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A Systems Analysis Approach to the Design of Efficient Water Pricing Policies Under the EU Water Framework Directive

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Abstract

This study uses systems analysis to design and compare two economic approaches to efficient management of groundwater and surface water given EU WFD ecological flow requirements. Under the first approach, all wholesale water users in a river basin face the same volumetric price for water. This water price does not vary in space or in time, and surface water and groundwater are priced at the same rate. Under the second approach, surface water is priced using a volumetric price, while groundwater use is controlled through adjustments to the price of energy, which is assumed to control the cost of groundwater pumping. For both approaches, optimization is used to identify optimal prices, with the objective of maximizing welfare while reducing human water use in order to meet constraints associated with EU WFD ecological and groundwater sustainability objectives. The second pricing policy, in which the energy price is used as a surrogate for a groundwater price, shifts a portion of costs imposed by higher water prices from low value crops to high value crops and from small urban/domestic locations to larger locations. Because growers of low value crops will suffer the most from water price increases, the use of energy costs to control groundwater use offers the advantage of reducing this burden.

Keywords

Systems analysis, Integrated modeling for water resources management, Water pricing, Positive Mathematical Programming, EU Water Framework Directive

Introduction

Rogers and Fiering (1986) provided an early review of the uses of systems analysis in water resources management. They defined systems analysis as a set of mathematical planning and design techniques that includes some formal optimization. A central feature of systems analysis that distinguishes it from other forms of simulation used in water resources management is that it is used to identify alternatives, and not just to evaluate alternatives. Rogers and Fiering noted that despite an already substantial academic literature, they were able to identify only one study in which the results of a systems analysis were actually implemented in a project. A number of reasons were cited for the failure of systems analysis to gain traction in professional practice, including limits on the extent to which economic, political, institutional, and environmental pressures that affect planning and decision-making can be incorporated into the formulation of a formal optimization problem.

Since the review by Rogers and Fiering, a substantial literature has documented efforts to improve the utility of systems analysis in water resources management. While a complete review is outside the scope of this paper, we would like to highlight two developments that contribute to the approach presented here. The first is the development of increasingly sophisticated methods for incorporating economic information and methods, which has improved linkages between water resources systems and the broader economic and social factors that drive water resources development (for recent reviews, see Harou, et al., 2009; Cai, 2008; Booker et al., 2012). The second is the integration of ecological and other natural systems models, which has improved understanding of the impacts of water resources development on natural systems (for a conceptual introduction, see Jakeman and Letcher, 2003; for recent examples, see Loucks, 2006 and Liu, et al., 2008).

The European Water Framework Directive (WFD), introduced in 2000 (EU Commission), is a major legislative effort to require river basin planning that includes consideration of hydrological, economic, and ecological components in an integrated framework. The WFD sets out objectives for the ecological and chemical status of rivers and requires the use of economic instruments to achieve these objectives, as well as to provide incentives for efficient use. The design of economic instruments to achieve the objectives of the WFD has emerged as a challenging aspect of implementation (e.g., Heinz et al., 2007; Deronzier et al., 2005; Brouwer, 2004; Ward and Pulido-Velazquez, 2009) and is an area where systems analysis has considerable potential to contribute to rational design.

This study builds on a previous effort to design economic instruments to achieve WFD objectives (Riegels et al., 2011). In that study, an integrated modeling framework linking hydrologic, economic, and ecological components was developed, and a robust optimization approach was used to design a water pricing policy intended to achieve ecological status objectives of the WFD while providing incentives for efficient water use. The current study builds on that effort by introducing a more flexible pricing policy that prices groundwater and surface water differently. We estimate the differential impact of this pricing policy by comparing it to the policy designed in the first study, which applied one volumetric price to all water uses in a river basin, regardless of whether human water use was supplied by surface water or groundwater. In addition, both pricing policies are evaluated using a more flexible economic model of farmer behavior to estimate how farmers might respond to different water pricing policies.

Methods

General approach

Under the first pricing approach considered in this study (hereafter called the Uniform water pricing policy), all wholesale water users in the basin face the same volumetric price for water. This water price does not vary in space or in time, and surface water and groundwater are priced at the same rate. Under the second approach (hereafter called the Mixed pricing policy), surface water is priced using a volumetric price, while groundwater use is controlled through adjustments to the price of energy, which is assumed to control the cost of groundwater pumping. For both approaches, optimization is used to set prices, with the objective of maximizing welfare given constraints associated with EU WFD ecological and groundwater sustainability objectives.

The optimization problem (objective function and constraints) that is solved in order to set prices under both approaches is:

$$
\begin{aligned}
&\max \sum_{i=1}^{N}\left(\overline{welfare_i}\right) \\
&s.t. \\
&eco\_stat <= eco\_stat\_thres \\
&gw\_stat <= gw\_stat\_thres
\end{aligned}
$$

where

$N =$ number of wholesale water use locations in the river basin

$i =$ wholesale water use location index

$\overline{welfare_i} =$ annual average economic welfare at location i

$eco\_stat =$ ecological status parameter value

$eco\_stat\_thres =$ threshold value of ecological status parameter that should not be exceeded

$gw\_stat =$ groundwater status parameter value

$gw\_stat\_thres =$ threshold value of groundwater status parameter that should not be exceeded

Equation 1

In this optimization problem, the decision variables are prices. Under the Uniform pricing policy, there is only one decision variable: the volumetric price of water. Under the Mixed pricing policy, there are two decision variables: the volumetric price of surface water, and the energy price, which is used to control groundwater use. The connection between the decision variables and the objective function (i.e., the method used to estimate the impact of water prices on welfare) varies by water use type. Irrigation, urban/domestic, industry, livestock, and tourism water use types are represented in the case study basin, and methods used to estimate the impact of prices on welfare are outlined below.

We assume that all water users engage in rational economic behavior as defined by microeconomic theory (e.g., Mas-Colell, et al., 1995). In other words, we assume that all producers adjust inputs, including water, in order to maximize profits, and that all consumers adjust consumption, including consumption of water, in order to maximize utility. Therefore, the amount of water abstracted at each water use location (and the resulting welfare at that location) is a function of the marginal cost of water. For all users, we further assume that decisions about how much water to use are based on expectations about average annual water availability.

The remainder of the Methods section is organized as follows. First, we provide a brief description of the case study river basin. Then, we explain the rationale for controlling groundwater use through energy prices under the Mixed poliy, instead of using a second volumetric price that is different from the price of surface water. Next, methods used to estimate the impact of water prices on welfare are described for the irrigation, urban/domestic, and industry water use types. (Methods are not described for the livestock and tourism types because these are similar to those used for industry.) This is followed by an explanation of how we represent ecological status and groundwater status constraints. We conclude the methods section by summarizing the overall optimization approach and describing methods used to solve the optimization problem.

Case study data set

This study uses a data set associated with the Aggitis River basin in northern Greece, which is a tributary of the Strymonas River. The case study river basin has been described in Riegels et al. (2011). The case study data were assembled during 2007 and are representative of conditions in that year. The case study data set includes information about irrigation, urban/domestic, industry, livestock, and tourism water use, as well as about the economic activities associated with these uses. The case study basin includes 15 irrigation locations, 19 urban/domestic locations, 11 industry water use locations, 12 livestock locations, and 2 tourism locations. A schematic of the river basin showing the locations of all water use locations is given in Riegels et al. (2011).

Rationale for controlling groundwater use with energy prices

Under the Mixed pricing policy, groundwater use is controlled with an energy price. We assume that the depth to groundwater depends on local drawdown only. The resulting quadratric cost function facilitates the selection of a profit-maximizing mix of surface water and groundwater because groundwater is then used at the point where the quadratic pumping cost function is tangent to the surface water price. We now present the model used to estimate local drawdown and groundwater pumping costs.

We assume that groundwater costs are a function of the energy required to pump groundwater, which is in turn a function of the depth to groundwater (or pumping lift) and the volume that is pumped (pumping rate). We further assume that the average groundwater level does not change during the simulation period, so that only local drawdown affects depth to groundwater. This assumption is reasonable because of constraints on total groundwater pumping that are described in the section "Representation of long-term groundwater use constraint" (for an approach to incorporating other variables affecting pumping depth into a groundwater pumping cost function, see Basagaoglu, et al., 1999).

