Gains from trans-boundary water quality management in linked catchment and coastal socio-ecological systems: a case study for the Minho region

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ABSTRACT

Sustainable economic development requires balancing of marginal costs from catchment water pollution abatement and associated marginal benefits from freshwater/coastal ecosystem appreciation. Hence we need to differentiate between intra- and trans-boundary catchments because benefactors and beneficiaries from water quality improvement are not one and the same. In trans-boundary catchments, private (national) welfare maximizing rates of water quality improvement differ across nations as benefits and/or costs from water quality improvement accrue to multiple nations. In this paper we develop a deterministic optimal control approach to explore private and social welfare maximizing rates of water pollution abatement in linked catchment and freshwater/coastal socio-ecological systems. For a case study of the Minho region (Iberian Peninsula), we estimate nation-specific water pollution abatement cost functions (based on management practice adoption) to determine and compare private (national) and social (trans-national) welfare maximizing rates of water pollution abatement and corresponding welfare implications. Results show that private (national) welfare maximization leads to increased rates of water pollution (+5%), while social (trans-national) welfare maximization leads to significant reductions in rates of water pollution (-14%) and maximum welfare gains (+1.4%). Non-cooperation in trans-national (social welfare maximizing) water quality management leads to increased rates of water pollution (up to +12%) and social welfare losses (up to -0.9%), though providing private (national) welfare gains for defecting nations (up to +3.8%).

KEY WORDS: *Water pollution, Abatement costs, Ecosystem services and values, Optimal control.*

INTRODUCTION

Freshwater and coastal ecosystems are affected by point and diffuse source water pollution originating from rural, urban and industrial land uses in coastal river catchments (e.g. Elofsson et al., 2003), even though these ecosystems are of vital importance from an environmental as well as an economic perspective (e.g. Cesar et al., 2002). Sustainable economic development of catchment regions requires balancing of the marginal costs from catchment water pollution abatement and the associated marginal benefits from freshwater/coastal resource appreciation (Hart & Brady, 2002; Gren & Folmer, 2003; Roebeling, 2006). In doing so, however, we need to differentiate between intra- and trans-boundary catchments as benefactors and beneficiaries from water quality improvement are not one and the same (Askari & Brown, 2001; Ward, 2007). In trans-boundary catchments the private (national) welfare maximizing rates of water quality improvement differ across nations as benefits and/or costs from water quality improvement accrue to multiple nations.

Economic incentives and market-based instruments can be used to internalize these beneficial spill-overs from water quality improvement, such that market behaviour could lead to social welfare maximizing outcomes (Shortle et al., 1998; Sadoff et al., 2008). This would, however, require international treaties and regulations that allow for international financial transfers of these welfare gains and that are based on verifiable water pollution measures or proxies (Elofsson et al, 2003; Ward, 2007). Provided full cooperation of all involved water polluting countries, market behaviour would then lead to efficient outcomes where marginal abatement costs and marginal abatement benefits are equal across all water polluting nations (Gren & Folmer, 2003).

The majority of studies on catchment water quality management do not take into account the downstream costs from water pollution and, thus, do not go beyond the usual cost-effectiveness analysis based on arbitrary 'tolerable' or target levels of pollution (see e.g. Elofsson et al., 2003; Janssen & Van Ittersum, 2007). Some of these studies carefully relate land use location and associated bio-physical conditions to economic production potentials, though either ignore or do not spatially explicit account for environmental impacts (e.g. Johnsen, 1993; Rounsevell et al., 2003; Hajkowicz et al., 2005). Other studies carefully relate land use location and associated bio-physical conditions to environmental impacts, though either ignore or do not spatially explicit account for economic impacts (e.g. Schleich et al., 1996; Neitsch et al., 2011; Lu et al., 2004). Only few of these studies integrate economic models with hydrological and/or soil models to explore opportunities for cost-effective water quality improvement through, for example, targeting of best management practices, land retirement and riparian buffers at the catchment scale (e.g. Braden et al., 1989; Khanna et al., 2003; Yang et al., 2005; Roebeling et al., 2006, 2009a).

