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Application of automated QUAL2Kw for water quality modeling and management in the Bagmati River, Nepal

Prakash Raj Kannel[a,*], *S. Lee*[a,*], *Y.-S. Lee*[b], *S.R. Kanel*[c], *G.J. Pelletier*[d]

[a] *Water Environment Remediation & Research Center, Korea Institute of Science and Technology, P.O. Box 131, Cheongryang, Seoul 130-650, Republic of Korea*
[b] *Department of Environmental Engineering, Kwangwoon University, Seoul 139-701, Republic of Korea*
[c] *Department of Civil Engineering, 238 Harbert Engineering Center, West Magnolia Ave., Auburn University, Auburn, AL 36849-5337, USA*
[d] *Washington State Department of Ecology, P.O. Box 47600, Olympia, WA 98504-7600, USA*

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ABSTRACT

The Bagmati River in Kathmandu Valley (Nepal) receives seven major polluted tributaries. Discharges of wastewaters containing degradable organics and nutrients have resulted in decrease in DO concentrations along its course. A one-dimensional stream water quality model QUAL2Kw was calibrated and confirmed using the data in 2000. The model represented the field data quite well with some exceptions. The sensitivity analysis showed the model was highly sensitive for water depth and moderate to point sources flow, TN, CBOD and nitrification rate. The model was applied to simulate various water quality management strategies during critical period to maintain the targeted water quality criteria (minimum DO at or above 4 mg/L; maximum CBOD, TN, TP and temperature at or below 3, 2.5 and 0.1 mg/L and 20 °C, respectively, and pH range 6.5–8.5) considering: (i) pollution loads modification (ii) flow augmentation and (iii) local oxygenation. Except for CBOD, all the stated quality limits were achieved with 30 mg/L CBOD, 5 mg/L TN, 0.25 mg/L TP limits at point sources and with flow augmentation of 1 m^3/s and local oxygenations at three critical locations. The simulated maximum CBOD was 8.5 mg/L. It was considered reasonable for the developing country, Nepal, as the European water quality with maximum CBDO of 3 mg/L is difficult to achieve. The results showed the local oxygenation is effective to maintain minimum DO concentrations in the river. The combination of wastewater modification, flow augmentation and local oxygenation is suitable to maintain the acceptable limits of water quality criteria.

1. Introduction

The human activity generated contamination from agricultural, municipal and industrial activities introduces significant amount of nutrients and organic materials into the rivers and streams. Discharge of degradable wastewaters in the flowing waters result in a decrease in dissolved oxygen concentrations due to metabolism of pollutants by microorganisms, chemical oxidations of reduced pollutants, and respiration of plants, algae and phytoplankton (Drolc and Konkan, 1996).

The decrease of dissolved oxygen is apparent during low flow periods. The impacts of low dissolved oxygen concentrations or, at the extreme, anaerobic conditions are an

* *Corresponding authors*. Tel.: +82 2958 5848; fax: +82 2958 6854.
E-mail addresses: prakash.kannel@gmail.com (P.R. Kannel), seocklee@kist.re.kr (S. Lee).
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unbalanced ecosystem with fish mortality, odors and aesthetic nuisances (Cox, 2003). A good river health meets the threshold levels of key parameters dissolved oxygen (DO), carbonaceous biochemical oxygen demand (CBOD), total nitrogen (TN), total phosphorus (TP), temperature and pH.

DO concentration is vital for the survival of fisheries. It is a barometer of the ecological health of a stream and is the most important parameter for protecting fish (Chang, 2005). Fish cannot survive when DO content is less than 3 mg/L (Novotny, 2002). The acute lethal limit of DO concentration is at or below 3 mg/L for salmonids (USEPA, 1986). The coldwater minimum has been established at 4 mg/L considering a proportion of the less tolerant insect species common to salmonid habitats (USEPA, 1986) and to support varying fish populations (Ellis, 1937; Thompson, 1925).

The limit of temperature is 28.3 °C for warm-water fisheries, 20 °C for cold-water fisheries (MADEP, 1997) and 15–35 °C for recreational and aesthetic uses (ANZECC and ARMCANZ, 2000). The permissible range of pH is 6–9 for bathing water quality (EEC, 1976) and 6.5–8.5 for the fisheries (EMECS, 2001). The permissible limit of BOD is 3 mg/L for fisheries of the type salmonid and 6 mg/L for cyprinid stated by European Union in its council directives (EEC, 1978).

The permissible limit of TN stated by ECE is 2.5 mg/L for rivers of classes IV (UNECE, 1994). TP limit set by environmental protection agency, USA is 0.1 mg/L (USEPA, 1986) to control eutrophication. USEPA (2000a) and Dodds et al. (1998) have recommended maximum levels of TP and TN as 0.075 and 1.5 mg/L, respectively. USEPA (2000b) has recommended nutrient criteria for "rivers and streams in nutrient eco-region VI as 2.18 mg/L for TN and 0.076 mg/L for TP.

To achieve the stated target of the water quality, the assimilative capacity of the river should remain sufficient all along the river (Campolo et al., 2002). This goal can be achieved by controlling the wastewater pollution loads (Herbay et al., 1983), by flow augmentation (Hayes et al., 1998) and by oxygenators (Campolo et al., 2002).

The water quality management strategy involves a series of complex inter-disciplinary decisions based on speculated responses of water quality to changing controls (McIntyre and Wheater, 2004). The complex relationships between waste loads from different sources and the resulting water qualities of the receiving waters are best described with mathematical models (Deksissa et al., 2004).

The widely used mathematical model for conventional pollutant impact evaluation is QUAL2E (Brown and Barnwell, 1987; Drolc and Konkan, 1996). However, several limitations of the QUAL2E/QUAL2EU have been reported (Park and Uchrin, 1990; Park and Lee, 1996). One of the major inadequacies is the lack of provision for conversion of algal death to carbonaceous biochemical oxygen demand (Ambrose et al., 1987, 1988; Park and Uchrin, 1996, 1997). QUAL2EU ignores the role of macrophytes in water quality calculations and differs from other available models which do so by expressing macrophytes as dry weight biomass, which is then related to other water quality constituents through stoichiometric relationships (Park et al., 2003).

QUAL2EU does not actively integrate the impact of sediment into the model structure as a biological conversion. As a consequence, the material cycles are not closed (Anh et al., 2006). The others include inability of reduction of CBOD due to de-nitrification and no DO interaction with fixed plants.

Park and Lee (2002) developed QUAL2K, 2002 after modification of QUAL2E, which included the addition of new water quality interactions, such as conversion of algal death to BOD, denitrification, and DO change caused by fixed plants. Pelletier et al. (2006) developed a model QUAL2Kw, by modifying QUAL2K, 2003 originally developed by Chapra and Pelletier (2003), which was intended to represent a modernized version of QUAL2E/QUAL2EU.

QUAL2Kw is one-dimensional, steady flow stream water quality model and thus its application is limited to steady state flow condition. It has many new elements (Pelletier and Chapra, 2005). It includes DO interaction with fixed plants, conversion of algal death to CBOD and reduction of amount of CBOD due to denitrification. Additionally, it has auto-calibration system. It is useful in data limited conditions and is freely available (http://www.ecy.wa.gov/). Applications of QUAL2Kw are found in various literatures such as Carroll et al. (2006), Kannel et al. (2007), Pelletier and Bilhimer (2004).

QUAL2Kw can simulate a number of constituents including temperature, pH, carbonaceous biochemical demand, sediment oxygen demand, dissolved oxygen, organic nitrogen, ammonia nitrogen, nitrite and nitrate nitrogens, organic phosphorus, inorganic phosphorus, total nitrogen, total phosphorus, phytoplankton and bottom algae.

A real situation of a river can be represented more closely using complex models. However, the complex models, such as 2D or 3D, are highly sophisticated and are usually reserved for large (i.e. deep and wide) rivers/estuaries where the mixing patterns are complex and require large amount of data (Cox, 2003).

The Bagmati River-reach being simulated is long with respect to the mixing length over the cross-section and the transport is dominated by longitudinal changes. Thus, the assumption of 1D process is valid. Moreover, this is the data limited study with modest management objective, and hence QUAL2Kw was chosen as a framework of water quality modeling.

