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ORIGINAL ARTICLE

Application of QUAL2Kw for water quality modeling and dissolved oxygen control in the river Bagmati

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Abstract A stream water quality model, QUAL2Kw, was calibrated and validated for the river Bagmati of Nepal. The model represented the field data quite well with some exceptions. The influences of various water quality management strategies have on DO concentrations were examined considering: (i) pollution loads modification; (ii) flow augmentation; (iii) local oxygenation. The study showed the local oxygenation is effective in raising DO levels. The combination of wastewater modification, flow augmentation and local oxygenation is necessary to ensure minimum DO concentrations. This reasonable modeling guarantees the use of QUAL2Kw for future river water quality policy options.

Keywords Water quality · Dissolved oxygen · Modeling · QUAL2Kw · Bagmati river

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1. Introduction

Increasing water scarcity together with decreasing quality is forcing developing countries into remediation options of river water quality. The assessment and evaluation of human impacts on the quality of surface waters have become the main objectives in river basin management (Barth, 1998). The problem of predicting chemical loads in a river system has remained a key issue in the determination of the impact of human activity on aquatic ecosystem environments (Sokolov and Black, 1996).

The human activity generated contamination from agricultural, municipal and industrial activities introduces significant amount of nutrients and organic materials into the rivers and streams, accelerating eutrophication process and decreasing dissolved oxygen below a threshold value which is apparent during low flow periods. The impacts of low dissolved oxygen (DO) concentrations or, at the extreme, anaerobic conditions are an unbalanced ecosystem with fish mortality, odors and aesthetic nuisances (Cox, 2003).

A water quality management policy, in general, should maintain the existing pollutions below certain threshold levels and ensure minimum DO concentrations depending upon aquatic animals, specifically fisheries. Minimum DO concentration is vital for the survival of fisheries. The Bagmati River has wide varieties of fisheries including coldwater types belonging either to the family Cyprinidae or Salmonidae. The acute lethal limit of DO concentration is at or below

3 mg/L for salmonids (US EPA, 1986). However, the coldwater minimum has been established at 4 mg/L (1 day minimum) considering a proportion of the less tolerant insect species common to salmonid habitats (US EPA, 1986) and to support varying fish populations (Thomposon, 1925; Ellis, 1937). 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: (i) controlling the river flow rates (Hayes *et al*., 1998), (ii) controlling the wastewater pollution loads (Herbay *et al*., 1983) and (iii) applying 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 (Dekissa *et al*., 2004). The most widely used mathematical model for conventional pollutant impact evaluation is QUAL2E (Brown and Barnwell, 1987) developed by United States Environmental Protection Agency (US EPA). However, several limitations of the QUAL2E 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; Park and Uchrin, 1996, 1997).

Park and Lee (2002) developed QUAL2K, 2002 after modification of QUAL2E. The modifications include the expansion of computational structures and addition of new constituent interactions: algal BOD, de-nitrification and DO change caused by fixed plants. Pelletier and Chapra (2005) developed a model QUAL2Kw, by modifying QUAL2K, 2003 originally developed by Chapra and Pelletier (2003), which is intended to represent a modernized version of QUAL2E.

QUAL2Kw includes many new elements (Pelletier and Chapra, 2005). It uses two forms of carbonaceous biochemical oxygen demand to represent organic carbon: slowly and rapidly oxidizing forms. It accommodates anoxia by reducing oxidation reactions to zero at low oxygen levels. It simulates attached bottom algae explicitly. It models sediment-water fluxes of dissolved oxygen and nutrients internally. In addition, its simulation includes de-nitrification, pH and sediment pore water quality.

QUAL2Kw is one-dimensional, steady state stream water quality model and is implemented in the Microsoft Windows environment. It is well documented and is freely available (http://www.epa.gov/). The model can simulate a number of constituents including temperature, pH, carbonaceous biochemical demand, sediment oxygen demand, dissolved oxygen, organic nitrogen, ammonia nitrogen, nitrite and nitrate nitrogen, organic phosphorus, inorganic phosphorus, total nitrogen, total phosphorus, phytoplankton and bottom algae.

For these reasons, QUAL2Kw was chosen as a framework for the study of the Bagmati River. This study has described the application of the model, examined the impact of waste loads on receiving water bodies and determined the total maximum pollution loads that the river can receive without violating the minimum DO standard.

2. Material and methods

2.1. Study area

The study area was about 20 km stretch of the Bagmati River, which lies in the Kathmandu Valley of Nepal. The river (Fig. 1) originates at Shivapuri Lekh (Lekh means high hills), 25 km north of Kathmandu city (Erlend, 2002), flows down to the valley floor, cuts the Mahabharat range to the south at about 1220 m altitude and emerges into the Gangetic plain (Fujii and Sakai, 2002). The river is the principal resource base of municipal water providing almost 92% of the wet season and 60% of the dry season water supply in the Kathmandu Valley (CBS, 1998). The river has religious and cultural meaning in the Hindu-Buddhist society and is worshiped by millions of people from Nepal and others over the world (Ha and Pokhrel, 2001).

About 20–30 years ago, the river was in drinkable condition, highly appreciated for its purity, both physical and ritual. But today, the ritual bathing is almost a thing of the past as pollution chokes this once beautiful river (Erlend, 2002). This holy river, once full with aquatic animals, receives heavy discharge of domestic and industrial wastewaters (MOPE, 2000) and is biologically dead. In such context, a length of 20.5 km stretch of the Bagmati River within the Kathmandu Valley from Atterkhel village to Chovar (an outlet of the river through the Valley) was selected for this study.

