Geography and Sustainability 6 (2025) 100294

Contents lists available at ScienceDirect

Geography and Sustainability

journal homepage: www.elsevier.com/locate/geosus

Perspective

The modeling framework of the coupled human and natural systems in the Yellow River Basin☆

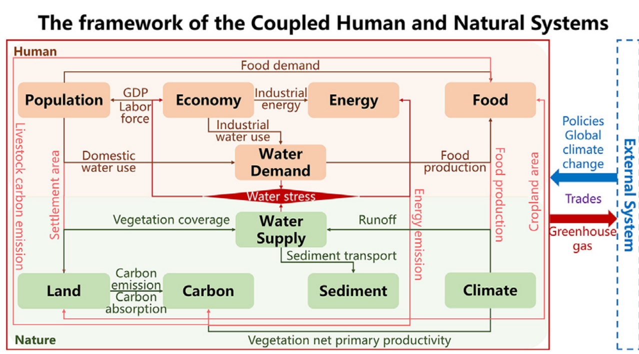
Shan Sang[a,b], Yan Li[a,b,*], Shuang Zong[a,b], Lu Yu[a,b], Shuai Wang[a,b], Yanxu Liu[a,b], Xutong Wu[a,b], Shuang Song[a,b], Xuhui Wang[c], Bojie Fu[a,b,d,*]

[a] State Key Laboratory of Earth Surface Processes and Hazards Risk Governance (ESPHR), Beijing Normal University, Beijing 100875, China
[b] Institute of Land Surface System and Sustainable Development, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
[c] Institute of Carbon Neutrality, Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China
[d] State Key Laboratory of Regional and Urban Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

HIGHLIGHTS

- A modeling framework of the coupled human-natural systems is proposed in the YRB.
- CHANS models support decision-making through scenario analyses and optimization.
- The framework is flexible and guides the development of regional CHANS models.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 November 2024
Received in revised form 18 March 2025
Accepted 23 March 2025
Available online 9 April 2025

Keyword:
Coupled human-natural systems (CHANS)
System dynamics
Regional modeling
Yellow River
Sustainable development

ABSTRACT

A mechanistic understanding and modeling of the coupled human and natural systems (CHANS) are frontier of geographical sciences and essential for promoting regional sustainability. Modeling regional CHANS in the Yellow River Basin (YRB) featuring high water stress, intense human interference, and a fragile ecosystem has always been a complex challenge. Here, we propose a conceptual modeling framework to capture key human-natural components and their interactions, focusing on human-water dynamics. The modeling framework encompasses five human (Population, Economy, Energy, Food, and Water Demand) and five natural sectors (Water Supply, Sediment, Land, Carbon, and Climate) that can be either fully interactive or standalone. The modeling framework, implemented using the system dynamics (SD) approach, can well reproduce the basin's historical evolution in human-natural processes and predict future dynamics under various scenarios. The flexibility, adaptability, and potential for integration with diverse methods position the framework as an instructive tool for guiding regional CHANS modeling. Our insights highlight pathways to advance regional CHANS modeling and its application to address regional sustainability challenges.

☆ Yan Li/Bojie Fu had no involvement in the peer-review of this article and had no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to Carla Sofia Santos Ferreira.

* Corresponding authors: Institute of Land Surface System and Sustainable Development, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, PR China.

E-mail addresses: yanli.geo@gmail.com (Y. Li), bfu@rcees.ac.cn (B. Fu).

https://doi.org/10.1016/j.geosus.2025.100294

1. Introduction

Modeling the coupled human and natural systems (CHANS) is the frontier area of geographical science (Fu, 2020) and is essential to predict the dynamics of the coupled systems and inform decision-making (Li et al., 2023). At present, various modeling efforts that focus on the dynamics of global scale CHANS have been made, such as the system dynamics models (e.g., ANEMI (Breach and Simonovic, 2021) and FeliX (Rydzak et al., 2013)), the integrated assessment models (IAMs) (Vaidyanathan, 2021), integrated Earth system model (iESM) (Jain et al., 2022). These models have been used to assess the impacts of climate change on natural and human components such as ocean and agriculture (Monier et al., 2018), land use (Alexander et al., 2018), water resources (Klassert et al., 2023), and investigate feedbacks on climate mitigation, food, and water security (Cheng et al., 2022; Fujimori et al., 2022; Luderer et al., 2018). However, these developed CHANS models at the global scale cannot fully address regional sustainable development challenges because of insufficient characterization of regional CHANS and a lack of representation of heterogeneous regional processes. There have been attempts to downscale and adapt global models to improve regional applicability, for example, the regional versions of the Global Change Analysis Model (GCAM) including the GCAM-USA model with subnational characterization of the United States (Binsted et al., 2022) and the GCAM-China model at provincial levels of China (Yu et al., 2019). Although these downscaled models can generate regional-scale outputs, they are unable to capture regional processes that differ from global dynamics and usually have low accuracy (Li et al., 2023). In comparison, regional CHANS models are better suited to capture the regional-level human-natural interactions and dynamics and provide more targeted guidance for regional development.

Modeling regional CHANS faces substantial theoretical and technical challenges. First, the regional CHANS is an open system with energy (e.g., winds, electricity transmission) and material (e.g., water transfer, food export) exchanging internally within the systems and externally with other regional and global systems, blurring the system boundary that is a prerequisite for modeling (Verburg et al., 2016). Second, the quantification of regional human and natural processes is tied to region-specific mechanisms and interactions that global models cannot resolve. Third, human and natural processes operating at different spatial scales and the scale-dependent data availability complicate regional CHANS modeling (Li et al., 2023). The apparent scale mismatch between human activities (at provincial, prefectural, and county scales) and natural processes (at sub-basin, grid, and point scales) requires scale transfer. Fourth, the lack of bidirectional feedback between human and natural processes in CHANS models may lead to misleading predictions of the evolution of coupled systems (Motesharrei et al., 2016). For example, the predicted future warming would be much smaller if the economic carbon cycle feedback from human responses to warming was considered (Woodard et al., 2019). Therefore, it is necessary to develop CHANS models with bidirectional feedback between the human-natural systems to simulate regional CHANS dynamics.

