

Application of hydroinformatics tools for water quality modeling and management: case study of Vientiane, Lao P.D.R

O. Mark, J. O. Lacoursière, L. B.-M. Vought, Z. Amena and M. S. Babel

ABSTRACT

The application of hydroinformatics tools is restricted in developing countries due to the non-availability of the required data and information under local conditions. This paper presents the state of water quality of the city of Vientiane (capital of Lao PDR) before the extensive rectification of its drainage network and describes an approach and methodology for water quality modeling. This is done with respect to the application of a combined hydrodynamic/water quality model based on minimal input data and observations for model verification. It further evaluates options to improve the deteriorating water quality observed in the rectified channels associated with the absence of suitable wastewater treatment. Two pollutants associated with the enrichment of receiving water bodies by wastewaters, total-P and $\text{NH}_4\text{-N}$, are modeled. The modelling study is carried out in three steps: dry weather flow simulation, wet weather flow simulation and nutrient modeling using MOUSE. The dry weather flow simulations are carried out to calibrate the model for hydraulic roughness coefficient, dispersion coefficient and travel time. The wet weather flow simulations analyze the effect on flooding of two channel states, namely unvegetated and vegetated conditions. Nutrient modeling therefore evaluates removal efficiency by the vegetation. Model results are compared with the observed data and recommendations are made with respect to the predicted effects of the water quality improvement schemes studied. In conclusion, the modeling approach herein presented can be applied for performance analyses of urban channels in the developing part of the world, where data are often limited.

Key words | flooding, MOUSE, nutrients modeling, urban drainage, water quality management, water quality modeling

O. Mark (corresponding author)
DHI Water and Environment,
Agern Allé 5,
Hørsholm DK-2970,
Denmark
Tel.: +45 4516 9373
Fax: +45 4516 9200
E-mail: Ole.Mark@dhi.dk

J. O. Lacoursière
L. B.-M. Vought
Sustainable Water Management Programme,
Kristianstad University,
Kristianstad SE-29188,
Sweden

Z. Amena
M. S. Babel
Water Engineering and Management,
Asian Institute of Technology,
P.O. Box 4,
Klong Luang Pathumthani 12120,
Thailand

INTRODUCTION

Rapid and unplanned urbanization in developing countries has resulted in increasing amounts of stormwater and pollution of receiving water bodies. In most cases, this is due to the lack of adequate wastewater treatment facilities and the absence of integrated stormwater management (Parkinson & Mark 2005). While countries of established economies now aim to incorporate or restore at great expense the use of aquatic systems into their urban

designs in what is classified as “state of the art”, developing countries tend to overlook this approach. Although not entirely recognized by the public or their leaders, the ponds, wetlands and channels of rapidly expanding cities still perform significant water quality maintenance along with water evacuation. These aquatic systems also play roles as the means of groundwater recharge, sediment trapping, habitat support and urban aesthetics. To make best use of

doi: 10.2166/hydro.2009.024

these systems, strategies should be developed towards an integrated approach of management both technically and institutionally (Parkinson *et al.* 2007).

One such instance is Vientiane, capital of Lao PDR, where just about half a million people had until recently been living in close contact with an intricate network of densely vegetated earth channels and wetlands (Lacoursière *et al.* 2003). This aquatic network served multiple purposes such as water quality enhancement through natural biological transformation, habitat support, irrigation and, although judged inefficient, removal of excess water in the rainy season. Managing the natural and man-made drainage network of Vientiane is therefore a challenging task, which calls for a comprehensive understanding of the benefits that all components provide.

This study was therefore carried out to evaluate, by the application of mathematical modeling, one of the suggested management solutions to improve water quality in a recently rectified channel in the southwest part of Vientiane; namely the timely maintenance of plants and sediments purposely kept in the drainage channel.

STUDY AREA AND EXTENT OF THE WATER QUALITY PROBLEM

Topography, climate and hydrology

Vientiane sits on low-lying alluvial soils deposited by the Mekong River. The area designated for urbanization extends along the east bank of the Mekong River and occupies an area of 210 km² with ground elevation ranging from 160–170 m above sea level. The first defense flood control dike and flood defense gates of the Municipality of Vientiane extend for more than 74 km and raise the banks of the Mekong to a level of 172 m a.s.l. to protect the city from 100 year recurrence flood levels (diking was initiated following the catastrophic flood of 1966, with sporadic improvement to extend and raise it to the present level)¹.

The climate is classified as tropical and dominated by the southwest monsoon, which brings heavy rainfall, high

humidity and high temperatures between mid-April and mid-October. Average annual precipitation in Vientiane is ca. 1,620 mm, with the heaviest rainfall occurring in August. About 94% of the precipitation occurs during the wet season. The average yearly temperature is 26°C, with a mean maximum of 30°C in April and a mean minimum of 21°C in December.