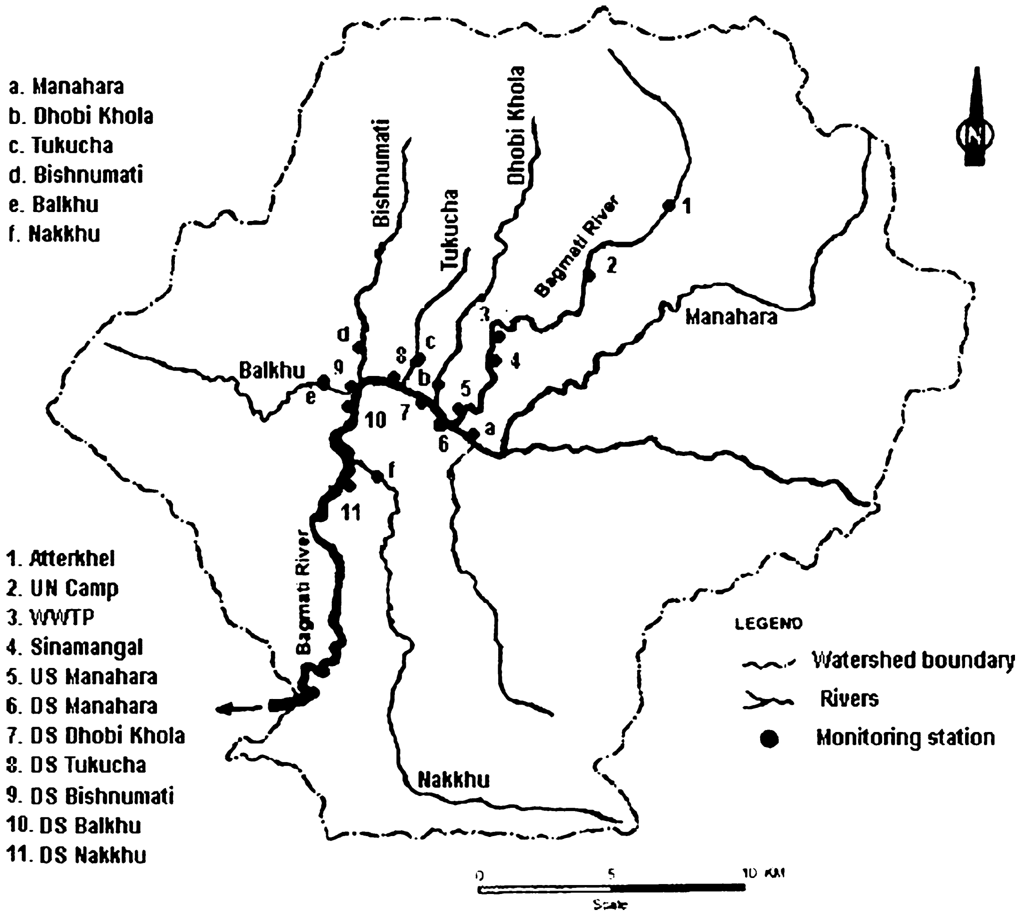


Fig. 1 Monitoring stations along Bagmati River in Kathmandu Valley

2.2. Data and monitoring sites

The data were collected on pre-monsoon (19–20 June, 2004) and post-monsoon (2–3 December, 2004) seasons in the Bagmati River and its tributaries and were of within 30 hours duration (Tables 1–3). The sampling events on pre-monsoon season were scheduled to monitor critical low flows as closely as possible. The meteorological data as air temperature, wind speed and relative humidity were obtained from Department of Hydrology and Meteorology.

The monitoring stations (Fig. 1) along Bagmati river were Station 1 (Atterkhel, chainage 0.000 km) at Atterkhel village near Gokarna, Station 2 (UN Camp, chainage 4.875 km) adjacent to United Nation Camp, Station 3 (WWTP, chainage 7.05 km) at wastewater treatment plant (WWTP) near Guheswori area, Station 4 (Sinamangal, chainage 7.9 km) at Sinamangal area just above steel bridge, Station 5 (US Manahara, chainage 12.12 km) at just upstream of confluence with Manahara khola (khola means small river), Station 6 (DS Manahara, chainage 12.17 km) at just downstream of confluence with Manahara khola, Station 7 (DS Dhobi khola, chainage 14 km) at just downstream of confluence with Dhobi khola, Station 8 (DS Tukucha, chainage 14.64 km) at just downstream of confluence with Tukucha khola, Station 9 (DS Bishnumati, chainage 15.94 km) at just downstream of confluence with Bishnumati river, Station 10 (DS Balkhu, chainage 16.95 km) at just downstream of confluence with Balkhu khola and Station 11 (DS Nakkhu, chainage 19.85 km) at just downstream of confluence with Nakkhu khola.

The monitoring stations along tributaries (Fig. 1) were station ‘a’ (Manahara khola, chainage 12.138 km) at just upstream of Bagmati river-Manahara khola confluence, Station ‘b’ (Dhobi khola, chainage 13.863 km) at just upstream of Bagmati river-Dhobi

Table 1 Water qualities of surface and sub-surface waters along Bagmati River in pre-monsoon season

Sampling Date	Chain. (Km)	Locations (–)	Temp (°)	pH (–)	DO (mg/L)	BOD (mg/L)	TN (mg/L)	TP (mg/L)	Organic-N (mg/L)	NH_4-N (mg/L)	NO_3-N (mg/L)	Organic-P ($\mu g/L$)	Inorganic-P ($\mu g/L$)	Flow (m^3/s)	Remarks (–)
June 19–20, 2004	0.000	Atterkhel	26	7.1	6.73	18.6	9.40	0.01	4.06	2.29	3.05	7	3	0.62	Main river
	4.875	UN Camp	24	6.9	3.37	30.5	17.34	0.21	3.70	11.21	2.43	72	138	0.26	Main river
	7.900	Sinamangal	24	7.4	0.97	296	17.34	0.63	3.70	11.21	2.43	192	438	0.59	Main river
	12.138	Manahara	25.5	8.6	0.40	434.4	18.55	0.26	3.63	13.05	1.88	48	212	2.98	Tributary
	12.170	DS Manahara	25	8.4	0.27	448.8	19.23	0.53	2.62	15.22	1.39	208	322	3.77	Main river
	13.863	Dhobi khola	25	7.2	0.00	2200	22.78	2.40	2.50	18.85	1.44	1248	1152	0.47	Tributary
	14.588	Tukucha	26	6.8	0.00	2144	21.65	1.20	2.44	17.42	1.79	390	810	1.40	Tributary
	14.630	DS Tukucha	27	9	0.00	441.9	19.55	0.56	2.47	16.04	1.05	328	232	5.64	Main river
	15.888	Bishnumati	30	10	2.09	789	56.02	0.26	7.19	45.59	3.24	114	146	1.28	Tributary
	16.913	Balkhu	25	7.7	5.50	29.5	15.14	0.56	2.27	10.50	2.37	113	450	0.20	Tributary
	16.950	DS Balkhu	28	7.1	0.57	1100	26340	0.51	3.32	21.61	1.41	299	211	7.23	Main river
	19.788	Nakkhu	20	7.5	1.21	23.3	44.43	0.41	15.15	22.78	6.50	93	320	1.00	Tributary
	19.850	DS Nakkhu	23	7.8	0.67	404	18.42	0.99	7.13	10.83	0.46	98	892	9.22	Main river
	3.5/8.2	Bouddha/Baneswor	24	6.8	0.60	416.8	52.75	2.27	9.36	40.00	3.39	1813	460	0.05/0.3	Wastewater flow
	16.913–19.85	Station 10–11	27	6.8	0.17	18.25	7.66	0.43	1.53	4.60	1.53	170	260	0.99	Groundwater flow

Table 2 Water qualities of surface and sub-surface waters along Bagmati River in post-monsoon season

