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Restoring water quality in the polluted Turag-Tongi-Balu river system, Dhaka: Modelling nutrient and total coliform intervention strategies

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HIGHLIGHTS

- First application of a WQ model to the Turag-Balu River System in Bangladesh
- Model of TC and nutrients illustrates the serious pollution problems in the river.
- Pollution control is possible with sufficient effluent treatment.
- Flow augmentation can dilute discharges in low flow conditions.

GRAPHICAL ABSTRACT

The study is set in the Dhaka region of Bangladesh close to the confluence of three rivers, the Ganga, the Brahmaputra and the Meghna, which dominate the hydrology of the Delta system of the Bay of Bengal. Home to millions of people, the Delta system is driven by hydrology, the pollution from 30,000 factories discharge into the river systems, sea level rise and climate change. Pollution creates a major threat to the people of Bangladesh.

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ABSTRACT

River water quality in rapidly urbanising Asian cities threatens to damage the resource base on which human health, economic growth and poverty reduction all depend. Dhaka reflects the challenges and opportunities for balancing these dynamic and complex trade-offs which goals can be achieved through effective policy interventions. There is a serious problem of water pollution in central Dhaka, in the Turag-Tongi-Balu River system in Bangladesh with the river system being one of the most polluted in the world at the moment. A baseline survey of water chemistry and total coliforms has been undertaken and shows dissolved oxygen close to zero in the dry season, high organic loading together with extreme levels of Ammonium-N and total coliform in the water. Models have been applied to assess hydrochemical processes in the river and evaluate alternative strategies for policy and the management of the pollution issues. In particular models of flow, Nitrate-N, Ammonium-N and indicator bacteria (total coliforms) are applied to simulate water quality in the river system. Various scenarios are explored to clean up the river system, including flow augmentation and improved effluent treatment. The model results indicate that improved effluent treatment is likely to have a more significant impact on reducing Ammonium-N and total coliforms than

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Modelling water quality
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flow augmentation, but a combined strategy would greatly reduce the pollution problems in the Turag-Tongi-Balu River System.

1. Introduction

Environmental pollution in large rapidly developing delta cities is a major problem responsible for over 12.6 million deaths annually according to the World Health Organization and UNICEF (Prüss-Üstün and Corvalán, 2006). Deltas have some of the highest population densities in the world with often poor and vulnerable residents (Nicholls et al., 2016). The presence of high population numbers, unsanitary conditions, poorly regulated industrial discharges and untreated domestic effluents has ensured that many urbanised delta rivers are highly polluted. These factors also pose a significant health threat to people using the rivers, groundwaters and associated water supply systems (Pimentel et al., 2007; Vörösmarty et al., 2010). Similar to urban rivers systems in other rapidly industrializing developing countries, the rivers of Dhaka City, Bangladesh, are heavily impacted by the scale and intensity of economic growth. While Greater Dhaka is a major engine of growth for Bangladesh, representing 40% of GDP production, high levels of pollution, over-abstraction of ground water, and inefficient use means that the Turag-Tongi-Balu river system in central Dhaka (Figs. 1 and 2) receives a huge load of domestic and industrial effluent. New industrial developments and townships enhance these pollution loads with devastating impacts on river water quality. In this paper we assess the impact of nutrient and faecal pollution in the Turag-Tongi-Balu River system and consider the mass balance of chemical constituents in the river system.

We have utilised a dynamic process based flow and water quality model INCA (Integrated Catchment Model, Whitehead et al., 1998a, 1998b, 2016, Wade et al., 2002a, 2002b, 2002c) to simulate the behaviour of the catchment and river system. Water quality modelling is a useful technique to improve our understanding of the spatial and temporal dynamics of nutrients and faecal pollution (total coliforms) in a river system, and can be used to explore the potential effects of different management and hydrological change scenarios on river water dynamics. Two management strategies have been considered in this study, namely, the introduction of effluent clean up technologies for key discharges along the river and the alteration of water flows in the upper Turag so as to increase the flows of water in low flow conditions. This study presents the first integrated flow and water quality model of pollution risks in urban Dhaka and aims to guide and support government efforts to systematically regulate pollution in the Dhaka region. The designation of rivers in Greater Dhaka as Ecologically Critical Areas (ECAs) by the Ministry of Environment and Forestry creates a foundation for future restoration activities (MoEF, 2010).

2. The Turag-Tongi-Balu catchment system

The city of Dhaka, capital of Bangladesh, is located in the centre of the country, north of the confluence of the River Padma (combined Ganga and Brahmaputra) and Meghna. The Turag-Tongi-Balu Rivers are part of a complex peripheral system of rivers surrounding Dhaka, as shown in Fig. 1. Seasonal flow variability in this river system is related to the region's climate, characterised by a hot pre-monsoon summer season (March to May), a rainy monsoon season (June to September), a post-monsoon autumn season (October to November), and a dry winter season (December to February) (WARPO, 2004; Shahid, 2010). The Turag River is fed by runoff coming from a predominantly agricultural area located upstream, as well as from other rivers such as the Bangshi River and the Brahmaputra River, and flows into the Buriganga River, in the South of Dhaka. Land use is changing rapidly in the peripheries of Dhaka, with multi-spectral satellite data showing rapid conversion from agricultural cultivated land to urban land uses along Tongi Khal over the past few decades (Dewan and Yamaguchi, 2009; Dewan et al., 2012). Improved sanitation coverage in this new urban area is currently low, with the drainage system used as a combined sewerage system in a large portion of the area, presenting a source of microbial contamination of the river system. Precise estimates of effluent loads from various sources along the river are unavailable, in part due to the rapid pace of change which means that data is quickly outdated. Dhaka is one of the most densely populated cities in the world, home to approximately sixteen million people, of which less than 25% are served by sewage treatment facilities (Islam et al., 2015). In the last twenty years, a convergence of unregulated industrial expansion, rural-to-city migration, overloaded infrastructure, unclear institutional responsibility for water quality management and ineffective enforcement of environmental regulations have all taken their toll on surface water quality. Though there are plans for a number of sewage treatment

