What are the main challenges facing the sustainable development of China’s Yangtze economic belt in the future? An integrated view

Haiyan Jiang1,2, Slobodan P Simonovic2, Zhongbo Yu1,3,4, and Weiguang Wang1
1 State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, 210098, People’s Republic of China
2 Department of Civil and Environmental Engineering, Western University, London, Ontario, Canada
3 Joint International Research Laboratory of Global Change and Water Cycle, Hohai University, Nanjing, 210098, People’s Republic of China
4 Yangtze Institute for Conservation and Development, Hohai University, Nanjing, 210098, People’s Republic of China
* Author to whom any correspondence should be addressed.
E-mail: zyu@hhu.edu.cn

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Abstract
Interactions among human and natural systems are fundamental to many issues facing today’s sustainable development. Yangtze Economic Belt (hereafter Belt), one of the most dynamic regions in China, is of no exception. The economic prosperity of the Belt, however, comes at the price of ecological and environmental degradation, which poses severe challenges to its sustainable development. This paper describes the application of the ANEMI_Yangtze system dynamics model, aiming at identifying the main challenges facing the Belt and the potential way out towards its sustainable development. Three scenarios are proposed to (i) explore the potential impacts of climate change; (ii) examine how changes in birth control policy affect population dynamics and the natural-environmental systems; and (iii) investigate how policies aimed at improving the eco-environment conditions affect the Belt. Results show that a moderate rise in temperature is beneficial to the Belt’s economy and energy-food-water systems, but further temperature rise is harmful. Population in the Belt peaks around 2030, 2080, and 2100 under one-child, two-child, and three-child policies, respectively. Suppose no major changes in economic, technological, and policy developments are introduced. In that case, the Belt may face a serious energy deficit ranging from 10 to 17 billion tce. A food self-sufficiency ratio will fall from around 0.7 to 0.39 by 2100 as the country’s birth control policy loosens. Water scarcity occurs if surface water is considered as the only supply and this situation becomes even more serious when water pollution effects are considered. However, water stress will be greatly alleviated if groundwater and wastewater reuse are introduced. The policy of increasing nutrient removal efficiency can save million lives. Finally, our results also suggest that the recently introduced 10-year fishing ban policy can not prevent the Yangtze fish stock from depletion in the long run.

1. Introduction
The global population was projected to peak at 8.5–10.9 billion around the mid-21st century, with much of this growth happening in the less developed Asian countries like India and China (KC and Lutz 2014, Vollset et al 2020). These developing Asian countries are thus facing an increasing challenge in meeting the growing demands for food, water, and energy, which is further compounded by climate change (Rasul and Sharma 2015). Byers et al (2018) conclude that for future populations in Africa and Asia who are more vulnerable to poverty, their exposure to climate change-related risks is very high. China, the world’s most populous country, feeds 22% of the global population with only 10% of the freshwater and 6.5% of the arable land (Peng 2011) and is also among the most affected countries by climate change (Turral et al 2011). The increasingly severe water-food-
energy scarcity seriously threatens the country’s sustainability (Jiang 2015). The challenges facing China are also widely recognized as the main economic and environmental issues facing the world today and the underlying mechanism of which can be attributed fundamentally to the interactions among human and natural systems (Liu et al 2007, Alberti et al 2011, Kramer et al 2017, Tromboni et al 2021). However, understanding those interactions and feedback is a demanding task and involves great cooperation among different disciplines (van Vuuren et al 2012, Dunford et al 2014, Hamilton et al 2015, Albrecht et al 2018, Liu et al 2019).

Integrated assessment modeling approach, with various ways of presenting system components, has been adopted for a long time to analyze complex feedback structures between human and natural systems which evolve over time (Meadows et al 1972, Sokolov et al 2005, Stehfest et al 2014, Calvin and Bond-Lamberty 2018, Calvin et al 2019). According to how they characterize the economy, Integrated Assessment Models (IAMs) can be classified into optimization and simulation models (Scrieciu et al 2013). Optimization models generally use neoclassical production functions, i.e., Constant Elasticity of Substitution (CES) functions, and assume that markets clear and that a general equilibrium can be reached. The computable general equilibrium models are the most representative optimization models due to the usual convergence to markets equilibrium; they are, however, often criticized for not being grounded in the complex and dynamic reality (Nieto et al 2020).

Simulation models are often policy evaluation models and do not optimize, which means markets may not clear, or reach the equilibrium. The most significant advantage of simulation models is that they allow the propagation of disturbances into the system to be examined and the outcomes of various policy scenarios to be evaluated. In addition, simulation models fit better with dynamic modelling and allow easier integration between the economic sector and the other social and biophysical system sectors. There are now many simulation-based IAMs, including the ANEMI (Simonovic 2002, 2002a, Davies and Simonovic 2010, 2011, Simonovic and Breach 2020, Breach and Simonovic 2020, 2021), IMAGE (Stehfest et al 2014), and AIM (Matsuoka et al 1995) to name a few. These available IAMs are usually developed at the global or regional scale and are therefore of less value to local policymakers. Downscaling global IAMs to regional scales to address local-specific challenges are therefore in urgent need (Akhtar et al 2019, Breach and Simonovic 2020, 2021). In addition, most of the current regional human–natural integrated assessment research is for North American and European countries, and limited research is available for Asian countries (Wang et al 2019).

Yangtze Economic Belt is one of the most dynamic regions in China in terms of population growth and economic development and constitutes up to 40% of the country’s population and GDP. From the introduction of the Belt in 2016, the processes of urbanization and industrialization are expected to continue to gain momentum in the foreseeable future (NDRC 2016). However, the fast urbanization and economic growth in the Belt pose severe challenges for its sustainable development under changing environment. The Yangtze river basin, especially its head region, is vulnerable to global warming. Accumulating evidence shows that climate change alters the hydrological cycle in the basin and results in more frequent extreme meteorological events (Gu et al 2015, Su et al 2017). Besides the exposure to climate change, the socioeconomic development of the Belt also occurs at the expense of depletion of non-renewable resources and degradation of the eco-environmental system. China has the world’s largest coal reserves and 56% of its energy consumption currently comes from coal (Su 2019). The Yangtze river basin, however, is very poor in fossil fuel endowments (Wang et al 2020). Data from China Energy Statistical Yearbook indicates that in 2015 the coal consumption in the Belt was 1.28 billion tonnes, of which 0.73 billion tonnes were imported (DENBS 2016). The population growth and urban expansion occupy many rich farmlands; data from 2000 to 2015 shows that urban areas in the Yangtze river basin experienced an increase by 67.5% whereas cropland decrease by 7.5% (Kong et al 2018). The declining rich farmland threatens food security as the plains in the middle and lower reaches of the Yangtze river basin are the national ‘granaries’ (Cai and Tu 2020). Besides, the increasing application of fertilizers and pesticides, municipal waste from a growing population and the rapid development of industry lead to serious water pollution problems (Wong et al 2007, Xu et al 2010, Li et al 2011, Xia et al 2016). It was documented that 86.9% of the major lakes and 35.1% of the major reservoirs in the Yangtze river basin suffered from eutrophication (YRWRC 2016). Also, fish stocks in the Yangtze river are seriously depleted. To date, wild fish catches dropped from about 427 thousand tonnes in the 1950s to less than 100 thousand tonnes (Zhang et al 2020). To repair the eco-environmental conditions of the Yangtze river, the development paradigm has shifted from ‘large-scale development’ to ‘green development’. For example, in response to this shift in policy, the government issued a 10-year commercial fishing ban on the Yangtze river in 2020; the 13th National People’s Congress passed a law on protecting the Yangtze river on December 26, 2020. However, it remains poorly understood how the socioeconomic and eco-environmental systems in the Belt interact and what is the synergy evolution of complex human–natural systems? Further, the 7th census completed by the end of 2020 shows that the Chinese population has reached 1.4 billion and the population aged 65 + accounts for 13.50%, which is an increase of 5.44% compared to the 6th census data from 2010, indicating an increasingly serious ageing problem (State Statistical Bureau 2021). To cope with the ageing problem, the Political Bureau of the CPC Central Committee held a meeting on May 31, 2021 and proposed a 3-child policy. This 3-child proposal raised wide public
concerns, like how will changes in national birth control policy affect population dynamics and what this might mean for consumption of resources and environmental degradation? All of these questions remain unanswered. Therefore, by applying the ANEMI_Yangtze model, which is 'downscaled' from its parent global model ANEMI to fit the Yangtze Economic Belt, this paper tries to address the above questions and assess potential way out towards sustainable development. In addition, the presented research also aims to contribute to the regional human-natural integrated assessment research.

