https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

Geoscientific Model Development
Discussions

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

Haiyan Jiang[1,2*], Slobodan P. Simonovic[1], Zhongbo Yu[2,3,4]

[1]Department of Civil and Environmental Engineering, Western University, London, Ontario, Canada

[2]State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, 210098, China

[3]Joint International Research Laboratory of Global Change and Water Cycle, Hohai University, Nanjing, 210098, China

[4]Yangtze Institute for Conservation and Development, Hohai University, Nanjing, 210098, China

Correspondence: Haiyan Jiang (sophia4637@163.com; hjiang95@uwo.ca)

Abstract: Yangtze Economic 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 (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 Yangtze Economic Belt. Understanding these interactions poses challenges because human and natural systems evolve in response to a wide range of influences. Accounting for these complex dynamics requires a system tool that can represent the fundamental drivers of change and responses of the individual system as well as how different systems interact and co-evolve. By adopting the system thinking and the methodology of system dynamics simulation, an integrated assessment model for the Yangtze Economic 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 identifies the opportunities and challenges facing the Yangtze Economic Belt and presents the ANEMI_Yangtze model structure. It also includes: (i) the identification of the cross-sectoral interactions and feedbacks involved in shaping Yangtze Economic 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 explanation of the theoretical and mathematical basis for those feedbacks.

ANEMI_Yangtze was developed and calibrated sector by sector before coupling them together into complete ANEMI_Yangtze model. After the validation and robustness test, the ANEMI_Yangtze model can be used to support decision making, policy assessment, and scenario development. This study aims to improve the understanding of the complex interactions among human and natural systems in the Yangtze Economic Belt to provide foundation for science-based policies for the sustainable development of the economic belt.

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 the human race to the biosphere are complex, and all aspects affect each other to a high degree. Therefore, 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 food, water, and energy insecurity (Rasul and Sharma, 2016; D'Odorico et al., 2018). The WEF nexus framework was introduced at a conference on "The Water-Energy-Food Security Nexus: Solutions for the Green Economy" in Bonn in 2011. The research and policy-making communities were rapidly attracted by the proposed framework (Daher and Mohtar, 2015; Smajgl et al., 2016; Garcia and You, 2016; Weitz et al., 2017; Liu et al., 2017; Xu et al., 2020). The WEF nexus offers a promising approach to identifying trade-offs and synergies of WEF systems and guiding cross-sectoral policies. Unfortunately, current applications of the WEF nexus methods fall short of adequately capturing interactions among the WEF system - the very linkages WEF nexus conceptually aims at addressing (Albrecht et al., 2018; Stoy et al., 2018).

Moreover, while the WEF nexus is relatively new, the concept of nexus thinking is not new. Dated back to 1970s, the Club of Rome's research has applied the nexus concept in developing an

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

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 feedback and including both the eco-environment dimensions such as biodiversity and ecosystem services and socio-economic dimensions such as population growth and economic development which are exactly what the WEF nexus unable to address (Kling et al., 2017). In recent years, as the awareness of climate change and sustainability challenges increases, numerous researchers have dedicated themselves to studying various aspects of global change, aimed at understanding these complex and long-term issues and to design effective response strategies. These efforts led to many IAMs with various details in incorporating different system components. They include the ANEMI model developed at Western University (Simonovic, 2002; 2002a; Davies and Simonovic, 2010; 2011; Akhtar et al., 2013; 2019; Simonovic and Breach, 2020; Breach and Simonovic, 2020; under review); the IMAGE model (Integrated Model to Assess the Global Environment) developed at Netherlands Environmental Assessment Agency (Stehfest et al., 2014), and the GCAM model (Global Change Analysis Model) developed at the University of Maryland (Calvin et al., 2019). While these global IAMs provide valuable tools to explore the multiple interactions among human and natural systems and to assess the impacts of global change and adaptation and vulnerability of human society, they are of less value to local policymakers (Holman et al., 2008; Bazilian et al., 2011; Simonovic and Breach, 2020; Breach and Simonovic, 2020; under review). There is thus an urgent need to find a way to “downscale” global IAMs and apply them at the smaller scales so as to address local-specific challenges (Akhtar et al., 2019; Simonovic and Breach, 2020; Breach and Simonovic, 2020; under review).

Yangtze Economic Belt is one of the most dynamic regions in China in terms of population growth and economic development and faces many resource constraints and environmental challenges. Promoting high-quality development of the Yangtze Economic Belt is an essential strategy that has a bearing on the overall national development as the Yangtze Economic Belt accounts for about half of China’s population and GDP. Therefore, researchers and decision makers are increasingly interested in knowing how the economic belt will unfold in the future. For example, how might changes in birth control policy affect population dynamics, and what might this mean for natural resources consumption and air and water pollutions? How depletion of natural resources and degradation of the environment constrains the growth of population and economy? How might changes in land-use policy alter the production of food and the withdrawal

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

of water? How might new emerging energy sources such as solar and wind power influence the way that energy is consumed, and what might this mean for greenhouse gas emissions? How policies aimed at improving the eco-environment situation affect the Yangtze Economic Belt system. In this study, an integrated ANEMI_Yangtze model, which is "downscaled" from the global ANEMI model, is developed to explore questions such as these. This paper focuses on the model description, that is, (i) the identification of the cross-sectoral interactions and feedbacks involved in shaping Yangtze Economic 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 explanation of the theoretical and mathematical basis for those feedbacks. The model application which helps us understand how the economic belt will evolve under a particular set of conditions and how the system will change in response to a wide range of policy scenarios, shall be presented in another coming paper. This paper is organized as follows, the opportunities and challenges facing the Yangtze Economic Belt are provided in section 2. A brief introduction of ANEMI and ANEMI_Yangtze and the theoretical basis for ANEMI_Yangtze is presented in section 3. The development of each sector in the ANEMI_Yangtze model is provided in section 4. Section 5 discusses the model validation and application, while section 6 offers the final conclusions.

2. Yangtze Economic Belt development, opportunities and challenges

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

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

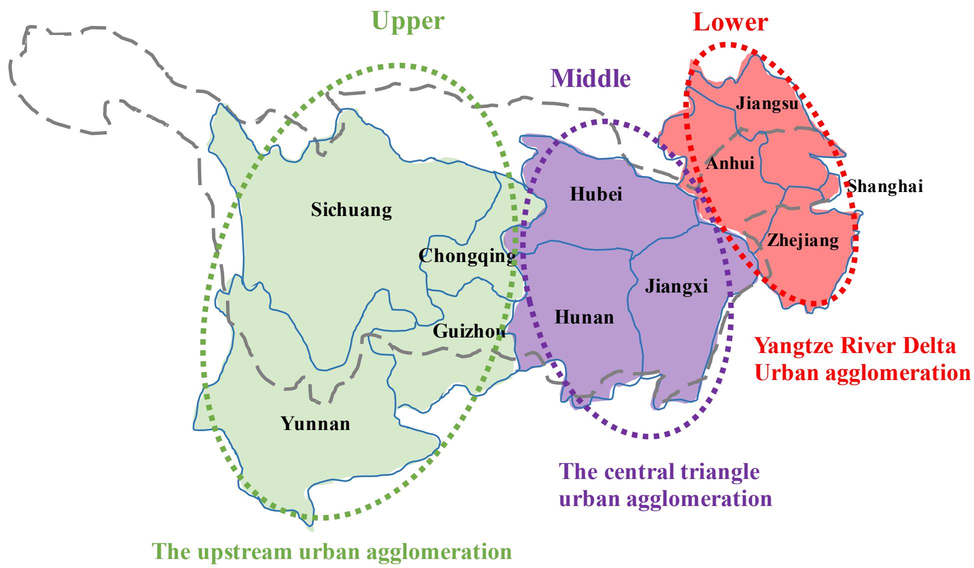

Figure 1. Yangtze river basin (black long dashed line) and the Yangtze Economic Belt

2.1 The great opportunities of the Yangtze Economic Belt

Over the past decades, especially after the reform and opening-up of China in the late 1970s, the Yangtze river basin has developed into one of the most vital regions in China. 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

Geoscientific Model Development Discussions

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, the fast development of urbanization and economic growth in the Yangtze Economic Belt pose severe challenges for its sustainable development. The significant challenges facing the sustainable development of the Yangtze Economic Belt include climate change impacts, energy supply, land availability, food self-sufficiency, water pollution and depletion of fish stock in the river.

