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Sustainability Assessment Model of the Buriganga River Restoration Project in Bangladesh: A System Dynamics and Inclusive Wealth Study

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Abstract: The Bangladesh government initiated the Buriganga River Restoration Project in 2010 to clean the heavily polluted Turag-Buriganga River. This study assessed the dynamic impact of the project on intergenerational well-being and developing a sustainable river system. The project outcomes were modeled for three future scenarios—varying waste control, streamflow, and migration control levels. System dynamics modeling—based on Streeter-Phelps' water quality model and inclusive wealth (IW) index—was applied to secondary data (including remotely sensed data). The simulation model indicated that the project (with increasing streamflow up to 160 m^3/s) will not ensure sustainability because dissolved oxygen (DO) is meaningfully decreasing, biological oxygen demand (BOD) is increasing, and IW is declining over time. However, sustainability can be achieved in scenario 3, an integrated strategy (streamflow: 160 m^3/s, waste control: 87.78% and migration control: 6%) that will ensure DO of 8.3 mg/L, BOD of 3.1 mg/L, and IW of 57.5 billion USD in 2041, which is equivalent to 2.22% cumulative gross domestic product by 2041. This study is the first to use combined modeling to assess the dynamic impacts of a river restoration project. The findings can help policymakers to achieve sustainability and determine the optimal strategy for restoring polluted rivers.

Keywords: water quality; human capital; natural capital; produced capital; dissolved oxygen; biological oxygen demand

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1. Introduction

A sustainable river system can provide vital economic, ecological, and social goods and services that sustainable development depends on. Hence, river restoration has become a global phenomenon as well as a highly profitable business [1,2] and restores a river system to its healthy state, thereby benefiting society [3]. Such programs are widely used to ensure river system sustainability, which maintains standard water and provides non-declining inclusive benefits over time [4].

Bangladesh is a riverine country located at the lowermost reaches of three mega rivers (1.72 million km^2): the Ganges, Brahmaputra, and Meghna. The country has four major and highly dynamic river systems: the Brahmaputra-Jamuna, Ganges-Padma, Surma-Meghna, and Chittagong region [5]. It has around 700 rivers and tributaries, comprising one of the world's largest river networks (24,140 km) [6]. These river systems have a remarkable bearing on people's lives and livelihoods. According to Hasan (2020), 60% of the population depends on river systems for their animal protein, and river fisheries and freight traffic contributed 3.61% and 0.64% to GDP, respectively [7]. However, irresponsible anthropogenic activities over the last 40 years have contaminated most river systems [8,9], which explains the popularity of river restoration projects in Bangladesh.

The Turag-Buriganga River, which flows through the capital Dhaka, is among the most important river systems in Bangladesh. It is pivotal to the socio-economic and environmental development of Dhaka [3], which contributes 40% to the GDP of Bangladesh [10]. However, given the water pollution caused by unplanned anthropogenic activities, the river body had a dissolved oxygen (DO) value below 3 mg/L and a biochemical oxygen demand (BOD) value above 34 mg/L in 2020 [11,12]. Furthermore, Khorshed and Marinova conducted a cost-benefit analysis of this river system in 2006 and highlighted that this polluted river system incurred a loss of 79.36 million USD due to the loss of socio-economic-environmental benefit [13]. Moreover, issues associated with polluted rivers, such as the spread of water-borne diseases, property value reduction, natural resource destruction, and unsustainable development, are also rampant [8].

Hence, the Bangladesh government initiated a river restoration program, the "Buriganga River Restoration Project", in 2010 to address the Turag-Buriganga River system water pollution [14] and increase the DO value above 4 mg/L by increasing streamflow from 5 m^3/s to 160 m^3/s. A successful restoration project is vital for sustainable development in Bangladesh, and it must be evaluated holistically and dynamically. However, policymakers have not conducted a dynamic assessment of the impact of this project. They have not analyzed the impacts of increasing river water pollution to determine water quality over time. They have also not considered feedback from and interaction of different sub-systems that affect the project and how assets are changing based on these feedbacks and interactions. Furthermore, they have not evaluated the intergenerational well-being of society as an outcome of the project [14,15]. Such issues must be analyzed to assess the sustainability of the project. For instance, combining comprehensive metric and system-based modeling would efficiently help determine the impacts while accounting for dynamic, multiple feedback, and coupling among different components [16]. Therefore, this study employed a combined modeling approach based on the inclusive wealth (IW) index (IWI) (an evaluation criterion for tracking intergenerational well-being), the Streeter-Phelps' model (a pioneer water quality model for rivers), and system dynamics (SD) (a tool for sustainability assessment through model building).

The United Nations University's International Human Dimensions Programme (UNU-IHDP) on Global Environmental Change and the United Nations Environmental Programme (UNEP) developed the IWI to estimate national, systemic, and regional intergenerational well-being and sustainability in 2012. It is the sum of the produced, human, and natural capital assets of a society [17]. Project evaluation based on three capital assets and IW might guide the transition toward sustainability. IW (GDP) tracks sustainability based on stocks (flow) [17]. It indicates the true assets or combined capital stocks of society, which are estimated based on shadow prices. It has three main features: an integrated index to evaluate human, natural, and produced capital wealth; sustainability evaluation internalization by measuring stocks; and analysis of trade-offs among capital assets. There are several other indicators for sustainability evaluation, such as GDP, green GDP, human development index (HDI), genuine progress indicator, ecological footprint, Happy Planet Index, environmental sustainability index, and environmental performance index [18]. However, they are limited in that they cannot capture holistic dimensions of sustainability. For example, GDP and green GDP do not consider negative externalities and all types of environmental damage, ecological footprint does not cover economic and social dimensions, and HDI does not include any nature aspect [18–22]. IWI considers various types of external factors and three dimensions of sustainability, and it can address the mismeasurement of development, which is estimated via conventional GDP [16].

SD is a computer-aided approach for representing a complex system and analyzing its dynamic behavior based on evolving cause-effect interrelations and information feedback [23]. Though project evaluations employ cost-benefit analysis and mathematical models, such methods lack a dynamic view when used by themselves as they do not consider multiple feedbacks and interrelations among system components. Hence, SD is more suitable to assess impacts, considering the interdisciplinary dynamics of the system [24]. Combined SD-IWI modeling could help assess the sustainability of the project, given multiple feedback and interrelations among different system components [25].

Several approaches have been employed to assess the sustainability of river restoration projects. Based on their sustainability purposes, they can be categorized into socio-economic, environmental, and socio-economic-environmental approaches. Cost-benefit analysis is the most widespread method to assess the socio-economic sustainability of a project [26–28]. However, it is static and ignores coupling relations among factors [24]. Economic impact assessment software (e.g., IMPLAN), based on input-output tables, is employed to estimate the direct and indirect impacts of river restoration programs [29,30]. Nevertheless, this approach does not consider the environmental aspects of a project. Cha et al. (2011) assessed only the environmental sustainability of a river restoration project for water quality development based on survey monitoring [31].

There are many model-based assessments, and among them, the SD model is prevalent in the water resources sector [32]. For instance, Bakhshian-lamouki et al. (2020) developed an SD model to assess the impacts of Urmia Lake restoration measures in Iran [33]. Similarly, Crookes et al. (2013) constructed an SD model to evaluate the economic viability and risk balance of ecological restoration programs in South Africa [34]. However, these studies covered specific strategies without accounting for IW-based sustainability. Therefore, combined SD-IWI modeling is an innovative socio-economic-environmental approach for a comprehensive sustainability assessment [16].

To the best of our knowledge, only three project evaluation studies on sustainability have employed this combined modeling. The first SD-IWI model was constructed for energy policy evaluation [35]. Aly and Managi (2018) developed a hybrid model to analyze the impacts of an energy infrastructure project [16]. Shimamura and Mizunoya (2020) produced an SD-IWI model to predict the sustainability of the capital city relocation project in Indonesia [25]. However, they did not consider the water quality aspect and did not combine IW and Streeter-Phelps' water quality model based on an SD approach. To the best of our knowledge, no study has considered SD-IWI modeling to assess the sustainability of such projects based on feedback, interrelations, and dynamic view.

This study primarily assessed the comprehensive and dynamic impacts of the Turag-Buriganga River Restoration Project on water quality, economy, ecology, and society, considering non-linear, feedback-based interactions among different components of the resource system. The main research questions were as follows: (1) Will the project (in increasing streamflow) maintain a DO value above 4 mg/L over time? (2) What is a sustainable strategy to maintain standard water? (3) Will the current investment be sustainable for ensuring intergenerational well-being? (4) How would the investment be sustainable?

In this study, we employed an SD-IWI model to evaluate the sustainability of the river restoration project on the trajectory of wealth and water quality. The model applied SD simulation and data analysis to quantitatively measure the effects of this restoration project on different capital assets, which comprise the wealth base of society, as well as the impacts on the water quality of the river system, which fuels asset formation. Specifically, this study aimed to (1) estimate water quality (DO and BOD) values based on related factors over 21 years; (2) estimate the IW value based on river water resources and the project over this period; (3) assess the sustainability of the project based on IW and water quality over 21 years; and (4) recommend alternative policy options for the sustainability of the river resource system. This study is the first to explore the sustainability mechanism of the Turag-Buriganga River system and dynamically show resource generation or loss. The model has remarkable implications for policymaking and may be applied to other river systems to measure sustainability and guide sustainable investment. The model could facilitate the formulation and application of different strategies for sustainable river ecosystem management by policymakers and stakeholders. For example, the model can be used to assess the potential adverse effects (loss in USD) of failing to restore polluted river systems. Similarly, it can be used to assess the optimal strategies of restoring polluted river systems for the benefit of society in the long term. Bangladesh has numerous river restoration projects. Policymakers can apply the model with slight modifications to assess the dynamic impacts of river restoration projects.