Studies have shown that the Bagmati River in the urban areas is heavily polluted with untreated municipal wastewaters that act as an important factor contributing to the DO sag within the city area and downstream sides. The low DO concentrations below 4 mg/L were observed to occur for 64.7% of the time in the river (Kannel et al., 2006). Thus, the main objectives of this study were: to examine the impact of waste loads on receiving water bodies, to determine the total maximum pollution loads that the river can receive ensuring the targeted water quality criteria for DO, CBOD, TN, TP, pH and water temperature.

2. Material and methods

2.1. Study area

The Bagmati River basin is situated approximately in the central part of Nepal. This study covered upper 25 km length of the Bagmati River with 650 km^2 drainage area within the Kathmandu Valley (Fig. 1). The Valley is of nearly round shape with

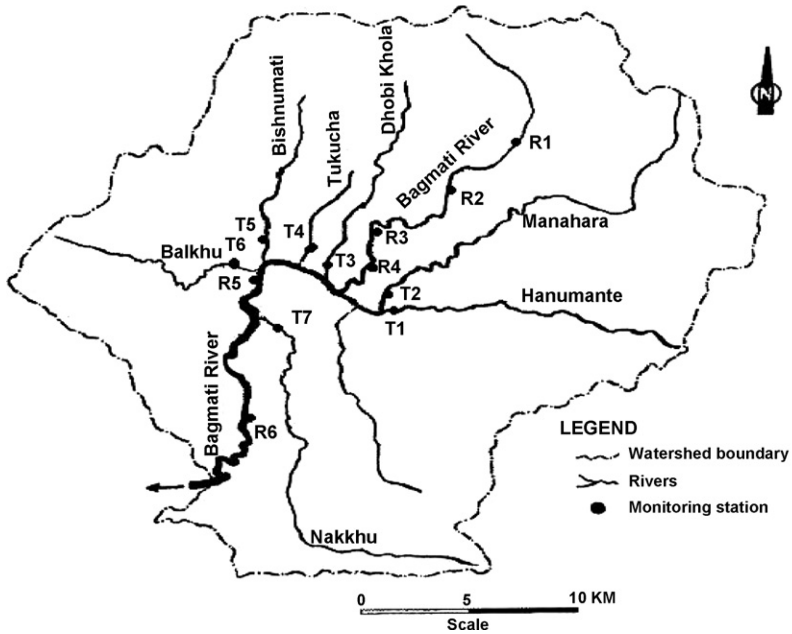

Fig. 1 – Monitoring stations along Bagmati River in Kathmandu valley.

diameters of about 30 km east–west and 25 km north–south (Dill et al., 2001). The altitude of the basin area varies from 1220 to 2800 m above mean sea level (Fujii and Sakai, 2002). There are three major settlements in the valley: Kathmandu (0.672 millions), Bhaktapur (0.163 millions) and Lalitpur (0.073 millions). The river is an important source of water for drinking, industrial, irrigation and recreation for about 1.6 million people (CBS, 2002).

About 20–30 years ago, the river was in drinkable condition (Erlend, 2002). In recent years, the surface waters are degraded due to inadequate wastewater treatment facilities that have accelerated the discharge of untreated wastes and wastewater from domestics, industries and hospitals into rivers (MOPE, 2000; UNPDC, 1999). The sewers lines have direct connection with the river and its tributaries with no wastewater treatment plants. The river water quality problems in the Bagmati River include low dissolved oxygen concentrations, bacterial contamination, and metal toxicity.

2.2. *Data and monitoring sites*

The monitoring stations (Fig. 1) taken for this study covered six stations R1–R6 along the main stem of the river and seven stations T1–T7 along the tributaries: Hanumante khola, Manahara khola, Dhobi khola, Tukucha khola, Bishnumati khola, Balkhu khola and Nakkhu khola (khola means small river in Nepalese term). The details of the monitoring stations are summarized in Table 1.

The monitoring works were performed at low flow conditions before and after monsoon season for applicability of the steady flow model QUAL2Kw. The monitoring works were conducted on January 2–6, 2000 in winter season and November 15–22, 2000 in post-monsoon season. With the objective of modest management goal, the fieldwork consisted of collecting a single sample in each station. The timings of samplings were varying.

Water quality parameters measured in this study include: flow, water temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), total suspended solids (TSS), total alkalinity as $CaCO_3$ (alkalinity), orthophosphates as phosphorus (PO_4P), total phosphorus (TP), ammonium as nitrogen (NH_4N), nitrate as nitrogen (sum of NO_3N and NO_2N), 5 days biochemical oxygen demand as O_2 (CBOD or BOD) and chemical oxygen demand as O_2 (COD).

Water samples were collected, transported and analyzed following methods described in APHA-AWWA-WPCF (1995) and USGS (1974). For physiochemical parameters, spectrophotometric determinations and TSS, samples were collected in a 1000 mL standard polythene bottles and stored in iceboxes. BOD samples were collected in 300 mL glass bottles and stored in iceboxes. COD samples were collected in 100 mL glass bottles and added few drops of concentrated sulphuric acid.

The test of physical parameters such as flow, temperature, pH, EC and DO were performed at the sites. Temperature, pH, DO and EC were measured using portable sensors. Water flow was measured using current meter. The other parameters were tested in a local laboratory.

Total suspended solids were determined by filtration and gravimetrically using temperature controlled oven. BOD concentration was determined measuring decreases in oxygen concentration after 5-days incubation in the dark at 20 °C. COD concentration was determined by oxidation with potassium dichromate in concentrated sulphuric acid medium (open reflux, titrimetric method). Ammonium nitrogen concentration was determined by nesslerization method. Nitrate and nitrite nitrogen concentrations were determined by diazotisation method. Orthophosphate concentration was determined by phosphomolybdate method. TP concentration was deter-

Table 1 – Water quality monitoring stations in the Bagmati River and its tributaries

Types	Stations (abbreviations)	km	Locations
Main river	Gokarna (R1)	0.000	Near Gokarna temple
	Downstream Gokarna bridge (R2)	3.000	About 200 m downstream of the Gokarna bridge
	Pashupati dam (R3)	10.400	Just downstream of Pashupati dam
	Minbhawan (R4)	14.000	About 500 m south of Bagmati bridge at Minbhawan
	Sundarighat (R5)	19.000	Just downstream of Bagmati-Bishnumati confluence
	Khokana (R6)	25.000	Near the Leprosy hospital (downstream of Nakkhu khola)
Tributaries	Hanumante khola (T1)	15.140	Just upstream of its confluence with Manahara khola
	Manahara khola (T2)	14.140	Just upstream of its confluence with Hanumante khola
	Dhobi khola (T3)	16.863	Just upstream of its confluence with Bagmati River
	Tukucha khola (T4)	17.588	Just upstream of its confluence with Bagmati River
	Bishnumati khola (T5)	18.888	Just upstream of Bishnumati bridge at Kalimati
	Balkhu khola (T6)	19.900	Just upstream of its confluence with Bagmati River
	Nakkhu khola (T7)	22.788	Just upstream of its confluence with Bagmati River
Wastewaters	Jorpati (W1)	2.800	Upstream of Jorpati bridge
	Pashupati (W2)	9.000	Near Pashupatinath temple
	Minbhawan (W3)	13.500	Upstream of Minbhawan bridge
	Sankhamul (W4)	15.400	Downstream of Bagmati-Manahara junction
	Thapathali (W5)	17.300	Downstream of Thapathali bridge above Tukucha khola

mined after converting total phosphorus compound into phosphates by oxidizing and decomposing organic matters and quantified colorimetrically by ascorbic acid reduction method using calibration curve.

