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Multibranch Modelling of Flow and Water Quality in the Dhaka River System, Bangladesh: Impacts of Future Development Plans and Climate Change

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Abstract: Long-term development and pollution clean-up plans are a continuing feature of megacities such as Dhaka, Bangladesh. Bangladesh needs to deal with a legacy of past pollution and manage current pollution from a rapidly expanding economy. Surveys in the rivers around Dhaka show extremely high pollution and very low dissolved oxygen levels, with subsequent ecological impacts. Millions of people are not on public treatment of effluents and thousands of factories discharge into the rivers. The Bangladesh Government is planning to install over 12 large Sewage Treatment Plants (STPs) over the next 20 years. To assess the efficacy of these, a water quality model has been applied to the Dhaka River System. Results show that the proposed plan has beneficial effects in the short term for the most densely populated areas of Dhaka, along the Turag and Buriganga Rivers, and in the medium term in other parts of the city (Tongi Khal). However, in several reaches dissolved oxygen levels will remain low or very low due to the lack of STP capacity, remaining misconnections of untreated sewage and large effluent loads. The proposed STPs, while certainly beneficial, will need to be upgraded in the future if the predicted rates of population growth are confirmed and industrial pollution is not significantly reduced alongside. Climate change is expected to have an impact on the Dhaka River System water quality, with increased monsoon flows and lower summer flows, but these changes will not greatly affect the extremes of water quality to any great extent due to the overwhelming impact of pollutant discharges into the system.

Keywords: Bangladesh; water pollution; modelling; effluent planning; climate change

Citation: Bussi, G.; Shawal, S.; Hossain, M.A.; Whitehead, P.G.; Jin, L. Multibranch Modelling of Flow and Water Quality in the Dhaka River System, Bangladesh: Impacts of Future Development Plans and Climate Change. *Water* **2023**, *15*, 3027. https://doi.org/10.3390/w15173027

Academic Editor: Clement D. D. Sohoulande

Received: 23 July 2023
Revised: 7 August 2023
Accepted: 14 August 2023
Published: 23 August 2023

1. Introduction

Industrial and domestic pollution and unsafe drinking water services affect large areas across the world, with the most vulnerable people facing the greatest risks to their lives and livelihoods [1]. Advances in water security policy and practice are emerging from governments, companies, and communities. Ensuring access to water and sanitation is included among the Sustainable Development Goals established by the United Nations General Assembly in 2015 [2,3].

However, progress is slow, uneven, and often unsustainable given the scale and scope of water insecurity challenges. The rivers of Dhaka City, Bangladesh, are heavily impacted by the intensity and consequences of economic growth [4]. Similar to urban river systems in other rapidly industrialising developing countries, Greater Dhaka is a major engine of growth for Bangladesh, representing over 40% of GDP production and generating a huge load of domestic and industrial effluent [5,6]. The city of Dhaka is built over a network of rivers. The city's life is strongly intertwined with the rivers, as they are used for multiple purposes, including transportation. However, the current state of the water quality of the river network is very poor, due to the discharge of raw effluent from domestic and industrial water use. Chemical surveys in the rivers near Dhaka show extremely high organic pollution loading, high ammonia, and very low dissolved oxygen levels, which are close to zero in the dry season. These hydro-chemical conditions have many serious ecological impacts [6–9]. There are also very high metal and pathogen levels from tanneries and domestic effluents [10,11]. Millions of people are not on public sewerage systems and thousands of factories discharge waste into the rivers. To solve this issue, the Bangladesh Government and the Dhaka Water Supply and Sewerage Authority (DWASA) are implementing an ambitious plan, called Dhaka Sewerage Master Plan, to treat most of the residential and industrial wastewater through the construction of several Sewage Treatment Plants (STPs). The Bangladesh Government is planning to install over 12 large new Sewage Treatment Plants (STPs) over the next 20 years [12]. In order to assess the efficacy of these, a suite of water quality models has been developed and applied to the Dhaka River System.

In this paper, we utilised a dynamic process-based flow and water quality model INCA—Integrated Catchment Model [13–16]—to simulate the behaviour of the catchment and the rivers around Dhaka. Water quality modelling is a useful technique to improve our understanding of the spatio-temporal dynamics of chemicals and water quality in river systems and can be used to explore the potential effects of different management and pollution control strategies on river water hydro-chemical dynamics. The INCA model has already been used in many parts of the world [17–19], also in complex river systems like the Ganga River, including Dhaka [6,10,20–22].

The importance of the Dhaka Sewerage Master Plan by installing 12 new STPs over the next 20 years [12] can hardly be understated. Understanding and evaluating the effects of such STPs on the water quality of the Dhaka River network is crucial. However, hydro-chemical data are limited, and a thorough assessment of such plan is difficult. To fill this gap, the INCA model has been coupled with an invaluable 5-year-long water quality monitoring campaign conducted by the Bangladesh University of Engineering and Technology (BUET), encompassing around 1800 measurements spread across 10 rivers, covering a network of more than 250 km of rivers. Dissolved oxygen, total dissolved solids, ammonia-nitrogen, nitrate, and phosphate concentrations were measured, along with a suite of other variables. The data collected were used to establish an INCA model setup for the Dhaka Rivers, which was then employed to evaluate the impact of the new STPs on the water quality of the Dhaka Rivers.

In order to produce robust forecasts into the next couple of decades, climate change and population growth impacts were also evaluated. Climate change will affect flow extremes (floods and droughts), water temperatures, and, hence, reaction rates of the controlling instream mechanisms which determine pollution recovery rates. Population growth is expected to increase the effluent load into the rivers. As the model is process-based and dynamic, the impacts of climate change and population growth were evaluated and used to assess the sustainability of the proposed development programme.

The aim of this study is to assess the benefits of the new STPs in terms of water quality improvement in Dhaka and provide an evaluation based on the most up-to-date tools and data. This task is of the uttermost importance given the level of public investment required to clean the Dhaka Rivers and the major impacts this plan will have on livelihoods of vulnerable communities in Dhaka. This study also aims at providing a set of results and recommendations to policymakers for building a path towards a better water quality status of the rivers in Dhaka and, therefore, an improvement in the urban life.

2. Study Area

Bangladesh is a densely populated country lying on a low, flat area. The city of Dhaka, capital of Bangladesh, is located in the centre of the country, north of the confluence of the Rivers Padma and Meghna. The city of Dhaka is built over a network of rivers, the Balu and Shitalakhya on the eastern side, Turag and Buriganga on the western side, Tongi

Khal to the north, and Dhaleswari to the south. Most of these rivers receive water from the Brahmaputra River through natural canals stemming from the main course of the Brahmaputra and flowing towards Dhaka, making the hydrology of the network highly complex (Figure 1).

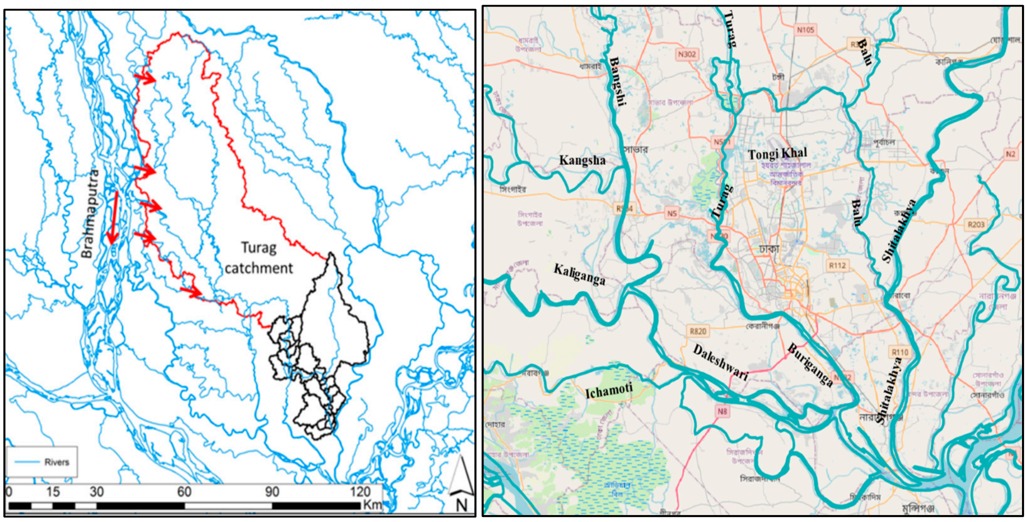

Figure 1. Dhaka river network, showing whole catchment (**left**) with the Turag upper reaches bordering the Brahmaputra River (red) and the INCA sub-catchments (black). The (**right**) hand map shows the detailed river network around Dhaka. Map source: Open Street Map. River network source: Bangladesh's Water Resources Planning Organization (WARPO).

Dhaka is also one of the most densely populated cities in the world, with around 21 million people. Wastewater treatment in the city is generally poor and very limited. Until April 2022, the only sewage treatment plant (STP) was the Pagla STP, with a capacity of 0.12 million cubic meters per day, corresponding to around 6% of the total domestic sewage output. Even so, it is estimated that only one-third of the plant's capacity can be used because of the poor state of the pipelines [23]. In April 2022, the Dasherkandi STP went into operation, with an estimated capacity of 0.5 million cubic meters per day, expected to be able to serve five million people [24]. An ambitious plan for the construction of several STPs around the city is being drawn by the local authorities (among which, the Dhaka Water Supply and Sewerage Authority—DWASA), named the Dhaka Sewerage Master Plan, and partly financed by the World Bank [25], which includes the potential construction of around 10 STPs, with a time frame for construction spanning from the next few years until the 2040s. Table 1 shows a list of completed and planned STPs in Dhaka [12].

