ANEMI_Yangtze v1.0: An Integrated Assessment Model of the Yangtze Economic Belt - Model Description

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Abstract: Yangtze Economic Belt (hereafter Belt) is one of the most dynamic regions in China in terms of population growth, economic progress, industrialization, and urbanization. It faces many resource constraints (land, food, energy) and environmental challenges (pollution, biodiversity loss) under rapid population growth and economic development. Interactions between human and natural systems are at the heart of the challenges facing the sustainable development of the Belt. By adopting the system thinking and the methodology of system dynamics simulation, an integrated assessment model for the Belt, named ANEMI_Yangtze, is developed based on the third version of the global integrated assessment model, ANEMI. Nine sectors of population, economy, land, food, energy, water, carbon, nutrients, and fish are currently included in ANEMI_Yangtze. This paper presents the ANEMI_Yangtze model description, which includes: (i) the identification of the cross-sectoral interactions and feedbacks involved in shaping the Belt's system behaviour over time; (ii) the identification of the feedbacks within each sector that drive the state variables in that sector; and (iii) the description of a new *Fish Sector* and modifications in the *Population*, *Food*, *Energy*, and *Water Sectors*, including the underlying theoretical basis for model equations. The validation and robustness tests confirm that the ANEMI_Yangtze model can be used to support scenario development, policy assessment, and decision making. This study aims to improve the understanding of the complex interactions among human and natural systems in the Belt to provide the foundation for science-based policies for the sustainable development of the Belt.

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Keywords: ANEMI_Yangtze; integrated assessment modeling; system dynamics simulation; Yangtze Economic Belt;

1. Introduction

Today global problems and challenges facing humanity are becoming more and more complex and directly related to the areas of energy, water, and food production, distribution, and use (Hopwood et al., 2005; Bazilian et al., 2011; Akhtar et al., 2013; van Vuuren et al., 2015; D'Odorico et al., 2018). The relations linking human race to the biosphere are so complex that all aspects affect each other. Knowledge and methods from a single discipline are no longer sufficient to address these complex, interrelated problems that characterize as fundamental threats to human society (Klein et al., 2001; Bazilian et al., 2011; Clayton and Radcliffe, 2018; Calvin and Bond-Lamberty 2018). Researchers and policymakers have promoted the WEF (Water-Energy-Food) nexus approach as a potential framework for addressing sustainability and protecting against risks of future WEF insecurity (Rasul and Sharma, 2016; D'Odorico et al., 2018). The WEF nexus framework was first introduced at a conference on "The Water-Energy-Food Security Nexus: Solutions for the Green Economy" in Bonn in 2011 and soon attracts the attention of research and policy-making communities (Daher and Mohtar, 2015; Smajgl et al., 2016; Garcia and You, 2016; Liu et al., 2017; Weitz et al., 2017; Xu et al., 2020). The WEF nexus offers a promising approach to identifying potential trade-offs and synergies of WEF systems and guiding cross-sectoral policies. However, current applications of the WEF nexus methods fall short of adequately capturing the interactions among the WEF system - the very linkages WEF nexus conceptually aims at addressing (Albrecht et al., 2018; Stoy et al., 2018).

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Moreover, while the WEF nexus is relatively new, the concept of nexus thinking has a long history in system dynamics research. Dated back to 1970s, the Club of Rome's research has applied the nexus concept in developing an integrated assessment model (IAM) to explore *The Limits to Growth* (Meadows et al., 1972). Actually, IAMs go far beyond the WEF nexus by emphasizing interactions and feedbacks and including both the eco-environment dimensions such as biodiversity and ecosystem services and socio-economic dimensions such as population and economic development which are exactly what the WEF nexus unable to address (Kling et al., 2017). In recent decades, as the awareness of climate change and sustainability challenges are increasing much broader research interest is devoted to studying various aspects of global change, aimed at understanding the complex and long-term issues and designing effective response

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strategies. These efforts led to many IAMs, including AIM (Matsuoka et al., 1995), MESSAGE (Messner and Strubegger, 1995; Messner and Schrattenholzer, 2000; Sullivan et al., 2013), POLES (European Commission, 1996), ANEMI (Simonovic, 2002; 2002a; Davies and Simonovic, 2010; 2011; Akhtar et al., 2013; 2019; Simonovic and Breach, 2020; Breach and Simonovic, 2020; 2021), TIMES (Loulou, 2007), REMIND (Bauer et al., 2012; Kriegler et al., 2017), IMAGE (Stehfest et al., 2014), and GCAM (Calvin et al., 2019), to name a few. These IAMs provide valuable tools to assess the impacts of global change and adaptation and vulnerability of human society despite the criticisms they received (Gambhir et al., 2019). However, as these models are highly aggregated, they are unable to address local-specific challenges. Therefore, there is urgent need for model downscaling (Holman et al., 2008; Bazilian et al., 2011; Akhtar et al., 2019; Fisher-Vanden and Weyant, 2020; Breach and Simonovic, 2020; 2021). For example, the GCAM model currently has several sub-national versions, including GCAM-USA (Shi et al., 2017), GCAM-China (Yu et al., 2020), GCAM-Korea (Jeon et al., 2020) and others in development. Model downscaling is an active area in integrated assessment modeling and requires ongoing effort. Recently there have even been calls for downscaling global IAMs to the city level (Dermody et al., 2018).

Yangtze Economic Belt, one of the most dynamic regions in China in terms of population growth and economic development, accounts for about 40% of the country's population and GDP and 1/15 of the global population. Over the past decades, the Belt has developed into one of the most vital regions in China. However, the Belt's fast urbanization and economic prosperity come at the cost of the environment (Xu et al., 2018). To repair its deteriorating eco-environment, the Belt's development paradigm has shift from "large-scale development" to "green development". However, it remains poorly understood how the human and natural systems in the Belt interact? For example, how might changes in birth control policy affect population dynamics, and what might this mean for resources consumption and environmental pollution? How does depletion of natural resources and degradation of the environment constrain the growth of population and economy? How might new emerging clean energy sources influence the way energy is consumed, and what might this mean for greenhouse gas emissions? How might policies aimed at improving the eco-environmental situation affect the Belt system performance? To enhance understanding of the complex interactions among human and natural systems in the Belt and to provide the foundation for science-based policy making for the sustainable development of the Belt, we

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developed the ANEMI_Yangtze model. This paper focuses on model description and is organized as follows: section 2 describes the Belt and its challenges; section 3 illustrates the theoretical basis for ANEMI_Yangtze; new aspects of the model development are provided in section 4; section 5 discusses the model validation and application; and section 6 offers the final conclusions.

2. Yangtze Economic Belt: system description

Yangtze river originates from the Tanggula Mountains on the Plateau of Tibet and flows eastward to the East China Sea. It has a total length of 6,300 km with a catchment area of about 1.8 million km^2. Located mainly in the Yangtze river basin, the Belt traverses eastern, central and western China, joining the coast with the inland and consists of 3 economic zones – the Chongqing-Sichuan upstream urban agglomeration, the central triangle urban agglomeration, and the Yangtze river delta agglomeration. The relationship between the Yangtze river basin and the Belt is shown in **Figure 1**.

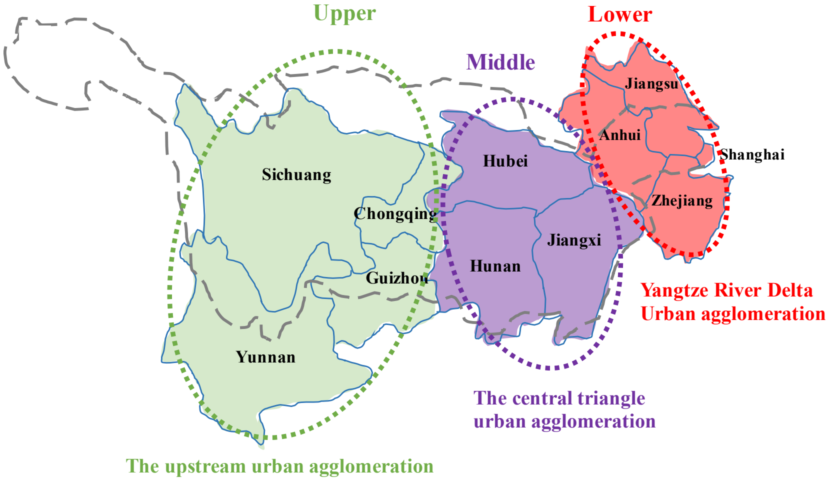

Figure 1. Yangtze river basin (black long dashed line) and the Yangtze Economic Belt

Over the past decades, especially after the reform and opening-up of China in the late 1970s, the Belt has developed into one of the most vital regions in China. It accounts for 21% of the country's total land area (2.05 million km^2) and is home to 40% of the country's total population, with an economic output exceeding 40% of the country's total GDP. The Belt is home to many advanced manufacturing industries, modern service industries, major national infrastructure projects, and high-tech industrial parks. As one of the most important industrial corridors in China,

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the Belt's output of steel, automobile, and petrochemical industries accounts for more than 36%, 47%, and 50% of the total national output, respectively (MIIT, 2016). In 2018, the Belt's population and GDP were about 599 million and 40.3 trillion RMB, accounting for 42.9% and 44.1% of the country, respectively. As the initiation of the Belt in 2016 and the gradual loosening of China's birth control policy, the Belt's processes of urbanization and industrialization are expected to gain momentum in the coming decades (NDRC, 2016). The fast urbanization and strong economic growth in the Belt, however, pose severe challenges for its sustainable development. These challenges mainly include the climate change impacts, energy crisis, land availability and food security, water pollution, and depletion of fish stock in the river.

2.1 Climate change impacts

The Yangtze river basin is vulnerable to global warming. Accumulating evidence shows that climate change affects the hydrologic regime in the river basin. For example, research finds that the glaciers in the Qinghai-Xizang Plateau in the head Yangtze regions shrank by 7% (3,790 km^2) over the past four decades (Li et al., 2010). This change in the hydrological cycle results in more frequent extreme meteorological events happening in the Yangtze rive basin (Cao et al., 2011; Gu et al., 2015; Su et al., 2017), exposing vast majority of the population to growing physical and socio-economic risks. For example, during the summer of 2020, eight provinces in the Yangtze river basin experienced severe floods, leaving hundreds dead and disrupting the economy's post-pandemic recovery.

2.2 Energy crisis

Yangtze river basin is very poor in fossil fuel endowments even though China's has the world's largest coal reserves. Data from China Energy Statistical Yearbook indicates that in 2015 about 60% of the Belt's coal consumption was imported (DENBS, 2016). Yangtze river basin has, however, abundant hydropower resources. It is estimated that the theoretical reserves of hydropower resources in the Yangtze river basin are about 278 million kilowatts (Wang, 2015). Moreover, Yangtze coastal areas are ideal locations for nuclear power construction. However, due to technical limitations and development cost, coal still dominates energy consumption, accounting for about 56% of total energy consumption currently (Su, 2019).

2.3 Land availability and food security

Statistics from the demographic yearbook indicate that the population in the Yangtze river basin grew from 500 million in 1990 to about 600 million in 2020, and is expected to reach its

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peak around 2030 if the one-child policy remains unchanged (Zeng and Hesketh, 2016). As the country's birth control policy gradually loosens, the population in the Belt will grow even faster. With a high population growth rate and rising income, the consumption of food, especially non-starchy food such as dairy and meat, is expected to increase (Niva et al., 2020). This higher food production has to come from the same amount of land or even less land due to the competing use of land for urbanization. Population growth and urban expansion occupy many rich farmlands. Research shows that from 2000 to 2015, urban area in the Yangtze river basin increased by 67.51% whereas cropland decreased by 7.53% (Kong et al., 2018).

2.4 Water pollution

The increasing application of fertilizers and pesticides in agriculture and discharging of wastewater from a growing population and rapid industry development lead to severe problems concerning pollution of freshwater, eutrophication of lakes, and deterioration of the water ecosystem. Statistical data indicate that 86.9% of major lakes and 35.1% of major reservoirs in the Yangtze river basin suffer from eutrophication (YRWRC, 2016). Among them, the most serious case is the widespread eutrophication of Lake Taihu, which is located in the floodplain of the middle and lower reaches of the Yangtze river (Li et al., 2011). In 2007, the blue algal bloom outbreak in Lake Taihu cut off drinking water supply for 2 million citizens in Wuxi city for a whole week (Qin et al., 2007). The last decade has witnessed some 70 million RMB flowing into the eutrophication control of the Lake Taihu annualy.

2.5 Depletion of Yangtze fish stock

Fishery resources in the Yangtze river are seriously depleted. To date, wild capture fisheries production decreased to less than 100 thousand tonnes, falling well short of the maximum output of 427 thousand tonnes in the 1950s (Zhang et al., 2020). The eggs and larvae of the four major Chinese carps (the dominant commercial species in the Yangtze River) were approximately 1.11 billion in 2015, accounting for only 1% of historical production in 1965 (Yi et al., 1988; Zhang et al., 2017). Habitat fragmentation and shrinkage as a result of reclamation of lakes for farmland and dam construction, together with overfishing and water pollution, are the main factors threatening aquatic biodiversity in the Yangtze river (Jiang et al., 2020; Zhang et al., 2020). In an effort to protect Yangtze's aquatic life, a 10-year commercial fishing ban on the Yangtze was introduced in 2020. Fishing in the main stream of Yangtze river, the Poyang-Dongting lakes, and the seven major tributaries is temporarily banned for a period of 10 years starting from 2021.

