Short Communications

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Short Communication

What dominates sustainability in endorheic regions?

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Diverse evidence suggests that the sustainability of endorheic regions will be the underbelly of achieving the transformative promise “leave no one behind” of the Sustainable Development Goals (SDGs) proposed by the United Nations; for example, “Aral Sea Syndrome” [1], “basin closure symptom” [2], and saline lake salinization [3] are undermining life support systems and human well-being [4]. Global warming is reducing the amount of solid water resources in mountainous regions [5], which, in turn, threatens the Asia water tower [6] that supports local life systems. This phenomenon is even more serious in endorheic basins [7], which are hydrologically landlocked mountain-oasis-desert systems. Increasing water stress is intensifying the risk of syndromes that will spread continually throughout these regions in the future [8,9], even in regions with increasing runoff from the cryosphere [10]. In addition, the combination of the growing population, advancing urbanization and the warming climate poses a new challenge in the water-food-ecosystem-economy nexus, driving endorheic basins toward an unsustainable future.

To address the above challenges, we propose an integrated framework to quantify the coaction of the driving and telecoupling factors, including climate (temperature and precipitation), technique (technological advance rate of three industries), population, urbanization and government management (ecological water flow refers to water resources that are forcibly separated by water policy for restoring and maintaining healthy ecosystems), on a complex system of ecohydrology and socioeconomy and identify sustainability shift pathways. In the Heihe River basin (Fig. S1 online), we propose an integrated framework that combines a watershed system model, watershed-scale SDGs, localized shared socioeconomic pathways (SSPs) (Fig. S2 online) and a sustainability assessment model (Fig. 1 and Materials and methods section in Supplementary materials). The watershed system model was developed by integrating the upstream ecohydrological surrogate model, the mid- and downstream ecohydrological surrogate model and a computable general equilibrium (CGE) model to simulate and project the interactions between ecohydrological and socioeconomic systems (Fig. S3 online). This watershed system model facilitates the establishment of key linkages between the regulation of the eight driving forces (agricultural technological advances, industrial technological advances, service technological advances, ecological water flow, precipitation, temperature, urbanization and population) and the calculation of the ten watershed-scale SDG indicators (water productivity, water stress, groundwater withdrawals, forest cover rate, green cover index, GDP (gross domestic product) per capita, GDP per employed person, urbanization, agricultural water productivity and farmland area). We applied the framework to a typical endorheic basin, i.e., the Heihe River Basin, to identify the determinants that dominate the sustainability of most endorheic regions and potential sustainability transformation pathways by analyzing the impacts of 2160 combinations of six driving and telecoupling factors (agricultural technological advances, industrial technological advances and service technological advances are merged into one technological advance that indicates the average technological level) on the trade-offs between diverse SDG indicators and their sustainability. This basin has the common features of most endorheic regions, such as high water stress, vulnerable ecosystems and rapidly growing populations and urbanization; in particular, this basin has been recovering from ecosystem catastrophes due to great effort by the scientific community and government [11,12].

We have considered five SSPs, i.e., SSP1 (sustainability), SSP2 (middle road), SSP3 (regional rivalry), SSP4 (inequality), and SSP5 (fossil-fueled development). The possible range of eight key driving factors (i.e., the scenario parameters of the SSPs) are identified using the regional climate model, population model, urbanization model and local policies based on the narratives of the SSPs (see Supplementary materials). Based on the range of six scenario parameters, we combine the 6 equalized values of the three critical parameters (i.e., precipitation, technological progress and ecological water flow) and the maximum and minimum values of the other three parameters (i.e., temperature, population and urbanization) to generate 2160 sets of scenarios ($C_6^1 \times C_6^1 \times C_6^1 \times C_2^1 \times 5 = 2160$).