The Yellow River, China's second-longest river at 5,464 km, flows through nine provinces, covering a basin area of 795,000 km^2 (Jiang et al., 2021). As the historical center of Chinese politics, economy, and culture for over 2,000 years, the Yellow River Basin (YRB) is a typical CHANS system under significant human control. Currently, 80 % of its water resources are utilized, far exceeding the 40 % ecological warning line (Feng and Zhu, 2022), making it one of the world's most water-stressed basins (Zhang et al., 2022). The high sediment load from the Loess Plateau (Yin et al., 2021) has caused river channel siltation and flooding, disrupting agricultural production and livelihood activities (Miao et al., 2016). Ecological issues vary across the basin, including degraded ecosystem and water retention in the upstream (Ning et al., 2022), soil erosion and ecological restoration in the midstream (Fu et al., 2011), and wetland conservation in the downstream (Fu et al., 2023).

Addressing these challenges requires system thinking that considers YRB as a complex CHANS in which human activities and natural processes in various sub-basins are connected by water flow and impact each other. On the one hand, insufficient water supply cannot meet the water demand of socio-economic development and restricts regional development (Bao and Fang, 2007; Cosgrove and Loucks, 2015). On the other hand, population and economic growth drive an increase in water withdrawal, which depletes water resources and leads to various resource and eco-environmental issues (Boretti and Rosa, 2019). The excessive consumption of upstream water sources undermines the capability of water provision for downstream areas (Wei et al., 2023). Moreover, the YRB region has been under strong policy interventions. For example, ecological restoration projects (e.g., afforestation, the Grain-to-Green project) increase vegetation cover and reduce sediments, but they also decrease streamflow and exacerbate water stress under the influence of external climate forcing (e.g., increasing drought) (X. Feng et al., 2016; Wang et al., 2016). The complex feedback between human and natural processes in the YRB emphasizes the importance of understanding human and natural dynamics from a coupled systems perspective.

Various CHANS models at regional scales have been developed, such as the system dynamics models in China (Qu et al., 2020) and in the Yangtze River Basin (Jiang et al., 2022), integrated models in Jordan (Yoon et al., 2021) and Heihe River Basin (Li et al., 2021). However, regional CHANS modeling tools are scarce compared to global models (Calvin and Bond-Lamberty, 2018), specifically for the YRB. Building on existing regional modeling efforts and our knowledge of YRB, we propose a modeling framework for the CHANS in the YRB with an emphasis on human-water interactions. The framework is flexible and practical enough to allow the adaptation of model structure, configuration of interactions, and integration of various modeling methods to develop regional CHANS models for YRB. Our framework modeling practices enrich the development of regional CHANS models and promote their application to support regional sustainable development.

2. Description of the modeling framework

Based on our understanding of CHANS and knowledge of the YRB, we conceptualize a coupled system model framework to represent the most critical human and natural components in the YRB, emphasizing human-water interactions (Fig. 1). The framework consists of 10 sectors for human and natural processes with feedback with each other. Specifically, human sectors include *Population, Economy, Energy, Food*, and *Water Demand*, and natural sectors include *Water Supply, Sediment, Land, Carbon*, and *Climate*. In addition to interactions within the YRB, the system is also affected by external systems through policies and climate change.

1) *Population*
   Population growth is a key driver of CHANS dynamics in the YRB as humans demand water, energy, and food resources for living. The *Population* sector simulates demographic dynamics in the YRB, including births, deaths, and migration, etc. Births are primarily influenced by the total fertility rate, shaped by both economic status and demographic policies (Peng, 2011). Deaths are determined by life expectancy, which is prolonged by an increase in per capita gross domestic production (GDP), higher education and healthcare (Qu et al., 2020). Migrants are driven by economic disparities within and outside the basin. This sector exports population of each one-year age group, with a distinction between urban and rural populations. The *Population* sector plays a crucial role in economic production through labor supply, which in turn affects mortality and migration rates. The total population drives food demand (*Food* sector), residential water withdrawal (*Water demand* sector) and electricity consumption (*Energy* sector), and it also influences settlement areas in the *Land* sector.

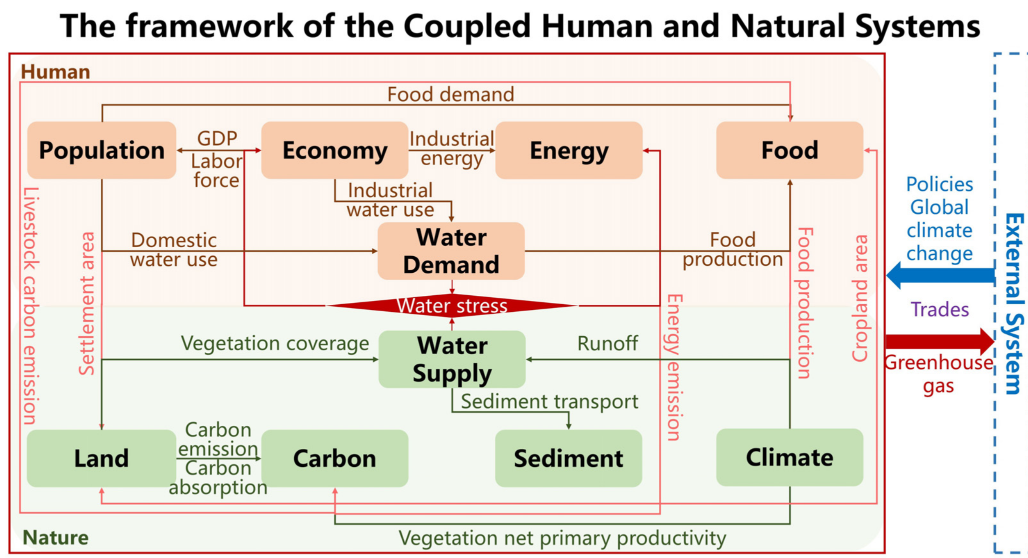


Fig. 1. Overview of the coupled human-natural system model framework in the Yellow River Basin (YRB). Orange boxes and lines represent human sectors and interactions between them, green boxes and lines represent natural sectors and interactions between them. Red lines represent interactions between human and natural sectors. Red rhombus shows the core of the framework. Red box represents the YRB system boundary. Blue boxes and lines represent external factors influencing the YRB system. The blue dotted box represents the external factors.