Table 1. Sewage treatment plants (STPs) in Dhaka (completed and planned). "Short term" means that the STP is planned to be operational in the next 5 to 15 years. "Medium term" means that the STP is planned to be operational in the next 15 to 25 years.

Name	Completed/Planned	Capacity (M Litres per Day)
Savar	Planned (medium term)	46
Narayanganj	Planned (medium term)	161
Uttara	Planned (short term)	184
Mirpur	Planned (short term)	322
Rayerbazar	Planned (short term)	184
Keraniganj	Planned (medium term)	46
Pagla	Completed	200 (current), 400 (short term), 600 (medium term)

Table 1. *Cont.*

Name	Completed/Planned	Capacity (M Litres per Day)
Dasherkandi	Completed	400 (short term), 500 (medium term)
DND-Demra	Planned (medium term)	103.5
Tongi	Planned (medium term)	92
Gazipur	Planned (medium term)	46
Purbachal	Planned (medium term)	57.5

Because of high population density, rapid urbanisation, and industrial expansion, pollution of water bodies in Dhaka is widespread. Untreated domestic sewage and industrial effluent are illegally discharged into rivers and canals. A variety of pollutants have been measured and studied, such as nutrients (nitrogen and phosphorus) [6,8], coliforms [6,26], metals [10,20,27], and pesticides [26].

3. Methods

3.1. Data

Daily precipitation and temperature data were obtained from a reanalysis product, ERA5-Land [28]. Era5-Land provides global gridded precipitation and temperature values (among other variables) every 3 h from 1950 until the present day at around 10 km resolution. In this study, precipitation and temperature values were aggregated at the daily time-step, averaged over the area of Dhaka and surrounding catchments and used as input of the model. Daily precipitation and temperature data from the meteorological station located at the Tejgaon Airport (station code BGM00041923, WMO code 41923, coordinates 23.78 N, 90.38 E) were also considered, but due to the presence of several gaps these data were discarded.

Terrain elevation for catchment and river network identification was obtained from the Shuttle Radar Topography Mission (SRTM). SRTM is an international research effort to obtained digital elevation models on a near-global scale from 56° S to 60° N. Land use information was obtained from the Copernicus Land Cover global land use map [29]. Nitrogen atmospheric deposition data information was obtained from the global map of atmospheric nitrogen deposition 1993 [30], distributed by the Distributed Active Archive Centre for Biogeochemical Dynamics of the Oak Ridge National Laboratory (DAAC ORNL). Population density map was also used, and it was obtained from the Gridded Population of the World (GPW) of the Socioeconomic Data and Applications Centre (SEDAC) [31].

Observed river flow records for model calibration were obtained from a flow gauge on the lower Buriganga, which measures continuously the discharge of the river (Figure 1). Water samples were collected for water quality analyses from the above-mentioned rivers during 2017–2021 from various locations, with at least once a month temporal resolution up to 2020, and once every two months in 2021. The spatial coverage increased with time. In 2017, only Turag, Tongi Khal, and Balu rivers were monitored, Buriganga, Dhaleswari, and Bangshi Savar were included in 2018, Shitalakhya in 2019, Bangshi and Kaliganga in 2020. Water samples were collected from 68 points in total from a boat at 2 m depth. Temperature, pH, dissolved oxygen, redox potential, electrical conductivity, and total dissolved solids of the samples were measured in the filed using HACH HQ40d multiparameter device and turbidity was measured with VELP Scientifica TB-1 portable Turbidimeter. Laboratory analyses of Colour, Alkalinity, Iron, ammonia-nitrogen, nitrate, phosphate, Sulphide, Sulphate, and chloride were conducted by spectrophotometric method and measuring ranges of the parameters were 15–500 mg/L Pt-Co, 0.02 to 3.0 mg/L, 0.02 to 2.50 mg/L, 0.3 to 30 mg/L, 0.3 to 45.0 mg/L, 5 to 800 µg/L, and 2 to 70 mg/L, respectively. Analysis of Alkalinity and chloride were performed by titrimetric method where the method ranges were 10–4000 mg/L (as $CaCO_3$) and 10 to 10,000 mg/L, respectively. Arsenic, Zinc, Lead, Cobalt, Cadmium, Nickel, Iron, Chromium, and Copper were measured in Perkin Elmer

ICP-OES Avio-200 machine. Most of the laboratory analyses were conducted at the Soil and Water Analysis Laboratory at Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology (BUET).

Urban effluent flows (i.e., the amount of wastewater from residential buildings discharged into the river network) were estimated based on the average daily consumption of water per capita. The Dhaka Water Supply and Sewerage System (DWASA) estimated that per capita water demand in Dhaka is 150 litres per day [12], while the 2030 Water Resources Group of the World Bank estimated the figure as 125 L/day [32]. Another study from the 2030 Water Resources Group [33] estimated 200 L/day per capita domestic wastewater generation in Dhaka. A study by the Brac University's Institute of Governance and Development (BIGD) found that, on average, per capita water usage is 310 litres per day among the households in the formal settlements [34]. Since DWASA is responsible for water supply and sewage disposal to the city dwellers of Dhaka, the estimate from DWASA has been chosen in this study. Urban effluent water quality concentrations (nitrate, ammonium, phosphorus, Ch-a, and dissolved oxygen) were estimated from local measurements and calibrated against river water quality observations. Table 2 shows the rivers monitored within the framework of the present study.

Table 2. Description of the rivers monitored in this study.

River	Length (km)	Length within Dhaka Urban Area (km)	Average Width (m)	Surrounding Landcover/Land Use
Balu	44	23	79	Mainly rural setup, urbanisation started and likely will accelerate
Bangshi	239	22	49	Semi-urban setup at upstream and downstream, rest rural setup
Bangshi	13	13	73	Semi-urban setup
Buriganga	29	29	302	Highly urbanised
Dhaleswari	292	60	144	Mainly rural setup with several industries and brickfields at different locations
Shitalakhya	108	60	228	Upstream urban setup, downstream highly urbanised
Tongi Khal	15	15	55	Highly urbanised
Turag	62	50	82	Upstream urban setup, downstream highly urbanised
Kaliganga	78	11	242	Rural settlements and croplands
Ichamoti	129	7.5	72	Rural settlements and croplands, with few brickfields

Estimating the industrial effluent flow (i.e., the amount of wastewater from industrial facilities discharged into the river network) is a complex task in Bangladesh, due to lack of data and data sensitivity issues. Industrial effluent flows were estimated based on the type of industry and the number of employees per industrial site. The largest water consuming industrial sectors in Dhaka are textiles and tanneries. Discharge data and effluent characteristics from 33 Washing, Dyeing and Finishing (WDF) textile industries under the International Finance Corporation (IFC) led Advisory Partnership for Cleaner Textile (PaCT) program were collected for the year 2016 (see for example [35]). The average value of those data, which is 1995 m^3/day for WDF textiles, was used to make an estimate of effluent volume. The 2030 Water Resources Group assessed that wastewater volume from non-WDF textiles is 15% of that of WDF textiles [32]. The 2030 Water Resources Group also estimated that production per employee is 11,500 kg in WDF textiles, while in other textiles it is considered as 8000 kg [33]. Wastewater generation per kg of production is considered to be 120 L and 70 L for WDF textiles and other textiles, respectively. The industry list with manpower information collected from Bangladesh Knitwear Manufacturers and Exporters Association (BKMEA) was used to estimate pollution load. It has been estimated that

349 million m^3 of wastewater was produced in 2021 by WDF textiles using conventional dyeing practices [36]. The figures from PaCT were selected for the effluent volume from textile industries. Industrial effluent water quality concentrations were also estimated from local measurements and calibrated against river water quality observations. The authors of [36] estimated that 54 million m^3 of wastewater will have been produced in 2021 in Bangladesh by tanneries. Dhaka alone houses 90% of all the tanneries [37]. Reference [38] observed that the tanneries are discharging approximately 20,000 m^3 of effluents per day into the Dhaleswari River, nearby agricultural lands, and wetlands. Reference [39] analysed the effluent characteristics in CETP-treated tannery effluent. Steel industries are prominent among the metal industries in Dhaka. Using electric arc furnace, which is the common method in Bangladesh, the average wastewater discharge is 26.5 m^3 per tonne of steel [40]. Bangladesh has the capacity to produce 9 million tonnes of steel a year and more than half of the annual demand is met from outside of Dhaka [41]. It can be derived that wastewater generation per industry per day in Dhaka is 9075.34 m^3. Reference [33] used the US standards for water usage and sewage strength, which give the following typical estimates: restaurants—11 L/day; shopping mall—37 L/day. The same has been used here to estimate the commercial wastewater discharge.

Future population growth was considered in one of the modelling scenarios (described in the corresponding section). Future population growth data for Bangladesh were obtained from the United Nations' World population prospects 2022 (https://population.un.org/wpp/, accessed on 18 September 2022), which project a population increase of 16% from 2021 to 2041. This projection is made at national level, so internal migration (e.g., from rural to urban areas) is not accounted for in this figure.