The urban area of Vientiane is located between an elaborate network of permanent and seasonal water bodies, floodplains, swamps and marches stretching north and east, and by the Mekong River to the south and west. Since 1966, the long flood defense dike stretching between the Mekong and the city constrains its drainage inland through the That Luang Marsh, the largest remaining wetland in Vientiane and a still highly significant source of economically important goods and services to Vientiane's urban inhabitants. Drainage from the city is done via three main networks, all of them former stream or river systems, part of the intricate network of ponds and wetlands still dominating the urban landscape less than a decade ago. Drainage waters from Vientiane finally reaches the Mekong River as water flows out of the That Luang wetland through the ca. 56 km Houay Mak Hiao River.

Water supply

Within the urban districts of Vientiane Capital City (formally called the Vientiane Prefecture), more than 80% of the households have access to potable water. The supply is abstracted from one of two intakes on the Mekong River, one of which is upstream and the other downstream of the urban core. Water is treated prior to distribution and the quality and reliability of supply is generally considered to be good. Of these, more than 90% have access to piped water supply from Nam Papa Lao, the water supply company of Vientiane (GHK International Ltd. & SMED Consultants 2001). In some villages, particularly in the poorer communities, households share water from supply connections. Average consumption is approximately 150 l per capita per day. The estimated water consumption and household wastewater production in Vientiane can be seen in Table 1. Because of the continuous supply and pressure in the distribution network, infiltration of contaminated water from groundwater into the distribution

¹Mr. B. Keosithamma, Project Director, Urban Environmental Sanitation Improvement Project, Dept. of Communication, Transport, Post and Construction of Vientiane Capital City, personal communication.

Table 1 | Estimated water consumption and household wastewater production in Vientiane (GHK & SMED 2001)

	Total water consumption (L/capita/d)			Sullage (greywater) (L/capita/d0)			Toilet water (blackwater) (L/capita/d)		
	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.
Toilet	20	30	40	0	0	0	20	30	40
Personal hygiene	30	60	80	30	60	80	0	0	0
Drinking water	10	10	10	0	0	0	5	5	5
Kitchen wastewater	20	35	60	20	35	60	0	0	0
Irrigation	0	5	20	0	0	0	0	0	0
Total	80	140	210	50	95	140	25	35	45

system is not considered to be a problem but, in poor areas where people use well water, the quality of water is very poor due to groundwater contamination.

Wastewater disposal

Because of the absence of sewage collection and treatment systems in most of Vientiane, wastewater from poorly operating household septic tanks still predominantly discharge into open drains along the roads and into natural wetlands, which in turn is evacuated by the rectified channel network.

The necessary components for the peri-urban on-site sanitation system are soak pits and septic tanks. A septic tank provides a way of pre-treatment processes prior to soak pits in order to reduce the solid load and to attenuate peak household wastewater discharges. Soak pits are essential to enable the wastewater to percolate into the surrounding soils. In Vientiane 67% of the households have the soak pit and septic tank facility, 26% have the holding tank facility, 5% of households have only the septic tank facility and 2% households don't have any wastewater disposal facility (Danish Ministry of Foreign Affairs & DANIDA 2000).

Physical conditions related to the high groundwater table (only 0.5 m from the surface) and low permeability of soil are reported to have significant impact in reducing the efficiency of soak pits to percolate wastewater into the soils in Vientiane (GHK International Ltd. & SMED Consultants 2001). As a result of this, polluted effluent overflows and pollutes surface waters, often in the low-lying areas of Vientiane.

The kitchen wastewater and other household wastewaters are disposed of directly to the drainage channels together with the collected stormwater (Figures 1 and 2).

Stormwater drainage

The catchment area of urban Vientiane is divided into a number of sub-catchments which drain via a series of open drains into the That Luang Marsh, which is located to the east of the urban area, through two natural drainage paths. These are the Hong Xeng and Hong Ke channels (Figure 3). While the Hong Ke drains the central part of the city, the larger Hong Xeng collects waters from the urban Nam Pasak II channel and the predominantly agricultural Nam Pasak drainage network.

At the time of the study, the outflow of the Hong Xeng drainage channel was controlled for irrigation purposes by a



Figure 1 | Household wastewater inflow to the Nam Pasak II, ca. 110 m from the top (photo: Vought & Lacoursière, February 2001).



Figure 2 | Stormwater inlet to the Nam Pasak II, ca 1300m from the top (photo: Lacoursière & Vought, August 2001).

sluice gate able to create impoundment on a distance reaching in excess of the two Nam Pasak junctions, the impoundment used then to supply the adjacent rice fields. The sluice gate, which was under the responsibility of the Irrigation Department, was observed to be 90% closed during most of the dry season. Although this backwater more seriously affected the urban drainage network during the onset of the rainy season (under the responsibility of the Vientiane Urban Drainage Administration Authority; VUDAA), it also provided excellent conditions for the rapid

growth of floating aquatic plants, a key component of year-round water quality maintenance. The sluice gate was removed as part of the full rectification of the Hong Xeng channel which was completed at the end of 2006. This, however, does not change the conclusion of this study as the backwater created by the dam simulated the effect of controlled impoundment on the studied channel.

