Gearing Urban Metabolism toward the Carbon Neutrality Target: A Case Study of Hebei Province, China

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Abstract: Urban metabolism has emerged over the past decades as an important new paradigm of regional and urban sustainability governance towards a Chinese national scheme of ‘carbon neutrality’ by 2060. Hebei province in China faces twin pressures related to its supply of water and energy resources, which has brought humans and nature into conflict. Overcoming this tension in the human-land relationship in Hebei and determining a suitable development path for the future has become a core issue for the achievement of coordinated development within the Beijing–Tianjin–Hebei region. This paper constructs a system to simulate the metabolism of water, energy, and human relationships, and uses this model to carry out simulations for Hebei province. The model establishes five scenarios: a natural development scenario, economic growth scenario, water conservation development scenario, energy conservation development scenario, and low carbon scenario. The simulation results show that, without intervention, the natural development scenario results in greater pressure on supply gaps and a greater demand for water and energy, with more production of industrial waste gas and domestic wastewater discharges. The economic growth, water conservation development, and energy conservation development scenarios focus on single economic, water conservation, and energy conservation measures by looking at core economic, water, and energy elements within the metabolic system; however, solving issues with individual elements merely leads to other, remaining problems. Under the low carbon scenario, issues with multiple elements in Hebei’s metabolic system are considered more comprehensively, so the simulation results are better than those in the other scenarios, and it better fits the future orientation of sustainable development of Hebei province.

Keywords: urban metabolism; water-energy-population nexus; system dynamics model; Hebei province; sustainability

1. Introduction

Urban metabolism has emerged over the past decades as an important new paradigm of regional and urban sustainability governance towards a Chinese national scheme of ‘carbon neutrality’ by 2060 [1–3]. Urban metabolism was initially coined as “all the materials and commodities needed to sustain the city’s inhabitants at home, at work and at play” [4], that is, the metaphor of cities as metabolic bodies [5,6]. This concept was rediscovered and upgraded to a deepening of conceptual discussions and case comparisons by various researchers. The urban metabolism paradigm is part of a broader trend towards integrated urban governance by increasingly internalizing material, water, food, and energy flows into cities, in which products and by-products are consequently generated and produced [7,8]. The concept is also valuable for addressing urban sustainability imperatives by the reintegration of natural processes, the increase in resource-use efficiencies, the recycling of wastes as valuable materials, as well as the conservation of (and even production of) energy [9]. Urban metabolic approaches include ecological networks [10], energy modeling [11], material flows [12], life cycle analysis [13,14], multi-sectoral systems...
analysis [15], urban metabolic related indicators, energy [16], water [17], carbon [18], as well as wastes. In general, urban metabolic approaches are useful to understand the natural sustainable development of cities, however, with limited interaction and certain concerns related to the interaction between selected entities, especially on urban physical and social processes. Such disconnections have constrained full understanding, limited explanation and hampered policy formulation in addressing urban territorial development challenges in an increasing interdependent human-land connected context [19]. In the era of planetary urbanization, the studies on urban metabolism still lack in interconnected, contingent, and standardized methods, making a comparison of cities’ metabolisms quite difficult [20].

The urban metabolic system, composed of water, energy, and other commodities, which have traditionally been regarded and governed separately, are increasingly being seen as an inexorably interconnected, concatenated system. This shift is illuminated by a plethora of emerging concepts, such as nexus thinking, virtual water, resilience, etc., especially Chinese traditional geographical thinking and human-land relationships [21,22]. All emphasize the harmony-oriented, socio-natural utopia [23]. The nexus thinking serves as an interdisciplinary perspective and broader trend towards an urban integrated system which embraces the urban metabolism metaphor by highlighting the mutual dependence of important material elements, such as energy and water, in terms of coupled, interlinked mechanisms and conversion processes embodied in intertwined, multi-disciplinary chains at multiple scales [24–27]. In particular, the discourse on the concept of the water-energy nexus emerged from managerial governance circles in response to increasing human-land tensions, integrating the energy embodied in economic activities in water systems and vice versa [28]. However, this paper argues that water-energy nexus thinking reduces complex socio-material heterogeneity to a set of manageable natural material flows and focuses disproportionately on the material elements. There are many calls from urban researchers and practitioners for more detailed and wider ranging synergies between human-nature relationships [29]. The urban metabolic research will contribute to the growing human-land relationship studies in the field of geographical research, the target of which being the human-land system. The human-land relationship specifically refers to the dynamic structure formed by interactions between humans and nature within a certain geographical space. It is a changing, open, and complex mega-system [21]. Geographical studies of major and cutting-edge research fields, including regional sustainable development, global climate change and its impacts, and territorial management, always include the human-land relationship and the interactions between them [22]. The human-land system through the lens of urban metabolism is a mega-system with extremely complex constituent elements. Simply speaking, these include human and natural elements. The “human” element refers to all social and economic activities of humankind and natural elements refer to the natural ecological environment that humans depend on to survive. Since the 1980s, the acceleration of industrialization and urbanization in China has resulted in significant human-made disturbances and destruction of the natural ecological environment. In turn, this destruction has severely affected human production and living activities, causing contradictions between humans and nature to become more prominent. How to fix this increasingly fraught relationship requires simulations of different development scenarios using a human-land system dynamics model, so as to provide targeted measures and suggestions based on various scenario simulation results. Due to changes in individual elements of the human-land system hysteretic and associated response mechanisms, a system dynamics model can more fully characterize the non-linear structure and dynamic characteristics of the system, and the positive feedback structure established in the model can clearly reflect the causal logic. It is also simple to operate [30]. This means that the system dynamics model has significant advantages in terms of simulating the human-land system. This model has been used widely in studies of complex socioeconomic and resource environment systems, such as the earth surface system [31–35], planning and development of urban agglomeration [18,35–37], ecological environment system research [38–41], water resources system [42,43], and energy systems [44,45].
This paper, then, offers two highlights. First, we argue that nexus thinking has been insufficiently handled in urban metabolism research so far. Thus, this paper sheds light on urban metabolism by nexus thinking through system dynamics (SD) model. The urban metabolism, from an SD perspective, is presented as a coupler between the natural system and the human system and production process from which interactions among material and resource flows arise. The SD model has the ability to uncover complicated relationships among different driving forces within a system and it can be employed to simulate a number of urban development scenarios under different policy recommendations [7]. Second, the paper focuses on the urban nexus and, in particular, interfacing water, energy, and population, as a significant, integrated framework to analyze regional-scale sustainability through an urban metabolic perspective. Indeed, the processes through which regional materials and economic systems become enrolled in nexus interactions are drastically overlooked in existing urban metabolic studies. Moreover, it provides a more comprehensive analytical tool for gearing urban metabolic sustainability at a regional scale than a traditional single urban case study, so it is helpful to transplant the integrated urban metabolism framework and practices to other regions using this approach.

