Agricultural Water Management 152 (2015) 233–242

Contents lists available at ScienceDirect

Agricultural Water Management

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

Trade-offs between midstream agricultural production and downstream ecological sustainability in the Heihe River basin in the past half century

Zhixiang Lu[a,b], Yongping Wei[c], Honglang Xiao[a], Songbing Zou[a,*], Juan Ren[a], Clive Lyle[d]

[a] Key Laboratory of Ecohydrology of Inland River Basin, Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou 730000, China
[b] University of Chinese Academy of Science, Beijing 100049, China
[c] Australia China Joint Research Centre on River Basin management, The University of Melbourne, Parkville 3010, Australia
[d] Department of Infrastructure Engineering, the University of Melbourne, Parkville 3010, Australia

ARTICLE INFO

Article history:
Received 2 April 2014
Accepted 26 January 2015
Available online 11 February 2015

Keywords:
Heihe River basin
Top–down hydrological model
Trade-off
Ecological degradation
Integrated river basin management
Water productivity

ABSTRACT

There is a knowledge gap and limited tools to readily identify trade-off relationships between competing economic and environmental goals, and between the upstream and downstream areas, of river basins. In this paper we aim to construct the trade-off relationship between midstream agricultural development and downstream ecosystem sustainability at the basin scale, using the Heihe River basin as an example. An improved top–down method was developed to understand the impacts of land use change on catchment hydrology. Based on this, trade-off relationships between cereal production in the midstream area and the runoff flowing downstream, and between cereal production in the midstream area and ecosystem service values in the downstream area, were constructed. The results showed that from 1960 to 2000 every 1000 t of increased cereal production in the midstream area (Zhangye catchment) was at the expense of 0.52 million m^3 of runoff flowing to downstream and $0.052 million of ecosystem service values in the downstream area (Ejina oasis). The analysis also showed that water productivity increased six-fold in the recent study period which greatly offset the trade-off impacts on downstream ecosystem sustainability. Linking conventional trade-off analysis involving competing economic and environmental goals to a simplified hydrological model and remote sensing image analysis to determine land use is a useful tool for integrated river basin management and will enable more transparent, informed, and inclusive water governance.

1. Introduction

In the past half century agricultural development has greatly increased global food supply but often with detrimental effects on the environment (Tilman et al., 2002; Wei et al., 2010). Agricultural production through changes in land use and irrigation in the upstream reaches of a river basin can substantially modify the catchment hydrological cycle and have negative impacts on economic development and ecosystem sustainability in lower reaches of river basins (De Fraiture et al., 2010; Qi and Luo, 2006; Zhou and Yang, 2006). Downstream systems are particularly susceptible to changes in upstream catchment management in arid regions where water is the most limiting factor of ecosystems and economic development. Identification of trade-off relationships between competing economic and environmental goals in river basins is important for integrated river basin management and sustainability (De Fraiture et al., 2010; Kalbus et al., 2012; Teutsch and Krüger, 2011; World Water Assessment Programme, 2009).

River basins are semi-closed ecological and economic systems that represent logical management units of the water cycle, through which all decisions and actions on land and water management have ecological, social and economic implications. Land and water use are inextricably entwined in river basins. Hydrological processes that transfer net precipitation to river flow and groundwater recharge vary with topography, soil, vegetation, hydrogeological and rainfall characteristics. Changes in land use exert a primary influence on fluxes of water at the catchment scale. Land use change impacts are manifested through modified moisture convection and heat, changes in albedo, net radiation, and evaporation/transpiration, leading to altered circulation and convection,

* Corresponding author. Tel.: +86 9314967144; fax: +86 9318273894.
E-mail address: zousongbing@lzb.ac.cn (S. Zou).

http://dx.doi.org/10.1016/j.agwat.2015.01.022
0378-3774/

and thus modification of the catchment water cycle. Identification of the trade-off relationships between competing economic and environmental goals in the upper stream and downstream reaches of a river basin is often not a simple exercise, and requires understanding of the dynamic interactions between land use, hydrologic water cycle, ecosystem sustainability and economical development at basin scale.

There has been much attention in the literature on how to deal with the consequences of upstream agricultural production on downstream river ecosystems at river basin scale. Numerous studies have been made from the disciplines of catchment eco-hydrology on understanding links between hydrologic processes and vegetation dynamics at catchment scale in order to improve the simulation of catchment runoff (Tang et al., 2011; Ford and Quiring, 2013; Tesemma et al., 2014). An increasing number of studies on ecological-economic models have constructed trade-off analyses between economic development and ecological conservation, or among ecosystem services, from either conceptual or empirical perspectives (Bostian and Herlihy, 2014; Gordon et al., 2010; Hussain and Tschirhart, 2013; Johnson et al., 2012; Lester et al., 2013; Pan et al., 2014; Xu et al., 2003; Yang and Yang, 2014; Zang et al., 2012). Few studies have coupled these two above-mentioned research purposes. The trade-off analysis at river basin scale without integration with hydrological analysis would not be able to assess if this trade-off is possible from the hydrological perspective, if it is, where it should be done to improve the trade-off efficiency. This paper aims to fill this knowledge gap.