Climate change impacts have been taken into account in the modelling framework. Results of two coupled General Circulation—Regional Circulation Models (GCM/RCM) from the CORDEX (Coordinated Regional Climate Downscaling Experiment) initiative were used in this study. CORDEX is a World Climate Research Programme (WCRP) framework to evaluate regional climate model performance through a set of experiments aiming at producing regional climate projections. The coupled GCM-RCMs were the regional RegCM4 model driven by the HadGEM2-ES model and the regional RegCM4 model driven by the NorESM1-M model. Both experiments are described in the CORDEX-CORE (Coordinated Output for Regional Evaluations) ensemble publication [42]. Both models were run over the East Asia regional domain (EAS-22, around 25 km resolution). The Representative Concentration Pathways (RCPs) 8.5 and 2.6 were chosen to explore the range of possible future evolutions of climate in Dhaka [43]. These two scenarios differ in terms of global emissions and are based on different policy assumptions. RCP8.5 was initially defined as a business-as-usual scenario, although its plausibility as such has been called into question [44]. RCP2.6, on the other hand, was defined as a very stringent scenario in terms of curbing carbon emissions. For the purposes of the present study, the difference between the two scenarios is very limited for the time horizon and area considered here.

3.2. INCA Model

The INCA model is a process-based model which simulates the main processes related with rainfall-runoff transformation [13,14] and the cycle and fate of several compounds, such as nitrate, ammonium, and phosphorus. Several publications can be found in the literature, regarding both the model conceptualisation and the model application. The main papers describing the model flow and nitrogen process structure are [13,14,45], with the phosphorus [15], DO and BOD model structure [16,46], the INCA-Sediment model structure. INCA has proved to be a powerful model for studying water flow and quality over the years, as it captures the main dynamical process in rivers and evaluates complex interacting hydrological and hydro-chemical systems. It has been widely used to assess such issues as land use change, effluent treatment systems, population change, and climate change, and is thus the best tool to use for the current study [17,18].

The hydrological and water quality sub-models of INCA have been applied to several basins around the world [19,47–50], including the Dhaka area [6,10]. INCA inputs are daily time series of precipitation, temperature, hydrologically effective rainfall, and soil moisture deficit. The latter two are estimated using another semi-distributed hydrological model, called PERSiST [51]. PERSiST is a semi-distributed catchment-scale rainfall-runoff model which is specifically designed to provide input series for the INCA family of models. It is based on a user-specified number of linear reservoirs which can be used to represent different hydrological processes, such as snow melt, direct runoff generation, soil storage, aquifer storage, and stream network movement. The description of its application to the river Thames can be found in [51].

The nitrogen sub-model of INCA [13,14,45] reproduces the cycle of nitrogen from its main sources (atmospheric deposition, fertilisers, wastewater, etc.) to the river. Two forms of nitrogen are considered as state variables: nitrate and ammonium. The most important soil processes are included, such as denitrification, nitrification, immobilisation, mineralisation, and leeching towards the aquifer. Nitrification and denitrification processes in the streams are also taken into account.

The phosphorus sub-model of INCA [15] incorporates the main sources of phosphorus, both diffuse (fertilisers) and point (wastewater), as well as the main processes involving phosphorus, such as sorption/desorption. The phosphorus sub-model of the INCA model also includes a sediment sub-model, which computes the detachment of soil particles from the hillslopes and their transport towards the catchment outlet. INCA-Peco is an extended version of the INCA-P model, whose equations are described in [16]. It includes biological oxygen demand (BOD), dissolved oxygen (DO), and algal growth and decay.

3.3. Model Set-Up

The INCA model is a semi-distributed model, and therefore the river network covered by the model needs to be divided into reaches, and the drainage area into sub-catchments. Twenty-four locations were identified on the Dhaka River network, also called river sections (Figure 2), located either close to water quality sampling points or in relevant locations (e.g., upstream/downstream the confluence of two rivers). Reaches were defined as stretches of river between two sections (for the most upstream reaches, a starting section in the headwater was identified) and drainage areas were identified using the MERIT-Hydro digital elevation model [52]. Table 1 shows the main characteristics of the INCA reaches and sub-catchments for this model set-up. Table 3 shows the location of reaches and sub-catchments.

Table 3. INCA model set-up for the Dhaka River network.

Reach ID	River	Long;Lat	Drainage Area (km^2)	Arable %	Forest %	Grassland %	Urban %	Water %
R01	Dhaleswari	90.242;23.835	100.81	96.03	0.00	0.52	2.33	1.12
R02	Dhaleswari	90.267;23.758	25.96	88.97	1.67	3.01	0.00	6.35
R03	Dhaleswari	90.453;23.618	205.11	93.04	0.34	2.99	0.00	3.63
R04	Dhaleswari	90.52;23.568	32.55	39.18	0.54	8.65	35.68	15.95
R05	Dhaleswari	90.575;23.569	11.27	43.75	1.56	17.19	0.00	37.50
R06	Turag	90.348;23.858	67.72	90.35	0.27	8.97	0.41	0.00
R07	Turag	90.339;23.817	54.14	8.22	0.00	3.70	88.08	0.00
R08	Turag	90.335;23.769	54.57	64.10	4.33	20.35	11.22	0.00
R09	Turag	90.337;23.749	58.71	58.90	0.30	4.75	36.05	0.00
R10	Turag	90.407;23.707	120.44	76.02	0.14	1.38	20.43	2.03

Table 3. *Cont.*

Reach ID	River	Long;Lat	Drainage Area (km^2)	Arable %	Forest %	Grassland %	Urban %	Water %
R11	Turag	90.455;23.627	49.55	35.56	0.00	7.75	50.70	5.99
R12	Balu	90.462;23.847	48.17	90.55	0.00	9.09	0.36	0.00
R13	Balu	90.482;23.807	61.13	10.44	1.14	9.71	78.57	0.14
R14	Balu	90.478;23.784	38.20	74.43	2.49	23.08	0.00	0.00
R15	Balu	90.481;23.761	43.64	6.50	0.00	5.31	88.19	0.00
R16	Balu	90.504;23.716	49.36	3.72	0.00	0.35	95.40	0.53
R17	Balu	90.534;23.571	66.58	1.19	0.00	0.26	92.62	5.93
R18	Tongi	90.433;23.894	25.23	34.75	0.71	5.32	59.22	0.00
R19	Tongi	90.46;23.877	64.26	44.79	0.14	1.62	53.45	0.00
R20	Lakhya	90.502;23.722	84.97	59.88	0.20	2.56	32.34	5.02
R21	Turag	90.348;23.926	23.05	97.02	0.00	2.61	0.37	0.00
R22	Turag	90.338;23.98	5.00	100.00	0.00	0.00	0.00	0.00
R23	Turag	90.326;23.987	815.17	97.55	0.06	0.40	1.74	0.25
R24	Turag	90.211;24.082	57.53	99.70	0.00	0.30	0.00	0.00

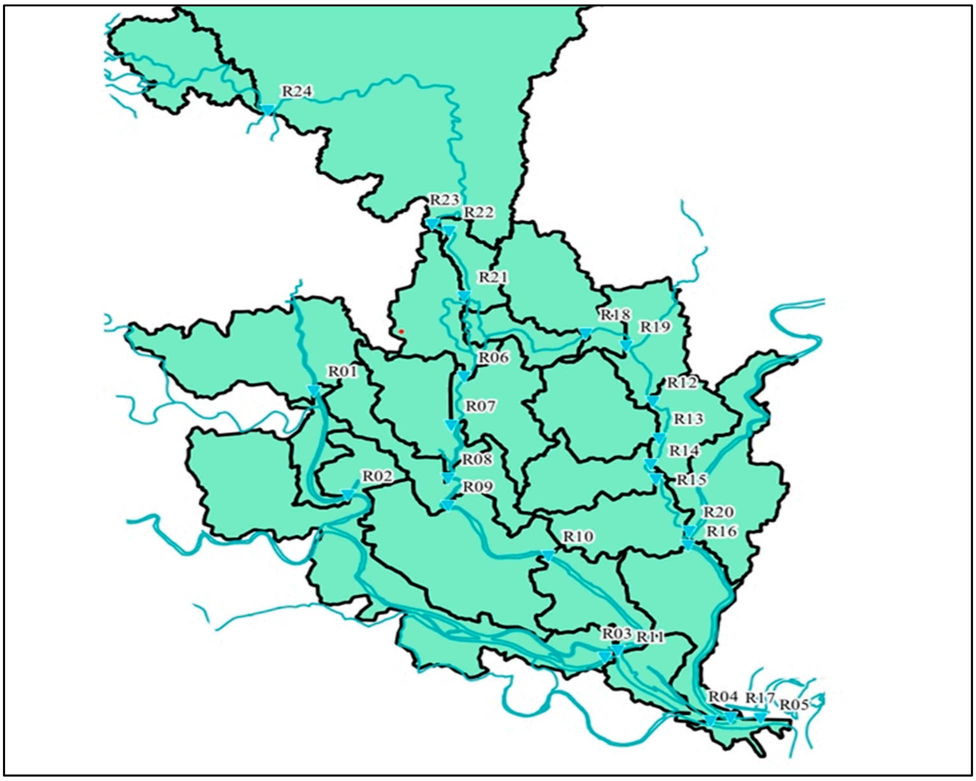

Figure 2. INCA structure for the Dhaka area with Reach Numbers.

