practical scale GIS framework. Land use has been further classified by the authors using three thematic raster layers of SPOT digital images that were generated during the period of 2004–2006. Application of global positioning system (GPS) helps verify the effectiveness of land use classification based on SPOT satellite image. The information gained from GPS can be divided into two groups. One group is prepared as a set of feature points that is designed for a direct calibration of land use classification in the Erdas Imagine® image processing system. The other group is designed as an additional set of feature points or ground-control points (GCPs) for validation purpose. The overall supervised group truth classification process can therefore be trained based on the first set of feature points in the first stage and then be validated by the given condition of land use pattern in watershed with the aid of the second set of feature points in the second stage. Final accuracy can be improved by using available aerial photographs simultaneously within any of these two stages (Lin 2009).

Water and soil sample analyses and multimedia modeling

In this study, five water quality monitoring locations (W1–W5) were selected along the Houjing River flow course for water quality analysis. The whole watershed was divided into seven major sub-basins, and soil samples were collected from seven sub-basins. Figure 1 presents the soil and water sampling locations. Water samples were collected monthly during the two-year investigation period. Flow velocity and flow rate were also monitored at the water monitoring stations at each sampling event. Soil samples were collected quarterly during the two-year investigation period. Half of the sampling events were performed in dry seasons (from Jan. to April and from Oct. to Dec.) and the other half events were performed in wet seasons (from May to Sep.). Flow velocity and flow rate were measured following the methods developed by TEPA (NIEA 2004). Water and soil samples were taken by the grab method. Soil sampling locations were selected by simple random sampling and composite sampling method was used for soil sampling (NIEA 2005). Samples were placed on ice until transferred to the appropriate analysis bottle and were kept refrigerated until analyzed. Collected water samples were analyzed for SS, TP, pH, NH_3-N, BOD, electric conductivity (EC), TC, and DO.

Instruments used for sample analyses included an Ion Chromatograph (Dionex) for inorganic nutrient and anion analyses, an Orion Ross pH meter for pH measurements, and an Orion DO meter (Model 840) for DO measurements. DO and pH measurements were performed in the field following the methods of NIEA W455.50C and W424.52A (NIEA 2009*a*,*b*). Analyses of TC, SS and BOD were performed in accordance with the methods in Standard Methods (APHA AWWA WPCF 2001). Collected soil samples were analyzed for organic matter, phosphate, nitrogen, pH, EC, water content following the methods developed by US EPA (EPA 2000).

In the modeling study, IWMM was applied to evaluate the impacts of NPS pollutants discharged from the agricultural areas on the Houjing River water quality. Within the studied area, each land-use has its vegetation characteristics and erosion coefficients. Each soil layer has its own volumetric soil moisture content, horizontal and vertical hydraulic conductivity, field capacity, and saturated soil moisture content (Lin 2009). Characteristics of different canopies and soil layers were taken into consideration in the simulation using this model. The model was calibrated and verified with field data collected in the Houjing River watershed from 2004 to 2006. Results from the IWMM modeling were also used as a pollutant input for the QUAL2K modeling. Thus, the contributions of NPS pollution to the deterioration of river water quality could be evaluated. The input parameters for the applied models include stream segmentation, locations of inflow and outflow, geological and atmosphere data, hydrological parameters, decay rates, water quality parameters, and soil parameters (Park & Lee 2002; Chen 2003; Ennet *et al.* 2008; Lin 2009). The input data for the parameters used for the models are described in Lin (2009).

