Can payments for ecosystem services secure the water tower of Tibet?

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Abstract

Tibet can be considered as the water tower of Asia and the protection of its water resources crucial. We show that a minimum data approach to model the supply of ecosystem services can potentially be applied to water conservation in Tibet. The approach integrates the spatial heterogeneity of the biophysical environment and the economic behaviour of farmers. A spatially distributed hydrological model is used to simulate the effect of irrigation on evapotranspiration reduction and stream flow enhancement in a Tibetan agricultural catchment. The results feed into an economic model that estimates the supply curve of conserved water from the distribution of net returns between irrigated and rain-fed barley cultivation. The analysis shows that it is theoretically possible to increase discharge out of the catchment in the critical months April–June by 11% on average. Accumulated over larger areas this could provide a significant increase in total upper Brahmaputra discharge. The methodology appears to be a transparent and cost effective tool to quantify the effect of financial incentives in the conservation of water resources. Policy relevant information can be generated without the need to conduct expensive field surveys and to set up more elaborate econometric simulation models. Given the anticipated effects of climate change the potential of payments for ecosystem services to conserve water may become increasingly more important in sustaining stream flow early in the growing season.

1. Introduction

The Tibetan plateau (TP) is often considered to be the water tower of Asia being the source of many major Asian rivers such as the Mekong, Yangtze, Brahmaputra, Indus and the Karnali. These rivers support hundreds of millions of people downstream. Since Asia is monsoon-dominated with precipitation concentrated in just a few months, the perennial flow of the rivers largely relies on the constant flux of the glaciers in Tibet. As the pressure on Tibet’s water resources is mounting because of rapid economic development, its conservation becomes ever more important. Population growth, increased incomes and urbanization have joined forces and agriculture cannot keep up with the increasing demands of this emerging, new society (Ecoregional Fund, 2005). Yields are restricted by a short growing season, large diurnal temperature ranges and above all a shortage of water. Annual precipitation is only 600 mm and is concentrated in the monsoon months July and August (Immerzeel et al., 2005). The proportion of arable land is only 0.3% of the total land area and more than 60% of this land is arid and has a low productivity. Gaps between actual and potential yields of the main crops barley and wheat are very large and this is caused by a poorly developed irrigation infrastructure (Tashi et al., 2002). To sustain the increased demand for more and diverse agricultural products it is inevitable that the acreage of irrigated area will increase over the years (Immerzeel, 2005).

Climate change is another major threat to the future of Tibet’s water resources. Widespread accelerated glacier
retreat and shifts in stream flow timing, from spring to winter, are likely to be associated with climate change (IPCC, 2001). There are serious concerns about the alarming rate of retreat of Himalayan glaciers. It has been predicted that the coverage of glaciers in western China, accounting for up to 70% of the Himalayan glaciers, will decrease by 27% by 2050 (Qin, 2002). In the short run the glacier melt may increase water availability, but eventually the base flow from glaciers will cease (Barnett et al., 2005). Changes in timing and available volume of water available for irrigation will threaten agricultural productivity (IPCC, 2001) and will impact heavily upon the economy of the region (Matthews et al., 1995).

Tibet supplies an important ecosystem service in the form of fresh water to a large part of Asia. During the monsoon months the water supplied by the TP is a negligible fraction of the total river flows. However, at the end of the winter and in early spring, glacial melt from the TP is the major water source for agriculture in the downstream agricultural areas of India, Bangladesh and China during a crucial period of the growing season (Barnett et al., 2005).

The increased demand for agricultural production in Tibet, the expected climate change and the need to sustain the water supply to downstream areas challenges policy makers to make the most appropriate trade-offs between agriculture and the environment.

Globally there has been a shift from traditional subsidy and trade policies to policies that provide farmers with incentives to increase the supply of ecosystem services from agriculture. This is being referred to as payments for ecosystem services (PES). PES is emerging as a new approach to managing the valuable services derived from ecosystems. The Millennium Ecosystem Assessment (2005) describes fresh water as one of the critical provisioning services that ecosystems provide. Protection of the New York City watershed is often cited as one of the earliest uses of the concept of payments for ecosystem services, a plan implemented in 1997 (World Resources Institute, 2000). Since then, there has been an increasing number of efforts to protect water quantity and quality by paying land owners to use practices that protect water resources, mostly through forest protection and re-forestation (FAO, in press). In water conservation policies the focus has been primarily on the development of water pricing instruments (Dinar, 2000). The concept of payments for ecosystem services applied in this study can be interpreted as a way to implement an efficient water pricing policy wherein farmers are assigned the initial rights to use irrigation water and downstream users (or governments) pay farmers to reduce water use. The analysis presented here combines analysis of biophysical potential for water conservation, which, together with economic analysis of farmers’ willingness to change management practices, simulates a water supply curve to downstream users. This water supply curve can be used by policy decision makers to assess how much water farmers are willing to supply at a given price per unit of water. Combined with an assessment of how much water is worth to downstream water users, an efficient water policy can then be implemented.