Contributing to this wider interdisciplinary urban metabolic agenda, this paper first outlines a water-energy-population nexus approach to better theorize urban embolism through a system dynamics (SD) model. This section also presents data sources and the profile of a case study. Second, it presents a case study of Hebei in China and modeling results of its urban metabolic flows through a system dynamics software—Vensim PLE, Ventana Simulation Environement Personal Learning Edition. Vensim 5.4a. Ventana Systems, Inc., Harvard, MA, USA. It also identifies a different water-energy-population nexus in various scenarios. Lastly, it draws some conclusions and policy implications surrounding the properties and dynamics of urban metabolism through the water-energy-population nexus network in Hebei.

2. The Framework of Modeling Urban Metabolism

2.1. Urban Metabolism Model via Water-Energy-Population Nexus by SD

The regional urban metabolism model via the water-energy-population nexus used in this paper covers the four subsystems of population, economy, energy, and water resources. Variables of these subsystems include the total population, GDP, value added of primary, secondary, and tertiary industries, household energy consumption, industrial energy consumption, total energy consumption, total energy supply, share of non-fossil energy consumption, carbon emission, industrial waste gases, total water demand, domestic water demand, industrial wastewater, water conservancy investment, water resources quantity, and water reuse efficiency etc. Data on the population, economic, and energy variables are mainly taken from the Hebei Economic Yearbook (2001–2019) and the Hebei Statistical Yearbook 2020, data on water variables are mainly taken from various years of the Hebei Water Resources Bulletin (2001–2019), and data on some energy variables are mainly from the China Energy Statistical Yearbook (2000–2020); some missing data were interpolated.

The system dynamics model was originally proposed by Professor Jay W. Forrester of the Massachusetts Institute of Technology in the 1950s. It is a variable structure that uses causality to study quantitatively non-linear, multiple-feedback and complex time-varying systems models using computer simulations. Due to the availability of data, historical data for the period 2000–2019 are used in this study, with the system dynamic operations period being 2000–2050 at time intervals of one year. Based on the historical data of Hebei’s economic resources and environmental system, the system dynamics computer software Vensim PLE is used for modeling. Models are compared with historical data to ensure that models in the period from 2000–2019 are in line with the more optimal parameters of historical development. On this basis, the simulation of the sustainable development of Hebei province for 2020–2050 has the following two main objectives: first, to clarify the overall development trends in the population, economy, energy, and water resources in Hebei province for the period from 2020–2050, and second, to adjust controllable parameters.
of system models to simulate different scenarios of Hebei’s future development, analyze, and compare them.

Clarifying the causal relationships of the system dynamics model helps to clarify the interrelationships between influencing factors during system modeling. Combining this with the real-life development situation in Hebei province, this paper uses data on population, economic development, water supply and demand, energy supply and demand, and wastewater and waste gases from the industry to construct the Hebei Province Human-Land System Model composed of four subsystems, namely population, economy, water, and energy. By summarizing the mutual influences and restraints of the various variables, we can create a logical framework of the causal relationships in the Hebei Province Human-Land System Model (see Figure 1).

\[
\begin{align*}
(1) & \quad \text{total population} \xrightarrow{\text{GDP}} \text{domestic wastewater} \xrightarrow{\text{industrial pollution discharge}} \xrightarrow{\text{death rate}} \text{total population} \\
(2) & \quad \text{total population} \xrightarrow{\text{GDP}} \text{per capita GDP} \xrightarrow{\text{birth rate}} \text{total population} \\
(3) & \quad \text{total population} \xrightarrow{\text{GDP}} \text{domestic water demand} \xrightarrow{\text{water demand of production}} \xrightarrow{\text{total water demand}} \\
(4) & \quad \text{GDP} \xrightarrow{\text{water conservancy investment}} \text{water reuse efficiency} \xrightarrow{\text{water resources quantity}} \\
(5) & \quad \text{GDP} \xrightarrow{\text{energy consumption of production}} \xrightarrow{\text{total population}} \text{household energy consumption} \xrightarrow{\text{total energy}} \\
(6) & \quad \text{GDP} \xrightarrow{\text{investment of energy industry}} \xrightarrow{\text{total energy supply}} \\
(7) & \quad \text{GDP} \xrightarrow{\text{investment of pollution treatment}} \xrightarrow{\text{industrial pollution discharge}} \\
(8) & \quad \text{GDP} \xrightarrow{\text{investment of energy industry}} \xrightarrow{\text{share of nonfossil energy consumption}} \xrightarrow{\text{carbon emission}} \\
(9) & \quad \text{total energy consumption} \xrightarrow{\text{carbon emission}}
\end{align*}
\]