Integrated river basin management (IRBM) has been promoted by both academics and practitioners as a mainstream water management strategy in the last two decades (Pahl-Wostl and Hare, 2004). IRBM is the "*the process of coordinating conservation, management and development of water, land and related resources across sectors within a given river basin, in order to maximise the economic and social benefits derived from water resources in an equitable manner while preserving and, where necessary, restoring freshwater ecosystems*" (Biswas, 2004). Despite of its popularity the definition of IRBM continues to be broad and vague, and its theoretical framework underpinning, e.g. how water and land should be integrated in river basins, is far from a practical guide for its application (Biswas, 2004; Hering and Ingold, 2012). This paper aims to support integrated land and water decision making at river basin scale by linking trade-off analysis between agricultural development and ecosystem sustainability with catchment hydrological analysis, and thus promote evidence-based river basin management (Avila-Foucat et al., 2009; Parker and Munroe, 2007).

The Heihe River basin (HRB), northwest inland China, is one of the most arid regions in the world (Zhou and Yang, 2006). The region is characterized by alternating bands of relatively humid mountains and arid plains. The mountainous areas receive precipitation, snowmelt and glacial melt so the upstream areas are the sources of river water flow. The mid- and down-stream areas of the HRB, where precipitation is scarce, are water consumption areas. The runoff from the upper reaches generates almost all of the water resources available to support social and economic developments and maintain the ecosystems for the entire basin (Guo et al., 2009; Kang et al., 2007).

There has been increasing competition for water between midstream agricultural development and downstream ecological purposes in HRB since the 1980s (Fig. 1). With consumption of water increasing dramatically because of rapid economic development in midstream areas, the terminal lakes dry out, *Populus euphratica* forests die, and sandstorms become more common in downstream areas (Wang et al., 2011; Xi et al., 2010). In order to restore ecosystems in the downstream areas a water reallocation scheme was implemented in 2000 by which the midstream area should discharge 950 million m^3 of water in normal years, as measured at the Zhengyixia Hydrological Station (ZYX) to downstream areas when the upstream Yingluoxia Hydrological Station (YLX) discharges 1580 million m^3 of water (Li and Zhao, 2004). This resulted in some improvements to downstream ecosystems, such as halting ecological and environment deterioration and restoring the rippling scene of lakes (Lu et al., 2006). The HRB is a compelling case study area for an empirical analysis of the trade-off relationships between competing economic and environmental goals at basin scale.

The overarching goal of this paper is to reveal the trade-off relationships between agricultural development and ecosystem sustainability in the HRB over the past half century. The specific objectives are: (1) to investigate the effects of the expansion of cultivated land in the midstream area on the hydrology; (2) to evaluate impacts of the change of midstream hydrology on downstream ecosystems; (3) to develop and test an efficient approach for undertaking trade-off studies in river basins, and, (4) to construct a trade-off relationship between the midstream agricultural development and downstream ecosystem sustainability.

2. Methods

2.1. Case study area

The HRB covers approximately 130,000 km^2 (Fig. 1), and includes (from south to north) the Qilian Mountains, the middle Hexi Corridor and the northern Alxa high-plain, as well as three different climatic zones: the cold and humid or semi-arid mountain zone, the midstream temperate zone and the downstream warm temperate zone (Qi and Luo, 2006). Starting from YLX, the Heihe River flows northward into Zhangye catchment, and then north-westerly through areas experiencing large-scale and complex surface water-groundwater interaction, and finally flows out of the Zhangye catchment at ZYX into the downstream area.

The Zhangye catchment is located in the midstream area of the HRB and has a total area of 10,700 km^2 (Fig. 1), constituting Ganzhou district, Linze county and Gaotai county of Zhangye city. Elevations in the catchment range from 1250 to 3619 m above sea level, but 93.6% of the area is lower than 2000 m, and 92.2% of the area has slopes of less than 5°. The mean annual precipitation ranges from 62 to 156 mm and annual evaporation up to 1000–2000 mm. Zhangye catchment is a highly developed irrigation district in the HRB with an agricultural history dating back nearly 2000 years. The past half century has witnessed the most rapid period of agricultural development in the catchment and the surface water resources showed a high level of utilization at 82% (Wang et al., 2007). In Zhangye catchment, the agricultural, industrial, domestic and ecological water uses account for 87%, 3%, 2% and 8% of the total water resource, respectively, since 2000 (Li et al., 2009). The area of cultivated land expanded continually and increased by 49% from 1965 to 2010 (Fig. 1). The main cropping system is intercropping of spring wheat and summer maize with high yields, but with relatively high water consumption when cultivated in the traditional way. 88% of the HRB population live, and 88% of the GDP of the HRB, is produced in the Zhangye catchment (Zhou and Yang, 2006).

Ejina oasis, consisting mostly of cultivated land, forest, grassland, built-up land, and water or wetland, is located in the downstream part of the HRB, which is an extremely arid region with high evaporation and annual precipitation of less than 50 mm. The ecosystems in Ejina oasis depend on groundwater, which mainly comes from the river water infiltration controlled by the discharge at ZYX, the outlet of Zhangye catchment (Zhang and Shi, 2002).