Simulating Water Resource Disputes of Transboundary River: A Case Study of the Zhanghe River Basin, China

Liang Yuan\textsuperscript{1,2}, Weijun He\textsuperscript{1,2}, Zaiyi Liao\textsuperscript{3,4}, Dagmawi Mulugeta Degefu\textsuperscript{3,4}, Min An\textsuperscript{1} and Zhaofang Zhang\textsuperscript{1}

\textsuperscript{1}School of Business, Hohai University, Nanjing, Jiangsu, 210098, China
\textsuperscript{2}College of Economics and Management, China Three Gorges University, Yichang, Hubei, 443002, China
\textsuperscript{3}Department of Architecture Science, Ryerson University, Toronto, ON, M5B 2K3, Canada
\textsuperscript{4}College of Hydraulic and Environmental Engineering, China Three Gorges University, Yichang, Hubei, 443002, China

E-mail: heweijun1519@ctgu.edu.cn

Abstract. Water resource disputes within transboundary river basin has been hindering the sustainable use of water resources and efficient management of environment. The problem is characterized by a complex information feedback loop that involves socio-economic and environmental systems. This paper presents a system dynamics based model that can simulate the dynamics of water demand, water supply, water adequacy and water allocation instability within a river basin. It was used for a case study in the Zhanghe River basin of China. The base scenario has been investigated for the time period between 2000 and 2050. The result shows that the Chinese national government should change the water allocation scheme of downstream Zhanghe River established in 1989, more water need to be allocated to the downstream cities and the actual allocation should be adjusted to reflect the need associated with the socio-economic and environmental changes within the region, and system dynamics improves the understanding of concepts and system interactions by offering a comprehensive and integrated view of the physical, social, economic, environmental, and political systems.

1. Introduction

A river basin shared by multiple administrative regions is called transboundary river. Like other fresh water resources, these rivers can also face water scarcity [1]. When water scarcity prevails in transboundary river, water resources disputes occur because the river water is not adequate to fully satisfy the total demand of all claimants.
The water dispute on a transboundary river can be regarded as a three-dimensional systemic issue. Horizontally, the level of water dispute is related to the recreation strategy of each sharing region and the relationship among different regions [2]. Vertically, the degree of water dispute mainly depends on the water demand, water shortage, risks of the riparian regions facing water stress and the strategy as well as adaption capacity of the regions to the changing socio-economic environmental factors [3]. Furthermore, all these horizontal and vertical factors change over time, making water dispute a dynamic process that varies with the internal and external factors of each sharing regions. As a result, a better understanding of water dispute among different administrative regions should be a complex system which consists of the three-dimensional elements linked through positive and negative feedback loops [4]. Thus, finding the causes, processes and characters of the water dispute is vital to solving water sharing problems.

Forrester developed System Dynamics (SD) for the first time by combining applied control theory, information theory, decision theory, and other relevant theories [5]. System dynamics method can not only properly describe the complicated issue of water dispute but also can provide a unique and comprehensive structure to simulate the degree of dispute among different stakeholders [6]. In this paper, the authors present a strategic analysis of a water allocation and dispute within transboundary river basins and an SD based model for simulating the regional water resources allocation and dispute.

Zhanghe River basin is a tributary of the southern Haihe River basin in China. The upstream consists of two rivers, the Qing Zhanghe and Zhuo Zhanghe rivers which originate from Shanxi Province and merge at the provincial border between Hebei and Henan Province. It is joined by a third branch in the downstream, namely Weihe river at Handan City of Hebei Province, forming a river basin called Zhangwei River basin (figure 1).

![Figure 1. Zhanghe River Basin](image_url)
Zhanghe River basin covers an area of 18284 km², travels a total distance of 460 km. 86.7%, 9.9% and 3.4% of the basin’s area lies in Shanxi, Hebei and Henan provinces respectively. Zhanghe river basin includes 18 counties located in 4 administrative regions of three provinces. 14 counties located in Changzhi and Jinzhong cities of Shanxi Province constitutes the upstream of the basin. In the downstream, 2 counties are located in Handan City of Hebei Province and the other 2 counties are located in Anyang City of Henan Province.