The rest of the paper is structured as follows: section 2 describes the methodology. Section 3 discusses simulation results under different policy scenarios. Section 4 summarizes the key findings and discussion. Section 5 offers some policy implications and future studies. Appendix in section 6 summarizes the major mathematic equations in ANEMI_Yangtze.

2. Methodology

2.1. Data
Historical data for population, economy, energy, and food in the Yangtze Economic Belt are collected from the China Statistical Yearbook published by the National Bureau of Statistics (NBS) of China annually (available online at http://stats.gov.cn/english/, last accessed Sep 12, 2021). Land use data are from ESA Climate Change Initiative - Land Cover (http://maps.elie.ucl.ac.be/CCI/viewer/ last accessed Sep 12, 2021). Historical precipitation, evapotranspiration, and temperature data are collected from the hydrometeorological stations within and around the Belt. Projected temperature and precipitation data under Representative Concentration Pathways RCP 4.5 and RCP 8.5 are from Yu et al (2018). Water withdrawal data are from the China Water Resources Bulletin published by Ministry of Water Resources of the People’s Republic of China annually. Fish data are from Zhang et al (2020).
2.2. ANEMI_Yangtze modeling framework

The ANEMI_Yangtze is a highly coupled integrated simulation modeling framework that captures the interlinkages and feedbacks between human and natural systems in the Yangtze Economic Belt (Jiang and Simonovic 2021, Jiang et al 2021). The architecture of ANEMI_Yangtze consists of three layers: (i) the upper policy layer; (ii) the middle interacting layer describing socio-economic, natural resources and eco-environmental systems; and (iii) the lower impacts assessment layer, see figure 1. Different policies can be proposed in the policy layer. They directly affect the socio-economic system, natural resources system, and eco-environmental system. In the systems interacting layer, the interactions among the nine sectors of population, economy, land cover and land use, food, energy, water, nutrients cycle, carbon cycle, and fish are captured. In the impacts layer, the GDP per capita, food self-sufficiency, energy deficit, water stress, nutrients concentration, carbon emissions, and fish yield can be assessed.

The ANEMI_Yangtze modeling framework provides support for: (1) scenario development: ANEMI_Yangtze model can develop possible alternative scenarios by combining inputs into different model sectors; (2) policy assessment: the ANEMI_Yangtze model evaluates the trade-offs reflected by different scenarios and answers the questions such as how will the future unfold if no apparent changes in economic, technology, and policy developments are assumed, and how will policies and management strategies within one sector affect the other sectors.

2.3. An example of a coupled system: the food sector

The nine sectors in ANEMI_Yangtze are highly interconnected. However given the manuscript length limitations, we only describe the ANEMI_Yangtze’s representation of the food sector as an example. The food sector is linked with the population, land, and water sectors. On the one hand, population growth drives the demand for food and land reclamation through clearing and burning forest and grassland, but on the other hand, it results in more agricultural land being claimed for urban use. Land reclamation drives the demand for...
irrigation, resulting in water stress, which reduces land yield and food production. The interactions and feedbacks within the food sector are presented in figure 2. Feedback loops A4, B4, and C4 illustrate the impacts of land yield technology, agricultural land development, and fertilizer subsidy, respectively, on food production measured by food self-sufficiency. The food self-sufficiency index is defined as the ratio of food production to food consumption. As the country’s three-child policy gradually comes into effect, the demand for food rises. An increase in food consumption decreases food self-sufficiency. When the value of food self-sufficiency ratio declines below 0.95 (a critical value) the country manages to ensure food security (Ye et al 2013) by providing incentives for land yield technology input, agricultural land development, and fertilizer subsidy that drive up the land yield. This eventually increases the food production and correspondingly the food self-sufficiency ratio, forming the negative feedback loops A4, B4, and C4. Feedback loops D4, E4, and F4 depict the introduction of multiple cropping practices and willingness to increase grain planting area and their impact on food production using as indicator the food price change. A decrease in food production decreases food stock and, correspondingly, the value of food stock coefficient, which is defined as the ratio of food stock to expected food stock. A decrease in the food stock coefficient increases the expected food price and the food price change, which encourages multiple cropping practices (multiple cropping index) and the willingness to increase grain planting area. An increase in grain planting area increases food production, thus forms the negative feedback loops E4 and F4. The positive feedback loop D4 offsets the positive effect of adopting multiple cropping practices by decreasing land fertility and the corresponding land yield. These interactions and feedbacks among/within the food sector and the population, land, and water sectors in ANEMI_Yangtze finally drive the dynamic behaviour of the food system in the Belt.

2.4. ANEMI_Yangtze model sector functionalities and underlying theory
The comprehensive model description, including the theoretical basis, the interactions and feedbacks among and within different sectors, causal feedback loops and stock and flow diagrams, are available in Jiang and Simonovic (2021) and Jiang et al (2021). The following brief presentation provides the basic methodological approach of each model sector and its functionalities. The mathematic equations are presented × in the Appendix. The symbols used in the equations are defined in table A1.

2.4.1. Population sector
This sector consists of three variables: births, deaths, and migrations and the dynamics of which are all affected by GDP per capita. The effect of water pollution on life expectancy is also taken into account. The population stock is split into three different demographics of ages 0 to 14, 15 to 64, and 65+ to capture the effects of delays in demographic responses to external changes, which thereby affect birth and death rate.

2.4.2. Economy sector
This sector is based on the FREE model by Fiddaman (1997) that is used to compute the gross output in the Belt. The gross output is represented as a function of labour and operating capital in the form of a Cobb-Douglas production function. Operating capital equals the long-run CES capital-energy aggregate. Climate damage is introduced to represent the effect of climate change impact on the output.

2.4.3. Land sector
This sector consists of six IPCC land categories, i.e., agricultural land, forest, grassland, wetland, settlement, and other lands. A transfer matrix is adopted to depict the change rate at which one land cover type changes into another, driven by the population growth rate. The land transfer matrix works as a reservoir where inflow is land transfer rate and outflow is drain transfer value, which is used in the model to avoid any negative term. The land transfer matrix is used to drive the change in biome area at a rate equal to the sum of the transfer rates from biome i to biome j, minus the sum of transfer rates from biome j to biome i.