Prior to 1999, Vientiane had no sewage collection and treatment system, and domestic wastewater, septic tank effluents and stormwater were all discharged into an increasingly inadequate drainage network of this low-lying city, leading to frequent local flooding during heavy rain events. An intensive infrastructure and services improvement programme was therefore initiated, but budgetary restrictions and the urgency of solving the flooding problem left the tackling of the core sanitation component to be initiated in a later phase; Asian Development Bank (ADB) and Vientiane Urban Development Administration Authority (VUDAA) (2001). Although local flooding was significantly reduced as the project was implemented, severe water quality problems during both monsoon and dry seasons were becoming common occurrences not only within the rectified channel network, but also in the

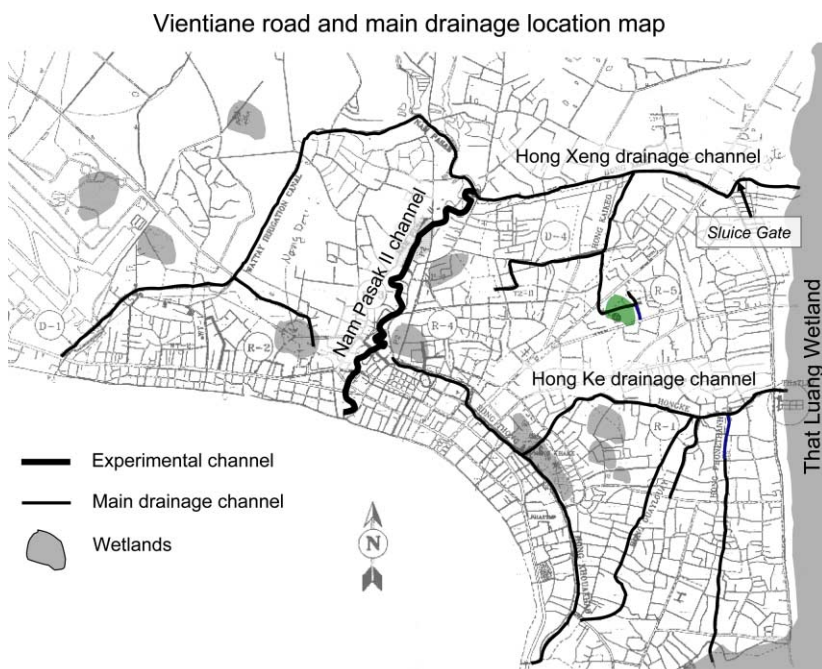


Figure 3 | Locations of the Nam Pasak II channel (study site) and other major drainage channels and wetlands in Vientiane.

receiving water bodies as a large amount of nutrients was now being discharged from the city. Monitoring initiated in 1986 shows that the intricate aquatic network of Vientiane then contained on average only 0.2 mg/l phosphorus, 2.5 mg/l nitrogen and 5.1 mg/l COD—less than the average agricultural streams of southern Sweden—thanks to the densely and heavily cropped plant biomass produced (Vought *et al.* 2000). Not only did nutrient concentrations surged tenfold, but the ammonia:nitrate ratio (a good indication of the loss of natural filtration capacity) increased 400-fold from the time the central portion of the system was completed. A recent study on the fate of detergent from the city drainage waters as it flows through the receiving That Luang wetland confirms that the increase in nutrients and organic loading is significantly impacting its ecological functioning, as indicated by the dominance of low-oxygen-tolerant invertebrates in benthic samples up to 4 km downstream of the outflow point.

The study area, which is now the narrow upper section of the Nam Pasak II–Hong Xeng channel, drains both wastewater and stormwater from the southwest part of Vientiane. This narrow channel was originally, like most of the natural system along the Mekong River, a natural shallow and tortuous stream draining into the river most of the year, with some flow reversal (i.e. water flowing from the Mekong River to the riparian wetlands) during the flooding season. Following a permanent reversal of the drainage pattern when the protective dike along the Mekong bank was reinforced over 50 years ago, the channel was modified in the mid-1990s from a wide,

shallow, soft-substrate, densely vegetated and meandering channel with adjacent wetlands to an excavated, straight, trapezoidal, concrete-lined channel. Figure 4 shows the mid-point section of the experimental reach, approx. 1.4 km from the top, in 1998 and then again eight years after rectification.

Evaluation of the state of pollution of the experimental reach

The range of values of nutrients ($\text{NO}_3\text{-N}$, $\text{NO}_2\text{-N}$, $\text{NH}_4\text{-N}$, $\text{PO}_4\text{-P}$ and Tot-P), pH and DO data, measured during the year 2000 for the Nam Pasak II channel, are listed in Table 2 along with the values of the same components for typical domestic wastewater and the Mekong River just upstream of Vientiane.