Sampling Date	Chain. (Km)	Locations (–)	Temp (°)	pH (–)	DO (mg/L)	BOD (mg/L)	TN (mg/L)	TP (mg/L)	Organic-N (mg/L)	NH_4-N (mg/L)	NO_3-N (mg/L)	Organic-P (μg/L)	Inorganic-P (μg/L)	Flow (m^3/s)	Remarks (–)
December 2–3, 2004	0.000	Atterkhel	8.8	6.3	8.50	4.5	1.48	0.07	0.64	0.36	0.48	50	23	0.76	Main river
	4.875	UN Camp	13.4	6.5	6.20	17	5.57	0.29	1.19	3.60	0.78	100	193	0.65	Main river
	7.050	WWTP	11.0	7.6	3.12	73.2	45.12	1.44	4.60	36.00	4.52	753	690	0.23	WWTP outlet
	7.900	Sinamangal	15.2	7.0	4.90	176	17.88	1.37	3.89	12.00	1.99	417	950	0.71	Main river
	12.138	Manahara	17.0	7.0	1.74	122.3	14.22	1.617	2.78	10.00	1.44	297	1320	2.39	Tributary
	12.170	DS Manahara	16.9	6.9	1.11	127.5	27.79	1.48	3.78	22.00	2.01	580	900	2.97	Main river
	13.863	Dhobi khola	16.5	7.0	0.13	247	48.35	2.15	5.30	40.00	3.05	1117	1030	0.56	Tributary
	14.588	Tukucha	13.8	7.4	0.00	600	93.20	3.87	10.50	75.00	7.70	1243	2630	0.19	Tributary
	15.888	Bishnumati	15.9	7.3	0.19	313.5	55.30	2.30	7.10	45.00	3.20	1013	1290	1.26	Tributary
	16.913	Balkhu	11.8	7.7	5.50	29.5	15.14	0.56	2.27	10.50	2.37	113	450	0.20	Tributary
	16.950	DS Balkhu	15.3	7.2	1.70	197.5	36.93	1.83	7.86	28.00	1.07	1170	660	5.51	Main river
	19.788	Nakkhu	18.5	7.9	6.60	17.8	14.43	0.41	4.92	7.40	2.11	93	320	0.55	Tributary
	19.850	DS Nakkhu	19.2	7.4	2.50	92.5	34.03	1.31	13.18	20.00	0.85	130	1177	7.69	Main river
	3.5/8.2	Bouddha /Baneswor	11.5	6.8	0.60	416.8	52.75	2.27	9.36	40.00	3.39	1813	460	0.02/0.3	Wastewater flow
	16.913–19.850	Station 10-11	19.0	6.8	2.04	7.5	10.6	0.40	2.00	6.30	2.31	150	250	1.63	Groundwater flow

Table 3 Reach hydraulic characteristics for the Bagmati River

Stations (–)	Reach Numbers	Velocity Coefficients	Velocity Exponents	Depth Coefficients	Depth Exponents	Pre-monsoon Flow (m^3/s)	Pre-monsoon Velocity (m/s)	Pre-monsoon Depth (m)	Post-monsoon Flow (m^3/s)	Post-monsoon Velocity (m/s)	Post-monsoon Depth (m)
Atterkhel	0–7	0.408	0.365	0.318	0.459	0.620	0.343	0.255	0.760	0.370	0.280
UN Camp	8–11	0.551	0.381	0.268	0.566	0.260	0.330	0.125	0.650	0.470	0.210
Sinamangal	12–21	0.513	0.350	0.197	0.430	0.590	0.427	0.157	0.710	0.460	0.170
US Manahara	22–24	0.717	0.334	0.192	0.686	1.100	0.740	0.205	0.910	0.690	0.180
DS Manahara	25–26	0.192	0.359	0.183	0.935	3.770	0.309	0.632	3.300	0.290	0.570
DS Dhobi khola	27–29	0.127	0.378	0.153	0.879	4.240	0.220	0.543	3.860	0.210	0.510
DS Tukucha	30–31	0.147	0.382	0.183	0.642	5.640	0.290	0.576	4.050	0.250	0.450
DS Bishnumati	32–33	0.388	0.360	0.126	0.773	6.92	0.780	0.562	5.310	0.710	0.400
DS Balkhu	34–38	0.389	0.373	0.112	0.714	7.230	0.825	0.475	5.510	0.730	0.380
DS Nakkhu	39–41	0.480	0.374	0.075	0.770	9.220	1.103	0.414	7.690	1.030	0.360

khola confluence, Station ‘c’ (Tukucha khola, chainage 14.588 km) at just upstream of Bagmati river-Tukucha khola confluence, Station ‘d’ (Bishnumati river, chainage 15.888 km) at just upstream of Bagmati-Bishnumati river confluence, Station ‘e’ (Balkhu khola, chainage 16.913 km) at just upstream of Bagmati river-Balkhu khola confluence and Station ‘f’ (Nakkhu khola, chainage 19.788 km) at just upstream of Bagmati river-Nakkhu khola confluence. Abstraction of surface water was observed between station 1 and station 2 at 2.000 km chainage. The quantities of water abstractions were 0.36 m^3/s flow in June and 0.14 m^3/s in December. In addition, one groundwater station downstream of Balkhu khola (not shown) was monitored to estimate the quality of subsurface water flowing into the river between 16.913 km $-$19.850 km. The subsurface flow was estimated by subtracting surface water flows at stations 10 and 11. The flow was assumed uniformly distributed and constant over time. The wastewaters flows into the river at 3.5 km (Bouddha area) and at 8.2 km (Baneswor area) were assumed same as WWTP inflow water quality measured at its inlet. Figure 2 shows the location map of the pollution sources and abstraction along the river.

2.3. Sampling and analysis

Water quality parameters monitored were: temperature, pH, dissolved oxygen (DO), 5-days biochemical oxygen demand (BOD), total nitrogen (TN), total phosphorus (TP), nitrite + nitrate-nitrogen (NO_3–N), organic-nitrogen (Organic-N), ammonia-nitrogen (NH_4–N), organic phosphorus (Organic-P), inorganic phosphorus (Inorganic-P), river flow (Q), river velocity (m) and river water depth (m). Flow was measured with float method determining cross-sections and measuring velocities at three to five points along river cross-sections. All the monitored parameters were expressed in mg/L or μg/L except pH, temperature (°C), velocity (m), depth (m) and flow (m^3/s). Sampling, preservation, transportation and analyzing of water samples were done following the standard methods (APHA-AWWA-WPCF, 1989). Water analysis for temperature and pH were performed in situ with a portable thermometer and pH-meter respectively. DO was measured in situ with a portable DO probe as well as in the laboratory by titration. BOD (carbonaceous biochemical oxygen demand, CBOD) was determined by azide modification method during five days incubation at 20°C. TP