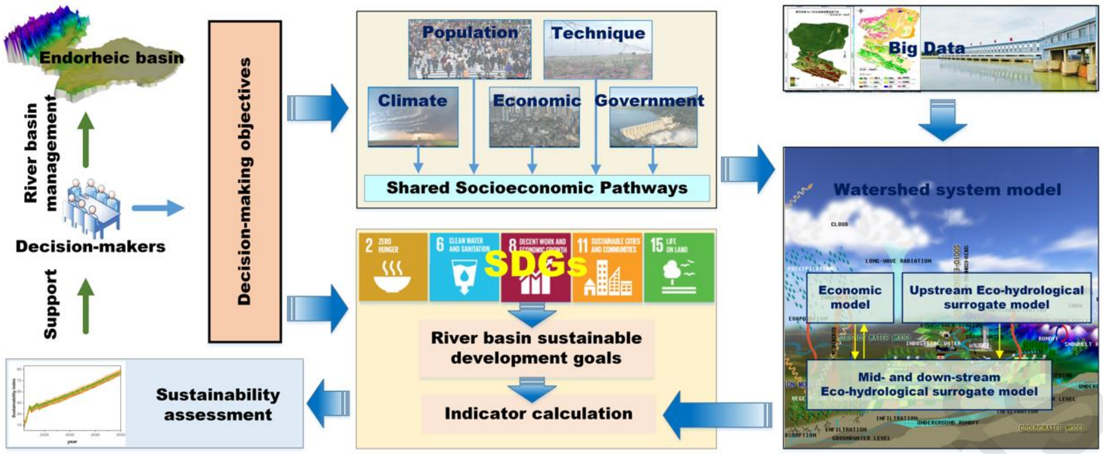

Fig. 1. Integrated framework. This framework integrates a watershed system model, river basin sustainable development goals, shared socioeconomic pathways, and a sustainability assessment model at the river basin scale.

Our analysis of the 2160 projected pathways reveals that sustainability in this endorheic basin is essentially dominated by the coactions of six driving forces (Fig. 2a). Regarding single impacts, technological advances are the most influential factor affecting sustainability, followed by urbanization, temperature and population growth, while precipitation has the weakest impact, followed by ecological water flow (Fig. 2b, main sensitivity index, MSI). Nevertheless, technological advances sometimes have a negative impact on the environment [13]. Regarding coimpacts, ecological water flow exhibits the strongest interactions with the other driving forces, followed by precipitation, urbanization and temperature, while population exhibits the weakest interactions, followed by technology (Fig. 2b, TSI-MSI, TSI: total sensitivity index).

We find that higher sustainability pathways through improved technology are unlikely to be as successful as tech-optimists believe. For example, an improvement in water use efficiency does not necessarily reduce water consumption (water stress) without rational water management (e.g., less or exorbitant ecological water flow) (Fig. S4a online), as the saved water is transferred to the food production system, resulting in the expansion of farmland (Figs. S4b and S5g online). This outcome has been shown by some facts (i.e., the saved-water engineering in Zhangye city in the basin did not essentially decrease irrigation water use; in contrast, the amount of water used for irrigation increased from 1.6 billion m^3 in 1999 to 1.9 billion m^3 in 2011). Accordingly, employing only technicisms may harm the achievement of sustainability (Fig. 2a). This technique paradox may be a key factor threatening sustainability in most endorheic regions.

In addition, many projected pathways reveal that high temperatures harm sustainability in this basin; in particular, lower sustainability is generated by rising temperatures under low technological advances (Fig. 2a). Temperature, as an exogenous driving force, cannot be deliberately controlled by local technological solutions and requires a global solution to carbon emission abatement. Most endorheic regions that contribute low carbon flux to the atmospheric carbon dioxide concentration are suffering from a risk of low sustainability produced by global warming caused by the telecoupling effect from high carbon emissions from developed regions.

However, we find that diverse combinations of high ecological water flow and technological level may enhance the adaptation to a warming climate to achieve higher sustainability; for example, the SDI GR (sustainable development index growth rate) increases from 93.6%–107.6% to 165.8%–177.7% under an improved technique ranging from the lowest level (4.0) to an above average level (10.5), and regulated ecological water flow increases from 0.91 to 0.94 billion m^3 a^{-1} with a future increase in temperature of 8.0 ℃ by 2050 (Fig. 2a).