RESULTS AND DISCUSSION

Land use and classification

Land use classification results can be delineated as an ArcView® cartographic output as shown in Figure 2. In this study, the Houjing River watershed was divided into seven sub-basins (C1–C7). Except the area covered by the cloud, the 27 different land use patterns have been categorized including farmland, forest, grassland, abandoned farmland, barren, water body, recreation area, etc. Six of those major land use patterns are delineated in Figure 2 including forest/turf, farm/orchard, river/lake, residential area, industrial area, and cultivation areas. Orchard land (2,831 ha) occupies approximately 44% of the total area in the basin. The orchard land is scattered around on both sides of the river corridor. Residential areas (1,760 ha) and industrial areas (1,492 ha) occupy approximately 27% and 23% of the total area, respectively. Table 2 presents the major land-use patterns identified inside the Houjing River watershed. Results show that most of the upper catchment is used for agricultural activities including orchard and farmland. The orchard farms occupy approximately 67% of the Dashe Creek sub-basin (C4). Moreover, the orchard farms also occupy approximately 60%, 70% and 74% of the land areas in C5, C6, and C7 sub-basins, respectively. The mid to lower catchments are mainly for residential and industrial uses. Therefore, NPS pollutants are the major source of river pollution in the upstream section of Houjing River, and domestic and industrial wastewaters play important roles in the deterioration of river water quality in the mid to downstream sections of the river.

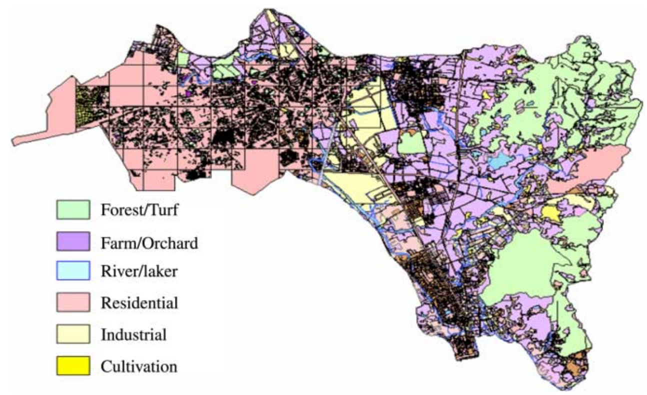

Figure 2 | Land use patterns in Houjing river watershed. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst.

Water and soil sampling and analyses

Table 3 presents the averaged results of different areas of soil sampling events in the dry and wet seasons, respectively, during the two-year investigation period. Results of the soil investigation show that both phosphate and nitrogen concentrations were higher in those soil samples collected from the upstream Houjing River watershed (C4–C7). In Taiwan, the potential evaporation rate in wet season

Table 2 | The major land-use patterns identified inside the Houjing River Basin

	C1 (%)	C2 (%)	C3 (%)	C4 (%)	C5 (%)	C6 (%)	C7 (%)
Forested	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Orchard	38.2	6.4	1.2	67.0	60.4	70.7	73.6
Grassland	0.9	22.2	5.9	7.5	9.4	6.2	2.9
Farm	2.6	3.9	1.4	0.0	0.8	1.5	1.5
Residential area	56.0	0.3	7.8	20.5	23.3	16.6	15.6
Industrial area	2.1	60.1	80.1	4.4	5.9	4.5	6.0

was high, especially in the summer. Because the Houjing River watershed is located in the southern Taiwan area, the outside temperature in the Houjing River watershed during the wet season reaches 28 to 35°C. This would cause the low water content in top soils in the wet season. Moreover, the observed organic matter and pH values as well as the water contents were also higher in the soils from upstream areas. This might be due to the application of fertilizers in orchard farms, which affected the physical-chemical conditions of the soils. The surface runoff and subsurface infiltration caused by the rain in the wet seasons would also cause the variations of soil chemical conditions. This would cause the increase of the NPS nutrient loads into the Houjing River during the wet season.