2) *Economy*
Economic activities are the primary drivers of water withdrawal in the YRB. The *Economy* sector simulates the production, distribution, and consumption of goods and services in different economic sectors (agriculture, industry, and services). Agricultural production consists of both crop and livestock production. Industry and services production is determined by an economic production function of total factor productivity, capital stock, and employment. The economic production in the *Economy* sector determines water withdrawal from the *Water Demand* sector and electricity, coal, oil and gas consumption from the *Energy* sector. Economic production also affects life expectancy and migration rates, which is mutually affected by population dynamics. Besides, livestock production in this sector contributes to carbon emissions.

3) *Energy*
The YRB is rich in energy resources (i.e., coal, oil, gas, wind, and solar) (Wang et al., 2024) and serves as an important electricity supply region. The *Energy* sector simulates the energy production, consumption processes, and energy structure. Energy production includes power generation from various sources (thermal, hydro, wind, solar, and nuclear power), with each source determined by its share in the energy structure. Energy consumption accounts for electricity use in households and industries, and coal, oil, and natural gas consumed by economic production. This sector is the primary contributor to carbon emissions (*Carbon* sector) through the use of fossil fuels.

4) *Food*
The YRB is a crucial food base that supplies food to various parts of China (Sun et al., 2023). The *Food* sector simulates crop and livestock production and food demand. The seven included crop types (rice, wheat, corn, soybeans, cotton, potatoes, and oil crops) collectively account for over 80 % of the total cropland area. Crop production is determined by the crop planting area and yield, with the latter being influenced by climatic factors (i.e., temperature, precipitation, and CO_2 concentration), investment, and irrigation. Livestock production is influenced by per capita GDP and total population, affecting livestock's feed need for crops. Crop demand encompasses both human and livestock dietary needs. The sector also exports metrics such as the food self-sufficiency ratio, which influences the cropland area (*Land* sector). A low self-sufficiency ratio would lead to expanding cropland to increase production. Additionally, the *Food* sector impacts agricultural production in the *Economy* sector through total crop production.

5) *Water Demand*
Human socio-economic activities consume an immense amount of water resources, which are responsible for the high water stress in the YRB (Wang et al., 2022; Zhang et al., 2024). The *Water Demand* sector simulates water withdrawal and consumption for various sectors, including domestic, agricultural, and industry. Domestic water withdrawal is related to per capita GDP and total population, while industrial and service sector water withdrawal is driven by sector water-use intensities and gross economic production. Agricultural water withdrawal is determined by irrigation areas and irrigation intensity. The total water consumption (*Water Demand* sector), combined with the available water resources (*Water Supply* sector), determines basin's water stress, which influences the economic production and water-use intensity across sectors.

6) *Water Supply*
The Yellow River accounts for only 2 % of the national streamflow (Hu et al., 2023), yet it sustains a densely populated region with substantial water demand. The *Water Supply* sector simulates runoff and streamflow and their changes in each sub-basin. Runoff is determined by precipitation and evapotranspiration (ET) based on the water balance principle derived from the Budyko equation (Yang et al., 2009). Given the water losses during the confluence process, natural streamflow is determined by the loss coefficient (defined by the ratio of natural streamflow to runoff) and runoff. Water withdrawal in upstream areas impacts the streamflow for downstream areas due to hydrological connectivity. By integrating changes in reservoir storage and human water consumption in sub-basins, the actual streamflow can be determined, which drives sediment transport (*Sediment* sector) in the river.

7) *Sediment*
The Yellow River is one of rivers with the highest sediment load due to severe soil erosion in its midstream. The *Sediment* sector simulates sediment load at sub-basin levels based on the empiri-

cal relationship between actual streamflow (*Water Supply* sector) and sediment load from the literature (Yin et al., 2023).

8) *Land*
Land use types vary widely in sub-basins of the YRB, with diverse ecosystem composition and varying degrees of human influence. The *Land* sector simulates the changes in the area of six land use types (cropland, forest, grassland, wetland, settlement, and others) driven by socio-economic activities. Land use relevant policies may alter the conversion rate of specific types, such as the Grain to Green program increasing forest area in midstream of the YRB (Li et al., 2020). Population growth leads to an increase in settlement (Deng et al., 2008). The historical land areas and their changes are determined by demographic dynamics from the *Population* sector and land policies (e.g., afforestation, reforestation). This sector influences runoff from the *Water Supply* sector because higher vegetation coverage reduces runoff. Land use conversion changes the carbon balance, impacting the region's carbon stock and emissions from the *Carbon* sector. Additionally, the cropland area directly impacts crop production in the *Food* sector.

9) *Carbon*
The *Carbon* sector simulates the basin's carbon balance processes, including carbon absorption and emission, which drive ecosystem processes and influence climate and socio-economic activities. Carbon absorption is primarily driven by ecosystem photosynthesis, with respiration subtracted as net primary productivity (NPP). The NPP is influenced by temperature, precipitation, CO_2 concentration, and vegetation coverage area. NPP, after deducting soil respiration from the decay of carbon stocks (biomass, litter, humus, and charcoal), gives NEP. Carbon emissions stem from various sources, including fossil fuel consumption, livestock excretion, and land use conversion, which can be derived using their respective emission coefficients. This sector can diagnose the overall carbon neutrality for the basin.

10) *Climate*
Climate is a fundamental driver of the CHANS, shaping ecosystem functions, resource availability, and human livelihoods. The *Climate* sector provides historical and future climate information required by other sectors: *Water Supply, Food*, and *Carbon*. Climate variables include temperature, precipitation, potential evapotranspiration, and CO_2 concentration. These climatic variables are exogenous and do not consider the feedback of human and natural processes on regional climate (Jiang et al., 2022).