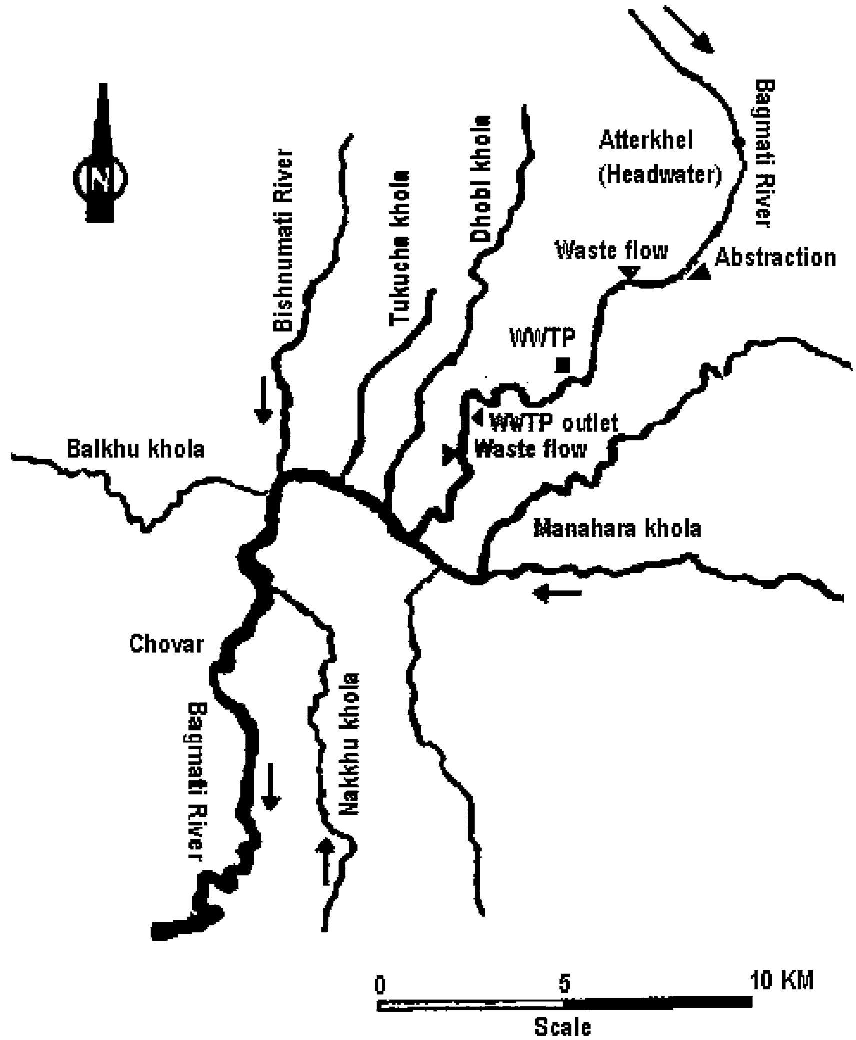


Fig. 2 Location of pollution sources along Bagmati River

was determined by digestion and ammonium molybdenum blue method. Samples were digested with concentrated nitric and sulphuric acids prior to determination of phosphate to convert all phosphates into orthophosphates form. TN was determined by determination of nitrite-N, nitrate-N and total kjeldahl nitrogen (TKN). Nitrite-N was determined by spectrophotometric method (diazo method). Nitrate-N was determined by ultraviolet (UV) spectrophotometric screening and brucine absorbity methods as applicable. TKN was determined using macro-kjeldahl method by following titration with standard hydrochloric acid. Ammonia-nitrogen was determined by nesslerization method and by titration. Organic-N was determined by subtracting the observed value of ammonia nitrogen from TKN.

2.4. Modeling tool

The modeling tool QUAL2Kw has a general mass balance equation for a constituent concentration c_i (Fig. 3) 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.*, 2005):

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

Where, Q_i: flow at reach i (L/day, *ab*: abstraction), V_i: volume (L), W_i: the external loading of the constituent

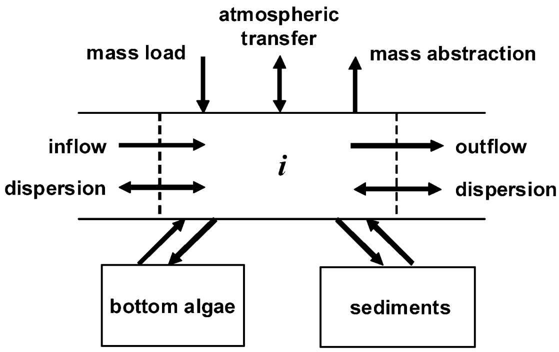


Fig. 3 Mass balance in a reach segment i

to reach i [mg/day], and 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), c_i: concentration of water quality constituent (mg/L), t: time in days.

Figure 4 represents the schematic diagram of interacting water quality state variables. A complete discussion of the model theory is described by Pelletier and Chapra (2005). 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 (Pelletier *et al.*, 2005). 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:

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

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.

2.5. Model calibration and validation

2.5.1. River descretization

The total study length of 20.5 km of the Bagmati River was descretized into 41 reaches with lengths of 0.5 km each. Figure 5 shows the river system segmentation along with the locations of pollution loads and abstraction. The model uses the headwater data to define upstream boundary condition. The portion of the river including the sampling station 1 was treated as headwater. The option of internal calculation was selected for the downstream boundary condition.

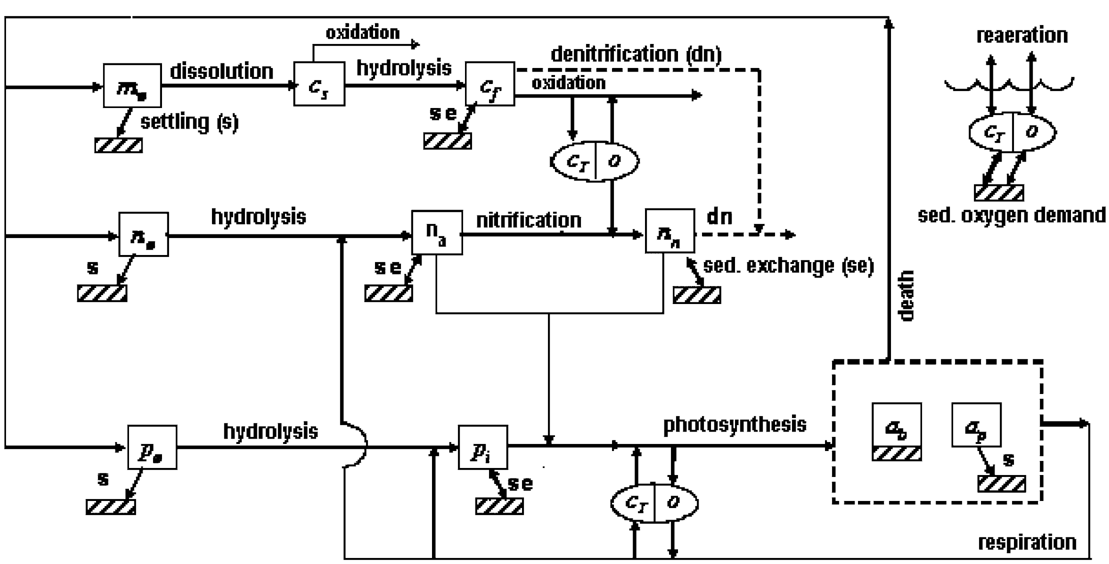
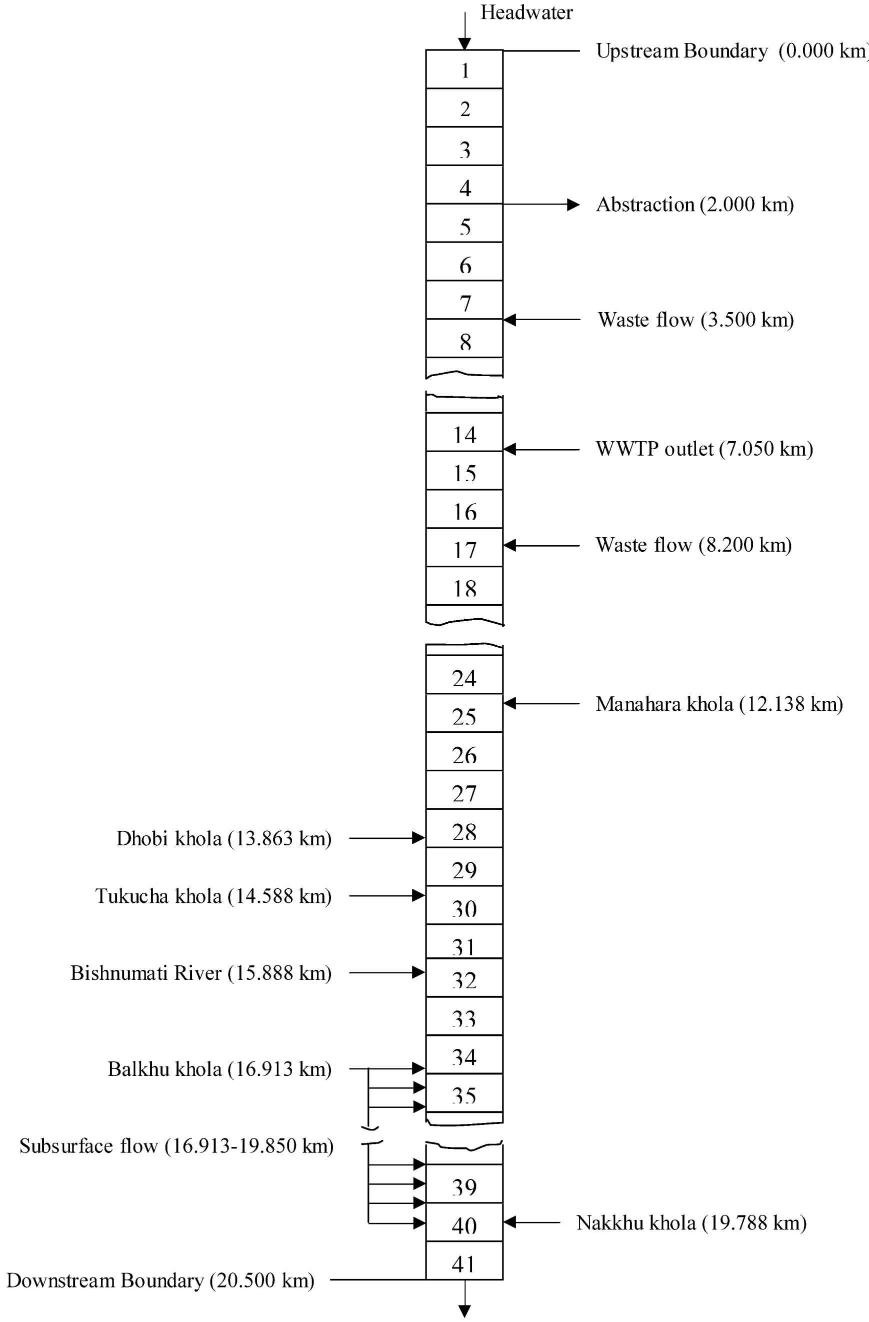