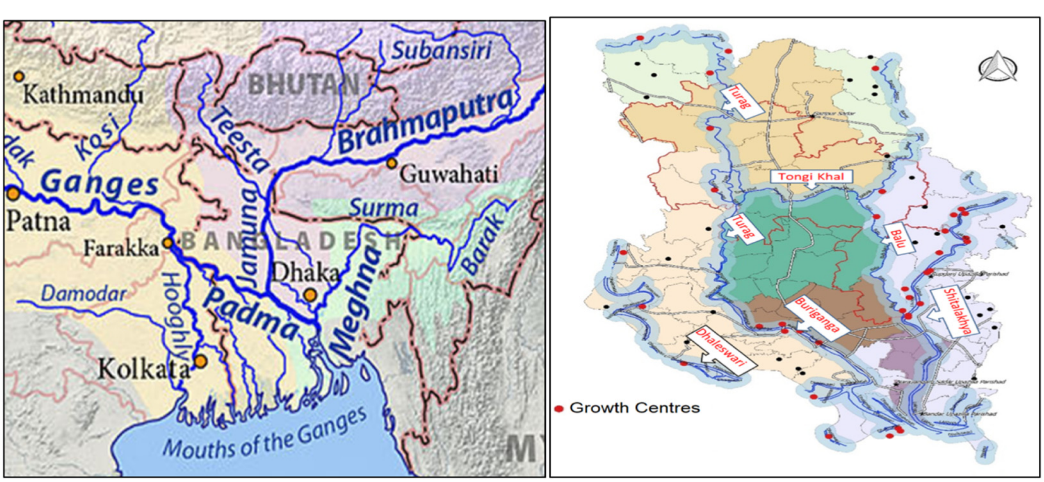

Fig. 1. Maps showing Ganges, Padma, Brahmaputra and Meghna Rivers feeding into the Bangladesh Delta (left) and details of the Turag-Tongi-Balu River System around Dhaka City (green/brown Zone) on the right hand map. Red dots on right map shows areas of rapid growth and development in Dhaka. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

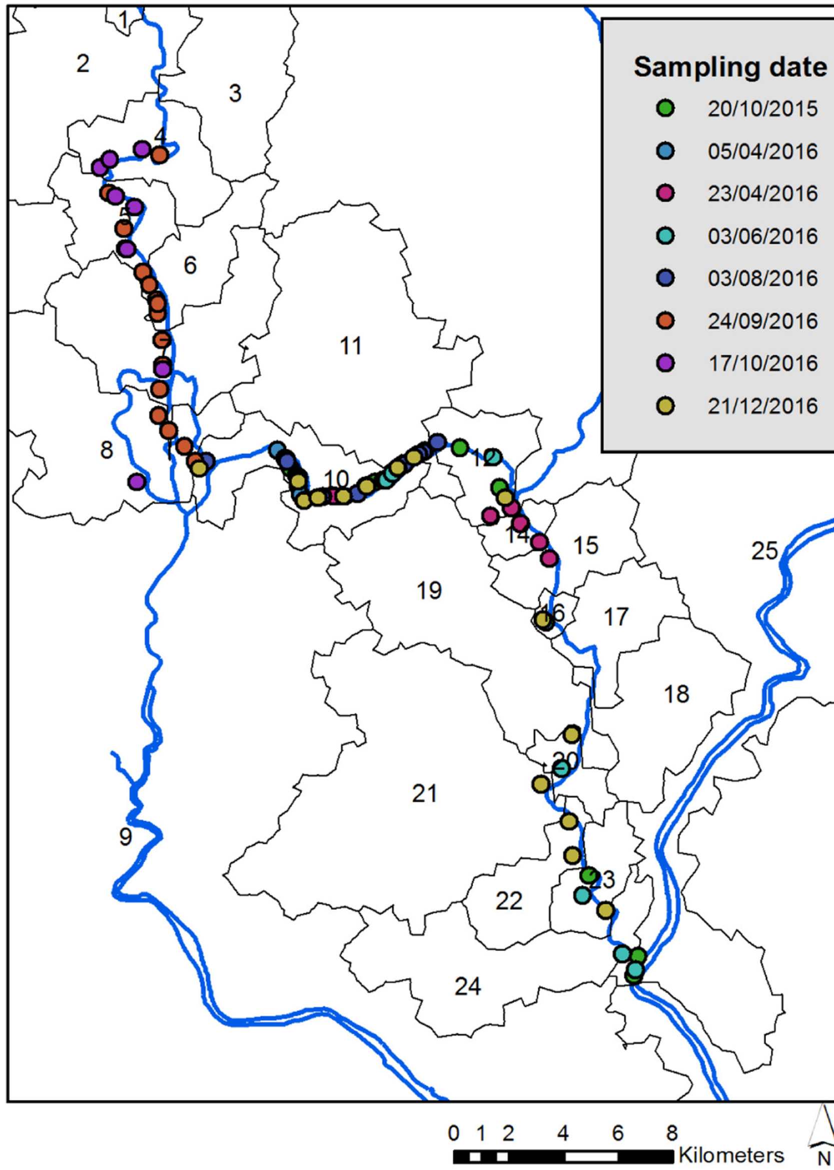

Fig. 2. The sub catchment numbered locations of sampling sites along the Turag-Tongi-Balu River System and the dates of sampling.

plants by 2025, there is no sewage treatment plant serving the northern part of Dhaka at the moment, which is of concern. Whilst many industries claim to have effluent treatment system, there is no clear evidence that these operate in any systematic manner. Almost all the waste from humans, industry, and millions of farm animals, along with tonnes of pesticides and fertilizers, make its way into Dhaka's surface water untreated and a percentage of these wastes infiltrate to the groundwater. As a result, pollutant levels in the groundwater are increasing, as are those in many sections of the rivers and canals in the city and surrounding areas and pollution increases to alarming levels in the dry season (MoEF, 2010). Sayed and Haruyama (2016) found significant changes in the major land use patterns of Dhaka city using remote sensing and reported that industrial expansion in Dhaka city increased approximately 20% between 2004 and 2010 and brickfields also increased 5% within the same period. Brickfields are also one of the major sources of water and air pollution in Dhaka city. The sewerage and sanitation network of Dhaka city covers only 25% of the total urban area. In the absence of an appropriate waste management system, over 50% of municipal waste is disposed into the water bodies of Dhaka city (MoEF, 2010). Therefore, it is a considerable challenge to identify the location of the pollution sources around the Turag-Tongi-Balu River System (Sabit and Ali, 2015; MoEF, 2010).