3. Implementation of modeling framework with system dynamics approach

Inspired by existing human-natural systems models (Jiang et al., 2022; Motesharrei et al., 2014; Qu et al., 2020), we implement the proposed modeling framework in the YRB based on system dynamics (SD) approaches. SD is a flexible and effective modeling approach that can capture the nonlinear behaviors and feedback in complex systems and their long-term evolution (M. Feng et al., 2016).

The implemented SD model of CHANS in the YRB consists of 10 sectors with more than 600 variables, including endogenous (i.e., calculated by the model) and exogenous (prescribed) ones. By collecting data in 1981 as initial condition (population, fertility rate, industrial capital, etc.), the model can simulate both historical (1981–2020) and future periods (2021–2100) on an annual scale. The historical data are used to calibrate various parameter values and verify the model performance. Future simulation predicts the evolution of CHANS in the YRB under different scenarios.

3.1. Spatial scale conversion between human and natural sectors

The YRB model faces the challenge of mismatched spatiotemporal scales between human and natural processes. Human processes are simulated at the provincial scale due to the intrinsic scale of human processes and their data availability, while natural processes are at the sub-basin scale (up-, mid-, and down-stream) to account for their hydrological connectivity (Fig. 2). To reconcile the scale mismatch, we use various gridded data as a proxy to convert variables between human and natural processes through upscaling or downscaling, e.g., the use of gridded GDP data (Xu, 2017a) to convert carbon emission from the provincial to sub-basin levels, and gridded population density data (Xu, 2017b) to calculate the population in the basin.

3.2. Data sources for modeling

The YRB model relies on data from various sources, including statistical bulletins/yearbooks, in-situ measurements, remote sensing products, and land surface model simulations (listed in Table S1 in the Supplementary materials). Data for human sectors are mainly from statistical data at the provincial level, including the China Statistical Yearbook and the Yellow River Water Resources Bulletin. Data for natural sectors are collected from remote sensing data and model simulations at the grid level. When multiple data sources are available, datasets designed explicitly for the YRB or China are preferred than global datasets.

Since most data sources do not provide full time series for the historical period (1981–2020), various data-filling techniques are employed to make complete records, including linear forward, backward, and nearest interpolations/extrapolation, substitution with literature values or national-level data.

3.3. Historical and future simulations

The YRB model built upon SD can simulate the CHANS dynamics in YRB. We visualized the key outputs of a historical simulation from 1981 to 2020 to demonstrate the model's capability (Fig. 3). Overall, the model can accurately capture historical changes in both socio-economic and natural processes in the YRB.

During the historical period (1981 to 2020), the five key variables of human sectors (total population, total GDP, coal consumption, food production, and total water withdrawal) show upward trends with fluctuations and well reproduce the historical changes in the YRB ($r > 0.85$). As for natural sectors, forest area (*Land* sector) and NPP (*Carbon* sector) increased slightly, sediment load (*Sediment* sector) dropped significantly around 2000, and runoff (*Water Supply* sector) fluctuated and rose after 2000. The natural sectors generally have a lower correlation with historical data ($r < 0.75$ for forest area of the *Land* sector) than human sectors because of the simplifications made in the modeling of physically complex natural processes within the SD.

The future trajectory of CHANS from 2021 to 2100 is simulated by climate change of the Shared Socioeconomic Pathways (SSP) 245 scenario (Alfred Wegener Institute Climate Model simulation results from https://aims2.llnl.gov/search/cmip6/) and other variables (e.g., total fertility rates, employment rates) kept constant at the 2020 values (Fig. 3). The designed future simulation is not to give credible inferences about the system states in the future but to showcase the model's capability for scenario analysis. The population is expected to peak at 423 million in 2021, while GDP and water withdrawal are projected to peak in the mid-21st century. With a stable cropland area, food production is anticipated to experience slight upward fluctuations, driven by rising CO_2 concentrations and the impacts of climate change. Climate change also leads to fluctuant increases in runoff and NPP.

4. Practical suggestions for implementing modeling framework

4.1. Adapt the framework to best represent the conceptualized modeled system

The proposed modeling framework effectively captures the key human and natural components in the YRB and their critical interactions,

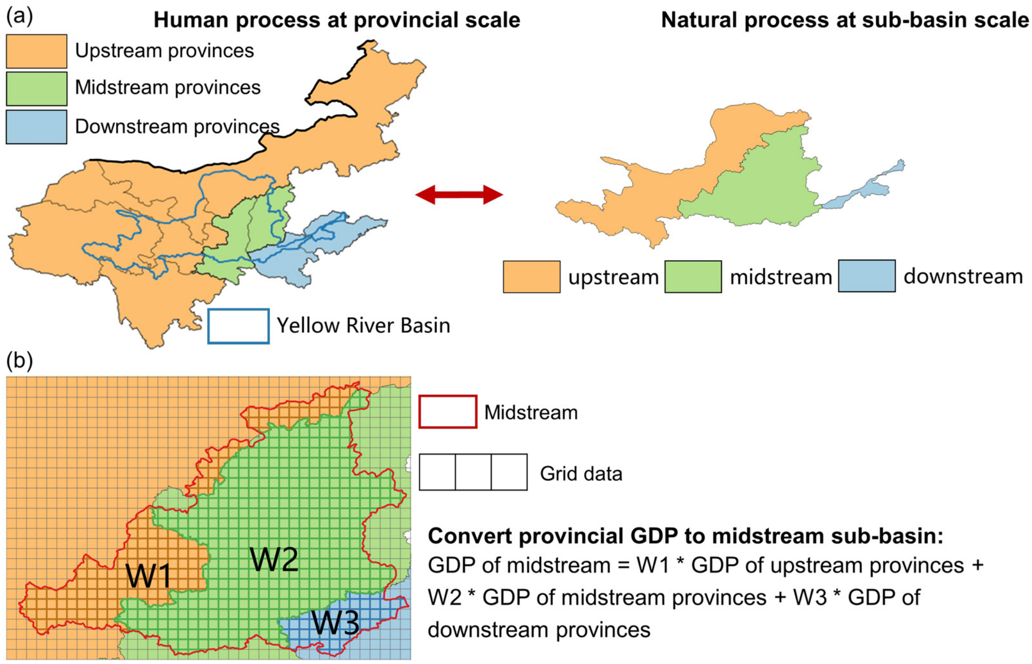


Fig. 2. Spatial scale of human and natural processes in the YRB model and their conversion. (a) Human processes at provincial level and natural processes at sub-basin level. (b) Example of scale conversion between provincial and sub-basin scales for GDP. Gridded data are used to calculate weights (W1, W2, W3) of each intercepted parts of sub-basin and corresponding provinces to enable upscaling and downscaling between specific human and natural processes.