2.4.4. Food sector
This sector consists of food production, food import, and food export. Food import/export is affected by local food price, and international price and its calculation is adapted from Wang et al (2009). Food production is affected by land yield, total arable land, and water stress. The behaviour of food production is mainly driven by the difference between perceived and desired food self-sufficiency which serves as an indicator for land yield technology input and fertilizer subsidy. The change of food price is another factor affecting food production through the adoption of multiple cropping practices.
2.4.5. Energy sector
This sector consists of energy requirement, energy capital, and energy production and considers six types of energy resources, three renewables (hydropower, nuclear, new energy sources) and three non-renewables (coal, oil, gas). Energy requirement by the source is the production of desired energy share, gross output, and energy consumption intensity. Energy capital is the capital stock accumulated into each energy source. Energy production is mainly determined by energy capital and production limitations which are in the form of depletion for non-renewables and saturation for renewables. The effect of technology on energy requirement and energy production is also simulated.

2.4.6. Water sector
This sector consists of the hydrological cycle, water demand, water supply, water supply capital, and water stress. The hydrological cycle simulates the circulation of water from the atmosphere (precipitation) to the land surface storage and groundwater and then back to the atmosphere (evapotranspiration) and to the East China Sea. Water demand is the sum of the demand from domestic, industrial, and agricultural sectors. Domestic water demand depends on structural water intensity, industrial water demand mainly consists of the water demand in generating electricity, agricultural water demand is the production of net arable land and per hectare water withdrawal and is also affected by changes in surfaces temperature. Water stress has four definitions: base water stress, water stress with groundwater and wastewater, water stress with pollution effects, and water stress with water supply capacity. Their calculations are provided in the Appendix. Total water supply capacity consists of three sources: surface, ground, and wastewater reclamation. The production of water supply is driven economically by investing in the capital stock for each water supply source. The effect of water stress on water supply capital investment is also included.

2.4.7. Carbon sector
This sector depicts the terrestrial cycle of carbon in the Belt, which includes the passing of carbon from the atmosphere to the biomass through net primary productivity and the passing chain from the biomass to litter, to humus, and to stable humus and charcoal. The total carbon emissions into the atmosphere consist of the fossil fuel emissions from the energy sector and the land-use emissions such as the burning and clearing of forests from the land sector.

2.4.8. Nutrients sector
This sector describes the movement of nitrogen (N) and phosphorus (P) from various reservoirs, including the atmosphere, vegetation, soils, and rivers and lakes in the Belt. The cycle of N depicts the passing of N from land biota to humus through the death of living biomass and to inorganic soil through organic decomposition and back to land biota through soil uptake. It also includes the passing of N from humus and inorganic soil to rivers through the weathering of organic and inorganic nitrogen. The P cycle follows the N cycle except that there exists a route passing the P from rivers to the land biota through the process of biological uptake. Anthropogenic inputs of N and P in the nutrients cycle are calculated from the wastewaters in the domestic and industrial sectors as well as from agricultural returnable flows. For domestic and industrial wastewaters, the nutrient inputs are calculated based on the amount of untreated wastewater adjusted for wastewater reuse and treated wastewater with exogenous removal efficiencies of N and P applied. Agricultural nutrients inputs are based on the amount of arable land that is used for food production and the nutrients leaching factors.

2.4.9. Fish sector
This sector describes the dynamic behaviour of fish biomass stock over time. The effect of water pollution which affects fish natural mortality and the effects of dams and reservoirs and ship cargo which affect fish birth rate are considered.

3. Simulation scenario analyses
A set of scenarios is proposed to analyze the human-natural system's behaviours in the Belt. The objective and policy setting for each scenario are summarized in table 1. The simulation results under each scenario are provided in the following sections. The time horizon of the model is 1990–2100 and the time step is one year. The reason why we project our simulation into 2100 is that the birth control policy usually shows its impact decades or generations later. In addition, integrated assessment modelling literature is commonly using 2100 as the simulation time horizon. In this paper, simulation results are only displayed and discussed for the period 2020–2100.
3.1. Climate change impacts

The main drivers of climate change are greenhouse gas emissions. In this research, the exogenous temperature and precipitation change under Representative Concentration Pathways RCP 4.5 and RCP 8.5 (corresponding to the $S_{\text{climate}}(1)$ and $S_{\text{climate}}(2)$ scenarios) from Yu et al (2018) are used. The major impacts of climate change on the Belt are shown in figure 3.

Climate change directly affects the Belt system in two ways. One is increasing surface temperature drives the water in the hydrologic cycle to move faster, resulting in an increase in evapotranspiration and more extreme and frequent rainfall and streamflow. Figure 3(j) shows the impact of increasing surface temperature on evapotranspiration. As can be seen, the evapotranspiration rates for RCP 4.5 and RCP 8.5 scenarios rise up significantly due to the increase in surface temperatures, leading to an increase in evapotranspiration by nearly 18% by 2100 for the RCP 8.5 scenario. For RCP 4.5 and RCP 8.5 scenarios, the surface water resources fluctuate around the base run value (figure 3(k)), with a slightly higher value for the RCP 4.5 scenario and a much lower

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Table 1. The objective and policy setting of each scenario.

| Scenario    | Objective                                                                 | Policy setting                                                                 |
|-------------|---------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| $S_{\text{base}}$ | Allows for the investigation of the human and natural systems’ general behaviour and serves as a starting point for comparison with other scenarios. | Use the original parameter set without any modifications: one-child policy; fish mortality remains at 2015 level (no fishing ban policy); N/P removal efficiency is 0. |
| $S_{\text{climate}}$ | Allows for investigating climate change impacts on socio-economic development and natural resources. | The exogenous temperature and precipitation change under RCP 4.5 and RCP 8.5 emission scenarios from Yu et al (2018) are used to drive the hydrological cycle in the Belt. |
| $S_{\text{population}}$ | Allows for the investigation of the feedbacks between population growth and the depletion of natural resources and water pollution. | $S_{\text{population}}(1)$ and $S_{\text{population}}(2)$: the woman of childbearing age shall give birth to 2 and 3 children after 2020, respectively. |
| $S_{\text{eco-environment}}$ | Allows for assessing various policies aimed at improving Yangtze’s eco-environment. | $S_{\text{N/P removal}}$: increase N/P removal efficiency from 0 to 0.6 and 0.7 for nitrogen and phosphorus respectively by 2100. $S_{\text{fish ban}}$: a fishing ban of 2, 5, and 10 years respectively starting from 2020. $S_{\text{fish mortality}}$: fish mortality ranges from 0.6 to 0.7. |
The availability of surface water directly affects the concentration of nutrients. Figure 3 generally shows a reduction in the concentration level of nitrogen for the RCP 4.5 scenario and an increasing trend for the RCP 8.5 scenario compared to the base run (the same change of behaviour is noted for phosphorus, results not shown in the figure). As high nutrient levels negatively impact life expectancy, it is expected to see a slight increase in population for RCP 4.5 scenario and a slight decrease for RCP 8.5 scenario by 2100 compared to the base run (figure 3(a)). The water demand for agriculture (figure 3(c)) increases substantially under the RCP 4.5 (S_climate(1)) and RCP 8.5 (S_climate(2)) climate scenarios as temperature feedback was considered when calculating the per hectare water withdrawal and consumption. The combined effect of water demand and available surface water finally results in generally higher water stress, especially under the RCP 8.5 scenario, as displayed in figures 3(f)–(i).