Fig. 4 Schematic diagram of interacting water quality state variables (a_b: bottom algae, a_p: phytoplankton, mo: detritus, c_s: slow BOD, c_f: fast BOD, c_T: total inorganic carbon, o: oxygen, n_o: organic nitrogen, n_a: ammonia nitrogen, n_n: nitrite and nitrate nitrogen), Source: (Pelletier and Chapra, 2005)

Fig. 5 System segmentation with location of pollution sources along Bagmati River



2.5.2. *Input data*

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

$$V = aQ^b \quad \text{and} \quad D = cQ^d$$

The coefficients a, c and exponents b, d were computed using flows, mean depths and velocities measured in the pre-monsoon and post-monsoon seasons. Table 3 shows the 10 sets of reaches (0–7, 8–11, 12–21, 22–24, 25–26, 27–29, 30–31, 32–33, 34–38, and 39–41) with different river hydraulic characteristics.

The water quality input parameters included in the model were flow, temperature, pH, DO, BOD, organic nitrogen, ammonia nitrogen, nitrite + nitrate nitrogen, organic phosphorus and inorganic phosphorus. The data on inorganic suspended solids, conductivity, fast CBOD, phytoplankton, detritus and pathogen were not measured and the inputs were left blank. A default value of 100 mg/L of calcium carbonate was adopted for alkalinity. The water qualities for the wastewater, groundwater, river tributaries and abstraction were the other input to the model.

The model input requires families of nitrogen and phosphorus. However, such data in pre-monsoon season survey were not measured. The literature study and post-monsoon survey were considered for extracting these missing data. A study conducted by Talyer *et al.* (2005) in urban storm-water in Melbourne, during base-flow, revealed that total nitrogen consists of organic-N 36%, NH_4–N 9%, NO_2+NO_3-N 39% and particulate organic-N 16%. In terms of total dissolved nitrogen it comes out to be organic-N 42.9%, NH_4-N 10.7% and NO_2+NO_3-N 46.49%. The study also found that the nitrogen composition did not vary between sites.

The review of international literatures revealed the composition of total nitrogen as organic-N 71%, NH_4-N 5% and NO_2+NO_3-N 24%. The organic-N makes up the largest component of nitrogen in the international data, but the proportion of organic-N that is particulate or dissolved was not reported (Talyer *et al.*, 2005). Considering 16% as the particulate nitrogen (as in Melbourne data), the organic nitrogen comes out to be 55%. In terms of total dissolved nitrogen the composition comes out to be organic-N 65.5%, NH_4-N 6% and NO_2+NO_3-N 28.5%. Similarly, Kucuksezgin *et al.* (2005) has reported composition of total dissolved nitrogen and phosphorus. The compositions of total dissolved nitrogen were: organic nitrogen 88.5%, NH_4-N 3.7% and NO_2+NO_3-N 7.8%. The compositions of total dissolved phosphorus were: organic-P 81.1% and inorganic-P 18.9%. In Bagmati River, the average compositions of TP were organic-P 36.8% and inorganic-P 63.2% (Table 4). The average compositions of TN were organic-N 20.6%, NH_4-N 68.7% and nitrite + nitrate-N 10.7% (Table 4). Considering site differences in composition of nutrients, these derived proportions along the Bagmati River and its tributaries were used in this modeling.

2.5.3. System parameters

The physical, chemical, and biological processes simulated by QUAL2Kw represented by a set of equations contain many parameters (Table 5). The ranges of model rate parameters were obtained from various literatures including Environmen Protection Agency (EPA)

Table 4 Composition (%) of nitrogen and phosphorus at sampling sites along Bagmati River and its tributaries

Locations	Organic-P	Inorganic-P	Organic-N	NH_4-N	NO_{2+} NO_3-N
Attarkhel	68.18	31.82	43.24	24.32	32.43
UN Camp	34.09	65.91	21.36	64.63	14.00
Sinamangal	30.49	69.51	21.76	67.11	11.13
DS Manahara	39.19	60.81	13.60	79.17	7.23
DS Tukucha	58.55	41.45	12.62	82.03	5.35
DS Balkhu	49.0	51.0	12.6	82.0	5.4
DS Nakkhu	9.95	90.05	38.73	58.77	2.50
Manahara khola	18.39	81.61	19.55	70.32	10.13
Dhobi Khola	52.02	47.98	10.96	82.73	6.31
Tukuchha Khola	32.10	67.90	11.27	80.47	8.26
Bishnumati River	43.93	56.07	12.84	81.37	5.79
Balkhu khola	20.1	79.9	15	69.4	15.6
Nakkhu Khola	22.58	77.42	34.10	51.28	14.62
Average values	36.8	63.2	20.6	68.7	10.7