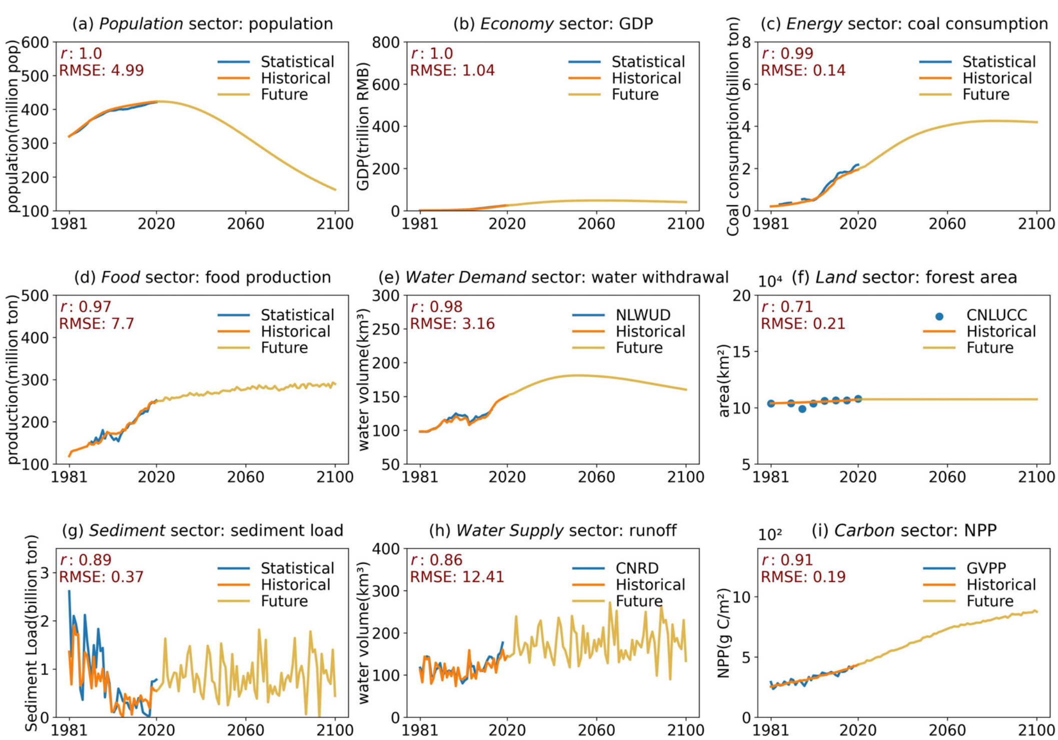


Fig. 3. Historical and future simulation with the YRB model built upon SD from 1981 to 2100. *r* and RMSE represent simulation accuracy in historical period (1981 to 2020). Blue lines represent historic data from various sources. Orange and yellow lines represent simulations in historical and future period. (a) Population of the *Population* sector; (b) GDP of the *Economy* sector; (c) coal consumption of the *Energy* sector; (d) food production of the *Food* sector; (e) water withdrawal of the *Water Demand* sector; (f) forest area of the *Land* sector, and the CNLUCC dataset is discontinuous; (g) annual sediment load of the *Sediment* sector; (h) annual runoff of the *Water Supply* sector; (i) net primary productivity of the *Carbon* sector. Note that natural runoff is simulated based on the land use conditions in 1981 to be consistent with the CNRD dataset (Gou et al., 2021).

providing insights into the human-natural coupling mechanisms of the basin. The framework is designed with a focus on the human-water nexus, but it is flexible to be modified to help conceptualize the modelled system of their own interest and to satisfy their specific research needs. The framework's flexibility manifests in the adaptation of system structure, interaction configurations, and integrations with modeling techniques. First, sectors in the framework can be added or modified to accommodate specific model system design, and they can be configured to be fully interactive, prescribed, or as a standalone model. For example, the *Population* and *Economy* sectors can be used as standalone models to investigate the influence of family planning policies on economic activities. Second, feedback between sectors can be enabled, disabled, or modified to study the impact of specific processes. For instance, pathways by which *Climate* affects the *Economy* sector can be incorporated to analyze economic damages caused by future climate change.

4.2. Choose suitable modeling approaches to quantify regional CHANS processes

Implementing the framework using the SD approach demonstrates a feasible and practical way of modeling CHANS in the YRB and offers a valuable modeling practice to advance regional CHANS models. However, the regional human and natural system processes are diverse, heterogeneous, and complex, showing unique and intricate features that are challenging and even infeasible to quantify (Jia et al., 2021). Also, the representation of geospatial processes is limited in the implemented SD. In practice, the sectors can be implemented with various modeling approaches and their combinations with different complexities, ranging from physical mechanisms (e.g., water balance (McDonnell, 2017)), simplified representations (e.g., precipitation partitioning into ET and runoff (Yang et al., 2009)), theories (e.g., economic production function (Akhtar et al., 2013)) to empirical relationships (e.g., water withdrawal and GDP (Flörke et al., 2013)) or approximation from data (e.g., irrigation water intensity). Depending on the goal, more detailed and advanced modeling methodologies can be applied to improve simulation accuracy for specific sectors or processes. It is also important to balance model complexity, effectiveness, and accuracy in the model implementation.