The main aquifer in the case study area is an unconfined aquifer with a mean thickness close to 100 m (Panilas, 1998). Hydraulic conductivity is assumed to equal 2.16 m/day and specific yield is assumed to equal 0.011. Based on results from a detailed groundwater model in the area (ENM Ltd., 2006), depth to groundwater is estimated to equal about 30 m throughout the study area. A pumping efficiency of 0.7 is assumed at all locations.

To estimate how the depth to groundwater changes at the wells as a function of groundwater abstraction, we assume no wells interfere (drawdown cones do not overlap) and use Neuman's solution for nonequilibrium radial flow in an unconfined aquifer (Neuman, 1974). The assumption that drawdown cones do not overlap is reasonable given hydrogeological condtions in the study area because all well are separated by at least 500 m. We assume that on an average annual basis, almost all drawdown is a function of gravity drainage and that the late drawdown portion of Neuman's solution prevails. In the late drawdown period, Neuman's solution is equivalent to the Cooper-Jacob equation with specific yield substituted for storativity.

The Cooper-Jacob equation estimates drawdown at an instantaneous point in time. To estimate average drawdown over a given time period, the Cooper-Jacob equation can be integrated with respect to time.

$$\overline{h_\circ - h} = \frac{1}{t_{pumping}} \cdot \frac{Q}{4 \cdot \pi \cdot T} \cdot \left(t \cdot \ln\left(\frac{2.25 \cdot T \cdot t}{r^2 \cdot S} \right) - t \right)_0^{t_{pumping}}$$

where

$t_{pumping} =$ length of pumping period

$\overline{h_\circ - h} =$ average drawdown (m)

Equation 2

We use the expression for average drawdown given in Equation 2 to estimate the cost of pumping a given volume of water over a single growing season.

$$\text{pumping cost (€)} = pe \cdot \left(gcf_1 \cdot V + gcf_2 \cdot V^2 \right)$$

where

$$gcf_1 = \frac{\rho \cdot g}{\eta} \cdot z$$

$$gcf_1 = \frac{\rho \cdot g}{\eta} \cdot \frac{W}{4 \cdot \pi \cdot T \cdot t_{pumping}}$$

$pe =$ energy price (€/kWh)

$V =$ volume of water pumped (m^3)

$\rho =$ density of water (kg/m^3)

$g =$ acceleration due to gravity (m/s^2)

$\eta =$ pumping efficiency

$z =$ intial depth to water table (m)

$t_{pumping} =$ length of pumping period (d)

Equation 3

Under the Mixed pricing policy, the quadratic cost function that results from using the price of energy to control the cost of groundwater pumping facilitates the selection of an optimal mix of surface water and groundwater. If surface water and groundwater were both priced volumetrically, then, given the assumptions used in this study, all users would use whichever source was cheaper. The quadratic cost function allows users to set groundwater use to the point where the marginal cost of groundwater is equal to the price of surface water, so that each user is able to select a mix of both supply types. We assume that users are able to switch between supply types without difficulty; however, irrigation locations without access to groundwater (surface water) in the base year data set are assumed to be unable to add surface water (groundwater) supplies (i.e., only location with both sources in the base year are assumed to have access to both sources under the pricing scenarios). We make a final assumption that, if the area under groundwater irrigation is reduced at a given location, then the number of wells in production is reduced proportionally.

Estimating the impact of prices on welfare: Irrigation water use

The welfare at each irrigation water use location is assumed to equal the total land rent minus the total cost of operating the irrigation system at that location. Each irrigation location is group of farmers served by one irrigation system that may have access to groundwater, surface water, or both. Each location is assumed to behave as a single profit-maximizing entity. The total land rent is the sum of the all the rents received by each of the farmers at the location.

$$\overline{welfare_i} = \sum_{j=1}^{N} lr_{ij} - sc_i$$

where

$j =$ crop index

$N =$ number of crops

$lr_{ij} =$ land rent for crop j at irrigation location i

$sc_i =$ irrigation system supply cost at location i

Equation 4

Land rent is assumed to equal revenue minus water and other input costs. Water costs are prices paid by famers under either of the two pricing policies simulated here, and are different from the costs of operating an irrigation system. We assume that the costs of operating the irrigation system are covered by revenue from the water pricing policies; these costs therefore do not affect the decision-making of individual farmers but still impact the overall welfare calculation.

$$lr_{ij} = \left(py_j + ps_{ij} \right) \cdot y_{ij} - cw_{ij} - x_{3ij}$$

$py_j =$ producer price of crop j (€/tonne)

$ps_{ij} =$ subsidy paid to crop j at location i (€/tonne)

$y_{ij} =$ yield of crop j at location i (tonnes)

$cw_{ij} =$ water cost for crop j at location i (€)

$x_{3ij} =$ sum of fertilizer, pesticide, seed, fuel, and labor inputs to production of crop j at location i (€)

Equation 5

Under the Mixed pricing policy, irrigation system supply costs are equal to fixed capital plus operating costs. Under the Uniform policy, supply costs are equal to fixed capital and operating costs plus groundwater pumping costs; we assume that the basin authority implementing the pricing policy assumes responsibility for pumping costs to ensure that the marginal costs of groundwater and surface water use are equal.

Land rents change in response to water price changes as farmers adjust the mix of land, water, and other inputs to maximize profits. We model these changes by assuming that the production of each crop can be modeled as a constant elasticity of substation (CES) production function with three inputs: land, water, and a third input that aggregates fertilizer, pesticide, seed, fuel, and labor costs, which are assumed to be used in fixed proportions.

$$y_{ij} = \alpha_{ij} \cdot (\beta_{1ij} \cdot x_{1ij}^{\gamma} + \beta_{2ij} \cdot x_{2ij}^{\gamma} + \beta_{3ij} \cdot x_{3ij}^{\gamma})^{1/\gamma}$$

where

$\alpha_{ij} =$ share parameter

$\beta_{1ij}, \beta_{2ij}, \beta_{3ij} =$ scale parameters

$x_{1ij} =$ land input to production of crop j at location i (hectares)

$x_{2ij} =$ water input to production of crop j at location i (m^3)

$\gamma = \dfrac{\sigma - 1}{\sigma}$

$\sigma =$ elasticity of substitution

Equation 6

In Equation 6, the parameters $\alpha_{ij}, \beta_{1ij}, \beta_{2ij},$ and β_{3ij} are estimated using an approach introduced by Howitt (1995b). This approach is based on Positive Mathematical Programming (PMP) (Howitt, 1995a), which assumes that allocations of land, water, and other inputs observed in a base year data set reflect profit-maximizing behavior; the parameters $\alpha_{ij}, \beta_{1ij}, \beta_{2ij},$ and β_{3ij} are then adjusted so that marginal profits are equal across all crop types, as the assumption of profit maximization requires. The adjustments are made so that the marginal product of each input is equal to the observed marginal cost of that input plus shadow prices associated with observed land allocation contraints and constaints on overall resouce availability. The elasticity of substitution, σ, is used in this study as a calibration parameter that is adjusted so that crop yields predicted by the CES production match base year crop yields.

Land costs are represented using a quadratic cost function:

$$c_{1ij} = a_{ij} \cdot x_{1ij} + 0.5 \cdot b_{ij} \cdot x_{1ij}^{2}$$

where

$c_{1ij} =$ cost of land for crop j at location i (€)

Equation 7

In Equation 7, the parameters a_{ij} and b_{ij} are estimated as explained in Howitt (1995b). Howitt's approach requires a quadratic land cost function because of the shadow prices on observed land allocation constraints that are incorporated into the CES production function parameters. These shadow prices are intended capture inputs to production that are not observable in the base year data set, such as farmer expertise. Because these shadow prices are incorporated into the marginal product of land, it is necessary to parameterize a quadratic land cost function so that the marginal product of each input is equal to that input's marginal cost, as required by the assumption of profit maximization. We assume no other constraints on the re-allocation of land to different crop types besides those incorporated into the CES production function and quadratic land cost function parameters.