Table 4 shows the averaged results of four water quality sampling and hydrology measurement events in the dry and wet seasons, respectively, during the two-year investigation period. Results of the hydrology investigation show that both river width and flow rates at all five monitoring stations were significantly increased. This indicates that the loads of NPS pollution to the Houjing River would be also increased during the wet season. The W3 was located at the downstream section of Dashe Cheek. Because the Dashe Cheek is a compound channel, the channel width is less than 6 m when the flow rate is less than 1 m^3/sec. Results from the upstream sampling point (W5) show that the nutrient concentrations are much higher in the wet seasons than the dry seasons. Because the farmland areas are one of the dominant land use patterns in the areas of

Table 3 | Average concentrations of soil sampling events performed in dry and wet seasons

	C1	C2	C3	C4	C5	C6	C7
Dry seasons							
Phosphate (mg/kg)	0.3	0.8	0.6	0.4	0.3	0.2	0.5
Nitrogen (mg/kg)	4.07	2.69	4.37	3.76	5.75	4.37	6.20
pH	5.90	6.56	6.65	6.82	7.45	7.26	7.32
Water content (%)	2.99	1.45	1.38	4.93	3.56	5.25	3.16
Electric conductivity (EC) (mmoh/cm)	0.26	0.55	0.13	0.22	0.47	0.28	0.14
Organic matter (%)	0.72	0.98	1.40	2.36	8.29	7.57	2.8
Wet seasons							
Phosphate (mg/kg)	1.22	1.79	2.86	9.15	10.65	6.64	8.45
Nitrogen (mg/kg)	6.02	6.31	11.49	28.06	33.26	16.14	20.11
pH	6.02	6.31	6.22	6.52	7.21	7.02	7.43
Water content (%)	0.51	0.85	0.44	0.66	0.98	0.56	0.84
Electric conductivity (EC) (mmoh/cm)	0.27	0.42	0.37	0.12	0.32	0.23	0.16
Organic matter (%)	0.24	1.81	0.01	2.67	4.18	2.87	2.81

Table 4 | Average concentrations of water sampling events performed in dry and wet seasons

Sampling location	W1		W2		W3		W4		W5	
Item	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
pH	7.4	7.1	7.4	7.0	7.2	6.9	6.9	6.9	6.9	6.5
Dissolved oxygen (DO) (mg/L)	1.2	3.3	1.3	3.4	1.9	2.9	1.8	3.0	5.7	5.3
Electric conductivity (EC) (mmho/cm)	2.07	0.85	2.09	0.74	2.29	0.65	2.23	0.86	0.49	0.60
Biochemical oxygen demand (BOD) (mg/L)	67.3	13.8	31.0	6.7	27.5	41.5	22.5	10.4	5.4	55.9
Suspended solid (SS) (mg/L)	15	500	22	640	122	223	20	817	220	373
Ammonia-nitrogen (NH_3-N) (mg/L)	24.7	10.8	24.9	6.3	45.5	18.1	10.5	6.6	5.2	16.4
Total phosphorus (TP) (mg/L)	1.53	0.97	1.89	0.77	2.66	1.66	2.63	1.41	0.46	4.25
Total coliform (TC) (cfu/100 ml)	6.4×10^5	3.5×10^5	1.6×10^6	1.8×10^5	2.3×10^6	8.8×10^5	1.1×10^6	1.1×10^5	8×10^4	2.5×10^6
River width (m)	65	68	12	28	3	11	26	34	18	19
Flow rate (m^3/s)	2.9	11.8	2.1	10.5	0.2	2.0	1.4	8.6	0.4	3.9

C6 and C7, NPS nutrient loads would cause the increase in nutrient concentrations in the wet seasons. Results from Table 4 also reveal that high SS concentrations were observed in the wet seasons due to the occurrence of soil erosion in the upper catchment areas.

Results indicate that most of the mid-to downstream sections (W1–W4) of the Houjing River had low DO (<2 mg/L) and high TC (>1×10^6 CFU/100 ml) and BOD values in dry seasons. This is due to the fact that improperly treated domestic and industrial wastewaters were discharged into the river.