2.2.1 Climate change impacts

Accumulating evidence shows that climate change affects the hydrologic regime in the Yangtze river basin. For example, research has found 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

Geoscientific Model Development Discussions
Open Access EGU

vast majority of the population to growing physical and socio-economic risks. 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.

2.2.2 Energy crisis

The characteristic of China's fossil energy endowment is rich in coal while low in oil reserves. However, Yangtze river basin is very poor in coal reserves compared to the other regions of China (Wang et al., 2020). The good news is Yangtze river basin has abundant water resources and thus rich 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). Energy, which is the engine of economic development, has become the top threat to the Yangtze Economic Belt's sustainable development.

2.2.3 Land availability and food security

Statistics from the demographic yearbook indicate that the population in Yangtze river basin grew from 500 million in 1990 to about 600 million in 2020, and is expected to reach its peak around 2030 if the one-child policy remains unchanged (Zeng and Hesketh, 2016). As the one-child policy gradually takes off, the population 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, thus threatening food security (Cai and Tu, 2020). 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).

2.2.4 Water pollution

The increasing application of fertilizers and pesticides in agriculture and municipal wastes from a growing population and the rapid development of industry associated with economic growth lead to severe problems concerning pollution of freshwater, eutrophication of lakes, and deterioration of the water ecosystem. 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.

2.2.5 Depletion of Yangtze fish stock

At present, the 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 Yangtze river, the Poyang-Dongting lakes, and the seven major tributaries is temporarily banned for a period of 10 years starting from 2021.

3. ANEMI_Yangtze: background and theoretical basis

In this section, the ANEMI and ANEMI_Yangtze models are briefly introduced.

3.1 From ANEMI to ANEMI_Yangtze

ANEMI, Greek word for winds of change, is an integrated society-biosphere-climate model that represents an alternative approach to understanding, mitigating, and adapting to global change and explores the manner in which interactions, or feedbacks, between different subsystems determine the behaviour of the whole Earth-system by using system dynamics simulation technique (Simonovic, 2002; 2002a; Davies and Simonovic, 2010; 2011; Akhtar et al., 2013; 2019; Simonovic and Breach, 2020; Breach and Simonovic, 2020; under review). The use of system dynamics modelling methodology in capturing the nonlinearity, delays, and feedbacks in determining long-term Earth-system behaviour make ANEMI unique in the realm of integrated assessment modelling. The model ANEMI, which has its roots in the *WorldWater* model by Simonovic (2002; 2002a), has undergone several updates as the Earth system becomes increasingly complex. The first version of the ANEMI model established the basic feedback structure of the society-biosphere-climate system (Davies and Simonovic, 2010; 2011). The second version of ANEMI (ANEMI2) incorporates a computable general equilibrium model to represent energy production within the global economy as well as a new disaggregated population sector, sea-level rise impacts on agriculture, and includes the effect of more greenhouse gases on climate (Akhtar et al., 2013; 2019). In the third version of ANEMI (ANEMI3) some new sectors and features were added. They include an energy-economy system based on the FREE (Feedback-Rich Energy-Economy) model from Fiddaman (1997), a water supply sector in the global economy that parallels the production of energy, and a nutrient cycle of nitrogen and phosphorus sector as indicators of global water quality (Simonovic and Breach, 2020; Breach and Simonovic, 2020; under review). The current version of ANEMI now consists of the following twelve individual 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.

ANEMI_Yangtze is "downscaled" from ANEMI and developed particularly for the Yangtze Economic Belt in China to address the specific challenges facing its sustainable development, which include climate change impacts, energy supply, land availability, food self-sufficiency, water pollution, and depletion of fish stock in the river. In ANEMI_Yangtze, hydrological cycle, water demand and water supply development, as well as wastewater discharge and treatment, are all combined in the *Water Sector*. Climate change is not part of the model. Instead, we use exogenous precipitation and temperature data for the Yangtze river basin to drive the *Water Sector*'s hydrological cycle. Sea level rise and persistent pollution sectors are not included either. The global cycles of carbon, nutrients, and hydrology are tailored to fit a regional context. Some major modifications are to be seen in the *Population*, *Food*, and *Energy Sectors*. Their details are presented in the following sections of the paper. A new sector of the fish population is added into

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

ANEMI_Yangtze to address the fish depletion issues in the Yangtze river. The ANEMI_Yangtze consists of the *Population Sector*, *Economy Sector*, *Land Sector*, *Food Sector*, *Energy Sector*, *Water Sector*, *Carbon Sector*, *Nutrients Sector*, and *Fish Sector*. In this paper, we focus on illustrating the theoretical basis for ANEMI_Yangtze. We focus on analyzing the nonlinearity, delays, and feedbacks in determining the long-term system behaviour in the Yangtze Economic Belt. The application of the ANEMI_Yangtze model to assist in policymaking and analyzing system behaviour under various policy scenarios is to be seen in another coming paper.

3.2 ANEMI_Yangtze cross-sectoral interactions and feedbacks

Unlike the global human-natural system, the human-nature system in the Yangtze Economic Belt undergoes constant exchange of goods and services with the outside world through market trade and migrations. So, some exogenous drivers are also significant for the ANEMI_Yangtze model. Even though the ANEMI_Yangtze model is not that highly endogenous like its parent model ANEMI, there is no doubt that it is the interactions and feedback processes among the various subsectors of the Yangtze Economic Belt system that drive the dynamic behaviour exhibited in the model runs. 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.