Recently a number of researchers have utilized site-specific data and models to assess the potential for ecosystem service payments (Pautsch et al., 2001; Antle et al., 2003; Wu et al., 2004; Lubowski et al., 2005). These studies utilize highly detailed data such as the National Resources Inventory in the United States or specialized longitudinal farm surveys. However, in most cases neither time nor resources are available to collect such detailed data. In this paper we show how a less data-intensive “minimum data” economic model can be used in combination with a hydrological and production model to assess whether it would be technically and economically feasible to pay farmers to reduce water consumption by changing from irrigated to rain-fed crop production and thus secure the water tower of Tibet.

2. Materials and methods

2.1. Study area

The elevation of the TP ranges from 400 m above sea level (m.a.s.l.) to the summit of Mt. Everest (8848 m.a.s.l) with an average altitude of over 4000 m. The TP covers an area of 1.2 million km². This paper focuses on a sub-catchment located between 27.47–29.33°N and between 88.51–90.20°E in the central southern part of the Tibetan plateau within the province of Ü-Tsang. This province has developed as Tibet’s cultural and political heartland and is commonly known as the grain bowl of Tibet. This is mainly caused by the fact that Ü-Tsang provides broad U-shaped valleys for agriculture below the upper limit of cultivation of approximately 4500 m.a.s.l. (Ryavec, 2001). The Nyangchu River drains the catchment, with a total contributing area of 14271 km² into the Yarlung Tsampo River, which is further downstream more commonly known as the Brahmaputra River as it descends down into India and Bangladesh. The catchment is located in Shigatse prefecture and overlaps with the Shigatse, Gyantse and Panam counties. Shigatse, which is the second largest city of Tibet, is located at the confluence of the Nyangchu and the Yarlung Tsampo rivers. Further upstream the Nyangchu River traverses the third largest town Gyantse. The altitude in the catchment ranges from 3827 to 6989 m.a.s.l with an average altitude of 4737 m.a.s.l. Irrigated agriculture is found below 4500 m.a.s.l. and 37134 ha. of the catchment (2.6%) is classified as irrigated cropland. The main crop is spring barley, which has been Tibet’s staple food crop for centuries. Over 80% of the catchment consists of extensive grasslands used for yak herding. The remainder of the catchment is comprised of bare soils at extreme altitudes (14.7%), urban areas (0.1%) and a number of large lakes (2.4%). The catchment receives on average 560 mm of precipitation annually with more than 70% of the annual rainfall concentrated in the months June, July, August and September. Annual potential evapotranspiration is relatively high and varies around
1500 mm due to low relative humidity, high solar radiation, and high wind speeds on the plains. Temperatures are lowest in January and highest in July with average temperatures of −8.3°C and 8.9°C, respectively, with extremely large diurnal ranges and spatial variation due to the high (variation in) altitude. Soils in the catchment are of sandy texture (50% sand) with a depth generally less than 0.65 m, except for the agricultural areas in the valleys where soil depths reach 1.5 m.

2.2. SWAT

The physically based distributed hydrological model Soil and Water Assessment Tool (SWAT) is used to simulate the hydrological processes as well as the crop growth in the catchment. SWAT represents all the components of the hydrological cycle including rainfall, snow, interception storage, surface runoff, soil storage, infiltration, evaporation, transpiration, lateral flow, percolation, pond and reservoir water balances, shallow and deep aquifers and channel routing. It also includes land use management such as irrigation, fertilization and tillage. The model is comprehensively described in the literature (Arnold et al., 1998; Srinivasan et al., 1998).

SWAT simulates crop growth on the basis of daily temperature sum and water availability. For each day of simulation, potential plant growth, i.e. plant growth under ideal growing conditions (adequate water and nutrient supply) is calculated according to Monteith (1977). First the photosynthetically active radiation, is computed from intercepted solar radiation as a function of Leaf Area Index (LAI). The radiation use efficiency (RUE), defined as the amount of dry biomass produced per unit intercepted solar radiation; is used to calculate the maximum daily plant growth. The RUE is essentially a function of carbon dioxide concentrations and vapour pressure deficits. Actual plant growth is then calculated and inhibited by temperature, water, and nutrient stress. The crop yield is computed therefore, first averaged per sub-basin and then converted to daily values using the inbuilt weather generator.

To avoid water stress irrigation water is applied automatically based on a specified water stress criterion. Water stress is 0.0 under optimal water conditions and approaches 1.0 as the soil water conditions vary from the optimal. Water stress is simulated according to:

\[ w_{wstr} = 1 - \frac{E_t}{E_t} = 1 - \frac{E_{act}}{E_t} \]

where \( w_{wstr} \) is the water stress for a given day, \( E_t \) is the potential plant transpiration on a given day (mm H2O), \( E_{act} \) is the actual amount of transpiration on a given day (mm H2O) and \( w_{actualup} \) is the total plant water uptake for the day (mm H2O).