The other direct impact of climate change is the damage to the economic output through a climate damage function, shown in figure 3(b). The climate damage effect, representing the impact on economic output, varies from 1 (base run, no climate impact) to a range between 0.9996 and 0.9983 for RCP 4.5 and RCP 8.5 climate scenarios in 2100. Under the RCP 4.5 scenario, climate damage appears to level off by the end of the simulation. In the case of RCP 8.5, the negative slope is increasing. The combined effect of climate damage and the population variation results in a reduction in economic output by 0.04% and 0.34% under RCP 4.5 and RCP 8.5 scenarios, respectively, compared to the base run output. These results confirm that the impact of climate change on the Belt’s economy is negligible, as shown in figure 3(b).

3.2. Population policy impacts

3.2.1. Population policy impacts on energy-economy system
Results in figure 4(a) show that the population in the Belt grows through 2030, 2080, and 2100, peaking around 642, 820, 1400 million under S_base, S_population(1) and S_population(2) scenarios, respectively (corresponding to the one-child, two-child, and three-child policies). The dynamic behaviour of population growth is the combined consequence of child policy and pollution, with the former positively impacts total fertility while the latter negatively on life expectancy. The dynamic behaviour of economic output in the Belt grows with the magnitude of the labour force as expected (shown in figure 4(b)). In the S_population(2) scenario, gross output reaches 66,169 billion 1990 RMB by 2100, nearly triples the S_base run value, 22,540 billion 1990 RMB. Even though the magnitude of gross output is relatively high, the GDP per capita tells quite a different story. As was shown in figure 4(c), the GDP per capita grows fastest under the S_base scenario and grows slowest under S_population(2) scenario. The dynamic behaviour of energy requirement follows basically the same pattern as gross output, except that it grows at a slower rate as can be seen from the shape of the relationships (figure 4(d)). This is because energy requirement is embodied in the economic output. This explains the similar behaviour of energy requirement and gross production. In our research, the effect of technology on energy consumption is also considered, explaining the difference between the two behaviour modes. Energy production, however, grows much slower than energy requirement, see figure 4(e), due to the minimum reserve of fossil fuel in the Yangtze river basin. The energy deficit, which is the difference between production and requirement, reaches roughly 10 and 17 billion tce by 2100 under S_population(1) and S_population(2) scenarios (see figure 4(f)).
3.2.2. Population policy impacts on food system

The dynamic behaviour of food production is quite complex because of the multiple feedbacks acting simultaneously on land yield and grain planting area, which together determine food production behaviour modes. As can be seen from figure 5(a), the food production for S_base scenario declines from 2020 to 2100 gradually under the combined effects of a decrease in agricultural land due to urban expansion and a decline of land fertility due to low fertilizer subsidy and a slow land yield technology improvement as a result of a rising food self-sufficiency (see figure 5(b)). Food self-sufficiency of 0.95 is treated as a critical point when the fertilizer subsidy and land yield technology inputs are needed to prevent its value from further decline (Ye et al 2013). The food productions for S_population (1) and S_population (2) scenarios both exhibit an overshoot and decline mode behaviour, where they both peak around 2040 and then drop rapidly afterwards. The increases in food production before 2040 are attributed to an apparent increase in land yield due to fertilizer subsidy and land yield technology inputs and an increase in grain planting area due to the increase in adopting multi-cropping practice and willingness to increase grain planting area both as a result of a declining food self-sufficiency. After 2040 the effects of adopting multi-cropping practice, which increases grain planting area, are outpaced by a shrinking agricultural land area (see figure 5(c)) because of the expanding human settlement area due to population growth. This results in a net decrease in grain planting area (see figure 5(d)), which eventually drives the production of food to drop rapidly expect the increase in land yield (figure 5(e)). In 2100, the food production under S_population (1) scenario declines to the base run value level while the food production under S_population (2) scenario even drops below the base run value. That causes the food self-sufficiency values to...
stabilize around 0.70 for S_population (1) scenario and continuously decline to 0.39 for S_population (2) scenario, far below the critical value 0.95, by the end of the simulation time horizon.

3.2.3. Population policy impacts on water and eco-environmental systems

Population growth affects all levels (domestic, industrial, agricultural) of water demand. In the case of domestic water demand (figure 6(a)), it follows the behaviour pattern of the population with peaks observed around 2040, 2080, and 2100 under S_base, S_population (1) and S_population (2) scenarios, respectively. Domestic water demand depends on structural water intensity, which relates GDP per capita to withdrawal rate per person based on the conceptual model of Alcamo et al (2003). Starting from around 35 m$^3$/person/year in 1990, the domestic structural water intensity in the Belt increases from 35 m$^3$/person/year in 1990 as the economy grows and finally stabilizes at about 75 m$^3$/person/year around 2040 as the region becomes developed. This explains the difference in peaking time between population (2030) and domestic water demand (2040) under the S_base scenario. In the case of industrial water demand (figure 6(b)), its growth is primarily based on economic output growth. The generation of electricity from coal and gas-fired thermal power plants typically dominates water withdrawal in the industrial sector. Agricultural water demand is determined mainly by the amount of irrigated agricultural land, so its behaviour mode, shown in figure 6(c), has the same pattern as the grain planting area as illustrated by figure 5(d) and discussed in the previous section. The total water demand in the Belt reaches 724 billion, 1.12 trillion, and 1.70 trillion m$^3$ by 2100 for S_base, S_population (1), and S_population (2) scenarios respectively (figure 6(d)).

Growing population and economic output increase the demand for water in domestic, industrial, and agricultural sectors, thereby increasing the pressure on freshwater resources. As visible in figure 6(e), the Belt’s water stress rises above the critical value around 2090 and 2070 for S_population (1) and S_population (2) scenarios, respectively, when surface water becomes the only source. When pollution effects are considered, the Belt’s water scarcity problem worsens and even the base run water stress exceeds 1 by the end of the simulation (figure 6(f)). However, when groundwater and wastewater reuse are considered, the water stress situation improves. The water stress values range from 0.4 to 0.8 by the end of the simulation under all three scenarios (see figure 6(g)). When the water stress is calculated as the ratio of water demand to water supply capacity, it is found that under all three scenarios its value is below the critical value 1 (figure 6(h)), indicating that the water supply development can provide enough water for human uses.

Figure 7. Impacts of improving nutrients removal efficiency on population system.
It is expected that with the growth of population and development of the economy, the emission of carbon from fossil fuel consumption and the emission of nutrients such as nitrogen and phosphorus rise up correspondingly (see figures 6(i)–(k)).

3.3. Eco-environment policy impacts
By improving the nitrogen removal efficiency in wastewater treatment, the levels of nutrient concentration decrease, as expected, by 27% for nitrogen and by 16% for phosphorus, as shown in figures 7(a), (b). As nutrients concentration acts as a negative multiplier that decreases life expectancy, it is expected to observe an increase in the lifetime multiplier from the reduction in pollution (figure 7(c)) and an improvement in life expectancy (figure 7(d)), leading to an increase in population by over 4 million persons by 2100 (figure 7(e)).
This section explores the impacts of various fishing bans lasting for 2, 5, and 10 years respectively and the effects of fish mortality on the fish biomass in the Yangtze River. The results are shown in figures 8 and 9.