From Table 2 it is quite clear that the values of most of the parameters for the Nam Pasak II channel fall within the range or very near to the typical values specified for domestic wastewater and far from the values observed in the Mekong River. Overall, the Mekong River is still viewed as an unpolluted system.

PROJECT APPROACH

In order to quantify and characterize the changes cascading through the urban aquatic ecosystem of Vientiane, research collaboration between Swedish and Laotian scientists was initiated in 1999. The main objective was to generate



Figure 4 | Example of Vientiane drainage channels: the Nam Pasak II experimental reach at a point ca. 1.4 km from the top, in 1998 and 2007 (photo: Lacoursière and Vought).

Table 2 | Water quality parameters for the Nam Pasak II channel, typical domestic wastewater and the Mekong River just upstream of Vientiane

Parameters	Nam Pasak II channel (Vought <i>et al.</i> 2000)	Typical domestic wastewater*	Mekong River at water supply intake†
pH	6.1–7.2	5–9	6.0–9.0
DO (mg/l)	0.42–11.6	<2	4.0–9.9
NO ₃ -N (mg/l)	0.03–0.11	0–1	<0.005–0.69‡
NO ₂ -N (mg/l)	0–0.1	0	
NH ₄ -N (mg/l)	5.79–27.28	12–50	<0.005–0.33
Tot-P (mg/l)	1.52–5.63	6–20	<0.005–0.36
PO ₄ -P (mg/l)	0.48–3.62	4–15	<0.005–0.17

*UN Department of Technical Cooperation for Development (1985), United States Environmental Protection Agency (1972).

†Water Quality Monitoring Laboratory, Dept. of Irrigation, Ministry of Agriculture and Forestry, Vientiane, Lao PDR (1985–2003).

‡NO₃-N + NO₂-N.

scientifically based in-channel management suggestions, including the retrofitting of small-head impoundments, aimed at reducing water quality impacts on the receiving ecosystems without unduly increasing flood risks in the urban area. This research collaboration has been coordinated by Kristianstad University (Sweden), with contributions from the Asian Institute of Technology (Thailand) and Sheffield University (UK), with the aim of providing management and risk-assessment tools to VUDAA and the Lao National Mekong Committee based on an adaptive environmental assessment and management approach (Lacoursière *et al.* 2003). Central to the success of such a method is the development of a flexible dynamic model integrating both hydraulic and biogeochemical processes. As part of this collaboration, the present study has been carried out to evaluate proposed alleviation schemes to improve water quality in the Nam Pasak II channel without increasing local flood risks.

Purposely maintaining both vegetation and sediment in the channel to promote nutrient removal through natural biological processes is part of the proposed strategy to mitigate water quality problems until the proper sewage treatment is established, and thereafter ensuring suitable stormwater management (Lacoursière *et al.* 2003). Dynamic coverage and the timely presence of plants is a departure from classic flood-protection scheme guidelines. Specific characterization of the influence of vegetation

(floating versus rooted) on the roughness coefficient is key to the acceptance of such an approach. In a first step toward this goal, mathematical modeling of a portion of the Nam Pasak II reach has been carried out in order to understand and characterize the complex physical and biological interactions simultaneously affecting water quality and flooding.

NUMERICAL MODEL FOR THE NAM PASAK CHANNEL

The uppermost 1.5 km of the Nam Pasak II channel was modeled in MOUSETRAP® (Garsdal *et al.* 1995), a modeling tool for urban drainage. This software effectively represents flows with a hydrodynamic model used in conjunction with an advection–dispersion model, which includes a first-order decay process.

The one-dimensional vertically integrated equation for the conservation of mass of a substance in solution, i.e. the one-dimensional advection–dispersion equation, is

$$\frac{\partial(AC)}{\partial t} + \frac{\partial(QC)}{\partial x} - \frac{\partial}{\partial x} \left(AD \frac{\partial C}{\partial x} \right) = -A \times K \times C + C_c \times Q \quad (1)$$

In the present numerical model, a more general description of the dispersion coefficient (D) has been implemented, with D determined as a function of mean flow velocity:

$$D = a|u|^b \quad (2)$$

where u = mean velocity (m/s) and a , b = user specified constants.

The mean travel time and dispersion coefficient for the channel are determined by using the properties of Gaussian distributions. The mixing process of any conservative and soluble substance in an aquatic environment is generally described by Fick's laws. The first Fick's law for the three-dimensional spreading of a substance is

$$\frac{\partial c}{\partial t} = e \left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2} \right) \quad (3)$$

where c is concentration, t is time, e is a molecular diffusion coefficient and x , y and z are the longitudinal, transverse and vertical coordinate direction, respectively.