The catchment is partitioned into a number of sub-watersheds or sub-basins. The sub-basin delineation is performed on the basis of the catchments’ topographic features derived from a 90 m resolution digital elevation model (DEM) acquired with the Shuttle Radar Topography Mission (SRTM) (Werner, 2001). The sub-basins (78) are further subdivided into hydrological response units (HRUs), which are unique combinations of soil and land use. A detailed land use map, based on aerial photograph interpretation, is provided by the Tibetan Bureau of Meteorology. This land use map was reclassified to land uses in the SWAT database. Soil variation is derived from the FAO soil map of the world with some local adaptations (FAO, 1995). By overlaying the sub-basins with the reclassified land use and soil map a total of 181 HRUs are delineated. The HRU is the smallest unit of calculation for the land phase of the model. Each sub-basin is linked to a single reach and all HRUs in a sub-basin drain their water into that reach by surface runoff, drainage and ground water flow. Subsequently the water is routed through the catchment from upstream to downstream. Water used for irrigation is extracted from the surface water and applied to the respective HRUs.

Monthly data on precipitation, temperature and relative humidity are extracted from the CRU TS 2.1 database (Mitchell and Jones, 2005). The CRU TS 2.1 is a set of monthly climate grids which are constructed for nine climate variables and interpolated onto a 0.5° grid and provide best estimates of month-by-month variations. Data from the Tibetan Bureau of Meteorology for Shigatse from 1971 to 1998 are used to scale the temperature and precipitation data to the local situation. Monthly cloud cover and wind speeds are derived from the IWMI climate atlas (New et al., 2002). The SWAT model is run for 20 years from 1983 to 2002. The most detailed spatial level on which meteorological data can be defined in SWAT is at sub-basin level. The monthly climate data derived from the CRU TS 2.1 database and the IWMI climate atlas are, therefore, first averaged per sub-basin and then converted to daily values using the inbuilt weather generator.

Spring barley is cultivated on all HRUs classified as irrigated agriculture. The spring barley is planted on April 15 and harvested on October 1 making full use of the short summer and monsoon rains. A total of 24 HRUs are cultivated with barley ranging in area from 108 ha to 3080 ha, with an average area of 1547 ha. The barley is fertilized with 300 kg/ha of urea in April and August. Two practices are simulated: (a) irrigated barley using auto-irrigation with a water stress criterion of 0.95., and (b) rain-fed barley. The SWAT model is used to determine how reductions in the use of irrigation water reduce crop transpiration and how this eventually affects discharge out of the catchment. For both practices the 20 year average crop yield as well average annual crop evapotranspiration reduction of each HRU are input to the MD model which simulates the water supply curve based on economic features of each scenario.

SWAT simulates the 20 year period with a daily time step, but the output is stored on a monthly basis. Monthly water balances are stored at sub-basin, HRU and reach level, while biomass, crop yields, water and nutrient stress are stored at HRU level with a monthly time step. The
monthly data at HRU level are input to the economic model. For a detailed overview of SWAT outputs reference is made to Arnold et al. (1998).

There are no hydrological data available for the catchment to validate the results of SWAT. In Tibet scientific research in this field is in its infancy, caused by the remoteness of the terrain and Tibet’s status as an outlying region, remote from the centre of power, and its limited capacity for local research (Bouma et al., 2007). It is stressed that this study is exploratory in nature and the major objective is to show whether PES could potentially work to conserve water. However, to be able to validate the results on their plausibility we have used two sources of information.

Firstly, stream flow data of the nearest gauge in the Brahmaputra River at Yangcun (29.28°N, 91.88°E) extracted from a database compiled by the global runoff data centre (Fekete et al., 2000) were analyzed and compared with the simulated average monthly discharge in the catchment. The monthly average evapotranspiration has been converted to actual evapotranspiration rates for the catchment. The monthly average evapotranspiration has been compared with the simulated evapotranspiration for the entire simulation period.