2.3. *Modeling tool*

The modeling tool QUAL2Kw has a general mass balance equation for a constituent concentration c_i (Fig. 2) in the water column (excluding hyporheic) of a reach i (the transport and loading terms are omitted from the mass balance equation for bottom algae modeling) as (Pelletier et al., 2006):

$$\frac{dc_i}{dt} = \frac{Q_{i-1}}{V_i}c_{i-1} - \frac{Q_i}{V_i}c_i - \frac{Q_{ab,i}}{V_i}c_i + \frac{E_{i-1}}{V_i}(c_{i-1} - c_i) + \frac{E_i}{V_i}(c_{i+1} - c_i) + \frac{W_i}{V_i} + S_i$$

where Q_i = flow at reach i (L/day), $Q_{ab,i}$ = abstraction flow at reach i (L/day), V_i = volume of reach i (L), W_i = the external loading of the constituent to reach i (mg/day), S_i = sources and sinks of the constituent due to reactions and mass transfer mechanisms (mg/L/day), E_i = bulk dispersion coefficient between reaches (L/day), E_{i-1}, E_i are bulk dispersion coefficients between reaches $i-1$ and i and i and $i+1$ (L/day), c_i = concentration of water quality constituent in reach i (mg/L) and t = time (day). Fig. 3 represents the schematic diagram of interacting water quality state variables. The complete description of process of interacting water quality state variables is available in Pelletier and Chapra (2005).

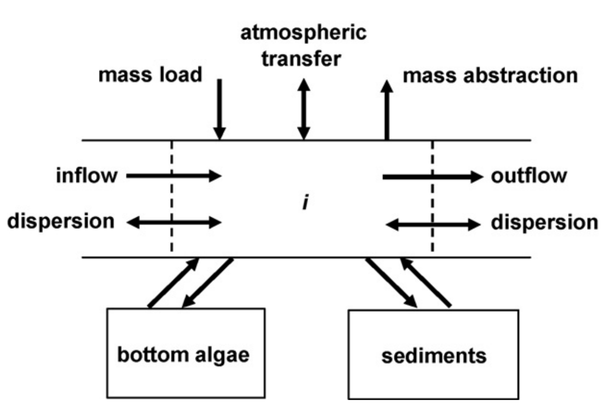

Fig. 2 – Mass balance in a reach segment i.

For auto-calibration, the model uses genetic algorithm (GA) to maximize the goodness of fit of the model results compared with measured data by adjusting a large number of parameters. The fitness is determined as the reciprocal of the weighted average of the normalized root mean squared error (RMSE) of the difference between the model predictions and the observed data for water quality constituents. The GA maximizes the fitness function $f(x)$ as:

$$f(x) = \left[\sum_{i=1}^{n} w_i\right]\left[\sum_{i=1}^{n}\frac{1}{w_i}\left[\frac{(\sum_{j=1}^{m} O_{ij}/m)}{[\sum(P_{ij}-O_{ij})^2/m]^{1/2}}\right]\right]$$

where $O_{i,j}$ = observed values, $P_{i,j}$ = predicted values, m = number of pairs of predicted and observed values, w_i = weighting factors, and n = number of different state variables included in the reciprocal of the weighted normalized RMSE. Detailed description of auto-calibration method can be found in Pelletier et al. (2006).

2.4. *Model calibration and confirmation*

2.4.1. *River descretization*

The total selected 25 km length of the Bagmati River was descretized into 50 reaches with lengths equal to 0.5 km each. Fig. 4 shows the river system segmentation along with the locations of point sources of pollution loads.

2.4.2. *Input data*

The measured river geometries and water velocities were used to determine the hydraulic characteristics at each sampling locations. The model allows the input of the river reach hydraulic characteristics (coefficients and exponents of veloc-

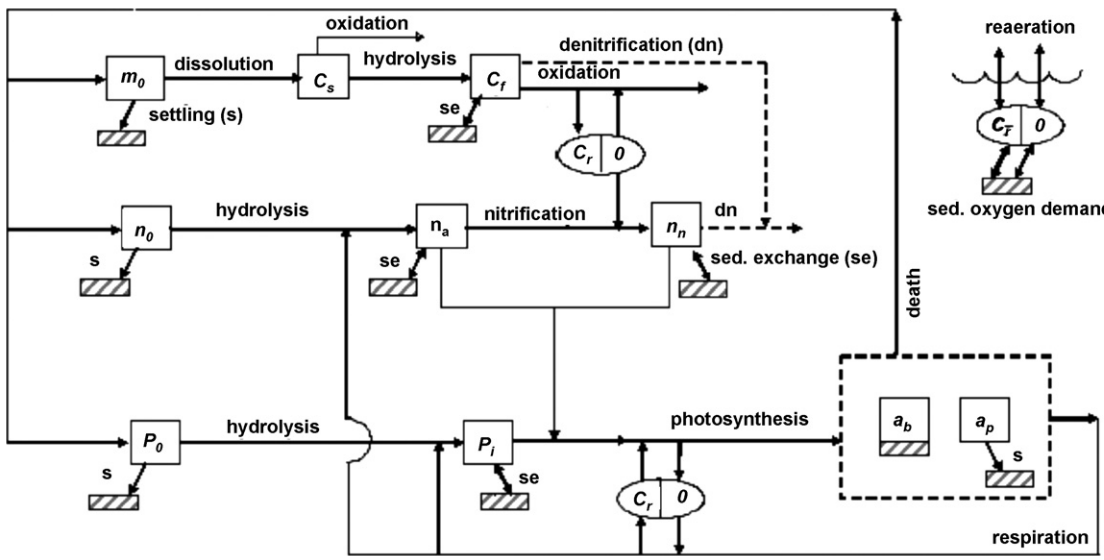

Fig. 3 – Schematic diagram of interacting water quality state variables (a_b: bottom algae, a_p: phytoplankton, m_o: detritus, c_s: slow CBOD, c_f: fast CBOD, c_T: total inorganic carbon, o: oxygen, n_o: organic nitrogen, n_a: ammonia nitrogen, n_n: nitrate nitrogen, p_o: organic phosphorus and p_i: inorganic phosphorus).

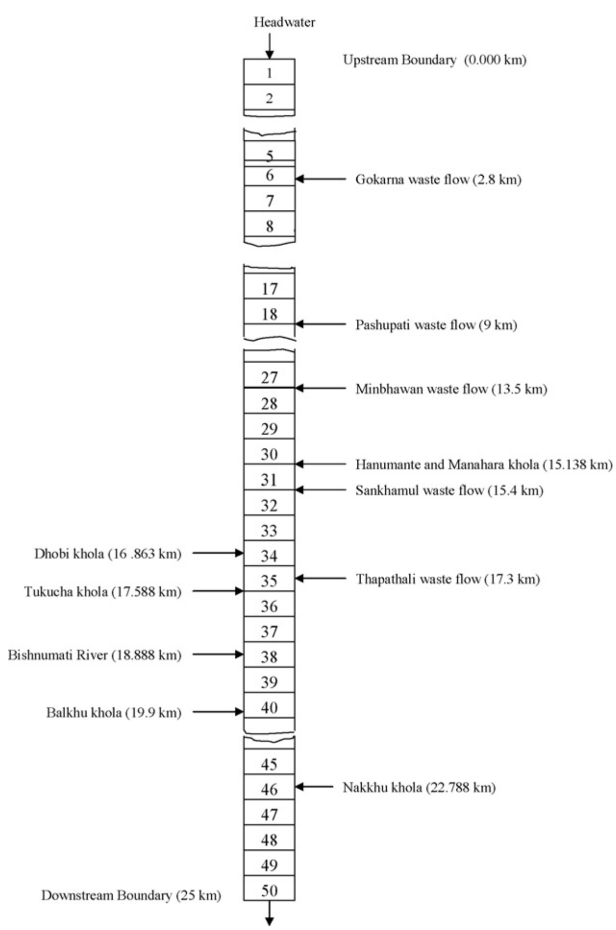

Fig. 4 – System segmentation with location of pollution sources along Bagmati River.

ity and depth) as empirical equations to estimate average water velocity (V) and depth (D) of the river:

$$V = \alpha Q^{\beta} \quad \text{and} \quad D = \gamma Q^{\delta}$$

The coefficients α, γ and exponents β, δ were computed using flows, mean depth and velocities measured in the winter and post-monsoon seasons. Table 2 shows the six sets of reaches (0–2, 3–10, 11–13, 14–18, 19–24 and 25) with different river hydraulic characteristics.