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

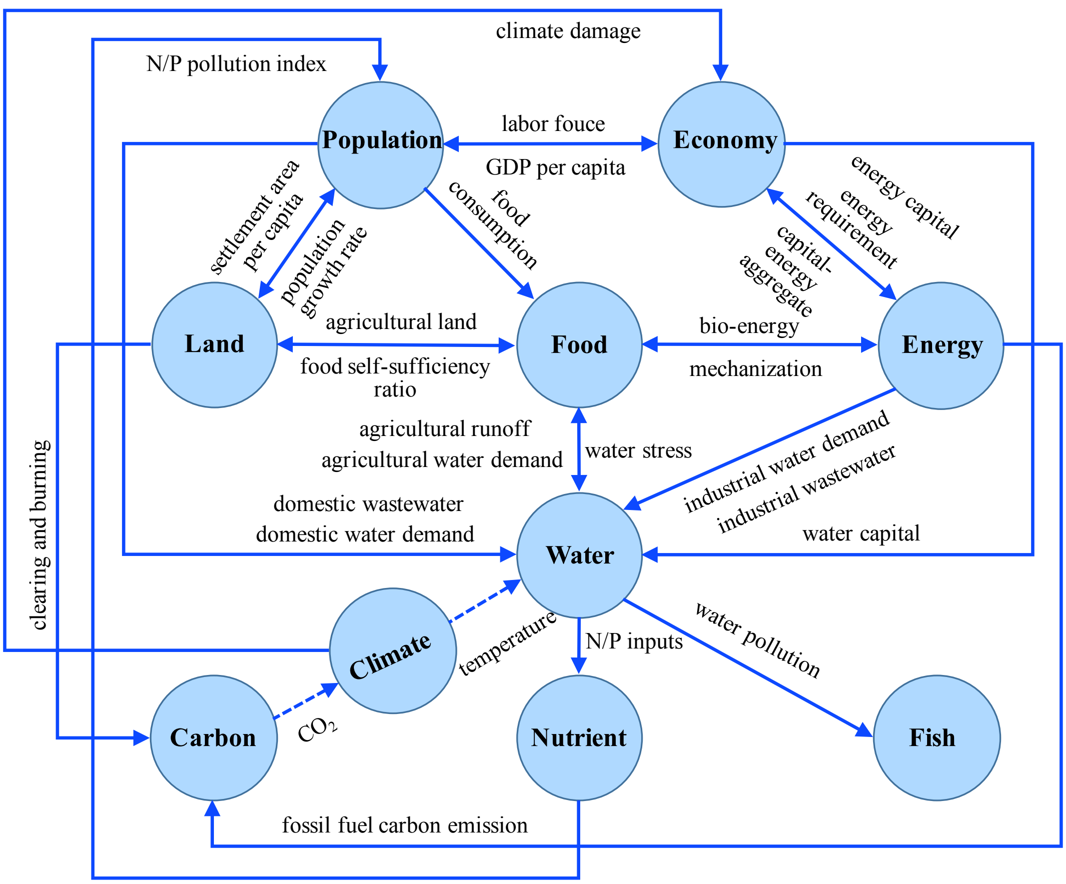

Figure 2. Interactions among the human-natural systems in the Yangtze Economic Belt

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 Yangtze Economic Belt and the rest of China also affects population migration. Usually, people tend to migrate from less developed regions to more developed areas.

The *Population*, *Food*, and *Land Sector*s are connected through *population growth rate*, *food self-sufficiency ratio*, and *settlement area per capita*. The population growth accelerates the

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

Geoscientific Model Development Discussions Open Access EGU

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 and burning forest and grassland. The population growth also leads to more agricultural land around the urban area be claimed for settlement use as urban expands. The *Land Sector* can act 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.

The *Economy* and *Energy Sector*s are linked through *capital-energy aggregate*, *energy capital*, and *energy requirement*. A growing economy increases the requirement 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.

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. Water 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, has a limiting effect on population growth and *food production*. The increase in water stress also drives more capital flowing into water supply development to alleviate water stress, thus connecting the *Economy* sector with the *Water Sector*.

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. As carbon and climate interactions happen globally, for the Yangtze Economic Belt, these two sector interactions are not considered. 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 increases evaporation and evapotranspiration within the Yangtze hydrological cycle. The *Climate Sector* influences the *Economy* sector through a temperature damage function.

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).

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 three variables - *births, deaths,* and *migrants*, which are all affected by *GDP per capita*, drive the dynamic behaviour of the *population*. 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, *GDP per capita* rises if the effect of the increase in the *gross output* outpaces the effect of the increase in population, and vice versa. This means all 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, the B1 and C1 loops in Figure 3).

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*

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

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.

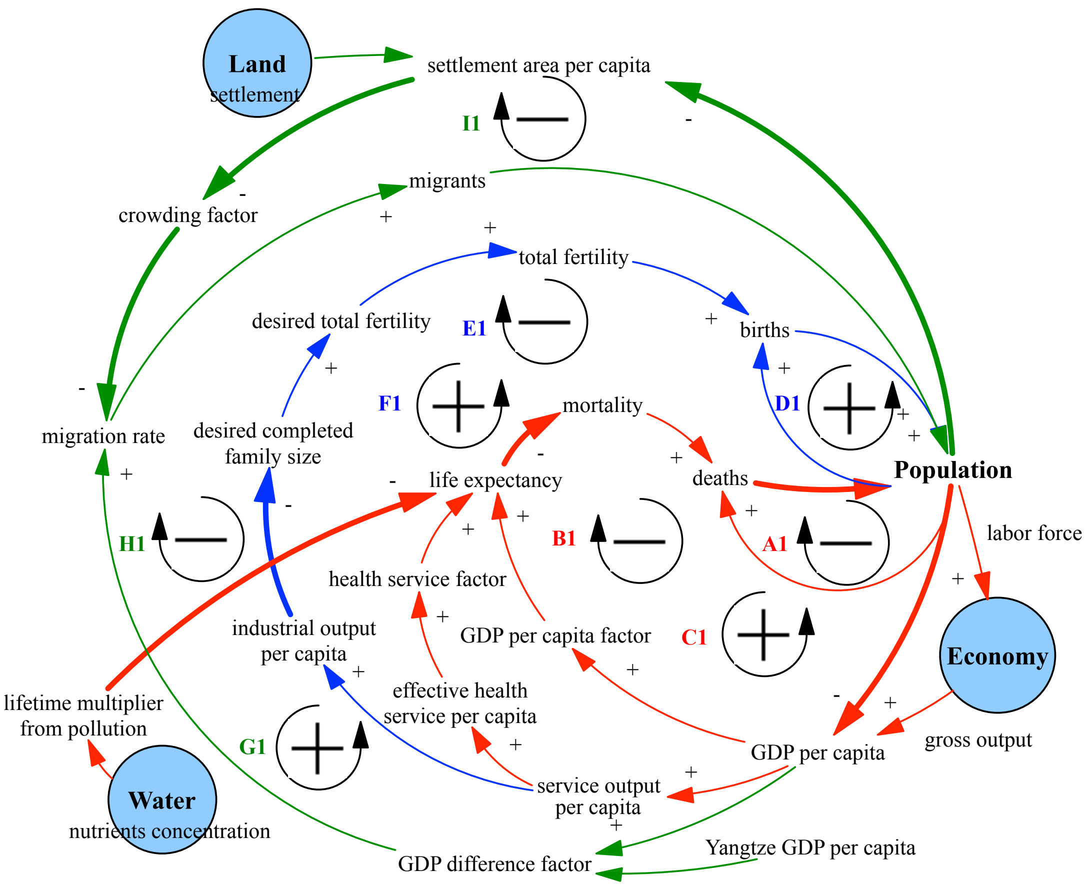

Figure 3. Causal feedback loops of the *Population Sector*

4.2 Economy Sector

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

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*.

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

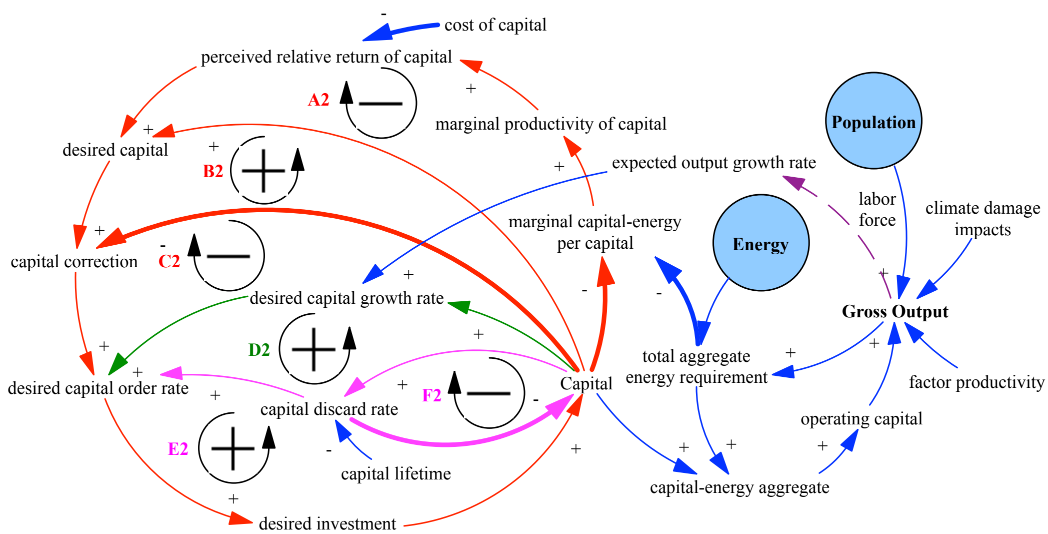

Figure 4. Causal feedback loops of the *Economy Sector*

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.*

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

Geoscientific Model Development
Discussions

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. Figure 5 illustrates the feedbacks in *agricultural land* (the feedback loops in *forest*, *grassland*, *wetland*, *settlement*, and *other land*, which are not shown in the figure, are the same as those in *agricultural land*). An increase in the stock of *agricultural land* increases its transfer rate to *forest*, *grassland*, *wetland*, *settlement*, and *other land,* which all together drain the stock of *agricultural land* and form the negative feedback loops A3, B3, C3, D3, and E3. 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. Please refer to Jiang and Simonovic (2021) for calculation details.