Figure 1. The Logical Framework of Causal Relationships in the Hebei Province Urban Metabolism Model.
In Figure 1, there are nine main causal chains of total population, total water demand, water resources quantity, total energy consumption, total energy supply, industrial pollution discharge, and carbon emission, they are listed from (1) to (9) above Figure 1. It displays the intertwined logical chain between the influencing factors and nexus changes in population, water resources, energy, industrial pollutant emissions, and carbon emissions. Moreover, the fundamental assumptions of energy and water should be defined as follows. The energy supply and demand gap equals to the total energy supply minus the total energy consumption. The water supply and demand gap equals to the total water resources minus the total water usage.

The details of the four subsystems of the regional urban metabolism model are as follows:

(1) Population subsystem: The population subsystem primarily reflects the relationship between the total population or the population birthrate, the population death rate, and other variables. The total population can affect water and energy demand and domestic wastewater discharge, thereby influencing other systems. The main variables of the population subsystem are the total population, increase in the population and the decrease population, and population birth rate and death rate.

(2) Economic subsystem: According to China’s national economy accounting theory, gross domestic product (GDP) is composed of the total value added from the primary, secondary, and tertiary industries. The economic subsystem mainly reflects the interrelationship between primary, secondary, and tertiary industries or GDP and other systems. Industrial development requires water and energy. The secondary industry produces the largest volumes of industrial wastewater and waste gases. The main variables of the economic subsystem embody the value added from the primary, secondary, and tertiary industries over time and their totals, GDP.

(3) Water resources subsystem: Hebei province suffers from a severe shortage of water resources all year round, but various industrial sectors are heavily reliant on water. If water-saving measures are not adopted, the water shortage will become an important factor constraining Hebei’s sustainable development. The main variables of the water resources subsystem include primary, secondary, and tertiary industry water demand, domestic water demand, industrial wastewater, domestic wastewater, water pollution rate, total water demand, water resources quantity, water reuse amount, water reuse efficiency, water conservancy investment for water supply, water supply and demand gap.

(4) Energy subsystem: Heavy industry is the predominant form of industry in Hebei province. The many industrial enterprises consume large volumes of fossil fuels and produce severe atmospheric and water pollution. Production and household energy use, industrial pollution discharges, and carbon emissions are reflected in the energy subsystem. The main variables of the energy subsystem include energy consumption of the primary, secondary, and tertiary industries, household consumption, total energy consumption, investment of energy industry, total energy supply, share of nonfossil energy supply, share of non-fossil energy consumption, carbon emission, gap of energy supply and demand, industrial sulfur dioxide and nitric oxide, and investment of waste gas treatment.

2.2. Flow Chart of the Model

Based on the above logical framework of causality relationships between population, economy, water, and energy, the variables of the system model can be introduced to complete the model’s structure. The various subsystems are integrated into an organic whole through the connections between variables. The detailed relationships between system variables are shown in Figure 2. Simultaneous equations were used to determine the parameters of the connections between the elements. The obtained parameters need to be further adjusted in the model to make them better correspond to real life and historical trends.
2.3. Case Study Area and Main Equations

The coordinated development of the Beijing–Tianjin–Hebei region is a major national strategy in China, with Hebei province positioned as an important modern commercial and logistics base, a pilot area for industrial transformation and upgrading, a new demonstration area for urbanization and urban-rural integration, and a support area for the ecological environment of the region. Covering a total area of 188,800 km², Hebei is rich in mineral resources and is the main base of the steel industry in China. Hebei is also China’s most populous province and it accounts for one-seventh of national per capita water resources. The province’s reliance on heavy industry has resulted in serious atmospheric and water pollution. In 2019, China released a list of the top ten smoggiest cities nationwide, seven of which were in Hebei (Xingtai, Baoding, Shijiazhuang, Handan, Hengshui, Langfang, and Tangshan). Hebei’s waste gas emissions have a high proportion in Chinese provinces and its levels of industrial dust, nitrogen oxides, and sulfur dioxide emissions are also high in the country, which has caused the human-land relationship to become increasingly fraught.