4.3. Design proper temporal and spatial scale for modeled processes

Modeling regional CHANS needs proper ways to define the system boundary and scales (Blair and Buytaert, 2016). For natural processes in our implemented SD model, sub-basins are selected to characterize the regional differences and interconnections among up-, mid-, and downstream and ensure hydrological closure (Oki and Kanae, 2006). In contrast, human processes are represented at the provincial scale due to socio-economic data availability. The spatial mismatch between human and natural processes is handled by conversion (upscaling and downscaling) using high-resolution gridded data (Chou et al., 2018). The conversion parameters derived from historical data may change and introduce biases for future extrapolations. While the implemented spatial characterization is suitable for a coupled model operating at the basin on an annual scale, it could not represent heterogeneity within province/sub-basin and seasonal variations. If finer spatial and temporal variations are key for the modeled processes, sub-province (prefectural or county-level for human processes) and sub-annual (monthly or seasonal scales) scales can be configured. However, this comes at the cost of higher data needs and complex scale conversion parameters. The feasible scale design should consider the requirement of key CHANS processes and data constraints.

5. Conclusions

In summary, we provide a modeling framework of CHANS incorporating key human and natural processes and interactions in the YRB, allowing for investigating human-natural dynamics in the YRB that are not possible with sector models. The framework implemented using the SD approach can represent feedback between systems and predict CHANS dynamics, and we offer practical suggestions for implementing the framework. The implemented regional CHANS model is a powerful tool to support the decision-making of policies through scenario analyses and seek ways to optimize the systems toward sustainability, with potential applications including climate change impact, carbon neutrality, water and food security, water resources management, socio-economic development, ecological restoration, and land use change in the Yellow River Basin.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Shan Sang: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Yan Li:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Shuang Zong:** Software, Methodology, Data curation. **Lu Yu:** Software, Methodology, Data curation. **Shuai Wang:** Writing – review & editing. **Yanxu Liu:** Writing – review & editing. **Xutong Wu:** Writing – review & editing. **Shuang Song:** Writing – review & editing. **Xuhui Wang:** Project administration. **Bojie Fu:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Acknowledgements

This study is supported by the National Natural Science Foundation of China (Grant No. 42041007), and the Fundamental Research Funds for the Central Universities. We thank Dr. Weishuang Qu for developing the Threshold 21 model in the Millennium Institute that inspired this study, and also for his and Dr. Haiyan Jiang's generous help with the YRB modeling. We also thank the data support from National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geosus.2025.100294.

References

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

Alexander, P., Rabin, S., Anthoni, P., Henry, R., Pugh, T.A.M., Rounsevell, M.D.A., Arneth, A., 2018. Adaptation of global land use and management intensity to changes in climate and atmospheric carbon dioxide. Glob. Change Biol. 24, 2791–2809. doi:10.1111/gcb.14110.

Bao, C., Fang, C., 2007. Water resources constraint force on urbanization in water deficient regions: a case study of the Hexi Corridor, arid area of NW China. Ecol. Econ. 62, 508–517. doi:10.1016/j.ecolecon.2006.07.013.

Binsted, M., Iyer, G., Patel, P., Graham, N.T., Ou, Y., Khan, Z., Kholod, N., Narayan, K., Hejazi, M., Kim, S., Calvin, K., Wise, M., 2022. GCAM-USA v5.3_water_dispatch: integrated modeling of subnational US energy, water, and land systems within a global framework. Geosci. Model Dev. 15, 2533–2559. doi:10.5194/gmd-15-2533-2022.

Blair, P., Buytaert, W., 2016. Socio-hydrological modelling: a review asking "why, what and how?". Hydrol. Earth Syst. Sci. 20, 443–478. doi:10.5194/hess-20-443-2016.

Boretti, A., Rosa, L., 2019. Reassessing the projections of the World water development report. npj Clean Water 2, 15. doi:10.1038/s41545-019-0039-9.

Breach, P.A., Simonovic, S.P., 2021. ANEMI3: an updated tool for global change analysis. PLoS One 16, e0251489. doi:10.1371/journal.pone.0251489.