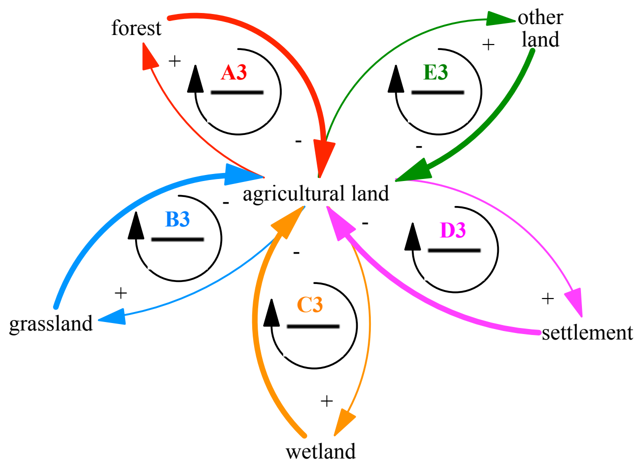

Figure 5. Causal feedback loops of the *agricultural land*

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

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

Geoscientific Model Development
Discussions
Open Access
EGU

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*. The feedback loops of the *Food Sector* are shown in Figure 6. 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*. Loops D4, 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*.

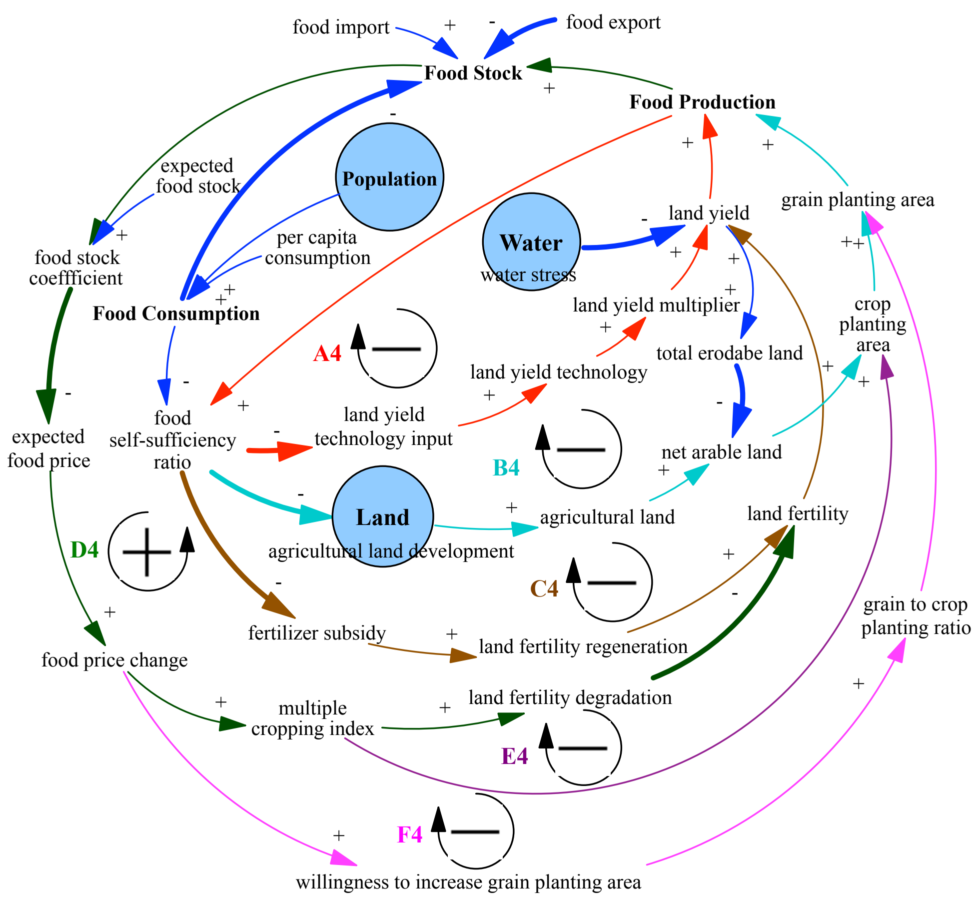

Figure 6. Causal feedback loops of the *Food Sector*

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

Geoscientific Model Development Discussions

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).

The feedback loops in the *Energy Sector* are presented in Figure 7. Feedback 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 has negative impact 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* for the same level of inputs of capital. Loop H5 depicts the effect of *energy technology* on energy consumption intensity per unit GDP.

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

Geoscientific Model Development
Discussions

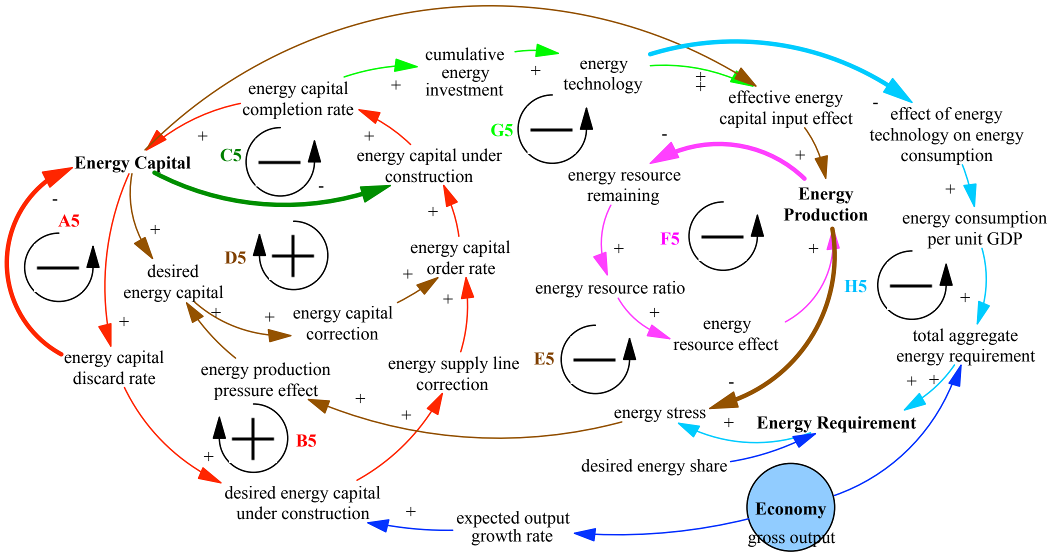

Figure 7. Causal feedback loops of the *Energy Sector*

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,

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

Geoscientific Model Development
Discussions

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*.

The causal loops in the *Water Sector* are illustrated in the causal loop diagram in Figure 8. Feedback 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*. With more *water supply capital*, there is more depreciation, which increases the *water capital order rate* (investment in the water supply), thus adding more *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*.