Physical parameters were estimated for each reach and sub-catchment, such as reach length, sub-catchment drainage area, reach slope, river width, total population in the sub-catchment, and fractions of five main types of land use: arable, forest, grassland, urban, and water.

Dhaka river network receives water from rivers which are often connected to other river catchments (particularly the Brahmaputra River) and whose flow thus depends on the flow of these other rivers. Given that the focus of this study is to reproduce the in-stream urban water quality dynamics of the Dhaka area and not the rainfall-runoff processes in the rural area upstream Dhaka and its complex hydrographic network, six inlet points were identified, and the flow from these six inlet points was modelled by calibrating the corresponding sub-catchment areas so that the model was able to reproduce faithfully the flow at the Buriganga flow gauge.

The model was calibrated by manually adjusting its parameters to reproduce the observed water quality at several sampling points along the river network. A thorough description of the model parameters and the model result sensitivity to them is provided in [16]. The calibrated model was used to run three scenarios, as detailed in Table 4: a current scenario; a short-term scenario; and a medium-term scenario.

Table 4. Model scenarios considered in the present study.

Scenario	Reference Year	STPs	Climate	Population
Current	2020	Pagla (200 ML/d) Dasherkandi (400 ML/d)	Current, from ERA5-Land	Current
Short-term	2027	Pagla (400 ML/d) Uttara Mirpur Rayerbazar Dasherkandi (500 ML/d)	Current, from ERA5-Land	Current
Medium-term	2041	Savar Narayanganj Uttara Mirpur Rayerbazar Keraniganj Pagla (500 ML/d) Dasherkandi (500 ML/d) DND-Demra Tongi Gazipur Purbachal	Future: ERA5-Land climatology modified based on climate change scenarios for 2026–2055 and RCPs 2.6 and 8.5 Inflows modified based on literature studies on the impacts of climate change on the Brahmaputra River	Future (based on UN population prospects for 2041)

The three scenarios differ in terms of amount of STPs, and therefore amount of raw/treated wastewater discharged into the river network, in terms of climate (current/future) and in terms of population, and therefore in terms of effluent flow.

Regarding how STPs were incorporated into the modelling framework, the following assumptions were made. First of all, a maximum connection rate of 65% was considered, meaning that at least 35% of the wastewater produced by a sub-catchment served by an STP was discharged into the river network untreated, despite the existence of an STP. The 65% threshold was communicated by DWASA. Second, the treated effluent flow discharged by each STP into the river network was estimated as the maximum between the STP maximum capacity and the total connected effluent flow generated by the sub-catchment (i.e., 65% of the total effluent flow generated by the sub-catchment). The water quality of the treated effluent from STPs was set as the design standards from DWASA, although some modifications were introduced for phosphorus and nitrate. Phosphorus and nitrate were initially defined by DWASA to be 35 and 250 mg/L, respectively, however with the available technology nowadays much lower values are attainable. In order to analyse more realistic scenarios, the values in Table 5 were used.

Regarding future climate, daily precipitation and temperature values were derived, both for the historical period (1980–2004) and the future period (2026–2055, to represent the expected climate for the year 2041, which was chosen as a representative year for the operation of STPs planned for the medium term). Then, monthly precipitation and temperature correction factors were derived from the precipitation and temperature daily values from the model and applied to the observed precipitation and temperature time series derived from ERA5-Land [53]. In order to account for the impacts of climate change on the flows of the interconnections between the Brahmaputra River and the Dhaka River network, a literature review of the effects of climate change on the Brahmaputra flows was carried out. No clear trend could be identified. The authors of [19] found an increase in high flows and a slight decrease in March, April, and May. The authors of [54] reported that extreme low flow conditions are likely to occur less frequently in the future and an increase in high flows might be possible. The authors of [55] pointed to a decrease of 20% in mean upstream water supply, with the reduction in melt runoff partly compensated for by increased upstream rainfall. The authors of [56] found that mean monthly flows are likely to increase, while flood flows and low flows are projected to increase. Most of the literature agrees that peak flows will increase, while the effect on low flows is less clear, although most studies suggest an increase as well. Therefore, in this study, a scenario with an increase of 20% in flows from the Brahmaputra was explored.

Table 5. STP effluent design standard.

Variable	Value (mg/L)
Suspended sediment	100
Phosphorus	2
Dissolved oxygen	5
BOD	35
Nitrate	12
Ammonium	5

Regarding population growth, UN population prospects for Bangladesh were used to determine an increase in population, estimated at 16% by 2041, which was used to increase sub-catchment effluent flows for the medium-term scenarios.

4. Results

The model was calibrated against observations of flow and water quality where available. In terms of flow calibration, only one daily flow gauge was available, on the Buriganga River. The model results were evaluated in terms of the Kling–Gupta Efficiency [57] computed on the daily values of observed and simulated flow, and the result was 0.69, which indicates a good model performance. In terms of water quality, the available data were collected by BUET between 2019 and 2021 with a monthly sampling frequency. It must be noted that the observations available from these samples are instantaneous measures that are not necessarily representative of the average water quality of a given day in a given river reach, while the INCA model provides water quality estimates that are daily and averaged over the whole reach. To give anecdotical evidence of this issue, the variability in the measured water quality parameters of reach R11, on the Buriganga River, can be taken as an example. This reach includes four sampling points: Chandni Ghat, Sadar Ghat, Dholaikhal, and BCF Bridge. On 17 July 2021, the ranges of the water quality parameters spanned the following values: dissolved oxygen 2.4–3.6 mg/L, suspended solids 43–63 mg/L, ammonium 0.3–0.5 mg/L, nitrate 3.3–7.7 mg/L, phosphate 0.6–0.8 mg/L. On 15–16 February 2021, these ranges were: dissolved oxygen 0.46–0.76 mg/L, suspended solids 54–94 mg/L, ammonium 14–21 mg/L, nitrate 8.9–21.7 mg/L, phosphate 6.3–6.8 mg/L. This pattern was repeated throughout the whole river network and for all the sampling dates. Clearly, this large variability in the observed values of water quality has a great impact on model calibration and must be taken into account. While from one side these measurements are the only reference available to ensure the robustness and reliability of the model, from the other side an expert interpretation of them is essential, beyond the values of the goodness-of-fit indicators.

Table 6 provides values of daily KGE for phosphorus, dissolved oxygen, nitrate, and ammonium for all reaches where sampling points were available in sufficient number.

Table 6. Daily KGE values for different water quality parameters and for different reaches.

Reach	Phosphorus	Dissolved Oxygen	Ammonium
R04	0.47	0.72	0.68
R07	0.41	0.25	0.23
R11	0.66	0.23	0.37
R12	0.60	0.55	0.54
R13	0.56	0.18	0.55
R14	0.50	0.66	0.49
R17	0.59	0.66	0.47
R18	0.35	0.35	0.45
R19	0.68	0.35	0.46

The model generates good results for phosphorus concentrations. Phosphorus is also the water quality parameter with the smallest inter-reach and sub-daily variability according to the samples used in this study, and therefore the comparison measurements vs. modelled values is more meaningful compared to other water quality parameters. We evaluated the model accuracy using the Kling–Gupta Efficiency (KGE) rather than other metrics like Nash–Sutcliffe Efficiency (NSE) and Root Mean Square Error (RMSE) because KGE is effectively a decomposition of NSE into several components (correlation, variability bias, and mean bias), and thus it already includes other commonly used metrics. It also addresses several perceived shortcomings in NSE. KGE has been extensively used for model calibration and evaluation in the past 10 to 15 years.

In terms of dissolved oxygen, the results are in general acceptable, with some good values of KGE in the Turag River but also some less satisfactory results elsewhere. However, dissolved oxygen is considerably variable in time and space, and the fact that it often reaches zero or very small values during the dry season (dry season: November to March, both included) has a strong impact on the KGE values. A more meaningful visual fit is shown in Figure 3. Nitrate is the most variable parameter in terms of inter-reach and sub-daily variability, and therefore the KGE values might be influenced by the time and location of the samples. Nevertheless, some good results are reached, especially in the Turag River. In terms of ammonium reproduction, the model results are in general satisfactory.

Figures 3 and 4 show dissolved oxygen and nitrate concentration time series, respectively, from both the observations and the model results. These two variables are shown since they have the lowest KGE values in Table 6 but also the greatest variability in observed values. Figure 4 shows that, despite the KGE values being not satisfactory at times, the model is actually able to reproduce the observed dissolved oxygen concentrations relatively well, especially the dry season/wet season patterns, i.e., when oxygen levels drop to zero due to low flows in the river network and when they recover due to a sharp increase in upstream flow. The model is able to reproduce the dry season/wet season patterns, but the assessment of the model goodness-of-fit from these plots is not conclusive and this affects the uncertainty in the model results.

The calibrated model was used to assess water quality at different locations on the Dhaka Rivers. The selected locations are shown in Figure 5, along with the locations of current/planned STPs (see list in Table 2), which are useful to interpret the results. As detailed above, three scenarios were analysed: a current scenario (referred to as "2020" for simplicity, it considers only STPs already in place, current population, and current climate conditions), short-term scenario (referred to as "2027", it considers STPs already in place and planned for the short term, current population, and current climate conditions), and medium-term scenario (referred to as "2041", it considers all operational and planned STPs, population growth, and future climate conditions).