Under the Uniform pricing policy the allocation of land, water, and other inputs to different crop types at each location is estimated by solving the following optimization problem:

$$\max \sum_{i=1}^{N_j} \left(py_i + ps_{ij} \right) \cdot \alpha_{ij} \cdot (\beta_{1ij} \cdot x_{1ij}{}^{\gamma} + \beta_{2ij} \cdot x_{2ij}{}^{\gamma} + \beta_{3ij} \cdot x_{3ij}{}^{\gamma})^{1/\gamma}$$

$$-a_{ij} \cdot x_{1ij} - 0.5 \cdot b_{ij} \cdot x_{1ij}{}^{2} - pw_{policy} \cdot x_{2ij} - x_{3ij}$$

subject to

$$\sum_{i=1}^{N_j} x_{1ij} \leq \sum_{i=1}^{N_j} A_{ij}$$

$$\sum_{i=1}^{N_j} x_{2ij} \leq \sum_{i=1}^{N_j} w\_irrigation\_base_{ij}$$

where

$pw_{policy} =$ volumetric water price (decision variable) (€/m^3)

$A_{ij} =$ area allocated to crop j at location i in baseline data set (hectares)

$w\_irrigation\_base_{ij} =$ water use by crop j at location i in baseline (m^3)

Equation 8

Water use is then distributed between surface water and groundwater based on use fractions observed in the base year data set.

Under the Mixed pricing policy, the optimization problem in Equation 8 is solved with the groundwater cost function described in Equation 3 substituted for the volumetric water price:

$$
\begin{aligned}
&\max \sum_{i=1}^{N_j} \left(py_i + ps_{ij} \right) \cdot \alpha_{ij} \cdot (\beta_{1ij} \cdot x_{1ij}{}^{\gamma} + \beta_{2ij} \cdot x_{2ij}{}^{\gamma} + \beta_{3ij} \cdot x_{3ij}{}^{\gamma})^{1/\gamma} \\
&- a_{ij} \cdot x_{1ij} - 0.5 \cdot b_{ij} \cdot x_{1ij}{}^{2} - pe_{policy} \cdot \left(gcf_1 \cdot x_{2ij} + gcf_2 \cdot x_{2ij}{}^{2} \right) - x_{3ij}
\end{aligned}
$$

where

$pe_{policy} =$ energy policy price (decision variable) (€/kWh)

Equation 9

The water use level identfied in Equation 9 is partitioned between surface water and groundwater by setting the marginal cost of groundwater equal to the volumetric surface water price; groundwater use is then limited to this amount, with the rest supplied by surface water.

$$
gw_{ij} = \frac{psw_{policy} - gcf_1 \cdot pe_{policy}}{2 \cdot gcf_2 \cdot pe_{policy}}
$$

$$
sw_{ij} = x_{2ij} - gw_{ij}
$$

where

$gw_{ij} =$ groundwater use by crop j at location i (m^3)

$psw_{policy} =$ volumetric surface water price (decision variable) (€/m^3)

$sw_{ij} =$ surface water use by crop j at location i (m^3)

Equation 10

In some cases, it is profit-maximizing to use water at a level where the marginal cost of groundwater is less than the surface water price. In these cases, only groundwater is used.

Estimating the impact of prices on welfare: Urban/domestic water use

The welfare at each urban/domestic water use location is assumed to equal consumers' surplus plus the profit of the water supply agency. All urban/domestic consumers are assumed to seek to maximize consumer's surplus. The water supply agency is assumed to maximize profits.

$$\overline{welfare_i} = cs_i + profit_i$$

where

$cs_i =$ consumers' surplus at urban/domestic location i

$profit_i =$ profit of water supply agency at urban/domestic location i

Equation 11

Consumers’ surplus is measured as follows:

$$cs_i = \int_{pr_i}^{p\_choke} k_i \cdot pw^e dp$$

where

$p\_choke =$ choke price (€/m^3)

$pr_i =$ retail water price at location i (€/m^3)

$k_i =$ demand function constant at location i

$pw =$ water price (integration variable) (€/m^3)

$e =$ price elasticity of demand

Equation 12

Equation 12 is the integral of a demand function that indicates how much water a household will consume each month as a function of the price of water. This function is developed using the point-expansion method (Griffin, 2006). The price elasticity of demand is estimated to be -0.5 at all water use locations (for a meta-analysis of price elasticities, see Dalhuisen et al., 2003, who report a mean value of 0.41). Because urban/domestic water use is a small portion of total use in the case study catchment (<5%), we did not investigate the sensitivity of the demand function to changes in price elasticity.

A parameter called the “choke price” is used as the upper limit of integration in Equation 12. The choke price is defined as a price level at which urban/domestic users would substitute an alternative source of supply, such as bottled water, rainwater collection, or perhaps portable desalination (e.g., Grafton, 2008). In this study, the choke price is based on the cost of rainwater collection and is set equal to 3 €/m^3.

The method used to estimate water supply agency profits varies depending on the pricing policy under consideration. All urban/domestic water use locations have access to groundwater supplies only. Under the Uniform water pricing policy, the profit of a water supply agency is:

$$profit_i = pr_i \cdot w\_domestic_i \cdot (1 - loss_i)$$
$$- pw_{policy} \cdot w\_domestic_i + c\_pumping_i \cdot w\_domestic_i + c\_fixed_i$$

where

$w\_domestic_j =$ volume of water abstracted at location j (m^3)

$loss_i =$ distribution system loss fraction at location i

$c\_pumping_i =$ pumping cost at location i in baseline data set (€/m^3)

$c\_fixed_i =$ fixed operating cost at location i in baseline data set (€)

Equation 13

Under the Mixed pricing policy, the profit of the water supply agency is:

$$profit_i = pr_i \cdot w\_domestic_i \cdot (1 - loss_i)$$
$$- pe_{policy} \cdot \left(gcf_1 \cdot w\_domestic_i + gcf_2 \cdot w\_domestic_i^{\,2} \right) + c\_fixed_i$$

Equation 14

We assume that each urban/domestic water supply agency operates at the point where marginal profits equal marginal costs and use this assumption to determine the retail water price.

$$pr_i = \frac{mcw_i}{1 - loss_i}$$

where

$mcw_i =$ marginal cost of wholesale water supply at urban/domestic location i

Equation 15

This price is substituted into the consumer demand function to estimate wholesale water use as a function of wholesale water prices.

$$w\_domestic_i = \frac{k_i \cdot pr_i^e}{1 - loss_i}$$

Equation 16

For many urban/domestic water supply entitites, it may not be reasonable to assume that the entity operates at the point where marginal benefits equal marginal costs, due to large fixed investments that increase average costs of supply. This problem could be remedied by using a combination of fixed and variable charges for urban/domestic water supply, as suggested by Griffin (2006).

Estimating the impact of prices on welfare: Industry water use

Welfare changes for industry water users are measured in terms of changes to profits.

$$\overline{welfare_i} = \sum_{j=1}^{N} turnover_{ij} - water\_costs_{ij} - other\_costs_{ij}$$

where

$j =$ industry index

$N =$ number of industries at industry location i

$turnover_{ij} =$ revenue to industry j at industry location i

$water\_costs_{ij} =$ water costs for industry j at industry location i

$other\_costs_{ij} =$ non-water input costs for industry j at industry location i

Equation 17

Industry water use is estimated by estimating a maximum willingness to pay for water for each industy and comparing this to the average cost of water supply. If an industry's maximum willingness to pay for water is greater than the average water cost, it is assumed that the industry will use water at the level identified in the base year data set. If the average cost of water supply exceeds maximum willingness to pay, it is assumed that the industry goes out of production and uses no water. The maximum willingness to pay for each industry is estimated using the residual imputation method (Griffin, 2006; Young, 2005).

$$WTP_{ij} = \frac{turnover_{ij} - other\_costs_{ij}}{w\_industry\_base_{ij}}$$

where

$WTP_{ij} =$ maximum willingness to pay for water for industry j at location i (€/m^3)

$w\_industry\_base_{ij} =$ annual water use by industry j at location i in base year data set (m^3)

Equation 18

This method estimates a maximum willingness-to-pay value that is probably higher than the true value. This is because of the difficulty of including all input costs apart from water in the willingness-to-pay calculation. The maximum willingness-to-pay should be interpreted as an upper limit on the value of water and not as a guide to identifying a profit-maximizing level of water use, as would be implied if marginal costs of water use were used. The water prices simulated as part of this study are generally not higher than estimated willingness to pay and, in fact, only one water-intensive industry in the study area is predicted to go out of business as a result of increased water costs. It may be reasonable to assume that a water-intensive industry would go out of business or relocate to another river basin if water prices were to increase significantly.