In Figure 2, constructing an SD model should be on the basis of the logical framework of the causal relationships in Figure 1. This paper utilized Xiong’s work [46], thus, there is one level variable, two rate variables, three shadow variables, thirty-five auxiliary variables, and twenty-seven equations in the regional urban metabolism model via the water-energy-population nexus in Hebei province. The method of simultaneous equations was applied to estimate the parameters among uncertain correlations of variables in the SD model, other variables equations are completely determined by socioeconomic common knowledge, such as GDP equates the sum of the value of all the industries. Key equations and variables in the population, economy, water resources, and energy subsystem are as follows:

(1) total population = increase in the population - decrease in the population
(2) increase in the population = birth rate \times population
(3) decrease in the population = death rate \times population
(4) GDP = value added 1 + value added 2 + value added 3
(5) water resource quantity = 13.238 + 0.086 \times \text{water conservancy investment} + 0.025 \times \ln(\text{water reuse efficiency})
(6) water reuse = 0.05 + 0.023 \times \text{water conservancy investment}
(7) domestic wastewater = -22495.9 + 341.876 \times \text{total population}
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(8) total water demand = water demand 1 + water demand 2 + water demand 3 + domestic water demand

(9) gap of water supply and demand = water resources quantity − total water demand

(10) total energy consumption = household energy consumption + energy consumption 1 + energy consumption 2 + energy consumption 3

(11) total energy supply = 68.473 + 0.009 × investment of energy industry

(12) gap of energy supply and demand = total energy supply − total energy consumption

3. Research Results

3.1. Testing the Model

The method applied in the modeling and simulation is Vensim PLE software, which is renowned for industrial-strength simulation to improve the performance of real systems, through simulating various scenarios, connecting to data, flexible distribution, and advanced algorithms. The Vensim model emphasizes a broader understanding of how the physical processes, information flows, and managerial policies interact so as to create the dynamics of the variables of interest. It has been widely applied in many related sustainable disciplines, especially in urban metabolism [7]. In this paper, Vensim PLE software was used to test the operability of the model. The results show that it can operate successfully. Historical data was then used to test the model’s main variables for margin of error. System dynamics requires the margin of error between predicted values and real-life values to be less than 15%. The variables chosen to test the model were total population, GDP, total water demand, domestic water demand, total energy demand, and carbon emission. Based on the simulation from 2010 to 2019, the calculation results are shown in Table 1. It shows that the relative error of the main variables is within 15% each year. The overall margin of error of the model is considered to be within the predetermined range, so it can simulate the operation results of the human-land system in Hebei province from 2020 to 2050.

Table 1. Relative error of the main variables in the population, economic, water resources, and energy simulation for Hebei urban metabolic system (unit: %).

<table>
<thead>
<tr>
<th>Year</th>
<th>Total Population (%)</th>
<th>GDP (%)</th>
<th>Total Water Demand (%)</th>
<th>Domestic Water Demand (%)</th>
<th>Total Energy Consumption (%)</th>
<th>Carbon Emission (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>-1.60</td>
<td>-3.49</td>
<td>1.41</td>
<td>1.35</td>
<td>-3.03</td>
<td>-2.65</td>
</tr>
<tr>
<td>2011</td>
<td>-1.55</td>
<td>-10.66</td>
<td>-0.43</td>
<td>-6.12</td>
<td>-5.92</td>
<td>-6.45</td>
</tr>
<tr>
<td>2012</td>
<td>-1.39</td>
<td>-9.43</td>
<td>-0.67</td>
<td>6.01</td>
<td>-4.77</td>
<td>-5.93</td>
</tr>
<tr>
<td>2013</td>
<td>-1.18</td>
<td>-6.17</td>
<td>0.84</td>
<td>4.61</td>
<td>-4.45</td>
<td>-6.46</td>
</tr>
<tr>
<td>2014</td>
<td>-1.10</td>
<td>-2.04</td>
<td>-0.46</td>
<td>4.12</td>
<td>-0.14</td>
<td>-3.13</td>
</tr>
<tr>
<td>2015</td>
<td>-0.84</td>
<td>1.11</td>
<td>2.02</td>
<td>3.52</td>
<td>-2.71</td>
<td>-6.63</td>
</tr>
<tr>
<td>2016</td>
<td>-0.69</td>
<td>0.99</td>
<td>4.13</td>
<td>-1.60</td>
<td>-1.13</td>
<td>-5.07</td>
</tr>
<tr>
<td>2017</td>
<td>-0.60</td>
<td>0.80</td>
<td>4.27</td>
<td>-4.89</td>
<td>-0.27</td>
<td>-4.26</td>
</tr>
<tr>
<td>2018</td>
<td>-0.28</td>
<td>1.82</td>
<td>3.44</td>
<td>-6.92</td>
<td>2.16</td>
<td>-1.73</td>
</tr>
<tr>
<td>2019</td>
<td>-0.01</td>
<td>1.06</td>
<td>3.16</td>
<td>-3.45</td>
<td>3.72</td>
<td>0.24</td>
</tr>
</tbody>
</table>

3.2. Simulation Results for the Natural Development Scenario

By simulating the historical development trends of the Hebei urban metabolic system during the period 2010–2019, we were able to simulate development trends for the period 2020–2050.

The simulated total population shows a continued upward trend (Figure 3a). As the population base increases year on year, total population continues to grow from 74.87 million to 85.26 million during the period 2020–2050. In the same period, the natural population growth rate will decrease from 5.34 ‰ in 2020 to 3.17 ‰ in 2050, showing a slowdown trend. The GDP per capita will increase from RMB 50.3 thousand in 2020 to RMB 163 thousand in 2050 (Table 2). It also reveals that the GDP of the Hebei urban metabolic system will maintain a steady upward trend (Figure 3b), reaching RMB 8073 billion in 2035,
2.14 times that of 2020, and reaching RMB 13,889 billion in 2050, which is 3.69 times that of 2020. The industrial structures of Hebei Province would be further optimized and adjusted, with the ratio of primary, secondary, and tertiary industries growth from 10%:39%:51% in 2020 to 8%:31%:61% in 2035 to 6%:25%:69% in 2050. As for the water subsystem, the water demand of the primary industry and the secondary industry will decline a little, while the water serving the tertiary industry and domestic water will rise, with the accelerated social economic development, optimization of industrial structure, as well as population growth. Total water demand (Figure 3c) displays a continued upward trend, albeit slow growth, increasing from 18.75 billion m$^3$ in 2020 to 20.73 billion m$^3$ in 2050, with an average annual growth rate of 0.33%. Ensuring supplies of water resources is a necessary condition for the stable development of the socioeconomic environmental metabolic system. Due to the improvement of water conservancy investment and reuse (Table 2), the gap between the supply and demand of water resources gradually narrows from $-2.49$ billion m$^3$ in 2020 to $-0.06$ billion m$^3$ in 2028. In 2029, the gap between the supply and demand of water resources will be narrowed down to 0.24 billion m$^3$, which could go a long way towards ensuring the local water demand in Hebei Province is met. It is more conducive to water saving and a greater guarantee the water demand of Hebei Province will be met by improving the efficiency of water reuse.