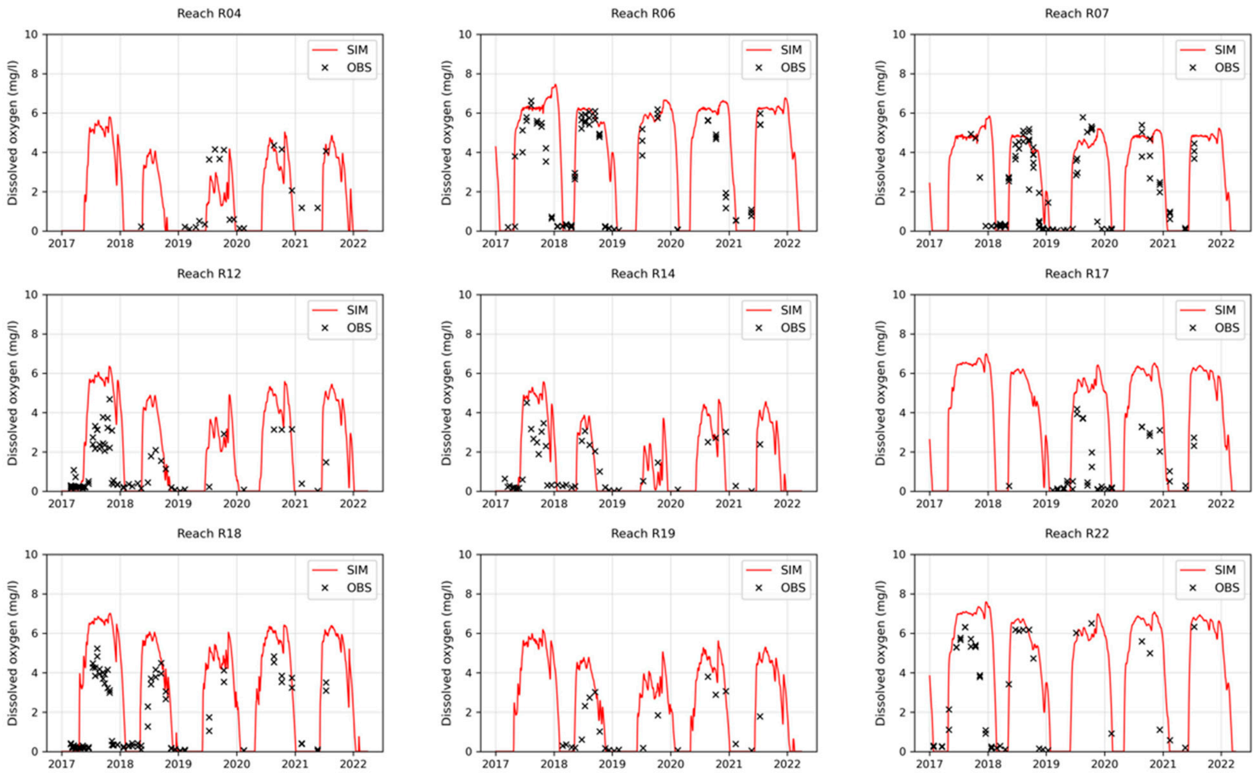

Figure 3. Observed and simulated time series of dissolved oxygen concentration at selected locations within Dhaka River network.

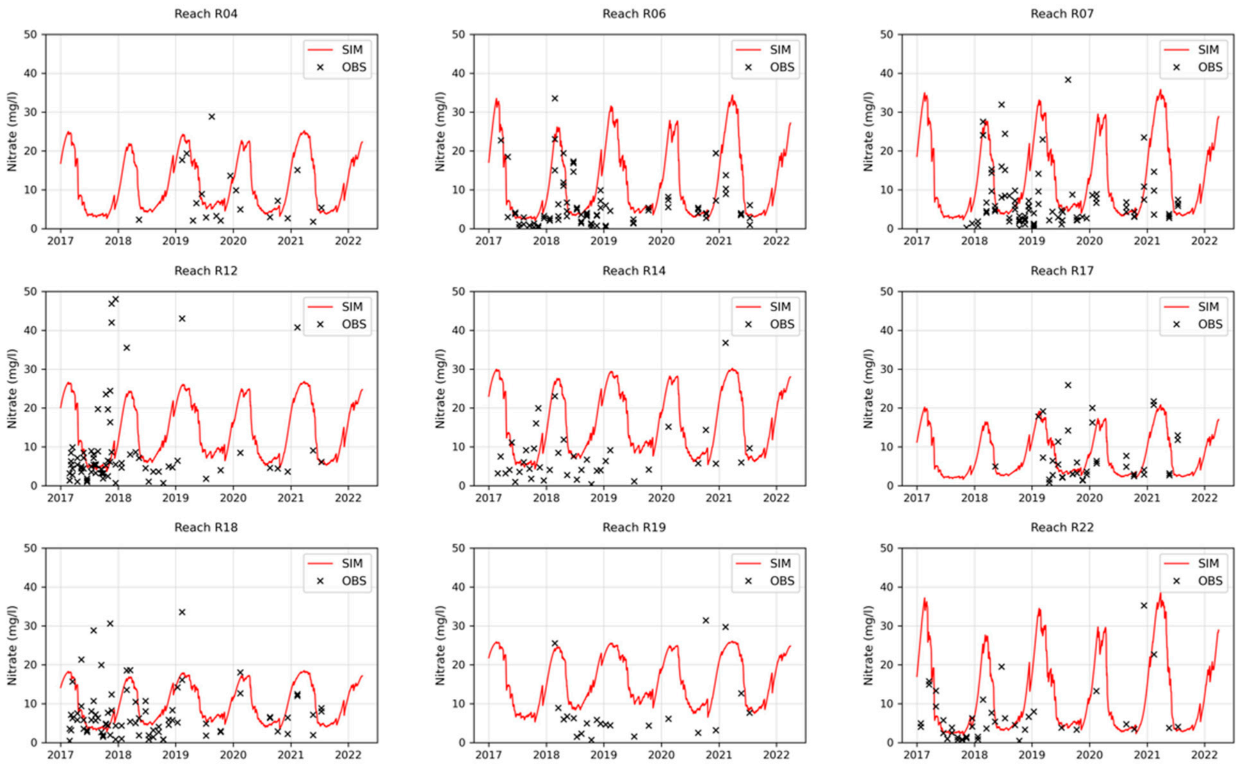

Figure 4. Observed and simulated time series of nitrate concentration at selected locations within Dhaka River network.

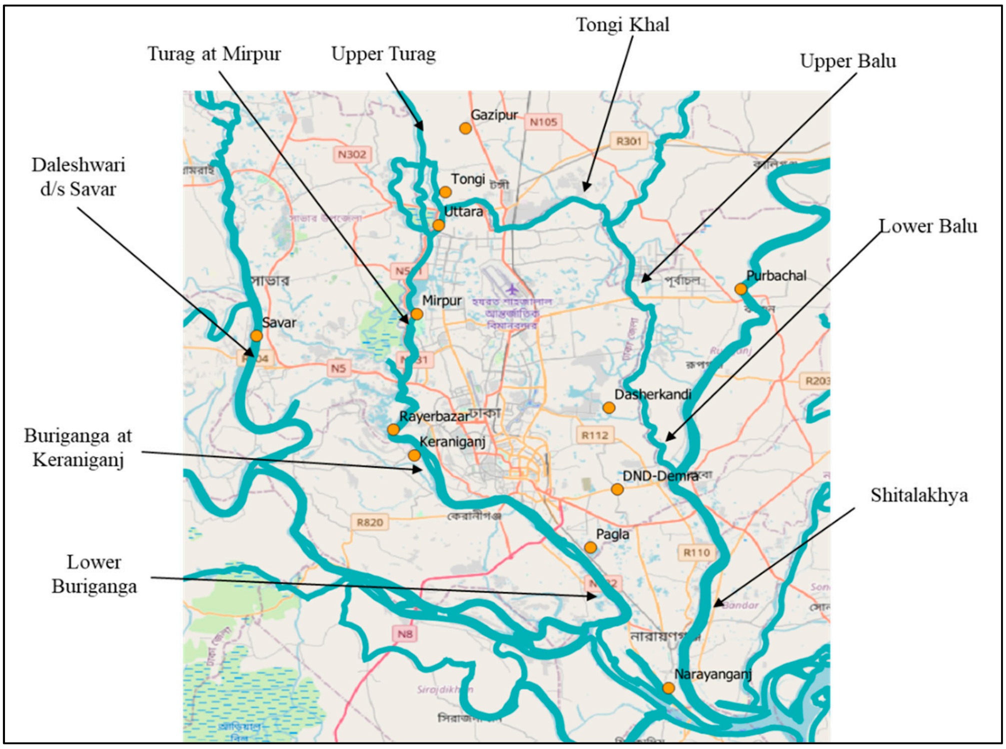

Figure 5. Location of the sections for which the scenario model results are shown, together with the location of the existing and planned STPs (orange solid circles).