2.3. MD model for analysis of ecosystem service supply

To implement the economic analysis, we use the minimum-data (MD) approach developed by Antle and Valdivia (2006) to model the supply of ecosystem services from agriculture. Whereas other studies of agriculture–environment processes have used highly complex, data-intensive models (e.g., Antle et al., 2003; Wu et al., 2004), the MD approach exploits the structure of the PES problem to obtain an approximation to the ecosystem service supply curve using relatively simple secondary data. The MD model assumes farmers take land use and management decisions to maximize their perceived economic well being. When the farmers are not provided with any incentives there is an initial equilibrium supply of ecosystem service. This provision of this ecosystem service is driven by the farmer’s economic motivation and ignores the demand for that ecosystem service, e.g. other downstream water users. To increase the supply of water above this initial equilibrium the downstream demanders must provide the farmers with financial incentives stimulating farmers to change their land use management. For each barley HRU in the catchment we consider the two practices a, i.e. irrigation, and b, i.e. rain-fed, as competing land uses. An amount of \( s(e) \) (m³/ha)/y) of ecosystem service is produced at site \( s \) when practice \( b \) is adopted and \( s(e) \) equals zero when practice \( a \) is adopted. Here \( s(e) \) is defined as the difference in evapotranspiration between the two practices. A farmer will receive a payment of \( c_s \) for each m³ that is produced. The amount of \( s(e) \) at a specific site within a HRU is however not known beforehand, but since the objective is to obtain a total quantity for the entire HRU payments can be based on an expected average rate of supply generated by the SWAT model.

A farmer will decide to adopt rain-fed barley if

\[
o_{(p, s)} = v(p, s, a) - v(p, s, b) \leq p_e s(e)
\]

where \( v \) is the net return, \( p \) is a vector of input and output prices, \( s \) indexes the site and \( a, b \) indicate the practice at the site. Thus \( o_{(p, s)} \) can be interpreted as the opportunity cost of changing from practice \( a \) to practice \( b \). This equation implies that farmers are willing to change practices to receive the payment if \( o_{(p, s)} \leq p_e \), i.e. if the opportunity cost per unit of water conserved is less than the price paid for the water. If we order all the sites \( s \) for a given \( p \) within an HRU in increasing order of \( o_{(p, s)} \) we can define the spatial distribution of opportunity cost per unit of ecosystem \( e, \phi(o/e) \). The fraction of the total number of farmers who adopt practice \( b \) without payment is given by

\[
r(p) = \int_{-\infty}^{0} \phi(o/e)d(o/e)
\]

The initial equilibrium supply of water before farmers are given payments is then given by

\[
S(p) = r(p) H e
\]

where \( H \) is the total area of the HRU. Similarly by integrating \( \phi(o/e) \) between zero and \( p_e \), the fraction of the total number of farmers is found who change from practice \( a \) to \( b \) given \( p_e \), \( r(p, p_e) \). The supply of ecosystem services in that case equals

\[
S(p, p_e) = S(p) + r(p, p_e) H e
\]

To model the supply of water per HRU we use the MD approach to parameterize the spatial distribution of opportunity cost by estimating the mean net returns of each practice and their variances and covariance. The opportunity cost per hectare can be calculated according to:

\[
o = p \cdot (Y_a - Y_b) - c_a + c_b
\]

where \( p \) is local market price for barley, \( c_a \) and \( c_b \) are the average local cost of production per hectare and \( Y_a \) and \( Y_b \) are the yields of practice \( a \) and \( b \), respectively.

Antle and Capalbo (2001) found that cost functions for barley production exhibited costs of production with approximately unitary output elasticities. Therefore, it can be plausibly assumed that cost of production is proportional to its yield, and that the coefficient of variation in net returns (CV) across land units in a region (at a point in time) can be estimated by the spatial CV for yield. Previous work showed that this approach provides an approximation that is well within an order of magnitude (Antle and Capalbo, 2001). The MD approach implemented in this study utilizes these assumptions. The 20 year average crop yields are calculated using the SWAT model for both practices and the coefficient of variance in yield for practice \( b \)
(CV\textsubscript{b}) has initially been assumed to be equal to the CV of field slope, e.g. if the variation in slopes within a HRU is high the variance in yields will be high, mainly because water cannot be retained in the soil. The CV of practice \(a\) (CV\textsubscript{a}) is assumed to be 20\% of CV\textsubscript{b}, because irrigation water is available and the effect of steep slopes will be much less. In order to estimate the covariance between yields, the correlation between the yields of irrigated and non-irrigated crops is assumed to be positive but less than unity. In many cases the correlation between the yields of different practices is likely to be high, but not perfect (Antle and Valdivia, 2006). Since this correlation is not readily observed, sensitivity analysis is used to assess the impact of alternative values. The opportunity cost is assumed to be normally distributed and its variance is calculated according to the following set of equations:

\[
\begin{align*}
\sigma_a^2 &= \sigma_a^2 + \sigma_b^2 - 2\rho_{ab} \\
\sigma_a^2 &= CV_a^2 \cdot \nu_a^2 \\
\sigma_b^2 &= CV_b^2 \cdot \nu_b^2 \\
\rho_{ab} &= \frac{CV_a \cdot \nu_a \cdot CV_b \cdot \nu_b \cdot \rho_{ab}}{\sigma_a \cdot \sigma_b}
\end{align*}
\]

where \(\sigma_a^2\) and \(\sigma_b^2\) are the variances in net returns of practice \(a\) and \(b\), respectively, \(\nu_a\) and \(\nu_b\) are mean yields, and \(\sigma_{ab}\) and \(\rho_{ab}\) are the covariance and spatial correlation coefficient in net returns between practice \(a\) and \(b\). The MD model constructs this distribution per HRU and by sampling this distribution at different \(p_e\) the supply curve of fresh water for each HRU is calculated. The model aggregates the supply curves for each HRU to obtain a supply curve for the entire catchment.