2. Materials and Methods

2.1. Study Area

The study area constitutes 162.5-km long Turag-Buriganga River resource system, which lies in the northwestern part of Dhaka, as shown in Figure 1 [14]. The shapefile of the study area was acquired from the DIVA-GIS website, which provides data-interpolating variational analysis (Retrieved on 17 February 2021, https://www.diva-gis.org/Data), from which the study area map was clipped and designed. As seen in Figure 1, this river system originates from the second largest river in Bangladesh, the Brahmaputra-Jamuna, which comprises the ecological area of interest in this study. The river channel flows through nine sub-districts (Tejgaon, Keranigong, Savar, Gazipur Sadar, Tangail Sadar, Basail, Kalihati, Kaliakoir, and Mirzapur), which made up the economic area of interest of this study. After crossing Dhaka, another branch of the Jamuna river, known as the Dhaleshwari River, emerges. The river channel flows southwards and ends in the Meghna River. Finally, this river channel drains into the Bay of Bengal. However, the water flow of this river system has reduced drastically in the last 16 years; recently, there has been no flow in the dry season [14]. Further, heavy pollution from different sources has severely damaged the resource system during the last 40 years [9]. Considering the destruction of the river ecosystem, the channel is disconnected due to encroachment and excessing anthropogenic activities. This river system is one of the most polluted river systems in Bangladesh [36,37].

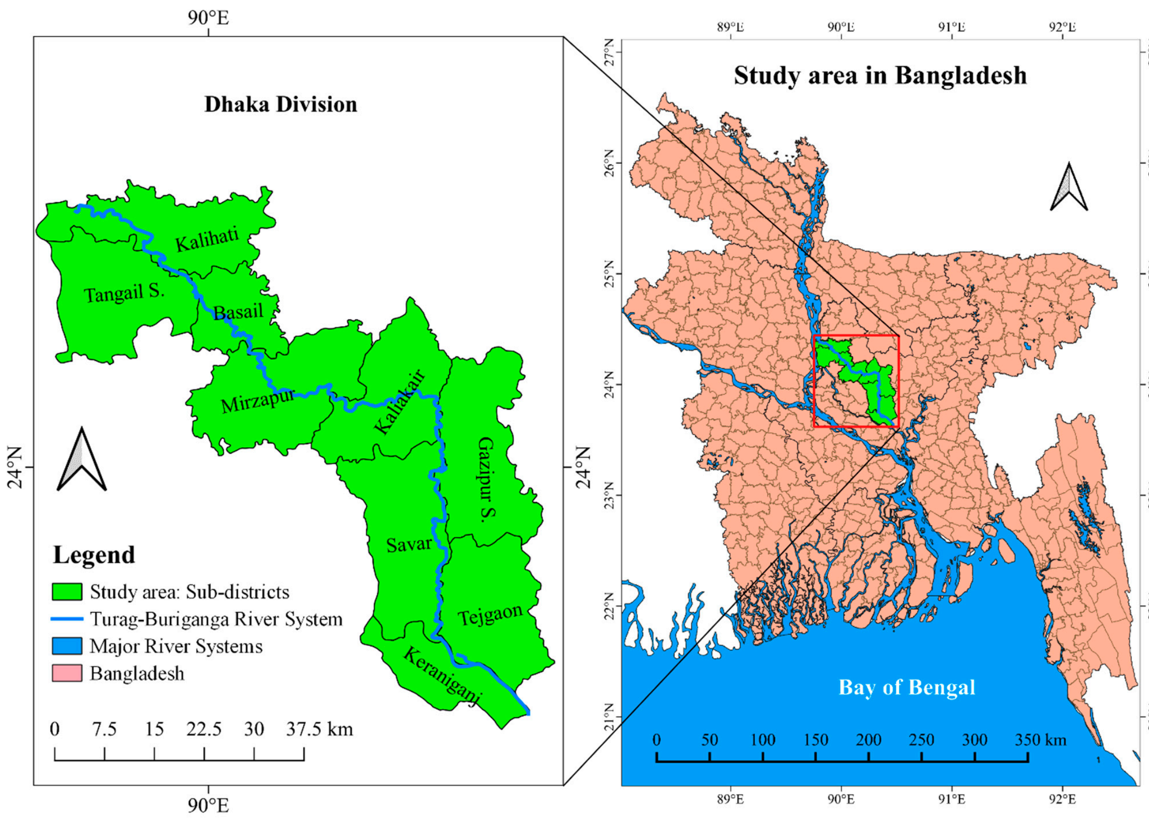

Figure 1. Map of the study area.

2.2. Scenario-Building Based on Streamflow, Waste Control, and Migration Control

Water quality mainly depends on streamflow, pollution control, and waste generation through increased anthropogenic activities. Therefore, the present study considered three scenarios based on these three strategic variables—streamflow for reoxygenation, waste control for pollution (BOD) load reduction [38], and migration control for controlling overpopulation. The first scenario is related to business, where policy variables are based on the current status of the river system. The river accommodates 80% of pollutants without treatment [39], the flow is minimal (5 m^3/s) [40], and the city has high internal immigration and no control in migration, as it is the primary economic hub in Bangladesh [41]. Therefore, scenario 1 considered a 5 m^3/s streamflow, 20% pollution control, and 0% migration control as the base line scenario. Scenario 2 is project-based, where river flow increases based on the project target (160 m^3/s), and pollution control and migration control in Scenario 1 are maintained. Scenario 3 is the integrated and sustainable strategy: policy variables are set following the empirical evidence. For example, Thenu and Karnaningroem (2019) established a similar scenario for their SD model to study water quality in the Remu River in Sorong city, Indonesia [42]. They established the sustainable scenario by combining a waste treatment plant for waste control and dredging for increased streamflow, and according to their simulation, the integrated strategy reduced BOD concentration by 89.82% and increased DO concentration by 19.07%, ensuring a sustainable river ecosystem. According to Kibria and Kadir (2015), population control, streamflow increasing through dredging, and pollution control must be synergistically considered to ensure a sustainable Buriganga river system [43]. The ideal population density for Dhaka city is below 50,000 individuals per square kilometer [44]. The present density is 70,956 individuals per square kilometer, and immigration trends suggest that the density will increase in the future [44]. Furthermore, according to Angello et al. (2021), BOD concentration has to be reduced by 87.78%, which is the optimal pollution control status of an influent for maintaining sustainable water quality in urban river systems [45]. Therefore, Scenario 3 considered a river flow of 160 m^3/s, an 87.78% pollution reduction in influent, and a 6% reduction in migration to maintain the ideal population density (>50,000 people/km^2) for achieving sustainable water quality.

2.3. Study Framework

Figure 2 illustrates the methodology adopted in this study. The dynamic problem was specified. Variables and parameters for the river resources system were then identified based on the dynamic problem. In this case, the IWI guided the identification of variables and parameters and tracked the sustainability of the river system. SD methodology was then used to construct the model, where both secondary data and data created by QGIS (Figure 3) were applied for project impact assessment. The model comprised causal loop and stock-flow diagrams (Figures 4 and 5). Vensim PLE (8.2.0) (https://vensim.com/, Ventana Systems, Harvard, MA, USA, 1 December 2020) was used to draw the causal loop and stock-flow diagram [46]. The causal diagram provides a comprehensive overview of the resource system. The stock-flow diagram is the main structure for the quantitative calculation of the model. Data was collected from a wide range of sources to develop the model database, which was categorized into four parts: water quality, natural capital, produced capital, and human capital. Data were collected directly from secondary sources and derived from remote sensing (Landsat 8) data. For example, the study employed QGIS to derive vegetation and abandoned land areas from vector and raster data. Administrative boundary vector data was used to mark the boundary of the study setting, obtained from DIVA-GIS website providing data-interpolating variational analysis. Raster data, which included the remote sensing images (Landsat 8), was obtained from the United States Geological Survey Earth Explorer (https://earthexplorer.usgs.gov/, Retrieved on 18 February 2021). The semi-automatic classification plugin in QGIS was employed to develop the land use land cover (LULC) map of this study area, after which the area of each class was calculated using raster calculator (unique values report) in QGIS (Figure 3) [47]. Similarly, the data on BOD per person were obtained through the linear interpolation of historical BOD and population data. To obtain this data, we had measurements of BOD for 2010, 2012, 2013, 2015, 2018, and 2019. We estimated the K1 as the outflow rate. We developed a model of BOD over time as a function of the inflow and the outflow. We knew the outflow was the BOD(t) * K1. We needed to estimate the inflow. We estimated the inflow as a smooth curve BODIn(t). We assumed the BODIn(t) was based on the Population(t) [48].

So, we found the BOD/person(t) that when multiplied by the Population(t) gave us then BODIn(t) that provided the minimum squared error between the measured BOD and the model BOD(t). That gave us values of BOD/person(t) for 2010, 2012, 2013, 2015, 2018 and 2019. Then we used linear interpolation to estimate the values of BOD/person(t) for the year of 2020. Data analysis was conducted by comparing different values of key variables obtained from the model simulation. For example, the three scenarios produced three DO, BOD, and IW values, based on different streamflow, waste control, and migration control values. Finally, sustainability was assessed by comparing water quality improvement and the alternative IW value based on the alternative scenarios.