Figures 6 and 7 show the distribution of the value of phosphorus concentration (Figure 6) and dissolved oxygen (Figure 7) at the nine locations shown in Figure 5 under the three scenarios considered. In this figure, the impact of planned STPs can be easily identified by comparing visually boxes and whiskers corresponding to different scenarios. Note: The diamonds in the figures represent the standard of box-and-whisker plots (https://en.wikipedia.org/wiki/Box_plot, accessed on 22 July 2023). Diamonds are the outliers, i.e., the data points that are on the tails of the distribution. In particular, in the boxplots in Figures 6 and 7 data points are classified as outliers if they are outside the range of Q1-1.5*IQR to Q3+1.5*IQR, where Q1 is the first quartile, Q3 the third quartile, and IQR the interquartile range.

Water quality in a reach can be improved by wastewater treatment, and therefore can be related to an STP. In some cases, climate change can also improve the water quality by increasing flows (this is only considered in the 2041 scenario). Reasons for deterioration are the increase in population, which increases the effluent loads; effluent discharge in a previously unpolluted reach (or a reach with low pollution); and climate change (only considered in the 2041 scenario), if it decreases the flows in the reach. It is important to note that the impact of STPs is not necessarily always positive: if the treated effluent from an STP is discharged into a river whose concentration of a certain water quality parameter is already lower than the design standard, the effect of the STP on that river will be negative (clearly, this occurs only when the river is not highly polluted, and therefore it does not represent an issue in terms of impacts on population).

In the short term, improvements in phosphorus and dissolved oxygen concentration can be seen in the Turag-Buriganga system, thanks to the Uttara, Mirpur, and Rayerbazar STPs, while in the rest of the river network the distributions of phosphorus and dissolved oxygen concentration remain the same. In the medium term, improvements can be seen in the Tongi Khal, upper Turag, the Balu, and the Shitalakhya. However, water quality worsens in the Turag-Buriganga system, mainly due to population growth. An interesting feature shown by Figures 6 and 7 is that STPs combined with population growth can have different impacts on the median values and on the water quality concentration peaks.

Table 7 shows the median concentration values and 90th percentile values for phosphorus, BOD5, dissolved oxygen, nitrate, and ammonium under the 2020 scenarios, and their variations under the 2027 and 2041 scenarios, for the nine locations in Figure 5. As opposed to Figures 6 and 7, which show the distribution of water quality parameters based on values all-year round, Table 7 values are computed based only on water quality parameter values for the dry season, i.e., from November to March, both included. In the dry season, water quality issues in Dhaka are exacerbated by the very strong reduction in river flows (sometimes even absence of flow), and therefore the assessment of dry season concentrations can paint a different picture compared to the all-year round values. In Table 7 cells in blue indicate an improvement in water quality (defined as a variation smaller than −20% in median/90th percentile concentrations of phosphorus, BOD5, nitrate and ammonium or a variation greater than 20% in median/90th percentile concentration of dissolved oxygen), while cells in orange indicate a deterioration in water quality (defined as a variation greater than +20% in median/90th percentile concentrations of phosphorus, BOD5, nitrate, and ammonium or a variation smaller than −20% in median/90th percentile concentration of dissolved oxygen).

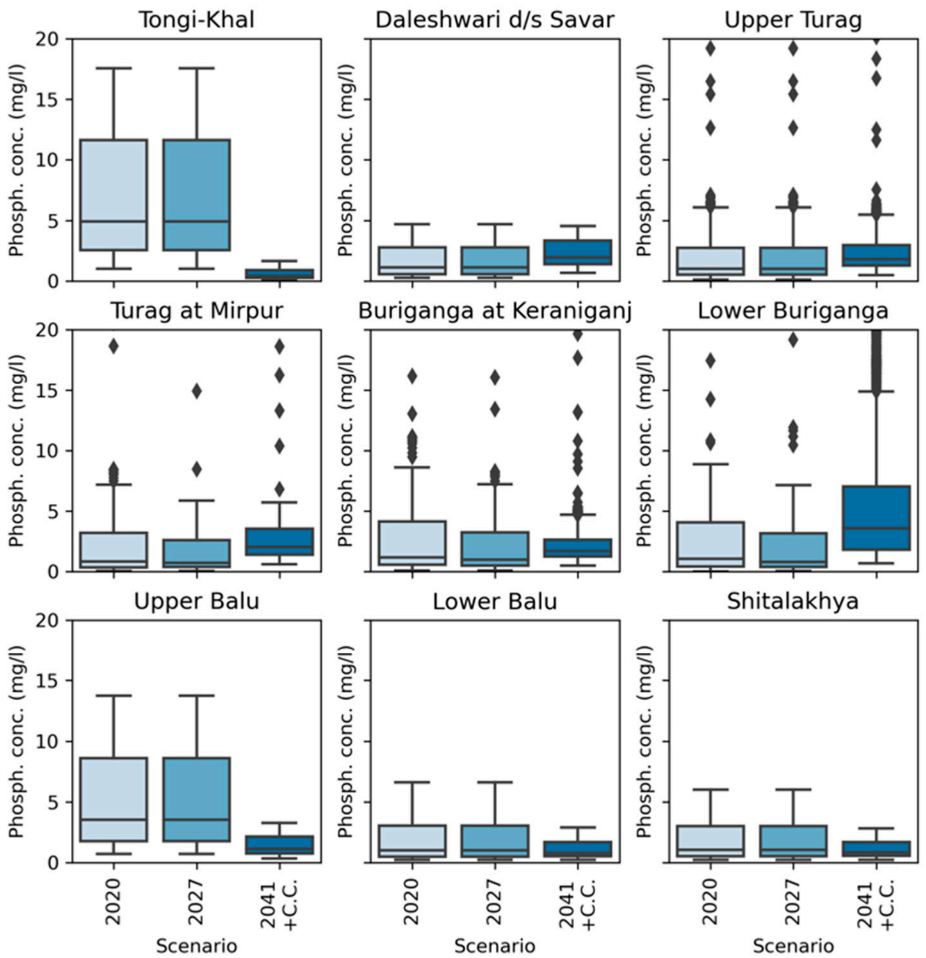

Figure 6. Distribution of the phosphorus concentration values at the nine river sections analysed here across the three scenarios considered.

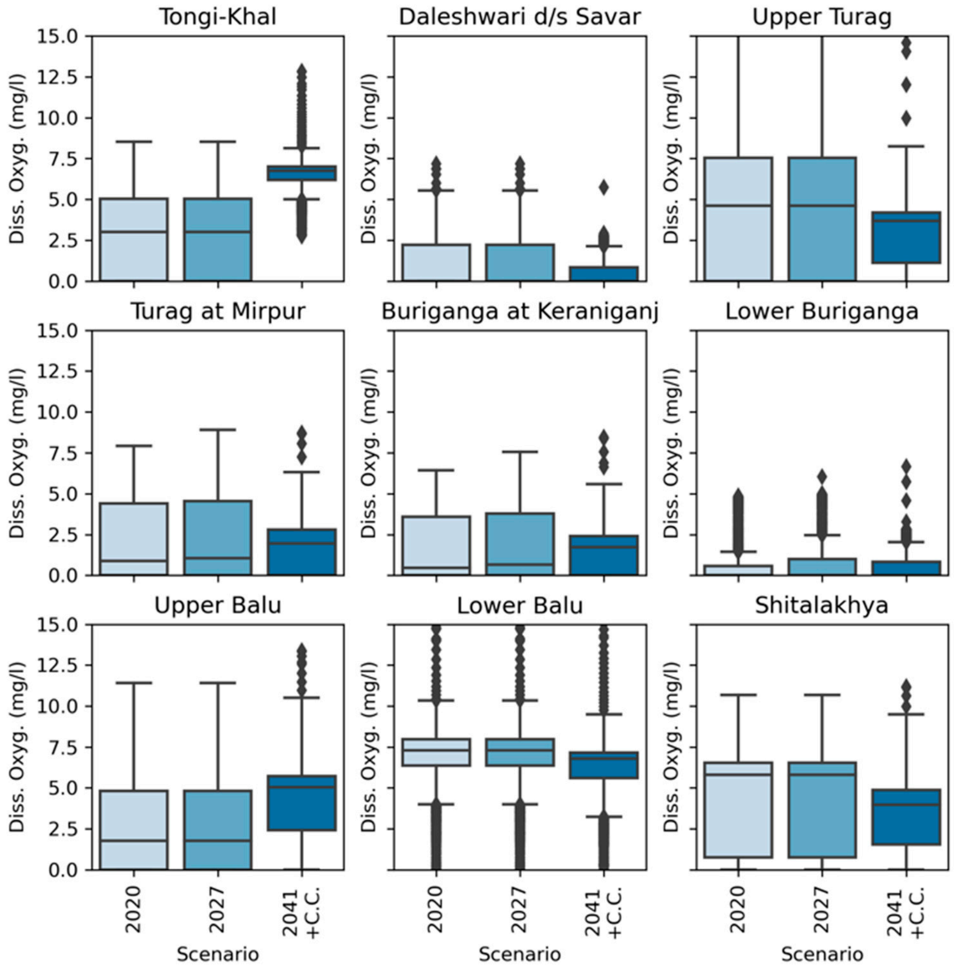

Figure 7. Distribution of the dissolved oxygen concentration values at the nine river sections analysed here across the three time horizons considered.

