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Economic compensation standard for irrigation processes to safeguard environmental flows in the Yellow River Estuary, China

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SUMMARY

Agriculture and ecosystems are increasingly competing for water. We propose an approach to assess the economic compensation standard required to release water from agricultural use to ecosystems while taking into account seasonal variability in river flow. First, we defined agricultural water shortage as the difference in water volume between agricultural demands and actual supply after maintaining environmental flows for ecosystems. Second, we developed a production loss model to establish the relationship between production losses and agricultural water shortages in view of seasonal variation in river discharge. Finally, we estimated the appropriate economic compensation for different irrigation stakeholders based on crop prices and production losses. A case study in the Yellow River Estuary, China, demonstrated that relatively stable economic compensation for irrigation processes can be defined based on the developed model, taking into account seasonal variations in river discharge and different levels of environmental flow. Annual economic compensation is not directly related to annual water shortage because of the temporal variability in river flow rate and environmental flow. Crops that have stable planting areas to guarantee food security should be selected as indicator crops in economic compensation assessments in the important grain production zone. Economic compensation may be implemented by creating funds to update water-saving measures in agricultural facilities.

1. Introduction

Large amounts of water are diverted for agricultural irrigation and other human activities in many river basins worldwide (Malano and Davidson, 2009). According to Calzadilla et al. (2010), approximately 70% of natural water resources are diverted annually from global river systems to supply agricultural irrigation. Some rivers are subjected to such high extraction rates that the water cannot reach the sea (Cai, 2004). The continued decline in water availability has a disproportionate impact on freshwater habitats, particularly riparian floodplains, wetlands, and estuaries (Arthington et al., 2006). As populations grow worldwide, we will become even more dependent on irrigation processes to ensure sufficient food supplies. Conflicting demands between water extracted for irrigation and water required to meet environmental needs become a key issue in sustainable ecological protection and socioeconomic development (Dunn et al., 2003; Vogel et al., 2007; Malano and Davidson, 2009), particularly in arid and semi-arid regions.

Environmental flow assessments, which define the amount of water needed in a given ecosystem, have become an important tool in ecosystem restoration, water resource management, and reservoir management (Richter et al., 1997; Arthington et al., 2006; Sun et al., 2008; McCartney et al., 2009; Poff et al., 2009). In general, methods for designing environmental flows with a primary objective of ecosystem protection have been divided into four groups: hydrological, hydraulic, habitat, and holistic methods (Tharme, 2003; Alcázar et al., 2008). However, water use stakeholders, such as those involved in agriculture, often have difficulty accepting water requirements for ecosystems defined on the basis of ecological objectives because of possible economic loss caused by the satisfaction of environmental flows under limited water resource conditions. Achieving a socioeconomically and ecologically healthy consensus becomes more important in sustainable water resource management under the condition of temporal variations in river flow and regional differences in economic development.

In general, economic compensation is considered to be an effective method of achieving both environmental goals and economic development. Such compensation is usually assessed based on the values of ecosystem services (Acharya, 2000; Woodward and Wui, 2001; Farber et al., 2002). Costanza et al. (1997) estimated the value of services per hectare for an ecosystem type from specific locations and applied these estimates to value all hectares of that ecosystem type across all regions. The value of ecosystem services has been argued to be related to factors such as the rarity of habitat, spatial configuration, and economic development in the surrounding region (Tallis and Polasky, 2009). Ecosystem service values also differ due to spatial heterogeneity in ecosystem

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functions. Moreover, the subjective nature of ecosystem services and weak linkages among them complicate their assessment. The diversity of ecosystem services, including temporal and spatial variability, limits the broad application of ecosystem service values in economic compensation assessments.

Recently, targeted approaches have focused on the implementation of water "buy-back" measures to transfer water more efficiently from agricultural use to ecosystems (CSIRO, 2009). With temporal variation in river flow and biological processes, outcomes of water allocation between agricultural processes and ecosystems may also be affected by temporal variations in flow regime (Khan et al., 2009; Vandenbohede et al., 2010). Attempts to quantify agricultural losses related to ecosystem protections have focused mainly on assessing the outcomes of water allocation plans under alternative agricultural and environmental policy scenarios (Mainuddin et al., 2007), or on analyzing differences in yield losses among crops (Sisto, 2009).

Our objective in this study was to develop an economic compensation assessment model to establish an economic compensation standard by taking into consideration agricultural losses resulting from the maintenance of environmental flows for ecosystems, using the Shandong irrigation district and the Yellow River Estuary, China, as a case study. The influences of variability in river flow rates on the economic compensation standard were also fully considered. This objective was achieved through: (1) the construction of an agricultural water shortage model that incorporated different levels of river and environmental flows, (2) the development of a production loss model to correlate production losses and water shortages for different crops, and (3) the calculation of the required economic compensation for irrigation stakeholders. Variations in agricultural water shortages and economic compensation under different scenarios were analyzed. Management suggestions are proposed for water resource use to balance the needs of agricultural processes and ecosystems.