Table 5 Calibrated system parameters in the Bagmati River

Parameter	Adopted values	Units	Minimum values	Maximum values
Carbon	40	gC	40	40
Nitrogen	7.2	gN	7.2	7.2
Phosphorus	1	gP	1	1
Detritus dry weight	100	gD	100	100
Chlorophyll-a	1	gA	1	1
Slow CBOD hydrolysis rate	3.83	/day	0	5
Slow CBOD oxidation rate	2.48	/day	0.04	4.2
Fast CBOD oxidation rate	3.20	/day	0.02	4.2
Organic N hydrolysis	0.4	/day	0.02	0.4
Organic N settling velocity	0.1	m/day	0.001	0.1
Ammonium nitrification	9.53	/day	0	10
Nitrate de-nitrification	1.48	/day	0	2
Sediment de-nitrification transfer coefficient	0.94	m/day	0	1
Organic P hydrolysis	0.7	/day	0.01	0.7
Organic P settling velocity	0.003	m/day	0.001	0.1
Inorganic P settling velocity	0.13	m/day	0	2
Sediment P oxygen attenuation half saturation constant	1.88	mgO_2/L	0	2
Bottom Algae:				
Max growth rate	106.1	$mgA/m^2/day$ or /day	0	500
Respiration rate	0.31	/day	0.05	0.5
Excretion rate	0.43	/day	0	0.5
Death rate	0.008	/day	0	0.5
External nitrogen half sat constant	33.83	$\mu gN/L$	10	300
External phosphorus half sat constant	30.12	$\mu gP/L$	1	50
Light constant	40.76	langleys/day	1	100
Ammonia preference	71.81	$\mu gN/L$	1	100
Subsistence quota for nitrogen	6.06	mgN/mgA	0.0072	7.2
Subsistence quota for phosphorus	0.30	mgP/mgA	0.001	1
Maximum uptake rate for nitrogen	80.59	mgN/mgA/day	1	500
Maximum uptake rate for phosphorus	490.42	mgP/mgA/day	1	500
Internal nitrogen half sat ratio	2.06	Dimensionless	1.05	5
Internal phosphorus half sat ratio	1.88	Dimensionless	1.05	5

guidance document (George *et al.*, 1985), QUAL2Kw user manual (Pelletier and Chapra, 2005) and Documentation for the enhanced stream water quality model QUAL2E and QUAL2E-UNCAS (Brown and Barnwell, 1987). QUAL2Kw has eight options to calculate re-aeration rate as a function of the river hydraulics. We have used Owens-Gibbs formula (Owens *et al.* 1964), which was developed for streams exhibiting depths ranging from 0.4 to 11 feet and velocities ranging from 0.1 to 5 feet/s (Ghosh and Mcbean, 1998). The range of CBOD oxidation rate was assumed as 0.04–4.2 as in 36 rivers in USA (US EPA, 1985). The settling of CBOD is considered insignificant. The ranges of other parameters were assumed default as in QUAL2Kw.

2.5.4. Model implementation

The measured data on post-monsoon season (2–3 December 2004), during which steady state is achieved, were used for calibration. The calculation time step was set at 5.625 min to avoid instability in the model. The solution of integration was done with Euler's method. The goodness of fit was performed with different weights given to various parameters. With trials, weights were found to minimize error between measured and modeled parameter values. The weight for DO was given as 10 and is justifiable as it is the most influential parameter. Weight of 2 was given for TN, TP, temperature, BOD, pH and 1 for other parameters.

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 of 100 with 50 generations. 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.*, 2005). 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 taken on pre-monsoon season (19–20 June 2004) without changing the calibrated parameters. Then, the calibrated model was used to simulate water quality conditions during the critical period in pre-monsoon season.

3. Results and discussions

3.1. Calibration and validation

The calibrated parameter values in the model are presented in Table 5. The model calibration results for the water quality data at six monitoring locations are shown in Fig. 6. The simulated results are presented as continuous lines and the observed data as symbols.

The model calibration results are in well agreement with the measured data, with some exceptions. The relative mean error between the simulated and observed values for flow, depth and velocity are 10%, 17.3% and 15% respectively. R^2 values indicate the effectiveness and interrelationships between the observed and simulated values; these are 0.98, 0.73, and 0.89 respectively. The relative mean errors and R^2 values (inside brackets) for DO, BOD, TN, TP, temperature and pH are 20.9% (0.97), 26.1% (0.85), 42.2% (0.97), 23.9% (0.94), 21%

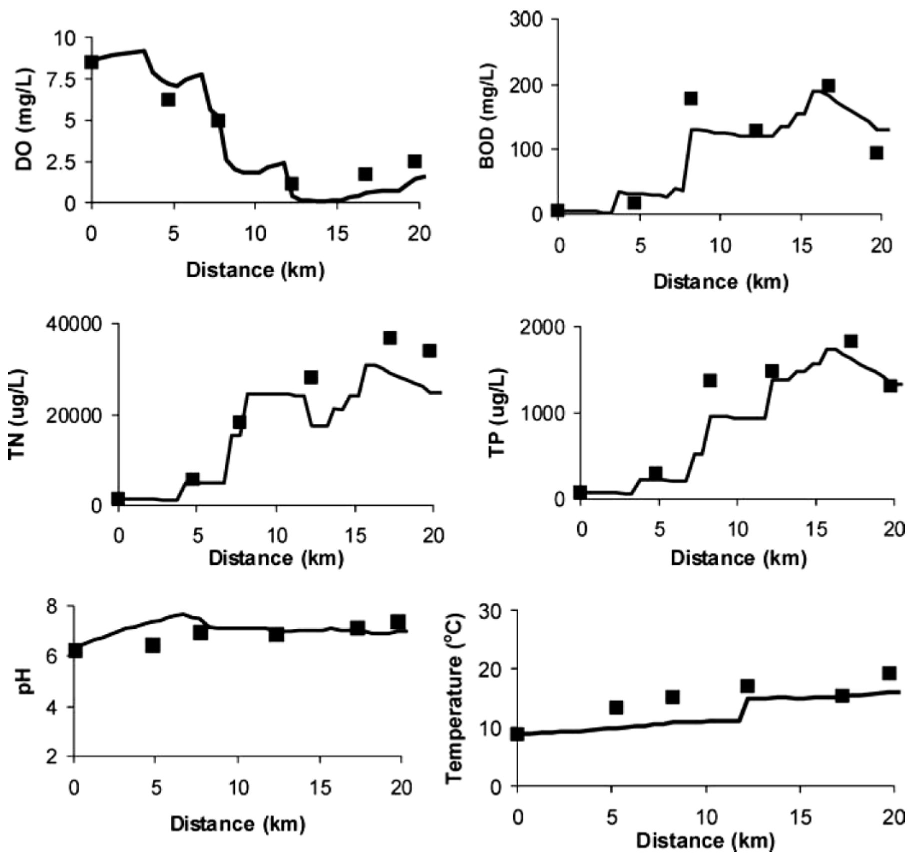


Fig. 6 Calibration in Bagmati River for data on 2–3 December 2004

(0.72) and 6.8% respectively. Low value of R^2 was observed for pH and thus not presented.