As the model simulates ultimate CBOD, the measured 5 day CBOD ($CBOD_5$) was transferred to ultimate CBOD ($CBOD_u$) using the following relationship (k = the CBOD decomposition in the bottle, 1/day) (Chapra et al., 2006):

$$CBOD_u = \frac{CBOD_5}{1 - e^{-5k}}$$

The bottle rates for sewage derived organic carbons are on the order of 0.05–0.3 day^{-1} (Chapra, 1997). As the average COD/$CBOD_5$ ratio was 2.06 in rural areas in the river (Kannel et al., 2006), ratio $CBOD_u/CBOD_5$ was assumed as 1.5, which results in rate coefficient as 0.22.

The water quality input parameters included in the model were flow, temperature, pH, DO, BOD, organic nitrogen, ammonium nitrogen, nitrate (nitrite + nitrate) nitrogen, organic phosphorus and inorganic phosphorus. The data on phytoplankton and pathogen were not measured and the inputs were left blank. The phytoplankton concentrations in the river Bagmati is negligible. The algae and bottom sediment oxygen demand coverage were assumed 50%. The sediment/hyporheic zone thickness, sediment porosity and hyporheic exchange flow were assumed as 10 cm, 0.4 and 5%, respectively. The water qualities for the wastewater, groundwater, river tributaries and abstraction were the other point and diffuse pollutions input to the model. The organic nitrogen was assumed as 35% in winter and 30% in post-monsoon (as it was not analyzed) after some trials minimizing the errors

Table 2 – Reach hydraulic characteristics at monitoring stations along Bagmati River

Location (km)	Reach	Velocity		Depth		Flow	
		Coefficient	Exponent	Coefficient	Exponent	Winter	Post–monsoon
0.00	0–2	0.460	0.350	0.287	0.650	0.207	0.202
3.00	3–10	0.509	0.432	0.235	0.568	0.349	0.293
10.40	11–13	0.544	0.658	0.208	0.342	0.461	0.466
14.00	14–18	0.462	0.439	0.195	0.561	0.663	0.617
19.00	19–24	0.244	0.408	0.126	0.592	3.450	2.818
25.00	25	0.219	0.458	0.215	0.542	4.060	3.096

in modeled and measured values. Similarly, the total phosphorus of the wastewater was assumed as 1:1 organic and inorganic.

The subsurface flows between 2.5 km and 3.0 km assumed were 0.12 m^3/s in winter season and 0.03 m^3/s in post-monsoon season considering the mass balance along the monitoring sites (not shown in figure). In the absence of data, wastewater qualities were assumed same for all five wastewaters W1, W2, W3, W4 and W5 (Fig. 5), which have discharges of 0.02, 0.1, 0.1, 0.02 and 0.06 m^3/s, respectively. The water qualities at uppermost station R1 was considered as upstream boundary. The downstream boundary was not prescribed considering absence of effects in modelling.

2.4.3. *System parameters*

The ranges of model rate parameters (Table 3) required by QUAL2Kw were obtained from various literatures including: Environment Protection Agency (EPA) guidance document (USEPA, 1985b), QUAL2Kw user manual (Pelletier and Chapra, 2005) and documentation for the enhanced stream water quality model QUAL2E and QUAL2E-UNCAS (Brown and Barnwell, 1987). To calculate re-aeration rate, Owens–Gibbs formula (Owens et al., 1964) was applied, which was developed for streams exhibiting depths from 0.4 to 11 ft and velocities from 0.1 to 5 ft/s (Ghosh and Mcbean, 1998).

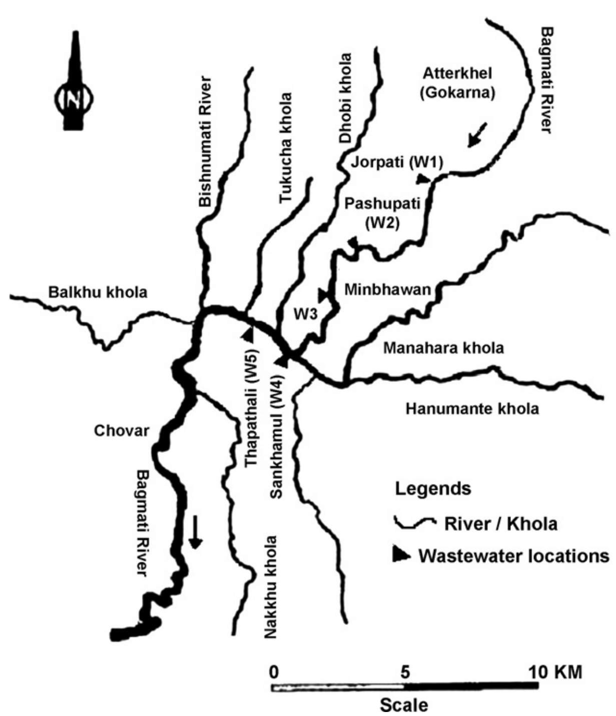

Fig. 5 – Location of pollution sources along Bagmati River.

Exponential model was chosen for oxygen inhibition for CBOD oxidation, nitrification, de-nitrification, phyto-respiration and bottom algae respiration. Wind effect was considered negligible. The range of CBOD oxidation rate was assumed as 0.04–4.2 as in 36 rivers in USA (USEPA, 1985a,b). The other parameters were set as default in QUAL2Kw.

2.4.4. *Model implementation*

The measured data on winter season were used for calibration. The calculation step was set at 5.625 min to avoid instability in the model. The solution of integration was done with Euler's method (Newton–Raphson method for pH modeling). The hyporheic exchange simulation was done for level I option in the model, which includes simulation of zero-order oxidation of fast-reacting dissolved CBOD with attenuation from temperature, CBOD, and dissolved oxygen.

The goodness of fit was performed with different weights given to various parameters. With trials and considering default values in QUAL2Kw, weights were derived to minimize error between measured and modeled parameter values. The weight for DO was given as 50 and is justifiable as it is the most influential parameter. Weight 2 was given for TN, TP, temperature, CBOD, COD and pH. Weight 1 was given for other parameters. Trial values of ratios for fast CBOD (C_f), slow CBOD (C_s) and detritus CBOD (C_{dr}) were used for the various runs (run I: $C_s = 0.6$, $C_f = 0.8$, $C_{dr} = 0.1$; run II: $C_s = 0.7$, $C_f = 0.7$, $C_{dr} = 0.1$ and run III: $C_s = 0.8$, $C_f = 0.6$, $C_{dr} = 0.1$).

The model was run until the system parameters were appropriately adjusted and the reasonable agreement between model results and field measurements were achieved. Model was run for a population size (model runs in a population) of 100 with 50 generations in the evolution. This is because a population size of 100 performs better than smaller numbers and as nearly as a population size of 500 (Pelletier et al., 2006).

In run I, the modelling resulted 64, 45.1 and 21.3% errors in C_s, C_f and C_{dr}, respectively. In run II, it resulted 54.5, 54.5 and 21.3% errors in C_s, C_f and C_{dr}, respectively. Similarly in third run, it resulted 29.7, 72.5 and 17.7% errors in C_s, C_f and C_{dr}, respectively. Thus, the modelling result with factors $C_s = 0.7$, $C_f = 0.7$ and $C_{dr} = 0.1$ was selected.

In order to test the ability of the calibrated model to predict water quality conditions under different conditions, the model was run using a complete different data set without changing the calibrated parameters. Then, the model was used to simulate water quality conditions during the critical period.