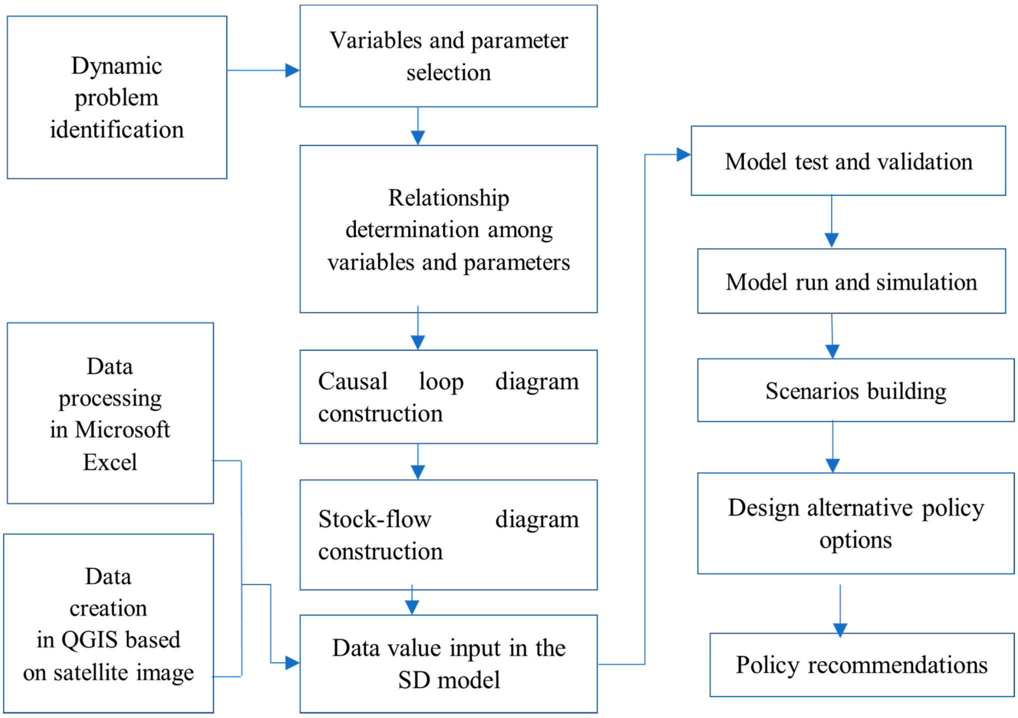

Figure 2. Study framework.

2.4. System Dynamics Model

This study developed an SD model (see Figures 4 and 5 for the causal loop and stock-flow diagrams) to assess the sustainability of the Turag-Buriganga River Restoration Project based on water quality and IW. It had four sub-models: water quality, natural capital, human capital, and produced capital. The change in IW is calculated via Equation (1) as follows [25]:

$$\Delta IW(t) = \Delta HC(t) + \Delta NC(t) + \Delta PC(t), \tag{1}$$

where ΔIW(t) is the change in IW in the Turag-Buriganga River system at time t, and ΔPC(t), ΔHC(t), and ΔNC(t) indicate changes in produced, human, and natural capital, respectively, in the river system at time t. IW is the aggregate value of three capitals: human, natural and produced capital, where the human capital means the economic value of an individual, which includes the economic value of health, education, employment etc.; the natural capital represents the natural resources, which provide goods and ecosystem services; and the produced capital represents physical assets such as infrastructure, land, etc. [17,25]. The growth of capital leads to overpopulation and increased BOD concentration through greater BOD inflows, which decreases water quality, thereby reducing IW. Because overpopulation creates more urban activities which are highlighted as one of the major causes of contamination in river's water. Liyanage and Yamada (2017) highlighted that there was highest correlation (0.70) between the concentration of BOD in river water and the population size in watershed area [48].

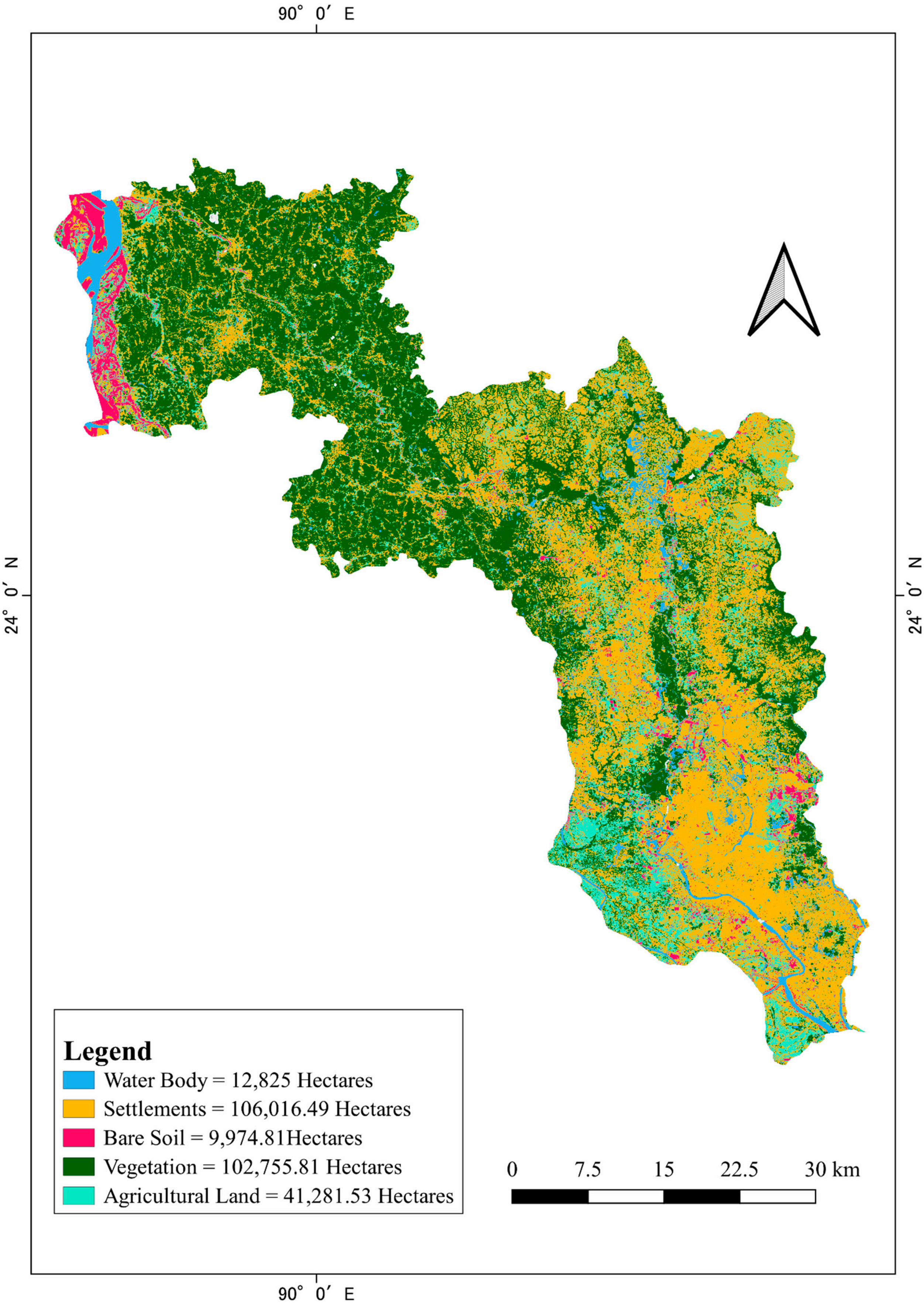

Figure 3. Area (in hectares) of each land use land cover type in the study area.

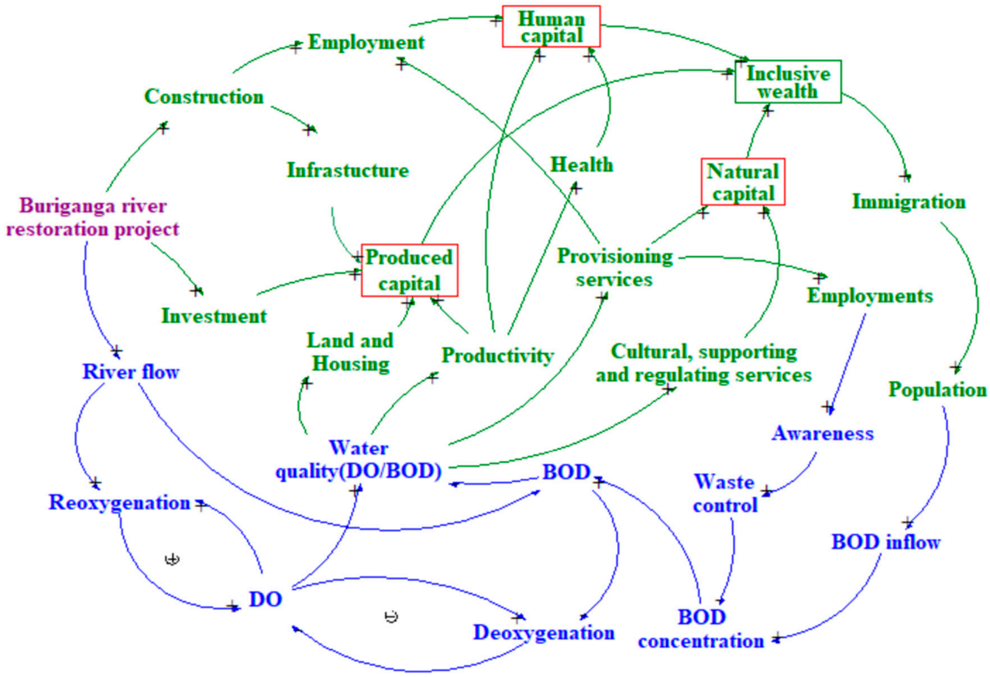

Figure 4. Causal loop diagram to evaluate the impacts on inclusive wealth (IW) index. Note: + and − indicate the causal links (arrows), referring to how the change in the independent variable influences the dependent variable. IW formation depends on balancing and reinforcing loops of the water quality model. Improved water quality enhances IW, which attracts immigration, leading to overpopulation, increased BOD concentration through greater BOD inflows, which decreases water quality, and in turn, reduces IW.

2.4.1. Model of Water Quality

The DO sag curve or equation, introduced by H.W. Streeter and Earle B. Phelps in 1925, presented a basis for developing the water quality model (DO model), and the equation determines the relationship between DO and BOD over time based on a first-order differentiation [38]. This DO modeling by Streeter Phelps equation is the most popular method to determine the water quality of a river, where the variation of only two parameters (DO and BOD) are considered and our model is constructed based on it [49,50]. However, to determine the variation of these two parameters, several factors such as temperature, velocity, water depth, river coefficients (deoxygenation and reoxygenation), oxygen solubility time, DO-saturation and riverbed coefficient, are also considered [50].