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Deleted: Disposal of industrial waste, municipal sewage, use of fertilizers, and intensive animal farming, make Yangtze one of the most polluted rivers in the World (Wong et al., 2007). In general, phosphorus and nitrogen are the key nutrients that limit primary productivity in most freshwater and coastal systems, respectively, making them primary drivers of eutrophication or nutrient enrichment (Elser et al., 2007; Conley et al., 2009). For example, in recent years, the increase in fertilizer use has led to problems of excess nutrient inputs (Sattari et al., 2014; Huang et al., 2017;) that have contributed to widespread eutrophication in the Lake Taihu Region (Xu et al., 2010; Li et al., 2011) and the East China Sea (Li et al., 2009; Xia et al., 2016). However, with the growing awareness of the eco-water security challenges, the central government has proposed the "Great Protection Strategy of the Yangtze". The water pollution problems in the Yangtze thus are expected to be alleviated.

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3. ANEMI_Yangtze: background and theoretical basis

In this research, ANEMI_Yangtze is developed to improve understanding of the complex interactions between human and natural systems in the Belt and to provide the foundation for science-based policy development and assessment. The model currently consists of nine sectors: *Population*, *Economy*, *Land*, *Food*, *Energy*, *Water*, *Carbon*, *Nutrients*, and *Fish*. The model, "downscaled" from ANEMI, is grounded in systems thinking and developed using the system dynamics simulation approach. System dynamics research originated in control engineering and is a valuable methodology for capturing the nonlinearity, feedbacks, and delays in determining the dynamic behaviour of complex systems (Forrester, 1961). In system dynamics, interactions and feedbacks between system components, illustrated using Causal Loop Diagram (CLD), are far more important for understanding system behaviour than focus on separate details (Sterman, 2000; Simonovic, 2009). There are two types of feedbacks, the reinforcing one (positive) and the balancing one (negative). A positive feedback is one in which an action produces a result that influences more of the same action, resulting in exponential growth or decay. A negative feedback dampens a system's outputs within each cycle and eventually brings stability to a system. It is widely recognized that it is the interactions and feedbacks that are responsible for the functioning of the complex human-nature system. In the following sections, we focus on illustrating the theoretical basis, *i.e.* CLD of the ANEMI_Yangtze. The development of the ANEMI_Yangtze model is presented in section 4.

3.1 Cross-sectoral interactions and feedbacks

The cross-sectoral interactions and feedback in ANEMI_Yangtze (Figure 2) are discussed in the following section. Capitalized italics are used for sector names and italics are used for names of state variables.

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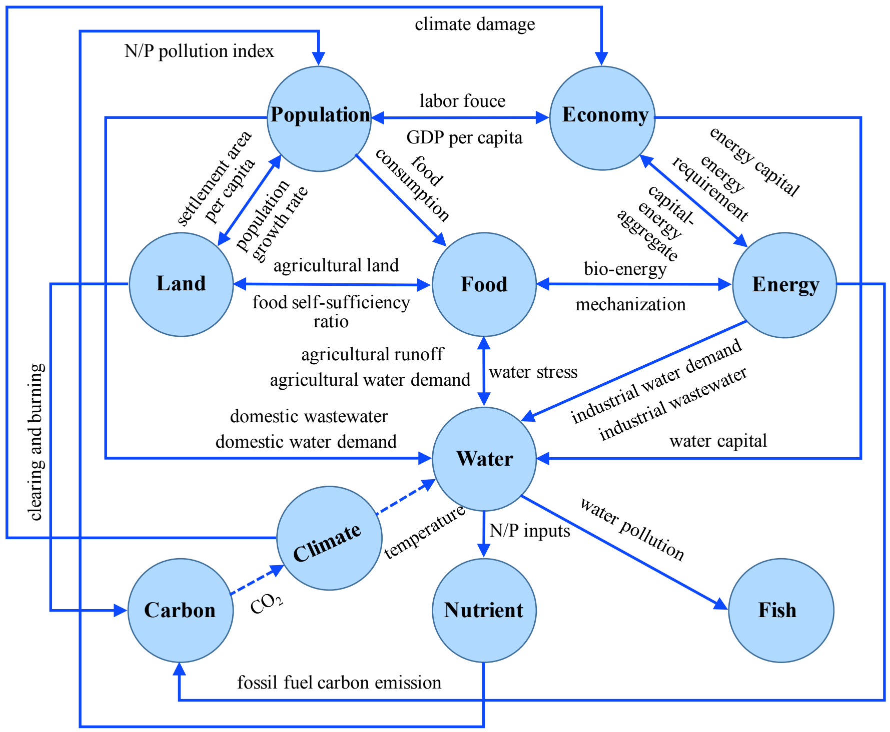

Figure 2. Cross-sectoral interactions among the human-natural systems in the Belt

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The *Population Sector* affects the *Economy Sector* positively by boosting the *labour force* and is affected by the *Economy Sector* both positively and negatively through *GDP per capita*. On the one hand, an increase in *GDP per capita* increases the *health service output*, which has a positive effect on *life expectancy* and thus reduces the death rate of the *population*. On the other hand, an increase in *GDP per capita* has the opposite effect on the *desired family size*, affecting *total fertility* and reducing the population's birth rate. The difference in *GDP per capita* between the Belt and the rest of China also affects population migration. Usually, people migrate from less developed regions to more developed areas.

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The *Population*, *Food*, and *Land Sectors* are connected through *population growth rate*, *food self-sufficiency ratio*, and *settlement area per capita*. Population growth accelerates the transfer rate of biome among different land-use types. Population growth drives *food consumption*, thereby decreasing *food self-sufficiency*, resulting in more agricultural land being converted by clearing

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and burning forests and grassland. Population growth also leads to more agricultural land around the urban area be claimed for settlement use as urban expands. The *Land Sector* acts as negative feedback on population growth as increased population places more stress on *settlement area per capita*. The pressure on the settlement area then acts as an opposing force on the migration rate.

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The *Economy* and *Energy Sector*s are linked through *capital-energy aggregate*, *energy capital*, and *energy requirement*. A growing economy increases the need for energy, which drives *energy production* through the increasing investment of *energy capital*. An increase in *energy capital* further intensifies the *capital-energy aggregate*, leading to the growth of the economy, thus forming a positive feedback loop.

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The *Population*, *Food*, *Energy*, and *Water Sector*s are connected via *domestic water demand* and *consumption*, *agricultural water demand* and *consumption*, and *industrial water demand* and *consumption*. Water (irrigation) plays a vital role in food production and is needed in almost every stage of energy extraction, production, processing, and especially consumption. With increased population and demand for food and energy, the total demand for and consumption of water increases, increasing water stress. *Water stress*, in turn, impedes population growth and *food production*. The increasing *water stress* also drives more capital flowing into water supply development so as to alleviate *water stress*, thus connecting the *Economy* sector with the *Water Sector*.

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The use of water by *Population*, *Food*, and *Energy Sector*s all result in water pollution in the form of increased concentrations of nitrogen (N) and phosphorus (P) through the discharge of *domestic* and *industrial wastewater* and *agricultural runoff*. This links the *Water Sector* with the *Nutrient Sector*. An increased level of *nutrients concentration* negatively affects population growth through the *life expectancy multiplier* from the N/P pollution index. Water pollution also endangers fish by increasing the population's *natural mortality rate*.

The *Carbon* and *Land Sector*s are connected through clearing and burning, while the *Carbon* and *Energy Sector*s are connected through *fossil fuel emissions*. The *Carbon-Climate* sector feedback depends on the atmospheric CO_2 concentration determined by the *Carbon* sector. The climate change effect is treated as exogenous input. The *Climate* and *Water Sector*s are connected via the *surface temperature change*. Since increased surface temperature will likely increase the intensity of the hydrological cycle, the model includes a temperature multiplier equation that

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increases evaporation and evapotranspiration within the Yangtze hydrological cycle. The *Climate Sector* influences the *Economy* sector through a temperature damage function.

3.2 Interactions and feedbacks within model sectors

CLD of the *Population Sector*: The three variables - *births, deaths,* and *migrants*, which are all affected by *GDP per capita*, drive the dynamic behaviour of the *population*. *GDP per capita*, which is affected by *labour force* (population) and *gross output*, rises if the effect of the increase in the *gross output* outpaces the effect of the increase in population, and vice versa. So, the feedback loops containing *GDP per capita* can either be positive or negative depending on whether *GDP per capita* is increasing or decreasing with population growth. For example, in Figure 3, the positive loop A1 and negative loop B1 depict the effect of *GDP per capita* on mortality, whereas positive loop C1 and negative loop D1 have the effect on fertility. The positive loop E1 and negative loop F1 illustrate the impact of *GDP difference factor* on migration. Loop G1 explains the effect of crowding on migration.

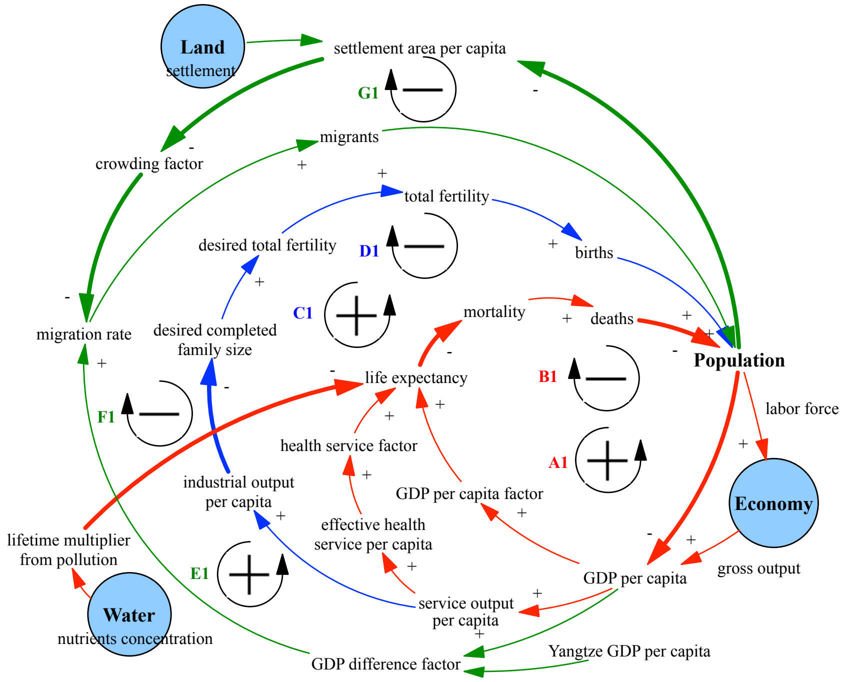

Figure 3. CLD of the *Population Sector*

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An increase in *GDP per capita*, on the one hand, means improvement in health services, thus increase of *life expectancy* and reduction of the *total mortality rate*. A decrease in mortality means fewer *deaths*, which drives the *population* to grow. On the other hand, an increase in *GDP per capita* leads to a reduction in the willingness to give birth, which will drive the population to decline. Migration is newly added. Usually, people migrate from poor regions to rich areas within China. In this research, migration behaviour is mainly driven by a variable named *GDP difference factor*, which calculates the difference between *national GDP per capita* and the *GDP per capita* in the Yangtze Economic Belt. Besides, the crowding effect is also taken into account, which acts as negative feedback on migration. On the global scale, water and food availability usually act as limits to *population* growth. At the regional scale, vital resources such as food and water can be traded, so in ANEMI_Yangtze, only the effect of pollution on the *population* is considered. ... [5]

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An increase in *GDP per capita*, on the one hand, means improvement in health services, thus increase of *life expectancy* and reduction of the *total mortality rate*. A decrease in mortality means fewer *deaths*, which drives the *population* to grow. On the other hand, an increase in *GDP per capita* leads to a reduction in the willingness to give birth, which will drive the population to decline. Migration is newly added. Usually, people migrate from poor regions to rich areas within China. In this research, migration behaviour is mainly driven by a variable named *GDP difference factor*, which calculates the difference between *national GDP per capita* and the *GDP per capita* in the Yangtze Economic Belt. Besides, the crowding effect is also taken into account, which acts as negative feedback on migration. On the global scale, water and food availability usually act as limits to *population* growth. At the regional scale, vital resources such as food and water can be traded, so in ANEMI_Yangtze, only the effect of pollution on the *population* is considered. ... [6]

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CLD of the *Economy Sector*: The interactions and feedbacks in the *Economy Sector* are presented in Figure 4. The A2 and B2 loops depict the adjustment of *desired capital* in response to relative cost and *marginal productivity of capital*. The C2 loop corrects the gap between *desired capital* and actual *capital*. The D2 loop illustrates the impact of the *expected output growth rate* on *desired capital order rate*. The E2 and F2 loops explain *capital* depreciation into investment in additional *capital*.