Table 3 – Calibrated parameters for the Bagmati River water quality modeling in 2000

Parameters	Values	Units	Auto-calibration	Min. value	Max. value
Carbon	40	gC	No	30	50
Nitrogen	7.2	gN	No	3	9
Phosphorus	1	gP	No	0.4	2
Dry weight	100	gD	No	100	100
Chlorophyll	1	gA	No	0.4	2
ISS settling velocity	0.01	m/day	Yes	0	2
O_2 reaeration model	Owens-Gibbs		No		
Slow CBOD hydrolysis rate	0.1	day^{-1}	Yes	0.04	4.2
Slow CBOD oxidation rate	3.6	day^{-1}	Yes	0.04	4.2
Fast CBOD oxidation rate	3.8	day^{-1}	Yes	0.02	4.2
Organic N hydrolysis	0.10	day^{-1}	Yes	0.02	0.4
Organic N settling velocity	0.06	m/day	Yes	0.001	0.1
Ammonium nitrification	5.2	day^{-1}	Yes	0	10
Nitrate denitrification	1.53	day^{-1}	Yes	0	2
Sed. denitrification transfer coeff.	0.56	m/day	Yes	0	1
Organic P hydrolysis	0.35	day^{-1}	Yes	0.01	0.7
Organic P settling velocity	0.01	m/day	Yes	0.001	0.1
Inorganic P settling velocity	0.85	m/day	Yes	0	2
Sed. P oxygen attenuation half sat constant	1.56	mgO_2/L	Yes	0	2
Detritus dissolution rate	0.39	day^{-1}	Yes	0	5
Detritus settling velocity	4.80	m/day	Yes	0	5
COD decay rate	0.58	day^{-1}	Yes	0	0.8
COD settling velocity	0.79	m/day	Yes	0	1
Bottom algae					
Growth model	zero-order				
Max Growth rate	475	$mgA/m^2/day$	Yes	0	500
First-order model carrying capacity	1000	mgA/m2	No	1000	1000
Respiration rate	0.07	day^{-1}	Yes	0.05	0.5
Excretion rate	0.12	day^{-1}	Yes	0	0.5
Death rate	0.16	day^{-1}	Yes	0	0.5
External nitrogen half sat constant	34.07	μgN/L	Yes	10	300
External phosphorus half sat constant	2.91	μgP/L	Yes	1	50
Inorganic carbon half sat constant	1.06E-05	moles/L	Yes	1.30E−06	1.30E−04
Light model	half saturation				
Light constant	67.92	langleys/day	Yes	1	100
Ammonia preference	67.23	μgN/L	Yes	1	100
Subsistence quota for nitrogen	1.45	mgN/mgA	Yes	0.0072	7.2
Subsistence quota for phosphorus	0.34	mgP/mgA	Yes	0.001	1
Maximum uptake rate for nitrogen	226.1	mgN/mgA/day	Yes	1	500
Maximum uptake rate for phosphorus	51.9	mgP/mgA/day	Yes	1	500
Internal nitrogen half sat ratio	4.06	–	Yes	1.05	5
Internal phosphorus half sat ratio	4.06	–	Yes	1.05	5

3. Results and discussion

The results for the water quality parameters are shown in Table 4 (water qualities measurements on 2–6 January 2000), Table 5 (water qualities measurements on November 15–22, 2000) and Table 6 (wastewater quality measurements). Figs. 6 and 7 show the calibration and confirmation results, respectively. Figs. 8–12 shows the various diagrams about scenarios of water quality control along the Bagmati River.

3.1. *Calibration and confirmation*

The calibration results (Fig. 6) showed that the profiles of water qualities above 9 km chainage are different from downstream. The Bagmati River water qualities did not meet the minimum dissolved oxygen standard beyond 9 km. In the upper part of the river, DO concentration was above 5 mg/L, an indication of better quality of water. Oxygen sag is clearly seen between 9 and 13 km lying after the wastewater flow from Pashupatinath area at 9 km. In addition, there exists input of pollution from decayed flowers, which people offer to the Pashupatinath temple and lots of cremation activities along the bank of the river.

The low DO concentrations between 9 and 25 km was due to entering highly polluted tributaries: Hanumante khola, Dhobi khola, Tukucha khola and Bishnumati khola, which add high organics and nitrogen materials and low DO waters. The concentrations of CBOD, COD, TN and TP increased sharply after 9 km due to discharge of local wastewater drains and polluted tributaries.

The model calibration results were in well agreement with the measured data, with some exceptions. The root mean square errors between the simulated and observed values for river width, velocity, flow, temperature, pH, DO, CBOD, COD, TN and TP were 31.4, 31.80, 4.0, 8.0, 7.0, 15.0, 52.0, 44.2, 20.3 and 31%, respectively (Table 7).

Table 4 – Water quality measurement at monitoring station along Bagmati River, tributaries and wastewaters on 2–6 January 2000

Station	Chain (km)	Flow (m^3/s)	Water temperature (°C)	pH	EC (µs/cm)	DO (mg/L)	TSS (mg/L)	Total alkalinity (mg/L)	Inorganic phosphorus (mg/L)	TP (mg/L)	NH_4N (mg/L)	NO_3N (mg/L)	[a]Organic nitrogen (mg/L)	TN (mg/L)	BOD (mg/L)	COD (mg/L)
R1	0.000	0.207	17.1	7.0	43	9.20	0.6	29	0.07	0.11	0.30	0.26	0.30	0.86	0.5	0.5
R2	3.000	0.349	18.3	6.5	152	6.60	0.6	33	0.24	0.32	1.45	0.36	0.97	2.78	10.0	11.0
R3	10.400	0.461	19.5	6.7	277	0.50	94.2	86	0.82	0.89	9.26	0.52	5.27	15.05	22.0	27.0
R4	14.000	0.663	18.7	6.7	415	0.25	57.0	123	1.73	1.78	17.97	0.55	9.97	28.49	33.0	39.0
R5	19.000	3.450	17.2	7.4	486	0.87	49.0	180	2.38	2.47	19.35	1.03	9.47	27.05	16.2	19.7
R6	25.000	4.060	16.6	7.5	384	0.96	0.3	141	1.35	1.49	12.49	0.58	5.48	15.65	12.9	20.6
T1	15.138	0.422	17.5	7.3	405	0.50	2.6	164	0.91	1.02	9.89	0.51	5.60	16.00	15.0	18.0
T2	15.138	1.000	17.5	7.1	104	5.30	29.0	33	0.22	0.28	1.02	0.81	0.99	2.82	6.0	8.0
T3	16.863	0.400	15.9	6.9	641	0.50	71.6	185	3.40	3.52	29.98	0.53	16.43	46.94	79.0	83.0
T4	17.588	0.279	15.0	7.2	821	0.50	371.5	262	5.72	6.08	62.58	0.13	33.77	96.48	52.0	55.0
T5	18.888	0.674	16.3	7.3	579	0.50	70.9	193	2.18	2.34	17.54	0.61	9.77	27.92	26.0	28.0
T6	19.900	0.100	12.0	7.4	232	5.40	49.7	58	0.10	0.10	2.60	3.50	3.29	9.39	6.0	148.4
T7	22.788	0.503	15.7	7.8	206	6.50	33.4	103	0.12	0.16	0.87	0.63	0.81	2.31	1.0	2.0

[a] Organic nitrogen was assumed 35% after some trials to fit the modeled and measured data.

Table 5 – Water quality measurement at monitoring station along Bagmati River, tributaries and wastewaters on 15–22 November 2000

Station	Chain (km)	Flow (m^3/s)	Water temperature (°C)	pH	EC (µs/cm)	DO (mg/L)	TSS (mg/L)	Total alkalinity (mg/L)	Inorganic phosphorus (mg/L)	TP (mg/L)	NH_4N (mg/L)	NO_3N (mg/L)	[a]Organic nitrogen (mg/L)	Total nitrogen (mg/L)	BOD (mg/L)	COD (mg/L)
R1	0.000	0.202	12.7	9.1	50	8.2	12.0	26	0.55	0.57	2.50	2.76	2.25	7.51	13	15
R2	3.000	0.293	13.4	8.1	145	7.4	0.4	77	0.37	0.42	7.50	2.79	4.41	14.7	24	36
R3	10.400	0.466	15.2	7.4	390	2.6	18.8	142	2.54	3.11	19.00	8.08	11.61	38.69	72	96
R4	14.000	0.617	12.2	7.7	420	1.8	7.8	154	2.80	2.97	21.32	6.67	11.99	39.99	79	102
R5	19.000	2.818	8.6	8.0	430	2.0	6.0	167	2.31	2.44	14.57	4.69	8.25	27.51	66	92
R6	25.000	3.096	10.4	8.2	460	1.6	3.9	103	1.88	1.96	16.50	3.47	8.56	28.53	74	98
T1	15.138	0.089	12.6	7.9	670	2.2	58.4	257	2.53	2.59	24.75	10.97	15.31	51.03	118	145
T2	15.138	0.704	15.8	8.3	110	7.6	76.1	51	0.51	0.62	4.00	3.98	3.42	11.4	29	36
T3	16.863	0.408	13.4	7.5	660	1.1	21.9	244	4.14	4.27	24.00	9.72	14.45	48.17	123	156
T4	17.588	0.208	14.8	7.6	990	3.3	26.3	334	3.90	4.12	35.42	18.05	22.92	76.39	148	172
T5	18.888	0.432	14.5	7.8	745	2.0	18.7	296	3.58	3.67	21.31	10.53	13.65	45.49	70	118
T6	19.900	0.100	12.0	7.4	232	5.4	49.7	58.3	0.08	0.10	2.58	3.45	2.61	8.69	6	15
T7	22.788	0.177	7.2	8.7	190	8.4	0.0	103	0.73	0.84	2.25	1.84	1.75	5.84	2	8

[a] Organic nitrogen was assumed 30% in post-monsoon after some trials to fit the modeled and measured data.