3. Water quality in the river system

Given the extensive sources of pollution in the Turag-Tongi-Balu system, it is not surprising that the observed concentration data highlights the poor water quality. A comprehensive sampling programme has been conducted by BUET (Bangladesh University of Engineering and Technology) and Fig. 2 shows the spread of sampling sites along the river system plus the sample dates. All the samples and measurements were taken from the middle of river at the designated sample points decided from literature, satellite imagery and a number of reconnaissance visits to the river system. Some of the parameters were analysed in-situ with HACH HQ40d multi-parameter meter which can measure pH, dissolved oxygen (DO), oxidation-reduction potential (ORP), electrical conductivity (EC) and total dissolved solids (TDS). Measurements were made and samples collected from a depth of 50 cm from the surface to avoid wave turbulence and debris. Samples of 500 ml were collected using an automatic wastewater sampler

(Global Water WS 755) and stored in pre-acid washed Teflon coated reagent grade plastic bottles. Bottles were capped following standard EPA guidelines to remove air and placed in ice boxes to limit biological activities. Filtered samples were used for measuring chemical oxygen demand (COD), Nitrate-N, Ammonium-N and phosphate using spectrophotometric methods. For this a HACH DR-6000 spectrophotometer was used following HACH pre-calibrated standard methods. Microbial analysis included measurements of total coliforms (TC) and *E. coli* cfu/100 ml undertaken using standard methods. Total coliforms are a group of bacteria that are found in the environmental and human or animal faeces, and are used as an indicator of faecal pollution. For each sample, 100 ml were filtered using 0.45 μm cellulose nitrate filters, which were attached to adsorbent pads soaked in m-ColiBlue24 broth in a sterilised Petri dish, and the assembly was incubated at 35 °C for 24 h. The colonies on the filters were counted using a digital colony counter after the incubation period. The dilution ranged from 1000 to 10,000 for samples where the dilution was determined from samples from reconnaissance visits and the literature. Fig. 3 shows plots of the profiles of water quality along the main river system with data means at different reaches for Nitrate-N, COD, DO and Ammonium-N. The Nitrate-N shows quite high concentrations higher up in the catchment reflecting agricultural development in the upper reaches of the Turag, but the concentration falls as the Nitrate-N moves down the river system, suggesting both dilution and denitrification. The COD levels are very high indicating significant effluent and industrial discharges. There is a major difference between the wet and dry periods, with much higher COD in the dry season. This is due to the low flows and hence reduced dilution of effluents and discharges. The high COD, and by association, high BOD, also causes extremely low DO levels, as shown in Fig. 3. DO is close to zero in certain reaches in the low flow period which creates anoxic conditions, leading to many pollution problems such as the release of noxious gases such as hydrogen sulphide, and dissolution of metals from the sediments into the water column. These can cause serious health problems. The Ammonium-N and Nitrate-N concentrations also become very high with Ammonium-N reaching 16 mg/l. Nitrate declines down the river system suggesting higher agricultural sources of nitrate and instream denitrification occurring together with dilution of the upstream N. The Ammonium-N also creates low oxygen conditions as Ammonium-N nitrifies to nitrate and utilises oxygen taken from the river water. Plus there will be a large release of nitrous oxide gas (a greenhouse gas) from denitrification processes. Thus the Turag-Tongi-Balu system is highly polluted and there is a need to make a major effort to clean up the river system and restore it to reasonable health.

4. The INCA (Integrated Catchment) flow and quality model

There are relatively few models of whole catchments that incorporate the soil and groundwater components as well as river channel dynamics, despite the fact that many problems are caused by nonpoint source or diffuse pollution. Where such models do exist they are often driven by overly complex hydrological models. In an attempt to develop a process-based water quality model with hydrology and water quality modelled at the same level of complexity, a model called the Integrated Catchments Model (INCA) has been developed. The INCA model simulates the main processes related with rainfall-runoff transformation and the cycle and fate of several compounds, such as Nitrate, Ammonium-N, total coliform, metals and phosphorus (Whitehead et al., 1998a, 1998b, 2016; Wade et al., 2002a, 2002b, 2002c; Whitehead et al., 2015; Jin et al., 2015). In terms of nitrogen, the modelled processes include mineralization, nitrification, denitrification, immobilization, plant uptake, and nitrogen fixation, as indicated in Fig. 4. Both surface soil zones and groundwater zones are simulated together with leaching of water into the river system (Fig. 4). Sources of nitrogen can be from atmospheric deposition (i.e. from local or remote sources such as power stations, industry, or vehicles), from point sources such as sewage discharges, or from distributed sources such as agricultural fertilizers or natural organic sources of nitrogen. The INCA-Pathogens model is also a process-based model and simulates total coliform stores in soils, groundwater, sediments, and river water (Whitehead et al., 2016). The model accounts for both diffuse total coliform sources, such as those from agricultural areas, as well as point sources, including sewage treatment works and industrial sources (see Fig. 5). The model simulates a range of processes governing microbial transport, growth and die-off, and parameters may be varied at a sub-catchment scale to enable a spatially variable representation of key processes. A full description of the total coliform model and applications in England, Wales and Finland are given by Whitehead et al. (2016), Bussi et al. (2017), and Rankinen et al. (2016).

