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Using Integrated Multimedia Modeling on NPS Pollution Evaluation for the Kaoping River Watershed

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Abstract: In Taiwan, non-point source (NPS) pollution is one of the major causes of the impairment of surface waters. The Kaoping River Basin is the largest and the most intensively used river basin in Taiwan. In the Kaoping River Basin, most of the upper catchment is used for agricultural activities including cropland and livestock farming. Field investigation results indicate that NPS pollutants contribute more than 10% of the overall pollution load to the Kaoping River. An integrated watershed management model was applied to investigate potential NPS pollution management plans in the Kaoping River watershed. Based on the results from the field investigation and model simulation, the following remedial strategies have been taken to reduce the impacts of NPS pollution on the water quality of Kaoping River: application of best management practice for NPS pollutant control; application of natural treatment systems for stormwater runoff treatment; and construction of the watershed geographical information system (GIS) and real time water quality monitoring system to effectively manage the watershed. Linking land utilization information with the NPS pollution simulation model may further provide essential information of pollution potential of NPS pollution for all sub-regions in the river basin. Experience obtained from this study will be helpful in designing the watershed management and pollution control strategies for other similar river basins.

Key-Words: Multimedia modeling, watershed management, NPS pollutant, GIS; water quality

1 Introduction

The Kaoping River basin is the largest and the most intensively used river basin in Taiwan. It is 171-km long, drains a catchment of more than 3,625 km^2, and has a mean flow of 239 m^3/s. Fig. 1 shows the Kaoping River, its catchment, and three major reaches (Chi-San Creek, I-Liao Creek, and Lao-Non Creek). It serves as a water supply to the Kaohsiung City (the second largest city in Taiwan), several towns, two counties, and a number of large industries (electronic, steel, petrochemical, etc.). Although the mean annual rainfall in this river basin is close to 3,000 mm, over 90% of which appears in the wet season. The period of high flow rate in the stream usually occurs in the late spring and summer due to the impacts of monsoon and typhoon [1]. Taiwan Environmental Protection Administration (TEPA) has developed a three-part classification system (Classes A, B, and C) for Kaoping River based on the purpose of water usage and degree of protection for each stream section. Table 1 presents the water quality criteria for the three classes in Kaoping River. Basically, the upstream is classified as Class A, mid-stream is Class B, and the downstream near the outfall is Class C. Thus, the highest degree of protection is given to Class A. Results from previous studies indicate that the concentrations of some major water quality indicators [e.g., biochemical oxygen demand (BOD), suspended solid (SS), ammonia-nitrogen (NH_3-N), total phosphorus (TP), and Escherichia Coliform (E. Coli)] were higher than the Kaoping River water quality criteria [2,3]. The major objectives of this study were to (1) investigate and identify the current contributions of point and NPS pollutants to the river pollution, (2) select appropriate water quality models for NPS and watershed management simulation, and (3) evaluate the effectiveness of the applied remedial strategies on water quality improvement.

2 Multimedia Modeling

Pollutants distribute in the ecosystem of the earth with the movement of air and water. Air and water move through multiple physical media such as atmosphere, soil, water body, and the human body. The computer programs that simulate the natural processes of certain materials throughout multiple media are called multimedia models. These models can be used to study the ecosystem, analyze certain environmental and public health problems and to evaluate the impact of changed conditions in the ecosystem. These components include 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. The global atmosphere module aims to predict the meteorological condition and the quantity of material deposition at any location on the Earth. It may not only be used for assessing effects of air pollutant exposures as affected by changes in ecosystem, but also provides input of a watershed scale or a river-basin scale multimedia model. The boundary conditions of a global atmosphere model include air-space, air-sea, air-ice, air-canopy, and air-land conditions.