Table 6 – Wastewater quality measurement at monitoring station along Bagmati River

Months	Water temperature (°C)	pH	EC (μs/cm)	DO (mg/L)	TP (mg/L)	Ammonia nitrogen (mg/L)	Organic nitrogen (mg/L)	BOD (mg/L)	COD (mg/L)	TSS (mg/L)
Winter	12.5	7.2	1034	0.00	7.56	59.72	12.74	180	225	640.7
Post-monsoon	13.4	7.7	1090	0.00	4.41	65.25	4.27	185	284	222.6

In the confirmation (Fig. 7), the root mean square errors (between assumed and modeled) for river width, velocity, flow, temperature, pH, DO, CBOD, COD, TN and TP were 27.9, 28.5, 3.6, 21.5, 17, 19.2, 20.8, 21.1, 25.3 and 42%, respectively (Table 7).

The modelling showed the sediment oxygen demand (SOD) along the river varied from 2.05 to 4.80 g/m^2/day in the post-monsoon season. In winter season, it was 0.77–4.09 g/m^2/day. According to USEPA (1985b), sediment oxygen demand rate in river just below the municipal wastewater pollution source fluctuates between 2 and 10 g/m^2/day.

Some errors in this modelling are inevitable as the filed work consisted of collecting a single sample in each station with the objective of modest management goal. As the model predictions are of daily average, the observed DO or pH may be different depending upon the time of samplings. For exam-

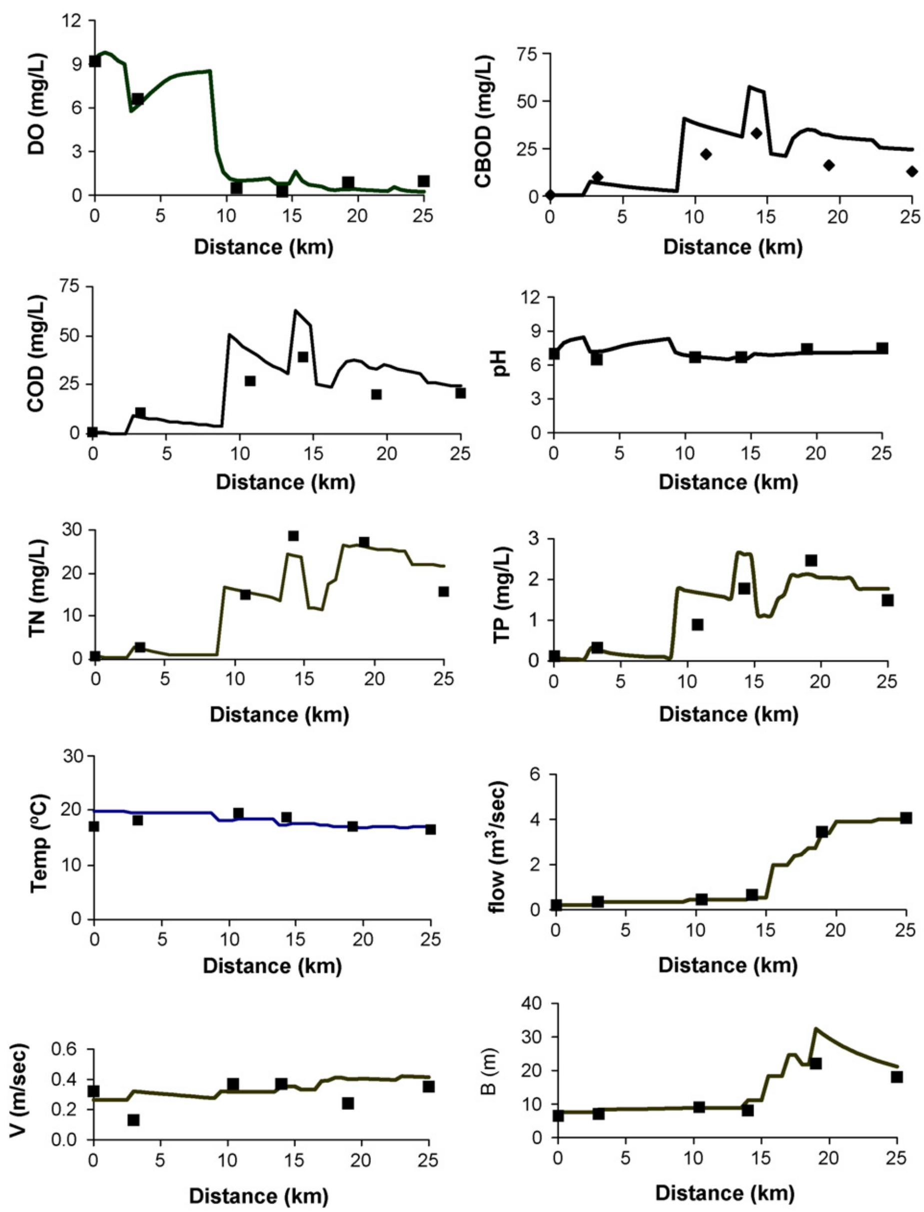

Fig. 6 – Calibration of water qualities in Bagmati River for data on January 2–6, 2000.