Rapid population growth stimulates the rapid expansion of farmland in the Heihe River Basin (Fig. S4b online), leading to a rapid increase in the demand for water resources (Fig. S4a online), which exceeds the limits of water resources due to low water use efficiency (flood irrigation causes a very large amount of wasted water resources), intensifying the water conflict among food, society, economy and ecosystems and resulting in low sustainability (Fig. 2a). In particular, under the scenarios with low technological advances, this population effect has a more pronounced effect on sustainability (Fig. 2a). However, appropriately increasing technological efficiency (i.e., agricultural water use efficiency) can reduce water stress (Fig. S4a online) and improve sustainability (Fig. 2a) in the context of rapid population growth. This outcome shows that a rapidly growing population is still the major internal factor causing the dilemma that it is difficult to achieve high sustainability in most endorheic regions; nevertheless, improving technological efficiency is an available solution to this dilemma.

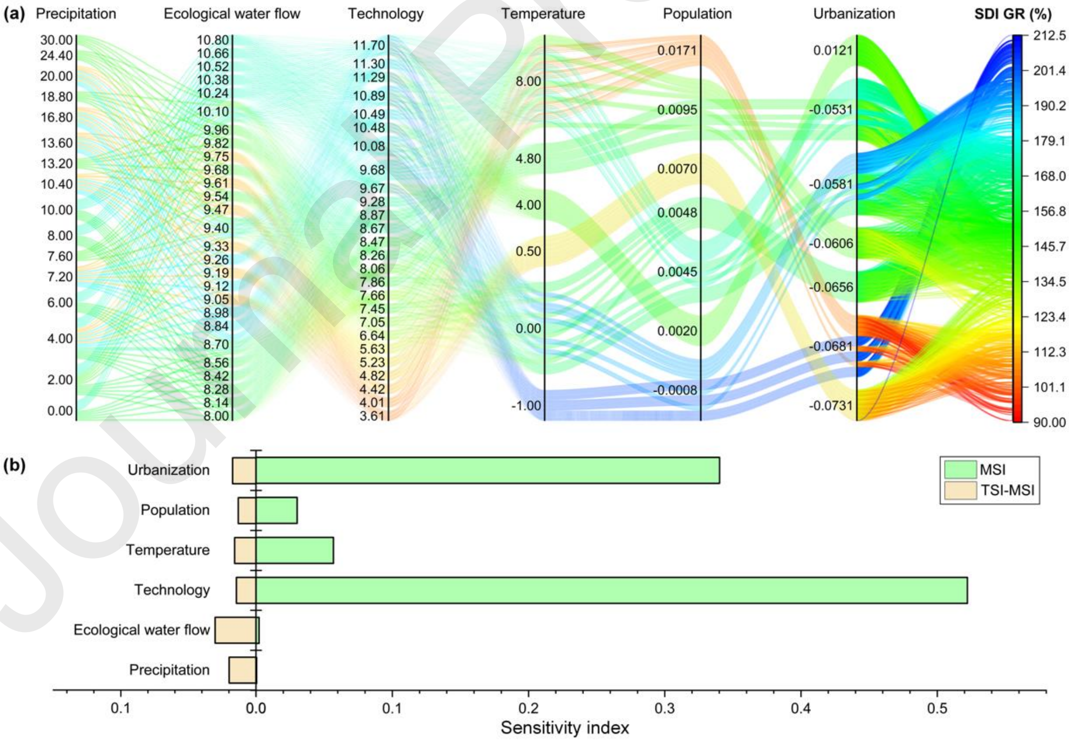

Fig. 2. Parallel set plots of the impacts of six drivers on the sustainable development index under the 2160 projected pathways. (a) The impacts of six driving forces on the sustainable development index growth rate (SDI GR (%)). The six vertical axes from left to right represent six drivers, i.e., precipitation (% (39 a)$^{-1}$), ecological water flow (10^8 m^3 a^{-1}), technology (dimensionless), temperature (℃ (39 a)$^{-1}$), population (dimensionless), and

urbanization (dimensionless). The numbers on the vertical axis represent the strength of the driving forces. Each line is a development pathway under a special combination of driving forces. The color of each line runs through the six drivers and corresponds to the color of the sustainability development index growth rate, where the red line indicates that the combination of the six drivers produces low sustainability, and the blue line indicates that the combination of the six drivers produces high sustainability. Among them, the urbanization progress control parameter ranges between −0.0731 (the highest urbanization progress) and 0.0121 (the lowest urbanization progress). The color bar on the right indicates the growth rate of the sustainable development index. The lines running through different vertical axes are the different pathways. (b) The rank of the importance of the six driving forces quantified by the sensitivity index for sustainability.