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

Cheng, Y., Huang, M., Lawrence, D.M., Calvin, K., Lombardozzi, D.L., Sinha, E., Pan, M., He, X., 2022. Future bioenergy expansion could alter carbon sequestration potential and exacerbate water stress in the United States. Sci. Adv. 8, eabm8237. doi:10.1126/sciadv.abm8237.
Chou, J., Hu, C., Dong, W., Ban, J., 2018. Temporal and spatial matching in human-earth system model coupling. Earth Space Sci. 5, 231–239. doi:10.1002/2018EA000371.
Cosgrove, W.J., Loucks, D.P., 2015. Water management: current and future challenges and research directions. Water Resour. Res. 51, 4823–4839. doi:10.1002/2014WR016869.
Deng, X., Huang, J., Rozelle, S., Uchida, E., 2008. Growth, population and industrialization, and urban land expansion of China. J. Urban Econ. 63, 96–115. doi:10.1016/j.jue.2006.12.006.
Feng, M., Liu, P., Li, Z., Zhang, J., Liu, D., Xiong, L., 2016. Modeling the nexus across water supply, power generation and environment systems using the system dynamics approach: hehuang Region, China. J. Hydrol. 543, 344–359. doi:10.1016/j.jhydrol.2016.10.011.
Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lü, Y., Zeng, Y., Li, Y., Jiang, X., Wu, B., 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nat. Clim. Change 6, 1019–1022. doi:10.1038/nclimate3092.
Feng, Y., Zhu, A., 2022. Spatiotemporal differentiation and driving patterns of water utilization intensity in Yellow River Basin of China: comprehensive perspective on the water quantity and quality. J. Clean. Prod. 369, 133395. doi:10.1016/j.jclepro.2022.133395.
Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., Alcamo, J., 2013. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: a global simulation study. Glob. Environ. Change 23, 144–156. doi:10.1016/j.gloenvcha.2012.10.018.
Fu, B., 2020. Promoting geography for sustainability. Geogr. Sustain. 1, 1–7. doi:10.1016/j.geosus.2020.02.003.
Fu, B., Liu, Y., Lü, Y., He, C., Zeng, Y., Wu, B., 2011. Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. Ecol. Complex. 8, 284–293. doi:10.1016/j.ecocom.2011.07.003.
Fu, B., Liu, Y., Meadows, M.E., 2023. Ecological restoration for sustainable development in China. Natl. Sci. Rev. 10, nwad033. doi:10.1093/nsr/nwad033.
Fujimori, S., Wu, W., Doelman, J., Frank, S., Hristov, J., Kyle, P., Sands, R., van Zeist, W.J., Havlik, P., Domínguez, I.P., Sahoo, A., Stehfest, E., Tabeau, A., Valin, H., van Meijl, H., Hasegawa, T., Takahashi, K., 2022. Land-based climate change mitigation measures can affect agricultural markets and food security. Nat. Food 3, 110–121. doi:10.1038/s43016-022-00464-4.
Gou, J., Miao, C., Samaniego, L., Xiao, M., Wu, J., Guo, X., 2021. CNRD v1.0: a high-quality natural runoff dataset for hydrological and climate studies in China. Bull. Amer. Meteorol. Soc. 102, E929–E947. doi:10.1175/BAMS-D-20-0094.1.
Hu, H., Tian, G., Wu, Z., Xia, Q., 2023. Cross-regional ecological compensation under the composite index of water quality and quantity: a case study of the Yellow River Basin. Environ. Res. 238, 117152. doi:10.1016/j.envres.2023.117152.
Jain, S., Mindlin, J., Koren, G., Gulizia, C., Steadman, C., Langendijk, G.S., Osman, M., Abid, M.A., Rao, Y., Rabanal, V., 2022. Are we at risk of losing the current generation of climate researchers to data science? AGU Adv. 3. doi:10.1029/2022AV000676, e2022AV000676.
Jia, B., Zhou, J., Zhang, Y., Tian, M., He, Z., Ding, X., 2021. System dynamics model for the coevolution of coupled water supply–power generation–environment systems: upper Yangtze River Basin, China. J. Hydrol. 593, 125892. doi:10.1016/j.jhydrol.2020.125892.
Jiang, H., Simonovic, S.P., Yu, Z., 2022. ANEMI_Yangtze v1.0: a coupled human–natural systems model for the Yangtze Economic Belt – model description. Geosci. Model Dev. 15, 4503–4528. doi:10.5194/gmd-15-4503-2022.
Jiang, L., Zuo, Q., Ma, J., Zhang, Z., 2021. Evaluation and prediction of the level of high-quality development: a case study of the Yellow River Basin, China. Ecol. Indic. 129, 107994. doi:10.1016/j.ecolind.2021.107994.
Klassert, C., Yoon, J., Sigel, K., Klauer, B., Talozi, S., Lachaut, T., Selby, P., Knox, S., Avisse, N., Tilmant, A., Harou, J.J., Mustafa, D., Medellín-Azuara, J., Bataineh, B., Zhang, H., Gawel, E., Gorelick, S.M., 2023. Unexpected growth of an illegal water market. Nat. Sustain. 6, 1406–1417. doi:10.1038/s41893-023-01177-7.
Li, C., Zhang, Y., Shen, Y., Yu, Q., 2020. Decadal water storage decrease driven by vegetation changes in the Yellow River Basin. Sci. Bull. 65, 1859–1861. doi:10.1016/j.scib.2020.07.020.
Li, X., Zhang, L., Zheng, Y., Yang, D., Wu, F., Tian, Y., Han, F., Gao, B., Li, H., Zhang, Y., Ge, Y., Cheng, G., Fu, B., Xia, J., Song, C., Zheng, C., 2021. Novel hybrid coupling of ecohydrology and socioeconomy at river basin scale: a watershed system model for the Heihe River basin. Environ. Modell. Softw. 141, 105058. doi:10.1016/j.envsoft.2021.105058.
Li, Y., Sang, S., Mote, S., Rivas, J., Kalnay, E., 2023. Challenges and opportunities for modeling coupled human and natural systems. Natl. Sci. Rev. 10, nwad054. doi:10.1093/nsr/nwad054.
Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O.Y., Pietzcker, R.C., Rogelj, J., De Boer, H.S., Drouet, L., Emmerling, J., Fricko, O., Fujimori, S., Havlík, P., Iyer, G., Keramidas, K., Kitous, A., Pehl, M., Krey, V., Riahi, K., Saveyn, B., Tavoni, M., Van Vuuren, D.P., Kriegler, E., 2018. Residual fossil CO_2 emissions in 1.5–2°C pathways. Nat. Clim. Change 8, 626–633. doi:10.1038/s41558-018-0198-6.
McDonnell, J.J., 2017. Beyond the water balance. Nat. Geosci. 10, 396. doi:10.1038/ngeo2964.
Miao, C., Kong, D., Wu, J., Duan, Q., 2016. Functional degradation of the water–sediment regulation scheme in the lower Yellow River: spatial and temporal analyses. Sci. Total Environ. 551–552, 16–22. doi:10.1016/j.scitotenv.2016.02.006.