Representation of ecological status constraint

We implement EU WFD ecological status objectives with a model constraint. Although the WFD provides definitions of surface water status in terms of a number ecological and chemical indicators, this analysis only considers WFD requirements with respect to hydrological regime, which is considered an indicator of ecological status. The term “hydrological regime” refers to the pattern of a river’s flow quantity, timing, and variability (Poff et al., 1997).

We estimate ecological status using an approach based on Arthington et al. (2006) and similar to the ELOHA approach described in Poff et al. (2010). Arthington et al. recommend developing flow-response relationships that link differences between the distribution of flows in an unmodified setting and the distribution of flows in a setting where flow patterns are modified by human abstraction.

Distributions of monthly flow volumes are used as indicators of natural flow variability. Flow patterns in the case study basin are highly seasonal, and significant inter-annual variation also exists. Therefore, in an unmodified setting, the distribution of flows in each month should show significant variation over a long time period, and the range over which flows are distributed should also vary from month to month. Unmodified distributions are developed for each reach in case study basin for each month by running a water resources planning model of the river basin with all demands set to zero. Because the model is driven by 20 year of historical hydrology, this is assumed to provide a representative distribution of natural flows. Modified distributions are developed by running the model of the case study basin with demands set to values identified using the economic methods described above.

To quantify the extent to which modified monthly flow patterns differ from natural patterns, we develop an indicator to measure the difference between modified and unmodified distributions. The ecological status of the basin is then quantified using this indicator, which ranges in value between 0 and 1. If the ecological status parameter value is equal to zero, then the flow regime is identical to the natural regime; higher values indicate flows that are increasingly modified. The optimization is constrained so that the value of the ecological status parameter is less than 0.5. More details about the method used to estimate ecological status are available in Riegels et al. (2011).

Representation of long-term groundwater use constraint

The EU WFD requires that groundwater pumping not exceed long-term rates of recharge. Long-term impacts of groundwater pumping are evaluated using the water resources planning model of the case study basin. The model of the case study basin is divided into 16 subcatchment areas, each of which is assumed to function as an independent groundwater body that is represented using a double-layer linear reservoir model. Groundwater recharge and linear reservoir parameters are based on simulations of groundwater flow developed using a MIKE SHE model of the Aggitis basin (ENM, Ltd., 2005). The model is run for a 20-year period using a sequence of the historical hydrology and demands identified using the methods described above. The storage volume of the deep layer at the end of the 20-year simulation period is used as an indicator of whether groundwater pumping is occuring at a sustainable rate. The final storage volume is constrained to be within 1% of the initial storage volume for all groundwater subcatchments. This small amount of depletion is allowed in order to facilitate a small amount of temporary groundwater mining as a drought mitigation strategy.

Solution of overall optimization problem

The overall optimization problem is solved using the following iterative approach:

1. Prices are selected.
2. Water use is estimated at all water use locations.
3. Welfare is estimated at all water use locations.
4. Water use estimates are written to the water resources planning model of the case study basin.
5. The water resources planning model is run for a twenty-year period, forced by historical hydrology (subcatchment runoff and groundwater recharge). Water use is assumed to

be constant over the 20-year period, with the exception of irrigation water use, which varies depending on hydrological conditions.

6. The groundwater constraint is checked. If the constraint is not met, steps 1-5 are repeated with new prices.
7. The ecological status constraint is checked. If the constraint is not met, steps 1-6 are repeated with new prices.
8. Basin-wide welfare is compared to welfare estimated under other prices for which the groundwater and ecological status constraints have been met.

The above steps continue until prices are found that maximize basin-wide welfare while satisfying constraints. Water use and welfare calculations are performed in Matlab. The optimization uses a gradient search algorithm that is part of the Matlab software package (The Math Works, 2011). The river basin simulation model is developed using the software package MIKE BASIN (DHI, 2011). An overview of the optimization process is given in Figure 1.

Results

Prices identified both pricing policies are presented in Table 1. The table also presents estimates of basin-wide welfare. The optimal surface water price under the Mixed pricing policy is higher than the optimal water price identified under the Uniform pricing policy. The Mixed pricing policy predicts more total water use because some crops that are not profitable to grow under the Uniform policy become profitable under the Mixed policy due to the availability of low marginal cost groundwater supplies. The resulting increased use of groundwater reduces groundwater discharge to the river system, which means that surface water use must be limited by a higher surface water price in order to meet the ecological status constraint.

The impact of introducing a separate price for groundwater is illustrated in Table 2, which presents aggregated crop areas and water use for all irrigation water locations that have access to both surface water and groundwater. We compare results when the Uniform policy's price and the Mixed policy's surface water price are both equal to 0.10 €/m^3. The table shows that a number of crops predicted to go out of production under the Uniform policy are still active under the Mixed policy. These crops, which include cotton, maize, and fodder, are all predicted to use groundwater but not surface water. Although it is not profitable to grow these crops when the marginal cost of water is equal to 0.10 €/m^3, continued production is possible if groundwater use is restricted to small amounts that limit drawdown and resulting marginal pumping costs. Because total water use is higher, the surface water price must be increased to 0.12 €/m^3 under the Mixed pricing policy to reduce surface water use to the point that ecological constraints are satisfied.

Marginal costs of water for each crop type are presented in Table 3, which compares marginal costs at one location under the Mixed pricing policy when the surface water price is equal to 0.10 €/m^3 and the energy price is equal to 0.39 €/kWh. The table shows that the marginal cost of water use is less than the surface water price for many crop types under the Mixed policy. All of these crops are assumed to use groundwater only.

Retail water prices estimated under both pricing policies are presented in Table 4. . Prices observed under the Mixed policy are positively correlated with water use. Higher retail water prices are estimated in locations with high water use because high water use increases groundwater pumping and drawdown. All urban/domestic water use locations are supplied by groundwater only.

Discussion

We compared two pricing policies in this study to investigate whether pricing groundwater and surface water differently might have beneficial welfare impacts. Our results suggest that there are indeed differences between the Uniform pricing policy, in which all wholesale water users in the basin face the same volumetric price, and the Mixed pricing policy, in which groundwater use is controlled through the price of energy. Both policies predict significant impacts to the agriculture sector. Both policies also predict that these impacts will be concentrated on low value crops such as maize, cotton, and fodder. However, the Mixed policy predicts that it will be profitable to continue growing these crops at reduced levels while the first policy predicts that these crops will go out of production entirely. It is frequently claimed that low value crops will not be profitable if environmental costs are internalized in irrigation water prices (e.g., in Spain, Gomez and Limon, 2004, and in Greece, Latinopoulos, 2008), a conclusion that is supported by this study. If water pricing is to be introduced as a tool for controlling water use, this study suggests that using an energy price to control groundwater use will reduce impacts on growers of low value crops.

Water supply varies in time and space, and water prices that give scarcity signals during times and locations where scarcity is higher could improve efficiency. The spatial and temporal variability of water supply have not been considered in the pricing policies investigated here. It is possible that basin-wide welfare could be increased, for example, by reduced groundwater pumping costs in subcatchments where groundwater use results in minimal impacts on associated surface water resources. It might also be possible to increase welfare by using pricing to implement a conjunctive management strategy in which price signals encourage surface water use during wet years and groundwater use during dry years (e.g., Schuck and Green, 2002).