The Fickian-based equations produce Gaussian distributions and the solutions can describe the three-dimensional spreading of a substance introduced to a still body of water. The standard mathematical solution of Equation (3) in the longitudinal direction is

$$c(x, t) = \frac{m}{\sqrt{4\pi et}} \exp\left(\frac{-x^2}{4et}\right) \quad (4)$$

where m is the mass of the injected substance area.

To get a complete picture of the advection–diffusion process of a substance in the aquatic environment, it is necessary to include the velocity terms in all directions in Equation (1) and hence have the solution by a complete description of the velocity profiles. But the complete description of velocity profiles is often too complex, time-consuming and uncertain for modeling purposes. Therefore the advection–diffusion Equation (ADE) is often depth- and width-averaged for simplification.

As longitudinal mixing is the point of interest of modeling in this study, the depth- and width-averaged form of the ADE used for longitudinal mixing is given below:

$$\frac{\delta c}{\delta t} + u \frac{\delta c}{\delta x} = D \frac{\delta^2 c}{\delta x^2} \quad (5)$$

where D is the longitudinal mixing coefficient and u is the mean flow velocity in the longitudinal direction.

The standard solution of Equation (5) is

$$c(x, t) = \frac{m}{\sqrt{4\pi Dt}} \exp\left(-\frac{(x - ut)^2}{4Dt}\right). \quad (6)$$

As the solution of ADE gives Gaussian distributions the properties of Gaussian solutions can be used to evaluate mean travel time and dispersion coefficient.

From the measured concentration distributions of salt, moments of Gaussian distribution are calculated. The expressions for these moments are

$$\text{Zeroth moment : } M_0 = \int_{-\alpha}^{\alpha} c(x, t) dt \quad (7)$$

$$\text{First moment : } M_1 = \int_{-\alpha}^{\alpha} tc(x, t) dt \quad (8)$$

$$\text{Second moment : } M_2 = \int_{-\alpha}^{\alpha} t^2 c(x, t) dt. \quad (9)$$

The mean μ and variance σ_t^2 is calculated for the concentration distributions at both the reading locations. The mean of any distribution is the centroid of mass for that distribution. This can be in terms of distance if the distribution is given in the form of concentration vs. distance and can be in terms of time if the distribution is given in the form of concentration vs. time. In this case the centroids of mass for the two distributions are in terms of time (seconds). The difference between the two centroids of mass is the mean travel time. Then the dispersion coefficient is calculated from mean velocity, variance of the distributions and trace distances. The expressions for mean, variance and dispersion coefficient are

$$\text{Mean : } \mu = \frac{M_1}{M_0} \quad (10)$$

$$\text{Variance : } \sigma_t^2 = \frac{M_2}{M_0} - \mu^2 \quad (11)$$

$$\text{Dispersion coefficient : } D = \frac{1}{2} u^2 \frac{\sigma_{t_2}^2 - \sigma_{t_1}^2}{t_2 - t_1}. \quad (12)$$

The methodology for modeling flow and water quality in the channel consists of applying flow and tracer data from the dry season to calibrate flow resistance and transport characteristics of the channel. The calibrated model is then applied to analyze the effect of adding vegetation on the nutrient transport phenomenon and uptake by the plants and on increased flooding during the monsoon.

Simulation for dry weather flow

The objective of dry weather simulation is to calibrate the flow resistance and transport characteristics of the channel in terms of Manning's roughness coefficient and dispersion coefficient. A tracer study using salt conducted in 2001 for the study channel provided the necessary observations for the dry weather flow calibration (Amena 2003). The hydrodynamic and advection–dispersion models are used for these analyses.

Data assumption

Due to the non-availability of some of the required data and information, the following assumptions are made for dry weather flow simulation:

- The injected salt slug is assumed to have a constant concentration.
- As flow rates of the inflow/pipes releasing wastewater to the channel are not exactly known, a uniform lateral inflow along the channel is assumed. Between any two locations, having measured discharges, the difference in flow is distributed linearly between locations.

Results of dry weather flow simulation

The calibrated value of the Manning M in the downstream part of the channel is $70\text{ m}^{1/3}/\text{s}$ and in the upstream part it ranges from $80\text{--}90\text{ m}^{1/3}/\text{s}$. A smooth concrete surface typically has Manning numbers of $90\text{ m}^{1/3}/\text{s}$. The calibrated values are lower than for smooth concrete, which is reasonable for concrete surfaces a few years after construction.

A sample calibration plot for the downstream reach of the channel is depicted in Figure 5. The simulated temporal concentration profile at the location at 1,323 m matches well the observed concentration data. The match is considered reasonably well at the upstream location (1,187 m) with the limited data available for the modeling. The calibrated values of dispersion coefficient and the mean travel time are compared with the calculated values based on the observed data and in general a good agreement is achieved (Table 3).