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

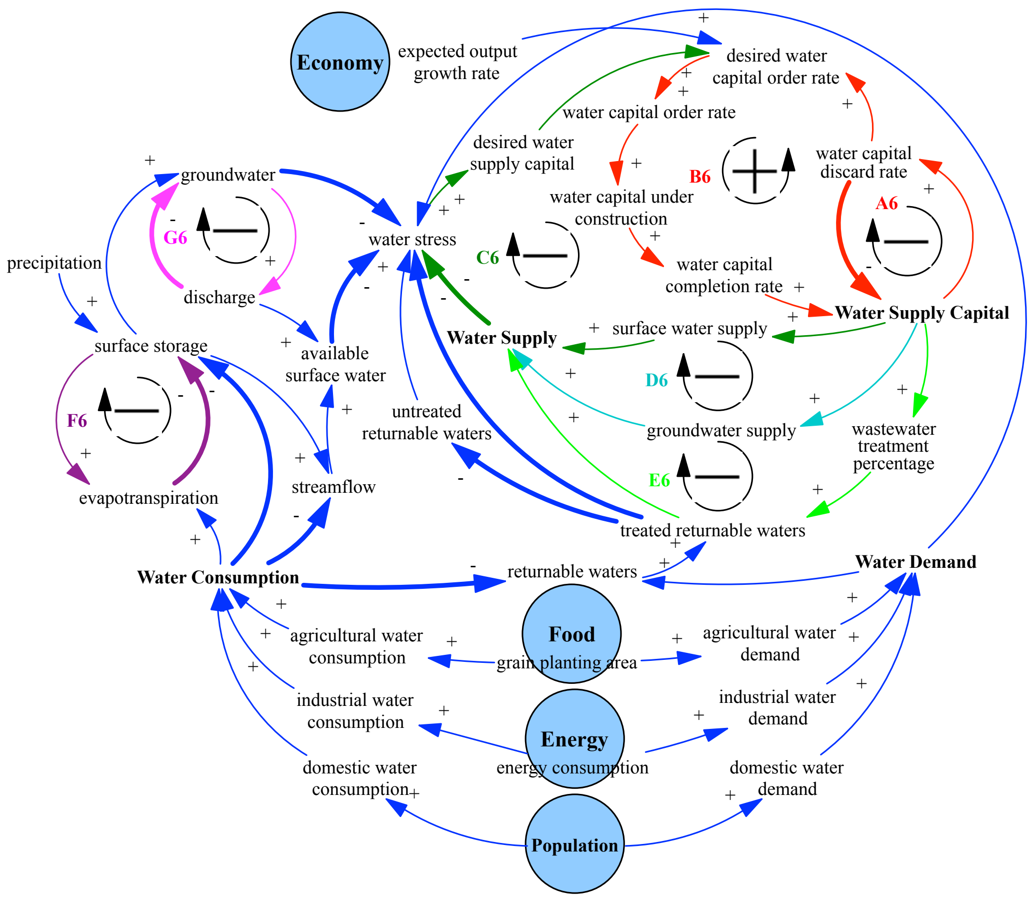

Figure 8. Causal feedback loops of the *Water Sector*

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*.

The causal loop diagram 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

Geoscientific Model Development
Discussions

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.

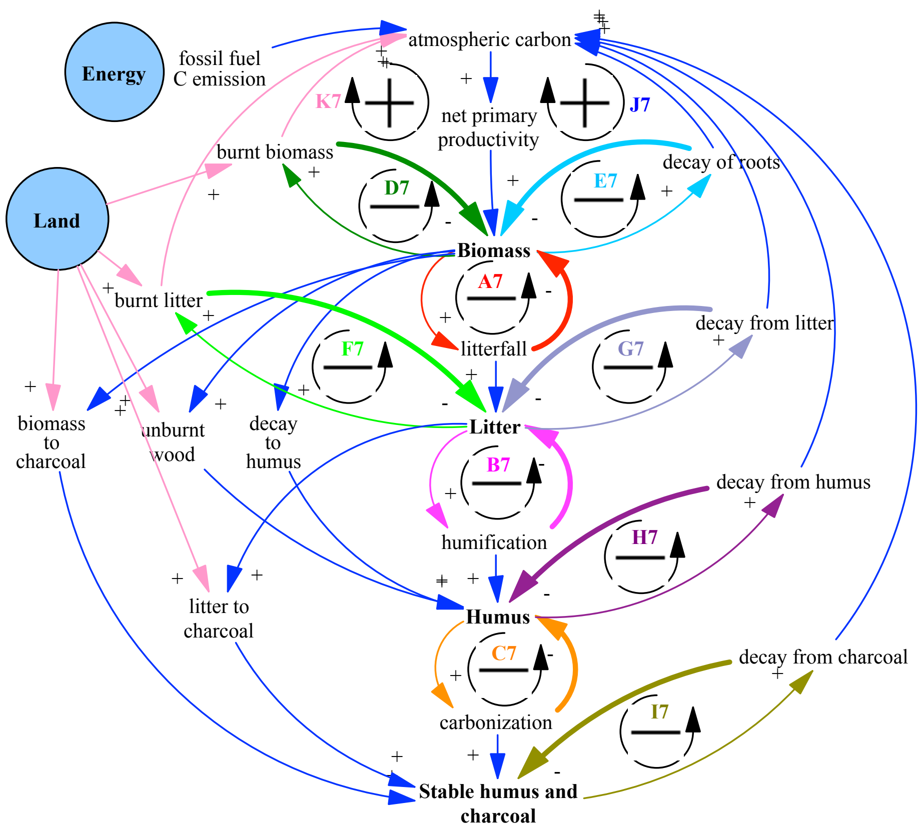

Figure 9. Causal feedback loops of the *Carbon Sector*

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*.

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

Geoscientific Model Development
Discussions
Open Access
EGU

The causal loop diagram 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.

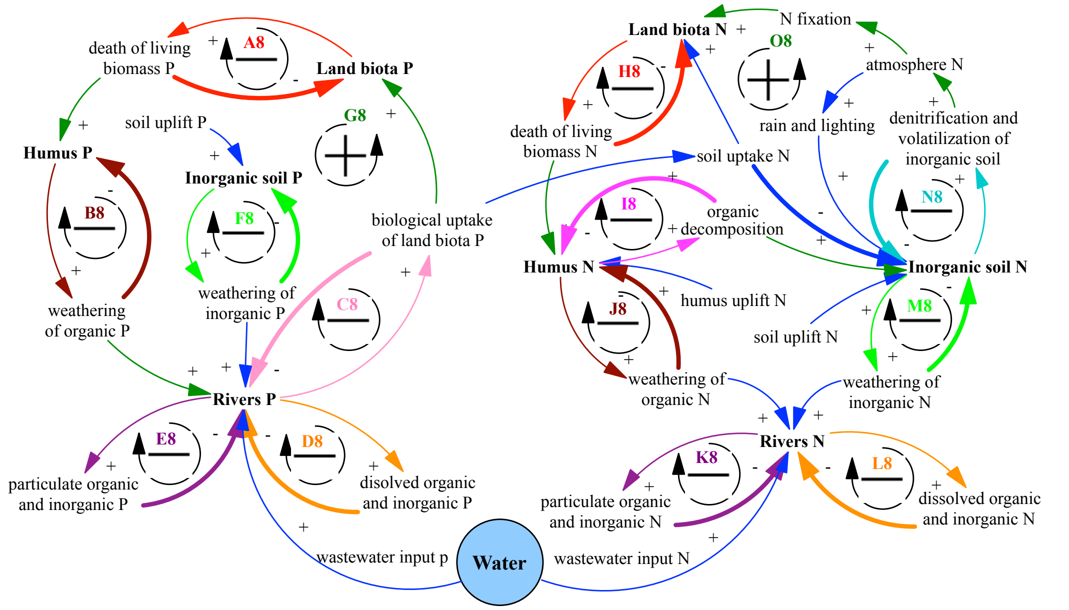

Figure 10. Causal feedback loops of the *Nutrients Sector*

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. 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

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

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*.