On the other hand, the introduction of temporally and/or spatially varying prices would be more computationally demanding and perhaps difficult to implement in real-world practice. More prices would introduce more decision variables into the modeling framework presented here, which would make it more difficult to ensure a globally optimal solution. It was straightforward to check the optima found by the gradient search algorithm used in this study because the number of decision variables was never greater than two. With a larger number of decision variables, a gradient search method might not be appropriate. In addition, more decision variables would increase the number of model iterations needed to converge to an optimal solution. Although our approach could easily be extended to optimize more prices, we have limited the number of prices to two to ensure computational efficiency and obtain a result that could be implemented in the basin.

Because the economic impacts of both pricing policies are concentrated in the agriculture sector, we should to ask whether the model of farmer behavior used here is reasonable. The CES production function approach used here predicts that low value crops will go out of production or else will be grown on much smaller areas in response to higher water prices. The approach also predicts that high value crops will continue to be grown at levels that are close to levels observed in the baseline data set. If high value crops are still profitable at higher water prices, then it is interesting that the approach does not predict that the areas of these crops will increase as low value crops go out of production. Instead, it predicts that land allocated to low value irrigated crops in the base year is converted to dry land agriculture. The approach is constrained by parameters estimated using Positive Mathematical Programming that are calibrated to base year conditions and are intended to represent hidden factors such as land quality, management ability, and entrepreneurial skill that are not observable in the baseline data set. There is some evidence that the production of high-value crops is riskier and more complex than the production of low value crops and also requires high-quality soils (Young, 2005). For these reasons, it may be reasonable to predict that many farmers will not be able to convert to high value crop production. However, the assumption that land allocated to low value irrigated crops can be converted to dryland agriculture assumes that land used to grow cotton and maize can be converted to wheat production, which may or may not be reasonable depending on soil conditions and other factors.

Conclusion

This study demonstrates the application of a systems analysis approach to identify water prices that allocate scarce water resources efficiently while constraining human water uses so that ecological and groundwater sustainability goals are met. The systems analysis approach is also used to compare two economic approaches (pricing policies) to the management of groundwater and surface water in a river basin. The Mixed pricing policy, in which the energy price is used as a surrogate for a groundwater price, shifts a portion of costs imposed by water prices from low value crops to high value crops and from small urban/domestic locations to larger locations. Because growers of low value crops will suffer the most from water price increases, the use of energy costs to control groundwater use offers the advantage of reducing this burden.

Acknowledgements

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Table 1
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Parameter	Baseline	Pricing policy 1	Pricing policy 2
Optimal water price (€/m^3)	not applied	0.10	0.12
Optimal energy price (€/kWh)	not applied	not applied	1.13
Basin-wide welfare (1000 €)	8.12E+04	6.85E+04	6.91E+04

Table 1: Comparison of optimal water prices and welfare.

Table 2
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Crop	Baseline		First pricing policy, water price=0.10		Second water pricing policy, water price=0.10 €/m^3, energy price=0.39 €/kWh			
	Land use (ha)	Water use (1000 m^3)	Land use (ha)	Water use (1000 m^3)	Land use (ha)	Groundwater use (1000 m^3)	Surface water use (1000 m^3)	Total water use (1000 m^3)
Vineyards	664	3716	624	2502	630	834	1885	2719
Cotton	1783	9658	0	0	155	581	0	581
Trees (pear, apple, cherry, walnut)	134	1016	131	737	132	878	0	878
Trees (peach, almond, chestnut, plum)	121	937	117	630	119	742	22	763
Olives	658	4248	193	639	300	991	186	1177
Sugar beet	1819	12128	1183	4212	1231	1392	3413	4805
Maize	12007	63173	0	0	152	785	0	785
Tobacco Virginia, Burley	149	611	144	396	146	491	0	491
Vegetables	303	1732	304	1739	307	1054	841	1895
Fodder	200	1550	14	31	60	275	0	275
Pulses	36	152	34	99	36	144	0	144
Potatoes	1355	6321	1326	5418	1340	975	4870	5845
Cereals	16800	0	32627	0	32090	0	0	0
Tomatoes	102	430	87	230	96	342	0	342
Clover	2005	15403	1352	4655	1343	1446	3772	5218
Totals	38137	121074	38136	21290	38137	10928	14988	25917

Table 2: Comparison of aggregated land and water use at all irrigation water use locations with access to both surface water and groundwater. Under second water pricing policy, energy price is set to the optimal price: 0.39 €/kWh.

Table 3
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Crop	Pricing policy 2, water price=0.10 €/m^3, energy price=0.39 €/m^3		
	Marginal cost of water use (€/m^3)	Groundwater use (m^3)	Surface water use (m^3)
Vineyards	0.10	258	608
Cotton	0.07	119	0
Trees (peach, almond, chestnut, plum)	0.10	258	22
Olives	0.10	258	2
Sugar beet	0.10	516	1843
Maize	0.05	376	0
Tobacco Virginia, Burley	0.07	136	0
Vegetables	0.10	258	635
Fodder	0.06	81	0
Pulses	0.05	13	0
Potatoes	0.08	141	0
Cereals	not irrigated	not irrigated	not irrigated
Tomatoes	0.08	181	0

Table 3: Comparison of marginal costs of water use at irrigation water use location 375.

Water use location	Retail water price, baseline (€/m^3)	Retail water price, pricing policy 1 (€/m3)	Retail water price, pricing policy 2 (€/m3)
1	0.45	0.17	0.14
2	0.43	0.17	0.23
3	0.45	0.17	0.20
4	0.45	0.19	0.26
5	0.45	0.33	1.02
6	0.28	0.28	0.43
7	0.28	0.26	0.29
8	0.43	0.28	0.60
9	0.28	0.23	0.23
10	0.30	0.19	0.24
11	0.45	0.19	0.29
12	0.28	0.28	0.53
13	0.45	0.17	0.07
14	0.30	0.19	0.24
15	0.43	0.28	0.19
16	0.43	0.28	0.30
17	0.28	0.28	0.25
18	0.28	0.23	0.11
19	0.28	0.23	0.12

Table 4: Comparison of retail water prices for urban/domestic users. The retail water price refers to water prices paid by households at each urban/domestic use location. All urban/domestic water use locations are supplied by groundwater only.