As shown in figure 8(a), fish yield drops exponentially for S_base run under the reference constant fish mortality, which is around 0.8. The fish yields under the 2, 5, and 10 years fishing ban scenarios are shown in figures 8(b)–(d). The significant difference among the three fishing ban scenarios is in the fish yield peak value of 28,000, 180,000, and 4 million tonnes shortly after the fishing ban is over. The fish yield decreases exponentially to the base run value around 2050 for all three scenarios, indicating that simply adopting a fishing ban policy cannot prevent Yangtze fish stock from depletion in the long run. To provide more information for decision-making, we test the dynamic behaviour of fish population at various fish mortality rates ranging from 0.6–0.7. For the time period of 1990 to 2100, the results in figure 9(a) show that when fish mortality is 0.61, fish yield exhibits a continuous increase, indicating that the positive feedback loop of fish birth and fish biomass stock dominates the fish system. When fish mortality ranges from 0.62 to 0.7, fish yield shows overshoot and collapse behaviour, indicating that the negative fish yield feedback replaces the positive feedback of fish birth. The accumulated fish yield decreases substantially with the increase in fish mortality (figure 9(b)).

4. Conclusions and discussion

In this study, we investigate the dynamic behaviour of the Yangtze Economic Belt in China under three policy scenarios focusing on climate change, birth control, and eco-environmental improvement, respectively. The objective of the S_climate experiment discussed in Section 3.1 is to assess the climate change impacts through feedback processes represented within the ANEMI_Yangtze model. The potential impacts of climate change on the Belt are assessed using exogenous inputs of precipitation and temperature in the Yangtze river basin under RCP 4.5 and RCP 8.5 scenarios. We found that a rising surface temperature results in higher agricultural water withdrawal and consumption. However, the higher agricultural demand does not significantly increase the stress of water resources since water demand in the agricultural sector is relatively small compared to the demand in the industrial sector. The impacts of climate change on the Belt’s economy, energy, and food systems are also negligible, and moderate temperature rise in RCP 4.5 scenario is beneficial for the availability of water resources and population growth. However, an obvious temperature rise as was shown in RCP 8.5 scenario is harmful to the Belt.

The objective of the S_population experiment presented in Section 3.2 is to investigate the impacts of birth control policy on population growth and the feedbacks between population growth and resources depletion, and water pollution. It is found that the population in the Belt peaks around 2030, 2080, and 2100 under the one-child, two-child, and three-child policies, respectively. It is also found that the Belt’s total gross output grows with the increase in the labour force boosted by the increase in population. The GDP per capita, however, drops with the relaxation of the birth control policy. As energy requirement is integrated in economic output, the Belt is expected to see a high increase in energy demand following population growth. The Belt’s ability to produce energy is, however, very limited because of the minimum reserve of fossil fuel in the Yangtze river basin. The Belt shall experience a serious energy shortage crisis, with a 17 billion tce energy deaccumulated from depletion in the long run. Therefore, the authors strongly recommend further investigation of sustainable fish yield.

This paper identifies the main challenges facing the sustainable development of the Yangtze Economic Belt from an integrated point of view. While the analyses provide important insights, the simulation results should be interpreted with caution. Firstly, it should be noted that there are several climate change-related impacts that are not yet captured by the current research, which may underestimate some of the findings. For example, the
impact of CO₂ fertilization on land yield; the impact of rising temperature on extreme hydrometeorological disasters; and other impacts are not incorporated in the model at the current development level. It should also be noted that the S_population experiment results are obtained by assuming that there are no significant changes in economic, technological, and policy developments. So the energy and food crisis in this research may be overestimated. The authors believe that this situation can be significantly alleviated under improved resource use efficiency, the adaptation of advanced new technology, and the implementation of favourable policies. Secondly, it is worthwhile to mention that ANEMI_Yangtze model is not meant to predict the future for the development of Yangtze Economic Belt. Rather, it aims to help understand the behavioural consequences of various policy options. In addition, even though ANEMI_Yangtze is time-efficient, user-friendly, and allows easier addition of more details into the model, as a simulation model, ANEMI_Yangtze can not optimize, which means the model can not provide the decision-makers with the ‘best’ solution.

5. Policy implications and future studies

Based on the study findings and conclusions, our recommendations for future research and for policy implications are as follows. The ANEMI_Yangtze model is the first integrated framework that captures the inter-linkages and feedback among various systems within the Yangtze Economic Belt, thus filling in the critical gaps through a comprehensive assessment of the development impacts on the socio-economic and natural-environmental systems. The model is designed to capture key characteristics of the underlying systems; however, because it focuses on the interactions among systems, some of the details that may still be important for capturing system dynamics are not included. For example, as discussed in the previous section, several climate change-related impacts have not yet been captured by the current research. Therefore, more details should be incorporated according to the state-of-the-art knowledge in the future. In addition, the current research does not include human adaptation to climate change and/or social, economic, and environmental changes. However, investigations of human adaptation by introducing changes in economic, technological, and policy developments shall be our future research focus. As for policy implications for the Belt, our research indicates that the most pressing issue facing the Belt is energy. By shifting the energy consumption pattern from fossil fuels to clean energy, the Belt can fulfill its duty of cutting carbon emissions and alleviating water stress and significantly decrease its dependence on energy import. The multiple benefits of raising the ratio of renewable energy sources are obvious, and prioritizing clean energy, such as hydropower and nuclear power, is of great urgency for sustainable development of the Belt. Yangtze fish stock, which is an important food source, is under serious decline. To restore the deteriorating ecosystem and enrich aquatic biodiversity in the Yangtze river, the central government recently passed a 10-year fishing ban. However, our results indicate that the 10-year fishing ban alone can not prevent the Yangtze fish stock from depletion in the long run. It is the ‘optimum sustainable yields’ that can ensure sustainable development of fishery in the Yangtze River. Therefore, further investigation of sustainable fish yield is strongly recommended.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
Appendix. Mathematic equations and symbols in the equations

The ageing chain of population groups can be represented as:

\[
P_{0-14} = \int \left( \text{births + net}M_{0-14} - P_{0-14} \cdot M_{0-14} - \frac{P_{0-14} \cdot (1 - M_{0-14})}{\tau_1} \right) dt
\]

\[
P_{15-64} = \int \left( \text{net}M_{15-64} + \frac{P_{15-64} \cdot (1 - M_{15-64})}{\tau_1} - P_{15-64} \cdot M_{15-64} - \frac{P_{15-64} \cdot (1 - M_{15-64})}{\tau_2} \right) dt
\]

\[
P_{65+} = \int \left( \text{net}M_{65+} + \frac{P_{15-64} \cdot (1 - M_{15-64})}{\tau_2} - P_{65+} \cdot M_{65+} \right) dt
\]

The total fertility, life expectancy, and migration rate are calculated using the following relations:

\[
\begin{align*}
\text{TF} &= \text{MIN} (\text{MTF}, (\text{MTF} \cdot (1 - F_{\text{control}}) + DTF \cdot F_{\text{control}})) \\
\text{LE} &= (\text{LE}_{\text{normal}} + F_{\text{GDP/capita}} + F_{\text{health}}) \cdot \text{Pollution}_{\text{multi}} \\
\text{MR} &= F_{\text{GDP/diff}} \cdot MW \cdot MP \cdot F_{\text{crowding}}
\end{align*}
\]