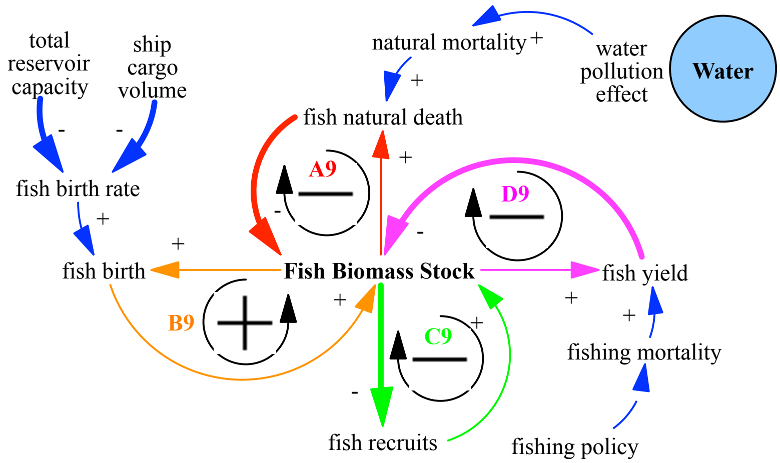

Figure 11. Causal feedback loops of the *Fish Sector*

5. Model validation and application

The ANEMI_Yangtze model was calibrated and validated sector by sector before putting all sectors together. In this section, we describe the validation of the model as a whole, i.e., all of the cross-sectoral feedback are activated.

5.1 Model validation

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.

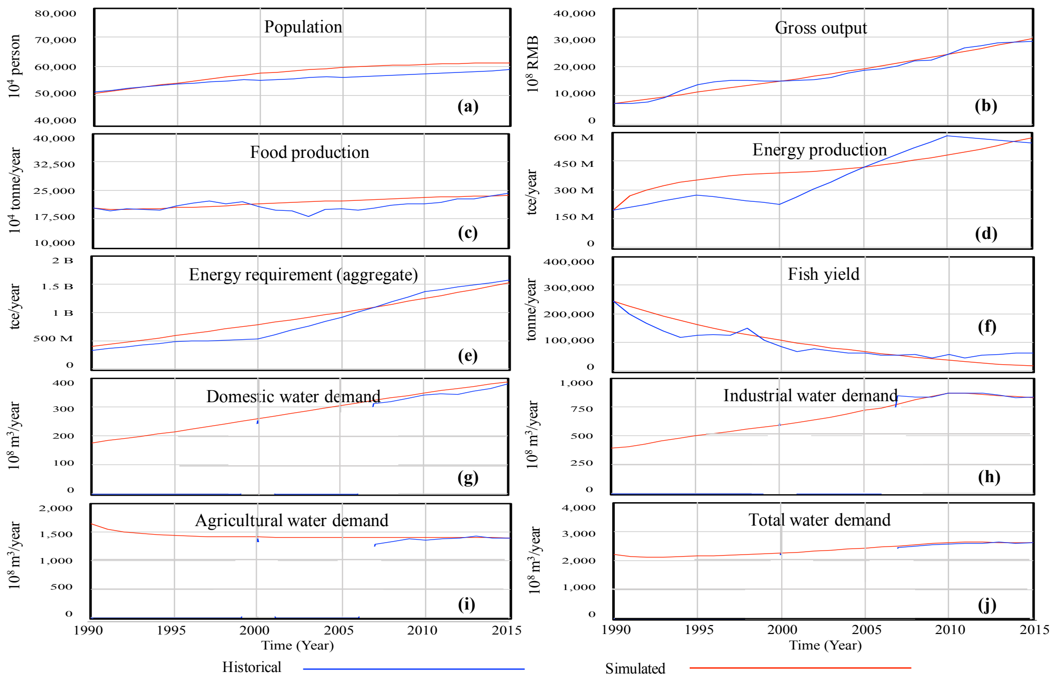

Figure 12. Comparison of simulated and historical behaviours in the Yangtze Economic Belt

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.

5.2 Model application

To test the capabilities of ANEMI_Yangtze, this section focuses on the application of the model system for the baseline policy scenario. Under the baseline, all the policies remain at the 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

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

removal efficiency in the *Nutrient Sector* is 0. The exogenous inputs of precipitation and temperature take their historical average annual values. The future dynamic behaviour of the human-natural system in Yangtze Economic Belt is shown in Figure 13.

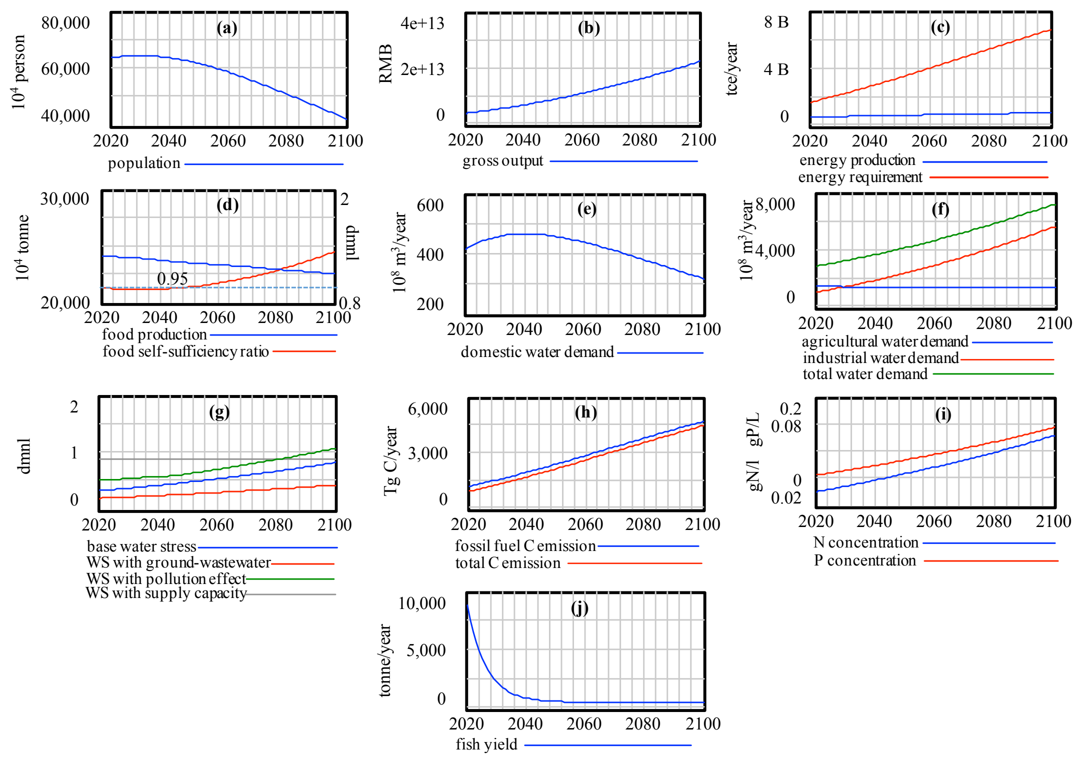

Figure 13. Dynamic behaviour of the Yangtze Economic Belt system

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

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

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.

6. Conclusions

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 illustrating the theoretical basis for

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

Geoscientific Model Development
Discussions

ANEMI_Yangtze. We focus on analyzing the nonlinearity, delays, and feedbacks in determining the long-term system behaviour in the Yangtze Economic Belt.

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. These findings enhance our integrated understanding of the dynamic behaviour of socio-economic development, natural resources depletion, and environmental impacts in the Yangtze Economic Belt. More in-depth model simulation analyses are needed to better understand the influences, responses, and feedbacks generic dynamic behavior of the economic belt. The devise of policy scenarios and the analysis of associated outcomes are presented in the coming paper.

This paper focuses on presenting the feedback that drives the Yangtze Economic 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. 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.

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.

Acknowledgements. This work was supported by the Fundamental Research Funds for the Central Universities (Grant No. B200202035); the Belt and Road Special Foundation of the State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering (Grant No. 2020490111); the National Key R&D Program of China (Grant No. 2016YFC0402710); National Natural Science Foundation of China (Grant No. 51539003, 41761134090, 51709074); the Special Fund of State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering (Grant No. 20195025612, 20195018812, 520004412). The authors are thankful for the financial support of the presented research provided to the second author by the Natural Sciences Research Council of Canada under the discovery grant program.