Figure 1
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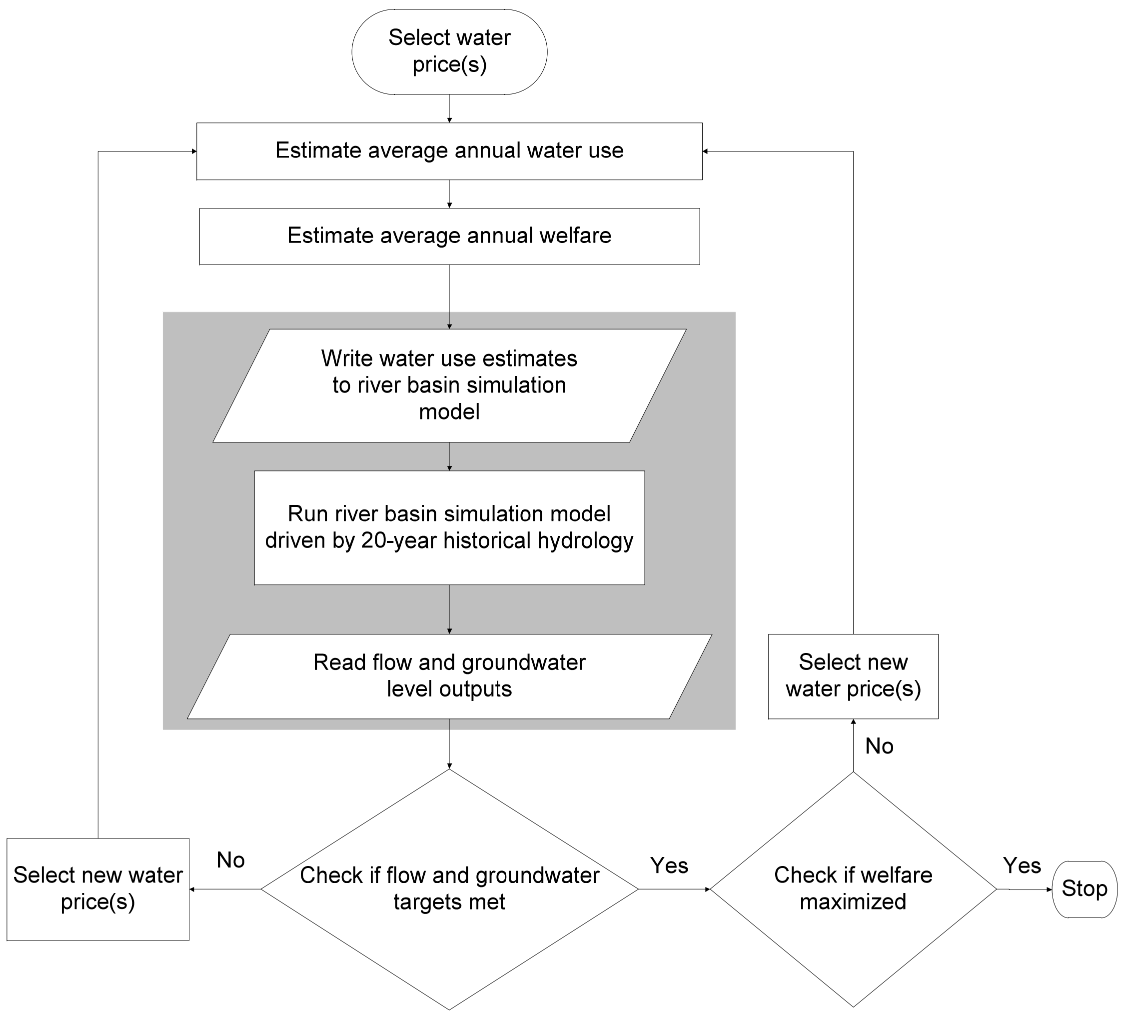

Figure 1: Solution of overall optimization problem.

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Type: Technical paper

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up to 51 lines = 473 word equiv.	up to 51 lines = 945 word equiv.
up to 68 text lines = 630 word equiv.	up to 68 text lines = 1260 word equiv.

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Tables	Word Equivalents	**Figures**
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3	630	3
4	630	4
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12	0	12
13	0	13
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Dear Editor,

We are pleased to submit a revised version of the article formerly titled "COMPARISON OF TWO WATER PRICING POLICIES IN A HYDRO-ECONOMIC MODELING STUDY" and now titled "A SYSTEMS ANALYSIS APPROACH TO THE DESIGN OF EFFICIENT WATER PRICING POLICIES UNDER THE EU WATER FRAMEWORK DIRECTIVE" by Niels Riegels et al. We thank you and the reviewers for the substantial and thoughtful comments, which helped us to significantly improve the manuscript. Please find below a detailed explanation of how we have addressed the individual issues. The review comments are listed in normal font and our replies in bold font.

We think that all problems have been resolved satisfactorily and we are looking forward to your final decision on this article.

Best Regards,

Niels Riegels

Comments from Associate Editor:

This paper has been well served by three reviewers. I believe a careful follow of their comments and suggestions will lead to an improved paper. In addition, please address in general how this paper contribute to the special issue topic: systems analysis for watershed management. Some literature review relating the focus of this paper to general system approaches for watershed management will be appreciated. I look forward to receiving your revision.

We have completely re-written the introduction to give some background on systems analysis for water resources management; outline important recent developments that have contributed to the approach presented in this paper; present some of the challenges and opportunities for systems analysis presented by the EU WFD; and describe how our paper contributes to the development of systems analysis approaches for designing economic tools for efficient water use.

Comments from Reviewer 1:

The paper describes the identification of a water price based on the impacts of the chosen water price on water uses for various water uses (irrigated agriculture and the environment, but also tourism, domestic, industry, livestock water uses. Environment relates to groundwater level and other environmental uses). The one price identified is then used to run the model for 20 years on a daily time step. This appears to be a very cumbersome approach to identify prices that maximize economic returns (irrigation, domestic, industry, tourism) and minimize ecological damage. The authors acknowledge that prices should vary across space and time, but the prices chosen in the modeling approach do not vary.

We have added an explanation of why we did not use prices that vary in space and time to the discussion section (lines 469-479).

The PMP approach chosen to identify irrigated crops and the use of energy costs instead of water prices for groundwater are well done. However, I do not agree that using energy prices instead of water prices would be a policy solution to be recommended in this basin. Why not use differential water prices for groundwater and surface water?

We have added a new section explaining the rationale for using an energy price to control groundwater use instead of a second volumetric price (lines 142-197).

At this point it is not clear to the reader what the innovation of the study is compared to previous hydro-economic modeling studies, some of which the authors list.

The introduction has been re-written to argue for how systems analysis can contribute to the design of economic approaches for efficient water management under the EU WFD and how this paper contributes to this effort.

The authors also need to state the relative innovation/difference compared to the Riegels et al. (2011) paper that is mentioned.

We have added a paragraph to the introduction (lines 77-88) explaining how this paper is different from the 2011 paper.

P1, line 22, "throughout a river basin", please change to "in a river basin"

We have made this change.

P2, line 27, suggest to delete "type" (regardless of water use)

This has been re-written to make it clear that "type" does not refer to water use type (i.e., domestic, irrigation, etc.) but rather to the source of water (surface water or groundwater).

P2, line 29, "the price of energy"; is the meaning here "the cost of energy to pump groundwater"?

We have tried to make this more clear by stating that we assume that the price of energy controls the cost of groundwater pumping.

P2, line 33, "the impact of water use changes on", better "impact of water use changes as a result of pricing policy on "

We have removed the original sentence in which this phrase was found. We now make a general reference to EU WFD ecological status constraints and no longer describe how we implement these constraints.

P2, line 35 "an optimization approach.. to identify prices". How many prices are identified?

We have added text to the Methods section (lines 105-112) to make it clear that we are talking about either one price (the Uniform pricing policy) or two prices (the Mixed pricing policy).

P2, line 39 "distribution of opportunity costs" -not clear

We have removed the term "opportunity costs" and summarized the differences in welfare impacts between the two pricing policies explicitly.

P4, line 68, please clarify if water use refers to withdrawals or depletion/consumptive use

We have removed this discussion from the introduction so this comment is no longer relevant. We decided to leave out the discussion of the importance of the irrigation sector in order to focus on the issues summarized in our response to the Associate Editor's comments.

P5, line 89/90, please slightly rephrase, districts are not systems

We have removed this discussion from the introduction so this comment is no longer relevant. We decided to leave out the discussion of the pros and cons of different irrigation water pricing schemes, again to focus on the issues summarized in our response to the Associate Editor's comments.

P5, line 96, which examples are there in Europe?

We have removed this discussion from the introduction so this comment is no longer relevant. We had thought that we had identified an example of real-world implementation of full marginal cost pricing in Spain; however, after reviewing a description again, we realized that the implementation was not consistent with the definition of full-marginal cost pricing. Again, we have decided not to focus on the pros and cons of different water pricing schemes in the introduction in favor of a concise argument for how our approach contributes to systems analysis for water resources management and the use of systems analysis to design economic approaches to implement the EU WFD.

P5, lines 99-100, how did these studies treat environmental use/relate to the WFD?

We have removed this discussion from the introduction so this comment is no longer relevant. These studies only considered the impacts of introducing higher volumetric water prices in the water sector; assumptions about environmental water use requirements or values were not integrated into any of the approaches.

However, all studies were motivated by the water pricing goals of the WFD and acknowledged that the purpose of introducing volumetric pricing would be to provide incentives for efficient use and increase the amount of water available for environmental purposes.

P6, lines 109-118, why is the shadow price not used as a water price?

We have added text to the methods section making it clear that water prices are the decision variables in the optimization problem, which is why shadow prices cannot be used (lines 105-112).

P6, line 123, how are welfare changes defined for the various users? Which are the water users apart from the environment and agriculture in the basin?