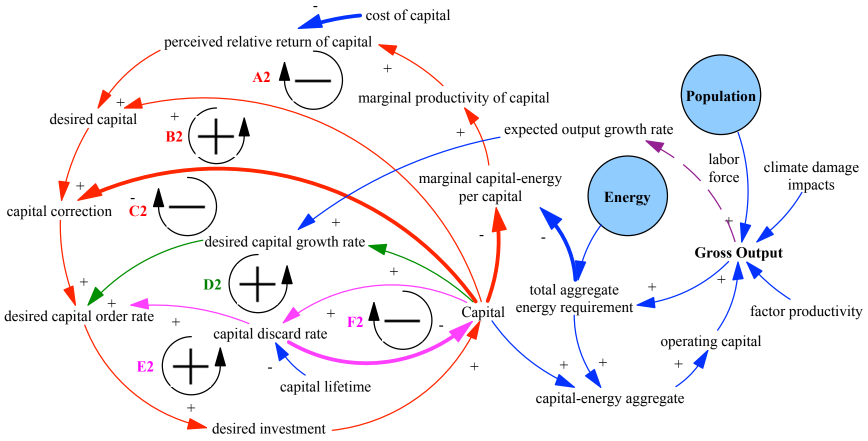

Figure 4. CLD of the *Economy Sector*

CLD of the *Land Sector*: Figure 5 illustrates the feedbacks in *agricultural land* (the feedback loops in the *forest*, *grassland*, *wetland*, *settlement*, and *other land*, which are not shown in the figure, are the same as those in the *agricultural land*). An increase in the stock of *agricultural land* increases its transfer rate to the *forest*, *grassland*, *wetland*, *settlement*, and *other land*, which all together drain the stock of *agricultural land* and form the negative loops A3, B3, C3, D3, and E3.

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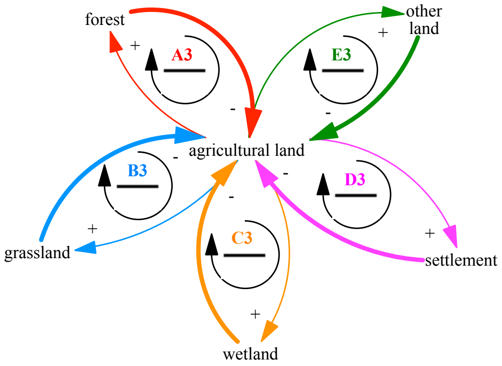

Figure 5. CLD of the *agricultural land*

CLD of the *Food Sector*: The CLD of the *Food Sector* is shown in Figure 6. Negative loops A4, B4, and C4 illustrate the impacts of *land yield technology*, *agricultural land development*, and *fertilizer subsidy*, respectively, on *food production* through the indicator of *food self-sufficiency ratio*. A decrease in *food self-sufficiency ratio* stimulates inputs in *land yield technology*, *agricultural land development*, and *fertilizer subsidy*, which all drive up *land yield*, resulting in increases in *food production* and *food self-sufficiency ratio*. Negative loops E4 and F4 depict the introduction of multiple cropping practices (*multiple cropping index*) and *willingness to increase grain planting area* on *food production* through *food price change*. Positive loop D4 counterbalances the effect of adopting multiple cropping practices by decreasing *land fertility* and the corresponding *land yield*.

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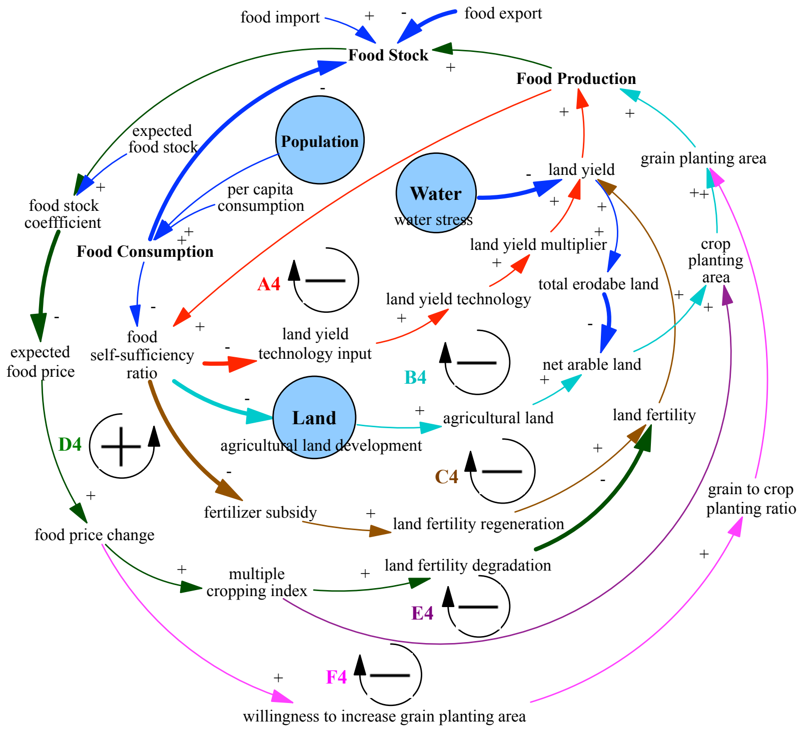

Figure 6. CLD of the *Food Sector*

CLD of the *Energy Sector*: The CLD of the *Energy Sector* is presented in Figure 7. Loop A5 depicts the process of *energy capital* depreciation, which slowly depletes the *energy capital* stock. Loop B5 compensates for depreciation by factoring it into *desired energy capital under construction*. Loop C5 moves *energy capital* from the construction phase to the completion phase. Loops D5 and E5 depict the effect of *energy production pressure* on *energy capital*. Loop F5 illustrates the impact of resource depletion on *energy production*. Energy resources gradually deplete as more energy is produced. This affects the ratio of *energy resources remaining*, which negatively impacts on *energy production*, creating a negative feedback loop. Loop G5, together with Loop E5 illustrate the impact of *effective energy capital input effect* on *energy production* through *energy technology* and *energy capital*, respectively. *Energy technology* plays a role in producing energy through *cumulative energy investment*, which acts to increase *energy production*

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for the same level of inputs of capital. Loop H5 depicts the effect of *energy technology* on the intensity of *energy consumption per unit GDP*.

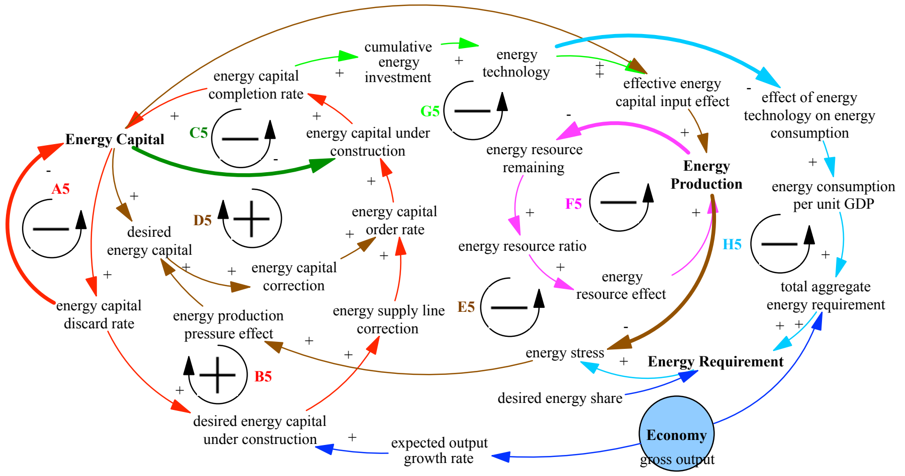

Figure 7. CLD of the *Energy Sector*

CLD of the *Water Sector*: The CLD of the *Water Sector* is illustrated in Figure 8. Loop A6 acts as negative feedback on *water supply capital* through depreciation. Loop B6 counteracts the A6 by having a positive feedback effect on *water supply capital*. Loops C6, D6, and E6 counteract *water stress* by prompting investment in *water supply capital* to increase water supplies in the form of *surface water*, *groundwater*, and *treated returnable waters*, respectively. Feedback loop F6 illustrates the movement of water from the atmosphere to the surface as *precipitation* and then back to the atmosphere through *evapotranspiration*. Loop G6 depicts the effect of *discharge* on *groundwater*.

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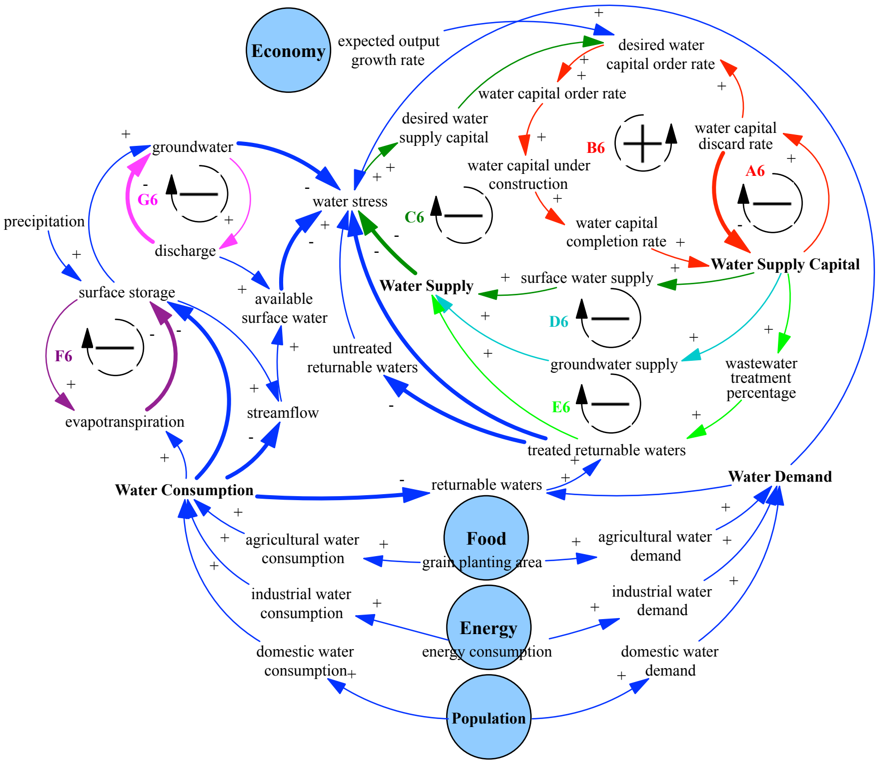

Figure 8. CLD of the *Water Sector* (Note: Water demand here is an economic term defined as as the volume of water requested by users to satisfy their needs)

CLD of the *Carbon Sector*: The CLD of the *Carbon Sector* is given in Figure 9. The chain of negative feedback loops passing through each of the terrestrial carbon stocks from the *biomass* to *litter*, to *humus*, and to *stable humus and charcoal* (A7, B7, C7) and the negative feedback loops depicting the decaying (E7, G7, H7, I7) and burning (D7, F7) process of each carbon stock all act as a positive feedback loop in the atmosphere-terrestrial carbon cycle (K7 and J7). An increase in atmospheric carbon results in higher uptake of carbon in the *biomass* through the effect of *net primary productivity*, which results in a greater transfer of carbon through the chain (*biomass*, *litter*, *humus*, *stabilized humus and charcoal*), thereby leading to an increase in decay and transfer of carbon back to the atmosphere.

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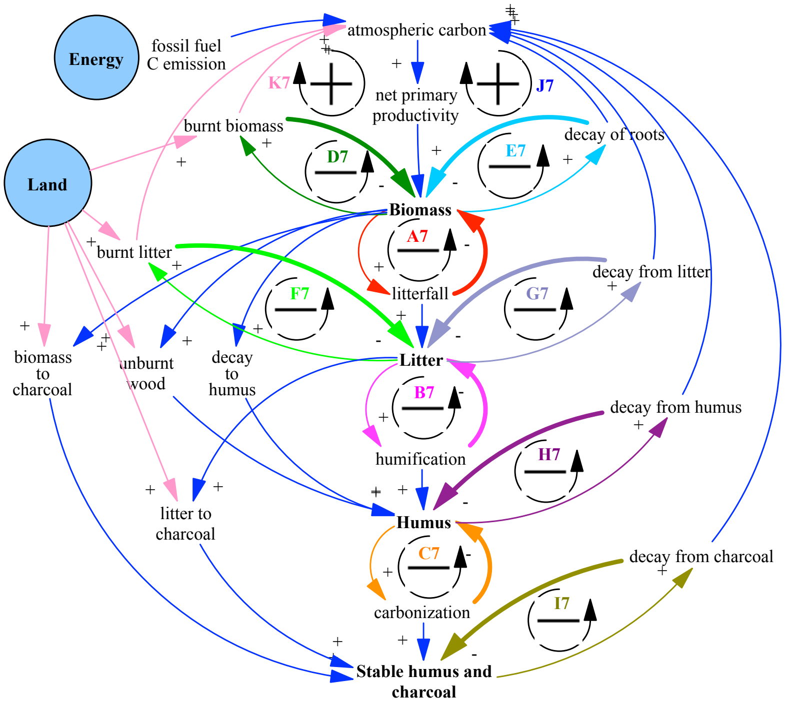

Figure 9. CLD of the *Carbon Sector*

CLD of the *Nutrient Sector*: The CLD of the *Nutrients Sector* is given in Figure 10. The cycles of phosphorous and nitrogen follow that of the carbon cycle. Take a phosphorous cycle for example, the chain of negative feedback loops passing through *land biota* to *humus* and to *rivers* (A8, B8, C8, D8, E8) and the negative feedback loops depicting the *weathering of inorganic P* (F8) act as a positive feedback loop in the terrestrial phosphorous cycle (G8). Because it represents a continuous cycle of negative feedback, it will attempt to reach equilibrium under natural conditions. Anthropogenic influences on this system in the form of wastewater discharge affect this equilibrium and drive change in the nutrient cycles.