There are a number of studies that do take into account the relationship between catchment water pollution and subsequent downstream costs from water pollution, while only a limited number of studies also consider the trans-boundary water management issues in these linked catchment and coastal ecosystems (Bennett, 2000; Elofsson et al., 2003; Ward, 2007). Earlier studies from Hawaii, the Caribbean, the Maldives and Australia are essentially numerical (e.g. Hodgson & Dixon, 1988;

Ruitenbeek & Cartier, 1999; Gustavson & Huber, 2000; Smith et al., 2005), whereas more recent studies also consider the underlying analytical features to water quality management in linked catchment and coastal ecosystems (e.g. Goetz & Zilberman, 2000; Hart & Brady, 2002; Roebeling, 2006, 2009b). Only sparsely these optimal control approaches are extended to the case of water quality management in trans-boundary catchments, thus establishing to what extent social welfare gains can be obtained through water pollution abatement across nations (e.g. Askari & Brown, 2001; Gren & Folmer, 2003).

In this paper we develop a deterministic optimal control approach to explore private (national) and social (trans-national) welfare maximizing rates of water pollution abatement in linked catchment and freshwater/coastal socio-ecological systems. For a case study of the Minho region (Iberian Peninsula), we estimate nation-specific water pollution abatement cost functions (based on management practice adoption) to determine and compare private (national) and social (trans-national) welfare maximizing rates of water pollution abatement and corresponding welfare implications.

METHODOLOGY

To explore private (national) and social (trans-national) welfare maximizing rates of water pollution abatement across nations, we adapt the Catchment to Reef Optimal Water Pollution Abatement (CROWPA) modelling approach (see Roebeling, 2006; 2009b) to the case of DIN water pollution by the key agricultural land uses across Spain and Portugal in the Minho catchment.

Let $B_{ter}(R_{t,ES})$ and $B_{ter}(R_{t,PT})$ denote national annual terrestrial benefits from agricultural production in Spain and Portugal, respectively, that are a function of the respective rates of DIN water pollution ($R_{t,ES}$ and $R_{t,PT}$; control variables). Let $B_{coa}(P_t)$ denote trans-national annual freshwater/coastal benefits from economic use and non-use values of the Minho freshwater/coastal ecosystems that are a function of the level of (Minho river) DIN water pollution (P_t; stock variable). National annual regional incomes, $\pi(P_t,R_{t,\mathrm{ES}})$ and $\pi(P_t,R_{t,\mathrm{PT}})$, are given by the sum of corresponding terrestrial and freshwater/coastal benefits:

$$\begin{aligned}\pi(P_t, R_{t,ES}) &= B_{ter}(R_{t,ES}) + zB_{coa}(P_t)\\ &= \left(\alpha_{1,ES} + \alpha_{2,ES}R_{t,ES} - \alpha_{3,ES}R_{t,ES}^2\right) + z(\beta_1 - \beta_2 P_t)\end{aligned} \tag{1a}$$

$$\begin{aligned}\pi(P_t, R_{t,PT}) &= B_{ter}(R_{t,PT}) + (1-z)B_{coa}(P_t)\\ &= \left(\alpha_{1,PT} + \alpha_{2,PT}R_{t,PT} - \alpha_{3,PT}R_{t,PT}^2\right) + (1-z)(\beta_1 - \beta_2 P_t)\end{aligned} \tag{1b}$$

where α_1 is the value of agricultural production without DIN water pollution, α_2 and α_3 are the linear and quadratic DIN water pollution benefit coefficients (note there are decreasing marginal benefits from DIN water pollution), where β_1 reflects the economic value of the Minho freshwater/coastal ecosystem in the absence of DIN water pollution and β_2 reflects the downstream DIN water pollution cost coefficient, and where z is the fraction of trans-national annual freshwater/coastal benefits accruing to Spain. Trans-national annual regional income, $\pi(P_t,R_{t,\mathrm{ES}},R_{t,\mathrm{PT}})$, is given by the sum of national annual terrestrial benefits and trans-national annual freshwater/coastal benefits:

$$\pi(P_t, R_{t,ES}, R_{t,PT}) = B_{ter}(R_{t,ES}) + B_{ter}(R_{t,PT}) + B_{coa}(P_t) \tag{1c}$$