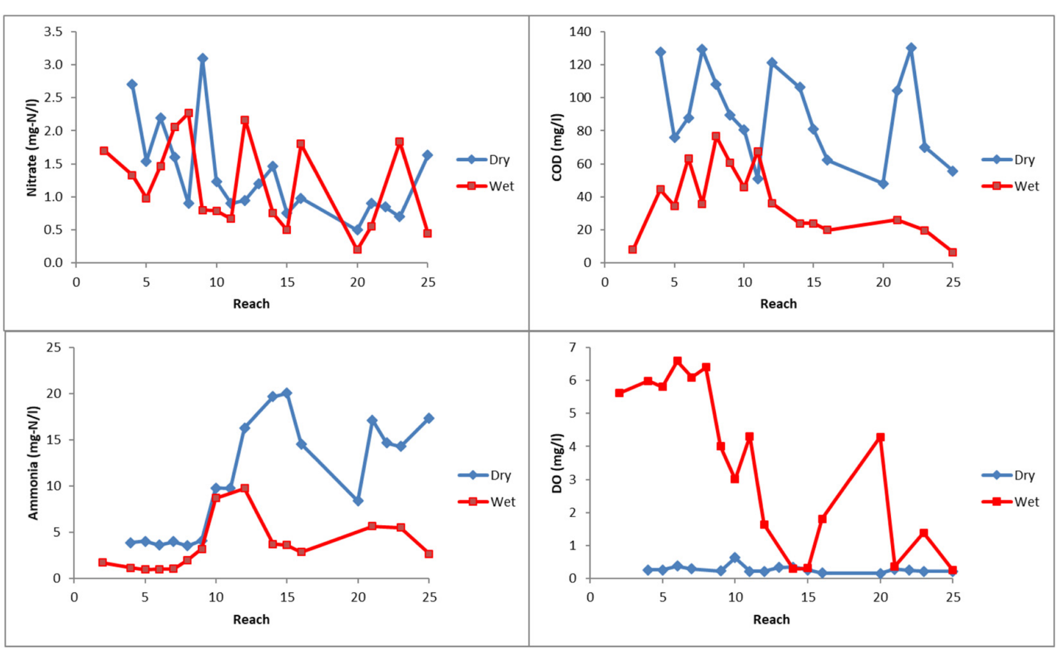

Fig. 3. Mean water quality concentrations along the Turag-Tongi-Balu System.

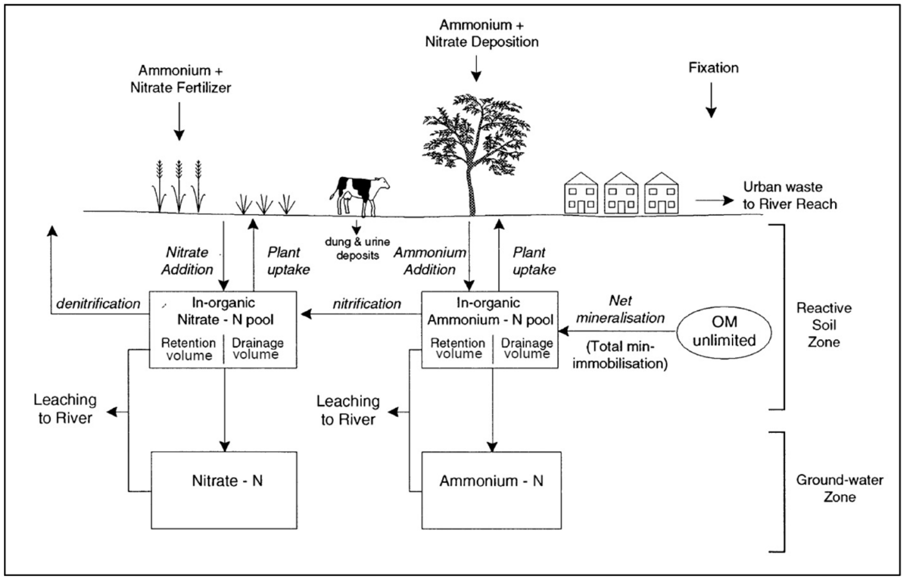

Fig. 4. The key process in the land component of nitrogen cycle.

4.1. Model sensitivity, uncertainty analysis and limitations

There are always issues concerned with model uncertainty and model limitations in any flow and water quality modelling study. Models are a simplification of reality and allow an approximation to any system to be evaluated (Whitehead et al., 1998a). The fact that the system is dynamic and that chemical processes are kinetic in nature and interact with the hydrology makes modelling a very complex process. There have been extensive studies of uncertainty using the INCA models with techniques such as generalized sensitivity analysis (Spear and Hornberger, 1980; Hornberger and Spear, 1980) used extensively to test INCA model uncertainty (Wade et al., 2002a, 2002b, 2002c; Rankinen et al., 2016) to evaluate both parametric uncertainty in the INCA model and uncertainty in the data used to drive the model. For example, Rankinen et al. (2016) found that the INCA-Pathogens model performance was sensitive to the parameters defining light induced microbial decay in river water and in the soil compartment as well. There are limitations in any water quality modelling study because of all the complexities. In this study a key limitation is the lack of frequent water quality data to allow a full calibration and validation of the model and even the flow data is fairly limited. So there will be uncertainty in any results from such a study. However, this work is regarded as a first step with more sampling and chemical analysis needed in order to give increased confidence in the models.

5. Application of INCA to Turag-Tongi-Balu system

The INCA N and INCA TC model requires daily time series of precipitation, hydrologically effective rainfall (HER), temperature and soil moisture deficit (SMD), as can be seen in Fig. 6. Observational data are

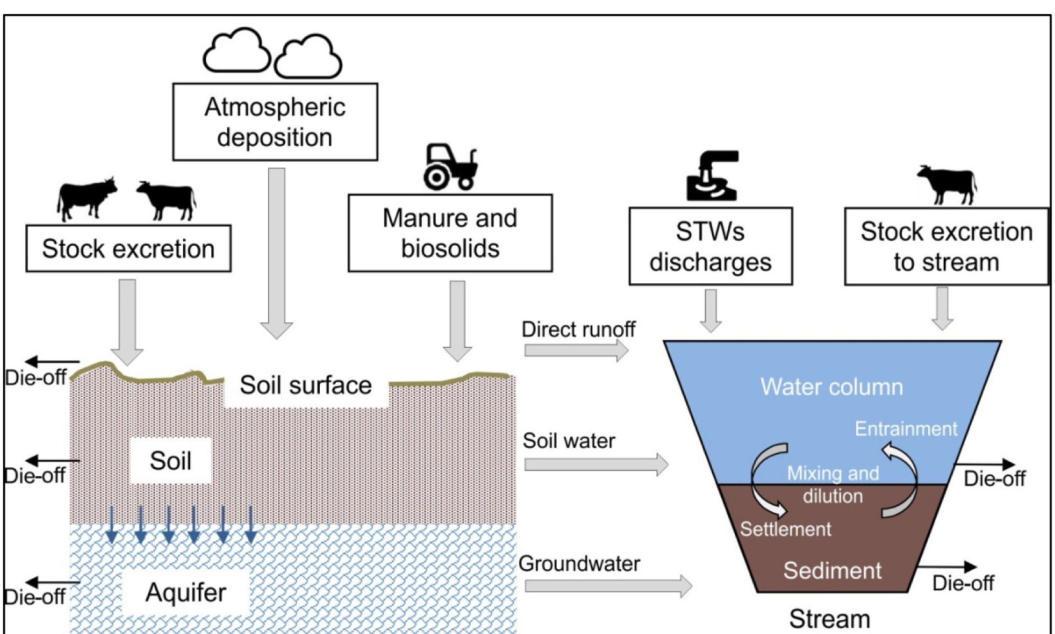

Fig. 5. Schematic representing the sources, transport mechanisms and stores of total coliform in the environment.