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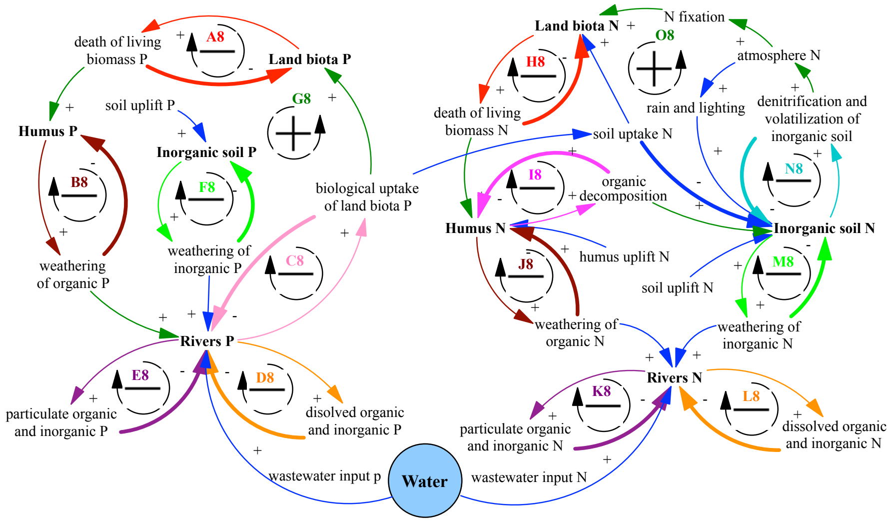

Figure 10. CLD of the *Nutrient Sector*

CLD of the *Fish Sector*: Four feedback loops drive the dynamics of *fish biomass stock* (see Figure 11). Loops A9, C9, and D9 represent negative feedback on *fish biomass stock* through *natural fish death*, *fish recruits*, and *fish yield*, respectively. The amount of wastewater water acts as a positive factor on *natural mortality*. Loop B9, which connects *total reservoir capacity* and *ship cargo volume* with *fish birth rate*, acts as positive feedback on *fish biomass stock*. As *the total reservoir capacity* and *ship cargo volume* increase, the *fish birth rate* decreases so too does the *fish birth*. The decline in *fish birth* decreases the *fish biomass stock*, further reducing the *fish birth*.

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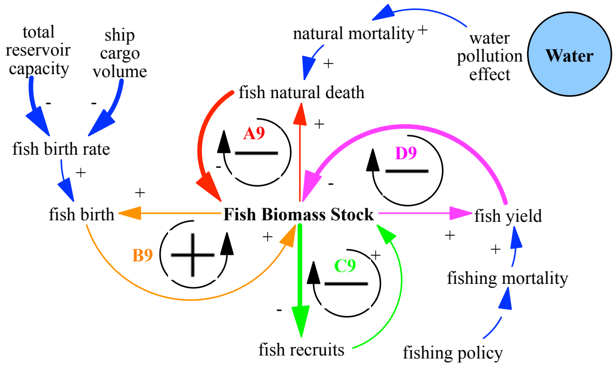

Figure 11. CLD of the *Fish Sector*

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4. ANEMI_Yangtze: model development

4.1 The ANEMI_Yangtze data system

The ANEMI_Yangtze data system contains (i) historical data that is used to initialize and validate the model and (ii) future parameters that govern changes in the future. Most of the historical data (1990-2015), such as population and GDP, energy production and consumption, food production and food trade, and water withdrawals and consumptions, come from the Statistical Yearbook published by the National Bureau of Statistics of China annually (also available on line at http://www.stats.gov.cn/english/, last accessed Sep 20, 2021). Historical precipitation, evapotranspiration, and temperature data are collected from hydrometeorological stations. Land use data come from ESA Climate Change Initiative - Land Cover (http://maps.elie.ucl.ac.be/CCI/viewer/, last accessed Sep 20, 2021). Adjustments are made to the historical data as needed to fill in the missing information. Future temperature and precipitation data come from Yu et al (2018). For the future parameters, the ANEMI_Yangtze data system uses information about technology cost and performance, information about future development policies, as well as the authors' experience of knowledge. Additional information on the data is also described in the sections below.

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4.2 Major changes: a glimpse

The ANEMI_Yangtze is "downscaled" from the global ANEMI model which has its roots in the *WorldWater* model by Simonovic (2002; 2002a). ANEMI has been updated continuously from its first publication in 2010 (Davies and Simonovic) to the most recent edition in 2020 (Breach and Simonovic). The current version of ANEMI consists of the following twelve sectors that reproduce the main characteristics of the climate, carbon, population, land use, food production, sea-level rise, hydrologic cycle, water demand, energy-economy, water supply development, nutrient cycles, and persistent pollution. In the ANEMI_Yangtze, the hydrological cycle, water demand and water supply development, as well as wastewater discharge and treatment, are all integrated in the *Water Sector*. Climate change is not explicitly simulated. Instead, we use exogenous precipitation and temperature to drive the *Water Sector*'s hydrological cycle. Sea level rise and persistent pollution are excluded. The global cycles of carbon, nutrients, and hydrology are tailored to fit a regional context. A new *Fish Sector* is added since fisheries are important for the regional economy and diet. Major modifications are in the *Population*, *Food*, *Energy*, and *Water Sectors*. Due to the space limitation, only new aspects of the model are described in detail.

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For full information of the model, please refer to ANEMI_Yangtze's technique report from Jiang and Simonovic (2021) and previous papers about ANEMI (Simonovic, 2002; 2002a; Davies and Simonovic, 2010; 2011; Akhtar et al., 2013; 2019; Simonovic and Breach, 2020; Breach and Simonovic, 2020; 2021).

4.3 Population

In the *Population Sector*, migration is newly added component that Is not part of the global ANEMI model. Usually, people migrate from poor regions to rich areas. In this research, migration behaviour is mainly driven by a variable named *GDP difference factor*. The effects of crowding, migration policy and willingness to change location are taken into account, acting as negative feedback on migration. The calculation of migration rate *MR* takes the following form.

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$$MR = F_{GDP\ diff} \cdot MW \cdot MP.F_{crowding} \qquad (1)$$

where $F_{GDP\ diff}$ is *GDP difference factor*, which is used to calculate the difference between *national GDP per capita* and the *GDP per capita* in the Belt. *MW* is *migration willingness* and is affected by the ratio of Chinese minorities to the country's total population (usually minorities are reluctant to change locations). *MP* represents migration policy and its value ranges from 0-1, with bigger value indicating policy that is in favor of migration. $F_{crowding}$ is a crowding factor and is affected by *settlement area per capita*.

In the ANEMI, water and food availability usually act as limits to population growth. At the regional scale, vital resources such as food and water can be traded, so in the ANEMI_Yangtze, only the effect of pollution on *life expectancy* is taken into account.

$$Pollution_{multi} = a \cdot PI^2 + b \cdot PI + c \qquad (2)$$

where $Pollution_{multi}$ is the lifetime multiplier from pollution, *PI* is the pollution index. *a*, *b*, and *c* are calibrated parameters.

4.4 Food

The *Food Sector* of ANEMI_Yangtze calculates production and consumption of food and *food import/export*, and its stock and flow diagram is shown in Figure 12. *Food consumption* is the production of *population* and *per capita food consumption*. In ANEMI_Yangtze, *per capita food consumption* is assumed to be 400 kg/year/person throughout the simulation. *Food production* is affected by several factors, including *land fertility*, *arable land*, and *water stress*. Its dynamic behaviour is mainly driven by the difference between *perceived food self-sufficiency* and *desired food self-sufficiency*. *The food self-sufficiency* index is defined as the ratio of *food production* to

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food consumption. When its value declines below 0.95 (a critical value) the country manages to ensure food security by providing incentives for *land yield technology input*, *agricultural land development*, and *fertilizer subsidy* (Ye et al., 2013).

$$FP = LY \cdot GPA \cdot (1 - Loss) \qquad (3)$$

$$LY = LF \cdot LY_{multi} \cdot F_{WS} \qquad (4)$$

where *FP* is *food production*, *LY* is *land yield*, *GPA* is *grain planting area*, *Loss* represents *processing loss*. *LF* is *land* fertility, LY_{multi} is *land yield multiplier*, F_{WS} represents *water stress to land yield factor*.

The *Food Sector* also enables food trade, *i.e.*, *food import* and *food export*, which is affected by *local food price* and *international food price* and its calculation is adapted from Wang et al. (2009).

$$FIE = F_{pop} \cdot f_1 + f_2 \cdot FP - f_3 \cdot IFP \qquad (5)$$

where *FIE* is *food import/export*, with positive *FIE* indicating import and negative ones export. F_{pop} is population rescale factor, approximately equals to the ratio of the Belt's population to the national total population. *FP* is *food price* and *IFP* is *international food price*. The historical values of *IFP* are from FAO (http://www.fao.org/worldfoodsituation/foodpricesindex/en/, last accessed Sep 20, 2021). The future values of *IFP* are set to the base year 2015 values. f_i are calibrated parameters. *Food price* is simulated as a stock variable and accumulates by *food price change*, which is another important factor affecting *food production* through influencing farmers' adopting of multiple cropping practices (*multiple cropping index*) and increasing *grain planting area*.

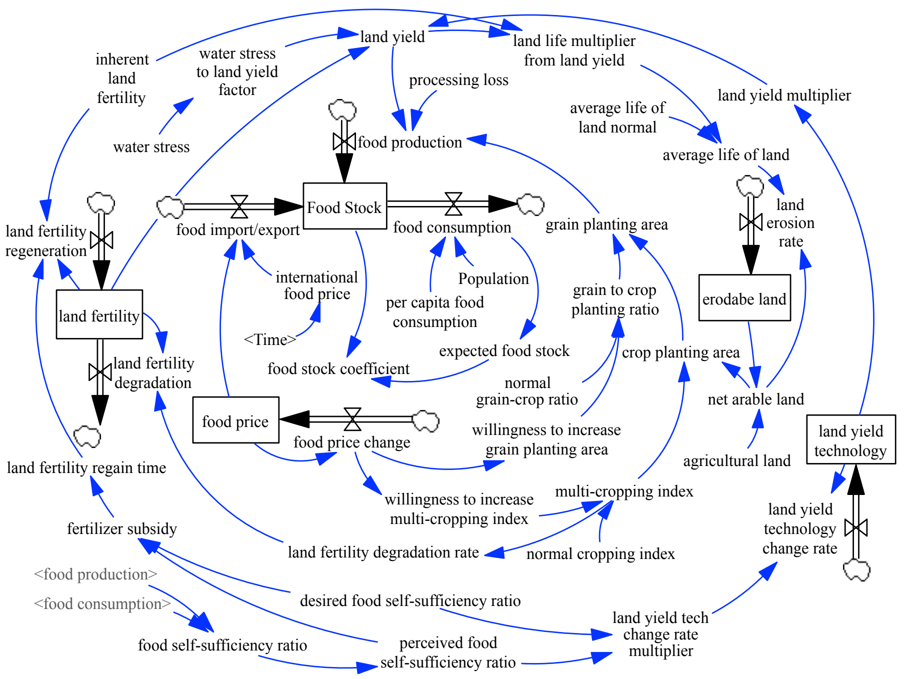

Figure 12. Stock and flow diagram of the *Food Sector*

4.5 Energy

The energy system of ANEMI_Yangtze includes the representation of *energy capital* development, *energy technology*, and *energy requirement*, *production*, and *consumption*. Figure 13 shows the stock and flow diagram of the *Energy Sector*. The structure of the energy system in ANEMI_Yangtze follows the structure of the ANEMI (which has its root in Fiddaman (1997)), with some minor modifications. For example, we do not simulate the effect of return on energy capital which is determined by energy capital cost and the marginal product of energy capital; the *total aggregate energy requirement* in ANEMI_Yangtze scales with economy and is represented as the production of *gross output* and *energy consumption per unit GDP*, whereas the *energy requirement* in ANEMI is embodied in *capital*; the *energy requirement* by sources is the production of *total aggregate energy requirement* and *desired energy share* (which is exogenously specified); *energy price* in ANEMI is endogenously simulated, whereas in ANEMI_Yangtze it is exogenously specified, with historical prices from China Customs Head Office and China Energy

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Statistical Yearbook and future prices assumed to remain their 2015 base year values. *Energy consumption* equals to *energy requirement* by assuming that requirement can always be met through production and trade. Energy trade is not simulated in this research.