Figure 5 shows the stock-flow diagram of water quality, whose idea was derived from the Streeter-Phelps model, a pioneer in river water quality modeling [51]. In Figure 5, DO is the state variable, which is the amount of gaseous oxygen (O_2) present in the river water. The DO value changes over time(t) based on two rate variables: reoxygenation and deoxygenation, where reoxygenation represents addition of molecular oxygen and deoxygenation represents its removal. Change in DO can be mathematically expressed as given below:

$$dDO/dt = Reoxygenation(t) - Deoxygenation(t), \quad (2)$$

where reoxygenation is increased when water gets agitated, resulting in more atmospheric oxygen mixing with river water. It is estimated by the multiplication of reoxygenation coefficient and the difference between DO and DO saturation. DO saturation is the greatest concentration of DO present in river water under natural pressure and temperature conditions. The reoxygenation coefficient is the multiplier that measures the property of reoxygenation, and it varies from one water body to another based on velocity and water depth. We calculated Kr, according to the Streeter-Phelps' reaeration rate equation for this river system [52].

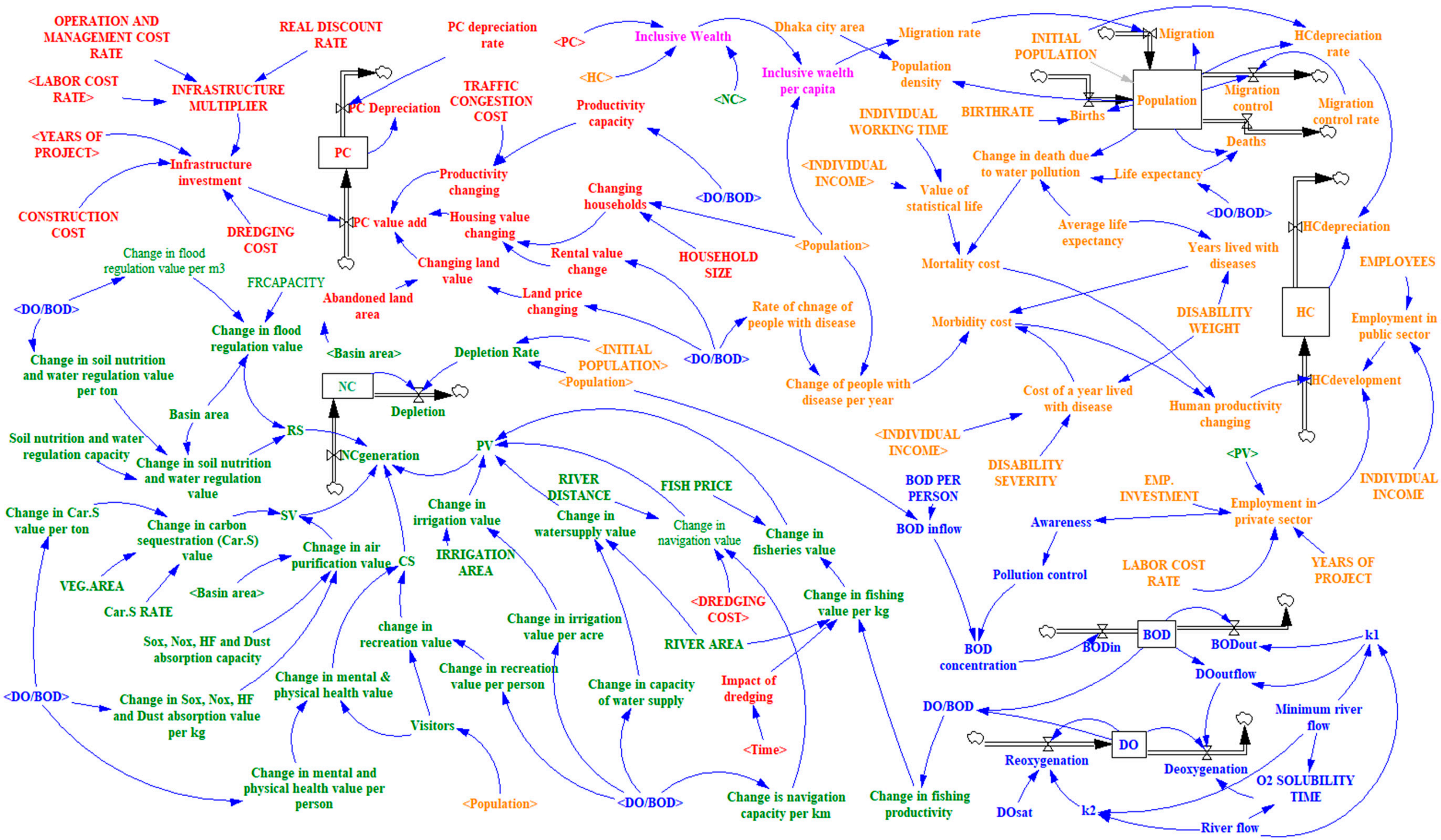

Figure 5. System dynamic stock-flow diagram representing the simulated system, including sub-systems of water quality, natural capital, produced capital, and human capital.

Deoxygenation is the removal of oxygen through pollution decay caused by bacteria. Bacteria consume DO to decompose the organic pollutant deposited in the river system. The deoxygenation depends on DO, O_2 solubility time, BOD, and pollution decay coefficient (Kd). O_2 solubility time corresponds to when oxygen is absorbed in river water by direct diffusion and surface-water agitation, and it is estimated to take six years for O_2 to diffuse from the surface to a depth of 6 m in water which is physically undisturbed [53]. Pollution decay coefficient (Kd) is a factor that determines the property of deoxygenation, and it varies from one water body to another based on water velocity, water depth, and riverbed activity coefficient. We calculated Kd according to the Streeter-Phelps' deoxygenation rate equation for Turag-Biriganga river system [54].

A riverbed is the ground or channel bottom, which a river flows over, and it is the physical confine of the normal water flow [55]. Typically, riverbeds are composed of gravel and sand beds. The riverbed of this river system is a sandbed, which is composed of sand and smaller-sized particles. The function and materials of the riverbed significantly affect the river water quality [56]. Therefore, the riverbed activity coefficient affects the decomposition of pollutants. River flow affects both Kr and Kd, and higher river flow leads to a higher coefficient value [57]. BOD represents the amount of oxygen consumed by bacteria and other microorganisms during the decomposition of organic matter under aerobic conditions [58]. It was calculated via Equation (3).

$$dBOD/dt = BODin(t) - BODout(t), \quad (3)$$

where BODin(t) is determined by the value of BOD concentration in the pollutant loads entering the river. BOD concentration increases when anthropogenic activities increases, resulting in greater pollutant loads. Conversely, BOD concentration decreases when stricter pollution control measures are applied and when awareness regarding pollution and pollution control is raised [59]. BODout is determined based on the multiplication of stock BOD and pollution decay coefficient (Kd).

2.4.2. Model of Natural Capital

The natural capital modeling was based on the 2012 IW report and the Irwell management catchment report in 2018. Figure 5 shows the stock-flow diagram of natural capital. Change in natural capital was calculated via Equation (4).

$$dNC/dt = NCg(t)(Ps + Rs + Cs + Ss) - NCd(t), \quad (4)$$

where NC is the change in natural capital at time t (USD), NCg(t) is the natural capital generation, Ps is provisioning services, Rs is regulating services, Cs is cultural services, Ss is supporting services, and NCd(t) is natural capital depletion. NCg(t) consists of four functions of the river ecosystem: provisioning (Ps), regulating (Rs), supporting (Ss), and cultural (Cs) services [60]. Provisioning services (Ps) are products and direct benefits obtained from the river ecosystem. This study considered three products (fisheries, water supply for domestic and industrial purposes, and irrigation water) and one direct benefit (navigation). Fisheries value was estimated by the multiplication of river area with fish productivity and fish price; higher water quality (DO/BOD) generates higher fish productivity [61]. However, dredging causes fluctuations in fish productivity. The water supply and navigation value depend on river area and capacity of water supply and navigation. Higher water quality (DO/BOD) causes higher capacity [3]. Regulating services (Rs) are benefits obtained from regulating ecosystem processes, including flood regulation, water regulation, and soil nutrition. The values of flood and water regulation and soil nutrition were obtained by multiplying their capacity per unit value and basin area; wherein higher water quality (DO/BOD) ensures a higher value per-unit value [62]. Cultural services (Cs) are non-material benefits (recreation, physical and mental health improvement) from the river ecosystem. The improvements in the values of recreation, physical and mental health were calculated based on per person unit value and the increase in the number of visitors; when population increases in an area, water quality (DO/BOD) increases per unit value [3]. Supporting services are necessary services that produce all other ecosystem services: carbon sequestration and air purification. The value of carbon sequestration was calculated from vegetation area, carbon sequestration capacity, and its per-unit value. Similarly, air purification values were estimated from basin area, NOx, Sox, HF, and dust retention capacity and per unit value. The capacity of carbon sequestration, NOx, Sox, HF, and dust retention increases with water quality (DO/BOD) [62]. Finally, natural capital depletion, NCd(t), depends on its stock and depletion rate, and a higher population number causes a higher depletion rate.