Development of remedial strategies for the upstream sections

Because the monitoring station W4 was located at the boundary of farmland areas, and the monitoring station W1 was located at the outlet of the Houjing River watershed, W1 and W4 were selected to evaluate the accuracy of the modeling results. Results indicate that the simulated flow, DO, temperature, and pH values at W1 and W4 matched with the observed data very well during the year of 2006 (Lin 2009). In this study, NH_3-N, one of the major NPS pollutants, was selected as the indicator to evaluate the effectiveness of the remedial strategies on the reduction of ammonia loads to the water bodies. Figure 3 shows the comparison of simulated and observed ammonia concentrations at the monitoring stations W1 and W4 during the year of 2006. The simulated results also matched with the observed data very well. In the upstream section (W4), higher ammonia concentrations (up to 20 mg/L) corresponded with severe rainfalls, and this indicates that NPS pollution was the major cause of the increase in the ammonia concentrations especially in the upper sections during the wet seasons. Based on the results of pollution investigation, the major cause of the river pollution in the upper catchment is the NPS pollutants. Most of the ammonia came from the wash off from the soils after storm rains. Because ammonia concentrations were far beyond the Class C standard (0.3 mg/L), two applicable best management practices (BMPs) are proposed for the NPS ammonia pollution management to protect public health and improve the river water quality. Effects of the two BMPs

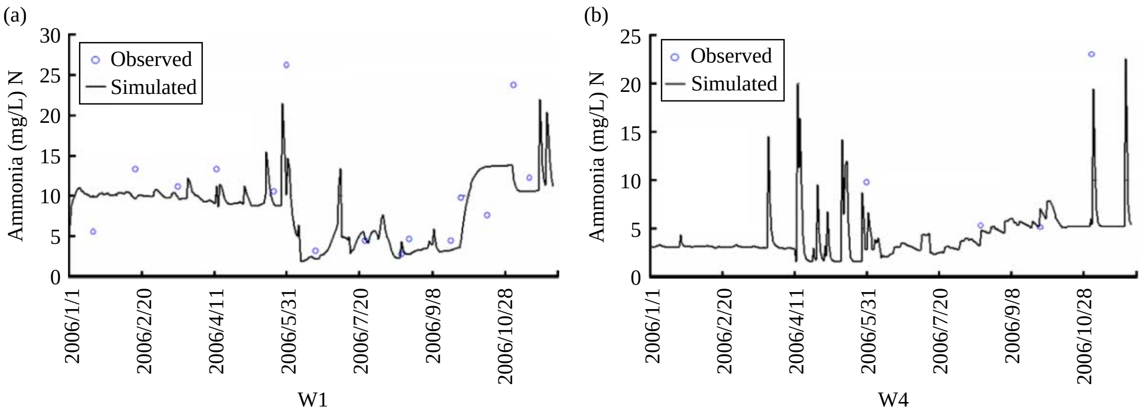

Figure 3 | Comparison of simulated and observed NH_3-N concentrations at the W1 and W4 water monitoring stations.

on the NPS pollution reduction and control were evaluated using the IWMM model.

The proposed BMPs include the following: (1) source (fertilizer) control (35% of reduction) to reduce the amounts of applied fertilizer in the upper catchment, and (2) conversion of 35% of the agricultural land use to grassy buffer zone along the river bank area. Figure 4 shows the simulated ammonia concentrations at W1 and W4 monitoring stations in 2006 after the application of two proposed BMPs. Results show that the peak ammonia concentrations at W4 can be reduced from 23 to below 5 mg/L after the application of two proposed BMPs (Figure 4(b)). This indicates that source control and agricultural land use reduction would be feasible applications for NPS ammonia control. However, the ammonia concentrations at W4 monitoring stations are still above 3 mg/L after several severe rainfalls (Figure 4(b)). Thus, some other BMPs (e.g. land use control, natural treatment systems) might be also required to meet the water quality standards.