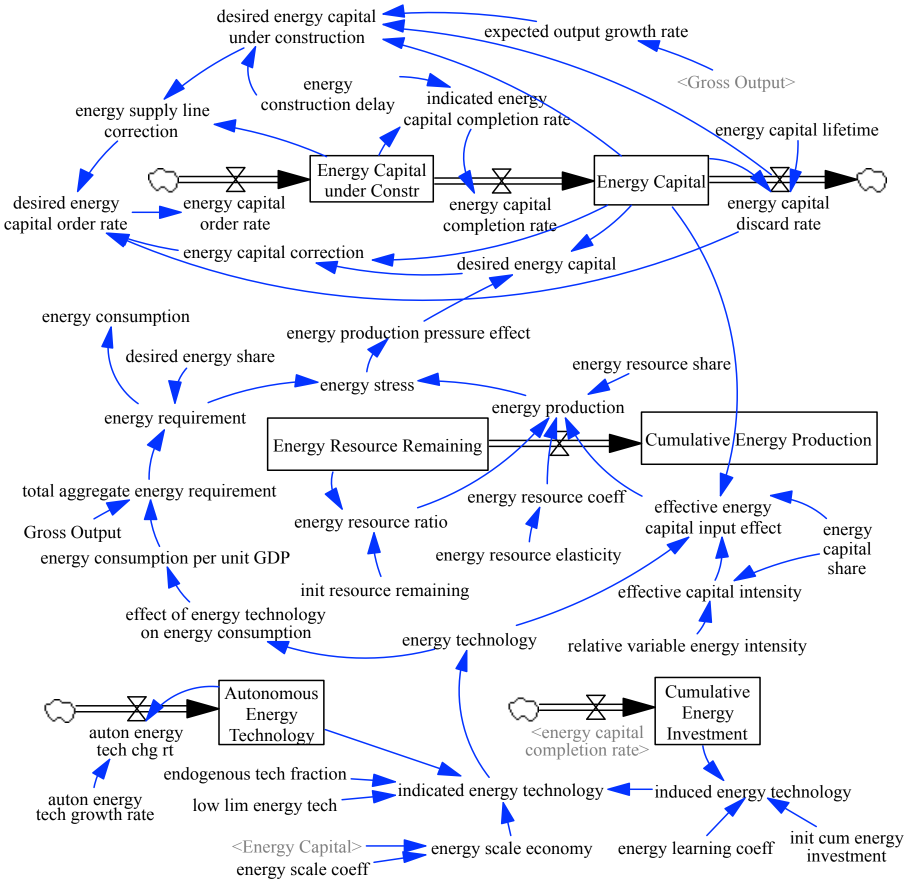

Figure 13. Stock and flow diagram of the *Energy Sector*

In ANEMI_Yangtze, energy source consists of both non-renewables (coal, oil, and gas) and renewables (hydropower, nuclear, and new energy sources) and their endowments are shown in Table 1. Reserves for renewables mean the upper limit to renewable output. The upper limit for hydropower is based primarily on the hydro endowment, nuclear potential implicitly assumed to be politically limited, and new energy is the sum of wind and solar potentials.

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Table 1 Energy endowments in the Belt

Type	Energy source	Reserves	Unit	Source
non-renewables	coal	128.556	billion tce	Yao et al. 2020
	oil	0.460	billion tce	Fang et al. 2018
	gas	19.188	billion tce	Fang et al. 2018
renewables	hydropower	0.379	billion tce/year	Liu and Ding, 2013
	nuclear	0.134	billion tce/year	SGERI and CNPD 2019
	new	318.386	billion tce/year	Song 2013; Zhu et al. 2006

4.6 Water

Water Sector consists of the hydrological cycle, *water demand* and *consumption*, water supply development, as well as wastewater discharge and treatment. Figure 14 shows the stock and flow diagram of the *Water Sector.*

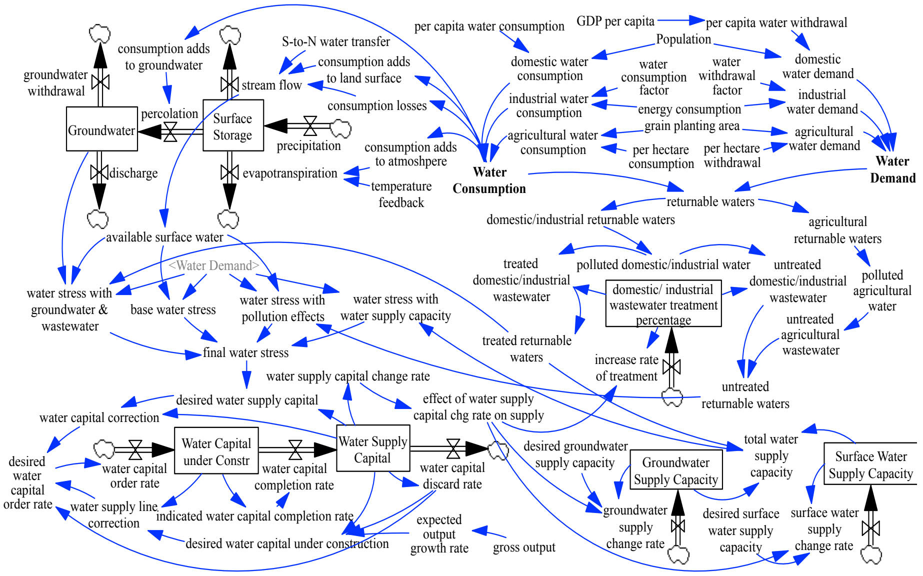

Figure 14. Stock and flow diagram of the *Water Sector*

The hydrological cycle describes the flow of water from the atmosphere in the form of *precipitation* to the land *surface storage* and through the *groundwater* back to the East China Sea. The South-to-North water transfers (west line, middle line, and east line) and *water consumption*

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are also taken into account. The calculation of *domestic* and *agricultural water demands* is the same as in the global ANEMI model. *Industrial water demand* is dominated by the generation of electricity, which consists of both non-renewable sources (coal-fired and gas-fired thermal power) and renewable sources (hydropower and nuclear power). The *water withdrawal factor* and *water consumption* of thermal energy vary substantially among different cooling methods and their values for different fuel sources are obtained from Zhang et al. (2016) and shown in Table 2. Nuclear power plants in the Belt are located in coastal areas and rely on the withdrawal of only seawater, so the freshwater withdrawal and consumption factors of nuclear power are all set to zero. The calculation of *electricity water demand* takes the following form.

$$W_{ele} = Tech_{ele} . \sum_{i=1}^{4} E_{P_i} \cdot \sum_{j=1}^{n} WWF_{i,j} \cdot F_{i,j} \qquad (6)$$

where W_{ele} is *electricity water demand* (10^8 m^3/year); E_{Pi} is *electricity production* for energy source *i* (10^8 kWh); WWF_i is *water withdrawal factor* for energy source *i* (m^3/MWh); $F_{i,j}$ is the fraction of cooling method *j* for energy source *i* and is externally prescribed; $Tech_{ele}$ is technological change for withdrawals in *electricity production* and is also exogenously specified. *Industrial water demand* is calculated as,

$$W_{ind} = \frac{1}{R_{ele}} \cdot W_{ele} \qquad (7)$$

where W_{ind} is *industrial water demand* (10^8 m^3/year); R_{ele} is the ratio of *electricity water demand* to *industrial water demand* and is set to 0.7 in this research.

Table 2 Water withdrawal and consumption factors for electricity production

Energy source *i*	Cooling method *j*	Water withdrawal factor (m^3/MWh)	Water consumption factor (m^3/MWh)
Coal	OT	98.54	0.393
	RC	2.466	1.972
	DRY	0.438	0.448
Gas	OT	34.07	0.379
	RC	2.902	2.114
Nuclear	OT (seawater)	178	1.514
Hydro		0	0

Note: OT=once through, RC=recirculating

In ANEMI, water supply is incorporated as a new production sector within the energy-economy sector and is developed based on the structure of the *Energy Sector*. In ANEMI_Yangtze, we significantly simplified the development of water supply by detaching it from the energy-economy sector. In other words, the water supply is developed independently. We also exclude the effect of water pricing (through depletion and saturation) on water supply development. In addition, we only consider three supply types: surface water, groundwater, and wastewater reclamation. The production of water supplies is driven economically by investing in *water supply capital* stocks for each source. *Water stress* is used as an indicator for *water supply capital* investment and has four definitions. The *base water stress* is represented as,

$$WS_{base} = \frac{W_{dom}+W_{ind}+W_{agr}}{SW_{avai}} \qquad (8)$$

where WS_{base} is *base water stress*, SW_{avai} is *available surface water*.

The *water stress with groundwater and wastewater* is represented as,

$$WS_{gw+ww} = \frac{W_{dom}+W_{ind}+W_{agr}}{SW_{avai}+r_{gw}\times GW+TRW} \qquad (9)$$

where WS_{gw+ww} is *water stress with groundwater and wastewater*; r_{gw} is *groundwater use ratio*, set to 0.01 based on the ratio of historical groundwater withdrawals to total withdrawals; *GW* is *groundwater*; *TRW* is *treated returnable waters*.

The *water stress with pollution effects* is represented as,

$$WS_{pollution} = \frac{W_{dom}+W_{ind}+W_{agr}}{SW_{avai}-f_{ww}\times UTRW} \qquad (10)$$

where $WS_{pollution}$ is *water stress with pollution effects*; f_{ww} is *wastewater pollution factor*, set to 8 (based on Shiklomanov (2000)); *UTRW* is *untreated returnable waters*.

The *water stress with water supply capacity* is represented as,

$$WS_{supply} = \frac{W_{dom}+W_{ind}+W_{agr}}{TWS} \qquad (11)$$

where WS_{supply} is *water stress with water supply capacity*; *TWS* is *total water supply capacity*, which is the sum of *surface water supply capacity*, *groundwater supply capacity*, and *treated returnable waters*.

4.7 Fish

The *Fish Sector*, which is an entirely new addition to the ANEMI_Yangtze model, is used to simulate the dynamic of *fish biomass stock* over time. Figure 15 shows the stock and flow diagram of the *Fish Sector*.

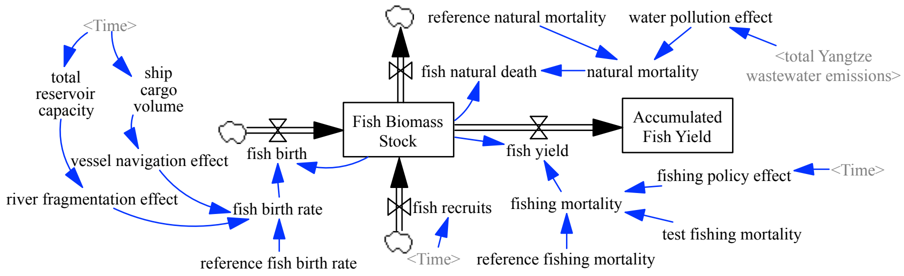

Figure 15. Stock and flow of the *Fish Sector*

The calculation of *fish biomass stock* is given as,

$$F = \int (f_b + f_r - f_d - f_y)dt \qquad (12)$$

where F is *fish biomass stock*, f_b is *fish birth*. f_r represents *fish recruits*, which is treated as an exogenous variable. f_d is *natural fish death*, f_y is *fish yield*.

Fish catch data come from Zhang et al. (2020). Major parameters in the *Fish Sector* are given in Table 3.

Table 3 Major parameters and their corresponding values in the *Fish Sector*

Variable	Value	Unit	Source
reference natural mortality	0.075	dmnl	Gilbert et al. (2000)
reference fishing mortality	0.7949	dmnl	Chen et al. (2009)
reference fish birth rate	0.826	dmnl	Zhang et al. (2020)

Note: for *reference fishing mortality* the value of 0.7949 is calculated based on Chen et al. (2009) by averaging the exploitation coefficients of 10 economically fish species (fishing mortality = 0.761, 0.706, 0.803, 0.829, 0.898, 0.876, 0.846, 0.774, 0.765 and 0.691). For *reference fish birth rate* the value of 0.826 is calculated based on Zhang et al. (2020) by averaging fish growth rates in the middle Yangtze reach, Dongting lake, and Poyang lake.

5. Model validation and application

5.1 Model validation and sensitivity analysis

The ANEMI_Yangtze model was validated by comparing model simulated results with available historical data for 1990-2015. The results shown in Figure 16 indicate that the model can reproduce the system behaviour very well for *population*, *gross economic output*, and *water demand* (Figure 16(a, b, and f)). The model can capture the general behaviour patterns for *energy*

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requirement, *energy production*, and *food production* (Figure 16(c-e)). The fluctuations of historical *food production* are mainly attributed to the flood and drought disasters, which are not currently captured by the model. The discrepancies between historical and simulated *energy requirement* and *energy production* are partly due to the previous energy policies acting on the energy system that the model doesn't consider. For example, in China, overcapacity in coal production gradually appeared after the mid-1990s, and this situation worsened after the outbreak of the 1997 Asian financial crisis. To alleviate the overcapacity crisis, the governments at all levels issued series of policies to reduce production, seen as the production drop around year 2000 (Figure 16(d)).