Total energy demand also shows an upward trend, from 346 million tonne of coal equivalent in 2020 to 612 million tonnes of coal equivalent in 2050. The manufacturing industry is the main energy consumption sector, increasing from 261.50 million tonnes of coal equivalent in 2020 to 361.11 million tonnes of coal equivalent in 2050 (Figure 3d). The average annual growth rate of energy consumption of living energy, primary industry, secondary industry, and tertiary industry is 2.02%, 1.13%, 1.08%, and 5.01% respectively. Due to the relative decline of the proportion of primary and secondary industries, the tertiary industry would serve as a mainstay industry characterized by the rapid growth of energy consumption. The industrial development of Hebei features heavy-oriented industry and a strong dependence on energy consumption. The optimization and adjustment of the industrial structure will be helpful to diminish the energy consumption of the secondary industry in Hebei. In addition, more work needs to be done to contract energy consumption in tertiary industries, such as transportation, in the near future. The energy supply and demand gap in Hebei Province could increase from $-275.32$ million tonnes of coal equivalent in 2020 to $-516.33$ million tonnes of coal equivalent in 2050, as shown in Table 2. According to the national planning of the Beijing Tianjin Hebei region, as Hebei undertakes the relief and the high energy consumption industries in the Beijing Tianjin Hebei region, most parts of the energy consumption of Hebei Province will come from the transfer of energy consumption in the Beijing and Tianjin region. Nevertheless, Hebei still needs to increase investment in the energy industry, develop renewable energy, adopt new energy-saving technologies, and speed up the elimination of energy-hungry industries.

In the context of the carbon neutrality target featured by stricter environmental protection requirements, the discharge of industrial wastewater and industrial waste gas in Hebei will also be subject to stricter supervision. Since 2020 to 2050, the discharge of industrial wastewater, industrial SO$_2$, and industrial NOx will show a steady downward trend, with an average annual growth rate of $-0.86\%$, $-8.81\%$, and $-7.95\%$, respectively. With the growth in the population, the discharge of domestic sewage shows an upward trend, from 3099.72 million tonnes in 2020 to 6652.08 million tonnes in 2050, with an average annual growth rate of 2.58% (Figure 3e). It is also a key area for water conservation in the future, achieved by accelerating the efficiency of urban domestic sewage treatment and reuse.

With the implementation of China’s 2030 carbon peak and 2060 carbon neutralization targets, Hebei has also been increasing investment in the energy industry in recent years, striving to reduce carbon emissions by increasing the specific weight of non-fossil energy consumption. In 2021, Hebei has outlined the roadmap of the carbon peak and carbon neutralization schedule, and the proportion of non-fossil energy will reach 13% and 19%, respectively in 2025 and 2030. According to the model simulation results, Hebei’s carbon
emissions rise from 797.97 million tonnes in 2020 to the peak of 856.37 million tonnes in 2029 and then begin to decline. The proportion of non-fossil energy consumption would increase from 6.83% in 2020 to 13.36% in 2025, and then to 22.12% in 2030. In 2050, the carbon emission of Hebei Province will drop to 210.32 million tonnes and the proportion of non-fossil energy will increase to 59.07% (Figure 3f). According to China’s national carbon peak and carbon neutralization target, the proportion of non-fossil energy consumption should reach more than 80% by 2060, thus, it is still a long way for Hebei to reach the low carbon development, considering the current reality of Hebei as a major coal consumption province. In sum, it is still an important direction for Hebei in the future to pump up the proportion of non-fossil energy consumption.

Figure 3. Trends of socioeconomic variables of natural development scenario in the Hebei urban metabolic system 2020–2050 (a). Total population and its growth rate; (b). GDP and share of three industries; (c). Total water demand and share of different water demand; (d). Total energy consumption and share of different energy consumption demand; (e). Amount of wastewater and waste gas; (f). Carbon emission and share of non-fossil energy consumption.
Table 2. Trends of social and economic variables in the Hebei urban metabolic system in 2020, 2035, and 2050.