Simulation for wet weather flow

Flood risk during the wet season is evaluated under three scenarios: design condition (roughness is the same as design

values for smooth concrete), present condition (a higher hydraulic roughness than smooth concrete—based upon the dry season calibration) and vegetated condition. Two cases are considered to represent an increasing vegetated condition. In Case 1, very dense rooted vegetation is present on the bottom and side of the channel, which is characterized by a Manning number of $10\text{ m}^{1/3}/\text{s}$ for the entire cross section. In Case 2, both rooted and submerged vegetation (approximately 20 cm tall) are present over the entire channel bottom. Consequently, a Manning number of 10 is used for the bottom-most 20 cm of the channel section and the flow area is reduced accordingly, while the calibrated Manning numbers are used for the upper part of the channel section.

For the three scenarios, simulations have been carried out for rainfall with return periods of: 2, 5 and 10 years. Runoff contribution from the catchment along the channel is computed using a time–area model and the hydrodynamic module is employed for simulating the flow in the channel. The scenario of the vegetated condition (Case 2) is simulated by using the sediment transport (ST) module. The ST module is based on the Einstein sidewall elimination procedure, which enables the model to compute the combined resistance from the sides of the channel and the vegetation on the bottom.

Data assumption

Again, due to non-availability of some of the required data and information the following assumptions are made in this step of modeling:

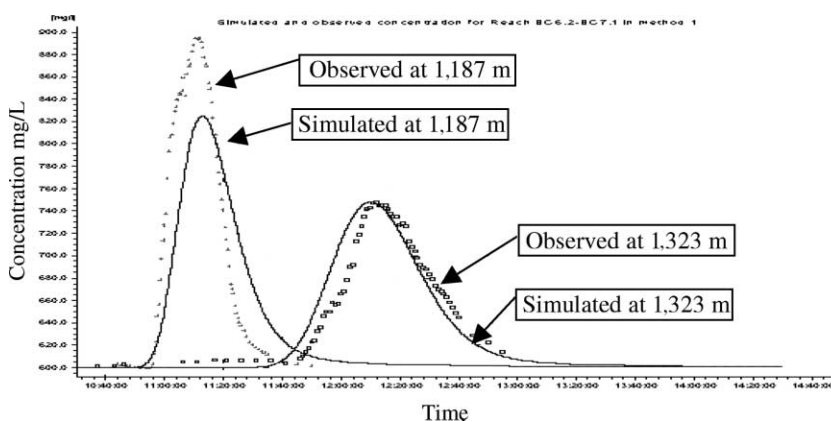


Figure 5 | Calibration plot for the downstream reach (1.05–1.35 km) of the Nam Pasak II experimental channel.

- Rainfall–runoff modeling of drainage canals and sewers requires time series data of rainfall at 5 min interval. As the observed rainfall data was not available for a sufficient long period, the IDF curves for Vientiane are used for runoff modeling (see Table 4). The rainfall duration of 15 min is found to be critical, giving the highest rainfall intensity for a specific return period according to the IDF curves (JICA 1990). The simulations are then made with a constant rainfall of 15 min duration.
- The catchment areas contributing flow to the drainage channel are at the moment determined through an iterative process based on the knowledge that the channel originally was designed for rain with a 10 yr return period. The model is run with varying catchment areas for the design condition of a 10 yr rainfall of 15 min duration until the bankful flow in the channel is simulated. The catchment areas thus obtained are taken as the design catchment areas and for all wet weather simulations.

Results of wet weather flow simulation

Simulation results show that there is no flooding in the surrounding areas due to overflow from the channel for a

Table 3 | Simulated and observed values of dispersion coefficient and travel time

	Dispersion coefficient (m ² /s)		Mean travel time (s)	
	Simulated	Observed	Simulated	Observed
Upstream reach	0.30	0.28	2688	1376
Downstream reach	0.10	0.08	3569	3920

Table 4 | IDF rainfall intensities for Vientiane

Return period (yr)	Rainfall intensity in specified time of concentration (mm/h)			
	15 min	30 min	60 min	120 min
2	74	61	38	26
5	92	80	51	36
10	106	95	61	44
20	120	110	71	52
25	124	115	74	55
50	137	130	84	63
100	151	144	94	71

10 yr return period rainfall event if the channel is in the design condition or present condition. In both cases, the highest water level remains below the channel banks. The results, however, indicate that if very dense rooted and submerged vegetation is maintained on the channel bottom (Case 2), flooding could occur even for a 2 yr return period rainfall (Figure 6).