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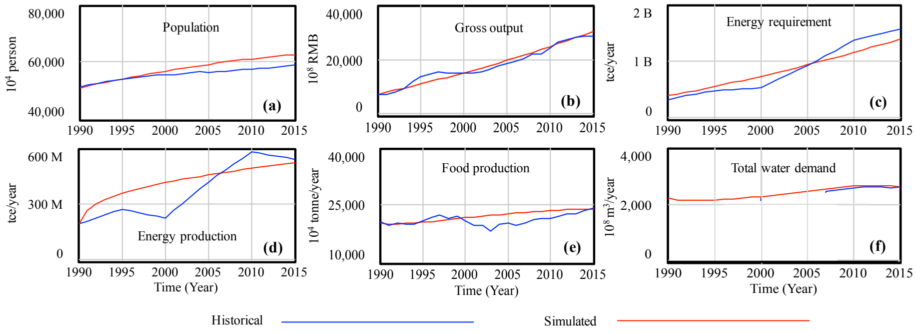

Figure 16. Comparison of simulated and historical system behaviour

Sensitivity analysis aims to build confidence in the model's ability to generate robust system behaviour by applying Monte Carlo simulation. The parameters used for sensitivity tests (shown in Table 4) are chosen due to uncertainty in their values. The selected parameters are varied by -10% ~ +10% (mild variation scenario) and -50% ~ +50% (extreme variation scenario) to determine whether the main state variables will exhibit alternative behaviour. Triangular probability distribution is used. The highest point of probability in the triangle is assigned to the baseline value of these parameters, where the outer limits are defined by the minimum and maximum percent changes of the value.

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The sensitivity simulations are performed by considering all the possible parameter change combinations together, and the results are shown in Figure 17. The lowercase letters show the results for the mild variation scenario and the capital letters for the extreme variation scenario. As can be seen, the range of the projected variables becomes smaller with the decreasing of the confidence level. For each of the examined variables shown in Figure 17 (a-f), the behaviour modes remain the same within the range of the parameters tested when the variation is mild (-10% ~ +10%). When the variation is extreme (-50% ~ +50%), the range in the trajectory of the state variables is larger, however, the behaviour of each variable still remains the same (Figure 17 (A-F)). The lack of changes in behaviour modes while testing model sensitivity is desirable, indicating the model is robust.

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Table 4 Parameters used for sensitivity tests of main state variables in the model

State variable	Parameters	Baseline value	Unit
Population	normal life expectancy	52.5	year
	female ratio	0.5	dmnl
	reproductive lifetime	35	year
Gross output	value share of labor	0.6	dmnl
	capital energy substitution elasticity	0.75	dmnl
	capital lifetime	40	year
Food production	per capita food consumption	400	kg/year/person
	normal average life of land	6000	year
	inherent land fertility	6300	kg/hectare/ year
Energy production	energy resource elasticity [coal, oil, gas, hydro, nuclear, new]	0.625, 0.657, 0.657, 0.303, 0.303, 0.527	dmnl
	energy capital lifetime [coal, oil, gas, hydro, nuclear, new]	15, 15, 15, 30, 30, 20	year
	reference energy consumption per unit GDP	6	tce/10000rmb
Water demand	reference water withdrawal factor [coalOT, coalRC, coalDRY, gasOT, gasRC, hydro, nuclearOT]	98.54, 2.47, 0.44, 34.07, 2.90, 0, 0	m^3/MWh
	initial water intake	4000	m^3/hectare/ year
Nitrogen concentration	N leaching coefficient of agricultural runoff	18.65	kg/hectare/year
	N concentration of domestic wastewater	60	g/L
	N concentration of industrial wastewater	60	g/L

Note: The values of N concentration of domestic/industrial wastewater are from Henze and Comeau (2008), and the value of N leaching coefficient of agricultural runoff is obtained from FAO (http://www.fao.org/3/w2598e/w2598e06.htm, last accessed Sep 20, 2021). Energy resource elasticities are from ANEMI (Breach and Simonovic, 2020).

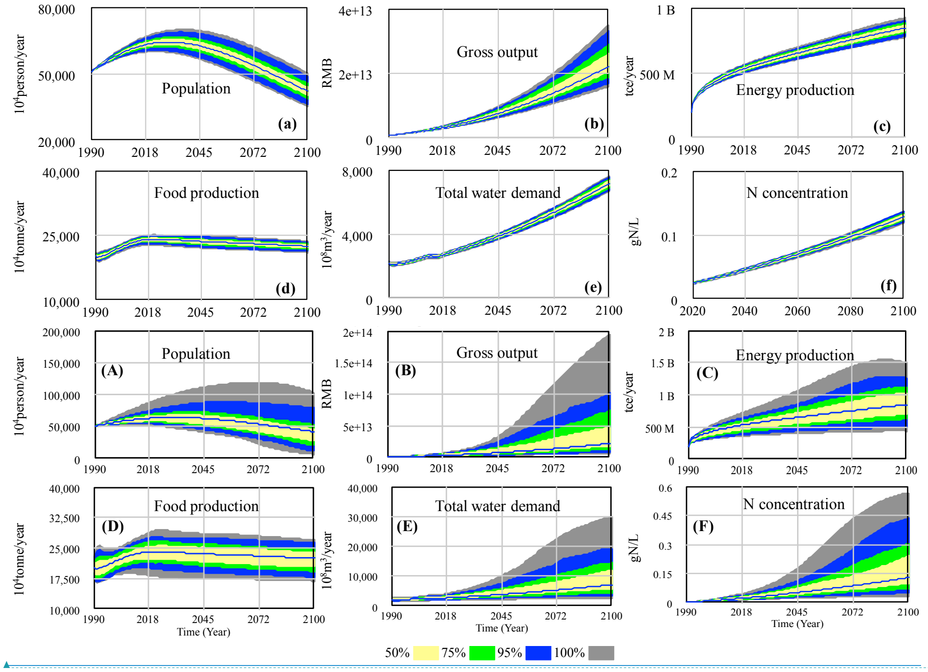

Figure 17. Sensitivity of the selected state variables

5.2 Model application

To test the capabilities of ANEMI_Yangtze, this section focuses on the applications of the model system for the baseline S_base scenario and S_energy scenario. Under the S_base scenario, all the policies remain at their 2015 values during the simulation. Specifically, the one-child policy remains unchanged for the *Population Sector*. The intensity of water withdrawals/consumptions in industry and agriculture for the *Water Sector*, the *energy shares* among different energy sources for the *Energy Sector*, and the *fishing mortality* for the *Fish Sector* shall all remain their 2015 values respectively. The N/P removal efficiency in the *Nutrient Sector* is 0. The exogenous inputs of precipitation and temperature take their historical average annual values. Under the S_energy scenario, the *energy share* of coal decreases linearly from around 60% (the 2015 share) to 30%, and the share of renewable energy (hydropower, nuclear, and new energy sources) increases from 15% to 30% by 2100. The simulation results are shown in Figures 18-19.

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As the share of gas and renewable energy sources increases in the S_energy scenario, the demand for those energy sources grows, placing more pressure on their production. The *energy production pressure effect* acts as a positive factor on *energy capital investment*. Therefore more money is poured into producing energy from gas and renewables sources. As more *energy capital* is mobilized for gas and renewable energy development, the improvement in *energy technology* advances correspondingly, leading to a decrease in *energy consumption intensity per unit GDP*, thus lowering the *energy demand* compared to the base run (see Figure 18(a)). Besides, the combined effects of growing *energy capital investment* and *energy technology* advancement lead to a substantial increase in effective production effort, resulting in increases in gas production, hydropower, nuclear power, and new energy sources, as seen in Figures 18 (f-i). The production of coal is expected to decrease compared to the base run, along with its decrease in energy share (Figure 18(d)). As the energy share of oil remains the same value as in the S_base scenario, its production also remains at the base run level (Figure 18(e)). Those combined effects of the increase in gas and renewable energy production and decrease in coal production result in a slight increase in the total production of energy compared to the base run result (Figure 18(b)).

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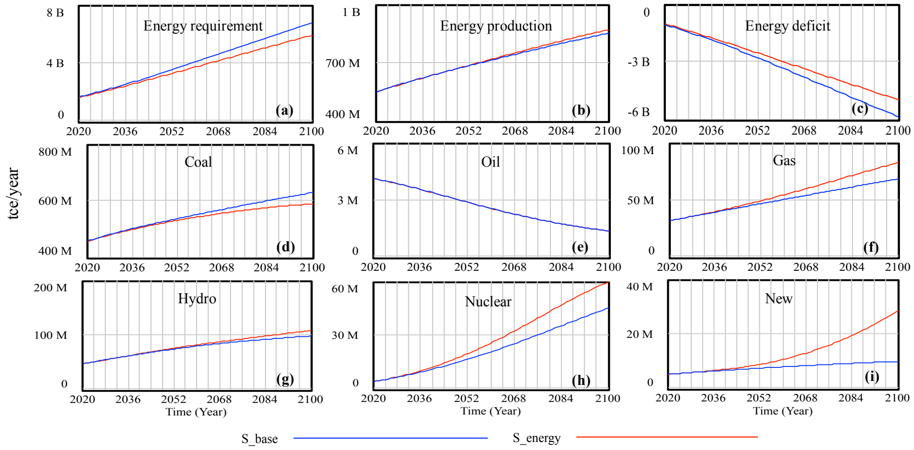

Figure 18. Effects of energy policy on energy system

The changing patterns of *energy consumption* have significant impacts on water and carbon systems. In the S_base run, the coal-fired thermal power plants dominate the *water demand* in the industrial sector. In this S_energy scenario, coal's share decreases from 60% to 30%, and the value share of renewable energy (hydropower, nuclear, and new energy sources) increases from 15% to

30% by the end of the simulation. The nuclear power plants in the Belt are usually located near the East China sea. The cooling water comes directly from the seawater, therefore not increasing freshwater withdrawal. The hydropower plants and the new energy sources (wind and solar power) do not consume any water. This leads to a considerable drop in industrial water demand, as can be seen in Figure 19(a). In the S_base run, the industrial water demand by 2100 approaches 600 billion m^3, while in the S_energy scenario, the value halves and lies below 300 billion. As the industrial sector replaces the agricultural sector, it becomes the most significant water consumer after 2030. Under all definitions, the *water stress* reduces substantially, with all values lying below the critical value of 1 (Figures 19(b-e)). A decrease in industrial water demand and withdrawal also reduces industrial wastewater in accordance and lowers the level of nutrients concentration. The concentration level of nitrogen is shown in Figure 19(g); the results of phosphorus concentration, which share the same behaviour as the nitrogen, are not shown in the figure. By the end of the simulation, the carbon emissions fall from 4,800 Tg in the S_base run to about 2,500 Tg in the S_energy scenario as a result of cutting the coal consumption by half.

The changing energy consumption pattern also has some impacts on population growth and economic development. A slight increase in population is observed under S_energy scenario (see Figure 19(h)) when compared to the base run. This is due to the reduction of nitrogen and phosphorus concentration levels, which improve *life expectancy* trough a variable - *lifetime multiplier from pollution*. As for the economy, even though there is a slightly higher supply of *labour force* resulting from an increase in population, the Belt's *gross output* in the S_energy scenario is a little bit lower than in the S_base output (Figure 19(i)). This is due to the reduced *energy requirement* as seen in Figure 19(a) and discussed in the previous section. A decrease in *energy requirement* decreases the *capital-energy aggregate*, which then decreases the *operating capital*, leading to the decline in economic output. The effect of boosting the *labour force* on economic output is outpaced by the impact of decreasing *operating capital* impact on economic output.

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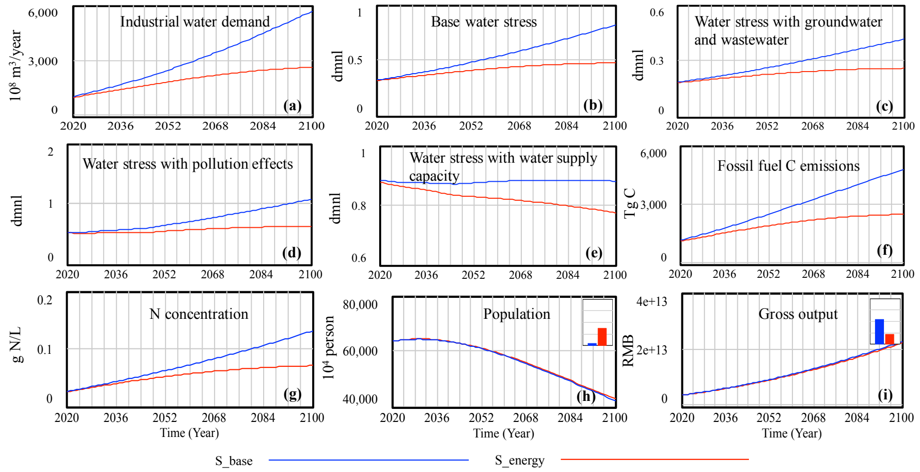

Figure 19. Effects of energy policy on the Belt system

6. Conclusion and discussion

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To address the specific challenges facing Yangtze Economic Belt's sustainable development, ANEMI_Yangtze, which consists of the *Population*, *Economy*, *Land*, *Food*, *Energy*, *Water*, *Carbon*, *Nutrients*, and *Fish Sectors* was developed based on the feedback-based integrated global assessment model ANEMI. This paper focuses on: (i) the identification of the cross-sectoral interactions and feedbacks involved in shaping the Belt's system behaviour over time; (ii) the identification of the feedbacks within each sector that drive the state variables in that sector; and (iii) the description of a new *Fish Sector* and modifications in the *Population*, *Food*, *Energy*, and *Water Sectors*, including the underlying theoretical basis for model equations. The model was validated by comparing simulated results with available historical data. Sensitivity analysis was conducted by varying the parameters with high degree of uncertainty by -10% ~ +10% (mild variation scenario) and -50% ~ +50% (extreme variation scenario). Results demonstrate the model's robustness in modeling system behavioural.