Monier, E., Paltsev, S., Sokolov, A., Chen, Y.H.H., Gao, X., Ejaz, Q., Couzo, E., Schlosser, C.A., Dutkiewicz, S., Fant, C., Scott, J., Kicklighter, D., Morris, J., Jacoby, H., Prinn, R., Haigh, M., 2018. Toward a consistent modeling framework to assess multi-sectoral climate impacts. Nat. Commun. 9, 660. doi:10.1038/s41467-018-02984-9.
Motesharrei, S., Rivas, J., Kalnay, E., 2014. Human and nature dynamics (HANDY): modeling inequality and use of resources in the collapse or sustainability of societies. Ecol. Econ. 101, 90–102. doi:10.1016/j.ecolecon.2014.02.014.
Motesharrei, S., Rivas, J., Kalnay, E., Asrar, G.R., Busalacchi, A.J., Cahalan, R.F., Cane, M.A., Colwell, R.R., Feng, K., Franklin, R.S., Hubacek, K., Miralles-Wilhelm, F., Miyoshi, T., Ruth, M., Sagdeev, R., Shirmohammadi, A., Shukla, J., Srebric, J., Yakovenko, V.M., Zeng, N., 2016. Modeling sustainability: population, inequality, consumption, and bidirectional coupling of the Earth and human systems. Natl. Sci. Rev. 3, 470–494. doi:10.1093/nsr/nww081.
Ning, X., Zhu, N., Liu, Y., Wang, H., 2022. Quantifying impacts of climate and human activities on the grassland in the Three-River Headwater Region after two phases of Ecological Project. Geogr. Sustain. 3, 164–176. doi:10.1016/j.geosus.2022.05.003.
Oki, T., Kanae, S., 2006. Global hydrological cycles and world water resources. Science 313 (5790), 1068–1072. doi:10.1126/science.1128845.
Peng, X., 2011. China's demographic history and future challenges. Science 333 (6042), 581–587. doi:10.1126/science.1209396.
Qu, W., Shi, W., Zhang, J., Liu, T., 2020. T21 China 2050: a tool for national sustainable development planning. Geogr. Sustain. 1, 33–46. doi:10.1016/j.geosus.2020.03.004.
Rydzak, F., Obersteiner, M., Kraxner, F., Fritz, S., McCallum, I., 2013. FeliX3–Impact Assessment Model: Systemic View Across Societal Benefit Areas beyond Global Earth Observation. International Institute for Applied Systems Analysis (IIASA), Laxenburg.
Sun, X., Zhou, Z., Wang, Y., 2023. Water resource carrying capacity and obstacle factors in the Yellow River basin based on the RBF neural network model. Environ. Sci. Pollut. Res. 30, 22743–22759. doi:10.1007/s11356-022-23712-3.
Vaidyanathan, G., 2021. Integrated assessment climate policy models have proven useful, with caveats. Proc. Natl. Acad. Sci. U.S.A. 118, e2101899118. doi:10.1073/pnas.2101899118.
Verburg, P.H., Dearing, J.A., Dyke, J.G., Leeuw van der, S., Seitzinger, S., Steffen, W., Syvitski, J., 2016. Methods and approaches to modelling the Anthropocene. Glob. Environ. Change 39, 328–340. doi:10.1016/j.gloenvcha.2015.08.007.
Wang, J., Guan, H., Zhao, A., 2024. Regional productivity in the energy structure transition of the Yellow River Basin in China - estimation based on a restricted cost function. Appl. Energy 375, 124178. doi:10.1016/j.apenergy.2024.124178.
Wang, S., Fu, B., Piao, S., Lü, Y., Ciais, P., Feng, X., Wang, Y., 2016. Reduced sediment transport in the Yellow River due to anthropogenic changes. Nat. Geosci. 9, 38–41. doi:10.1038/ngeo2602.
Wang, Y., Song, J., Zhang, X., Sun, H., Bai, H., 2022. Coupling coordination evaluation of water-energy-food and poverty in the Yellow River Basin, China. J. Hydrol. 614, 128461. doi:10.1016/j.jhydrol.2022.128461.
Wei, H., Wang, Y., Liu, J., Zhang, X., Cao, Y., 2023. Coordinated development of cultivated land use and ecological protection in cities along the main stream of the Yellow River in Henan Province, China. Ecol. Indic. 156, 111143. doi:10.1016/j.ecolind.2023.111143.
Woodard, D.L., Davis, S.J., Randerson, J.T., 2019. Economic carbon cycle feedbacks may offset additional warming from natural feedbacks. Proc. Natl. Acad. Sci. U.S.A. 116, 759–764. doi:10.1073/pnas.1805187115.
Xu, X.L., 2017a. Kilometer grid dataset of China's GDP spatial distribution. https://doi.org/10.12078/2017121102
Xu, X.L., 2017b Kilometer grid dataset of China's population spatial distribution. https://doi.org/10.12078/2017121101
Yang, D., Shao, W., Yeh, P.J.F., Yang, H., Kanae, S., Oki, T., 2009. Impact of vegetation coverage on regional water balance in the nonhumid regions of China. Water Resour. Res. 45 (7), 507–519. doi:10.1029/2008WR006948.
Yin, S., Gao, G., Ran, L., Li, D., Lu, X., Fu, B., 2023. Extreme streamflow and sediment load changes in the Yellow River Basin: impacts of climate change and human activities. J. Hydrol. 619, 129372. doi:10.1016/j.jhydrol.2023.129372.
Yin, S., Gao, G., Ran, L., Lu, X., Fu, B., 2021. Spatiotemporal variations of sediment discharge and in-reach sediment budget in the Yellow River from the headwater to the delta. Water Resour. Res. 57,. doi:10.1029/2021WR030130, e2021WR030130..
Yoon, J., Klassert, C., Selby, P., Lachaut, T., Knox, S., Avisse, N., Harou, J., Tilmant, A., Klauer, B., Mustafa, D., Sigel, K., Talozi, S., Gawel, E., Medellín-Azuara, J., Bataineh, B., Zhang, H., Gorelick, S.M., 2021. A coupled human–natural system analysis of freshwater security under climate and population change. Proc. Natl. Acad. Sci. U.S.A. 118, e2020431118. doi:10.1073/pnas.2020431118.
Yu, S., Horing, J., Liu, Q., Dahowski, R., Davidson, C., Edmonds, J., Liu, B., Mcjeon, H., McLeod, J., Patel, P., Clarke, L., 2019. CCUS in China's mitigation strategy: insights from integrated assessment modeling. Int. J. Greenh. Gas Control 84, 204–218. doi:10.1016/j.ijggc.2019.03.004.
Zhang, T., Su, X., Zhang, G., Wu, H., Liu, Y., 2022. Projections of the characteristics and probability of spatially concurrent hydrological drought in a cascade reservoirs area under CMIP6. J. Hydrol. 613, 128472. doi:10.1016/j.jhydrol.2022.128472.
Zhang, W., Liang, W., Gao, X., Li, J., Zhao, X., 2024. Trajectory in water scarcity and potential water savings benefits in the Yellow River basin. J. Hydrol. 633, 130998. doi:10.1016/j.jhydrol.2024.130998.