<table>
<thead>
<tr>
<th>Variable (Unit)</th>
<th>Per Capita GDP (CNY per Person)</th>
<th>Water Reuse Efficiency (%)</th>
<th>Gap of Water Supply and Demand (Billion Cubic Meter)</th>
<th>Gap of Energy Supply and Demand (Million TCE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>50,333.6</td>
<td>5.08</td>
<td>−2.49</td>
<td>−275.32</td>
</tr>
<tr>
<td>2035</td>
<td>100,229.0</td>
<td>16.42</td>
<td>2.10</td>
<td>−397.17</td>
</tr>
<tr>
<td>2050</td>
<td>162,904.0</td>
<td>33.03</td>
<td>6.81</td>
<td>−516.33</td>
</tr>
</tbody>
</table>

3.3. Scenario Simulation Analysis

The above simulation results are for the natural development scenario, in which there is no human interference, for the period from 2020–2050. To further simulate different types of development, we chose nine variables, especially via the water-energy-population nexus, as the focus of artificial measures for the future development of the Hebei urban metabolic system. By adjusting the parameters of seven of the variables from the natural development simulation for 2020–2050, four types of development scenarios were created: an economic growth scenario, water conservation development scenario, energy conservation development scenario, and low carbon scenario.

In the economic growth scenario, the main consideration is the growth rate of the primary, secondary, and tertiary industries for the acceleration of economic growth based on the natural development scenario. In the water conservation development scenario, the main aim is to increase water conservancy investment and water reuse efficiency based on the natural development scenario, so as to improve water resource supply and reuse. In the energy conservation development scenario, the urban metabolic system will slow down household energy consumption and secondary industrial energy consumption and improve industrial energy investment based on the natural development scenario. In the low carbon scenario, the main purpose is to appropriately enhance the growth rate of the tertiary industry and increase the investment in the water conservancy and energy industry and improve the water reuse efficiency, share of non-fossil energy consumption, and decrease the water demand of the primary industry under a combination of various development scenarios. Under the above five scenarios, the basic assumptions are that the average annual growth rate of economic and social variables in Hebei will be less than 10%, thus, the specific parameters will be adjusted accordingly, as shown in Table 3. In the natural development scenario, each variable will be kept unchanged. The average annual change rate of the relevant variables in the economic growth scenario will rise by 1%. In the water and energy conservation development scenarios targeting the reduction of water and energy consumption and concomitantly increasing their supply, the relevant variables will be adjusted to 10% and 5%, respectively. In the low carbon scenario, the development of the tertiary industry would accelerate with the reduction of the consumption of water resources and energy, as well as an increase in the supply of water resources and energy.

Table 3. Average annual adjusted rates of every variable in the five scenarios of the Hebei urban metabolic system simulation from 2020–2050.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Natural Development Scenario</th>
<th>Economic Growth Scenario</th>
<th>Water Conservation Development Scenario</th>
<th>Energy Conservation Development Scenario</th>
<th>Low Carbon Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary industry growth (%)</td>
<td>-</td>
<td>Up 1%</td>
<td>-</td>
<td>-</td>
<td>Up 0.5%</td>
</tr>
<tr>
<td>Secondary industry growth (%)</td>
<td>-</td>
<td>Up 1%</td>
<td>-</td>
<td>-</td>
<td>Up 0.5%</td>
</tr>
</tbody>
</table>
Table 3. Cont.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Natural Development Scenario</th>
<th>Economic Growth Scenario</th>
<th>Water Conservation Development Scenario</th>
<th>Energy Conservation Development Scenario</th>
<th>Low Carbon Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary industry growth (%)</td>
<td>-</td>
<td>Up 1%</td>
<td>-</td>
<td>-</td>
<td>Up 1%</td>
</tr>
<tr>
<td>Water demand of the primary industry</td>
<td>-</td>
<td>-</td>
<td>Down 5%</td>
<td>-</td>
<td>Down 2.5%</td>
</tr>
<tr>
<td>Water conservancy investment (billion CNY)</td>
<td>-</td>
<td>-</td>
<td>Up 10%</td>
<td>-</td>
<td>Up 5%</td>
</tr>
<tr>
<td>Water reuse efficiency (%)</td>
<td>-</td>
<td>-</td>
<td>Up 10%</td>
<td>-</td>
<td>Up 5%</td>
</tr>
<tr>
<td>Household energy consumption (million TCE)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Down 5%</td>
<td>Down 5%</td>
</tr>
<tr>
<td>The secondary industrial energy consumption (million TCE)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Down 5%</td>
<td>Down 5%</td>
</tr>
<tr>
<td>The investment of energy industry (billion CNY)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Up 5%</td>
<td>Up 6%</td>
</tr>
<tr>
<td>Share of non-fossil energy consumption (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Up 5%</td>
<td>Up 6%</td>
</tr>
</tbody>
</table>

It is shown that various trends of urban metabolic systems in Hebei Province under the five different scenarios, as shown in Figure 4. In the natural development scenario, no additional policy toolkits are applied to the existing development path. In comparison, the economic development scenario reflects the pursuit of the growth of the various industries. In the water and energy conservation development scenarios respectively, the mounting delivery of water resource and energy efficiency will be pursued, as well as maintenance of the sustainability of the urban metabolic system in Hebei Province. Moreover, the long-term solution to the urban metabolic efficiency improvement is reflected in the low carbon scenario, which emphasizes sustainable development, combining both the efficient water, energy use, and industrial growth. The most significant target is to increase the proportion of non-fossil energy consumption and minimize total carbon emissions while pursuing green industrial development.