Fig. 1 shows how the supply of water is derived from the spatial distribution of opportunity costs for changing practices. Fig. 1 actually contains two graphs. The left side of the graph shows the spatial distribution of opportunity cost per unit of ecosystem service. The price per unit of \(e\), \(P_e\), is shown on the vertical axis and the density function \(\phi(\omega/e)\) is shown on the horizontal axis. The area under this curve in the price range from \(-\infty\) to 0 is the initial equilibrium supply of fresh water. The shape of the distribution is estimated by Eqs. (7)–(10). The right side of the graph shows the supply curve. The horizontal axis shows the supply of fresh water as a function of the price per unit \(e\) on the vertical axis. The supply curve crosses the horizontal axis at the initial equilibrium and logically further increases as \(P_e\) increases. The rate of increase (slope of the supply curve) depends on the shape of the distribution of opportunity costs. The supply curve approaches a vertical asymptote equal to the maximum amount of ecosystem service (\(H_e\)) that can be produced when every HRU switches to activity \(b\).

3. Results

3.1. Hydrological modelling

Fig. 2 shows the average annual water balance for the 20 year period 1983–2002 for the entire catchment. The catchment receives an average annual precipitation of 563 mm of which, on average 418 mm (73\%) evaporates. Given a potential evapotranspiration of 1457 mm/y it is evident the catchment is under severe water stress. Around 15\% of
the incoming water is returned as stream flow through direct runoff. The remainder infiltrates in the soil and exits the catchment as sub-surface flow or ground water flow. Only a very small proportion is lost from the catchment through percolation to the deep aquifer (1 mm/y). On a catchment scale, the amount of irrigation water applied is limited due to the relatively small proportion of irrigated agriculture. However, it is, as will be shown subsequently, a very important and manageable proportion. Based on this analysis it is concluded that water conservation in the catchment should be sought in the reduction of evapotranspiration.

Fig. 3 shows the results of the validation. The average monthly discharge in mm/month shows good agreement. Some caution is warranted as the Yangcun gauge is located in the Brahmaputra downstream of the study catchment and drains a much larger area (153,191 km²) that includes the study catchment. The drainage areas is however relatively homogeneous and the comparison of area weighted discharges shows that SWAT simulates plausible monthly discharges. The comparison of actual evapotranspiration further supports this finding. The NCEP/NCAR and modelled actual evapotranspiration are in a similar range. The NCEP/NCAR data are generally higher than SWAT in the summer. A possible explanation could be that the NCEP/NCAR dataset is grid based with a spatial resolution of 2° and the selected grid cell includes an area north of the

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**Fig. 2.** Average annual water balance from 1983 to 2002. (P = precipitation, I = irrigation, ET = actual evapotranspiration, R = surface runoff, IN = infiltration, CR = capillary rise, PC = percolation, QL = sub-surface flow, RF = return flow, RC = recharge to deep aquifer.)

**Fig. 3.** SWAT validation results: (i) modelled discharges at the catchments’ outlet vs. average monthly measured discharges at Yangcun (left figure), (ii) modelled monthly actual evapotranspiration vs. monthly NCEP/NCAR derived actual evapotranspiration from 1983 to 2002 (right figure).
catchment, which, due to the wide Brahmaputra floodplain, includes a large wetted surface resulting in a higher evapotranspiration rate.

To gain insight into how to achieve the largest water savings, the analysis of monthly partitioning into precipitation, irrigation and actual evapotranspiration (ET\text{act}) for irrigated barley is useful. Fig. 4 shows these components for practice \textit{a} and \textit{b}, respectively. The left figure shows that irrigation amounts are highest in the months April and June and decrease later in the growing season when the monsoon rains provide sufficient water to sustain crop water requirements. In April the soil water content is replenished to field capacity and sufficient to sustain the relatively low crop water requirements in April and May. The months April–June are critical months for the downstream agricultural areas and water conservation efforts should focus on increasing discharge out of the catchment in the early months of the growing season.

An increase in discharge can be achieved by reducing irrigation and thus ET\text{act}. However the response of ET\text{act} to changes in irrigation amounts is governed by the biophysical conditions of the system. Fig. 5 shows, for each agricultural HRU, the relation between a reduction in irrigation (\Delta I) and a reduction in ET\text{act}(\Delta ET\text{act}). The relation can be approximated by linear regression (intercept = 630, slope = 0.5, \textit{R}^2 = 0.4). The figure shows (i) that a decrease in irrigation leads to a decrease in ET\text{act}, (ii) the decrease in ET\text{act} is always less than the decrease in irrigation, and (iii) there are large differences between the various HRUs. These differences are mainly explained by the fact that different HRUs receive different amounts of precipitation and by the differences in soil type. Deeper soils with a high water retaining capacity respond less directly to reduction in irrigation.