The contribution of Zhanghe River to the surface water supply for the upstream region, Anyang City and Handan City is 30%, 20% and 15% respectively. However, their demands are largely influenced by the changing socio-economic, environmental, and demographic conditions. Due to increased water demands caused by mushrooming population and socio-economy, more than five major incidents related to water resource allocation have occurred since 2008. The national government has involved in seeking solutions for all these cases [7]. Handan and Anyang cities always complain that the upstream region withdraw excessive amounts of water resources, leaving insufficient water for them [8].

At present, the national government is yet to rule on the allocation of the river’s water among the three provinces in the basin. The State Council has only ruled that 48% of the available water resources of downstream Zhanghe River allocated to the Anyang City of Henan Province and 52% allocate to the Handan City of Hebei Province in 1989. But the allocation of water resources in the other areas of Zhanghe River basin was not clearly stipulated. The change in the socio-economic and environmental status of the riparian regions makes the water allocation scheme that was put into effect in 1989 inapplicable and outdated. It’s important to forecast the degree of water resources dispute in the Zhanghe river basin in the future.

2. System Dynamics Modeling
The water dispute system can be represented by a complex information cycle with feedback loops mainly consisting of socio-economic-environmental drivers. Hence, the water dispute system in the Zhanghe River basin is driven by these factors that are interrelated through a complex feedback system. Therefore, SD was employed to develop the model that can not only effectively organize and reveal the internal interaction and feedback mechanism among the various factors within the nonlinear composite system, but also reflect the essential relationship among the factors by causal feedback loops. The steps taken during system dynamics modeling of the water dispute within Zhanghe River basin are following [9]:

2.1. Defining Simulation Objectives
Applying system dynamics model to analyze the Zhanghe river basin water resources dispute through the simulation of riparian provinces water demand, supply and allocation. This might provide the basis for water resources planning and management.

2.2. Determining System Boundary
The riparian provinces and their respective cities are categorized as upstream and downstream. The upstream region comprises 14 of counties located in Changzhi and Jinzhong cities of Shanxi Province, while downstream region consisting of the Handan City of Hebei Province and Anyang City of Henan Province. The simulation period for this study is from 2000 to 2050.
2.3. Designing an Interface Graphical Structure of the System

According to the water demand of the three riparian provinces’ cities located within the basins, divided the complex water dispute system into six sub-systems [11]: domestic water demand subsystem, industrial water demand subsystem, irrigation water demand subsystem, ecological water demand subsystem, water resources allocation and dispute subsystem. The domestic water demand subsystem simulates the riparian cities water demand changes which is the result of both the rural and urban population change. The industrial water demand subsystem simulates the water demand changes due to the influence of industrial scale water consumption. The irrigation water demand system simulates the impacts of the irrigated agricultural area on water demand. The ecological water subsystem simulates the impact of changes in forest cover on water demand. The water allocation subsystem simulates the available water resources supply under allocation policies. The causal loop diagram of the water dispute in the Zhanghe River basin is shown in Figure 2.

\[ A_i = \frac{(WA_i - WD)_i}{WD_i} \]  

Figure 2. Causal loop diagram of the basic model

In Figure 2, each arrow indicates the influence of one element on another. This influence is considered as positive (+) if an initial change is amplified in the same direction as all components are traced through the loop, or negative (-) if an increase in one element causes a decrease in another [12]. The decrease in water dependence rate of the Zhanghe River basin could decrease the regional water demand on the Zhanghe River basin and increase the regional water adequacy of the basin’s riparian cities. On the other hand, the climate change due to global warming could decrease the river’s runoff as well as the water supply of riparian regions, thereby decreasing the water adequacy of basin’s riparian cities. Water adequacy, population, industrial production, irrigated farmland area, forest area, and water demand are the parts of the balanced causal loop.