The national private welfare (W_{ES} and W_{PT}) maximization problems now become:

$$\underset{R_{t,ES}}{Max}\, W_{ES} = \int_0^\infty \left[\pi(P_t, R_{t,ES})\right] e^{-rt}dt \tag{2a}$$

subject to $\dot{P}_t = b + R_{t,ES} + R_{t,PT} - aP_t$ (3)

$$\underset{R_{t,PT}}{Max}\, W_{PT} = \int_0^\infty \left[\pi(P_t, R_{t,PT})\right] e^{-rt}dt \tag{2b}$$

subject to $\dot{P}_t = b + R_{t,ES} + R_{t,PT} - aP_t$ (3)

with $P_0 > 0$, $R_0 > 0$, $P_t \geq 0$ and $R_t \geq 0$, and where r is the time discount rate, $\dot{P}_t$ is the equation of motion for P_t, and where a dot over a variable denotes the derivative of that variable with respect to time t. The equation of motion $\dot{P}_t$ (Eq. 3) is determined by the rate of DIN water pollution originating from other sources (b), the rate of DIN water pollution from agricultural production ($R_{t,ES}$ and $R_{t,PT}$) and the fraction of total DIN water pollution permanently lost from the system through deposition, transport, uptake and other biophysical processes (aP_t).

The steady state (i.e. $\dot{\lambda} = \dot{P} = 0$) private welfare maximizing rates of DIN water pollution from agricultural production in Spain and Portugal (R_{ES}^* and R_{PT}^*) as well as the private welfare maximizing level of DIN water pollution (P^*) are given by:

$$R_{ES}^* = \frac{\alpha_{2,ES}(r+a) - (z\beta_2)}{2\alpha_{3,ES}(r+a)} \tag{4a}$$

$$R_{PT}^* = \frac{\alpha_{2,PT}(r+a) - ((1-z)\beta_2)}{2\alpha_{3,PT}(r+a)} \tag{4b}$$

$$P^* = \frac{b + R_{ES}^* + R_{PT}^*}{a} \tag{5}$$

where the private welfare maximizing rates of DIN water pollution (R_{ES}^* and R_{PT}^*) are decreasing in α_3 and β_2, and increasing in α_2, r and a (Eq. 4a and 4b), while the private welfare maximizing level of DIN water pollution (P^*) is decreasing in a, and increasing in b, R_{ES}^* and R_{PT}^* (Eq. 5).

The trans-national social welfare (W) maximization problem is given by:

$$\underset{R_{t,ES},R_{t,PT}}{Max}\, W = \int_0^\infty \left[\pi(P_t, R_{t,ES}, R_{t,PT})\right] e^{-rt}dt \tag{2c}$$

subject to $\dot{P}_t = b + R_{t,ES} + R_{t,PT} - aP_t$ (3)

The corresponding steady state (i.e. $\dot{\lambda} = \dot{P} = 0$) social welfare maximizing rates of DIN water pollution from agricultural production in Spain and Portugal (R_{ES}^{**} and R_{PT}^{**}) as well as the social welfare maximizing level of DIN water pollution (P^{**}) are given by:

$$R_{ES}^{**} = \frac{\alpha_{2,ES}(r+a)-(\beta_2)}{2\alpha_{3,ES}(r+a)} \qquad (4c1)$$

$$R_{PT}^{**} = \frac{\alpha_{2,PT}(r+a)-(\beta_2)}{2\alpha_{3,PT}(r+a)} \qquad (4c2)$$

$$P^{**} = \frac{b+R_{ES}^{**}+R_{PT}^{**}}{a} \qquad (6)$$

THE MINHO CASE STUDY

The CROWPA modelling approach presented in the previous section is now used to compare rates of water pollution and corresponding welfare implications across Spain and Portugal in the Minho region (see Figure 1), for private (national) and social (trans-national) welfare maximization scenarios as well as partial non-cooperation scenarios. To this end we first determine parameter estimates for the terrestrial benefit functions for agricultural production in Spain ($B_{ter}(R_{ES})$) and Portugal ($B_{ter}(R_{PT})$), and freshwater/coastal benefits from use and non-use values of the Minho freshwater/coastal ecosystems ($B_{coa}(P_t)$).