Development of remedial strategies for the mid and downstream sections

Simulated results also indicate that higher ammonia concentrations were observed in the downstream section (W1) compared with the upstream section (W4) of the Houjing River. Significant decrease in peak ammonia concentrations at W1 were observed after the application of two proposed BMPs. However, part of the ammonia concentrations at W1 monitoring station was still above 10 mg/L. Because the point source pollution contributed significant amounts of pollutants into the river at the middle to downstream sections, application of the natural

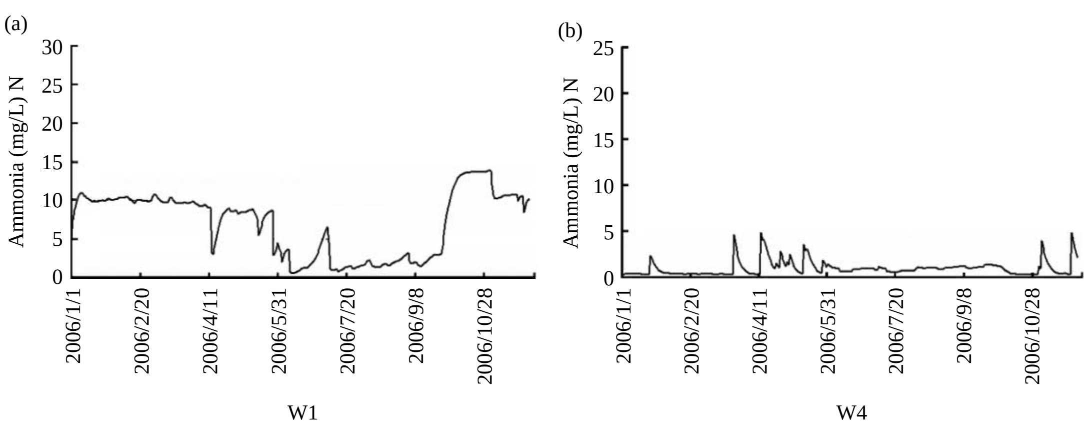

Figure 4 | Simulated NPS NH_3-N concentrations after the application of two BMPs at W1 and W4 water monitoring stations.

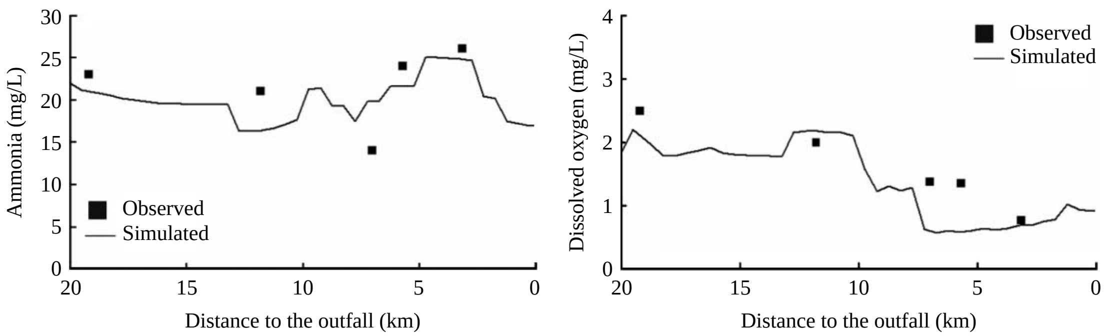

Figure 5 | Measured and simulated water quality results for DO and NH_3-N from the outfall (0 km) to the 21 km upstream location.

treatment system was still unable to effectively improve the river water quality.

Because the major pollution source of the mid and downstream sections of Houjing River came from the discharge of domestic and industrial wastewaters into the river, the QUAL2K model was selected as a management and planning tool to perform the water quality evaluation and carrying capacity calculations. Figure 5 presents the measured and simulated water quality results for DO and ammonia concentrations in the Houjing River from the river upstream (21 km) to the outfall (0 km). Results demonstrate that the simulated data had a good match with the observed water quality data. The carrying capacity calculation for NH_3-N was performed using the calibrated QUAL2K water quality model to obtain the maximum acceptable NH_3-N loading per day without violating the preliminary water quality criteria (NH_3-N ≤ 0.3 mg/L in Class C) for the Houjing River (Table 1). The calculated NH_3-N carrying capacity was approximately 31 kg per day. However, the calculated NH_3-N loading (10,518 kg per day) was much higher than the calculated carrying capacity.