The water dispute was represented by the instability of water allocation. Higher instability of water allocation is translated as more intense water dispute. The regional water adequacy \( A_i \) can be represented as equation (1), \( i=1,2,...,n \) refers to the regions.
Assuming that the average value of water adequacy of different regions is $V_i$, the instability of water allocation $S_A$ described as equation (2), higher value of $S_A$ means that water allocation is highly unstable and the water dispute is grave.

$$S_A = \begin{cases} 0, & A > 0 \\ \sqrt{(1/n) \sum_{i=1}^{n} (A_i - V_i)^2}, & \text{else} \end{cases}$$

\[ (2) \]

Figure 3. Water dispute model of Zhanghe River basin
2.4. Developing Stock-Flow Diagram

The simulation model used in this article was developed using Vensim PLE software. This software is capable of developing a complex water resources system dynamics model with less programming efforts, in addition, the software makes it easy for model expansion. The model comprises of three main sectors capable of simulating the riparian cities water demand, water allocation and water dispute. The model includes 94 parameters and 15 state variables. The flow diagram for water dispute of Zhanghe River basin is shown in Figure 3. It is originated from a basic demand and supply framework based on cause loop. On the demand side, population level, agriculture and industry development, economic growth and ecological requirements determines the water demand of six sub-systems in three different regions. On the supply side, water supply determines by simulated the current water allocation policies. On the dispute side, the water dispute was represented by the instability of water allocation $S_i$.

2.5. Formulating a Mathematical Model

All information used in the model was collected from peer reviewed journals, government records, newspapers, and publicly shared interviews. All elements contained in the model and their relationships are presented in Appendices.

3. Simulated Results

Until now, the national government has only ruled on the water sharing ratio for the sub-basin of Zhanghe River basin located in the downstream section of the basin. The water sharing ratio which considers every riparian city from the upstream to the downstream of the river is yet to be established. Defining the base scenario according to the current water allocation policy of the upstream and downstream riparian regions: 60% of the basin’s water was allocated to upstream and 40% allocated to the downstream for the time period from 2000 to 2050 [13]. Through the simulation of the base scenario, it could predict the water resource adequacy of the riparian cities and the instability of the existing water allocation scheme under the current policy for the time period from 2018 to 2050.

With the increase in water demand in the riparian regions, the water adequacy began to decrease since 2000. From 2000 to 2012, upstream regions obtained enough water by constructing water reservoirs and many other water conservative hydraulic structures, but leaving the downstream cities with the problem of water scarcity. The difference among the three riparian regions in terms of water adequacy is expected to result in the instability of water allocation. Figures 4, 5, and 6 also showed the significant gap among the riparian region’s water adequacy and the instability water allocation. Such high water allocation instability raises water sharing problems and possible water conflict within the river basin.

From 2012 to 2021, the water adequacy of all the regions continues to decrease and will reach its lowest point in 2021; the gap among the water adequacy of the riparian areas shows a clear decreasing trend (figure 4). As the result, the instability of water allocation is also expected to decrease from 2012 to 2021 (figures 5 and 6). During the time period from 2021 to 2040, the water adequacy will increase because the water utilization efficiency of the three riparian regions is expected to increase. But it is not enough to fully satisfy their water demand. The instability of water allocation will increase after 2021, but the extent of the instability of water allocation among three riparian regions is lower than the one during the time period from 2000 to 2013, and the instability between two downstream regions
will increase. Figures 4 and 5 shows that upstream regions have adequate available water to satisfy their demand but downstream riparian cities will be water scarce under base scenario after 2014. The instability of water allocation among three riparian regions will keep growing. On the contrary, the instability of water allocation between two downstream regions will decrease.

There are two water dispute systems within Zhanghe River basin. The first one involves the upstream and downstream sections of the river. The second one is among the cities located in the downstream reach. Hence the decision-makers should consider both water dispute systems when they try to design methods to solve the water sharing problem within the river basin. Under the base scenario, the degree of water dispute among three riparian regions will decrease from 2018 to 2022, and then increase between 2022 and 2050.

**Figure 4.** Water adequacy of three regions under base scenario

**Figure 5.** The instability of water allocation in Zhanghe River basin under base scenario

**Figure 6.** The instability of water allocation in downstream under base scenario

### 4. Conclusion

In this paper, system dynamics method not only provides the ability to implement system dynamics thinking, but also apply nonlinear causal thinking to water resources allocation and disputes problems. During the model development process, system dynamics help to comprehend the interactions among the different drivers of the issue via the experiences conveyed, lessons learned and perceptions gained.
It also improves the understanding of concepts and system interactions by offering a comprehensive and integrated view of the physical, social, economic, environmental and political systems, stimulates the issue of water resource system for better understanding of the system and allows managers and stakeholders to better visualize the key hydrologic elements and management constraints within river basins.