Analyzing the driving and telecoupling factors simultaneously is, therefore, essential for understanding endorheic regions’ sustainability; nevertheless, achieving sustainable development goals depends on decoupling the growing economy from the environmental impact. However, as intense as the trade-offs between the economy and the environment might seem, our results indicate that decoupling them is possible under diverse projected pathways by regulating the key driving forces, although the future water demand is high under most scenarios. Regarding the economy, a rapidly increasing economy represented by a growing GDP per employed person (GDP PE) (Fig. S5a online), GDP per capita (GDP PC) (Fig. S5b online), agricultural water productivity (Fig. S5c online), and water productivity (Fig. S5d online) can be achieved in this basin by 2050 across diverse pathways. Regarding the environment, we found that environmental pressures can be mitigated by increasing green cover indices (Fig. S5e online) and forest cover rates (Fig. S5f online) and easing water stress (Fig. S5h online). Notably, these decouplings cannot lead to a reduction in the sustainability of the codevelopment of water, ecosystems and socioeconomic systems (Fig. S5i online).

We find that the forest cover rate can be clearly decoupled from the climbing economy in most pathways, rising to approximately 1.5-fold by 2050 in 50% of the projected pathways in the SSP1 space (Fig. S5f online). This decoupling is essentially achieved through a telecoupling factor (ecological water flow) by building feedback between water allocation and environmental performance over the entire basin. However, the green cover index cannot be decoupled from the rapidly growing economy driven by high technological advances because a rapid decrease in grassland area outstrips the increase in the forest area. In addition, decoupling water stress from the growing economy and mitigating environmental pressure are possible by 2050, thus achieving negative growth. However, this decoupling requires synergies among the appropriate ecological water flow, rational improvement in techniques, and a modest population growth and urbanization progress (Fig. S4a online).

The coaction of both technological advances and ecological water flow on the economy and ecological environment is a major determinant that can strengthen decoupling in the endorheic basin, and ecological water flow can lead to positive spillover effects on economic and environmental-related targets, such as the forest cover rate and water stress (Fig. S5f, h online). Nevertheless, a silo approach focusing on technological advances and ecological water flow alone would strengthen the harmful trade-offs between the economy and the ecological environment (Figs. S5b, f and S4b online). These findings reveal that decoupling the growing economy and the environmental pressure is central to preventing “Aral Sea syndrome” in most endorheic regions and imply that the ecological water flow plays a crucial role in achieving multiple sustainable development goals.

In addition, determining how to transform the ecosystem catastrophe toward sustainability is significant for sustainability science and policy. Regarding water-limited endorheic regions with high urbanization progress and population growth, designing transformation pathways requires the simultaneous implementation of a rapidly improving technological level and a corresponding dynamic regulation of the reallocation of the saved water to ecosystems and human society (particularly demands from population growth). For example, a 3.2-fold improvement in technology, in parallel to a 1.4-fold increase in the ecological water flow, can promote the growth rate of the sustainable development index from 90.0% to 212.5% (Fig. 2a). Although Hardin [14] argued that no technical solution can solve the problem of the tragedy of commons due to overpopulation, we find that appropriate adjustments to technological advances and the ecological water flow can mitigate the negative impacts of moderate population growth rate on sustainability under a changing climate on mid- and long-term scales. For example, the combination of a rising technological level (e.g., from 3.61 to 7.65) and ecological water flow (e.g., from 0.91 to 0.94 billion $m^3 a^{-1}$) increases the growth rate of the sustainable development index from 90% to 123.3% under the scenario of an increase in the population from the lowest level (0.0070) to an above average level (0.0095) (Fig. 2a).