available from in situ weather stations and also from satellite measurements and these have been integrated into observational datasets which cover the region as part of the Aphrodite online data system (Yatagai et al., 2012; Whitehead et al., 2015). Observations of flows, total coliform numbers, Nitrate-N and Ammonium-N concentrations are required in order to adjust the INCA model parameters in order to calibrate and validate the model. River flows and water chemistry data have been used to compare observed and simulated values for calibration and validation. Flow data are available at the Mirpur Bridge on the Turag River for the high flow season (June–October).

Spatially distributed information is required in order to estimate several of the INCA model parameters. Some of them are detailed as follows.

- Digital elevation model. The elevation information was obtained from the Shuttle Radar Topography Mission (SRTM) (https://www2.jpl.nasa.gov/srtm/). SRTM is an international research effort to obtain digital elevation models on a near-global scale from 56° S to 60° N. The DEM scale is 90 m.
- Land use/land cover. The land use information was obtained from the GlobCover Portal. GlobCover is an ESA (European Space Agency) initiative whose aim is to develop a service capable of delivering global composites and land cover maps using as input observations from the 300 m MERIS sensor on board the ENVISAT satellite mission (http://due.esrin.esa.int/page_globcover.php).
- Atmospheric deposition. This information was obtained from the global map of atmospheric nitrogen deposition (Dentener, 2006), distributed by the Distributed Active Archive Centre for Biogeochemical Dynamics of the Oak Ridge National Laboratory (DAAC ORNL). The average value is 29 kg ha^{-1} yr^{-1}. (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=830)
- Population map. This map can be used to define the flow and nutrient concentrations of treated wastewater discharges, in case direct measurement is not available. It was obtained from the Gridded Population of the World (GPW) of the Socioeconomic Data and Applications Centre (SEDAC): (http://sedac.ciesin.columbia.edu/data/collection/gpw-v3)

5.1. Model set-up- sub-catchment and reach structure

The reach structure of the Turag-Tongi-Balu System is complex, with the Tongi Khal connecting the Turag and Balu Rivers, as shown in Fig. 7. This figure also shows the upper reaches of the Turag and the linkage to the Brahmaputra, as well as the details of the lower reaches. The river system has been divided up into 24 reaches as indicated in Table 1, which gives the reach lengths and the sub catchment areas associated with each reach, as well as the land use percentages for each reach sub-catchment. In terms of hydrology the system is complicated by the overland flows from the Brahmaputra during flood conditions (Fig. 7). These Brahmaputra overland flows feed into the upper Turag and need to be accounted for in any flow simulation so that the correct flows are simulated in the lower reaches. This also ensures the correct dilution factors are computed in the INCA model and are applied to effluent discharges and diffuse runoff pollution in all reaches. The extent of the connection between the Brahmaputra and the upstream Turag is difficult to estimate, as it is not measured. However, we have estimated the extra flows by comparing the observed flows in Reach 8 with the simulated natural catchment flows. The difference then gives an estimate of the Brahmaputra overland flows entering the upper Turag. This extra flow can then added back into the model as the additional flood flows into the upper Turag. As shown in Fig. 8, we generated model simulated flows that match the limited wet season observation data. The simulated Nitrate-N and Ammonium-N (Fig. 8) indicate low concentrations in monsoon periods when flows are high and the dilution is large, but higher concentrations in the low flow periods when little dilution occurs.

Due to a lack of data, effluent discharges for each reach were estimated by running the model in a “reverse-mode” and comparing the pattern of simulated and observed water quality along the river. In the case of the total coliform model, observations for total coliforms were sourced from the water quality surveys, which measured water quality at numerous locations along the Turag-Tongi-Balu River System (Fig. 2) and over a range of dates, as shown in Fig. 2. A similar method of running the model in a “reverse-mode” to estimate the contaminant discharges was used in a study of perfluoroalkyl substances by Sharma et al. (2016) in a similarly data-scarce context. Effluent discharges were estimated separately for the wet (May to October) and dry (November to April) seasons due to the substantially higher runoff (and hence higher effluent loads) during the wet season. The total coliform concentration of the effluents was calibrated by comparing the distribution of simulated values to observed data. Model process parameters such as the total coliform die-off rate, growth rate and light decay rate were based on values from the literature, as shown on Table 2 (Whitehead et al., 2016), and this was necessary because of the lack of any process rate data for the river system. As shown in Figs. 9 and 10 the profile