We have changed the structure of the Methods section so that the description of methods used for each water use type begins with the welfare measure used. In addition, we now provide a list of the different water use types for which welfare changes are estimated near the beginning of the Methods section (lines 110-112).

P7, line 137. Please describe what is new/different in this paper compared to Riegels et al. (2011) that also relates to ecological flows and uses the same data.

We have a added a paragraph to the discussion section explaining what is new and different in this paper compared to the 2011 paper (lines 77-88).

P7, line 144. "Predicting groundwater drawdown"—Suggest to change title. We might predict climate or climate change, but we generally do not predict groundwater drawdown. Maybe replace with "Assessing groundwater drawdown"

We changed the title of this section to "Rationale for controlling groundwater use with energy prices.

P7, line 144: Please describe how many wells are in the system and if farmers have access to both, surface and groundwater, or how the system is laid out. From p. 12, line 214, it appears that all farmers can effortlessly switch between surface water and groundwater irrigation?

We have not described how many wells are in the system because of space constraints (this would require a table). We have stated that we assume that the number of wells is reduced in proportion to the size of the area irrigated by groundwater. We also state that we assume that water users can switch effortlessly between surface water and groundwater at locations where both sources are observed to be used in the baseline data set. These assumptions are presented in lines 185-197.

P14, line 256 repeats line 250 (marginal costs equal marginal benefits)

We have re-stated this to avoid repetitive language (lines 303-306).

P19, line 369, remove ".",

We have made this change.

P19, line 371, change Cotton to cotton, etc.

We have made this change.

P 19, line 374, if it is feasible to pump groundwater to irrigate fodder, then the energy price is either very low, or other pumping costs, such as labor and machinery are not included? Please explain.

We think it is not necessary to make changes in response to this comment. We think it is clear from the text that it is feasible to irrigate fodder and other crops using groundwater because the marginal cost of pumping is low.

P21, line 411. The suggestion is that instead of a water price an energy price should be used for groundwater. What is the implied water price of the energy price used?

We have added text to the Methods section making it clear that the assumption of profit maximization means that the marginal cost of groundwater use is less than or equal to the surface water price (lines 263-269). We have summarized marginal costs of water use for one irrigation water use location given a surface water price of 0.10 €/m^3 in Table 3. We have summarized the impact of using energy prices to control groundwater on retail water prices for urban/domestic use locations in Table 4.

Generally, groundwater pumping is more costly but also more efficient (higher water-use-efficiency). What is the difference in the case study basin. Please explain.

We think it is not necessary to make changes in response to this comment. Groundwater irrigation only needs be more efficient if it is more expensive to use groundwater than surface water. Here, we are assuming that the marginal costs of groundwater use are less than or equal to the marginal costs of surface water use.

P32, Table 4, please explain the baseline water price. Is this what users are currently paying? (appears high for irrigation).

We have added text to the caption for Table 4 that makes it clear that the prices described as "baseline" water prices are retail water prices paid by urban/domestic consumers (households).

Comments from Reviewer 2:

The paper "Comparison of two water pricing policies in a hydro-economic modelling study" by Riegels et al. seeks to test two pricing policies in order to meet water pricing objectives of the

European Union Water Framework Directive (WFD). I appreciate the straightforward goal of the paper. My comments mainly concern the implications of the modeling study and how to modify the manuscript to have a better applicability for the readership base.

1. As a suggestion, the authors may want to consider changing the title of the paper to reflect the WFD goal or to highlight the purpose of the pricing schemes. Specifically the phrase "in a hydro-economic modelling study" could be modified to better reflect the motivations of the paper and perhaps attract a larger audience (since the use of a hydro-economic model is fairly obvious here).

We have proposed a new title.

Another clarifying point could be to give the two pricing policies a descriptive name (instead of referring to them as the first policy and the second policy).

We have given both pricing policies descriptive names.

2. The authors may also want to reduce some repetitive language in the text; "it is assumed" is used quite frequently.

We used the active voice as much as possible in this revised version.

3. [page 3, line 61-62] This study assumes that under classical economic theory, customers have full knowledge of the water pricing and have full knowledge of how they can change their water use to best maximize their utility and producers modify their behavior to maximize the profit. I would like to see the authors make a comment on the real-world applicability of this assumption. While I value the insight that studies such as this one can lend on how economic optima can inform policy making, the optimal conditions from the model result are often surprising. For example, Table 2 suggests that location 375's allocation of land to cotton would decrease from 620 ha to 0 under the first pricing policy, while the allocation to cereals more than doubles from 5752 ha to 12792 ha. Since the policy recommendations for the WFD hinge on the results of the optimization model, the tacit assumption is that such changes are plausible. How difficult is it for farmers to make such a change? Do the farmers know that their current crop decisions are suboptimal? This is a general comment that can be addressed with a few lines explaining the implication of the rationality assumption at the beginning of the manuscript.

We do not assume that current crop decisions are sub-optimal. They only become that way once the new pricing policies are introduced. We added a sentence to make it clear that the base year cropping pattern is assumed to be profit-maximizing in lines 228-232. We added text to make it clear that we assume no other constraints on re-allocation of land beside those incorporated into the CES production function and quadratic cost function parameters in lines 248-250. We have added a sentence to acknowledge that the assumption that cotton and maize can be converted to wheat may not be reasonable in the Discussion section (lines 496-499). We have added a paragraph to make it clear that we assume economic rationality in the beginning of the methods section (lines 114-120).

4. [pages 4-5, lines 87-91] The phrase "which are generally pressurized..." should be rewritten for clarity.

We have removed the discussion in which this phrase was found from the introduction so this comment is no longer relevant. We removed the discussion of water pricing from the introduction in order to focus on how this paper contributes to systems analysis for water management and the design of economic instruments to implement the EU WFD.

5. [page 5, line 102] "A general conclusion..." if the agricultural water demand is not elastic with respect to price, is it a safe assumption to make that the farmers will fully adjust their practices when water price changes? (Or rather, if they do follow the elasticity, and the elasticity is not high, are price changes worth making?)

We have removed this discussion from the introduction so the comment is no longer relevant. However, we were not trying to say that irrigation water use is price inelastic in general—only that irrigation water use by low value, high water use irrigated crops is inelastic. We make this point in the Discussion section (lines 481-484).

Later in the manuscript [page 14, line 246], the authors state a constant elasticity for all water uses. It would seem that based on the citation in line 102 that there may be a different elasticity for municipal versus agricultural use.

We do not use elasticities to model economic behavior or welfare impacts for any water use categories besides urban/domestic. We did not add additional text to clarify this because of space constraints and because we think it should be clear from a close reading of the Methods section.

6. [page 9, line 184] Use of Positive Mathematical Programming - Beyond the citations of the Howitt articles, the authors may want to expand upon what data was used to set the alpha and beta variables. In the seminal article, PMP was used to match the base-year crop allocations in a manner consistent with economic theory. Does such data exist in this case study? I'm assuming that it does, but this may be confusing to the readers without further explanation.

We have added a brief explanation of how land allocation and resource constraints observed in the base year data set are used to estimate the values of the CES production function parameters (lines 227-236).

7. [Discussion Section] For clarity, the statements made in the discussion section should refer back to prior concepts in the manuscript. For example, I would recommend reiterating the differences between the first and second policy in the beginning of this section. "The distribution of welfare impacts ... is different" is fairly obvious, so some of these lines can be omitted for a more precise comparison of the policies. Also, the authors refer to the PMP approach on lines 430-445 without reminding the readers what that approach is. I would also reconsider starting those sentences with "The PMP approach" -- the authors have created a model using the PMP approach, but the results quote in this section are really results from the

model and not from the generic PMP calibration method. The whole use of PMP in this paper, as pointed in comment 6, should be better explained, with the assumptions behind the approach clearly stated.

We have added a review of differences between the two pricing policies to the beginning of the Discussion section (lines 444-448). We have changed the reference to the "PMP approach" given in the Discussion section to a reference to a "CES production function approach" (lines 482-483), and have added a reminder to the readers that we estimate parameters of the CES production function using Positive Mathematical Programming (line 490). We think the expanded description of how we estimate the parameters of the CES production function and associated quadratic land cost function (lines 227-250) provides a clear explanation of the assumptions behind PMP and how the method was used in this paper.