To protect public health and improve the river water quality, the following river management strategies are proposed: (1) construction of the intercepting systems, (2) increase the flow by transporting 0.5 m^3/s unpolluted surface water from other sources to dilute the polluted river water. In this study, results from the IWMM modeling was also used as a pollutant input for the QUAL2K modeling. Thus, the contributions of NPS pollution to the deterioration of river water quality can be evaluated. Because the residential and industrial areas are one of the dominant land use patterns in sub-basins of C1–C3, construction of the intercepting systems in this area was an appropriate management strategy to lower the NH_3-N loads to the river.

Figure 6 presents the simulated water quality results for NH_3-N in the Houjing River after the application of the river management strategies. Results show that the ammonia concentrations at middle to downstream can be reduced from 10 to below 5 mg/L after the application of the two proposed river management scenarios (Figure 6). Approximately 50 to 60% of NH_3-N can be removed from the intercepting systems before it is discharged into the Houjing River. Results also show that the peak ammonia concentrations at W4 can be reduced from 23 to below 5 mg/L after the application of two proposed BMPs (Figure 4(b)). The NH_3-N loads could be further reduced with the application of the two proposed river management scenarios. However, the NH_3-N concentrations in the mid stream of Houjing River were still higher than 7 mg/L, and thus, some other pollution control strategies (e.g. enforcement of the industrial wastewater discharge standards, construction of sewer system for domestic wastewater collection and treatment, application of on-site wastewater

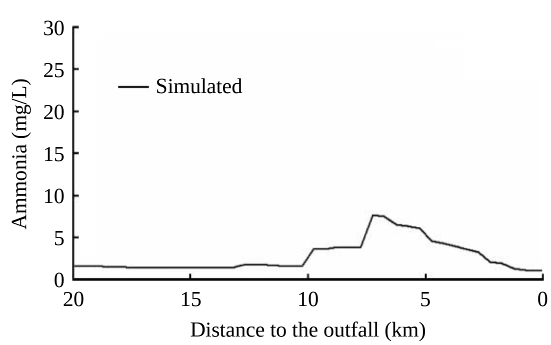

Figure 6 | Simulated NH_3-N results after the implementation of river management strategies.

treatment) are also required to reduce the ammonia loads into the river. Moreover, because illegal discharges of polluted industrial wastewaters into the river are sometimes practiced, enforcement of the industrial wastewater discharge standards is still a required institutional control measure to improve the water quality of the Houjing River.

CONCLUSIONS

Both point and non-point source pollutants are the major causes of the poor water quality in the Houjing River. Thus, improvements of conventional wastewater collection and treatment, as well as reductions in the contaminant loads from point and non-point sources are required to improve the river water quality. A comprehensive strategy for the Houjing River watershed management has been proposed based on the results from water quality investigation and modeling. In this study, land use identification in the Houjing River watershed was performed by properly integrating the skills of GIS and GPS systems. In this study, 27 types of land use patterns in the watershed area of the basin were classified with the aid of Erdas Imagine® process system and ArcView® GIS system. The results indicate that the major land-use patterns in the upstream areas were mainly orchard farms and farmlands. The major land-use patterns in the middle to downstream catchments were mainly residential and industrial areas. The IWMM and QUAL2K models were selected to develop NPS and river management strategies to effectively control the point and NPS pollution. Based on the results from this study, the following remedial strategies have been proposed to minimize the impacts of NPS and point source pollution on the water quality of Houjing River: (1) application of BMPs (e.g. source (fertilizer) reduction, construction of grassy buffer zone, and land use management) for NPS pollutant control; (2) application of river management scenarios (e.g. construction of the intercepting and sewer systems) for point source pollutant control; (3) institutional control (e.g. enforcement of the industrial wastewater discharge standards); and (4) application of on-site wastewater treatment for the polishment of treated wastewater for water reuse. Results and experience obtained from this study will be helpful in designing the watershed management strategies for other similar river basins.

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