A reduction in ET\text{act}, assuming that the irrigation water originates from within the catchment, will yield an increase in discharge at the outlet of the catchment. Fig. 6 shows the increase in discharge (m\textsuperscript{3}/s) from April to June at the outlet of the catchment when all agricultural HRUs shift from irrigated to rain-fed barley. The simulated average total discharge in these months is 87 m\textsuperscript{3}/s (16 mm/month). This means that discharge can potentially be increased in these critical months between 2% and 30% with an average of 11%. These are very considerable amounts especially when considering only 2.6% of the total catchment area is irrigated agriculture.

3.2. Economic model

Table 1 shows the inputs for the MD model. The average yield in the irrigated case is 4404 kg/ha and this is in good agreement with barley yields reported in literature (Tashi et al., 2002). The yields in the rain-fed case are on average 1646 kg/ha (37% of the irrigated case) and the average rate of ecosystem service (reduction in actual evapotranspiration) is 191 mm. The ecosystem service rates are based on crop water requirements and biophysical conditions within the HRUs. The average amount of required reduction in irrigation water to achieve this ecosystem service rate is 276 mm per growing season. The average barley market price in 2005 in Tibet’s capital Lhasa ranges between 0.18$/kg and 0.20$/kg. For both case \textit{a} and \textit{b} an average of 0.19$/kg is used. The local cost of production is 330$ ha\textsuperscript{-1} y\textsuperscript{-1} for the irrigated case (personal communication 1/8/2006; Dr. Quimei) and the gross income for the irrigated case is on average 837$/ha. The cost of production is assumed to be proportional to yield,
and the cost of the rain-fed case was estimated accordingly. In addition, the rain-fed cost was further reduced because no water fees for irrigation water are required. A water fee of 0.004S m$^{-3}$ irrigation water (Loeve et al., 2001) is multiplied by the required amounts of irrigation water and deducted from the production costs for case a. Irrigation costs are on average only 3% of total production costs. Average cost of production for the rain-fed case averages 119$/ha, while the average gross income for the rain-fed case equals 313$/ha.

Fig. 7 shows the results of the economic simulation for a single year of HRU 1. The left side of the graph shows the distribution of the difference in net returns between case a (irrigated) and case b (rain-fed) per unit ecosystem service ($\Delta Q_{\text{act}}$). The initial distribution (solid line) reveals that the centre of the distribution is located around a $P_e$ of 0.15S/m$^3$. The tail of the distribution approaches zero at $P_e \approx -0.098$/m$^3$ at the left side and at a $P_e \approx 0.37$/m$^3$ at the right side (nearly all farmers change from practice a to b). In case a there is, therefore, a limited equilibrium supply of water ($S_p$). This means that a number of farmers adopt practice b even if no additional financial incentives are provided, because their yields are low and irrigation is costly, i.e. they are better off without irrigation.

The right side of the graph shows the associated supply curve. At the right side of the graph the supply curve approaches the vertical asymptote equal to 1755 ha * 1857 m$^3$/ha $\approx 3.3 \cdot 10^6$ m$^3$. The slope of the supply curve
is least steep at the centre of the distribution. The figure also shows the effect of the CV on the shape of the distribution of opportunity cost and the supply curve. An increase in CV widens the opportunity cost distribution and increases the slope of the supply curve. A decrease in CV causes the opposite.

It is interesting to note that with a CV of 200% of the initial CV the left tail of the distribution is now located at a $P_e \approx -0.2$ S/m$^3$. This means that the equilibrium supply of fresh water has increased considerably due to the relative large spatial variation in yields between the two cases.

Fig. 8 shows the accumulated results for the entire catchment over a period of 20 years. The slope of the supply curve is smallest at a price of 0.15 S/m$^3$. At that point approximately 50% of the farmers enter into a contract. The maximum achievable amount of evapotranspiration reduction accumulated over the 20 years roughly equals $1.4 \cdot 10^9$ m$^3$ (= $7.0 \cdot 10^7$ m$^3$/y), which will result in very significant increases in April–June discharge (2–30%). Besides conservation of water, there is considerable additional income generated by the farmers as is shown in the lower half of Fig. 8.