The major equations in the economic sector are as follows:

\[
\begin{align*}
Y &= \Omega_0 A_0 \left( \frac{L}{L_0} \right) \left( \frac{KO}{K_{00}} \right)^{(1-\alpha)} \\
\Omega &= \frac{1}{1 + \theta} \left( \frac{T - T_a}{T_{\text{ref}}} \right)^{\phi}
\end{align*}
\]

The main equations in the land sector are originally based on the model of Goudriaan and Ketner (1984) and represented as,

\[
\begin{align*}
L_{\text{trans}} &= L_{\text{tn}} - L_{\text{td}} \\
L_{\text{tn}} &= \int (L_{\text{trans}} - L_{\text{td}}) \cdot dt \\
\frac{dA_j}{dt} &= \sum_{i=1}^{6} a_{ij} - a_{ji}
\end{align*}
\]

The main equations in the energy sector shown in equation (6) are based on those developed by Fiddaman (1997), which incorporates the energy and economy models from Sterman (1980).

\[
\begin{align*}
\text{ER}_i &= \gamma_{\text{decrease}} Y \cdot \text{ERI}_{\text{agr},0} \cdot f_{\text{FE}} \\
\text{KE}_i(t) &= \int \left( \frac{K_{0i}}{\tau_{C}} - \frac{\text{KE}_{0i}}{\delta_{i}} \right) dt \\
\text{EP}_i &= \text{EP}_{t,0} \left( \frac{R_{i}}{R_{t,0}} \right)^{\alpha_{i}} + (1 - \alpha_{i}) \text{EI}_{i,0}^{(1-\delta_{i})} \right) \frac{1}{\tau_{i}} \\
\text{EI}_{i} &= T_{E} \left( \frac{\text{KE}_{i}}{\text{KE}_{t,0}} \right)^{\beta_{i}} \left( V_{\text{relative},0} \right)^{(1-\delta_{i})}
\end{align*}
\]
| Sector | Symbol | Description                      | Unit       |
|--------|--------|----------------------------------|------------|
| Population | $P_i$ | population                       | $10^6$ person |
|         | $netM_i$ | net migrations                 | $10^6$ person/year |
|         | $M_i$ | mortality rate                   | $10^6$ person/year |
|         | $\tau_i$ | length of time spent in sub-demographic | year |
|         | $TF$ | total fertility                   | dmnl |
|         | $MTF$ | maximum total fertility           | dmnl |
|         | $F_{control}$ | fertility control effectiveness | dmnl |
|         | $DTF$ | desired total fertility           | dmnl |
|         | $LE$ | life expectancy                   | year |
|         | $LE_{normal}$ | normal life expectancy         | year |
|         | $F_{health}$ | health service factor            | dmnl |
|         | $F_{crowding}$ | lifetime multiplier from pollution | dmnl |
|         | $MR$ | migration rate                    | $10^6$ person/year |
|         | $F_{GDP\_diff}$ | GDP difference factor           | dmnl |
|         | $MW$ | migration willingness             | dmnl |
|         | $MP$ | migration policy                  | dmnl |
| Economy | $Y$ | gross output                      | RMB |
|         | $L$ | labour force                       | $10^6$ person |
|         | $KO$ | operating capital                 | operating RMB |
|         | $A_t$ | factor productivity               | dmnl |
|         | $\alpha$ | value share of labour           | dmnl |
|         | $\Omega$ | climate damage effect         | dmnl |
|         | $Y_0$ | reference gross output            | RMB |
|         | $L_0$ | reference labour force            | $10^6$ person |
|         | $KO_0$ | reference operating capital       | operating RMB |
|         | $\theta$ | climate damage scale factor     | dmnl |
|         | $T$ | atmospheric temperature           | °C |
|         | $T_a$ | adapted temperature               | °C |
|         | $T_{ref}$ | reference temperature           | °C |
|         | $\phi$ | climate damage non-linearity factor | dmnl |
Table A1. (Continued.)