The level of water dispute among basin sharing parties depends on their socio-economic and environmental conditions [14]. The situation in the Zhanghe River basin is not different. The study presented in this paper indicates that in order to maintain the regional sustainable development and avoid water conflicts in Zhanghe River basin the national government should introduce a new water allocation management scheme that takes into account the two water disputes simultaneously. In the long term, the national government should design system dynamic water management and planning scheme to manage the water issues of Zhanghe River basin and consider the overall conditions crossing the entire river basin while making a new water allocation management scheme. In the short term, the national government should establish a new water allocation scheme to replace the 1989 non-basin wide water allocation scheme, more water needs to be allocated to the downstream cities and the actual allocation should be adjusted to reflect the need associated with the socio-economic and environmental changes within the region.

The following strategies should be implemented in order to maintain the regional sustainable development and avoid water conflicts in a trans-boundary river basin. Firstly, the water resource allocation should make according to the changing socio-economic and environmental conditions, and the managers and stakeholders need to realize the unified dispatching and management in whole river basin [15]. Secondly, the river should be managed with a thorough understanding of the river dynamics so that the water distribution is coordinated to satisfactorily serve all the regions in the entire river basin. Thirdly, water conservation measures should be enforced to reduce the water demands of all affected regions. These measures include new technologies to improve water resources efficiency, enhancing water conservation, changing the water supply structure and expanding the use of recycled water [16]. Finally, sufficient mechanism should be established to ensure effective communications among all affected regions so that any potential conflicts can be avoid through cooperation.