Table 7. Dry season (November to March) median values and 90th percentile values (both in mg/L) of phosphorus, BOD5, dissolved oxygen, nitrate, and ammonium concentration under current climate and population and expected delta change (in mg/L) in 2027 (considering planned short-term STPs) and in 2041 (considering planned medium-term STPs, climate change, and population growth). Table cells in blue indicate an improvement larger than 20% in water quality, while table cells in orange indicate a deterioration larger than 20% in water quality.

		Values in mg/L Referred to the Dry Season (November to March)					
Water Quality Parameter	**Reach**	**2020 (Median Value)**	***2027 (Median Value Delta Change)***	***2041 (Median Value Delta Change)***	**2020 (90th Percentile)**	***2041 (90th Percentile Delta Change)***	***2027 (90th Percentile Delta Change)***
		mg/L	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
Phosph. Conc. (mg/L)	Buriganga at Keraniganj	2.6	−0.6	0.5	6.8	−1.5	−1.2
	Dhaleswari d/s Savar	2.4	0.0	0.8	3.8	0.0	0.3
	Lower Balu	2.6	0.0	−1.0	4.7	0.0	−2.3
	Lower Buriganga	2.5	−0.6	2.6	6.5	−1.5	16.6
	Shitalakhya	2.5	0.0	−1.0	4.4	0.0	−2.1
	Tongi-Khal	11.0	0.0	−10.1	15.1	0.0	−13.8
	Turag at Mirpur	1.9	−0.1	1.4	5.5	−1.0	0.2
	Upper Balu	7.4	0.0	−5.4	11.3	0.0	−8.4
	Upper Turag	2.2	0.0	0.6	4.8	0.0	0.0

Table 7. *Cont.*

		Values in mg/L Referred to the Dry Season (November to March)					
Water Quality Parameter	**Reach**	**2020 (Median Value)**	***2027 (Median Value Delta Change)***	***2041 (Median Value Delta Change)***	**2020 (90th Percentile)**	***2041 (90th Percentile Delta Change)***	***2027 (90th Percentile Delta Change)***
		mg/L	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
BOD5 (mg/L)	Buriganga at Keraniganj	15.9	−5.4	−8.4	27.7	−9.9	−13.4
	Dhaleswari d/s Savar	41.3	0.0	201.6	176.8	0.0	219.4
	Lower Balu	48.8	0.0	−5.2	70.2	0.0	35.6
	Lower Buriganga	3.4	−0.6	−1.5	9.1	−2.7	−4.1
	Shitalakhya	5.6	0.0	−2.6	8.6	0.0	−2.5
	Tongi-Khal	46.6	0.0	−45.9	112.5	0.0	−111.7
	Turag at Mirpur	8.0	−5.0	0.6	17.4	−10.7	−0.2
	Upper Balu	23.4	0.0	−15.4	75.6	0.0	−63.8
	Upper Turag	4.7	0.0	−1.1	18.7	0.0	−6.9
Diss. Oxyg. (mg/L)	Buriganga at Keraniganj	0.0	0.0	0.0	0.0	0.0	0.0
	Dhaleswari d/s Savar	0.0	0.0	0.0	0.0	0.0	0.0
	Lower Balu	8.1	0.0	−1.3	3.6	0.0	−1.2
	Lower Buriganga	0.0	0.0	0.0	0.0	0.0	0.0
	Shitalakhya	4.0	0.0	−1.3	0.0	0.0	0.0
	Tongi-Khal	0.0	0.0	6.9	0.0	0.0	5.0
	Turag at Mirpur	0.0	0.0	0.0	0.0	0.0	0.0
	Upper Balu	0.0	0.0	4.4	0.0	0.0	0.8
	Upper Turag	0.7	0.0	1.5	0.0	0.0	0.0
Nitrate (mg/L)	Buriganga at Keraniganj	18.0	−3.1	1.9	25.7	−4.2	−0.3
	Dhaleswari d/s Savar	13.0	0.0	2.3	18.4	0.0	0.3
	Lower Balu	6.8	0.0	−1.1	10.9	0.0	−3.1
	Lower Buriganga	17.7	−3.1	1.7	25.0	−4.2	−0.5
	Shitalakhya	7.8	0.0	−1.8	12.0	0.0	−3.9
	Tongi-Khal	15.1	0.0	−7.8	18.0	0.0	−8.7
	Turag at Mirpur	15.3	−2.0	4.0	22.8	−2.8	2.1
	Upper Balu	15.9	0.0	1.3	20.5	0.0	1.4
	Upper Turag	13.5	0.0	4.6	21.2	0.0	2.6
Ammon. (mg/L)	Buriganga at Keraniganj	5.7	−1.6	−0.2	8.2	−2.3	−1.0
	Dhaleswari d/s Savar	5.5	0.0	1.2	7.8	0.0	0.4
	Lower Balu	3.7	0.0	−1.4	6.1	0.0	−2.9
	Lower Buriganga	5.6	−1.6	−0.2	8.0	−2.2	−1.0
	Shitalakhya	4.3	0.0	−1.8	6.9	0.0	−3.3
	Tongi-Khal	13.3	0.0	−10.5	15.9	0.0	−12.3
	Turag at Mirpur	3.9	−1.0	0.9	5.8	−1.4	0.5
	Upper Balu	11.6	0.0	−3.2	15.0	0.0	−4.3
	Upper Turag	2.6	0.0	0.9	4.2	0.0	0.5

From Table 7, for phosphorus and ammonia in certain reaches the beneficial effect of improved sewage treatment is offset by population growth and effluent discharge. However, it must be noted that most of such reaches are the ones where phosphorus and ammonia concentrations are already relatively low and, thus, similar to the design standards used in this study. For example, the Turag, Buriganga, and Dhaleswari Rivers show median concentrations of phosphorus very close to 2 mg/L and ammonium concentrations very close to 5 mg/L used as design standards. One thing to note is that though industrial growth is considered, improved industrial technologies to come in the future are not taken into consideration here. According to the River Master Plan 2019 [58], there are several projects going on such as Partnership for Cleaner Textile 2, Zero Discharge of Hazardous Chemical, Green Industry Development Cell, etc., the outcome of which will reduce the effluent load hopefully [58].

The model results suggest that the STPs are more efficient in reducing high pollutant loads than in reducing median values of water quality parameters. In very few cases, the 2040 scenario shows deterioration of the water quality if the metric used is the 90th percentile, while if the median concentration is used as a reference, the resulting picture is mixed, with some reaches improving and some deteriorating.

5. Discussion

The model presented here shows in general good results with a few local exceptions. The KGE values obtained for water quality are in line with or slightly better than other applications of the INCA model [16,49,59,60] and other models [61,62]. It is important to note that the KGE values presented in this paper were calculated on water quality concentrations rather than loads, and this in general tends to return worse goodness-of-fit indicators. It is also relevant to mention that the model was evaluated for its ability to reproduce daily water quality concentrations, but then it was mostly used to determine long-term average concentrations of pollutants. It is reasonable to assume that if a model is able to reproduce satisfactorily daily concentrations, its performance in reproducing long-term water quality average values will be far superior (although this cannot be verified as long-term water quality average concentrations are not available, neither in Dhaka nor elsewhere).

The Dhaka Sewerage Master Plan [12] foresees the construction of three new STPs (Uttara, Mirpur, Rayerbazar) and the expansion of two existing STPs (Pagla, Dasherkandi) in the near future. All STPs apart from Dasherkandi serve areas drained by the lower Turag-Buriganga rivers, where the most densely populated areas of Dhaka lie. Logically, the most noticeable impacts of the short-term scenario are on the lower Turag-Buriganga system: a slight decrease in phosphorus concentration, in particular, during the dry season (to an average concentration lower than 2 mg/L), strong decrease in BOD5 concentration (in some reaches BOD5 concentrations lower by around 50%), and moderate decreases in ammonium concentration (reaching dry season average value below 4 mg/L). Regarding dissolved oxygen, concentrations in these rivers are so low (actually, the dry season average concentrations are nearly zero) that the impact of the new STPs is barely noticeable. The fact that the flow in these rivers during the dry season is very small contributes to the very low dissolved oxygen concentrations. However, there are several ongoing flow augmentation projects like the Buriganga Restoration Project and canal development projects, the results of which could not be quantified and accounted for in this study [58]. Other rivers in the Dhaka River System are obviously unaffected by the short-term scenario. Dasherkandi STP, on the lower Balu, is expected to be expanded, and this is taken into account in the present study, but its expansion is relatively small compared to the scale of the pollution in the river and the effluent loads from the area, and therefore the effects are not noticeable in the short term.

For the second phase of STP implementation (i.e., the medium-term scenario analysed in this study), the Dhaka Sewerage Master Plan foresees the implementation of the following STPs: Savar (upper Dhaleswari River), Narayanganj (lower Dhaleswari River), Keraniganj (Buriganga River), DND-Demra (lower Balu-Shitalakhya Rivers), Tongi (Tongi Khal canal), Gazipur (upper Turag River, Tongi Khal canal), Purbachal (Shitalakhya River). The medium-term scenario thus expands the systematic sewage water treatment to the whole Dhaka area. However, the effects are mixed. In terms of phosphorus concentration, the impacts are very positive on the highly polluted Tongi Khal canal, especially during the dry season, and on the Balu-Shitalakhya system, but are much less significant on the upper Dhaleswari and the upper Turag. Surprisingly, in the lower Buriganga the phosphorus concentrations are expected to increase due to population growth (the lower Buriganga drains the most densely populated areas of the city). This suggests that, even if the Turag-Buriganga system is the main target of the Master Plan, with five new STPs, population growth and increased industrialisation might render these efforts locally ineffective. In terms of dissolved oxygen, most benefits can be found in the Tongi Khal, the upper Turag, and the upper Balu, while in other reaches the changes are of little significance. In terms of BOD5, the impacts are positive almost across the entire river network, while in terms of ammonium they are largely positive on the Tongi Khal, the Buriganga River, the Balu River, and the Shitalakhya River. Nitrate impacts are smaller than impacts on other water quality parameters, due to nitrate levels not being extremely high in the Dhaka Rivers, probably because diffuse pollution from agricultural areas upstream of the city is limited.