| Sector | Symbol | Description | Unit |
|--------|--------|-------------|------|
| Land   | $L_{\text{trans}}$ | land transfer rate | km$^2$/year/year |
|        | $L_{\text{tm}}$ | transfer matrix | km$^2$/year |
|        | $r$ | population growth rate | 1/year |
|        | $L_{\text{dr}}$ | drain transfer value | km$^2$/year/year |
|        | $A_j$ | current area of biome $j$ | km$^2$ |
|        | $u_{ij}$ | rate of transition of area from biome $i$ to biome $j$ | km$^2$/year/year |
| Food   | $LY$ | land yield | kg/hectare/year |
|        | $LF$ | land fertility | kg/hectare/year |
|        | $LY_{\text{multi}}$ | land yield multiplier | dmnl |
|        | $F_{\text{W/S}}$ | food production | dmnl |
|        | $FPA$ | water stress to land yield factor | 10$^4$ t/year |
|        | $LFH$ | grain planting area | 10$^4$ t/year |
|        | $Loss$ | processing loss | 10$^4$ t/year |
|        | $FIE$ | food import/export | 10$^4$ t/year |
|        | $F_{\text{pop}}$ | population rescale factor | 10$^4$ t/year |
|        | $f_i$ | constant factors | 10$^4$ t/year |
|        | $FP$ | food price | 10$^4$ t/person |
|        | $ICP$ | international cereal price | kg/year/person |
|        | $FC$ | food consumption | kg/year/person |
|        | $P$ | population | kg/year/person |
|        | $FC_{\text{per capita}}$ | per capita food consumption | kg/year/person |
|        | $R_{\text{self}}$ | food self-sufficiency ratio | |
|        | $FP$ | food production | |
|        | $t$ | the six types of energy resources | |
|        | $ER_i$ | energy requirement | tce/year |
|        | $ERI_{\text{agg0}}$ | initial aggregate energy | tce/year |
|        | $f_{\text{TE}}$ | requirement intensity | kg/year |
|        | $\gamma_{\text{des},i}$ | exogenous desired energy | kg/year |
|        | $KE_i$ | energy capital | RMB |
|        | $KE_{i,0}$ | initial energy capital | RMB |
| Sector | Symbol | Description | Unit |
|--------|--------|-------------|------|
| KCi    | energy capital under construction | RMB |
| τc     | capital construction delay | year |
| δi     | energy capital lifetime | year |
| EPi    | energy production | tce/year |
| EPi,0  | initial energy production | tce/year |
| αi     | energy resource share | dmnl |
| Ri     | energy resource remaining | tce |
| Roi    | initial energy resource remaining | tce |
| ρi     | energy resource substitution coefficient | dmnl |
| EIIi   | energy effective input intensity | dmnl |
| TEi    | energy technology | dmnl |
| βi     | energy capital share | dmnl |
| Vrelative,i | relative variable energy intensity | |
| Water  | LS     | land surface water storage | $10^8$ m$^3$ |
| LSi    | initial land surface water storage | $10^8$ m$^3$ |
| GS     | groundwater storage | $10^8$ m$^3$ |
| Pr     | precipitation | $10^8$ m$^3$/year |
| ET     | evapotranspiration | $10^8$ m$^3$/year |
| St     | stream flow | $10^8$ m$^3$/year |
| GP     | groundwater percolation | $10^8$ m$^3$/year |
| Gwithdrawal | groundwater withdrawal | $10^8$ m$^3$/year |
| GD     | groundwater discharge | $10^8$ m$^3$/year |
| γatm   | consumption adds to atmosphere | $10^8$ m$^3$/year |
| C0s    | consumption adds to land surface | $10^8$ m$^3$/year |
| Cgw    | consumption adds to groundwater | $10^8$ m$^3$/year |
| Closs  | consumption loss | $10^8$ m$^3$/year |
| WTStoN | South-to-North water transfer | $10^8$ m$^3$/year |
| Tfeedback | temperature feedback | dmnl |
| Sector | Symbol | Description | Unit |
|-------|--------|-------------|------|
|       | $\kappa$, $\zeta$, and $\eta$ | calibrated parameters | dmnl |
|       | $W_{\text{dom}}$ | domestic water demand | $10^6$ m$^3$/year |
|       | $W_{\text{ind}}$ | industrial water demand | $10^6$ m$^3$/year |
|       | $W_{\text{agr}}$ | agricultural water demand | $10^6$ m$^3$/year |
|       | $\text{DSWI}$ | domestic structural water intensity | m$^3$/person |
|       | $\Delta\text{TFP}$ | change in total factor productivity and represents changes in domestic water use efficiency | dmnl |
|       | $\text{GDP}_{\text{per}}$ | GDP per capita | RMB/person |
|       | $\text{DSWI}_{\text{min}}$, $\text{DSWI}_{\text{max}}$, and $\gamma_{ij}$ | calibrated parameters | dmnl |
|       | $R_{\text{ele}}$ | ratio of electricity water demand to industrial water demand, which takes the value of 0.7 in this research | dmnl |
|       | $W_{\text{ele}}$ | electricity water demand | $10^6$ m$^3$/year |
|       | $E_{\text{Pi}}$ | electricity production for energy source $i$ | $10^6$ kWh |
|       | $\text{WWW}_{i}$ | water withdrawal factor for energy source $i$ | m$^3$/MWh |
|       | $F_{ij}$ | fraction of cooling method $j$ for energy source $i$ | dmnl |
|       | $\text{Tech}_{\text{ele}}$ | technological change for withdrawals in electricity production | dmnl |
|       | $\text{Tech}_{\text{agr}}$ | technological change factor for irrigation | dmnl |
|       | $A_i$ | net arable land | hectare |
|       | $PHW$ | per hectare water withdrawal | m$^3$/hectare/year |
|       | $T_{\text{feedback}}$ | temperature feedback multiplier | dmnl |
|       | $\text{WS}_{\text{base}}$ | base water stress | dmnl |
|       | $\text{WS}_{\text{pp+w}}$ | | dmnl |
| Sector          | Symbol     | Description                                                      | Unit        |
|---------------|------------|------------------------------------------------------------------|-------------|
|               | WS\_pollution | water stress with pollution effects                             | dmnl        |
|               | WS\_supply  | water stress with water supply capacity                          | dmnl        |
|               | SW\_avail  | available surface water, which is the production of surface renewable water (discharge + stream flow) and stable and useable runoff ratio (0.37) | $10^8$ m$^3$/year |
|               | $r_{gw}$    | groundwater use ratio, which takes the value of 0.01             | dmnl        |
|               | GW          | groundwater                                                      | $10^8$ m$^3$ |
|               | TRW         | treated returnable waters                                       | $10^8$ m$^3$/year |
|               | $f_{uw}$    | wastewater pollution factor, which takes the value of 8         | dmnl        |
|               | UTRW        | untreated returnable waters                                      | $10^8$ m$^3$/year |
|               | TWS         | total water supply capacity                                      | $10^8$ m$^3$/year |
| Carbon        | CA          | atmospheric carbon                                               | Tg C/year   |
|               | DB          | decay of biomass                                                 | Tg C/year   |
|               | DL          | decay of litter                                                  | Tg C/year   |
|               | DH          | decay of humus                                                   | Tg C/year   |
|               | DK          | decay of charcoal                                                | Tg C/year   |
|               | NPP         | net primary productivity                                         | Tg C/year   |
|               | BB          | burning of biomass                                               | Tg C/year   |
|               | BL          | burning of litter                                                | Tg C/year   |
|               | $E_{ind}$   | industrial emissions                                            | Tg C/year   |
|               | $j$         | biome type (agricultural land, forest, grassland, wetland, settlement, other land) | /           |
|               | $k$         | biomass component (leaf, branch, stem, root)                    | /           |
|               | $p_{jk}$    | fraction of biomass partitioned to component $k$ of biome $j$    | dmnl        |
| Sector | Symbol | Description | Unit |
|--------|--------|-------------|------|
|        | $\sigma (NPP_j)$ | variable surface density of net primary production | g C/m²/year |
|        | $A_j$ | biome area | m² |
|        | $\sigma (NPP_j)_0$ | base surface density | g C/m²/year |
|        | $\beta$ | CO₂ fertilization factor | dmm |
|        | $C_A$ | current atmospheric CO₂ | Tg C |
|        | $C_{A0}$ | initial atmospheric CO₂ | Tg C/yr |
|        | $FL_{hk}$ | amount of litter falling from biomass to litter layer | Tg C/yr |
|        | $FH_{hk}$ | decay of litter into humus | Tg C/yr |
|        | $FR_{hk}$ | decay of roots | Tg C/yr |
|        | $B_{hk}$ | burning of biomass | Tg C/yr |
|        | $BK_{hk}$ | burning of biomass to charcoal | Tg C/yr |
|        | $UB_{hk}$ | unburned remainder of biomass | Tg C/yr |
|        | $D_{ij}$ | decay of carbon from litter to atmosphere | Tg C/yr |
|        | $FH_{ij}$ | decomposition of litter into humus | Tg C/yr |
|        | $B_{ij}$ | burning of carbon from litter to atmosphere | Tg C/yr |
|        | $FL_{ij}$ | burning of carbon from litter directly to charcoal | Tg C/yr |
|        | $FH_{ij}$ | decomposition of litter into humus | Tg C/yr |
|        | $FK_{ij}$ | decomposition of humus to charcoal | Tg C/yr |
|        | $D_{ij}$ | decay of humus to the atmosphere | Tg C/yr |
|        | $\sum_{k=1}^{a} UB_{jk}$ | unburnt remainder of biomass | Tg C/yr |
|        | $FH_{ij}$ | internal flow of humus | Tg C/yr |
|        | $FK_{ij}$ | flow of carbon from humus to charcoal | Tg C/yr |
|        | $D_{ij}$ | decay of charcoal | Tg C/yr |
|        | $\sum_{i=1}^{a} FK_{hd}$ | | Tg C/yr |
Table A1. (Continued.)