References

Akhtar, M. K., Simonovic, S. P., Wibe, J., and MacGee, J.: Future realities of climate change impacts: An integrated assessment study of Canada, Int. J. Global Warm., 17, 59-88, https://doi.org/10.1504/IJGW.2019.10017598, 2019.

Akhtar, M. K., Wibe, J., Simonovic, S. P., and MacGee, J.: Integrated assessment model of society-biosphere-climate-economy-energy system, Environ. Modell. Softw., 49, 1-21. http://doi.org/10.1016/j.envsoft.2013.07.006, 2013.

Albrecht, T. R., Crootof, A., and Scott, C. A.: The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment, Environ. Res. Lett., 13, 043002, https://doi.org/10.1088/1748-9326/aaa9c6, 2018.

Alcamo, J., Döll P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., and Siebert, S. : Development and testing of the WaterGAP 2 global model of water use and availability, Hydrolog. Sci. J., 48, 317-337, https://doi.org/10.1623/hysj.48.3.317.45290, 2003.

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R. S. and Yumkella, K. K.: Considering the energy, water and food nexus: Towards an integrated modelling approach, Energ. Policy, 39, 7896-7906, https://doi.org/10.1016/j.enpol.2011.09.039, 2011.

Breach, P. A., and Simonovic, S. P.: ANEMI 3: Tool for investigating impacts of global change, Water Resources Research Report no. 108, Facility for Intelligent Decision

Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 133 pages. ISBN: (print) 978-0-7714-3145-6; (online) 978-0-7714-3146-3, https://www.eng.uwo.ca/research/iclr/fids/publications/products/108.pdf., 2020.

Breach, P. A., and Simonovic, S. P.: ANEMI: A tool for global change analysis, Plos One, under revision.

Cai, W., Tu, F..: Spatiotemporal characteristics and driving forces of construction land expansion in Yangtze River economic belt, China, Plos One, 15(1), e0227299, https://doi.org/10.1371/journal.pone.0227299, 2020.

Calvin K., and Bond-Lamberty, B: Integrated human-earth system modeling—state of the science and future directions, Environ. Res. Lett., 13, 063006, https://doi.org/10.1088/1748-9326/aac642, 2018.

Calvin, K., Patel, P., Clarke, L., Asrar, G., Bond-Lamberty, B., Cui, R.Y., Vittorio, A.D., Dorheim, K., Edmonds, J., Hartin, C., and Hejazi, M.: GCAM v5.1: Representing the linkages between energy, water, land, climate, and economic systems, Geosci. Model Dev., 12, 677-698, https://doi.org/10.5194/gmd-12-677-2019, 2019.

Cao, L., Zhang, Y., and Shi, Y.: Climate change effect on hydrological processes over the Yangtze River basin, Quatern. Int., 244, 202-210, https://doi.org/10.1016/j.quaint.2011.01.004, 2011.

Clayton, T., and Radcliffe, N.: Sustainability: a systems approach, Routledge, 2018.

Conley, D. J., Paerl, H. W., Howarth, R. W., Boesch, D. F., Seitzinger, S. P., Havens, K. E., Lancelot, C., and Likens, G. E.: Controlling eutrophication: nitrogen and phosphorus, Science, 323, 1014-1015, https://doi.org/10.1126/science.1167755, 2009.

Daher, B. T., and Mohtar, R. H.: Water-Energy-Food (WEF) nexus tool 2.0: Guiding integrative resource planning and decision-making, Water Int., 40, 748-771, https://doi.org/10.1080/02508060.2015.1074148, 2015.

Davies, E. G. R, and Simonovic, S. P.: ANEMI: A new model for integrated assessment of global change, Interdisciplinary Environmental Review, 11, 127-161, https://doi.org/10.1504/IER.2010.037903, 2010.

Davies, E.G.R, and Simonovic, S. P.: Global water resources modeling with an integrated model of the social-economic-environmental system, Adv. Water Resour., 34, 684-700, https://doi.org/10.1016/j.advwatres.2011.02.010, 2011.

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

D'Odorico, P., Davis, K. F., Rosa, L., Carr, J. A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G. K., Seekell, D. A., Suweis, S., and Rulli, M. C.: The global food-energy-water nexus, Rev. Geophys., 56, 456-531, https://doi.org/10.1029/2017RG000591, 2018.

Elser, J. J., Bracken, M. E., Cleland, E. E., Gruner, D. S., Harpole, W. S., Hillebrand, H., Ngai, J. T., Seabloom, E. W., Shurin, J. B., and Smith, J. E.: Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems, Ecol. Lett., 10, 1135-1142, https://doi.org/10.1111/j.1461-0248.2007.01113.x, 2007.

Fiddaman T. S.: Feedback complexity in integrated climate-economy models, Department of Operations Management and System Dynamics, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1997.

Garcia, D. J., and You, F.: The water-energy-food nexus and process systems engineering: A new focus, Comput. Chem. Eng., 91, 49-67, http://dx.doi.org/10.1016/j.compchemeng.2016.03.003, 2016.

Goudriaan J., and Ketner, P.: A simulation study for the global carbon cycle, including man's impact on the biosphere, Climatic Change, 6, 167-192. http://dx.doi.org/10.1007/BF00144611, 1984.

Gu, H., Yu, Z., Wang, G., Wang, J., Ju, Q., Yang, C., and Fan, C.: Impact of climate change on hydrological extremes in the Yangtze river basin, China, Stoch. Env. Res. Risk A., 29, 693-707, https://doi.org/10.1007/s00477-014-0957-5, 2015.

Holman, I. P., Rounsevell, M. D. A., Cojacaru, G., Shackley, S., McLachlan, C., Audsley, E., Berry, P. M., Fontaine, C., Harrison, P. A., Henriques, C., and Mokrech, M.: The concepts and development of a participatory regional integrated assessment tool, Climatic Change, 90, 5-30, https://doi.org/10.1007/s10584-008-9453-6, 2008.

Hopwood, B., Mellor, M., and O'Brien, G.: Sustainable development: Mapping different approaches, Sustainable Development, 13, 38-52, https://doi.org/10.1002/sd.244, 2005.

Huang, J., Xu, C. C., Ridoutt, B. G., Wang, X. C., and Ren, P. A.: Nitrogen and phosphorus losses and eutrophication potential associated with fertilizer application to cropland in China, J. Clean. Prod., 159, 171-179, https://doi.org/10.1016/j.jclepro.2017.05.008, 2017.

Jiang, H., and Simonovic, S. P.: ANEMI_Yangtze - A regional integrated assessment model for the Yangtze Economic Belt in China. Water Resources Research Report no. 110, Facility for Intelligent Decision Support, Department of Civil and Environmental Engineering, London, Ontario, Canada, 75 pages. ISBN: (print) 978-0-7714-3155-5; (online) 978-0-7714-3156-2, 2021. https://www.eng.uwo.ca/research/iclr/fids/publications/products/111.pdf.

Jiang, H. , Simonovic, S. P., Yu, Z. , and Wang, W.: System dynamics simulation model for flood management of the three gorges reservoir, J. Water Res. Plan. Man., 146, 05020009, https://doi.org/10.1061/(ASCE)WR.1943-5452.0001216, 2020.

Klein, J. T., Grossenbacher-Mansuy, W., Häberli, R., Bill, A., Scholz, R. W., and Welti, M. eds.: Transdisciplinarity: Joint problem solving among science, technology, and society: An effective way for managing complexity, Springer Science & Business Media, 2001.

Kling, C. L., Arritt, R. W., Calhoun, G., and Keiser, D. A.: Integrated assessment models of the food, energy, and water nexus: A review and an outline of research needs, Annu. Rev. Resour. Eco., 9, 143-163, https://doi.org/10.1146/annurev-resource-100516-033533, 2001

Kong, L., Zheng, H., Rao, E., Xiao, Y., Ouyang, Z., and Li, C.: Evaluating indirect and direct effects of eco-restoration policy on soil conservation service in Yangtze River Basin, Sci. Total Environ., 631, 887-894, https://doi.org/10.1016/j.scitotenv.2018.03.117, 2018.