2.4.3. Model of Produced Capital

This study considered four factors in the development of the model of produced capital: infrastructure investment, productivity, housing, and abandoned land. Figure 5 shows the stock-flow diagram of produced capital. Change in natural capital was calculated via Equation (5).

$$dPC/dt = PCg(t)(Iv + ALv + Hv + Prv) - PCd(t), \tag{5}$$

where PC is the change in produced capital at time t (USD), PCg(t) is the produced capital generation, Iv is the infrastructure value, ALv is the abandoned land value, Hv is the housing value, Prv is the productivity value, and PCd(t) is the produced capital depreciation. PCg(t) is the aggregate value of infrastructure (Iv)), abandoned land (ALv), housing (Hv), and productivity (Prv) value [25]. The River Restoration Project contributed to the produced capital through infrastructure development such as the guide bank, sediment basin, and dredging. Infrastructure value (Iv) was calculated from the construction and dredging cost, years of projects, labor rates, real cost, and maintenance. Productivity value (Prv) was calculated from the traffic congestion cost and its capacity, where higher water quality (DO/BOD) causes higher capacity [3]. Notably, Dhaka faces severe traffic jams. Improved river transportation through improving the river ecosystem can save the opportunity cost, and this value would be added to the produced capital as productivity. This capacity is assumed to be 10%, as nearly 10% of people use river transportation annually in Bangladesh [63]. The abandoned land in the river basin would be valuable given following the improvement of the river system due to restoration, particularly in water quality. Similarly, the rental prices of housing in the basin area would increase. Such increases in value would then contribute to capital development. The depreciation of produced capital is a decrease in the value of assets over time due to use, wear, or tear, and is calculated by multiplying the stock of an asset and its depreciation rate.

2.4.4. Model of Human Capital

This study considered four factors in the development of the human capital model: morbidity cost, mortality cost, private employment, and public employment. Figure 5 shows the stock-flow diagram of produced capital. Change in human capital was calculated via Equation (6).

$$dHC/dt = HCd(t)(HPv + PEv + PrEv) - HCdr(t), \tag{6}$$

where HC is the change in human capital at time t (USD); HCd(t) is human capital development; HPv is human productivity change, determined by the mortality and morbidity cost; PEv is public employment value; PrEv is private employment value; and HCdr(t) is human capital depreciation. HCd(t) consisted of the values of productivity (HPv), determined by the mortality and morbidity cost, and private (PrEv) and public (PEv) employment [25]. Morbidity cost depends on the cost of living with a disease for a year, the percentage of people affected by water pollution, disability weight, disability severity weight, the years lived with the disease, and individual income [64]. Water quality affects this cost through the percentage of people affected by water-borne diseases associated with water pollution, where a higher proportion of the population is affected by a decrease in water quality [65]. Mortality cost depends on the number of deaths from water pollution, the value of statistical life, individual income, and working time [25,64]. Water quality affects this cost through life expectancy, where higher water quality is associated with higher life expectancy [66]. Private and public employment investments are based on project investment, labor cost rate, and individual income. Furthermore, the provision of services via natural capital positively affects private employment. The change in population in the study area is determined by births, deaths, immigration, and migration control. Dhaka city is the most densely populated city in the world, and a further increase in population would enhance the negative effects of the dense population on human capital as it exceeds the carrying capacity of the area, and investment in human development would be challenging. Therefore, human capital depreciation, HCdr(t), would increase with population growth in the area [67].

2.5. Validation and Model Test

Sterman (2000) presented 12 tests to measure the SD model's robustness [68]. As some model tests are employed for pre-modeling, this study used three robustness tests: calibration, sensitivity analysis, and extreme condition test.

The model calibration was conducted in two steps: checking the correspondence of the model parameters with relevant descriptive and numerical knowledge of the real system and testing the accuracy of historical fit [23]. We collected six years of DO and BOD field data during the 2010–2020 period. We then simulated the model retrospectively from 2010 to 2020 using these data. We then compared the models using simulated and historical data and observed a similar pattern (Figure 6a,b). Thus, our model reflected reality and correlated with historical data. Moreover, we collected the projected population data of the study area from the United Nations from 2020 to 2030 [69]. We then compared the models using projected and simulated data and observed similar trends (Figure 6c). Thus, the model forecasted population trends perfectly.

In addition to the calibration tests, we carried out extreme condition and sensitivity tests. The extreme condition test was conducted considering the values of three policy variables: streamflow, waste control, and migration control [68]. We set two extreme values of waste control (streamflow, migration control) from 0% to 100% (0–160 m^3/s, 0–6%). We then simulated the model and obtained no shocks. Each equation was found to be applicable despite the extreme input values, and model behavior was appropriate (Figure 6d).

Subsequently, we performed the univariate sensitivity test [68]. We selected waste (BOD) control and set the optimum reduction value in influents to 87.778%, as Angello et al. (2021) indicated that a reduction by 87.778% is the optimum value for maintaining sustainable water quality in an urban river system [45]. Afterward, we applied 10% standard deviation to optimum BOD reduction value (87.778%) of influents, which resulted in three BOD reduction values: 79.009% (10% low), 87.78% (optimum value), and 96.56% (10% high). After the simulation, the three values generated three different IW values, which varied significantly (Figure 7a). Similarly, we selected three values of migration control such as 0%, 3% and 6% and run the sensitivity analysis. The results indicated that 0% and 3% migration control produced negative IW after 26 years and 70 years respectively as population density exceeded the carrying capacity in this area. On the other hand, 6% migration control produced non-declining IW over the time. Therefore, we set it as the optimum value for migration control (Figure 7b). Overall, the validation, calibration and extreme condition tests, and sensitivity analysis confirmed that the model was valid and appropriate for application in impact assessment.

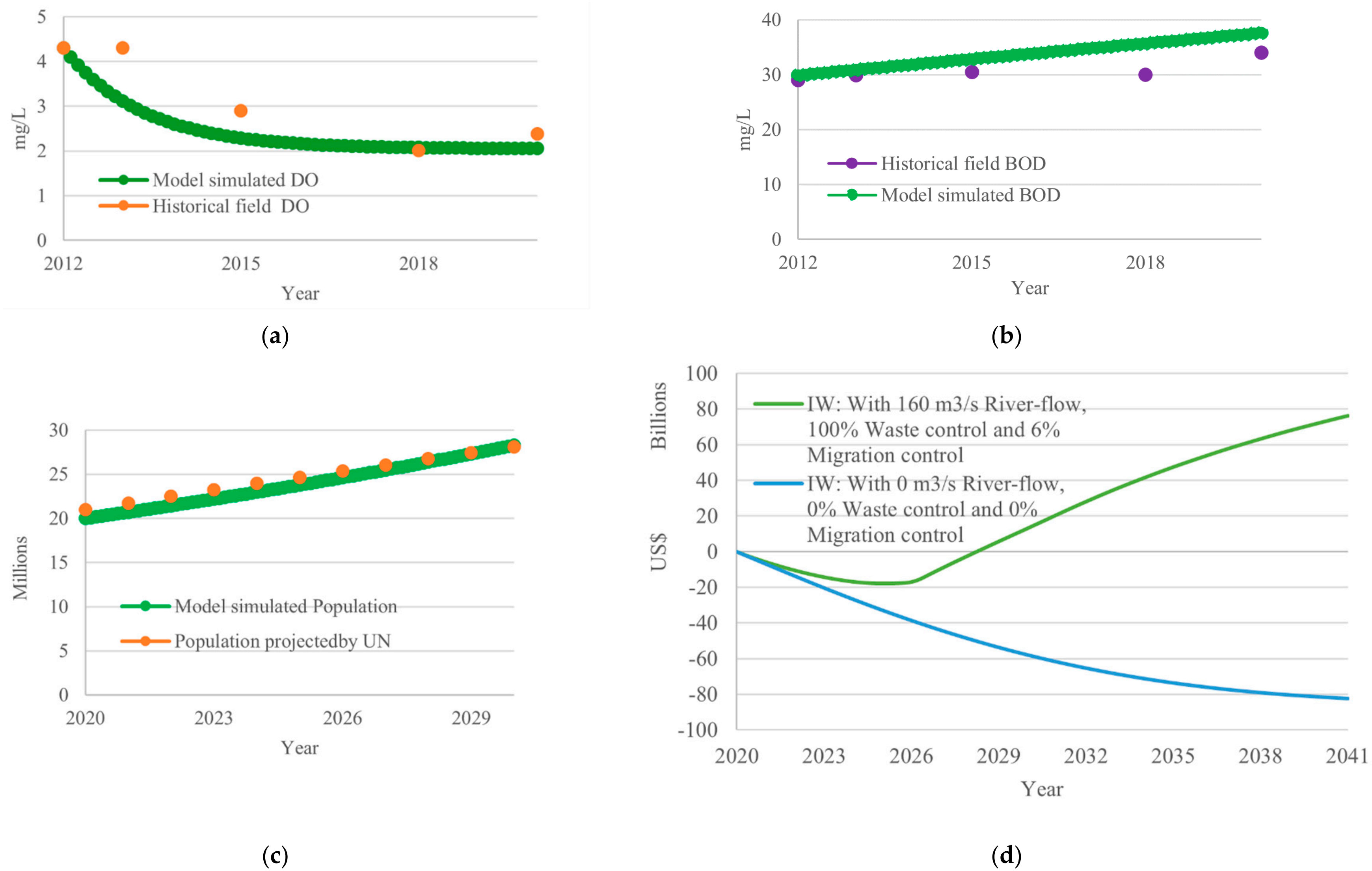

Figure 6. Model test results of calibration (**a**) dissolved oxygen (DO)), (**b**) biological oxygen demand (BOD), (**c**) population and (**d**) Extreme condition test: Inclusive Wealth (IW).