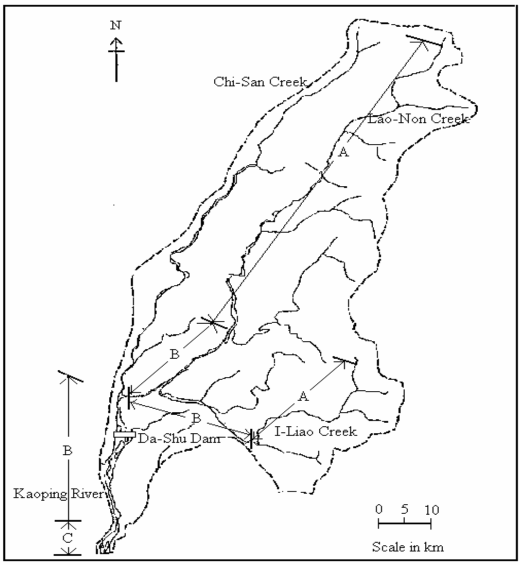

Fig. 1. Kaoping River Basin and three major reaches.

The human impact module includes risk assessment due to exposure to environmental chemicals and analysis of metabolic problems caused by those chemicals. Canopy studies have been focused on understanding the role of forest canopies in biodiversity and predicting the effects of climate and climate change on terrestrial ecosystems. The knowledge developed and the data collected in these studies lay a good foundation for the development of the canopy module. The physical media of the land module include soil layers (unsaturated and saturated), creeks, lakes, reservoirs, rivers, and estuaries. For the purpose of watershed or river basin management, this module is the centerpiece of the multimedia modeling work. Technically, it is the most successfully developed part of the whole multimedia model so far. In this study, the integrated watershed management model (IWMM) developed by Systech Engineering, Inc. was applied for simulating hydrology and water quality in the Kaoping River Watershed [4]. The model includes five major components: air and canopy, land surface and subsurface, mountain stream, river and estuary, and reservoir/lake. It dynamically simulates hydrological, physical, chemical and biological processes through these components. The output of the model includes water temperature, pH, total alkalinity, nutrients, pesticides, sediments, organic carbon, dissolved oxygen, algae, chloride, and sulfate, etc.

3 Pollutant Source Investigation

Results from the pollutant sources investigation demonstrated that both point and NPS pollutants are the causes of BOD, nutrients, and pathogens in the river [5]. Before the year of 2001, the main water pollution sources were livestock wastewater from hog farms, municipal wastewater, industrial wastewater, NPS pollutants from agricultural areas, and leachate from abandoned riverbank landfills. To reduce the hog population in the upper catchment of the Kaoping River Basin, the Taiwan Government enforced the hog ban and compensation project within the Drinking Water and Source Water Protection Area (DWSWPA). A total of 510 thousand pig capitals were removed/relocated from the DWSWPA in 2001. Thus, the manure from hog farming is no longer causing the deterioration of the water quality in the upper stream of the Kaoping River. It is believed that the drinking water quality for 12 million residents in the areas can be effectively improved.

Due to the rapid urban and industrial expansion, the percent of sewer system connection in the Kaoping River basin is less than 5%. Most of the municipal wastewater in the basin (especially in the rural areas) is discharged into the river without proper treatment. The untreated municipal wastewater contributes more than 40% of the daily BOD loading. Moreover, there are 229 registered industrial factories discharge their wastewater into the Kaoping River. However, it also contains a number of small and medium scale industries in the middle and downstream regions. The illegal or expedient discharges are sometimes practiced feeding polluted industrial flows into the river. Therefore, the untreated municipal and industrial wastewaters are also two causes of the poor water quality.

In the Kaoping River Basin, most of the upper catchment is used for agricultural activities including cropland and livestock farming. A fast and effective approach for assessing the potential of NPS pollution to assist in the planning of best management practice (BMP) becomes imperious demands for achieving the goals of a total maximum daily load (TMDL) [1,2]. To approach the goals of water resource conservation, water quality management, and land use effectiveness, the regulation of “Rules of Drinking Water and Source Water Protection Area Delineation” was promulgated in 1997. Most of the upper catchment of the Kaoping River Basin has been delineated and identified as the DWSWPA [6]. The rules prohibit any developing activities that endanger the quality of source water within DWSWPA. However, field investigation results reveal that more than 15% of the areas located inside the Source Water Protection Zone have been illegally developed into farmlands [2]. Investigation results also show that the NPS pollution contributes more than 10% of the overall pollution loads to the Kaoping River each year [3,7]. Thus, NPS pollutants have significant adverse impacts on the river water quality, and should be effectively controlled.