2. Methods

2.1. Economic compensation assessment framework

We developed an economic compensation assessment model to determine the appropriate amount of economic compensation for the maintenance of environmental flow requirements to ensure ecosystem health (Fig. 1). Within this framework, a water balance analysis was first conducted to examine agricultural water usage and initial environmental flow allocations under the condition of temporal variations in hydrological processes. Next, production losses as a function of water use and allocation under specific environmental flows were determined. Finally, the amount of economic compensation for irrigators is recommended on the basis of economic losses.

2.2. Sub-models in the economic compensation assessment model

2.2.1. Agricultural water shortage model

With limited water resources in river basins, water use conflicts usually arise when the amount of water needed for human activities disrupts the natural flow regime required for ecosystem health. To ultimately determine the economic losses that could result from environmental flows designed to protect ecosystem health, the shortage of water in the agricultural sector that would occur when water previously used for irrigation is diverted back to maintain ecosystem health must be calculated. Agricultural water shortage can be calculated as the difference in water volume between agricultural demands and actual supply after maintaining environmental flows for ecosystems:

$$W_s^i = \begin{cases} (1-\mu)W_a^i - W_0^i & (1-\mu)W_a^i > W_0^i \\ 0 & (1-\mu)W_a^i \leqslant W_0^i \end{cases}, \quad (1)$$

where W_s^i is the agricultural water shortage, W_a^i is agricultural water demand in the irrigation district, and W_0^i is agricultural water usage after deducting downstream commitments for environmental flows, all in month i (m^3); μ is a dimensionless water-saving coefficient.

The agricultural water demand W_a^i can be determined according to water consumption and evapotranspiration in the irrigated area:

$$W_a^i = ET_m^i S, \quad (2)$$

where S is the planting area (ha) and ET_m^i is actual evapotranspiration (mm), which can be estimated using the following relationship (Khan et al., 2009):

$$ET_m^i = k_c^i ET_0^i, \quad (3)$$

where ET_0^i is the evapotranspiration (mm) of the reference crop and k_c^i is a dimensionless crop coefficient.

Agricultural water usage (W_0^i) can be calculated using the water balance principle. The water sources (river discharge, groundwater, precipitation, water transfer projects) and water utilization (domestic and industrial water use, agricultural water demand, and environmental flow requirements) include various factors required for the economic compensation assessment model:

$$W_0^i = W_u^i + W_p^i + W_g^i - W_d^i - W_f^i - W_e^i \pm W_t^i, \quad (4)$$

where W_u^i is the river discharge, W_p^i is precipitation, W_g^i is water supply depleted from groundwater, W_d^i is amount of domestic water used, W_f^i is amount of water used for industrial purposes, W_e^i is initial environmental flow that satisfies ecological objectives, all in month i (m^3); and W_t^i is the amount of water transferred outside or inside the watershed.

The environmental flow W_e^i is usually determined based on typical ecological objectives for ecosystem protections. Sun et al. (2008) developed a method for quantifying environmental flows in estuaries, while integrating multiple ecological objectives:

$$W_e = \sum_{i=1}^{n} W_i + \mathrm{MAX}(W_{j1}, W_{j2}, \ldots, W_{jm}), \quad (5)$$

where W_e is the environmental flows for the estuary (m^3), MAX(a, b) denotes the maximum of variables a and b, W_i is consumptive water volume (m^3), W_j is non-consumptive water volume (m^3), and n and m indicate the number of objectives of consumptive and non-consumptive water volumes, respectively. The rule of summation is used to calculate consumptive water requirements, and the rule of compatibility (i.e., maximum principle) is adopted to estimate non-consumptive requirements.

2.2.2. Production loss model

Production losses may occur when water is diverted from the agricultural sector to maintain ecosystem health. In general, the D-K model (Doorenbos and Kassam, 1979) is used to evaluate crop yield losses with respect to the relative evapotranspiration deficit at different growth stages:

$$\frac{q_m - q_a}{q_m} = k_y^i \frac{ET_m^i - ET_a^i}{ET_m^i}, \quad (6)$$

where q_m is the maximum crop yield (kg/ha), q_a is actual crop yield (kg/ha), ET_a^i is actual evapotranspiration in month i (mm), and k_y^i is a dimensionless crop yield response factor in month i.

To establish the relationship between production losses and agricultural water shortages after maintaining environmental