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Co-evolutionary dynamics of the human-environment system in the Heihe River basin in the past 2000 years

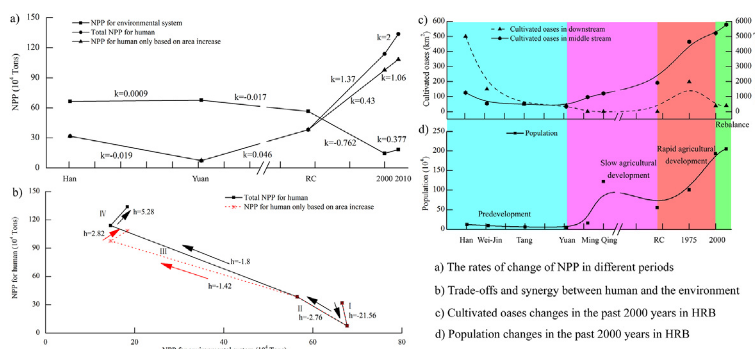
Zhixiang Lu [a], Yongping Wei [b,*], Qi Feng [a], Jiali Xie [c], Honglang Xiao [a], Guodong Cheng [a]

[a] Key Laboratory of Ecohydrology of Inland River Basin, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China
[b] School of Earth and Environmental Sciences, the University of Queensland, Brisbane, Australia
[c] Key Laboratory of Desert and Desertification, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, China

HIGHLIGHTS

- Water and NPP allocation in human and the environment in HRB in past 2000 years
- The trade-offs and synergies between human and the environment in past 2000 years
- Provided a quantitative approach for the co-evolution of human and the environment
- Impacts of human on the environment and their responses to the environmental stress

GRAPHICAL ABSTRACT



a) The rates of change of NPP in different periods
b) Trade-offs and synergy between human and the environment
c) Cultivated oases changes in the past 2000 years in HRB
d) Population changes in the past 2000 years in HRB

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ABSTRACT

There is limited quantitative understanding of interactions between human and environmental systems over the millennial scale. We aim to reveal the co-evolutionary dynamics of the human-environment system in a river basin by simulating the water use and net primary production (NPP) allocation for human and environmental systems over the last 2000 years in Heihe River basin (HRB) in northwest China. We partition the catchment total evapotranspiration (ET) into ET for human and environmental systems with a social-hydrological framework and estimate the NPP for human and environmental systems using the Box-Lieth model, then classify the co-evolutionary processes of the human-environment system into distinct phases using the rate of changes of NPP over time, and discover the trade-offs or synergies relationships between them based on the elasticity of change of the NPP for humans to the change of NPP for environment. The co-evolutionary dynamics of human-environment system in the HRB can be divided into four periods, including: Phase I (Han Dynasty-Yuan Dynasty): predevelopment characterized by nearly no trade-offs between human and environment; Phase II (Yuan Dynasty-RC): slow agricultural development: characterized by a small human win due to small trade-offs between human and environment; Phase III (RC-2000): rapid agricultural development: characterized by a large human win due to large trade-offs between human and environment, and Phase IV (2000—2010): a rebalance characterized by large human wins with a small-environment win due to synergies, although these occurred very occasionally. This study provides a quantitative approach to describe the co-evolution of the human-environment system from the perspective of trade-offs and synergies in the millennial scale for the first time. The relationships between humans and environment changed from trade-off to synergy with the implementation

* Corresponding author.
E-mail address: yongping.wei@uq.edu.au. (Y. Wei).

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of the water reallocation scheme in 2000. These findings improve the understanding of how humans influence environmental systems and responses to environmental stresses.

1. Introduction

The fall of many ancient cities and civilisation along rivers (such as the Sumerian civilisation in Euphrates River basin, the Loulan ancient city in the Tarim River basin and Black City in the Heihe River basin) arose from water shortage and environment destruction (Sivapalan et al., 2012; Lu et al., 2015b). This is because the benefits of water provision to economic productivity are often accompanied by impairment to environment, with potentially serious but unquantified costs (Abell et al., 2008; Vörösmarty et al., 2010). As river basin systems are highly co-evolved complex systems based on long term and complex 'negotiations' between culture and nature, the status quo of a river basin is the consequence of cumulative synergies/trade-offs between human and environmental systems (Angus-Leppan et al., 2010; McShane et al., 2011; Alexandra, 2012). Trade-offs in the form of human choices can be of many kinds and among different sectors that use water, and these could bring about the different levels of disturbance to human and environmental systems in river basins. Understanding the hydrologic system, human system and environmental system and the interactions between them that resulted from trade-offs is a fundamental hydrological research question for sustainable water use and resilient interaction between human and environmental systems.