4 Water Quality Modeling

In this study, IWMM was applied to evaluate the impacts of NPS pollutants discharged from the upstream agricultural areas on the Kaoping River water quality. The Kaoping River watershed was divided into three sub basins (Chi-San Creek Basin, I-Liao Creek Basin, and Lao-Non Creek Basin). 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. The model takes the characteristics of different canopies and soil layers into consideration in the simulation. The model was calibrated and verified with field data collected in the Kaoping River Watershed from 2002 to 2003.

Fig. 2 presents the monitoring stations located in the Kaoping River Watershed. Fig. 3 shows the comparison of simulated and observed flows at the Li-Ling (G1) monitoring station. The model results had a reasonable match with the data. 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 loading to the Kaoping River. Fig. 4 shows the comparison of simulated and observed ammonia concentrations at the Li-Ling (G1) monitoring station. The simulated results also matched with the measured data very well. Fig. 5 and Fig. 6 present the simulated NPS ammonia concentrations in Chi-San Creek and I-Liao Creek basins during the low water period from July 2002 to Jan. 2003. Results indicate that the NPS ammonia loadings caused the increase in the ammonia concentrations in the mid-stream of Chi-San and I-Liao creeks in the Kaoping River Basin. Ammonia concentrations higher than the Class B water quality criteria (0.3 mg/L) were also observed after the storms during the investigation period (Figs. 5 and 6). The calibrated model was used to investigate the potential management plans for the reduction of NPS loadings. Table 2 shows the measured and simulated results at monitoring station G1 for flow rates and ammonia loadings from point and NPS pollutants. Results indicate that NPS ammonia loading contributes 8% of the total ammonia loading during the period from July 2002 to January 2003. However, the contribution of NPS ammonia loading increased to 64% of the total loading during the period from July to August in 2002. This indicates that the summer storms had serious impact on the downstream water quality and caused significant increase in the NPS ammonia loadings into the downstream water bodies.

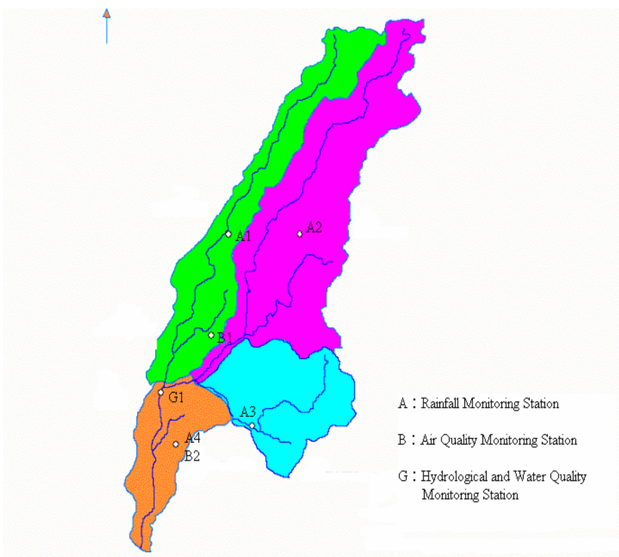

Fig. 2. Monitoring stations located in the Kaoping River Watershed.

5 Development of Remedial Strategies

To protect public health and improve the river water quality, three NPS ammonia pollution management scenarios are proposed. The scenarios for NPS ammonia reduction were proposed using the IWMM model to evaluate several BMPs for NPS pollution prevention and control. Table 3 presents the simulated NH_3-N loadings after the completion of each proposed plan to meet the Class B water quality criteria for Kaoping River. For both Chi-San Creek and I-Liao Creek basins, Scenario 1 is to impose the source (fertilizer) control to reduce the amounts of applied fertilizer in the upper catchment. Scenario 2 is to construct grassy buffer zone (overland flow system), and Scenario 3 is to combine the source reduction and buffer zone construction. With the application of each proposed scenario, the NPS NH_3-N loadings could be significantly reduced, and thus, the ammonia concentration in monitoring station G1 can be dropped to below 0.3 mg/L. However, Scenarios 1 and 2 would not be feasible due to the high percentages of required source (fertilizer) reduction rates and grassy buffer zones in the watershed. Thus, Scenario 3 might be more applicable for the practicability point of view. The operation manuals of the BMP for NPS pollution prevention and control for the industrial parks, recreational areas, agricultural zones, and construction sites have been edited and published by TEPA to be used as the basis of NPS control. During the initial stage of implementing the BMP for croplands, extra cost and decreasing harvest may be caused. Thus, the Government might need to apply the subsidy program to encourage farmers to adopt a proper BMP for NPS control. Except for the grassy buffer zone, applications of other natural treatment systems (e.g., land treatment, constructed wetland, riverbank sedimentation pond) are also applicable for the treatment of stormwater runoff in the upper catchments. It is estimated that more than 60% of SS, BOD, and NH_3-N can be removed from the stormwater runoff before it is discharged into the Kaoping River with the application of those natural treatment systems. Moreover, constructions of the watershed GIS and real time water quality monitoring system are also necessary to effectively monitor and manage the watershed. Construction of urban sewer systems for five major cities along the Kaoping River corridor are undertaken to resolve the domestic wastewater pollution problem. The percent of sewer system connection in the Kaoping River basin can be increased from 5% to more than 15%. Thus, the water quality can be further improved after the completion of the urban sewer systems. Since 2001, the Government has increased the budget and manpower to cleanup the polluted spots along the riverside, and to improve the river ecosystem.