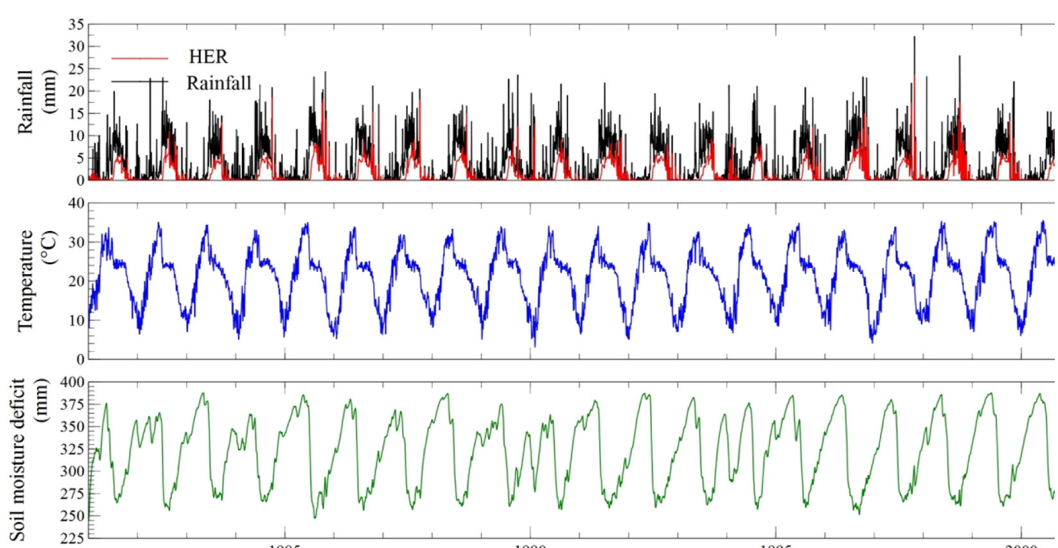

Fig. 6. INCA model inputs of daily rainfall, hydrologically effective rainfall (HER), temperature and soil moisture deficit (SMD).

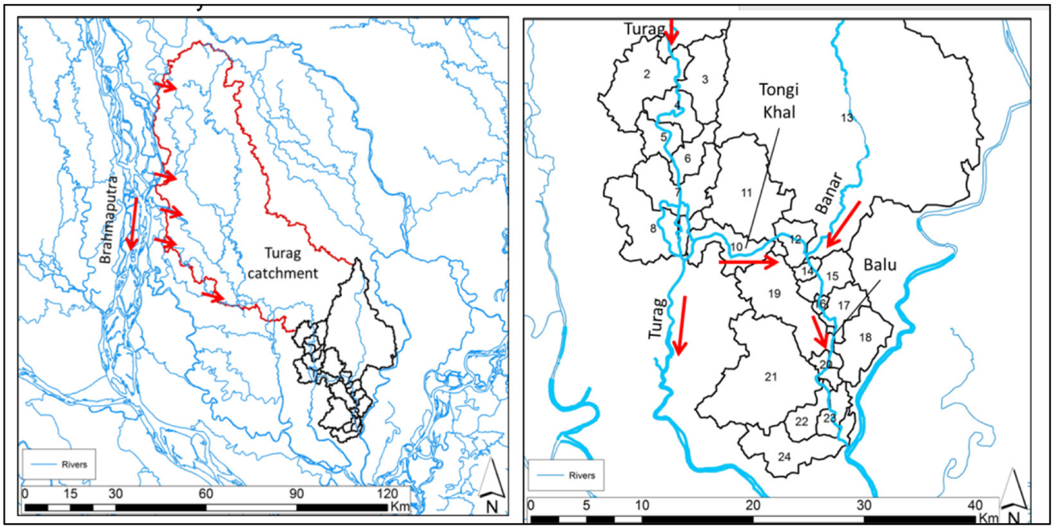

Fig. 7. Reaches and sub-catchments of the Turag-Tongi-Balu River System around Dhaka. Left map shows the upper Turag sub-catchment 1 (in red) and the flood flows (in red) moving across to the Turag from the Brahmaputra. The right map shows the reach boundaries in the middle and lower reaches of the Turag-Tongi-Balu System from subcatchment 2 to 24 (red arrows indicate directions of flow in the wet season). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

down the river system from the model compares well with the observed profiles of mean TC and mean Ammonium-N, although Ammonium-N shows some spikes probably due to the sampling site being immediately downstream of an effluent discharge. The model fits to the data along the river gives R^2 of 0.79 for Ammonium-N and 0.76 for total coliform, so this gives some confidence that the model is representing the water quality in the river system.

6. Restoration measures

Having established the INCA models for total coliforms and Ammonium-N, we can use the model setup to evaluate a series of management alternatives to address the serious pollution problems along the river system. Two management strategies have been considered in this study: the introduction of effluent treatment technologies for all discharges along the river, and the alteration of water flows in the upper Turag to increase the flows of water in low flow conditions. Fig. 11 shows the effects of these strategies on the Ammonium-N concentrations along the river system, as well as what would happen if both were implemented together. With a modern effluent treatment plant it can be assumed that the Ammonium-N concentrations could be reduced from 19 mg/l in the effluent discharges to 5 mg/l, then this would result in a significant reduction in Ammonium-N in the river system, as shown in Fig. 11. Flow augmentation would involve creating a canal or link between the Brahmaputra and the upper Turag. Allowing an augmentation flow of 20 m^3/s during the dry period the dilution effects would be significantly enhanced, halving the Ammonium-N concentrations to approximately 6 mg/l (Fig. 11). The best solution is to combine these policies, and this would reduce the Ammonium-N levels to low concentrations of 1 to 2 mg/l. These two strategies would also reduce the concentrations of other pollutants such as BOD and COD, as well as metals and organics. This would therefore transform the river from being one of the most polluted in the world to being a safe river of average to good water quality with dissolved oxygen concentrations of 5–7 mg/l or at 80% saturation. This combined strategy would also prevent the anoxic conditions in the sediments preventing the release of metals into the water column and contribute to a reduction in noxious gas formation.

Table 1
Turag-Tongi-Balu River System reaches, sub-catchments and land use.