This study also attempts to provide an assessment of the impacts of climate change on water quality. While this task is very much uncertain, it is certainly unavoidable to include changes in climate into the picture. In this study, two types of changes were considered: (a) local changes, which were summarised as changes in local precipitation and temperature, and (b) large-scale changes, summarised as changes in the flows from the Brahamputra River into Dhaka. In terms of local changes, different models provide quite different assessments: the RegCM4 + HadGEM2-ES models forecast a sharp increase in temperature for the months of February, March, April, and May, up to 4 degrees, and a decrease for the months of August, September, and October, up to −4 degrees. RegCM4 + NorESM1-M forecast a sharp increase for January, February, and March (+4 °C) and a decrease in October and November (1–2 °C). Regarding precipitation, RegCM4 + HadGEM2-ES predict a very large increase in average monsoon rainfall (May, June, and July), while RegCM4 + NorESM1-M predict a small increase in the first six months of the year and a small decrease in the rest of the year. For both models, results are very similar under RCP4.5 and RCP8.5 scenarios. In terms of net impact of local climate change, these changes translate into very small impacts. The increase in precipitation causes a greater dilution capacity of the rivers, thus decreasing pollutant concentrations, but changes are in the order of 5%, because the runoff from the city of Dhaka only constitutes a small part of the total discharge of the Dhaka Rivers, which are fed by flows from the Brahmaputra. However, it is impossible to predict the effect of climate change on flows in networks linking the main Brahmaputra River with the city of Dhaka, due to the enormous complexity of the channel network and the flatness of the terrain. Previous studies on the flows of the Brahmaputra paint a mixed picture and there is no consensus on how this river will change its flows in the future. The most recent studies [19,54–56] generally indicate that flows are not expected to decrease; thus, it is reasonable to assume that the dilution capacity of the Dhaka Rivers will not decrease.

Finally, some limitations to the findings of this study need to be highlighted. The first one is certainly the model uncertainty. Sources of uncertainty are multiple: the complexity of the river network and its links with the Brahmaputra, the uncertainty in precipitation and temperature data from both reanalysis and climate scenarios, the variability of water quality process, reflected in the variability of observed data, etc. The goodness-of-fit analysis provided in this paper can assist in determining, at least qualitatively, the levels of uncertainty. The model seems to be working better for phosphorus and ammonium and, on a lesser extent, for dissolved oxygen. Nitrate results are probably the ones most affected by uncertainty, although nitrate levels in Dhaka are less worrying than other pollutants. Another source of uncertainty is population and industrial growth with technological advancements. Population dynamics and industrialisation follow patterns that are partly governed by unforeseeable factors, yet they are proven to be a fundamental driver of water quality changes. Results of ongoing projects aiming at reducing effluent loads could not be quantified and taken into consideration. Therefore, the results of this study will need to be updated if the population and industrialisation trends are going to be different than the ones assumed here. Several ongoing flow augmentation projects will also result in increased flow and, thus, decreased pollutant concentration. Furthermore, the results of this paper are strongly affected by the assumptions made in terms of STP design standards. If different standards were to be employed, certain figures would undoubtedly change. For example, if phosphorus stripping technologies were to be implemented in the new STPs, phosphorus effluent concentrations would decrease from around 2 mg/L to something in the order of 0.3 mg/L, with evident impacts on the phosphorus concentration of the rivers in Dhaka. Lastly, this study assumed a rate of domestic and industrial connection equal to 65%, as suggested by DWASA. However, if this rate was to be improved, the impact of the construction of new STPs on river water quality would certainly be much more beneficial.

Another thing to note is that though industrial growth is considered, improved industrial technologies to come in the future are not taken into consideration here. According to the River Master Plan [12], there are several projects going on, like Partnership for Cleaner Textile 2, Zero Discharge of Hazardous Chemical, Green Industry Development Cell, etc., the outcome of which will reduce the effluent load hopefully [12]. The ongoing cleaner production drive within BGMEA- and BKMEA-registered industries, along with their synergistic relationship with the 3R (Reduce, Recycle, Reuse) strategy undertaken by the Department of Environment as entailed under the National Environmental Policy 2018 [63], are reportedly having an impact on pollution through lesser pollution load per unit production. However, in the absence of a detailed report on the present status or a pollution load database per se, the current study adopted a steady industrial pollution load which obviously would present a relatively conservative assessment of pollution reduction. A more detailed assessment can be carried out in case such data become available.

6. Conclusions

In this paper, the INCA multi-branch water quality model was employed together with direct measurements of hydrometeorological variables, climate change scenarios, and population projections with the aim of assessing the impacts of the development of multiple STPs in the city of Dhaka (Bangladesh). It is difficult to understate the relevance of this development plan for a megacity of more than 20 million inhabitants, most of whom have low incomes and are highly vulnerable to pollution, especially women and children. People are deeply intertwined with the river network, living with rapid industrialisation and with one of the highest levels of water pollution in the world [4]. The results of the present analysis show that the plan, although certainly ambitious and highly beneficial for the city of Dhaka, might underperform compared to the expectations due to population increase and misconnections (i.e., raw effluent still discharged into the river network despite the existence of an STP in the area).

While some rivers are expected to see a significant water quality improvement in the short term (e.g., Turag and Buriganga) and in the medium term (e.g., Tongi Khal and Lower Balu), others might still have very poor water quality even after the implementation of the whole plan, especially during the dry season. Population increase is the main driver of future change and must be considered very carefully in the design of new STPs, together with the expansion of industry. It is prudent to assume that industrial growth, if not accompanied by advanced production techniques and better functioning treatment systems, would mean no significant reduction in pollution load and would exacerbate the pollution scenario improvement of production systems aiming for lesser water usage and lesser pollutant generation; the adoption of state-of-the-art ETPS/CETPs are thus essential. Good quality data with adequate spatiotemporal resolution are essential for any proper modelling exercise for future scenarios, as could be evidenced in the higher uncertainty levels for certain parameters modelled. Climate change is expected to have a minor role compared to population increase as a driver of future pollution, although the large uncertainty in the estimation of the connection flows from the Brahmaputra to the Dhaka network suggests caution in the interpretation of this conclusion.

Finally, we suggest some recommendations that arise from this work, as follows:

1. Install P stripping reductions at all STPs to help reduce phosphorus concentrations, restore ecology, and to control eutrophication going forward.
2. Bring forward the building of the Tonge Khal STP so that there is an earlier impact, i.e., by 2030 instead of 2041.
3. Ask the industry to match government efforts to improve effluent treatment at their factories.
4. Increase dilution and flushing in low flow periods via canal transfers from Brahmaputra.

5. Increase monitoring of chemistry and ecology so that the government can observe improvements over time and install some automatic water quality monitoring systems in the river to enhance understanding and control.
6. Restore and expand the Savar tannery treatment STPs so it can treat all the waste from the tanneries.
7. Devise ways to remove contaminated sediments from the Buriganga, Tongi Khal, Turag, and Dhaleswari, followed by safe disposal of such waste to ensure reduced legacy. This will ensure a more effective clean up result from the planned STPs.

Author Contributions: Conceptualisation, P.G.W. and M.A.H.; methodology, P.G.W., M.A.H. and G.B.; software, G.B.; validation, G.B. and L.J.; formal analysis, P.G.W., G.B. and S.S.; investigation, S.S. and G.B.; resources, P.G.W.; data curation, G.B.; writing—original draft preparation, G.B. and P.G.W.; writing—review and editing, S.S., M.A.H. and L.J.; visualisation, G.B.; supervision, P.G.W. and M.A.H.; project administration, P.G.W.; funding acquisition, P.G.W. and M.A.H. All authors have read and agreed to the published version of the manuscript.

Funding: Funded by UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO) for the benefit of developing countries (Programme Code 201880).

Data Availability Statement: Data are available from Prof P G Whitehead or Prof Abed Hossain.

Acknowledgments: This document is an output from the REACH programme funded by UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO) for the benefit of developing countries (Programme Code 201880). However, the views expressed, and information contained in it, are not necessarily those of or endorsed by the FCDO, which can accept no responsibility for such views or information or for any reliance placed on them. We acknowledge the World Climate Research Programme's Working Group on Regional Climate, and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. We also thank the climate modelling groups (UK Met Office Hadley Centre and Norwegian Climate Centre) for producing and making available their model output. We also acknowledge the Earth System Grid Federation infrastructure, an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling, and other partners in the Global Organisation for Earth System Science Portals (GO-ESSP).

Conflicts of Interest: The authors declare no conflict of interest.

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