| Sector | Symbol | Description | Unit |
|--------|--------|-------------|------|
| **Burning of biomass directly into charcoal** | $FK_{ij}$ | carbon flow from litter to charcoal | Tg C/year |
| **Internal flow of charcoal from one biome to another** | $FK_{ij}$ | internal flow of charcoal from one biome to another | Tg C/year |
| **Nutrient** | | | |
| | $i$ | index for originating nutrient reservoir | / |
| | $j$ | index for receiving nutrient reservoir | / |
| | $k_{ij}^N$ | rate constant matrix for N flows from nutrient reservoir $i$ to $j$ | dmnl |
| | $k_{ij}^P$ | rate constant matrix for P flows from nutrient reservoir $i$ to $j$ | dmnl |
| | $N_i$ | nitrogen reservoir $i$ | n N |
| | $P_i$ | phosphorus reservoir $i$ | n P |
| | $F_{ij}^N$ | constant nitrogen flow from reservoir $i$ to $j$ | n N/year |
| | $F_{ij}^P$ | constant phosphorus flow from reservoir $i$ to $j$ | n P/year |
| | $NE$ | nutrients emission | n N/year for nitrogen and n P/year for phosphorus |
| | $DW$ | domestic wastewater | $10^6$ m$^3$/year |
| | $IW$ | industrial wastewater | $10^6$ m$^3$/year |
| | $W_{uw}$ | wastewater reuse | $10^6$ m$^3$/year |
| | $N_{removal}^{off}$ | exogenous N removal efficiency | dmnl |
| | $P_{removal}^{off}$ | exogenous P removal efficiency | dmnl |
| | $N_{con}$ | concentration of N in wastewater | g N/L |
| | $P_{con}$ | concentration of P in wastewater | g P/L |
| Sector | Symbol | Description                  | Unit   |
|--------|--------|------------------------------|--------|
| Fish   | $F$    | fish biomass stock          | t      |
|        | $f_b$  | fish birth                  | t/year |
|        | $f_r$  | fish recruits               | t/year |
|        | $f_d$  | natural fish death          | t/year |
|        | $f_y$  | fish yield                  | t/year |
The mathematical formulation of the hydrologic cycle is as follows,

\[
\begin{align*}
LS &= \int (P - ET - S_t - GP) \, dt \\
GS &= \int (GP - G_{\text{withdrawal}} - GD) \, dt \\
S_t &= \kappa \cdot \left( \frac{LS}{LS_0} \right)^2 - C_{\text{atm}} - C_{\text{gw}} - C_{\text{ls}} - C_{\text{loss}} - WT_S + N \tag{7}
\end{align*}
\]

\[
GP = \zeta \cdot \left( \frac{LS}{LS_0} \right) + C_{\text{gw}} \\
ET = \varphi \cdot \left( \frac{LS}{LS_0} \right) \cdot T_{\text{feedback}} + C_{\text{atm}}
\]

The mathematic equations of the water demand are as follows,

\[
\begin{align*}
W_{\text{dom}} &= DSWI \cdot P \cdot \Delta \text{TFP} \\
DSWI &= DSWI_{\text{min}} + DSWI_{\text{max}} \left( 1 - \exp(-\gamma d GDP_{\text{pup}}^{1.5}) \right) \\
W_{\text{ind}} &= \frac{1}{R_{\text{ele}}} \cdot W_{\text{ele}} \\
W_{\text{ele}} &= Tech_{\text{ele}} \cdot \sum_{i=1}^{4} E_{P_i} \cdot \sum_{j=1}^{n} W_{\text{WF}_{ij} \cdot F_{ij}} \\
W_{\text{agr}} &= PHW \cdot A_{\text{t}} \\
PHW &= B_{\text{Wagr}} \cdot Tech_{\text{agr}} \cdot T_{\text{feedback}} \tag{8}
\end{align*}
\]

The four types of water stress are calculated as follows,

\[
\begin{align*}
WS_{\text{base}} &= \frac{W_{\text{dom}} + W_{\text{ind}} + W_{\text{agr}}}{SW_{\text{avai}}} \\
WS_{\text{gw+ww}} &= \frac{W_{\text{dom}} + W_{\text{ind}} + W_{\text{agr}}}{SW_{\text{avai}} + r_{\text{gw}} \times GW + TRW} \\
WS_{\text{pollution}} &= \frac{W_{\text{dom}} + W_{\text{ind}} + W_{\text{agr}}}{SW_{\text{avai}} + r_{\text{ww}} \times UTRW} \\
WS_{\text{supply}} &= \frac{W_{\text{dom}} + W_{\text{ind}} + W_{\text{agr}}}{TWS} \tag{9}
\end{align*}
\]

The main equations in the carbon sector are based on Goudriaan and Ketter (1984) and are shown in the following.

\[
\begin{align*}
C_A &= \int (D_R + D_L + D_H + D_K - NPP + B_R + B_L + L_{\text{ind}}) \, dt \\
NPP_{jk} &= p_{jk} \cdot \sigma(NPP) \cdot \frac{A_{j}}{10^{12}} \\
\sigma(NPP) &= \sigma(NPP)_{\text{t0}} \cdot \left( 1 + \beta \cdot \ln \left( \frac{C_A}{C_{\text{t0}}} \right) \right) \\
B_{jk} &= \int (NPP_{jk} - FL_{B_{jk}} - HH_{B_{jk}} - FR_{B_{jk}} - B_{B_{jk}} - BK_{B_{jk}} - UB_{B_{jk}}) \, dt \\
L_j &= \int \left( \sum_{k=1}^{4} FL_{B_{jk}} - D_L - HHH - B_L - FL_K \right) \, dt \\
H_j &= \int \left( \sum_{k=1}^{4} FB_{B_{jk}} + FH_{B_{jk}} - RH_{B_{jk}} - D_H + \sum_{k=1}^{4} UB_{jk} + FH_{R_{jk}} \right) \, dt \\
K_j &= \int \left( FK_{R_{jk}} - D_K + \sum_{k=1}^{4} FK_{R_{jk}} + FK_{H_{jk}} - FK_{K_{jk}} \right) \, dt \tag{10}
\end{align*}
\]

The mathematical representation of the nutrients cycle is based on Breach and Simonovic (2018), which has its origins in Mackenzie et al (1993).
\[
N_i = \int (k_{jN} \cdot N_i + F_{jN}) \, dt \quad [nN]
\]
\[
P_i = \int (k_{jP} \cdot P_i + F_{jP}) \, dt \quad [nP]
\]

The nutrient emissions from domestic and industrial sectors are calculated as:
\[
\begin{align*}
NE_{N_{\text{dom}}} &= (DW_{\text{untreated}} - W_{W_{\text{dom}}}) + DW_{\text{treated}} \cdot (1 - N_{\text{conc}_{\text{dom}}}) \cdot N_{\text{conc}_{\text{dom}}} \\
NE_{P_{\text{dom}}} &= (DW_{\text{untreated}} - W_{W_{\text{dom}}}) + DW_{\text{treated}} \cdot (1 - P_{\text{removal}_{\text{dom}}}) \cdot P_{\text{removal}_{\text{dom}}} \\
NE_{N_{\text{ind}}} &= (IW_{\text{untreated}} - W_{W_{\text{ind}}}) + IW_{\text{treated}} \cdot (1 - N_{\text{conc}_{\text{ind}}}) \cdot N_{\text{conc}_{\text{ind}}} \\
NE_{P_{\text{ind}}} &= (IW_{\text{untreated}} - W_{W_{\text{ind}}}) + IW_{\text{treated}} \cdot (1 - P_{\text{removal}_{\text{ind}}}) \cdot P_{\text{removal}_{\text{ind}}}
\end{align*}
\]

The nutrient emissions from agricultural sector are calculated as:
\[
\begin{align*}
NE_{N_{\text{agr}}} &= A_1 \cdot N_{\text{leaching}} \\
NE_{P_{\text{agr}}} &= A_1 \cdot P_{\text{leaching}}
\end{align*}
\]

The calculation of fish biomass stock is given as,
\[
F = \int (f_f + f_r - f_d - f_p) \, dt
\]

ORCID iDs

Haiyan Jiang © https://orcid.org/0000-0001-8524-6963

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