Reach number	Reach length (m)	Catchment area (km^2)	Urban (%)	Arable (%)	Wetland (%)	Natural-mixed (%)
1	150,000	3026.28	0.02	99.5	0.12	0.36
2	3140	35.79	38.31	59.28	0	2.41
3	550	23.72	0	98.53	0	1.47
4	4320	14.17	0	71.25	0	28.75
5	4030	11.48	0	85.71	0	14.29
6	2530	11.22	0	100	0	0
7	4880	28.19	4.6	85.58	0	9.82
8	1870	36.66	1.43	84.01	0	14.56
9	340	2455.98	70.48	26.87	0	2.65
10	10,950	19.90	64.62	35.2	0	0.18
11	470	49.84	6.45	68.55	0	25
12	4020	10.65	0.38	92.97	0	6.65
13	600	507.07	0	66.67	0	33.33
14	1370	3.50	0	88.59	0	11.41
15	2310	12.83	0	50	0	50
16	1450	1.87	0	77.24	0	22.76
17	3330	12.25	0	68.75	0	31.25
18	830	21.53	59.78	17.14	0	23.08
19	1540	39.36	0	75	0	25
20	1780	4.91	94.41	2.11	0	3.48
21	550	70.28	80.95	17.46	0	1.59
22	2220	10.70	62.63	29.29	0	8.08
23	2865	8.69	100	0	0	0
24	1680	27.45	0.83	95.17	0.99	3.01

In terms of total coliform a similar set of conclusions can be drawn. The calibrated value of effluent total coliforms was 1×10^6 cfu/100 ml. If waste were collected and treated in well-managed Sewage Treatment Works (STWs), this discharge might be reduced and, as in the case of ammonia, the instream total coliform concentrations would be reduced. This would also be enhanced in the dry period with flow augmentation, although augmentation has a limited benefit compared to sewage treatment in this model. As shown in Fig. 12, the model results show that flow augmentation and improved effluent treatment will reduce total coliform counts in the Turag-Tongi-Balu River System. The darker blue boxes show the effects of full flow augmentation up 20 m^3/s and the x-axis shows a set of simulations for the different effluent discharge concentrations. These combined effects have a considerable impact, lowering the TC instream levels. Thus the modelling shows that improved municipal effluent treatment and flow augmentation has the potential to provide reductions in total coliform counts. The changes in concentrations can also be assessed in terms of health hazards and to investigate the potential for improving health conditions of people living close to the river or using water from the river. The strategies

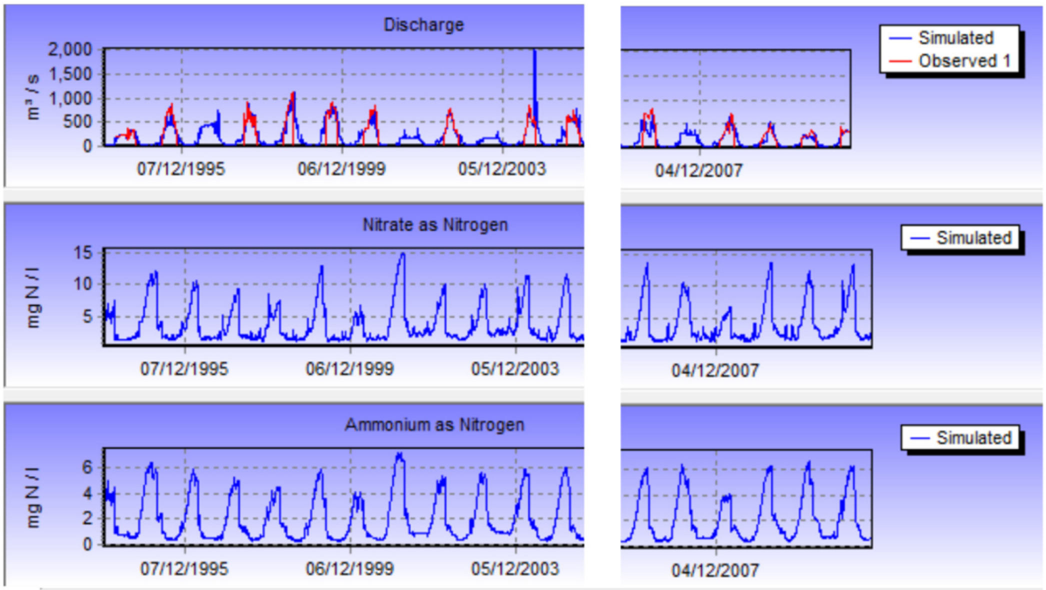

Fig. 8. Simulated and observed flow in reach 8 of the Turag Model and simulated Nitrate-N and Ammonium-N concentrations. Left graph shows a flow calibration period and right graph show the flow validation period.

proposed here to improve water quality will be expensive and their application is likely to be influenced by wider economic and political considerations.

7. Conclusions

The Turag-Tongi-Bula River System is in a poor condition from a pollution perspective and is in need of major restoration. The high concentrations of pollutants affect livelihoods and are damaging to people's health and to ecosystems. Dissolved oxygen is a key indicator of ecosystems health and with DO levels close to zero there is a strong need to significantly improve current DO levels to bring them back to internationally accepted ranges.

The INCA-N and total coliform models are able to simulate spatial and temporal patterns in ammonia, nitrate and total coliform along the Turag-Tongi-Balu River System. The scenario analyses indicate that improved effluent treatment and flow augmentation are likely to have a great impact on reducing pollutant levels in the river system. This combined strategy to reduce pollution and enhance the low flows is recommended. This approach also aligns with government policy, as there are major STWs planned. However the costs of new STWs plus the cost of canals or diversions to enhance summer flows upstream will be high. The model can be used to evaluate alternative designs such as the number, efficiency and location of STWs, the flows required by the canal, and hence canal size in order to evaluate the most cost effective solution. Improving water quality is a key priority for the government and a stronger evidence base can help target the most beneficial investments for people, ecosystems and industry. Also, there are wider economic considerations of how pollution can be monitored, regulated and reduced to balance competing priorities. This study provides evidence of two important dimensions but further work needs to consider agriculture, industrial, infrastructure and land management interventions under uncertain climate and growth futures. Industries such as the garment industry are large engines of growth but with a critical role in responsible investment and behaviour to reduce pollution. There are many initiatives led by government and other partners in recognising the legacy of rapid and often unplanned growth. There is a need to find socially-acceptable pathways to manage ambitious industrial strategies

Table 2
Generic parameters for Turag-Tongi-Balu River system INCA-total coliform model.