The coregulation of multiple internal driving forces on the economy-environment nexus can promote the decoupling of the growing economy from environmental pressure, which is likely an essential solution to end these environmental tragedies and progress toward the coprosperity of humans and nature. Technological advances can promote economic growth and accelerate the sustainable transformation process, which, nevertheless, requires ecological water flow to avoid the water rebound effect and mitigate environmental pressure. The telecoupling effect of rational ecological water flow across the whole basin can essentially control the trade-offs among the economy, society and environment, which may not only enhance the ability to adapt to warming climates but also lead to sustainability transformation pathways.

In addition, external driving forces such as precipitation and temperature cannot be modified by local technological solutions. We need to steer the internal driving forces to adapt the changing external driving forces. Water saved by technological advances is transferred to not only ecosystems, producing a win–win situation, i.e., avoiding the water efficiency paradox (Fig. S4b online) and mitigating environmental pressure (Fig. S4c online), but also social systems, counteracting the increasing demands from population growth and urbanization. Importantly, we need to identify the tipping point of the ecological water flow according to local technological advances, population growth, urbanization progress and the climatic context in special endorheic regions.

Significantly, achieving sustainability transformation requires addressing the considerable, real challenges involved in determining how scientific findings can be substantially translated into policies and actions and how to implement them. Substantially translating scientific understandings into practical strategies across policy domains covering diverse sectors and strictly executing the committed actions across these reformed policies are essential for transforming the dilemmas (the imbalance between the economy and environment) of many endorheic regions into sustainable pathways (decoupling between the economy and the environment). The implementation of policy actions requires not only enforceability covering all agents (governments, organizations, sectors and individuals), even those whose benefits are impaired, but also overcoming psychological challenges (self-interests) from expectations regarding the rapidly growing GDP and living standards. Individually or collectively free-acting in self-interests is likely to impede policy progress, leading to the tragedy of the commons [15].

Thus, from the perspective of a single driver, technological progress dominates sustainable development in the Heihe River Basin, followed by urbanization, although these drivers sometimes have a negative impact on sustainability [13]; nevertheless, the independent action of the ecological water flow on sustainability plays a weak role in this basin. The quantity of water resources is not a major factor determining the sustainability of the basin. Most negative impacts of water resources on sustainable development are caused by water scarcity resulting from irrational water management rather than the physical scarcity of water. From the perspective of multiple driving forces, ecological water flow has the strongest coaction on sustainability; thus, ecological water flow, technological advances, population and urbanization are key positive determinants of the sustainability of this basin, and in particular, the rational coordination between technological advances and ecological water flow can transform the sustainability of the basin [11].

These outcomes imply that it is possible to reverse the ecological tragedy in endorheic regions toward sustainability. A precondition for achieving this reversion is to decouple the growing economy from environmental pressure, which requires the commodification of four driving forces, i.e., technology, ecological water flow, population and urbanization, across the whole basin, not the silo part. Identifying the tipping points of the four driving forces plays a crucial role in understanding the interactions between economic development and ecological health and helping stakeholders adopt policy action.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Yingchun Ge and Xin Li conceived the study and designed the methodology. Guodong Cheng and Bojie Fu designed the integrated framework and contributed to the interpretation of the results. Yingchun Ge wrote the original draft and performed the model simulation and analysis. Fanglei Zhong and Shengtang Wang processed the SDG indicator data. Xin Li, Jianguo Liu, and Lei Gao reviewed and revised the manuscript. Ling Zhang polished the language of the manuscript. All authors reviewed and edited the manuscript.