Parameter estimates

The terrestrial benefit functions for agricultural production in Spain and Portugal in the Minho catchment (corn, vineyards and pastures), are estimated using the Soil and Water Assessment Tool (SWAT; see Neitsch et al., 2011). SWAT is a long-term catchment scale model that, on the one hand, integrates parameters related to water quality, hydrology, topography, climate, soil and vegetation cover to infer the water and nutrient balances at the catchment and sub-catchment scale and, on the other hand, includes a crop growth module (EPIC-based) to determine long-term agricultural production as a function of adopted agricultural practices (Neitsch et al., 2011). In combination with gross-margin analysis for the (plot level) financial-economic assessment of agricultural practice adoption (following Roebeling et al., 2012), SWAT can, as a result, be used to relate agricultural land use and practice location to corresponding (long-term) agricultural production, water pollution delivery and terrestrial benefits from agricultural production (Roebeling et al., 2012).

For reductions in nitrogen fertilizer application rates from current (100%) to reduced (from 80% to 20%, in steps of 20%) application rates, we estimate the terrestrial benefit functions per country by plotting the rates of DIN water pollution (R_{ES} and R_{PT}) against the corresponding terrestrial benefits ($B_{ter}(R_{ES})$ and $B_{ter}(R_{PT})$) and fitting the quadratic terrestrial benefit functions (see Eq. 1a and 1b). The terrestrial benefit functions for Spain and Portugal are, respectively, given by (in 2007 Euros):

$$B_{ter}(R_{t,ES}) = 78.1 + 42.867R_{t,ES} - 1.9754R_{t,ES}^2 \qquad (7)$$

$$B_{ter}(R_{t,PT}) = 13.3 + 17.420R_{t,PT} - 2.1891R_{t,PT}^2 \qquad (8)$$

with $B_{ter}(R_t)$ in m€/yr and R_t in kt DIN/yr.

The freshwater/coastal benefits from economic use and non-use values of the Minho freshwater/coastal ecosystems are based on De Groot et al. (2012), who estimate the total ecosystem service value of inland wetlands at 16,336 €/ha/yr and the value of rivers and lakes at 2,714 €/ha/yr. Considering that the Minho river is composed of river as well as wetland sections and given its total length of 74 km and average width of 450m, the total ecosystem service value of the Minho river (in its current state) is estimated at 31.8 m€/yr. The freshwater/coastal benefit function is given by (in 2007 Euros):

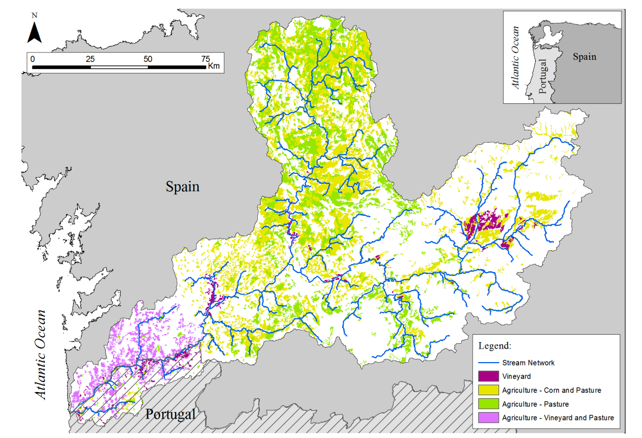

Figure 1. Land use in the Minho catchment (EEA, 2009).

$$B_{coa}(P_t) = (31.8 + \beta_2 P_0) - \beta_2 P_t \qquad (9)$$

with $B_{coa}(P_t)$ in m€/yr and P_t in kt DIN. The first term on the right-hand-side of Eq. (9) determines the maximum attainable freshwater/coastal benefits $B_{coa}(P_t)$ for specified marginal costs from freshwater/coastal water pollution β_2.

Results

Based on these parameter estimates we compare the rates of DIN water pollution from Spain and Portugal (R_{ES} and R_{PT}; using Eqs 4) and corresponding welfare implications, for private (national) and social (trans-national) welfare maximization scenarios as well as partial non-cooperation scenarios. Given downstream DIN water pollution costs of 10.0 €/kg DIN (β_2 = 10.0 m€/kt DIN), a time discount rate of 5% per year (r = 5%), no other sources of DIN water pollution (b = 0), ignoring re-suspension of DIN water pollutants (a = 1) and equal distribution of trans-national annual freshwater/coastal benefits between Spain and Portugal (z = 0.5), scenario simulation results are shown in Figure 2 and 3.