The GDP simulation results under the different scenarios show (see Figure 4) that GDP growth under the economic growth scenario is far higher than it is under the other scenarios, reaching RMB 14,028 billion in 2050, followed by the low carbon development scenario, reaching RMB 14,006 billion; whereas in the economic growth scenario, water-saving and energy-saving scenarios and the natural development scenario do not change dramatically. Population growth needs to be maintained at an appropriate level to provide the demographic dividend. The simulation results of the total population under the five scenarios show that the total population will maintain continuous growth. The population growth is highest in the natural development scenario, reaching 85.3 million in 2050, followed by the energy-saving scenario, economic development scenario, the water-saving scenario, and the low carbon scenario, respectively. As for the GDP per capita, it is highest under the economic development scenario, followed by the low carbon scenario. The water demands under the five scenarios decline slowly from 2020 to 2026 and then rise steadily from 2027 to 2050. The simulation results show that the consumption of water resource and energy is the lowest in 2050 under the water-saving scenario and the energy-saving scenario, at 20.45 billion m³ and 590.2 million tonnes of coal equivalent (TCE), respectively. The low carbon scenario will reach the second position, arriving at 20.6 billion m³ and 592.3 million TCE, respectively. The natural development scenario and the energy conservation development scenario will have the highest water demand, both achieving 20.7 billion m³, while the economic scenario could have the highest energy consumption, reaching 614.6 million TCE. As for the balance of water supply and demand, it will be achieved before 2050 under all scenarios. In contrast, the energy supply gap will be existing for a long time, as shown in Table 4. Under the water-saving scenario, the
target of balancing the water supply and demand will be achieved earliest, followed by
the low carbon scenario, indicating that water conservation measures have a significant
effect on alleviating water pressure. In terms of energy supply and demand, the gap
constantly narrows, until eventually supply fully meets demand. Similarly, the energy
supply and demand gap under the energy-saving scenario is the smallest, followed by the
low carbon scenario.

Figure 4. Metabolic trends of social and economic variables of natural development scenario for
Hebei metabolic system and the ratios of that of other different scenarios to natural development
scenario from 2020–2050 (a). Total population; (b). GDP; (c). Total water demand; (d). Total energy
consumption; (e). Carbon emission; (f). Domestic wastewater).
### Table 4. Metabolic trends of the main water and energy variables for Hebei under the five scenarios from 2020–2050.

#### Gap of Water Supply and Demand (Unit: Billion Cubic Meter)

<table>
<thead>
<tr>
<th>Year</th>
<th>Natural Development Scenario</th>
<th>Economic Growth Scenario</th>
<th>Water Conservation Development Scenario</th>
<th>Energy Conservation Development Scenario</th>
<th>Low Carbon Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025</td>
<td>−0.977</td>
<td>−0.881</td>
<td>0.006</td>
<td>−0.977</td>
<td>−0.438</td>
</tr>
<tr>
<td>2035</td>
<td>2.100</td>
<td>2.231</td>
<td>3.310</td>
<td>2.100</td>
<td>2.772</td>
</tr>
<tr>
<td>2050</td>
<td>6.810</td>
<td>6.994</td>
<td>8.516</td>
<td>6.810</td>
<td>7.758</td>
</tr>
</tbody>
</table>

#### Gap of energy supply and demand (Unit: Million TCE)

<table>
<thead>
<tr>
<th>Year</th>
<th>Natural development scenario</th>
<th>Economic growth scenario</th>
<th>Water conservation development scenario</th>
<th>Energy conservation development scenario</th>
<th>Low carbon scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025</td>
<td>−316.7</td>
<td>−318.2</td>
<td>−316.6</td>
<td>−300.0</td>
<td>−300.9</td>
</tr>
<tr>
<td>2035</td>
<td>−397.2</td>
<td>−399.0</td>
<td>−397.1</td>
<td>−377.9</td>
<td>−379.0</td>
</tr>
<tr>
<td>2050</td>
<td>−516.3</td>
<td>−518.7</td>
<td>−516.1</td>
<td>−493.4</td>
<td>−494.7</td>
</tr>
</tbody>
</table>

#### Industrial SO\(_2\) emission (Unit: Thousand Tonne)

<table>
<thead>
<tr>
<th>Year</th>
<th>Natural development scenario</th>
<th>Economic growth scenario</th>
<th>Water conservation development scenario</th>
<th>Energy conservation development scenario</th>
<th>Low carbon scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025</td>
<td>501.4</td>
<td>494.3</td>
<td>501.4</td>
<td>501.4</td>
<td>497.9</td>
</tr>
<tr>
<td>2035</td>
<td>281.8</td>
<td>274.6</td>
<td>281.8</td>
<td>281.8</td>
<td>278.2</td>
</tr>
<tr>
<td>2050</td>
<td>40.3</td>
<td>33.1</td>
<td>40.3</td>
<td>40.3</td>
<td>36.7</td>
</tr>
</tbody>
</table>

#### Industrial NO\(_x\) emission (Unit: Thousand Tonne)

<table>
<thead>
<tr>
<th>Year</th>
<th>Natural development scenario</th>
<th>Economic growth scenario</th>
<th>Water conservation development scenario</th>
<th>Energy conservation development scenario</th>
<th>Low carbon scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025</td>
<td>536.7</td>
<td>529.3</td>
<td>536.7</td>
<td>536.7</td>
<td>533.1</td>
</tr>
<tr>
<td>2035</td>
<td>307.7</td>
<td>300.3</td>
<td>307.7</td>
<td>307.7</td>
<td>304.1</td>
</tr>
<tr>
<td>2050</td>
<td>57.0</td>
<td>49.5</td>
<td>57.0</td>
<td>57.0</td>
<td>53.3</td>
</tr>
</tbody>
</table>

The carbon emissions simulated for the different scenarios show an inverted U-shaped trend in the period from 2020–2050. Under the natural development scenario, carbon emissions have been rising from 2020 to 2029, reaching a peak of 856.4 million tonnes in 2029 and then decreasing in 2050. The low carbon scenario has the lowest carbon emissions, peaking at 824.7 million tonnes in 2027 and 27.4 million tonnes in 2050. The energy conservation development scenario has the second lowest carbon emissions, peaking at 826.8 million tonnes in 2028. Carbon emissions under both the economic growth scenario and the water-saving scenario will peak in 2029 at 856.2 million tonnes and 856.3 million tonnes, respectively. This indicates that Hebei Province should use low carbon-oriented toolkits to achieve the carbon peaking target in 2030 and the carbon neutrality target in 2060.