3.3. Sensitivity analysis

The model has been parameterized with model simulations, expert judgements and statistics available from literature and personal communications. However there are no
long-term locally measured data available to calibrate the results. It was shown that the output of the hydrological model is plausible and subsequently a sensitivity analysis was performed for the most important physical and economic parameters in the economic model to indicate the range in which realistic results may be expected. Three parameters have been chosen which are governed by the local biophysical conditions (CV_a, CV_b, and e) and three parameters have been chosen that relate to the economic model (P, C_a, and C_b). The sensitivity analysis was performed at a fixed P_e level (0.15$/m^3), which equals the centre of the distribution of the base model. All parameters were increased and decreased by 30%, respectively, and the effects on the total catchment supply, the slope of the supply curve and the number of farmers entering into a contract are shown in Table 2. The CV, which is the parameter which is least known, does not have a large influence on S, ∆S/∆P_e and e. In other words we may reasonably accurately simulate the supply of ecosystem service at catchment level without accurate knowledge of the CVs. The supply of ecosystem service is however very sensitive to e. An increase of 30% in e results in a near doubling of the total amount of ecosystem service produced. A decrease in e also considerably reduces the slope of the supply curve. An increase in market prices causes fewer farmers to shift from case a to b; e.g. a higher financial incentive is required to compensate the larger difference in net returns. An increase of costs of the irrigated barley system will reduce the difference in net returns between the two practices and more farmers will adopt rain-fed barley production at the same P_e. The opposite is true for the costs of rain-fed agriculture.

### 4. Discussion and conclusion

Providing payments for ecosystem services has the potential to contribute to the preservation of Tibet’s water tower. We have shown that when farmers are provided with a sufficiently high economic incentive the river discharge in the critical pre-monsoon period can be increased significantly even if the percentage of irrigated lands is relatively low. This approach could yield substantial water savings at a critical period of the growing season, if sufficient economic incentives are provided to farmers to change practices. The concept was showcased for a relatively small catchment on the Tibetan plateau; however the presented methodology could be applied to the entire Tibetan plateau. Depending on the physical characteristics (e.g. soil, slope and land use) and the agricultural water use, implementation of the approach at a larger scale may yield significant water savings in critical periods of the year at basin scale.

The methodology presented above, which combines biophysical simulation models with an economic approach, appears to be a transparent and cost effective tool to quantify the effect of financial incentives in the conservation of water resources. Policy relevant information can now be generated without the need to conduct expensive field surveys and set up more elaborate econometric simulation models for which there is generally no time in a political context. As argued by Antle and Valdivia (2006) the MD approach is motivated by the fact that policy makers demand timely, quantitative information with sufficient level of detail, which needs to be accurate within an order of magnitude.

This study was intended to be a proof-of-concept, and the objective was to show that the PES concept can be applied for the conservation of water in data scarce areas. The purpose of the analysis is to have an assessment of economic feasibility of payments for the ecosystem service with readily available data that can be carried out in a timely matter to support policy decision making. It is not intended to be a full-blown assessment of all the possible factors that might affect farmers’ decision making (e.g., risk aversion, other institutional constraints). The point of the MD analysis is to get a first-order approximation to the supply curve without taking a long time to do detailed surveys and understand farmers’ decision processes. We have used the combination of the SWAT and MD model in an area where limited data is available and a fully-fledged validation of both the economic and hydrological results was impossible. However using secondary sources of information we have shown that SWAT simulates plausible hydrological outputs and the explorative sensitivity analysis revealed the range in which results may be expected. This validation issue will always remain, particularly because PES contracts are generally signed for a multi-year period in the future based on plausible ranges from the past. The strength of the tools presented lies in the ability to provide these

### Table 2

Sensitivity of the total supply of ecosystem service (S), the slope of the supply curve (∆S/∆P_e) and the fraction of farmers participating in a contract (e) at a fixed P_e of 0.15 Sm^{-3}.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base</th>
<th>S (10^6 m^3)</th>
<th>∆S/∆P_e (10^9 m^3 S^{-1})</th>
<th>e (–)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical parameters</td>
<td>716</td>
<td>2.9</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>CV_a</td>
<td>CV_a +30%</td>
<td>711</td>
<td>3.2</td>
<td>0.50</td>
</tr>
<tr>
<td>CV_b</td>
<td>CV_b −30%</td>
<td>716</td>
<td>2.7</td>
<td>0.50</td>
</tr>
<tr>
<td>CV_b</td>
<td>CV_b +30%</td>
<td>717</td>
<td>2.1</td>
<td>0.50</td>
</tr>
<tr>
<td>CV_b</td>
<td>CV_b −30%</td>
<td>699</td>
<td>4.8</td>
<td>0.49</td>
</tr>
<tr>
<td>e</td>
<td>e +30%</td>
<td>1232</td>
<td>4.2</td>
<td>0.67</td>
</tr>
<tr>
<td>e</td>
<td>e −30%</td>
<td>306</td>
<td>1.2</td>
<td>0.29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Economic parameters</th>
<th>P</th>
<th>P</th>
<th>C_a</th>
<th>C_a +30%</th>
<th>963</th>
<th>2.3</th>
<th>0.68</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>P</td>
<td>P</td>
<td>C_a</td>
<td>C_a −30%</td>
<td>381</td>
<td>2.8</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>P</td>
<td>C_b</td>
<td>C_b +30%</td>
<td>559</td>
<td>4.3</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>P</td>
<td>C_b</td>
<td>C_b −30%</td>
<td>792</td>
<td>2.3</td>
<td>0.55</td>
</tr>
</tbody>
</table>