Parameter	Value
Land phase	
Soil water processes: die-off rate	0.6 day^{-1}
Soil water processes: growth rate	0 day^{-1}
Soil water processes: light decay rate	0.1 day^{-1}
Inputs: manure: manure addition rate: arable	1E6 cfu/ha/day
Inputs: animals: animal addition rate: arable	1.4E6 cfu/ha/day
Inputs: animals: animal addition rate: urban	6E6 cfu/ha/day
Inputs: animals: animal addition rate: natural-mixed	1.4E6 cfu/ha/day
Direct runoff residence time	1.2 days
Soil water residence time	5.7 days
Water column	
Light decay proportionality constant	0.5
Decay rate	0.6 day^{-1}
Growth rate	0 day^{-1}
Sediment	
Shear velocity threshold for resuspension	0.005 m/s
Deposition rate	0.5 day^{-1}
Resuspension rate	0.1 day^{-1}
Growth rate	0 day^{-1}
Decay rate	0.5 day^{-1}
Physical attributes	
Base flow index	0.7

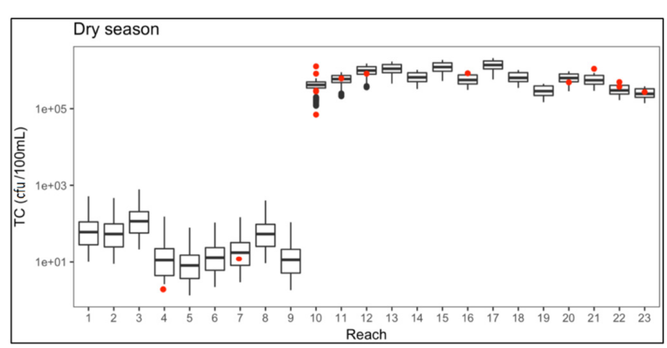

Fig. 9. Comparison of modelled (boxplot) and observed (red dots) total coliforms for the reaches of the Turag-Tongi-Balu River system. The first and third quartiles are represented by the lower and upper boxplot hinges, respectively. The median is represented by a line, and the upper and lower whiskers extend to the largest and smallest values, respectively, within 1.5 times the interquartile range of the upper and lower hinges. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

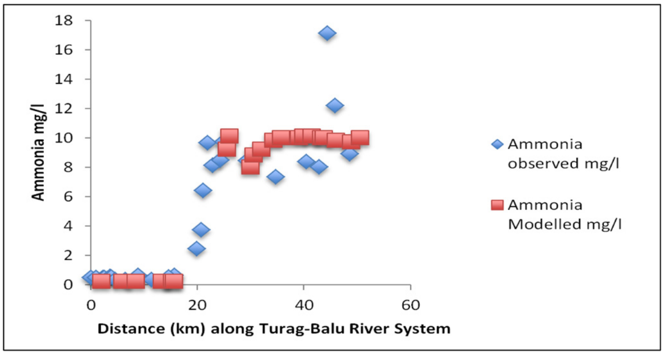

Fig. 10. Mean modelled and observed Ammonium-N along the Turag-Tongi-Balu River System in the dry period.

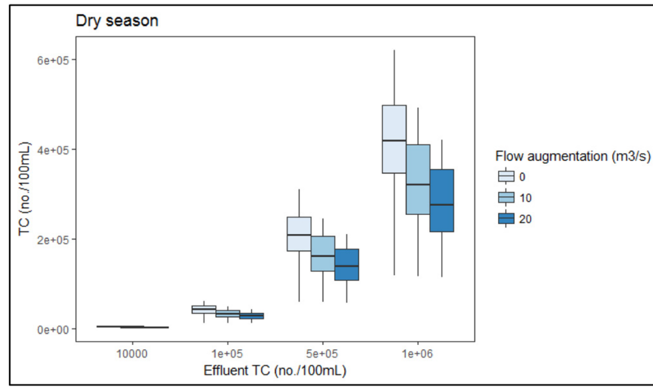

Fig. 12. Modelled TC at reach 10 under 3 flow augmentation strategies (0 m^3/s, 10 m^3/s and 20 m^3/s - shown as light blue to dark blue) and with sewage treatment imposed for effluent total coliforms of 1E+06, 5E+05, 1E+05 and 1E+04 cfu/100 ml, corresponding to a 0%, 50%, 90% and 99% reduction respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

where the environmental costs and the spatial distribution of industry can be evaluated. Also the legacy of pollution and how it affects future generations is poorly understood. This study will contribute to wider government, academic and industry debate and action to promote water security for sustainable growth and poverty reduction.

It should be noted that there are always limitations on studies of water quality and modelling in complex river systems. There is limited data available on the effluent discharges as many discharges are not monitored or measured, plus there are model uncertainties associated with parameterisation of the models. Many model uncertainties can be eliminated as more data is collected on the river system and improved calibration of the models becomes possible. So this is a first step in modelling this complex river system, but with over 50 applications of INCA worldwide there is considerable confidence that the model provides a good initial representation of the river system. Also, the scenarios selected are just some example evaluations of restoration strategies. Further scenarios can be considered with the model in collaboration with stakeholders. In addition, any scenario has to be followed up in detail in collaboration with government and local stakeholders.

This study has highlighted the role of mathematical modelling in low resource environments where data are both sparse and difficult to capture given the complexity and dynamic nature of the environmental, economic and political context. The rapid growth of Dhaka and the importance of rapid growth industries such as the garment industry which is generating over USD 25 billion per year is a key issue for Bangladesh. Such industries create work for mainly female workers lifting multiple more people out of poverty. However planned future growth to double such development by 2021 will depend on protecting the river to balance growth with environmental sustainability, human health and job creation.

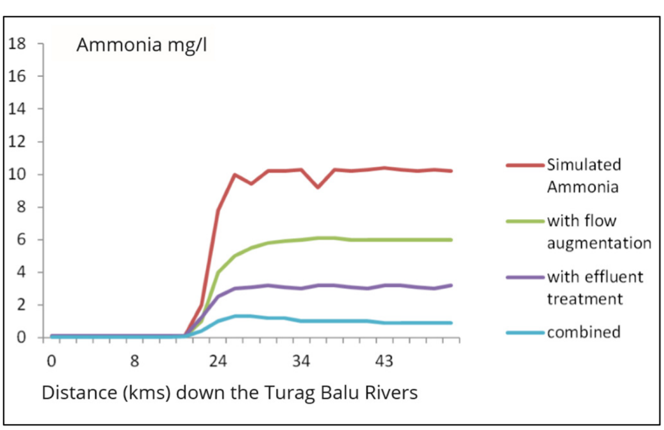

Fig. 11. Simulated Ammonium-N on the Turag-Tongi-Balu System under scenarios of effluent treatment and flow augmentation.

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