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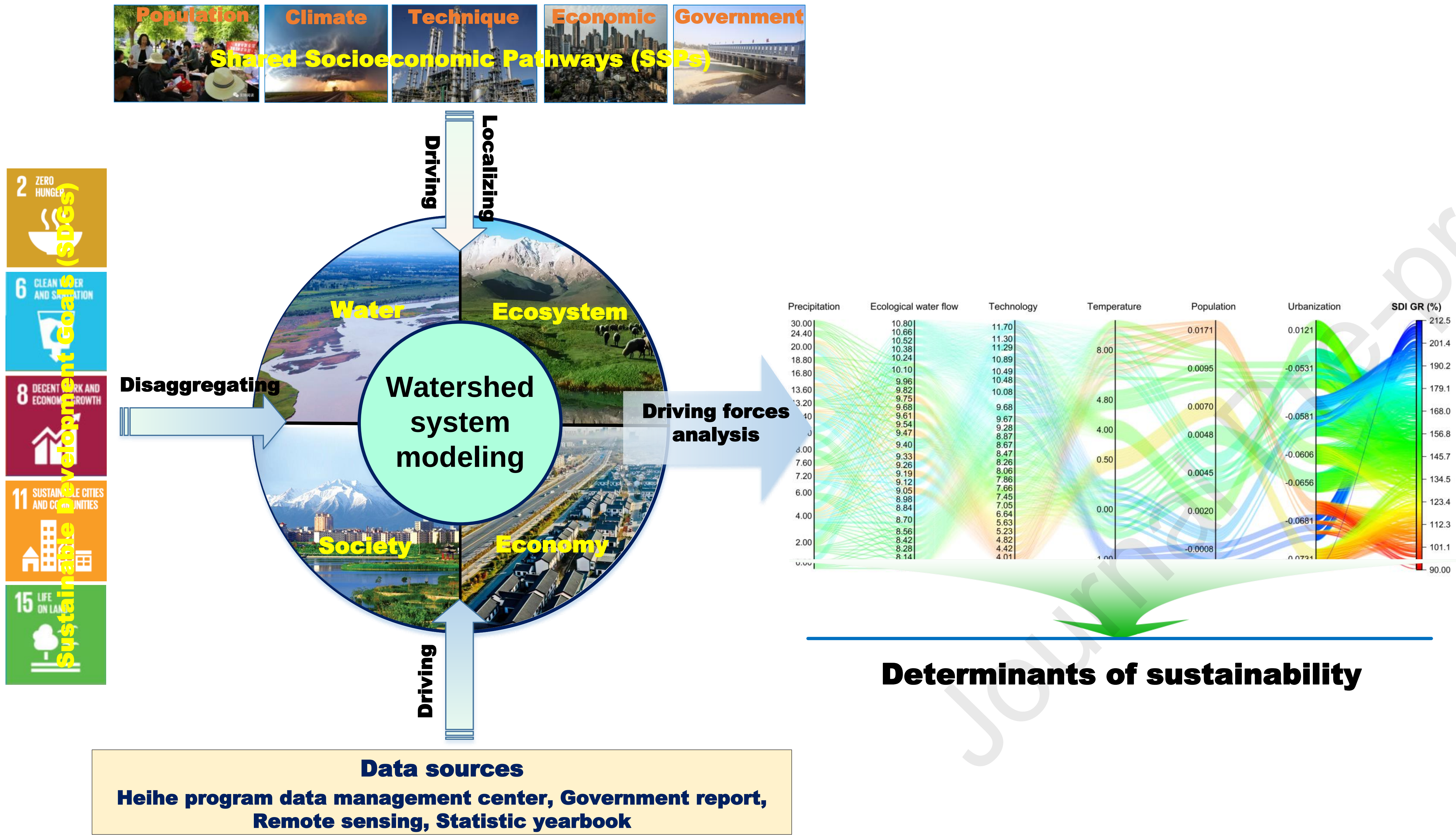
Population
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Technique
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Shared Socioeconomic Pathways (SSPs)
Driving
Localizing
Sustainable Development Goals (SDGs)
2 ZERO HUNGER
6 CLEAN WATER AND SANITATION
8 DECENT WORK AND ECONOMIC GROWTH
11 SUSTAINABLE CITIES AND COMMUNITIES
15 LIFE ON LAND
Disaggregating
Water
Ecosystem
Society
Economy
Watershed system modeling
Driving forces analysis
Driving
Precipitation
Ecological water flow
Technology
Temperature
Population
Urbanization
SDI GR (%)
Determinants of sustainability
Data sources
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