CV_a, CV_b, C_a, and C_b are the coefficients of variation in the net returns of irrigated and rain-fed barley, respectively. P is the market price of barley, P_e is the economic incentive provided to farmers, and C_b is the cost of production of rain-fed barley.
plausible ranges. This contract is also important in forcing the farmers’ decision to adopt the prescribed water conserving practice, i.e. rain-fed barley cultivation. The farmers enter a contract with the buyer of water and it defines at least the amount of ecosystem service to be supplied, the alternative practice and the financial compensation.

We have used a process based hydrological model in an ungauged basin. This is an issue many scientists face and recently, interest in using simulation models in ungauged or sparsely gauged basins has increased, leading to some concerted actions. The most relevant is the Prediction in Ungauged Basin (PUB) initiative; an International Association for Hydrological Sciences (IAHS) initiative for the decade of 2003–2012, aimed at uncertainty reduction in hydrological practice (Sivapalani et al., 2003). PUB focuses on the development of new predictive approaches that are based on “understanding” of hydrological functioning at multiple space-time scales. SWAT is such a process based model that comprehensively covers all components of the hydrological cycle, and which has been applied in numerous studies around the world (Arnold and Fohrer, 2005).

For the economic input a number of important assumptions were made. This is legitimate, since no regional data are available as will often be the case in these types of studies, but some caution is required. Two important assumptions were made, which directly affect the output of the MD model. Firstly, it was assumed that the CV of rain-fed barley yield was equal to the CV in slope, because slope is important in characterising the HRUs potential to retain water. This approach is preferred over using a constant CV for all HRUs. The sensitivity analysis showed that the influence of the CV in characterising the potential of the HRU to retain water is limited. More research into the estimation of the CV in yield based on biophysical properties is however recommendable. Secondly, it was assumed that the CV in net returns can be estimated by the CV in yield, because data from a variety of studies show that cost of production tends to be proportional to yield (Antle and Capalbo, 2001). However, the CV of net returns may be higher than the CV of yields when yield is highly variable (as in this case of rain-fed barley) and farmers apply inputs in fixed proportions per hectare. Note that this tendency will be mitigated in semi-subsistence systems with low use of variable inputs, as illustrated by the data in Table 1. Sensitivity analysis to the assumption of a substantially lower or higher CV shows that the results are not highly sensitive to the CV in any case (Fig. 7).

Conservation of water is not straightforward. We have shown that through the reduction of evapotranspiration, discharges can be enhanced during the dry season. A possible way to reduce evaporation is the reduction of irrigation and the associated change in land cover. In this study we have compared rain-fed agriculture with irrigated agriculture. However there may be other crops which transpire less than spring barley, which may provide additional savings. Rain-fed agriculture still consumes a considerable amount of water. It might also be a viable option to pay farmers to leave their fields partially fallow.

Water is a common property resource, and there are always two issues to consider, efficiency and equity. For efficiency in the TP case the general principle that is pursued with PES is to create an incentive for farmers to use water efficiently from a social point of view. In TP the argument is that water may be worth much more to downstream users (agriculture, urban or hydropower) than to crop producers in the highlands. In this context, PES has been applied as a way to implement water pricing. An efficient outcome can be obtained in two equivalent ways: farmers using irrigation can be made to pay a positive price per unit of water consumed; or farmers can be paid a positive price per unit of water not used. The opportunity cost calculation is exactly the same in both cases. In other words, “taxing” water-using farmers per unit of water consumers, or “subsidizing” farmers per unit of water not consumed, are equivalent ways to achieve the same outcome. For equity, the question is, who has the rights to the water? If downstream users have the rights, then farmers should pay for using the water; and if farmers have the rights, then downstream users should pay farmers not to use water. So in this case the PES concept of paying farmers not to use water implies they have the rights to the water. The key policy questions that remain to be addressed are how much the water is worth, and who should pay for it. The PES analysis has shown how much water will be delivered at various water prices, but does not provide conclusive answers on which price is the “right” or socially efficient price. The challenge for policy makers thus is to choose the appropriate level for \( P_w \). \( P_c \) should be set equal to the marginal social value of the water downstream. The payment will not be higher due to transaction costs; rather, the net price received will be lower.

The concept of payments for ecosystem service for the conservation of water resources may prove to become increasingly important in light of the pending impacts of climate change. A recent study (Immerzeel, in press) has shown that the Tibetan Plateau is highly sensitive to climate change. Glacial melt will increase river discharge in the decades ahead, but once the glaciers have melted away completely river discharges will decline rapidly. Water conservation through agricultural adaptation may be one of few viable alternatives.

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References