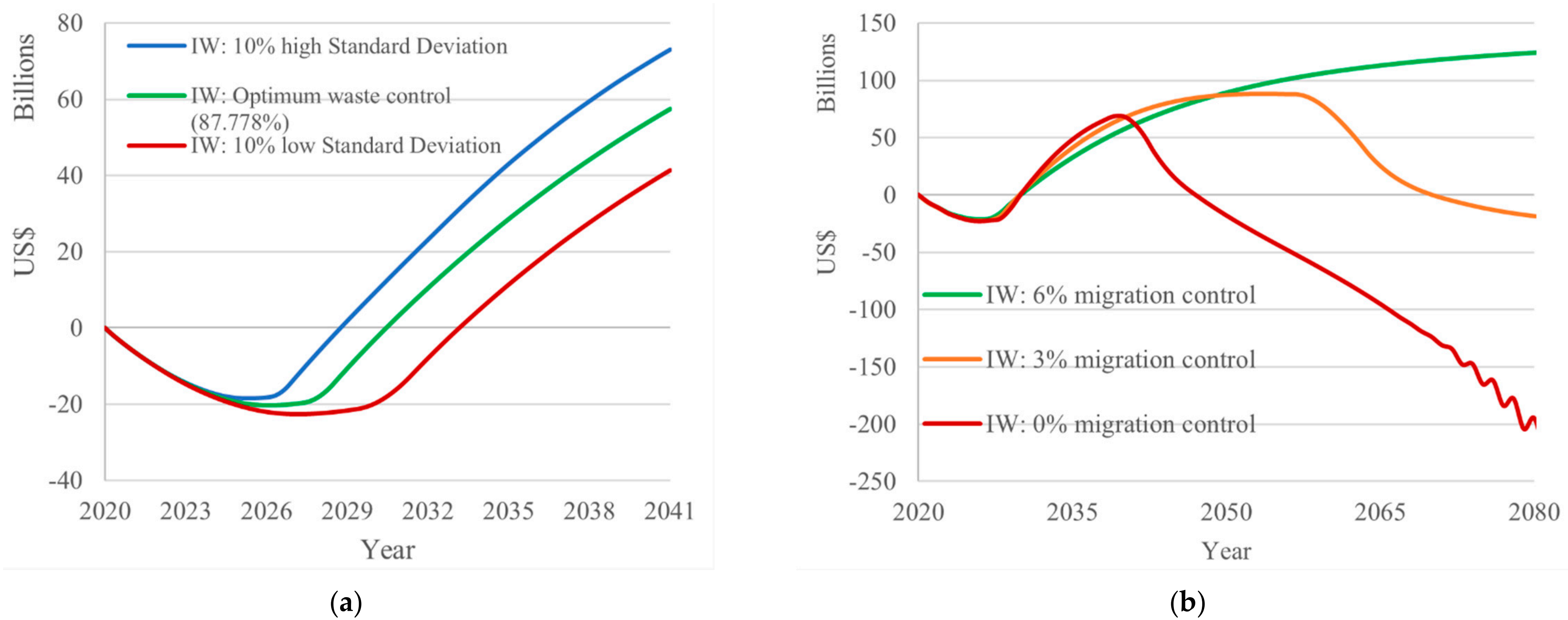

Figure 7. Model test results, sensitivity analysis: Inclusive Wealth (IW), (**a**) Based on waste control and (**b**) Based on migration control.

3. Result and Discussion

This study investigated the comprehensive and dynamic impacts of the Turag-Buriganga River Restoration Project on water quality, economy, ecology, and society, considering non-linear, feedback-based interactions among different components of the resource system. The simulation was run for each scenario over 21 years by setting the value of the river flow (RF), waste control (WC: BOD) and migration control (MC) policy variables.

3.1. Simulation Results of Water Quality

The water quality was determined as the ratio of DO to BOD. Bornilla et al. (2019) indicated that increasing streamflow could decrease BOD value (≤6 mg/L) and increase DO value (≥6 mg/L) [51]. However, they did not consider the dynamic waste generation and BOD loads that enter the river. In the current study, we considered a combination of pollution loads, waste generation due to increasing population, and increases in river flow to predict the DO and BOD value.

Scenarios 1 and 2 produced a significantly lower DO (average 3.28 mg/L) and higher BOD (average 60.85 mg/L) than the standard values (DO ≥ 6 mg/L and BOD ≤ 6 mg/L for Bangladesh) over the simulation period. For example, the simulation results of changes in DO values in 2041 were 2.05 mg/L in Scenario 1 and 3.4 mg/L in Scenario 2 (Figure 8a). Similarly, BOD values in 2041 were 86.3 mg/L and 47.4 mg/L in the two scenarios, respectively (Figure 8b). Thus, the scenarios indicated that the river would become an extremely polluted ecosystem. However, the Turag-Buriganga River Restoration Project will not positively impact water quality improvement, as it primarily aimed to increase river flow from 5 m^3/s to 160 m^3/s. This situation occurs mainly because of the heavy pollution loads, and sediment pollutants consume considerable DO from the river water [70].

However, Scenario 3 is a sustainable condition for maintaining standard river water DO (≥6 mg/L) and BOD (≤6 mg/L) given the introduction of pollution load control (BOD) (optimum threshold: 87.78%), migration control (≥6%), and increased river flow (≥160 m^3/s) (Figure 8a–c). From the simulation result, this strategy could improve DO concentration by 248% and reduce BOD concentration by 90.8% in 2041, compared to their concentrations in 2020. These findings supplement those of Thenu and Karnaningroem (2019), who found that the combined strategy (waste treatment and streamflow) could improve DO by 19.7% and reduce BOD by 89.92% [42].

The DO/BOD ratio should be considered as the indicator of water quality instead of only DO value because a higher DO value can co-exist with a higher BOD value. For example, Rahman (2012) estimated DO and BOD in the same river system and found values of 6.5 mg/L and 30 mg/L, respectively, at Ashulia station [71]. Thus, to produce standard water over time, the DO value must be higher than 6 mg/L, and the BOD value must be lower than 6 mg/L.

Scenarios 1 and 2 generated significantly lower ratios (0.024 and 0.07, respectively) (Figure 8d) than the standard values because they had lower DO (2.05 mg/L and 3.4 mg/L) and higher BOD (86.3 mg/L and 47.4 mg/L) values. However, Scenario 3 maintained a standard ratio (2.35) (Figure 8d) with a higher DO (8.3 mg/L) and lower BOD (3.1 mg/L) values. Thus, Scenario 3 will maintain a sustainable river ecosystem in the future.

3.2. Simulation Results of Inclusive Wealth and Inclusive Wealth per Capita

The simulation results showed that the IW for Scenarios 1 and 2 were −78 billion USD and −63 billion USD, respectively, equivalent to −3.02% and −2.44% of the cumulative GDP (2580 billion USD) [72] in Bangladesh from 2020 to 2041 (Figure 9a). The results also showed that IW per capita values in 2041 were −1838 USD in Scenario 1 and −1479 USD in Scenario 2 (Figure 9b). Hence, IW would decline, imposing a massive loss on the economy.

The decline in IW occurred because of the decrease in the DO/BOD ratio over time, ending at a critical value (0.024 and 0.07). This declining ratio destroys the river ecosystem, exerting negative impacts on IW generation [43]. IW comprises the produced, human, and natural capital. Figure 10a–c show the change in the values of the three capitals in Scenarios

1 and 2 over 21 years. These results showed that human, natural, and produced capital decline over time. The corresponding values for the two scenarios were −69, −4.3, and −4.2 and −58, −2.7, and −2.2 billion USD, respectively, in 2041. Human capital declines the most (89% and 92%), and produced and natural capital account for almost the same proportion (Figure 10d).

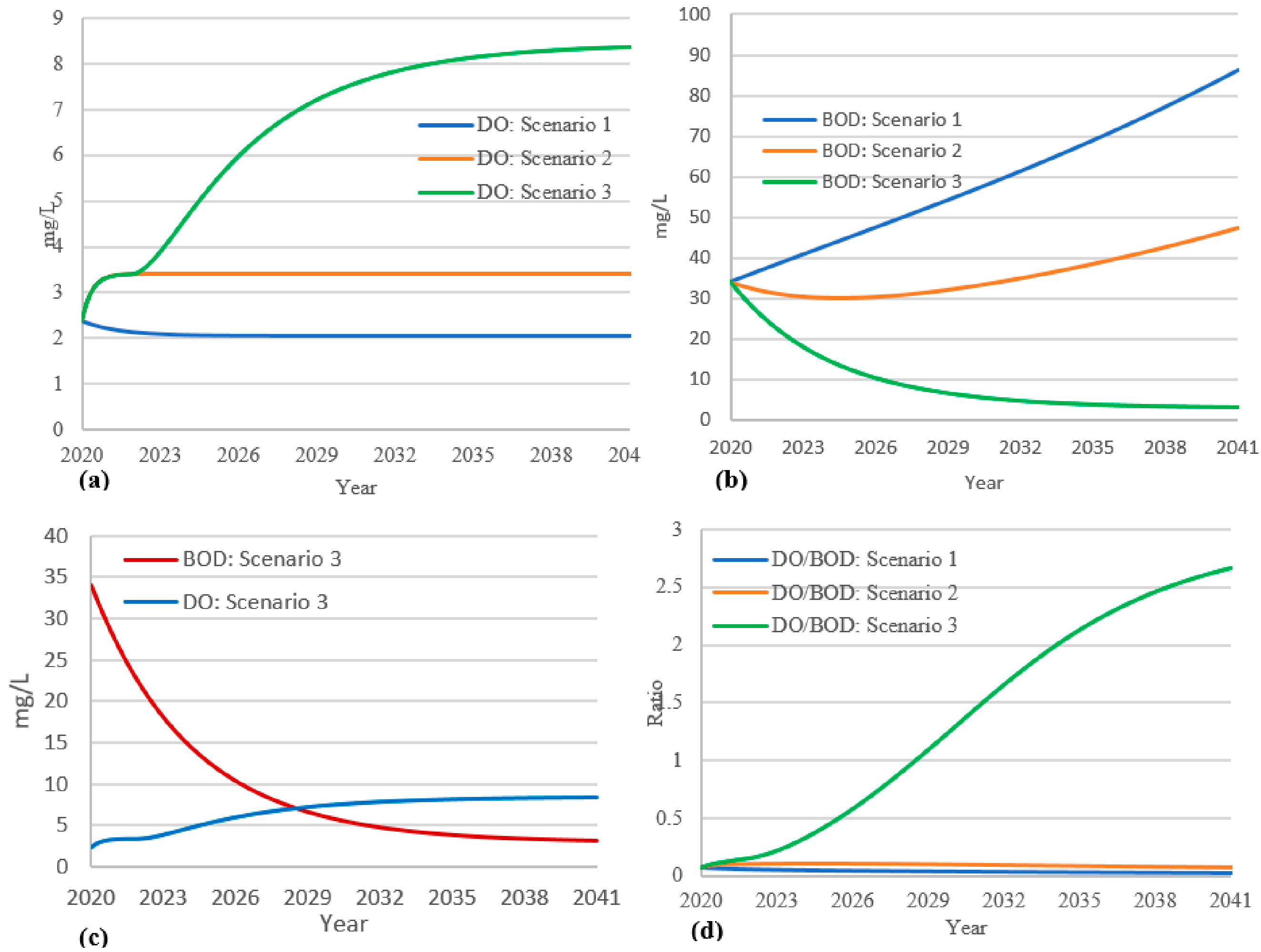

Figure 8. Simulation results of three scenarios, (**a**) DO, (**b**) BOD, (**c**) Sustainable water quality and (**d**) DO/BOD ratio.