Nutrient modeling

Modeling of nutrient dynamics, i.e. transport, decay and nutrient uptake by aquatic plants, is done using ammonium nitrogen (NH₄-N) and total phosphorus (total-P) as parameters. Data of domestic wastewater discharges and flows in the Nam Pasak II channel collected in March 2000 as part of the nutrient mass-balance assessment of the entire channel is used to calibrate the model. The NH₄-N and total-P are simulated along the channel, at first without considering pollutant decay to analyze the effect of dilution on transport processes, and then with the calculated decay rates for the two nutrients to understand and analyze the effect of both transport phenomena and nutrient uptake by plants as well as the decay process. The hydrodynamic module and the advection–dispersion module are used for this purpose. Simulations are made for the two cases of the vegetated condition described above. Using the average steady state concentration found from the simulation without decay, the decay rates for NH₄-N and total-P are estimated based on the assumed N and P uptake rates of water hyacinth of 1,875 kg ha⁻¹ yr⁻¹ and 352 kg ha⁻¹ yr⁻¹, respectively (Vought *et al.* 2000).

Results of nutrient modeling

The results of nutrient modeling in terms of outflow concentrations are presented in Table 5. Simulation of the reduction in total-P concentration in the channel (21% and 18%, Cases 1 and 2, respectively) predict well the reduction of ca. 22% calculated from a nutrient budget conducted in the experimental reach. The present model, however, significantly underestimates NH₄-N removal by forecasting reduction levels of ca. 10% compared to the calculated 62%. This indicates that, contrary to the more

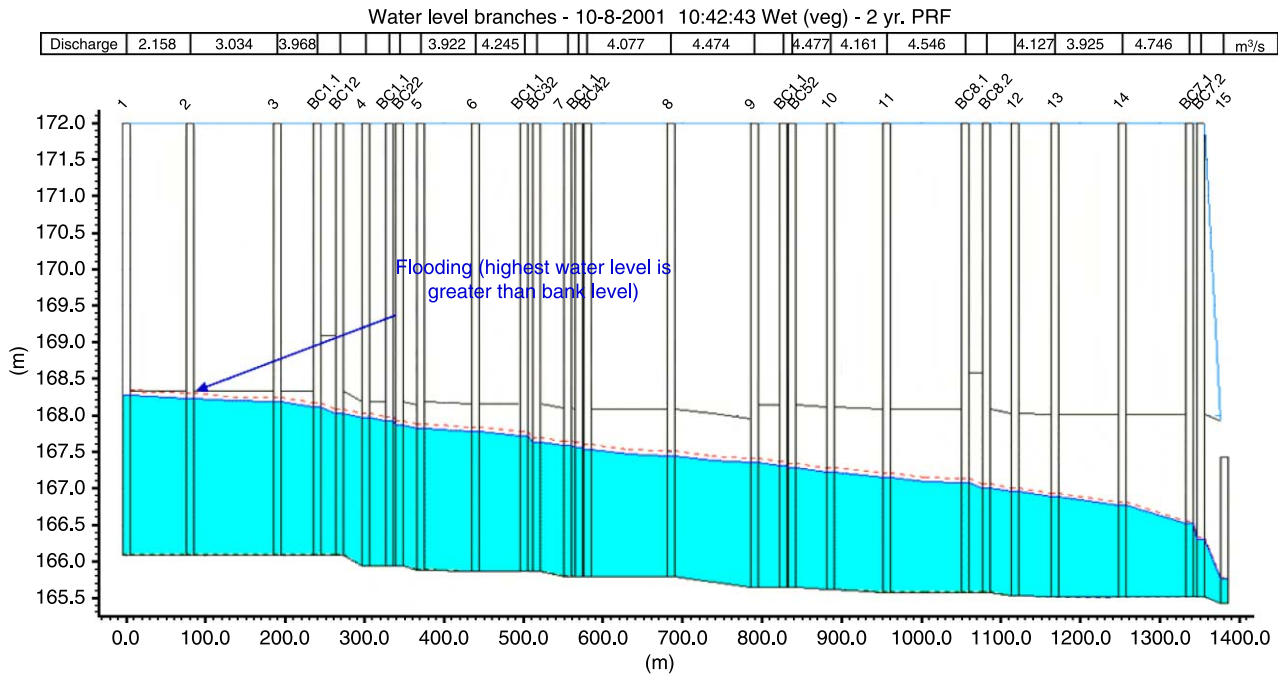


Figure 6 | Water level along the Nam Pasak II channel for a 2 yr return period rainfall in vegetated condition Case 2.

simple P particulate-dominated process, the dynamics of nitrogen in this system is likely to be complex, with ammonium concentration representing a balance between formation (from the mineralization of organic nitrogen) and losses (due to volatilization, plant and microbial uptake, sorption to solids and nitrification).

The main limitations of the hydrodynamic and the water quality modeling approaches presented in this paper are:

1. The advection–dispersion modeling carried out in the project assumes that all dissolved substances are evenly distributed over the cross section of the channel and that the flow in all parts of the channel can be approximated by a one-dimensional flow model.

2. No detailed water quality processes are included in the present modeling. Hence, all water quality processes are lumped into the decay rate.