Model calibration results showed that the Bagmati River water qualities do not meet the minimum dissolved oxygen standard of 4 mg/l beyond 8 km. It is to be noted that the profiles of water qualities at the proximity of about 7 km are different from downstream. In the upper part of the river, DO concentration is above 5 mg/L, an indication of better quality of water. This is because a sewer is constructed all along the right bank of the river for collecting domestic, industrial and rain wastewater. This collected wastewater is treated in a wastewater treatment plant and finally is thrown to the river at 7.05 km. Two DO sags are clearly seen between 3–7 km and 8–11 km. First sag lies after the wastewater leakage at 3.5 km. The second sag lies after the outlet of wastewater treatment plant at 7.05 km and wastewater flow at 8.2 km. Beyond 12 km, DO concentration gradually decreases and reaches minimum between 14.25–15.25 km. This is because highly polluted tributaries Manahara khola, Dhobi khola and Tukucha khola add high CBOD and low DO waters. In addition, the re-aeration coefficient was found low (6–8.7 day^{-1}) due to decrease in velocities. Beyond 15.25 km, there is gradual increase in DO concentrations due to increase in re-aeration and addition of increased DO water from Bishnumati River, Balkhu khola and Nakkhu khola.

The concentration of CBOD, TN and TP rises sharply at the proximity of 8 km due to discharge of local wastewater drains and wastewater treatment plant effluent. BOD simulation shows some marked difference between measured and modeled values at 7.9 km. This discrepancy is partially due to non-inclusion of input of pollution from decayed flowers, which people offer to the temple Pashupatinath (at 6–7 km). In addition, there are lots of cremation activities along the bank of the river.

The validated results for the model are shown in the Fig. 7. The results are quite acceptable with some exceptions. The relative mean errors and R^2 values (inside brackets) between the simulated and observed values

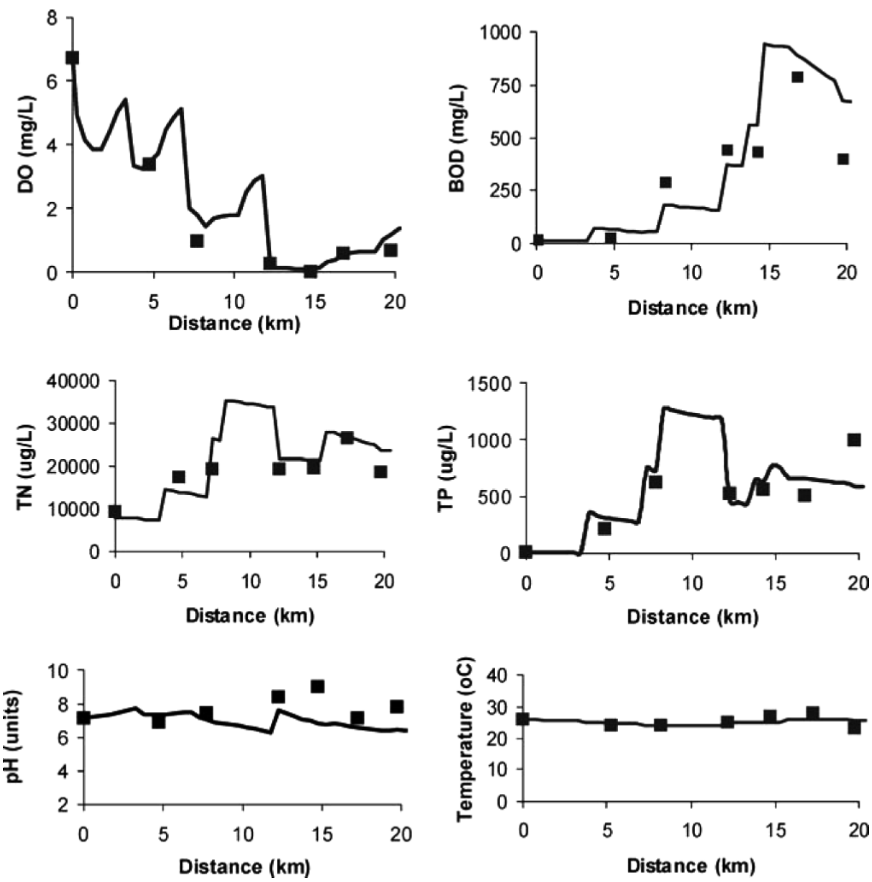


Fig. 7 Validation in Bagmati River for data on 19–20 June 2004

for DO, BOD, TN, TP, temperature and pH are 15.5% (0.97), 33.0% (0.86), 18.8% (0.73), 21.2% (0.55), 5.5% (0.37) and 15% respectively.

In spite of the differences between measured and simulated data sets at some points, the calibration and validation results are acceptable especially for the developing countries where the financial resources are often limited for frequent monitoring campaigns and higher accuracy data analysis.

3.2. Strategies for water quality control

We evaluated the influences of point sources (wastewater treatment plant, local sewers and river tributaries) have on DO concentrations along the river using validated model considering low flow period of pre-monsoon season in 2004 instead of 7Q10 flow (7 day consecutive low flow with a 10 year return frequency), as there was unavailability of sufficient water quality and flow data. We assumed absence of wastewater leakage from sewers and examined the influence of various water quality management strategies considering: (i) pollution loads modification (ii) flow augmentation and (iii) local oxygenation.

(i) Pollution loads modification
We fixed trial values of CBOD as 15 mg/L, 10 mg/L, 5 mg/L and TN as 0.3 mg/L for point sources after several trials. The point sources represent the tributaries of the Bagmati River and existing wastewater treatment plant for which modification is assumed. This is possible after enforcement of policies and acts in the tributaries of the river. Figure 8 shows DO profiles obtained by simulation. All the DO profiles do not completely meet the minimum oxygen concentrations of 4 mg/L.

(ii) 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 Valley (MWSP, 2000). Figure 9 shows the DO profiles after simulation with 1 m3/s flow augmentation in addition to wastewater reductions. None of the DO profiles completely meets the minimum DO requirement.

(iii) Local oxygenation.
We evaluated the effects of oxygenators using series of weirs along the critical locations of the rivers in addition to 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 (Pelletier

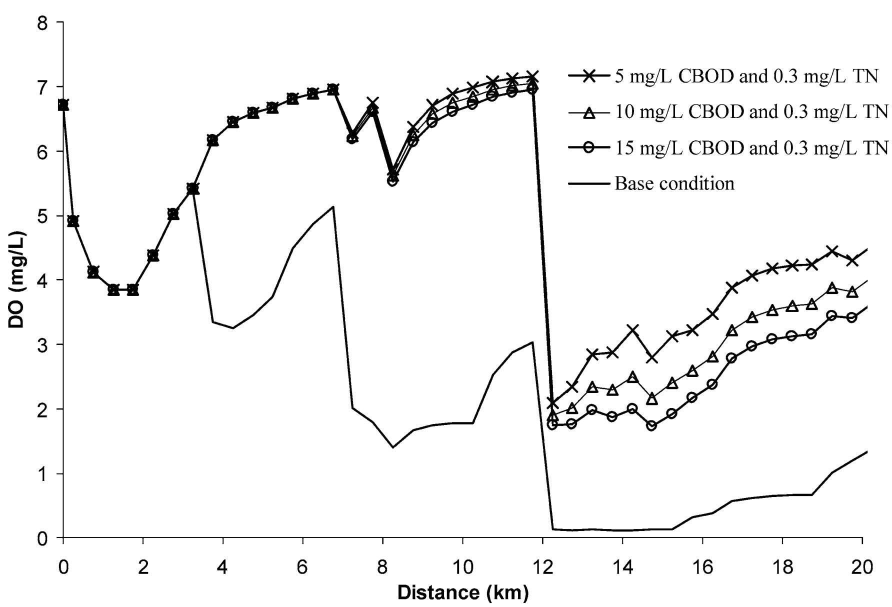


Fig. 8 DO profiles along Bagmati River for different CBOD and 0.3 mg/L TN limits at point loads