Current baseline rates of DIN water pollution (R_0) by Spain and Portugal are, respectively, 8.7 kt DIN/yr and 3.2 kt DIN/yr – totalling about 11.9 kt DIN/yr for the Minho catchment. Corresponding annual terrestrial benefits are estimated at 301.3 m€/yr for Spain and 46.8 m€/yr for Portugal (totalling about 348.0 m€/yr for the Minho catchment), while freshwater/coastal benefits are estimated at 31.8 m€/yr. Total trans-national annual regional income is, hence, estimated at 379.8 m€/yr.

Compared to the baseline situation, private (national) welfare maximization, that takes into account national terrestrial benefits and shared freshwater/coastal benefits (see Eq. 1a and 1b), leads to a 11% increase in rates of water pollution by Spain (to 9.6 kt DIN/yr) and a 10% decrease in rates of water pollution by Portugal (to 2.9 kt DIN/yr) – leading to an overall 5% increase for the Minho catchment (to 12.5 kt DIN/yr). Annual terrestrial benefits

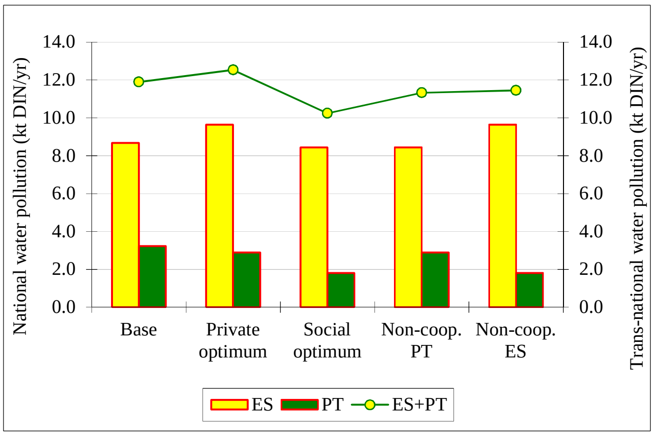

Figure 2. National and trans-national water pollution (in kt DIN/yr) for private (national) and social (trans-national) welfare maximization scenarios, and partial non-cooperation scenarios between Portugal (PT) and Spain (ES).

increase to 307.8 m€/yr in Spain (+2%) and decrease to 45.4 m€/yr in Portugal (-3%), while freshwater/coastal benefits decrease to 25.4 m€/yr (-20%). Total trans-national annual regional income decreases to 378.5 m€/yr (-0.3%).

Social (trans-national) welfare maximization, that takes into account trans-national terrestrial benefits and trans-national freshwater/coastal benefits (see Eq. 1c), leads to an almost 3% decrease in rates of DIN water pollution by Spain (to 8.4 kt DIN/yr) and a 44% decrease in rates of water pollution by Portugal (to 1.8 kt DIN/yr). Overall, rates of DIN water pollution from the Minho catchment decrease by about 14% (to 10.2 kt DIN/yr). Annual terrestrial benefits in Spain and Portugal decrease by 1% (to 299.2 m€/yr) and 20% (to 37.6 m€/yr), respectively, while freshwater/coastal benefits increase by 52% (to 48.3 m€/yr). Subsequent total trans-national annual regional income increases to 385.1 m€/yr (+1.4%).

Compared to the social (trans-national) welfare maximization situation, non-cooperation by Portugal in social (trans-national) welfare maximization, results in a 11% increase in rates of DIN water pollution from the Minho catchment (to 11.3 kt DIN/yr), while total trans-national annual regional income decreases by 0.8% (to 382.0 m€/yr). National annual regional benefits for Portugal increase, however, from 61.8 m€/yr to 64.1 m€/yr (+3.8%). Similarly, non-cooperation by Spain results in a 12% increase in rates of DIN water pollution from the Minho catchment (to 11.5 kt DIN/yr), while total trans-national annual regional income decreases by 0.9% (to 381.7 m€/yr). National annual regional benefits for Spain increase, however, from 323.3 m€/yr to 325.9 m€/yr (+0.8%).