Major accomplishments include the provision of highland green areas along the riversides and fishpond eco-garden in the wetlands. Recreational areas are also provided for the general public along several points of the riverside. In the upper catchments and rural areas of the Kaoping River Basin, sewer system construction is not applicable.

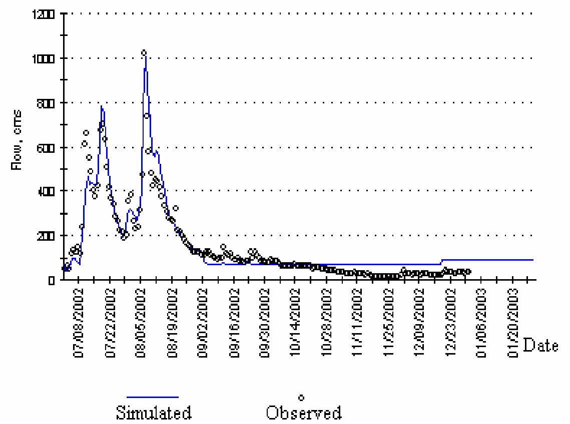

Fig. 3. Comparison of simulated and observed flows at the Li-Ling (G1) monitoring station.

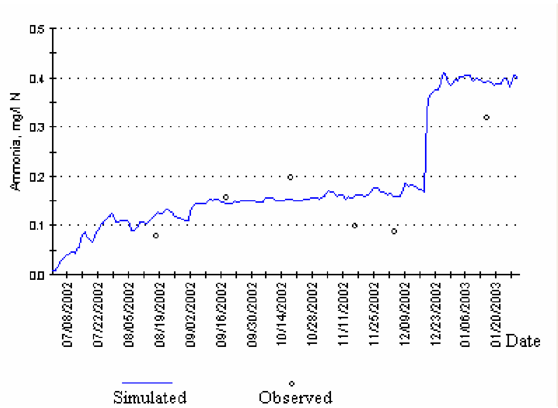

Fig. 4. Comparison of simulated and observed ammonia concentrations at the Li-Ling (G1) monitoring station.

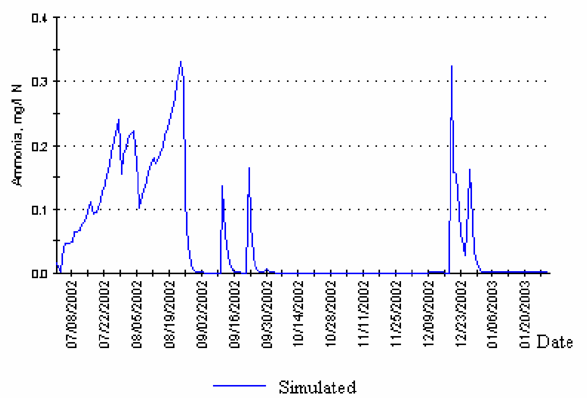

Fig. 5. Simulated NPS ammonia concentrations in Chi-San Creek Basin during the period from July 2002 to Jan. 2003.