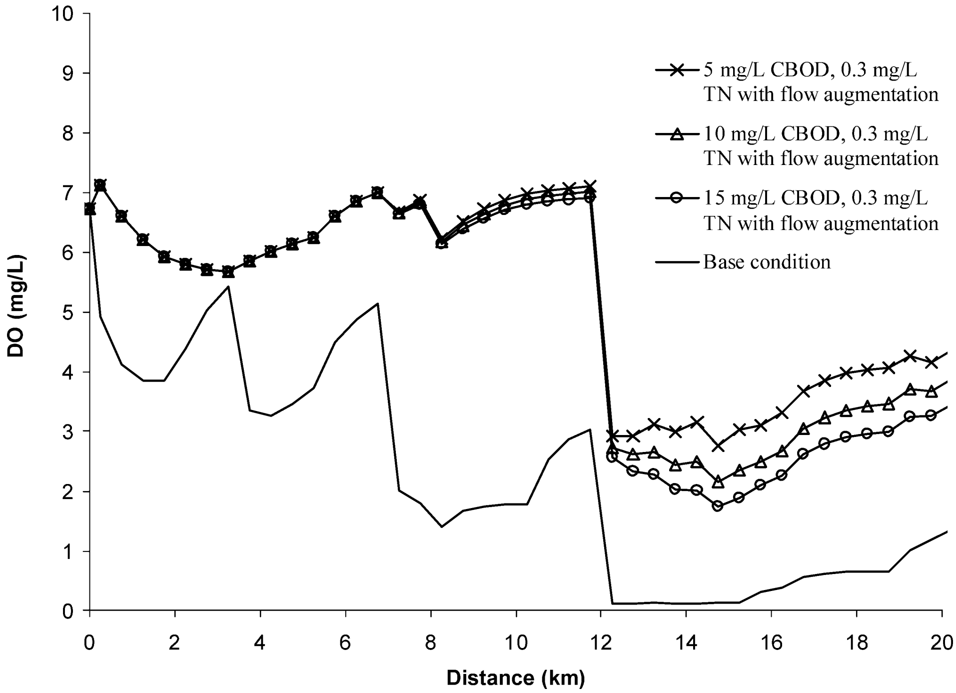
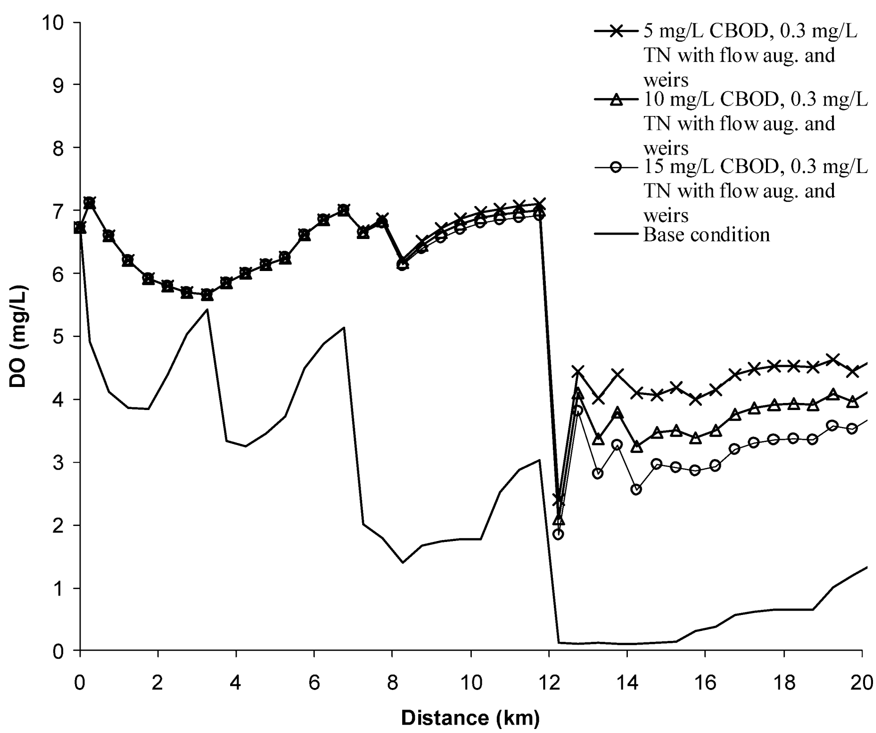


Fig. 9 DO profiles along Bagmati River for different CBOD and 0.3 mg/L TN limits at point loads with 1 m^3/s flow augmentation

Fig. 10 DO profiles along Bagmati River for different CBOD, 0.3 mg/L TN limits at point loads with 1 m^3/s flow augmentation and weirs at 12.5 km, 13.5 km and 14.5 km



and Chapra, 2005). After series of simulations, we found three critical positions at 12.5 km, 13.5 km and 14.5 km for the installment of the weirs. The weir heights needed were 1.35 m at 12.5 km and each 0.75 m at 13.5 km and 14.5 km locations. The DO profile with 5 mg/L CBOD limit with flow augmentation and weirs at critical positions meets the minimum DO concentrations of 4.0 mg/L at all locations except at 12.25 km in which DO concentration is 2.4 mg/L (Fig. 10). The decrements of DO concentration observed at 12.25 km, 13.25 km and 14.25 km are due the effect of weirs at 12.5 km, 13.5 km and 14.5 km respectively resulting in increased water depths and thus decreasing aeration coefficients behind the dams, consistent with the results found by Campolo *et al.* (2002).

4. Conclusions

A stream water quality model, QUAL2Kw, was calibrated and validated for the Bagmati River using the data collected in 2004. The model represented the field data quite well with some exceptions. In calibration, the relative mean errors and R^2 values between the simulated and observed data for DO, BOD, TN, TP, temperature and pH were 20.9% (0.97), 26.1% (0.85), 43.1% (0.97), 23.9% (0.94), 21% (0.72) and 6.8% respectively. In validation, these values were 15.5% (0.97), 33% (0.86), 18.8% (0.73), 21.2% (0.55), 5.5% (0.37) and 15% respectively.

The model was applied to simulate various water quality management strategies during the critical period to maintain minimum DO concentrations of 4 mg/L considering (i) pollution loads modification (ii) flow augmentation and (iii) local oxygenation. The simulation showed that the local oxygenation is effective in raising the DO levels. The combination of wastewater modification, flow augmentation and local oxygenation is necessary to ensure minimum DO concentrations. This reasonable modeling application guarantees the use of QUAL2Kw for future river water quality policy options.

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