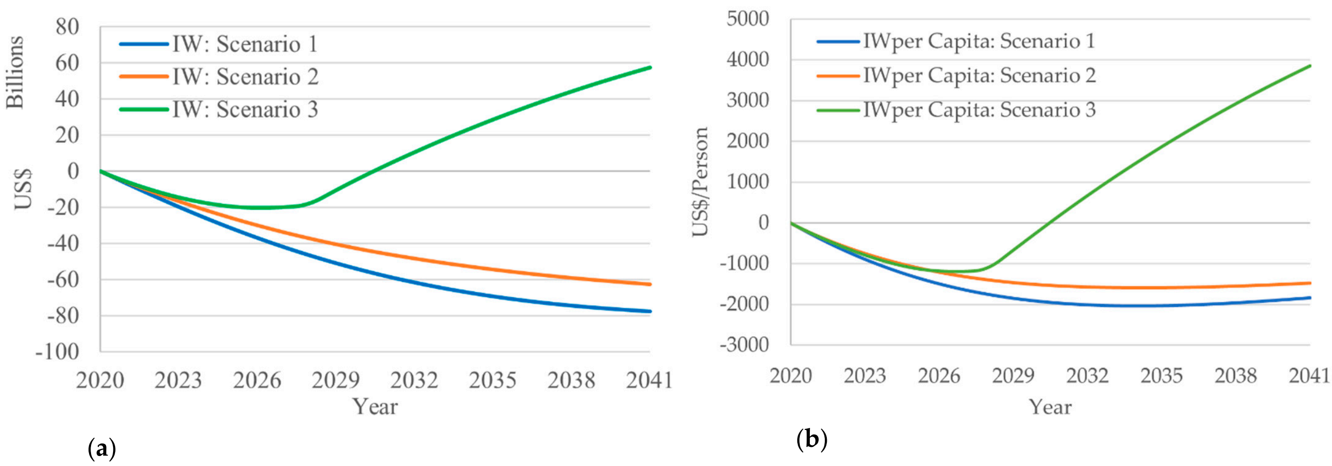

Figure 9. Simulation results of three scenarios, (**a**) IW and (**b**) IW per Capita.

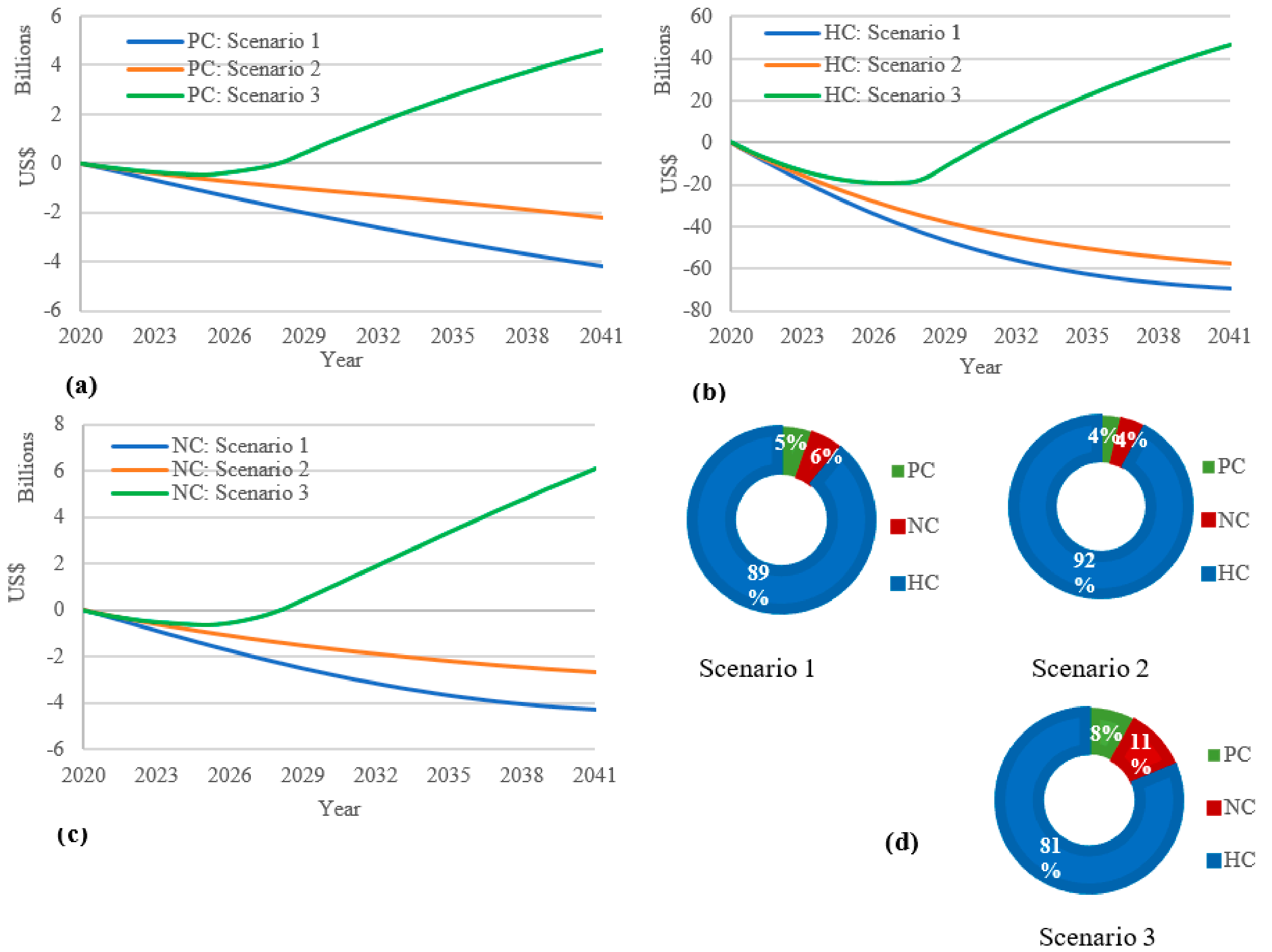

Figure 10. Simulation results in three scenarios, (**a**) Produced capital, (**b**) Human capital (HC), (**c**) Natural capital (NC) and (**d**) the contribution rate to IW of the three capitals.

The primary reason for the decline in human capital is the effect of poor water quality on human health and life expectancy [65]. As the population density increases, river water pollution increases and affects a larger population. Similarly, the DO/BOD ratio decreases as pollution increases because of increased anthropogenic activities, which further decreases the water quality. Thus, water-borne diseases are likely to affect more people. The situation increases the years of living with water-borne diseases, resulting in a huge morbidity cost. Similarly, increased river pollution kills more people, imposing a colossal mortality cost.

Natural capital declines as the value of the river ecosystem services decrease over time. We employed four river ecosystem services (supporting, provisioning, cultural, and regulating) to quantify the natural capital. Supporting services comprise carbon sequestration and air purification. Clean river water can absorb dust, nitrogen oxide, sulfur oxide, and hydrogen fluoride from the air, purifying the atmosphere [62]. Similarly, standard water quality leads to healthy aquatic and terrestrial vegetation, which capture CO_2 from the atmosphere and help ward against global warming and reduce climate change. The World Air Quality Report (2020) noted that Dhaka was the second-most air-polluted city globally in 2020. The report also showed that 13% to 22% of deaths are caused by air pollution, and the associated estimated cost is 7.4% of Bangladesh's GDP [73]. Mahmood (2011) likewise noted that air pollution kills 15,000 people yearly, and Bangladesh could save 800 million USD yearly if air pollution was managed [74].

Provisioning services include fisheries, navigation, irrigation, and water supply. In Scenarios 1 and 2, the DO/BOD ratio negatively affected provisioning service values, inducing a decline over time. Regulating services comprise flood, water, and soil nutrition regulating value. Bangladesh is a flood-prone area as it is situated at the lower part of the Ganges delta. In both scenarios, the regulating service values declined as the polluted river system lacked flood, water, and soil nutrition regulation. Cultural services comprise recreation, mental and physical health. The polluted river negatively affected people regarding recreational, mental, and physical well-being.

Produced capital declines as property prices decline because of polluted rivers [75]. This study considered four factors (infrastructure, housing, abandoned land, and productivity) to estimate produced capital. River pollution negatively affects housing and land rental prices, thereby inducing a decline [3]. Dhaka experiences serious traffic jams. Hence, an improved river system could be used as an alternative route for communication and save opportunity cost, adding to produced capital as productivity. However, in the two scenarios, the river system was destroyed as productivity declined over time.