The wastewater and waste gas emissions simulated for the different scenarios in the period from 2020–2050 show the following: First, industrial SO\(_2\) and industrial NO\(_x\) have been displaying a downward trend. Surprisingly, the economic development scenario will maintain a relatively low proportion of emissions in the future at 33.1 thousand tonnes and 49.5 thousand tonnes, respectively. That might be attributed to the snowballing of environment investments due to the accelerated economic growth. Second, the low carbon scenario has the second lowest emissions at 36.7 thousand tonnes and 53.3 thousand tonnes, respectively. Third, the discharge of domestic sewage is lowest under the low carbon...
scenario and the water-saving scenario at 6632.5 million tonnes and 6633.2 million tonnes in 2050, respectively. It is safe to conclude that under the low carbon scenario, economic development is relatively quick, but wastewater and waste gas emissions are far lower than in the other scenarios.

Summarizing the above analysis for the period from 2020–2050, variegated landscapes of urban embolic systems in Hebei Province under different scenarios are curated. Rather than a homogeneous simplistic system, the modelling evidence shown enables us to argue that the urban metabolism model via water-energy-population reveals a complex heterogeneous and interlinked nature, characterized by multi-scalar and multifactorial rationalities, processes, and the nexus. Although there are no one-size-fits-all solutions to iron out such metabolic problems as degraded water delivery, waste discharge, fuel-energy consumption, and exhaust emissions, a comprehensive toolkit for regional urban metabolism aiming towards achieving the carbon neutrality target that combines all intertwined factors and dynamics is urgently needed. The single pursuit of economic growth, water conservation, and energy conservation in the urban metabolic system might solve some problems while ignoring the other and may even lead to the exacerbation of existing and emerging issues. Indeed, it is revealed through this scenario simulation analysis that the low carbon scenario might serve as a better way for the future urban metabolic system in terms of economic development, resource, and energy supply security, reducing pollution emissions, as well as achieving carbon neutrality goals.


In this paper, the system dynamics method was applied to construct a system to simulate the urban metabolism of water, energy, and human relationships and conduct a comparative analysis of multiple simulated scenarios, taking China’s Hebei province as a case study. The Hebei urban metabolic system currently has much lower water resources per capita than the national average for China, but its industrial development requires vast water resources. This lack of water has become an important factor restricting economic development. In addition, Hebei’s industrial structure is dominated by heavy industry, which uses large quantities of fossil fuels. This causes severe atmospheric and environmental problems. As a result, Hebei needs to step up efforts to save energy and reduce emissions. As China’s one populous province, the relationship between humans and nature is perennially tense. Through modeling the urban metabolism via the water-energy-population nexus, it is safely concluded that focusing only on economic growth, or only on water or energy conservation development, or not applying any measures to development (natural development) are not sufficient or comprehensive enough to alleviate the tension in the human-land relationship and are limiting. By comparison, the low carbon scenario is the most effective at easing tension in the human-land system as it targets the metabolic system. This low carbon model not only focuses on economic growth and appropriate population growth, but also considers how to couple the key factors of water and energy.

The simulation results also indicate that increasing water conservancy investment and water reuse efficiency can effectively alleviate the pressure on water supply. Hebei’s water shortage issue can be solved using two approaches: first, increasing investment in water conservancy facilities is still the most important method, as building water conservancy infrastructure combined with the national South-to-North Water Diversion Project will increase water reserves; second, widely adopted water conservation measures will increase water reuse efficiency and the development of water conservation technologies will promote water recycling. Likewise, reducing industrial energy consumption will promote energy saving and reduce industrial air pollution emissions. Also, accelerating Hebei’s industrial transformation and upgrading will eliminate backward production capacity and improve overall energy conversion efficiency. In terms of population growth, Hebei province not only needs to maintain moderate population growth but also control excessive population growth to avoid putting added pressure on resources and the environment. Paying attention to balancing the development of internal elements of the human-land
system is the most suitable development model for Hebei province in the future. Of course, the human-land system is extremely complex and this article has created a system dynamics model based only on the main elements via the water-energy-population nexus of the urban metabolic system in Hebei, so there is room to further expand this research.

The urban metabolic paradigm is extremely complex and of great significance for the achievement of the Chinese national target of ‘carbon neutrality’ by 2060. This paper creates a system dynamics model based only on the dominant water and energy and population elements of the metabolic system in Hebei. In the future, research could be expanded into simulations of metabolism that integrate multiple factors and multiple scales. In particular, research that combines water and energy coupling with metabolism should use water and energy industry sectors and urban managers as application exports to explore a regional sustainable development model guided by water and energy factors. In addition, further comparative studies on inter-regional and detailed regional metabolism are needed to build a system of metabolic research.

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