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In the application section, the impacts of shifting energy consumption patterns was investigated. As the Belt gradually shifts its *energy consumption* from coal to natural gas and renewable energy sources, the total *energy production* increases slightly. In contrast, the total *aggregated energy requirement* declines significantly due to the effects of *energy technology* advances. It is also found that the industrial *water demand* and the fossil fuel carbon emissions are

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greatly reduced, leading to a decrease in nutrient concentration levels and an increase in population. The Belt's *gross output* in the S_energy scenario is lower than the base output as the effect of boosting the *labour force* is outpaced by the impact of decreasing *operating capital*, which is caused by a decrease in total *aggregated energy requirement*. These findings enhance our integrated understanding of the dynamic behaviour of socio-economic development, natural resources depletion, and environmental impacts in the Belt. More in-depth model simulation analyses are needed to better understand the influences, responses, and feedbacks generic dynamic behavior of the Belt. The development of policy scenarios and the analyses of associated outcomes are presented in another coming paper (Jiang et al., 2021).

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This paper focuses on presenting the feedback that drive the Belt's dynamic system behaviour based on the authors' current knowledge and understanding. It should, however, be kept in mind that some of the feedbacks might be missing due to the data necessary to describe these feedbacks are currently not available. For example, in China, fish plays an important dietary role and therefore, there should exist feedback connecting the *fish yield* and *food production*. There are thus constant drivers to extend and improve the model framework as the state-of-the-knowledge progresses or as scientific questions become more complex.

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Code availability. The version of ANEMI_Yangtze described in this paper is archived on Zenodo (http://doi.org/10.5281/zenodo.4764138). The code can be opened using the Vensim software to view the model structure. A free Vensim PLE licence can be obtained from https://vensim.com, which can be used to view the stock and flow diagram that makes up the model structure. Due to the advanced features used in the ANEMI_Yangtze model, a Vensim DSS license is required to run the model.

Author contribution. **Haiyan Jiang**: Methodology, Investigation, Validation, Writing - original draft. **Slobodan P. Simonovic**: Conceptualization, Software, Writing - review & editing, Supervision. **Zhongbo Yu**: Funding acquisition, Writing - review & editing.

Competing interests. The authors declare that they have no conflict of interest.

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is presented in section 3. The development of each sector in the ANEMI_Yangtze model is provided in section 4. Section

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The Yangtze Economic Belt, proposed by the central Chinese government in 2016, is set to become yet another critical national-level development goal of China. The Yangtze Economic Belt follows earlier initiatives such as the Coastal Development, Western Region Development, Central Region Development, and Beijing-Tianjin-Hebei Integration.

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and covers a land area of about 2.05 million km^2, accounting for 21% of the China's total land area. The Yangtze Economic Belt is home to 40% of the country's total population, with an economic output exceeding 40% of its entire GDP.

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The Yangtze Economic Belt has unique economic advantages and huge development potential in terms of: geographic location, available water resources, and its comprehensive industrial infrastructure.

2.1.1 Geographic location

Yangtze Economic Belt traverses eastern, central and western China, joining the coast with the inland. The Yangtze Economic Belt's intensive railway, highway, and aviation transportation systems link east to west and connect south to north, making the movement of goods and services more efficient. Also, the Yangtze Golden Waterway, which ranks first among inland rivers in the World in terms of transport volume, also provides competitive low water transport cost and low power consumption. Future networks of standardized intelligent, integrated three-dimensional transport corridors are to be built so that the Yangtze river's main artery will further extend its reach, propelling the development of the vast hinterland.

2.1.2 Natural resources

Yangtze Economic Belt has been the country's main grain and crop production center since ancient times. The nine provinces and cities along the Yangtze river account for more than 40% of the country's grain, cotton, and oil production. The abundance of agricultural biological resources highlights the region's important agricultural foundations. Yangtze river basin has abundant freshwater resources, and its average annual discharge into the East China Sea is about 905 km^3/year (Yang et al., 2015).

2.1.3 Comprehensive industrial system

Yangtze Economic Belt is one of the most important industrial corridors in China. It is home to many advanced manufacturing industries, modern service industries, major national infrastructure projects, and high-tech industrial parks. They all offer strong industrial innovation capabilities, supporting capabilities, goods supply systems and broad market radiation space.

2.1.4 Culture

Yangtze Economic Belt is one of the cultural cradles of the Chinese nation. It has many well-known cultural and tourist resources. The main cities along the river are well-developed for commerce. Famous universities and research institutions are located within the region. Traditional culture and modern civilization are intertwined there.

2.2 The major challenges facing the development of the Yangtze Economic Belt

Yangtze Economic Belt is one of the most dynamic regions in China in terms of population growth, economic progress, industrialization, and urbanization. However, t

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4. ANEMI_Yangtze model structure development

The cross-sectoral interactions and feedbacks are responsible for the functioning of the whole human-nature system in the Yangtze Economic Belt. For each sector in the ANEMI_Yangtze model, the relevant feedbacks drive the dynamics of state variables. This section presents the causal feedbacks within each sector and provides the general description of the ANEMI_Yangtze model structure. For more detail of the model (the stock and flow diagram for each sector and major equations) please refer to Jiang and Simonovic (2021).

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4.1 Population Sector

The causal loop diagram in Figure 3 illustrates the feedbacks associated with the *Population Sector* in the Yangtze Economic Belt. The

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The *Population Sector* is affected by *Land Sector*, *Water Sector*, and *Energy Sector*. On the one hand, the increase of population decreases *GDP per capita* as the *population* is a denominator. On the other hand, the rise in population boosts the *labour force* Thus, the *gross output* as economic output is represented as a function of capital and labour in the form of Cobb-Douglas production function. The increase of the *gross output* eventually increases the value of *GDP per capita*. Overall,

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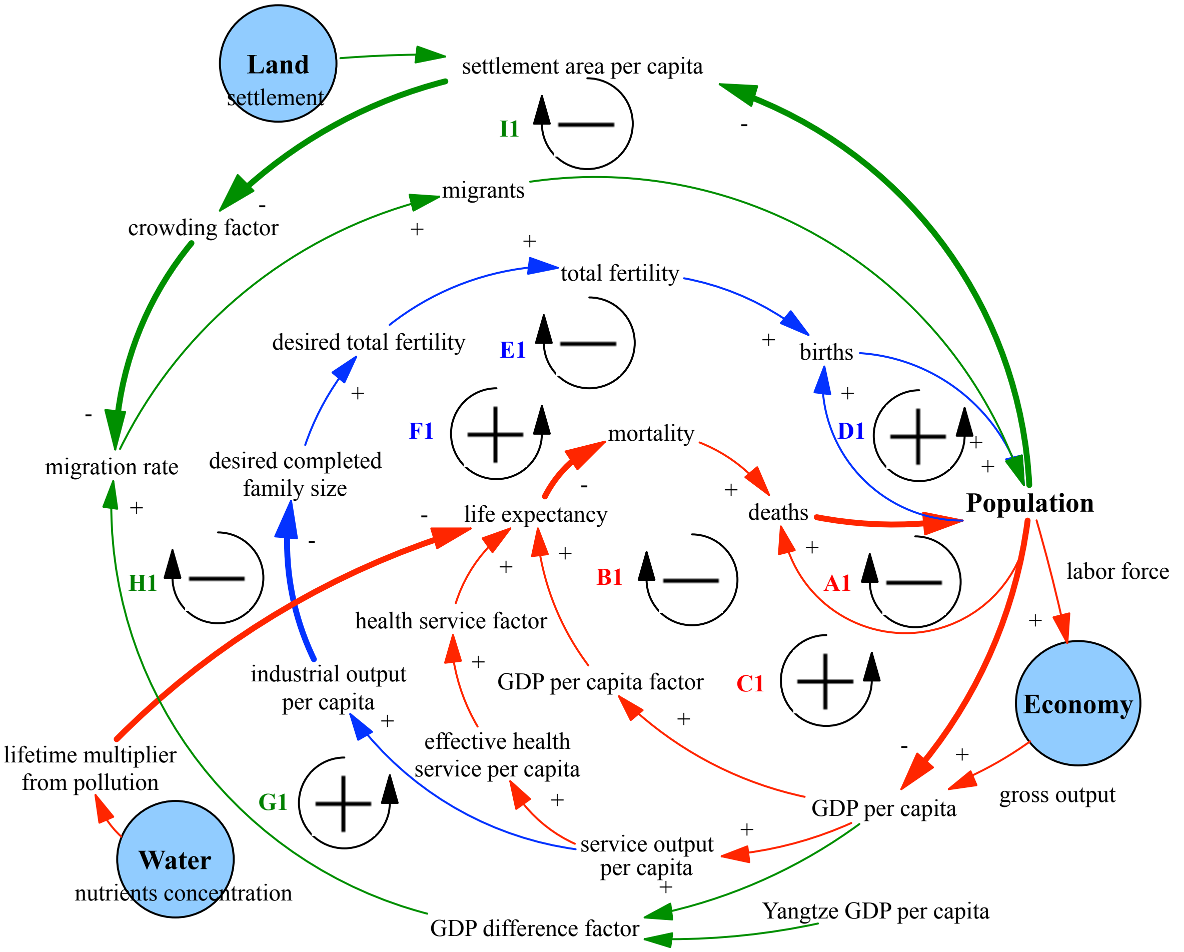
An increase in *GDP per capita*, on the one hand, means improvement in health services, thus increase of *life expectancy* and reduction of the *total mortality rate*. A decrease in mortality means fewer *deaths*, which drives the *population* to grow. On the other hand, an increase in *GDP per capita* leads to a reduction in the willingness to give birth, which will drive the population to decline. Migration is newly added. Usually, people migrate from poor regions to rich areas within China. In this research, migration behaviour is mainly driven by a variable named *GDP difference factor*, which calculates the difference between *national GDP per capita* and the *GDP per capita* in the Yangtze Economic Belt. Besides, the crowding effect is also taken into account, which acts as negative feedback on migration. On the global scale, water and food availability usually act as limits to *population* growth. At the regional scale, vital resources such as food and water can be traded, so in ANEMI_Yangtze, only the effect of pollution on the *population* is considered.



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4.2 Economy Sector

The *Economy Sector*, which is developed and adjusted based on the FREE model from Fiddaman (1997), computes the *gross output* of the Yangtze Economic Belt. The *gross output* is represented as a function of *capital* and *labour* in the form of a Cobb-Douglas production function (see Jiang and Simonovic (2021) for calculation details). The *Economy Sector* is affected by *Population Sector* and *Energy Sector*.

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4.3 Land Sector

The *Land Sector* is used to describe the distribution of land use and cover over time. It is adapted from ANEMI (Simonovic, 2002; 2002a; Davies and Simonovic, 2010; 2011; Akhtar et al., 2013; 2019; Simonovic and Breach, 2020; Breach and Simonovic, 2020; under review), which was initially based on the model of Goudriaan and Ketner (1984). What's different from ANEMI, is that in ANEMI_Yangtze, land cover classes are grouped into the six IPCC land categories, *i.e.* *agricultural land* (cropland), *forest*, *grassland*, *wetland*, *settlement*, and *other land*. In ANEMI_Yangtze the land use transfer occurs simultaneously within all the six land cover classes.

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4.4 Food Sector

The *Food Sector* in ANEMI_Yangtze is taking into consideration the importance of *food self-sufficiency* in China. The country manages to keep the value of the *food self-sufficiency* index at 0.95 to maintain food security. In ANEMI_Yangtze, the dynamic behaviour of *food production* is mainly driven by the difference between perceived *food self-sufficiency* and *desired food self-sufficiency* which serves as an indicator for land yield technology input and fertilizer subsidy. The *Food Sector* also enables the trade of food, *i.e*., *food import* and *food export* (which is affected by local food price and international price). The import and export of food affect the *food stock* and the *food price*. The *food price change* is another factor affecting *food production*. An increase in *food price change* acts as positive feedback on farmers' adoption of multiple cropping practices (*multiple cropping index*) and increasing *grain planting area*.

Food production is affected by several factors, including *land fertility*, *arable land*, and *water stress*. The *Food Sector* is affected by *Population Sector*, *Land Sector*, and *Water Sector*.

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4.5 Energy Sector

The *Energy Sector* consists of *energy requirement*, *energy capital*, and *energy production*. In ANEMI_Yangtze, the *total aggregate energy requirement* is calculated based on the *gross output* multiplied by the *energy consumption per unit GDP*. The *energy requirement* of different energy sources (coal, oil, gas, hydropower, nuclear, new energy sources) is the product of *total aggregate energy requirement* and *desired energy share* (which is treated as an exogenous variable). *Energy capital* for different energy sources is structured similarly to *capital* stock in the *Economic Sector*. The significant difference is that there is a stock representing *energy capital under construction* which after a delay time becomes new *energy capital*. The production of energy is determined by the amount of *capital* stock accumulated into each energy source and is influenced by production pressures. Limitations on *energy production* are in the form of depletion for nonrenewable energy sources (coal, oil, gas) and saturation for renewable energy sources (hydropower, nuclear, new energy sources).