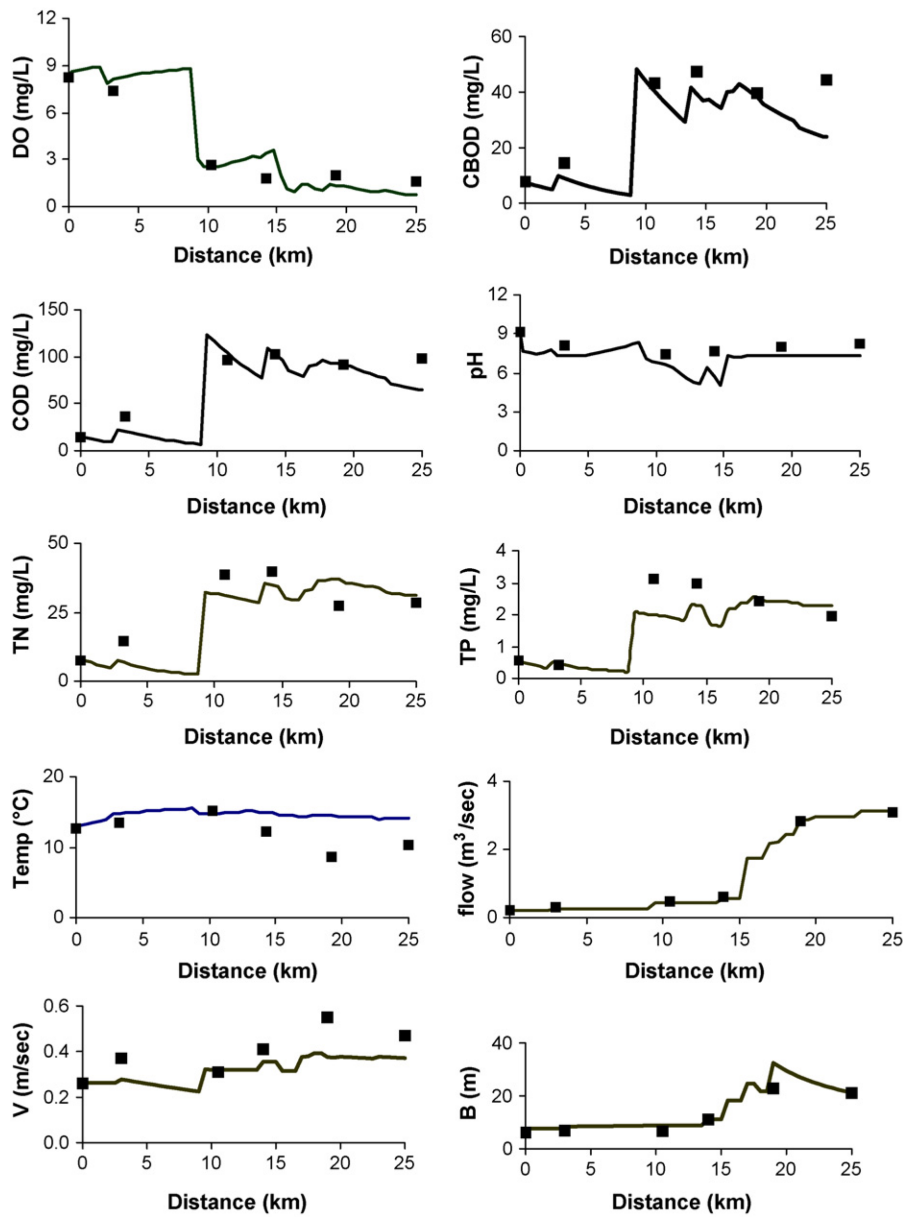

Fig. 7 – Confirmation of water qualities in Bagmati River for data on November 15–22, 2000.

ple, the observed DO or pH may be expected to be somewhat higher than the daily average that the model predicts for the data collected in the afternoon. The DO levels decrease during the night hours because of lower rates of photosynthesis by river plants. Then, the level of pH decreases due to release of CO_2 in water column. At daytime, DO (and thus pH) increases because of the higher rates of photosynthesis of the plants.

In spite of some errors, the modeling results were quite acceptable to achieve modest management goals for such a data limited condition developing country, where the financial resources are often limited for frequent monitoring campaigns. However, the greater accuracy could be achieved through monitoring various input variables including algae coverage, sediment oxygen demand, organic nitrogen, etc. and using sophisticated 2D or 3D models.

3.2. *Sensitivity analysis*

A sensitivity analysis was performed to identify the parameters of the river water quality model that have the most influence on the model outputs, in post-monsoon season. The analysis was performed for the thirteen model parameters and forcing functions (Table 8) keeping all the parameters but one constant, that one being increased or decreased by 20%. It was found that the model was highly sensitive to depth coefficient and moderate to point sources flow, TN, CBOD and nitrification rate.

Table 7 – Root mean squared errors (RSME) for predicted vs. measured water quality parameters

S.N.	Parameters	Root mean squared error (RSME) %	
		Calibration	Confirmation
1	Flow	4	3.6
2	Velocity	31.8	28.5
4	River width	31.4	27.9
5	DO	15	19.2
6	PH	7	17
7	Temperature	8	21.5
8	CBOD	52	20.8
9	COD	44.2	21.1
10	TN	20.3	25.3
11	TP	31	42

3.3. *Strategies for water quality control*

We evaluated the water quality parameters along the Bagmati River with pollution loads modification, flow augmentation and placement of weirs at critical locations to meet the targeted quality criteria for survival of fisheries: minimum DO at or above 4 mg/L, maximum CBOD, TN, TP, temperature at or below 3 mg/L, 2.5 mg/L, 0.1 mg/L, 20 °C, respectively, and pH range 6.5–8.5, in low flow winter season.

The strategies of cleanup of the Bagmati River are based on the fact that the modification of the point sources representing the tributaries of the Bagmati River is possible after enforcement of policies and acts. Nepal has set 30–100 mg/L as the tolerance limit of CBOD to discharge into inland surface water systems (MOST, 2006). This analysis examined the various limits of CBOD, TN and TP for getting the stated water quality results along the Bagmati River with imposing rules for pollution discharges at point sources.

3.3.1. *Pollution loads modification*

With trials, TN and TP concentrations were set at 5 and 0.25 mg/L, respectively to limit the simulated concentrations of 2.5 and 0.1 mg/L along the Bagmati River. We fixed trial values of CBOD as 50, 40, 30 and 20 mg/L for point sources. Fig. 8 shows DO profiles obtained by simulation. All the profiles did not meet the required of minimum DO concentrations of 4 mg/L.

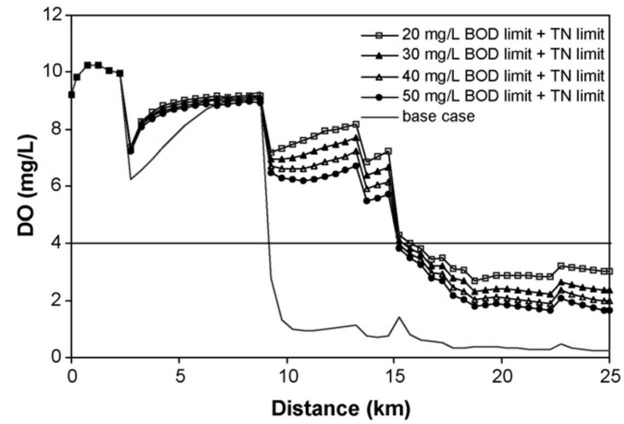

Fig. 8 – DO concentrations along Bagmati River for different BOD and 5 mg/L TN limits.

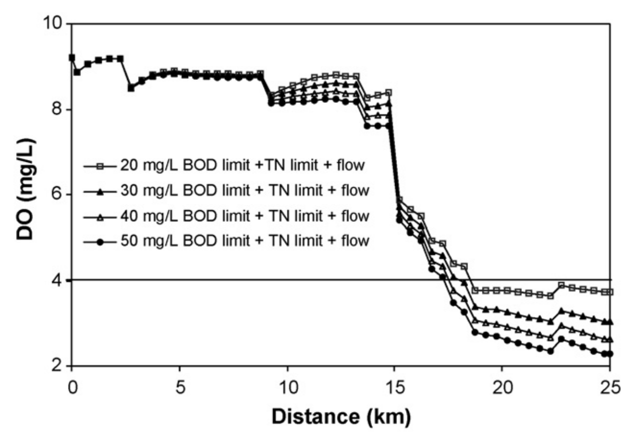

Fig. 9 – DO concentrations along Bagmati River for different BOD and 5 mg/L TN limits with 1 m^3/s flow augmentation.

Table 8 – Sensitivity analysis for the data on Bagmati River in 2000

Parameters	Description	%DO change	
		+20% parameter	−20% parameter
γ	Depth coefficient	−9.73	16.46
Q	Point sources flow	−4.60	6.95
TN	Point sources TN	−3.21	3.89
CBOD	Point sources CBOD	−2.92	3.59
k_n	Nitrification rate	−2.09	2.65
Temperature	Point sources temperature	−1.67	1.91
k_{cs}	Slow CBOD oxidation rate	−1.13	1.34
k_{cf}	Fast CBOD oxidation rate	−1.05	1.23
α	Velocity coefficient	1.79	−1.76
k_{gb}	Bottom algae growth rate	1.43	−1.60
δ	Depth exponent	1.41	−1.15
q	Headwater flow	0.51	−0.56
β	Velocity exponent	0.19	−0.11

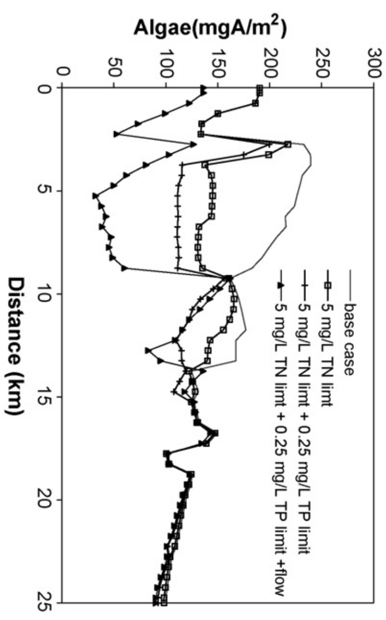

Fig. 10 – Algae concentrations along Bagmati River for combinations of TN limit, TP limit with and without flow augmentation.