However, from the simulation results, the IW for Scenario 3 was 57.5 billion USD, equivalent to 2.22% of Bangladesh's cumulative GDP (2580 billion USD) from 2020 to 2041 (Figure 9a) [72]. Similarly, IW per capita values in 2041 will be 3859.6 USD in Scenario 3 (Figure 9b), indicating a non-declining IW, thereby ensuring intergenerational well-being. A steady increase will be observed in IW 10 years after 2020 as the DO/BOD ratio meets the standard level after eight years, maintaining standard water over time. Figure 10a–c show the simulation results of produced, human and natural capital in 2041, with values of 4.6 billion USD, 46.7 billion USD and 6.1 billion USD, respectively. Human capital contributes the highest value (81%) as more people benefit from an improved river ecosystem; the natural and produced capital have 11% and 8% IW share in 2041 (Figure 10d). The positive values observed were potentially because the water quality improves over time, reaching a standard level that facilitates resource generation and benefits society in the form of ecosystem services and leads to a sustainable river resource system [76].

3.3. Sustainability of the River System

This study considered sustainability from two perspectives: maintaining standard DO and BOD values and non-declining IW over time. Scenarios 1 and 2 were not sustainable as they could not maintain standard DO ($\geq$6 mg/L) and BOD ($\leq$6 mg/L) values. Further, the combined IW declined. Note that the current river restoration project would not ensure sustainability; hence, the project's investment plan is not sustainable. However, Scenario 3 generated a DO value above 6 mg/L and BOD below 6 mg/L over time and will have a positive IW (57.5 billion USD) in 2041. Thus, it provided a reliable and sustainable strategy to maintain standard water and non-declining IW over time. Therefore, investment following the proposed policy of Scenario 3 will be sustainable and ensure intergenerational well-being.

3.4. Alternative Policy Option

The current Buriganga River Restoration Project, initiated in 2010, is not sufficient to maintain a standard water level in the future. Moreover, it cannot ensure intergenerational well-being because it cannot generate non-declining IW over time. Furthermore, this strategy is not a long-term solution as increased waste generation and heavy pollution loads have considerable negative effects on water quality. Hence, an alternative policy option is to consider the strategy proposed in Scenario 3. This strategy can alleviate water pollution globally and locally and ensure non-declining IW. Note that the range of policy variables (river flow, migration control, and waste control) should not be less than 160 m^3/s, 6%, and 87.78%, respectively, because lowering this range would delay the achievement of a standard water level and positive IW. Additionally, it would negatively affect the achievement of Vision 2041 as IW is the foundation of socio-economic and environmental growth. Therefore, this study suggested a collaborative policy that integrates the interests of all stakeholders and a sub-policy to improve the river ecosystem and ensure intergenerational well-being. Fortunately, Bangladesh government already has initiated three projects separately for increasing river flow, waste control and migration control. This study highlights the significance of collaborative policy approach and determines the optimum values of three policy variables.

4. Conclusions

This study developed an SD-IWI model for assessing the sustainability of the Buriganga River Restoration Project. The model covered water quality, human capital, natural capital, produced capital, and wealth sub-systems. These sub-systems had feedback, nonlinear relationships, and dynamic interactions in the resource system, which dictated their behavior over time. We tested the model qualitatively and quantitatively. Calibration, validation, extreme condition, and sensitivity analysis confirmed the fidelity and reliability of the model.

This study also investigated the sustainability of the river restoration project based on sustainable river water quality and non-declining IW and could provide tools for assessing and ensuring the sustainability of river resource systems. This study contributes significantly to the comprehensive and dynamic evaluation of river restoration, combining water quality, natural capital, human capital, and produced capital in Bangladesh, and could be applied in other river basins globally. No previous study combines the four sub-systems through an SD approach based on IW and the Streeter-Phelps' water quality model. The results of this model indicate that the Buriganga River Restoration Project (only with 160 m^3/s streamflow) would not ensure sustainability, mainly because of the negative effects of excessive waste generation through the increasing population and heavy pollution load, as increased amounts of pollutants (BOD) consume high DO amounts from the river water. In contrast, the sustainable strategy applied in Scenario 3 would ensure standard water quality and non-declining IW over time. As increased river flow enhances self-purification, waste control reduces pollutant (BOD) loads, and migration control reduces waste generation by reducing the population. Therefore, the results of the present study suggest a collaborative policy approach and the adoption of dynamic impact assessment techniques to ensure sustainability. For instance, Mizunoya et al. (2021), while analyzing the impact of a municipal merger on watershed management in Lake Kasumigaura in Japan, noted that a municipal merger would have positive effects on the socio-economic and water environments [77]. Therefore, this study emphasizes the establishment of institutional coordination and joint ventures to ensure the joint implementation of 160 m^3/s streamflow, 87.78% waste control, and 6% migration control for the achievement of sustainability in river resource utilization. Fortunately, Bangladesh government already has initiated three projects separately for increasing river flow, waste control and migration control. This study highlights the significance of collaborative policy approach and determines the optimum values of three policy variables. According to the results of the present study, successful river restoration projects would facilitate sustainable development significantly. It also highlighted the immense challenges in achieving sustainable development without a sustainable river system, suggesting caution for riverine countries. Therefore, our model has significant implications for policymaking and could be applied to other river systems to assess sustainability and guide sustainable investment.

4.1. Policy Recommendations

First, this study recommends dynamic impact assessment of river restoration projects. It showed that dynamic impact assessment explores different potential impacts of the projects on populations. This future trend analysis provided insights for successful and sustainable projects. Bedarkar et al. (2018) offered a similar suggestion for sustainable river management [78].

Second, comprehensive metrics for evaluating the success of river restoration projects are beneficial. Such metrics should be quantitative and comprehensive, encompassing physical, ecological, social, water quality, and wetland vegetation characteristics. This study considered IWI as a holistic metric for tracking project sustainability, moving the evaluation approach in a specific direction to analyze the project goals. Bedarkar et al. (2018) suggested using comprehensive metrics for impact assessments of any river restoration program [78].

Third, this study recommends investment in river restoration programs to ensure the sustainability of the river system. The findings showed that ecosystem destruction could lead to significant economic losses (78 billion USD) to society. However, an ecosystem is the base of economic development and provides vast benefits (57.5 billion USD). The ecosystem can be improved through the investment in the river restoration project, as it will stop the damages of river ecosystem and helps to regenerate its natural functions. In that case, multiple projects should be formulated and implemented jointly and concurrently to address the entire problem comprehensively [79].

Fourth, the increasing dynamic trends of waste generation through increased population and pollution loads must be considered. This study showed that dynamic pollution load and overpopulation could lead to a highly polluted river system. Along the same lines, the fifth recommendation is the establishment of clear-cut communication channels for stakeholder engagement and participation in the restoration process. In the present study, we illustrate a stock-flow diagram of dynamic impact assessment for the Buriganga river restoration program, which makes it possible to view the gains or losses of different stakeholders over time in a straightforward manner. Hence, it will increase stakeholders' understanding of the dynamic impact of the project.

Sixth, the DO/BOD ratio for determining water quality for resource growth or decline must be considered instead of just the DO value. Evidently, river water could have a higher DO value along with a higher BOD value. For example, Rahman (2012) measured DO and BOD in the Buriganga River and found values of 6.5 mg/L and 30 mg/L, respectively [71]. Therefore, despite the higher DO value, the water may be polluted, considering a relatively high pollutant concentration.

The seventh recommendation is controlling migration to 6% for the maintenance of the optimal population density in the city area by reducing immigration and introducing out-migration. The migration can be controlled by implementing the detailed Dhaka area plan, developed by the government in 2015, which describes strategies such as institutional and infrastructural decentralization, communication improvement, relocation of industries, and employment creation in other urban areas. JICA (2010) developed a report and introduced a multi-core mega plan for a sustainable Dhaka city [80]. The mega plan incorporated immigration control through decentralization. The mega plan considered four key issues, including (1) strategic urban development of satellite communities, (2) effective transport network with surrounding growth poles, (3) economic integration between the dominant urban center and surrounding urban/peri-urban/rural settlement, and (4) good governance to manage the urban region effectively and efficiently. Similarly, Haque et al. (2019) proposed a transit-oriented development plan in Dhaka city to manage overpopulation [81].

The eight recommendation is the establishment of institutional coordination and a joint venture to ensure the implementation of a 160 m^3/s streamflow, 87.78% waste control, and 6% migration control jointly to achieve a sustainable river system. In that case, an independent supreme authority named restoration committee can be established by law that will coordinate and formulate necessary programs for restoring the river system. The Kushiro Wetland Restoration Committee in Japan is a good example of a restoration committee. The Kushiro wetland restoration committee was established in 2003 by dint of nature promotion law to restore the wetland through a collaborative venture involving different ministries and stakeholders. The committee members are residents, stakeholders, NGOs, experts, municipalities, the prefectural government, the national government, and other organizations. The committee has the supreme power to formulate projects regarding the wetland, and every ministry must implement the proposed project [79].

Finally, this study highlights the potential impacts or achievements of an integrated river basin management approach involving all stakeholders. Mersey River Basin, UK restoration campaign (1985–2010) is the best example of an integrated river basin management for the improvement of water quality [82].

4.2. Limitations and Future Works

While this research has provided an impact assessment model to understand the sustainability mechanism of river water and its effects on asset formation, some limitations have been identified. Firstly, this DO modeling by Streeter Phelps equation is the most popular method to determine the water quality of a river, where the variation of only two parameters (DO and BOD) are considered [49,50] and, to determine the variation of these two parameters, several factors such as temperature, velocity, water depth, river coefficients (deoxygenation and reoxygenation), oxygen solubility time, DO-saturation and riverbed coefficient, are also considered [50]. However, some important parameters such as COD, NO_3, PO_4, and NH_3, can be considered to develop better water quality model to explore more insight into the system [11]. Secondly, this study has faced data limitations. For example, we do not have updated data for many variables such as water supply, navigation, dust, NOx, Sox, HF, flood, water, and soil nutrition regulation value. We have adjusted these values to get updated data. Therefore, such data generation would be a significant future research work. Finally, we did not consider investment costs in waste control, decentralization for maintaining sustainable river water, and the trade-off between IW and the cost, which will be an important aspect of future research.

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