Consequently, results show that private (national) welfare maximization leads to increased rates of water pollution (+5%), as respective nations equate marginal costs from water pollution abatement against a fraction (z) of the corresponding marginal benefits from freshwater/coastal resource appreciation. Social (trans-national) welfare maximization leads to significant reductions in rates of water pollution (-14%) and maximum welfare gains (+1.4%), as the marginal costs from water pollution abatement are balanced against the full marginal benefits from freshwater/coastal resource appreciation. Non-cooperation in trans-national (social welfare maximizing) water quality management leads to increased rates of water pollution (up to +12%) and social welfare losses (up to -0.9%), though providing private (national) welfare gains for defecting nations (up to +3.8%).

CONCLUSIONS AND DISCUSSION

In this paper we develop a deterministic optimal control approach to explore private (national) and social (trans-national) welfare maximizing rates of water pollution abatement in linked catchment and freshwater/coastal socio-ecological systems. The developed approach differs from existing approaches in a number of ways. First, we explicitly present an analytical derivation of private (national) and social (trans-national) welfare maximizing rates of water pollution using nation-specific abatement cost functions. Second, the developed analytical optimal control approach provides an elegant, stylized and easily understandable solution concept, thus contributing to the identification of efficient water quality improvement targets. Finally, we go beyond the usual cost-effectiveness analysis based on arbitrary 'tolerable' or target levels of pollution as we specifically account for the environmental benefits of water quality improvement in the downstream freshwater/coastal environment.

Results for the case study of the Minho region (Iberian Peninsula) show that private (national) welfare maximization leads to increased rates of water pollution (+5%), while social (trans-national) welfare maximization leads to significant reductions in rates of water pollution (-14%) and maximum welfare gains (+1.4%). Non-cooperation in trans-national (social welfare maximizing) water quality management leads to increased rates of water pollution (up to +12%) and social welfare losses (up to -0.9%), though providing private (national) welfare gains for defecting nations (up to +3.8%).

A number of caveats to this study need to be mentioned. First, while this study shows that social welfare gains can be obtained through a reduction in water pollution as compared to the current situation, continuous population growth and

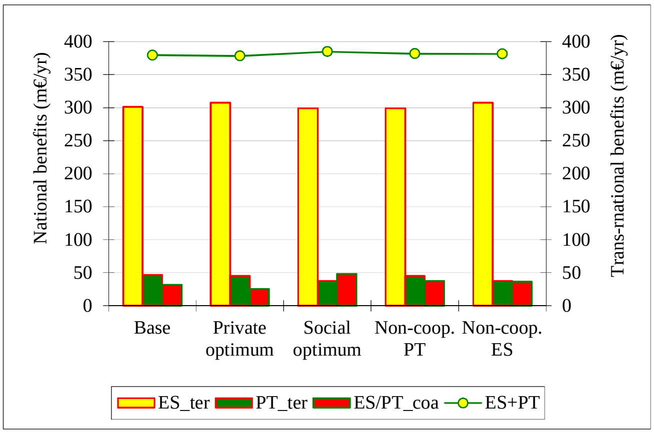

Figure 3. National and trans-national terrestrial (_ter) and coastal (_coa) benefits (in m€/yr) for private (national) and social (trans-national) welfare maximization scenarios, and partial non-cooperation (Non-coop.) scenarios between Portugal (PT) and Spain (ES).

economic development may lead to further increases in water pollution and critical freshwater/coastal ecosystem thresholds may be reached. Addressing these socio-economic development dimensions requires the inclusion of non-linear water pollution cost functions that reflect rapidly increasing costs from freshwater/coastal resource degradation beyond specific water pollution threshold values. Second, it must be emphasized that the water pollution abatement cost functions are based on current land use patterns as well as current land use practices in the Minho catchment and, consequently, do not include land use change and future land use practices. It can be expected that water pollution abatement costs are lower if land use change and future land use practices would be taken into account. Finally, the welfare maximizing rates of water quality improvement presented in this study are most likely underestimated as re-suspension of water pollutants and uncertainty in benefits from coastal and marine resource conservation have not been taken into account. Consequently and self-evidently, presented results provide a first indication of the gross direction and magnitude of change – not an exact recipe for change.

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