Research into the dynamic relationship between human, water and environment, especially on a regional or basin scale, has attracted much scholarly attention and considerable progress has been made at the scale of a few decades in recent years (Lu et al., 2016). For example, Liu et al. (2014) qualitatively divided the socio-hydrological systems (SHSs) in the Tarim River basin (TRB) in Western China into four phases: primitive agriculture, traditional agriculture, industrial agriculture and urbanized system. Van Emmerik et al. (2014), Kandasamy et al. (2014) and Zhou et al. (2015) developed socio-hydrologic models to understand the competition for water resources between environmental health and agricultural development in the Murrumbidgee River basin (MRB) in Australia in the past 100 years, using parameters including environmental awareness, reservoir storage, technology and gross basin product. Di Baldassarre et al. (2013, 2015) developed a model on human-flood interactions with a mathematical formalization of relative flood damage, population density, flood protection level and societal memory of floods. While there exists many aspects on selection of variables and model formalization of SHSs to be improved (Liu et al., 2014), we argue that the critical dynamics of SHSs is determined by 'slow' ecological and social variables, and system thresholds determined by the slow variables which, if crossed, causes the system to move into a new state (Norgaard et al., 2009). Some of these slow variables change in a time scale of hundreds of years, thousands of years or even longer. Therefore, the longer-term trade-offs and synergies between the human and environmental systems in river basins should be known. Without such knowledge, we could not understand the long-term complex negotiations between culture and nature.

The human and environmental systems in river basins are linked by water and material flows (Montanari et al., 2013). Water flow connects the human and environment from the hydrological perspective. The water balance, derived from the principle of conservation of mass, has been commonly applied in the partitioning of precipitation into evapotranspiration (ET) and surface runoff for studying hydrological cycles (Lu et al., 2015b; Zhou et al., 2015). Furthermore, the socio-hydrological water balance, expressed as the partitioning of ET in social and ecological systems, can be used to seek a balance of water allocation between societal and ecological systems in SHSs (Zhou et al., 2015). Humans have been increasingly the "winner" in the 'negotiations' between culture and nature since ancient times and this has had a profound effect on modifying the hydrological response of catchments and the water cycle through increasing social water use. Material flow connects human and environment from the ecological perspective in river basins. Net primary production (NPP) refers to the amount of dry organic matter produced by plants per unit time and per unit area, which is a key link in the biogeochemical cycle and a 'slow' ecological variable (Chen et al., 2015; Melillo et al., 1993). NPP is an important ecological indicator for examining the magnitude of human impact on terrestrial ecosystems (Haberl et al., 2007; Ma et al., 2012). Humans can appropriate NPP through both direct and indirect consumption of terrestrial photosynthetic products through agriculture and natural vegetation, otherwise they lose NPP due to other forms of land use changes e.g. urbanization and land degradation (Vitousek et al., 1986; Zhang et al., 2014). Therefore, ET and NPP can be used as critical links between human and environment for understanding the co-evolutionary dynamics of human-environment system in river basins.

The Heihe River basin (HRB), a typical inland watershed, is an ecologically fragile area with an arid climate. However, due to stable runoff from upstream mountains, fertile soil and sufficient annual sunshine duration, the HRB has a long agricultural history dating back nearly 2000 years and is an important part of the ancient Silk Road developed in the Han Dynasty and the Silk Road Economic Belt at present (Huang et al., 2017; Lu et al., 2015b). The evolution of the HRB is a history of the human long-term scramble for water and material flow from environmental systems. As a consequence, a number of water-related environmental challenges have emerged in the HRB in historical periods and have become more severe since the 1950s (for example, degradation of natural vegetation and drying-up of terminal lakes due to too much water consumption in irrigation agriculture) (Cheng et al., 2014; Xiao et al., 2017). The severe deterioration of ecosystems in the downstream areas of the HRB has been greatly alleviated since a water reallocation scheme was successfully implemented by the central government of China in 2000. Therefore, the HRB is an ideal river basin for studying the co-evolution of the human-environment system over the long term.

This paper aims to reveal the co-evolutionary dynamics of human-environment systems in the HRB over the past 2000 years by describing the processes in which humans influence the environmental systems and how they respond to the environmental stress from the perspective of trade-offs and synergies. Specifically, we simulated the feedbacks between the human and environmental systems with changes in ET and NPP of the human and environmental systems.

2. Methods

2.1. Study area

The Heihe River basin (HRB), located in northwest inland China, is one of the most arid regions in the world. If there is water, there is an oasis (a unique intrazonal landscape in arid and semi-arid regions of the world); if there is no water, it becomes desert (Lu et al., 2015b). As the principal water source area of the Heihe River, the Qilian Mountains have a mean annual precipitation varying between 250 and 500 mm. The midstream oases are a part of the Hexi Corridor with mean annual precipitation ranging from 100 to 250 mm. The lower reaches are located on the Inner Mongolian Plateau where the mean annual precipitation is less than 50 mm (Qin et al., 2010). The HRB is an important area for grain and vegetable production in China and is a