Thus, the natural treatment systems described above have been constructed for domestic wastewater treatment or stream water purification. Other major strategies, which have been applied in the basin include the strict enforcement of the site investigation along the riverside, enhancement of water quality in the upstream reservoirs, management of highland wetlands, construction of the watershed GIS system, and enforcement of the industrial wastewater discharge standards [3,7]. Although 510 thousand pig capitals have been removed/relocated from the DWSWPA, the follow-up investigation and strict enforcement of the rules of DWSWPA is required. Besides the DWSWPA where the prohibition and compensation policies have been implemented, various low/zero pollution technology and management strategies have also been promoted in hog farms beside the water source zones. The key solution to resolve the problem is to adjust the basic raising pattern in hog farms. The Government encourages the farmers to incinerate the solid manure for energy recovery, or to compost the manure to generate useful organic fertilizers.

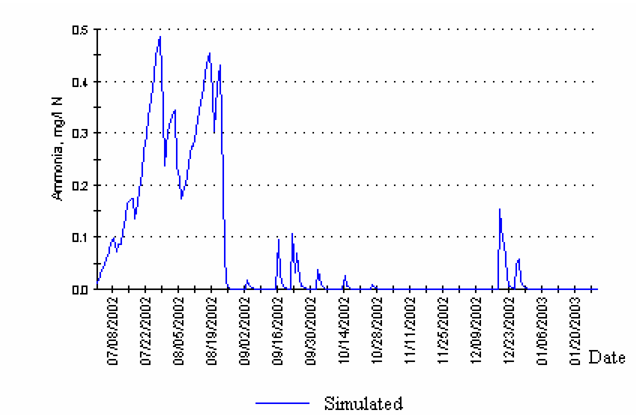

Fig. 6. Simulated NPS ammonia concentrations in I-Liao Creek Basin during the period from July 2002 to Jan. 2003.

6 Conclusions

Continuous discharge of industrial organic matter, stock manure, and domestic wastewaters into flowing waters of the Kaoping River system, where most water intakes are located in this region, has resulted in the need of a systematic policy for improving the water quality condition. Both point and NPS pollutants are the major causes of the poor water quality. 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 remedial strategy for Kaoping River Basin management has been proposed. The NPS pollution management strategy consists of the following measures: construction of the watershed geographical information system (GIS) and real time water quality monitoring systems, source (fertilizer) reduction, and construction of grassy buffer zone or other natural treatment systems. The point source pollution management strategy consists of the following measures: riverbank landfills removal, application of natural wastewater treatment systems for domestic wastewater treatment in rural areas, enhancing the river environmental quality and creating the recreational spaces, sewer system construction along the river corridor, and land use management and legislation (e.g., enforcement of wastewater discharge standards and rules of DWSWPA). Recent water quality investigation results indicate that the BOD and nutrient loadings to the Kaoping River have been significantly reduced and the water quality has been effectively improved after the implementation of the remedial strategies described above. 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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Table 1. Water quality criteria in the Kaoping River.

Water Quality Item	Category A[1] Most upstream reach[1]	Category B Most midstream reach[1]	Category C Downstream reach[1]
DO (mg/L)	>=6.5	>=5.5	>=4.5
BOD (mg/L)	1	2	4
NH_3-N (mg/L)	0.1	0.3	0.3
NO_3-N (mg/L)	10	-[2]	-
Total Phosphorus (mg/L)	0.02	0.05	-
E. Coli (CFU/100 mL)	<50	<5,000	<10,000

[1]Illustrated in Figure 1; [2]No criteria.

Table 2. Measured and simulated flow rates and ammonia loadings from point and NPS pollutants at monitoring station G1.

Date / NH_3-N Loading	July 2002 - Jan. 2003		July 2002 - Aug. 2002	
	Measured	Simulated	Measured	Simulated
Ave. Flow (CMS)	152.3	151.3	333.3	341.1
NH_3-N Conc. (mg/L)	0.16	0.18	0.08	0.09
P Source[1] + NPS Loading (kg/day)	2,079	2,405	2304	2,685
P Source Loading kg/day	-	2,207	-	977
P/(P+NPS) x100%	-	91.7	-	36.4
NPS Loading (kg/day)	-	199	-	1,708
NPS/(P+NPS) x100%	-	8.3	-	63.6

[1]P Source: Point Source.