Both of these assumptions have an impact on the water quality modeling results. Based on analyses of the tracer studies in Figure 5, it can be seen that the assumption about that flow being one-dimensional is justified as the timing of the two concentration peaks shows that the flow velocity in the model is close to the observed one. From the discussion just above concerning the dynamics of nitrogen, it is concluded that the decay model presented in this paper most likely is too simplified for analyses of nitrogen in this kind of waterway.

Table 5 | Results of the nutrient model

Parameter	Outflow concentration (mg/L)			% removal by plants		Observed (Vought et al. 2000)
	Without decay	With decay		Simulation*		
		Case 1	Case 2	Case 1	Case 2	
NH ₄ -N	5.82	5.32	5.36	9%	8%	62%
Total-P	0.78	0.62	0.64	21%	18%	22%

* (without decay - with decay) / without decay × 100.

CONCLUSION

This application of hydroinformatics tools demonstrates the applicability of the current tool in a developing country. This basic water quality modeling study indicates that nutrients can effectively be removed from the Nam Pasak II channel in Vientiane by pro-actively maintaining vegetation in it. In line with classic drainage strategies, it also indicates that, under the permanent presence of rooted vegetation, the flooding risk is significantly increased. Nevertheless, results also indicate that significant water quality gain can be achieved year round if proper cropping strategies are in place. This model therefore forms the base against which observed vegetation type (floating versus rooted) and coverage, water heights and nutrient loads can be related. Results also clearly indicate that, when enforcing the “classic” de-vegetation approach to channel management, the impact on water quality must be considered, even more so if the channel is heavily polluted.

The assumptions made and the limitations of the hydroinformatic tools presented in the present study can be useful lessons for similar cases of water quality enhancement and stormwater management schemes for cities in the tropical environment. Further work is needed to analyze the effect of both rooted and free-floating vegetation on flow resistance and its ultimate impact on flooding and water quality.

ACKNOWLEDGEMENTS

The study was part of the research sponsored by the Department for Research Cooperation of SIDA (SAREC/SIDA, grants SWE-1998-184-2, SWE-1999-202 and SWE2001-403) to JOL. The authors are grateful to Prof. I. Guymer (Warwick University, UK; formally from the University of Sheffield, UK) and Dr D. Luketina (Water Corporation, Perth, Australia), both former visiting faculty members in the Water Engineering and Management

Field of Study at AIT for their contribution. Special thanks are due to Mr. Bounchanh Keosithamma (Project Director, Urban Environmental Sanitation Improvement for Vientiane) for his insights on Vientiane’s drainage and sanitation. Acknowledgement is also made to Dr R. Larsson (University of Lund, Sweden) also supported by a grant from SIDA (SAREC/SIDA, grant SWE-1999-191).

REFERENCES

- Amena, Z. 2003 *Water Quality Modeling of the Nam Pasak Channel in Vientiane, Lao P.D.R.* Master’s Thesis, Asian Institute of Technology, Thailand.
- Asian Development Bank (ADB) and Vientiane Urban Development and Administration Authority (VUDAA) 2001 *Final Report: Sanitation, Drainage and Wastewater Management.* Vientiane Urban Infrastructure and Services, TA no. 3333- LAO.
- Danish Ministry of Foreign Affairs, DANIDA 2000 *Draft Project Document: Improvement of Urban Environment in Vientiane, Lao PDR.* DANIDA, Denmark.
- Garsdal, H., Mark, O., Dørgé, J. & Jepsen, S. E. 1995 **MOUSETRAP: modeling of water quality processes and interaction of sediments and pollutants in sewers.** *Water Sci. Technol.* **31** (7), 33–41.
- GHK International Ltd., London & SMED Consultants, Vientiane, Lao PDR 2001 *Final Report: Sanitation, Drainage and Wastewater Management, Vientiane Urban Infrastructure and Services.* TA no. 3333-LAO. Vientiane Urban Development and Administration Authority, Lao PDR.
- Japan International Cooperation Agency (JICA) 1990 *Feasibility Study on Improvement of Drainage System in Vientiane.* Final Report, Vol. 2 Japan International Cooperation Agency, Japan.
- Lacoursière, J. O., Mark, O., Vought, L. B.-M., Amena, Z. & Babel, M. S. 2005 To vegetate or not vegetate? *Water* **21**, 55–58.
- Parkinson, J. & Mark, O. 2005 *Urban Stormwater Management in Developing Countries.* IWA, London.
- Parkinson, J., Tayler, K. & Mark, O. 2007 Planning and design of urban drainage systems in informal settlements in developing countries. *Urban Water J.* **4** (3), 137–149.
- Vought, L. B. -M, Lacoursière, J. O. & Larsson, R. 2000 Multi-purpose channels in urban flood control: a case study–Vientiane, Lao PDR. In *Proc. Hydrologic and Environmental Modeling in the Mekong Basin*, pp. 50–60. Technical Support Division, Mekong River Commission, Phnom Penh, Cambodia.

First received 25 July 2006; accepted in revised form 29 September 2009. Available online 5 December 2009