8. [page 22, lines 425-428] "Although the WFD..." This assertion needs some justification. If the authors are using economic theory to justify not valuing environmental flows, they should expand upon this theory here. It doesn't seem like there is enough evidence to support their statement as written.

We were not making any conclusions about whether valuation of environmental flows is appropriate. We were only saying that it appears to us that the WFD guidance is inconclusive about whether environmental water use values should be internalized in water prices. However, we decided to remove this paragraph because it is not part of the main argument of the paper and we want to avoid unnecessary confusion.

9. [Table 4] There may be a better way to show the data in Table 4. What locations do the numbered locations (e.g. 286, 287..) refer to?

The numbering referred to ID numbers that we used in our model. We changed the numbering of the water use locations to 1-15 to avoid confusion.

10. [Figure 2] Is there a way to quantify the differences between these panels? The 3d graphics did not print very well on my copy of the manuscript, so the authors may want to consider something to increase their clarity.

We removed this diagram from the revised version to save space and because we have already presented a similar diagram in Riegels, et al., 2011.

Comments from Reviewer 3:

This paper uses an iterative hydro-economic optimization modeling to analyze the effects of different water and energy pricing policies on surface and groundwater resources. This combination or pricing, conjunctive water sources, and hydro-economics will be of interest to journal readers as will the results of the different price policies and what they mean for agricultural activities.

I had a difficult time following how the iterative optimization modeling method works and the methodology could be explained more clearly. I would suggest working from a global explanation: first explain the overarching optimization problem (decision variables, objective function, and constraints), how the various surface/groundwater, PMP, environmental and other components fit into the global optimization problem, and finally how the gradient search method iterates to find the globally optimal prices. The only optimization formulation presented (Equation 5) seems incomplete (only presents the PMP formulation?) and missing several of the key components which determine the optimal set of water prices.

Some more on the methods: much of the description of the methods focuses on the various assumptions made. Numerous assumptions are required for this kind of study and that is fine and even helpful as far transparency of work done. But the mathematical notation indicates both the economical and hydrological data and modeling are disaggregated by water use location whereas the text reads like there was an assumption used that the economic data is constant across the basin. Also, the paper never explains how the two pricing scenarios were actually implemented in the model. Thus, I would like to see the authors clarify the aggregation/disaggregation used in each model sub-component, how they integrate (see also the previous paragraph), and what parameter or structure changes were made to represent the pricing scenarios.

Additionally, I would suggest the authors use a more active writing style in the methods to focus on the work actually done rather than assumptions made.

We have re-written the Methods section following these suggestions.

Another major area for improvement is in the abstract and introduction. Currently they jump right in with the methodology undertaken (comparing two pricing policies). A much broader view is needed—what is the current problem motivating the work, why is it necessary to compare two pricing policies, and what is the contribution of the paper? Without this context, it's hard to evaluate whether the comparisons, methods, and results are appropriate.

We have re-written the Abstract and Introduction following these suggestions.

This is still a paper I would encourage the authors to revise and resubmit according to my comments. Below, additional line-by-line comments elaborate on and add to these general points.

1. Line 49. "'environmental and resource costs'". If this term is in quotes so early in the intro, it should be defined.

   We have removed the discussion in which this phrase appeared from the Introduction. We decided that it was enough to refer to the challenge of designing economic instruments to implement WFD objectives without getting into a discussion of the interpretation of the term "environmental and resource costs".

2. Line 77, “Probably the most significant…” In the intro, this statement should be more definitive. It is either the most significant or it is not.

   We have removed the discussion of the pros and cons of volumetric pricing from the introduction in order to focus on the systems analysis approach presented here, as we feel that this is the major contribution of this paper.

3. Line 87. “bionomial tariffs (combining…)”. The definition is fine but I have never before heard the term bionomial. In the U.S. these tariff structures are simply referred to as rate structures with fixed and variable charges. Also, in the U.S., these structures are not limited to agriculture -- many municipal U.S. water providers often use them too.

   Same comment as above.

4. Line 106. So I’m still unclear what exactly is the problem motivating the work? What will be done in this paper? What is the contribution?

   We have addressed this comment by re-writing the abstract and introduction as suggested in this reviewer’s general comments.

5. Lines 120-125. I’m confused about what is happening. In the optimization model, what is the objective function and constraints? Are they embedded directly into the model? Or tested with some outside simulation model? Is the optimization model choosing the price decision variables – or something outside? How are the prices used to estimate annual water demands? Again, is this part of the optimization, simulation, or something else? Then, “simulated flows and groundwater storage levels are checked…” Again, this sounds like this is part of the simulation… but shouldn’t it be a constraint in the optimization? To clarify all this, I would suggest more formally writing the optimization formulation in mathematical form on which the iterative approach is based.

   We have addressed this comment by re-writing the Methods section as suggested in this reviewer’s general comments. We now begin the Methods section with a formal statement of the overall optimization problem (lines 101-104).

6. Line 130. “gradient search”. What ensures the global optimal solution (set of prices) is found? If a starting set of prices must first be chosen, then it seems the gradient algorithm will point in the direction of steepest descent from the starting point and could end up at a local rather than global optimum.

   We have added a discussion of the pros and cons of our optimization approach to the Discussion section (lines 469-479).

7. Lines 162 – 163. “we assume no wells interfere.” Is this assumption appropriate or for mathematical tractability? If the former, the assumption should be substantiated, such as using results from the existing groundwater model.

We have provided support for this assumption in lines 167-169.

8. Lines 211-213. OK, here is the optimization formulation. The formulation still needs to explain in words what are the decision variables, objective function, and constraints.

   We have re-written the Methods section so that the overall optimization problem is stated at the beginning (lines 101-112).

9. Lines 214 – 238. So what in the model formulation/implementation actually changes to represent the second pricing policy where supply costs equal fixed capital plus operating costs?

   We now restate the optimization problem that is solved to estimate land use changes under the second (Mixed) pricing policy (lines 259-269).

10. Lines 236-238. Again, how is this assumption regarding responsibility for pumping costs implemented in the model?

    Pumping costs are incorporated into the supply cost term in Equation 4, which is a new equation that has been added to this revised version in order to make the welfare estimate for irrigation more clear. We think that it is now clear that pumping costs are included in this term under the first (Uniform) pricing policy, in which the irrigation operator assumes responsibility for groundwater pumping costs.

11. Line 246. From where is the price elasticity of demand estimate derived? From the meta analysis data presented by Dalhuisen et al? These elasticities can vary by region and I would like to see data more specific to the study site (or, alternatively, sensitivity analysis that shows a wide range of elasticities give the same result).

    Data specific to the study location were not available. We added text explaining that the elasticity value that we assume is similar to the average reported by Dalhuisen et al., and we do not investigate sensitivity to this assumption because urban/domestic use is less than 5% of total use in the case study basin (lines 282-286).

12. Lines 324-329. A few more words would be appropriate to describe how the ecological status indicator is actually calculated for intermediate values. Also, how is this indicator embedded in the model? I didn't see anything of this sort in the two constraints in Equation 5.

    More details about how the ecological status indicator is estimated have been added (lines 342-363). More information about how the indicator is used in the optimization approach is given in the statement of the overall optimization problem that has been added to the beginning of the Methods section (lines 91-104), and also in the summary of the overall optimization problem that has been added to the end of the Methods section (lines 388-

408). We think these additions make it clear how the ecological status indicator functions as a constraint in the overall optimization approach.

13. Line 367. "Predicted at one irrigation water use location…" Is there a way to synthesize results to show impacts at and across more locations?

    We have aggregated the results presented in this paragraph (lines 419-430) and in Table 2 across all irrigation water users that have access to both surface water and groundwater supplies. We have not aggregated results presented in the next paragraph (lines 432-436) or in Table 3 because the comparison of marginal costs would not be meaningful if aggregated across water use locations.