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6. Appendices A
Definitions: 1. UCRUP: the change rate of urban population of upstream regions; 2. UCRRP: the change rate of rural population of upstream regions; 3. UCUP: the change of urban population of upstream regions; 4. UCRP: the change of rural population of upstream regions; 5. UUP: urban population of upstream regions; 6. URP: rural population of upstream regions ; 7. URPCWC: rural per capita water consumption of upstream regions; 8. UUPCWC: urban per capita water consumption of upstream regions; 9. URHWD: rural household water demand of upstream regions; 10. UUHWD: urban household water demand of upstream regions; 11. UTHWD: total household water demand of upstream regions; 12. UTFPCIVAWD: table function of water demand of per unit of industrial value-added of upstream regions; 13. UPCIVAWD: water demand of per unit of industrial value-added of
upstream regions; 14. UCRIVA: the change rate of industrial value-added of upstream regions; 15. UCTIVA: the change of total industrial value-added of upstream regions; 16. UIVA: industrial value-added of upstream regions; 17. UIVAWD: water demand of industrial value-added of upstream regions; 18. UTFIFWD: table function of water demand of per thousand hectares irrigated farmland in upstream regions; 19. UQIFWD: quote of water demand of irrigated farmland in upstream regions; 20. UCRAIF: the change rate of irrigated farmland area of upstream regions; 21. UCAIF: the change of irrigated farmland area of upstream regions; 22. UAIF: irrigated farmland area of upstream regions; 23. UIFWD: water demand of irrigated farmland in upstream regions; 24. UTFEFWD: table function of water demand of ecological forestry in upstream regions; 25. UQEFWD: quote of water demand of ecological forestry in upstream regions; 26. UCRAEF: the change rate of ecological forestry area of upstream regions; 27. UCAEF: the change of ecological forestry area of upstream regions; 28. UAEF: ecological forestry area of upstream regions; 29. UEWD: ecological water demand of upstream region
30. UTWD: total water demand of upstream regions for Zhanghe River; 31. UWDDZ: the ratio of upstream regions dependent on Zhanghe River water resources; 32. ACRUP: the change rate of urban population of Anyang City; 33. ACUP: the change of urban population of Anyang City; 34. AUP: urban population of Anyang City; 35. AUUPCWC: urban per capita water consumption of Anyang City; 36. AUHWD: urban household water demand of Anyang City; 37. ACRRP: the change rate of rural population of Anyang City; 38. ACRP: the change of rural population of Anyang City; 39. ARP: rural population of Anyang City; 40. ARPCWC: rural per capita water consumption of Anyang City; 41. ARHWD: rural household water demand of Anyang City; 42. ATHWD: total household water demand of Anyang City; 43. ATFPCIVAWD: table function of water demand of per unit of industrial value-added in Anyang City; 44. APCIVAWD: water demand of per unit of industrial value-added of Anyang City; 45. ACRIVA: the change rate of industrial value-added of Anyang City; 46. ACTIVA: the change of total industrial value-added of Anyang City; 47. AIVA: industrial value-added of Anyang City; 48. AIVAWD: water demand of industrial value-added of Anyang City; 49. ATFIFWD: table function of water demand of per thousand hectares irrigated farmland in Anyang City; 50. AQIFWD: quote of water demand of irrigated farmland in Anyang City; 51. ACRAIF: the change rate of irrigated farmland area of Anyang City; 52. ACAIF: the change of irrigated farmland area of Anyang City; 53. AAIF: irrigated farmland area of Anyang City; 54. AIFWD: water demand of irrigated farmland in Anyang City; 55. ATTFEFD: table function of water demand of ecological forestry in Anyang City; 56. AQEFWD: quote of water demand of ecological forestry in Anyang City; 57. ACRAEF: the change rate of ecological forestry area of Anyang City; 58. AAEF: ecological forestry area of Anyang City;59. ACAEF: the change of ecological forestry area of Anyang City; 60. AEWD: ecological water demand of Anyang City;61. AWDDZ: the ratio of Anyang City dependent on Zhanghe River water resources; 62. ATWD= total water demand of Anyang city for Zhanghe River; 63. HCRUP: the change rate of urban population of Handan City; 64. HCUP: the change of urban population of Handan City; 65. HUP: urban population of Handan City; 66. HUUPCWC: urban per capita water consumption of Handan City; 67. HUHWD: urban household water demand of Handan City; 68. HCRRRP: the change rate of rural population of Handan City; 69. HCRP: the change of rural population of Handan City; 70. HRP: rural population of Handan City; 71. HRPCWC: rural per capita water consumption of Handan City; 72. HRHWD: rural household water demand of Handan City; 73. HTHWD: total household water demand of Handan City; 74. HTFPCIVAWD: table function of water demand of per unit of industrial value-added in Handan City; 75. HPCIVAWD: water demand of per
unit of industrial value-added of Handan City; 76. HCRIVA: the change rate of industrial value-added of Handan City; 77. HCTIVA: the change of total industrial value-added of Handan City; 78. HIVA: industrial value-added of Handan City; 79. HIVAWD: water demand of industrial value-added of Handan City; 80. HTFIFWD: table function of water demand of per thousand hectares irrigated farmland in Handan City; 81. HQIFWD: quote of water demand of irrigated farmland in Handan City; 82. HCRAIF: the change rate of irrigated farmland area of Handan City; 83. HCAIF: the change of irrigated farmland area of Handan City; 84. HAIF: irrigated farmland area of Handan City; 85. HIFWD: water demand of irrigated farmland in Handan City; 86. HTFEFWD: table function of water demand of ecological forestry in Handan City; 87. HQEFWD: quote of water demand of ecological forestry in Handan City; 88. HCRAEF: the change rate of ecological forestry area of Anyang City; 89. HCAEF: the change of ecological forestry area of Handan City; 90. HAEF: ecological forestry area of Handan City; 91. HEWD: ecological water demand of Handan City; 92. HTWD: total water demand of Handan City for Zhanghe River; 93. HWDDZ: the ratio of Handan City dependent on Zhanghe River water resources; 94. CER: the effect of climate on runoff; 95. ZCR: the change of runoff of Zhanghe River; 96. ZTR: total runoff of Zhanghe River; 97. RWW: the ratio of available water supply of Zhanghe River; 98. ZAWS: available water supply of Zhanghe River; 99. UWRA: water resources allocate to upstream Region; 100 UWRR: ratio of water resources allocate to upstream regions; 101. DWRA: water resources allocate t downstream regions; 102. AWWR: ratio of the downstream water resources allocate to Anyang City; 103. UWA: water adequacy of upstream regions; 104. AWWA: water resources allocate to Anyang City; 105. HWWA: water resources allocate to Handan City; 106. AWA: water adequacy of Anyang City; 107. HWA: water adequacy of Handan City; 108. ZIWRA: the instability of water resources allocation in downstream region; 109. DIWRA: the instability of water resources allocation in Zhanghe river basin

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