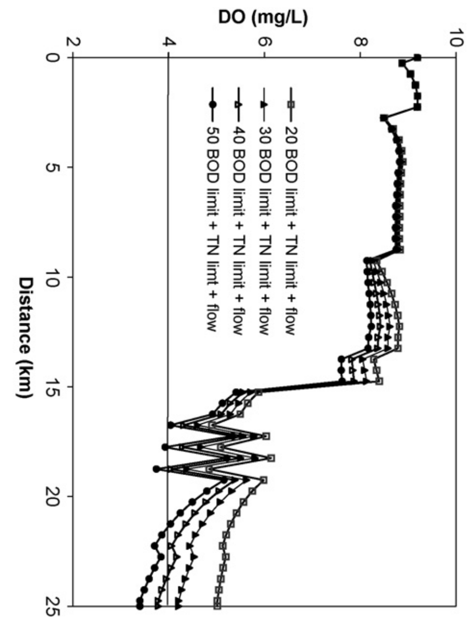

Fig. 11 – DO concentrations along Bagmati River for different BOD and 5 mg/L TN limits with 1 m^3/s flow augmentation and weirs at 17, 18 and 19 km.

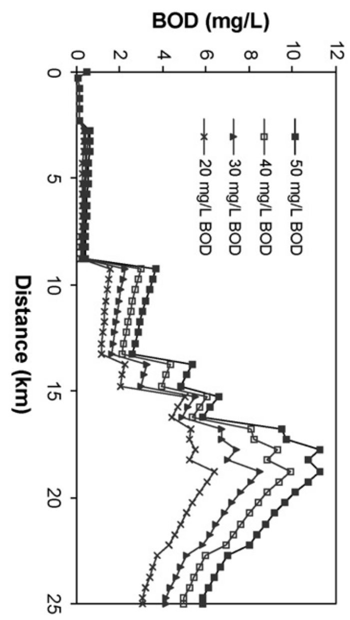

Fig. 12 – BOD concentrations along Bagmati River for 20–50 BOD, 5 mg/L TN, 0.25 mg/L TP limits with flow augmentation (1 m^3/s) and three weirs at 17, 18 and 19 km.

Table 9 – Strategies for water quality control along Bagmati River

Items	Resulting water quality (mg/L)					
	Min. DO (mg/L)	Max. CBOD$_5$ (mg/L)	Max. TN (mg/L)	Max. TP (mg/L)	pH	Water temperatures (°C)
Base case	0.2	56.6	26.4	2.2	6.3–8.7	16.8–19.1
50 mg/L CBOD + 5 mg L TN limits	1.6	18.2	3.1	0.2	7–8.9	16.8–19.1
50 mg/L CBOD + 5 mg/L TN limits with 1 m^3/s flow augmentation	2.3	14.1	2.4	0.1	7–8.1	13.4–17.1
50 mg/L CBOD + 5 mg/L TN limits with 1 m^3/s flow augmentation and 3 weirs	3.4	11.3	2.5	0.1	7–8.2	13.4–17.1
40 mg/L CBOD + 5 mg L TN limits	1.9	15.8	3.1	0.2	7–8.9	16.8–19.1
40 mg/L CBOD + 5 mg/L TN limits with 1 m^3/s flow augmentation	2.6	12.3	2.4	0.1	7–8.1	13.4–17.1
40 mg/L CBOD + 5 mg/L TN limits with 1 m^3/s flow augmentation and three weirs[a]	3.8	9.9	2.5	0.1	7–8.2	13.4–17.1
30 mg/L CBOD + 5 mg L TN limits	2.2	13.6	3.1	0.2	7–9	16.8–19.1
30 mg/L CBOD + 5 mg/L TN limits with 1 m^3/s flow augmentation	3.0	10.6	2.4	0.1	7–8.1	13.4–17.1
30 mg/L CBOD + 5 mg/L TN limits with 1 m^3/s flow augmentation and three weirs[a]	4.2	8.5	2.5	0.1	7–8.1	13.4–17.1
20 mg/L CBOD + 5 mg L TN limits	2.7	10.2	3.1	0.2	7–9	16.8–19.1
20 mg/L CBOD + 5 mg/L TN limits with 1 m^3/s flow augmentation	3.7	8.0	2.4	0.1	7–8.2	13.4–17.1
20 mg/L CBOD + 5 mg/L TN limits with 1 m^3/s flow augmentation and three weirs[a]	4.8	6.4	2.5	0.1	7–8.2	13.4–17.1

[a] Three weirs (each 1 m height) are placed at 17, 18 and 19 km along the Bagmati River.

3.3.2. Flow augmentation

The flow augmentation of 1 m^3/s scheme is possible after completion of ongoing Melamchi Water Supply Project in Nepal, which is planned to supply 5.1 m^3/s of water to Kathmandu city (MWSP, 2000). Fig. 9 shows the DO profiles for 1 m^3/s flow augmentation in addition to wastewater reductions. Beyond, the proximity of 17 km, all locations have DO concentrations profile below 4 mg/L.

Fig. 10 shows the algae profiles for various combinations of TN, TP and flow augmentation. The algae concentrations are more sensitive for various pollution loads modification between 3 and 9 km. In this region, algae reduced with reduction in either in TN or in TP. The flow augmentation has same effect as reduction in TN or TP in algae concentrations.

3.3.3. Local oxygenation

We evaluated the effects of oxygenators using series of weirs along the critical locations of the river including flow augmentation and wastewater reductions. Flow over weirs produces strong oxygenation through air entrainment (Campolo et al., 2002). The amount of DO entering the stream is calculated by an empirical equation relating DO deficit above and below dam to the geometrical properties of the weir, weir type, quality of water and water temperature (Butts and Evans, 1983). After series of trials, we have found three critical positions at 17, 18 and 19 km for installment of 1 m high weirs.

The DO profiles after simulation are shown in Fig. 11. The DO profiles for 30 and 20 mg/L CBOD limits have DO concentrations above 4.0 mg/L. The decrements of DO concentrations observed at 16.75, 17.75 and 18.75 km (Fig. 11) are due the effect of installment of weirs at 17, 18 and 19 km, respectively which resulted in increased water depths and thus decreased aeration coefficients behind the dams.

The 20 mg/L CBOD limit is difficult to impose, as the legal limit of CBOD in Nepal is 30–100 mg/L for wastewaters discharging into surface waters (MOST, 2006). Thus, for practical reasons, 30 mg/L CBOD limit can be considered. At this CBOD limit, DO concentrations at all locations are above 4.2 mg/L and the maximum CBOD concentration is 8.5 mg/L (Table 9, Fig. 12). It is considered reasonable for a developing country, Nepal as the European water quality with CBDO less than or equal to 3 mg/L (EEC, 1978) is difficult to achieve at present. The acceptable range of pH 6.5–8.5 (EMECS, 2001) and maximum temperature criteria (MADEP, 1997) of 20 °C for cold-water fisheries (Table 9) are also satisfied.

4. Conclusion

The one-dimensional stream water quality model QUAL2Kw was calibrated and confirmed using the data in 2000. The model represented the field data quite well with some exceptions. The model was highly sensitive to depth coefficient and moderate to point sources flow, TN, CBOD and nitrification rate.

The model was applied to simulate various water quality management strategies during the critical period to maintain stated water quality criteria (minimum DO of 4 mg/L, CBOD at or below 3.0 mg/L, TN at or below 2.5 mg/L, TP at or below 0.1 mg/L, pH between 6.5 and 8.5 and maximum temperatures 20 °C for coldwater fisheries) considering (i) pollution loads modification (ii) flow augmentation and (iii) local oxygenation.

With point source loadings limits of 30 mg/L CBOD, 5 mg/L TN, 0.25 mg/LTP together with 1 m^3/s flow augmentation and three weirs at critical locations, the minimum DO concentrations were above 4 mg/L along the river. The maximum levels of CBOD, TN and TP were at or below 8.5, 2.5 and 0.1 mg/L, respectively. The pH and temperature were within acceptable ranges of 6.5–8.5 and <20 °C, respectively. The maximum CBOD concentration of 8.5 mg/L is considered reasonable for the developing country, Nepal as the European water quality with CBDO less than or equal to 3 mg/L (EEC, 1978) is difficult to achieve at present.

The results showed the local oxygenation is effective to keep DO concentration well above minimum levels. The combination of wastewater modification, flow augmentation and local oxygenation is suitable to meet the water quality criteria within acceptable limits.

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