Li, J., Glibert, P.M., Zhou, M., Lu, S., and Lu, D.: Relationships between nitrogen and phosphorus forms and ratios and the development of dinoflagellate blooms in the East China Sea, Mar. Ecol. Prog. Ser., 383, 11-26, https://doi.org/10.3354/meps07975, 2009.

Li, Y., Acharya, K., and Yu, Z.: Modeling impacts of Yangtze River water transfer on water ages in Lake Taihu, China, Ecol. Eng., 37, 325-334, https://doi.org/10.1016/j.ecoleng.2010.11.024, 2011.

Li, Z., He, Y., Pu, T., Jia, W., He, X., Pang, H., Zhang, N., Liu, Q., Wang, Sh., Zhu, G., Wang, Sh., Chang, L., Du, J., and Xin, H.: Changes of climate, glaciers and runoff in China's monsoonal temperate glacier region during the last several decades, Quaternary International, 218, 13-28, https://doi.org/10.1016/j.quaint.2009.05.010, 2010.

Liu, Y., Wang, S., and Chen, B.: Regional water-energy-food nexus in China based on multiregional input-output analysis, Energy Procedia, 142, 3108-3114, https://doi.org/10.1016/j.egypro.2017.12.452, 2017.

Meadows D. H., Meadows D. L., Behrens W. W., and Randers, J.: Limits to growth, Universe Books, New York, 1972.

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

Niva, V., Cai, J., Taka, M., Kummu, M., Varis, O.: China's sustainable water-energy-food nexus by 2030: Impacts of urbanization on sectoral water demand, J. Clean. Prod., 251, 119755, https://doi.org/10.1016/j.jclepro.2019.119755, 2020.

Rasul, G., and Sharma, B.: The nexus approach to water-energy-food security: An option for adaptation to climate change, Climate Policy, 16, 682-702, https://doi.org/10.5004/dwt.2018.22950, 2016.

Sattari, S. Z., Van Ittersum, M. K., Giller, K. E., Zhang, F., and Bouwman, A. F.: Key role of China and its agriculture in global sustainable phosphorus management, Environ. Res. Lett., 9, 054003, https://doi.org/10.1088/1748-9326/9/5/054003, 2014.

Simonovic, S. P.: Global water dynamics: Issues for the 21st century, Journal of Water Science and Technology, 45, 53-64, https://doi.org/10.2166/wst.2002.0143, 2002.

Simonovic, S. P.: World water dynamics: Global modeling of water resources, J. Environ. Manage., 66, 249-267, https://doi.org/10.1006/jema.2002.0585, 2002a.

Simonovic, S. P., and Breach, P. A.: The role of water supply development in the Earth system, Water, 12, 3349, https://doi.org/10.3390/w12123349, 2020.

Smajgl, A., Ward, J., and Pluschke, L.: The water-food-energy nexus - Realising a new paradigm, J. Hydrol., 533, 533-540, https://doi.org/10.1016/j.jhydrol.2015.12.033, 2016.

Stehfest E., van Vuuren D., Kram T., and Bouwman L.: Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications, PBL Netherlands Environmental Assessment Agency, ISBN: 978-94-91506-71-0, 2014.

Stoy, P. C., Ahmed, S., Jarchow, M., Rashford, B., Swanson, D., Albeke, S., Bromley, G., Brookshire, E. N. J., Dixon, M. D., Haggerty, J., and Miller, P.: Opportunities and trade-offs among BECCS and the food, water, energy, biodiversity, and social systems nexus at regional scales, BioScience, 68, 100-111, https://doi.org/10.1093/biosci/bix145, 2018.

Su, B., Huang, J., Zeng, X., Gao, C., and Jiang, T.: Impacts of climate change on streamflow in the upper Yangtze River basin, Climatic change, 141, 533-546, https://doi.org/10.1007/s10584-016-1852-5, 2017.

Su, M.: Research on the coordinated development of energy in the Yangtze River Economic Zone, Macroeconomic Management, 12, 37-41, 2019. (in Chinese)

van Vuuren, D. P., Kok, M., Lucas, P. L., Prins, A. G., Alkemade, R., van den Berg, M., Bouwman, L., van der Esch, S., Jeuken, M., Kram, T., and Stehfest, E.: Pathways to

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model, Technological Forecasting and Social Change, 98, 303-323, https://doi.org/10.1016/j.techfore.2015.03.005, 2015.

Wang, H: Yangtze Yearbook, Changjiang Water Resources Commission of Ministry of Water Resources, 2015. (in Chinese)

Wang, H., Wang, G., Qi, J., Schandl, H., and Liang, S.: Scarcity-weighted fossil fuel footprint of China at the provincial level, Appl. Energ., 258, 114081, https://doi.org/10.1016/j.apenergy.2019.114081, 2020.

Weitz, N., Strambo, C., Kemp-Benedict, E., and Nilsson, M.: Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance, Global Environ. Chang., 45, 165-173, https://doi.org/10.1016/j.gloenvcha.2017.06.006, 2017.

Wong, C. M., Williams, C. E., Collier, U., Schelle, P., and Pittock, J.: World's top 10 rivers at risk, Nature, 228, 10-10, https://doi.org/10.1038/367764a0, 2007.

Xia, Y., Tabeta, S., Komatsuda, S., and Duan, F.: The impacts of fishing and nutrient influx from Yangtze River on the ecosystem in East China Sea, Modeling Earth Systems and Environment, 2, 1-9, https://doi.org/10.1007/s40808-016-0211-x, 2016.

Xu, H., Paerl, H.W., Qin, B., Zhu, G., and Gao, G.: Nitrogen and phosphorus inputs control phytoplankton growth in eutrophic Lake Taihu, China, Limnol. Oceanogr., 55, 420-432, https://doi.org/10.4319/lo.2010.55.1.0420, 2010.

Xu, Z., Chen, X., Liu, J., Zhang, Y., Chau, S., Bhattarai, N., Wang, Y., Li, Y., Connor, T., and Li, Y.: Impacts of irrigated agriculture on food-energy-water-CO_2 nexus across metacoupled systems, Nat. Commun., 11, 1-12, https://doi.org/10.1038/s41467-020-19520-3, 2020.

Yang, S., Xu, K., Milliman, J. Yang, H., and Wu, C.: Decline of Yangtze River water and sediment discharge: Impact from natural and anthropogenic changes, Sci. Rep., 5, 12581, https://doi.org/10.1038/srep12581, 2015.

Yi, B. L., Yu, Z. T., and Liang, Z. S.: Gezhouba Water Control Project and four famous fishes in the Yangtze River, Wuhan: Hubei Science and Technology Press, 1988. (in Chinese with English abstract).

Zeng, Y., and Hesketh, T.: The effects of China's universal two-child policy, The Lancet, 388, 1930-1938, https://doi.org/10.1016/S0140-6736(16)31405-2, 2016.

https://doi.org/10.5194/gmd-2021-115
Preprint. Discussion started: 31 May 2021

Zhang, H., Kang, M., Shen, L., Wu, J., Li, J., Du, H., Wang, C., Yang, H., Zhou, Q., Liu, Z., and Gorfine, H.: Rapid change in Yangtze fisheries and its implications for global freshwater ecosystem management, Fish Fish., 21, 601-620, https://doi.org/10.1111/faf.12449, 2020.

Zhang, H., Li, J. Y., Wu, J. M., Wang, C. Y., Du, H., Wei, Q. W., and Kang, M.: Ecological effects of the first dam on Yangtze main stream and future conservation recommendations: A review of the past 60 years, Appl. Ecol. Env. Res., 15, 2081-2097, https://doi.org/10.15666/aeer/1504_20812097, 2017.