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4.6 Water Sector

The hydrological cycle in the Yangtze Economic Belt describes the flow of water from the atmosphere in the form of *precipitation* to the land *surface storage* and through the *groundwater* back to the East China Sea. The *surface storage* and *groundwater* are treated as a reservoir from which water flows to and from. *Water demand* is the sum of the desired water withdrawals from agricultural, domestic, and industrial sectors. *Domestic water withdrawal* depends on *structural water intensity* which relates GDP to withdrawal rate per person based on the conceptual model presented in Alcamo et al. (2003). The generation of electricity typically dominates water withdrawals in the industrial sector. In ANEMI_Yangtze, electricity production consists of both nonrenewable sources (coal-fired and gas-fired thermal power) and renewable sources (hydropower and nuclear power). The *water withdrawal factor* and *water consumption* of thermal energy vary substantially among different cooling methods. The nuclear power in the Yangtze Economic Belt only withdraws seawater, so the freshwater withdrawal and consumption factors of nuclear power are all set to zero. *Agricultural water demand* is the production of *per hectare water withdrawal* and *net arable land*. Changes in surface temperature are also included as additional factors affecting water demand for *food production*. In ANEMI_Yangtze, three water supply types are considered by adding capital stocks to produce *water supply* in the form of surface, ground, and wastewater reclamation water sources. The production of water supplies is driven economically by investing in *capital* stocks for each source. *Water stress* is used as an indicator for *water capital investment*.

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4.7 Carbon Sector

The carbon cycle in ANEMI_Yangtze is based on the carbon cycle of ANEMI, which has its origin in Goudriaan and Ketner (1984). As the ANEMI_Yangtze is a regional model, the ocean and atmosphere's carbon cycles are excluded. Only the carbon cycle at a terrestrial scale is considered. The total carbon emissions into the air consist of the fossil fuel carbon emissions from the *Energy Sector* and the land-use carbon emissions from the *Land Sector*.

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4.8 Nutrients Sector

In ANEMI_Yangtze, nutrients (nitrogen, phosphorus) concentration in surface waters is used to indicate water pollution. Wastewater from domestic and industrial users and agricultural inputs are the main contributors to water quality degradation. The index of water pollution is a multiplier on life expectancy in the *Population Sector*.

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4.9 Fish Sector

The *Fish Sector*, which is an entirely new addition to the ANEMI_Yangtze model, is used to describe the dynamics of *fish biomass stock* and *fish yield* over time.

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To verify the feasibility of ANEMI_Yangtze, simulation results for the major state variables were compared to available historical data for 1990-2015. The results are shown in Figure 12.

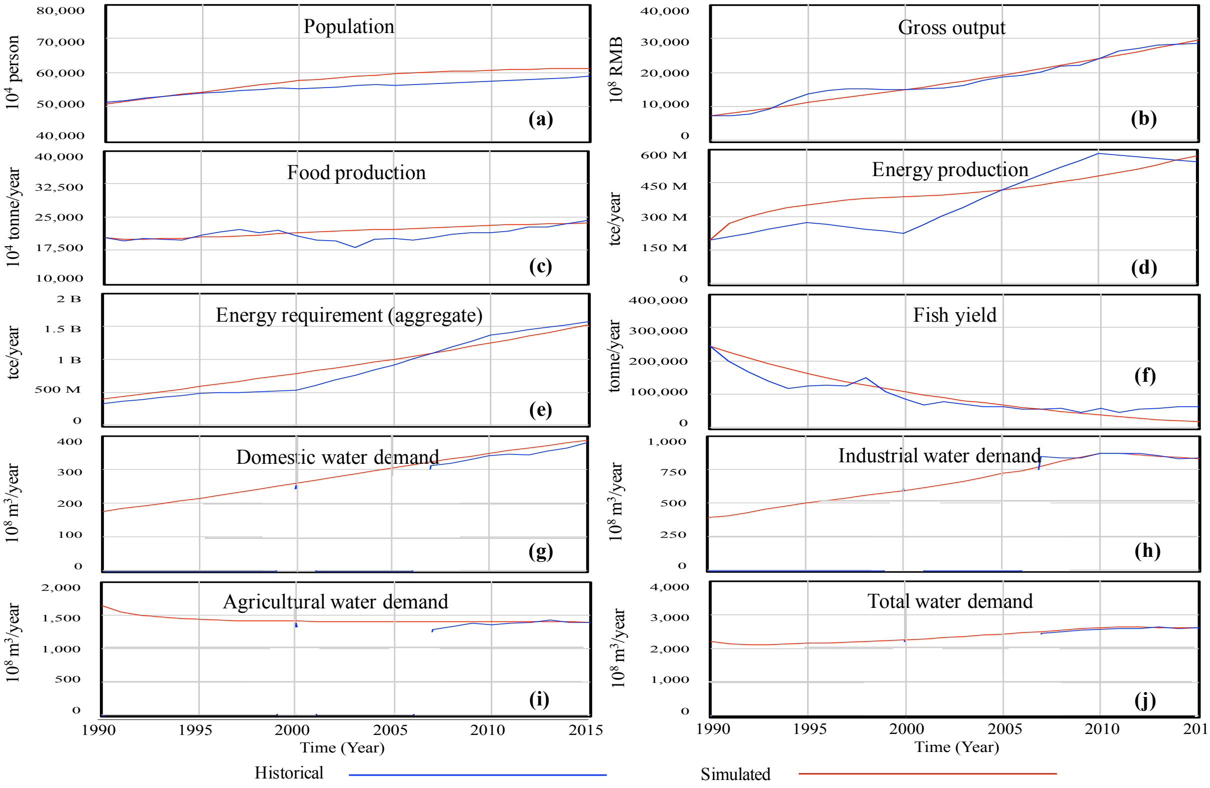

Figure 12. Comparison of simulated and historical behaviours in the Yangtze Economic Belt

As shown in Figure 12, the model can reproduce the system behaviour very well for *population*, *gross output*, *food production*, *energy requirement*, *fish yield*, and *water demand* (Figures 12(a-c, e-j)). The model can capture the general system behaviour pattern for *energy production* (Figure

12(d)). The discrepancy between historical and simulated *energy production* is partly due to the past energy policies acting on the energy system that the ANEMI_Yangtze model doesn't consider. Overall, ANEMI_Yangtze demonstrates its capability by producing a very close agreement with the observed data.

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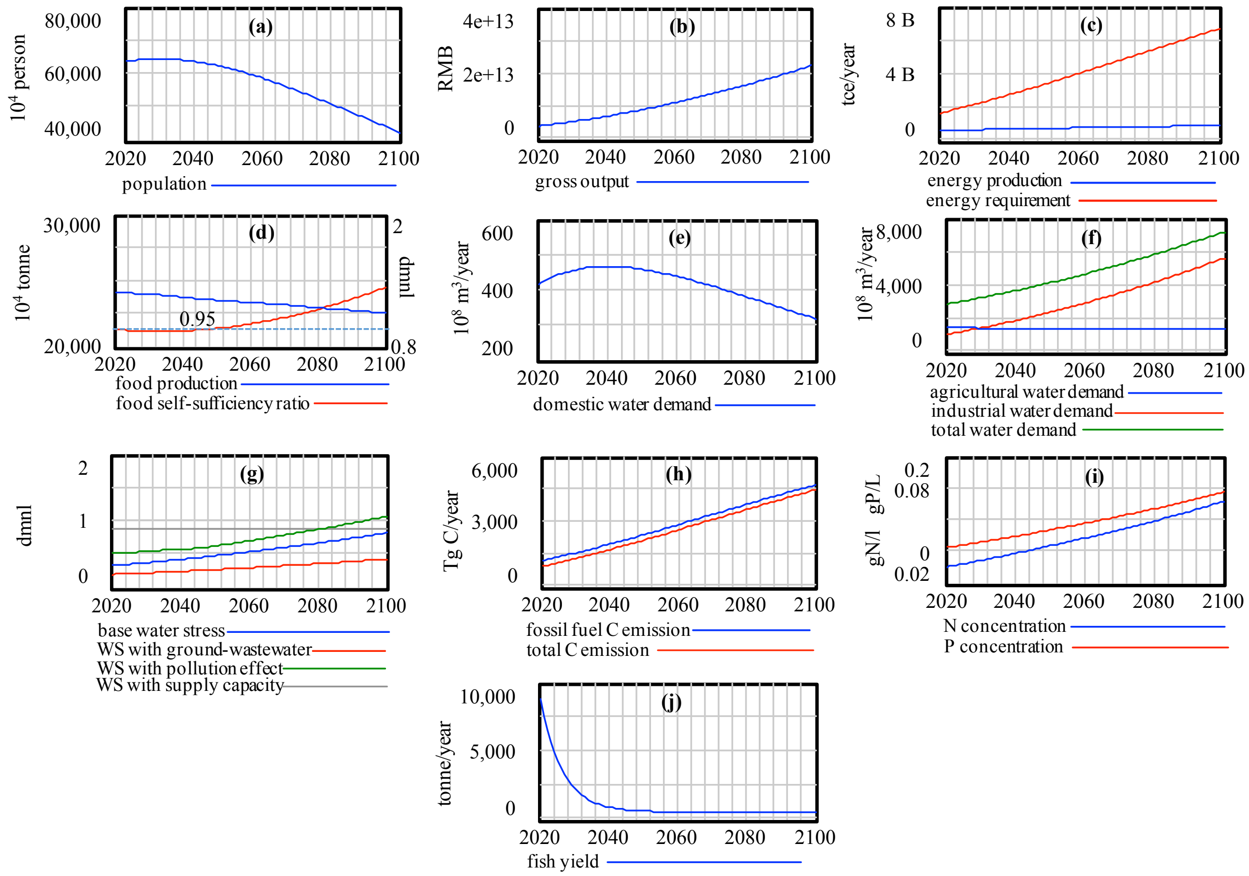

Figure 13. Dynamic behaviour of the Yangtze Economic Belt system

As can be seen from Figure 13(a), *population* in Yangtze Economic Belt peaks around 2030 and then decreases to around 400 million by 2100 when only one child is allowed for each family. Yangtze Economic Belt's *gross output* rises gradually up to 22 trillion 1990 RMB by the end of the simulation (Figure 13(b)). *Energy requirement* shares the similar behaviour mode of *gross output* as its calculation is based on every unit economic output and reaches about 6.7 billion tce by 2100 (Figure 13(c)). *Energy production*, however, grows very slowly when compared to *energy requirement*. This is partly due to the general low reserve of fossil fuel in the Yangtze Economic Belt region, so *energy production* is negatively affected by the *resource remaining factor*. Another factor that contributes to the slow growth of *energy production* is the relatively low share of renewable resources (about 15%) even though Yangtze River Basin has abundant hydropower resources as the energy shares among different energy sources remain their 2015 values during the whole simulation. The dynamic behaviour of *food production*, which is determined by both the *land yield* and the *grain planting area*, exhibits a declining behaviour, indicating that the effects of an increase in *land yield* are outpaced by the decrease in the *grain planting area* (Figure 13(d)). The decline in the *grain planting area* is caused by a reduction in *agricultural land*. The *food self-sufficiency ratio*, however, increases to its desired value 0.95 around 2050 due to the drastic decrease of *population* size (Figure 13(d)). The dynamic behaviour of *domestic water demand*, shown in Figure 13(e), follows a pathway that is almost identical to that of the *population*, except that the peak of *domestic water demand* comes around 2040, which is 10 years later than the *population* peak. This is due to the *domestic structural water intensity* increases at first with the rise in *GDP per capita* and then stabilizes around 2040. *Industrial water demand* (Figure 13(f)) exhibits a strong rise trend because of the considerable increase of *energy consumption*, which equals the *energy requirement* value as shown in Figure 13(c). *Agricultural water demand*, however, shows a decline mode during the simulation (Figure 13(f)). When comparing *agricultural water demand* to *industrial water demand*, it is found that agriculture is the largest water user sector before 2030, however after 2030 industrial sector far dominates the water use. The total water demand by 2100 approaches 8,000 10^8 m^3/year. Figure 13(g) shows the dynamic behaviours of *water stress* under different definitions. For details of *water stress* definition please refer to the Jiang and Simonovic (2021). As can be seen from Figure 13(g), the *water stress* falls below the critical value of 1.0 in most cases except when taking water pollution effects into account, indicating that the water resources in the Yangtze Economic Belt are sufficient to support the development of the economic belt. Figures 13(h-i) show that the total carbon emissions and the nitrogen and phosphorus concentrations rise all the way to the end of simulation under current policy scenario. The Yangtze *fish yield* drops drastically, which confirms that the Yangtze river fish stock may be completely depleted if there is no fish ban policy.

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Through the identifications of the cross-sectoral interactions and feedback and feedback within each model sector, some of the major insights gained from this research include: (1) a boosting population places increasing demand on food, energy, and water resources produces more and more pollution to the environment. The deteriorating eco-environment in turn, limits further growth of population through a water pollution index; (2) a growing economy drives energy production and consumption, resulting in more greenhouse gas emissions and a rising surface temperature. This in turn results in negative feedback on economic growth through climate damages.