Estimating water pollution abatement cost functions using the Soil and Water Assessment Tool (SWAT)

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Abstract

Coastal ecosystems are increasingly affected by water pollution from anthropogenic sources in coastal catchments, even though these ecosystems are important from an environmental, social and economic perspective. Sustainable development of coastal regions requires Integrated Catchment and Coastal Zone Management (ICCZM) that specifically acknowledges the inherent relationship between coastal catchment land use, water pollution, ecosystem state and associated environmental values. In particular, to warrant sustainable economic development of coastal regions we need to balance the marginal costs from coastal catchment water pollution abatement and the associated marginal benefits from coastal resource appreciation. Diffuse source water pollution abatement costs across agricultural sectors are, however, not easily determined given the spatial heterogeneity in bio-physical and agro-ecological conditions as well as the available range of best agricultural practices for water quality improvement. We demonstrate how the Soil and Water Assessment Tool (SWAT) can be used to estimate diffuse source water pollution abatement cost functions across agricultural sectors – based on a stepwise adoption of identified best agricultural practices for water quality improvement and, corresponding, estimates for water pollution deliveries and agricultural incomes. A case study is presented for Dissolved Inorganic Nitrogen (DIN) water pollution by the key agricultural sectors in the Vouga catchment, Portugal. Results indicate that DIN water quality improvements of up to about 15% can provide a private gain to the agricultural sectors, while water quality improvements of up to 30% can be obtained at no additional cost to the agricultural sectors. DIN water quality improvements beyond these levels lead, however, to significant costs for the involved agricultural sectors.

Keywords: Diffuse source pollution; Abatement costs; Best agricultural practices.

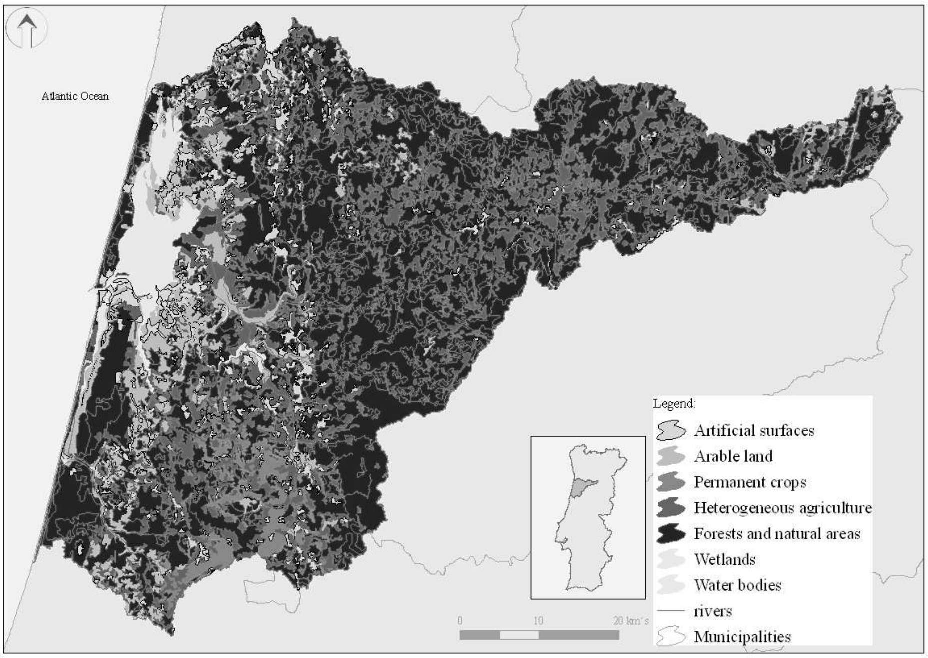
Introduction

Diffuse source water pollution from agricultural activities in coastal catchments tend to have negative impacts on coastal ecosystems which, in turn, are of vital importance from a social, environmental as well as an economic perspective (Roebeling et al., 2009b). Therefore, sustainable economic development of coastal regions requires balancing of the marginal costs from coastal catchment water pollution abatement and the associated marginal benefits from coastal resource appreciation (Gren & Folmer, 2003; Roebeling, 2006).Water pollution abatement costs are, however, substantial and differ between the several agricultural sectors as they are conditional upon: i) the specific bio-physical and agro-ecological conditions and ii) the range of available Best Agricultural Practices (BAPs) for water quality improvement.

This study aims to determine the costs related to the adoption of BAPs across agricultural sectors, using the Soil and Water Assessment Tool (SWAT; Neitsch et al., 2005). Based on a gradual adoption of identified BAPs for water quality improvement and, corresponding, (SWAT-based) estimates for water pollution deliveries and agricultural incomes, we estimate diffuse source water pollution abatement cost functions across agricultural sectors. A case study is presented for Dissolved Inorganic Nitrogen (DIN) water pollution by the major agricultural sectors in the Vouga catchment (Portugal).

The remainder of this paper is structured as follows. The next section encompasses the biophysical characterization of Vouga catchment, followed by a literature review regarding the estimation of water pollution abatement cost functions. Section 4 describes how SWAT can be used for estimating water pollution abatement cost functions, and Section 5 presents the application of this approach to the case of DIN water pollution in the Vouga catchment. Finally, in Section 6 we present the main conclusions and observations of this study.

Figure 1 – Land use in the Vouga catchment (CLC, 2006).



The Vouga catchment

The Vouga catchment covers an area of about 3685 km^2 and extends to a length (East-West) of ~150 km (Figure 1). The catchment has a complex hydrologic structure, characterized by a large lagoon area (~126 km^2 of wetland and water bodies) on the far West end of the stream network. Regarding the morphostructural structure, the catchment is divided into two major areas (West and East) which, in fact, are created by a tectonic ridge which confers distinct geological, morphological, hypsometric, hydrological and terrain characteristics (MAOT/INAG, 2000).

Table 1. Land use areas in the Vouga catchment (CLC, 2006).

Land use class	Land use category	Area (1000ha)	Area (%)
Artificial surfaces	All	28.6	6.4
Agricultural areas:	Arable land/Annual crops (I)	30.5	6,8
	Permanent crops (II)	11.5	2.6
	Heterogeneous agriculture (III)	69.3	15.4
	Other	3.1	0.7
Forest and natural areas	All	292.3	65.2
Wetlands	All	7.7	1.7
Waterbodies	All	5.5	1.2
Total			100.0

Climate in the Vouga catchment is typically Mediterranean, with only 5% of annual rainfall (@1300mm/yr) occurring in the summer months. Average daily temperature ranges between 6.9-10.2ºC in winter and 20.2-21.4ºC in summer (MAOT/INAG, 2000). Forest and natural areas are the major land use in the Vouga catchment, covering in total more than 65% of the total catchment area (Figure 1 and Table 1; CLC, 2006). The agricultural area covers about 25% of the total catchment area, and comprises heterogeneous agriculture (beet, cereals and fodder crops; ~15%), arable (annual) crops (maize, cereals and potatoes; ~7%) and permanent crops (vineyards; ~3%). Artificial surfaces, wetlands and water bodies constitute less than 10% of the total Vouga catchment area.

Table 2. Distribution of key types and sources of water pollutants in the Vouga catchment (MAOT/INAG, 2000).

Source	BOD5 (t/yr)	COD (t/yr)	TSS (t/yr)	N (t/yr)	P (t/yr)
Domestic	13276	29971	19914	1770	332
Industry	8675	31754	7726	-	-
Agriculture:					
Pig farming	560	1400	840	84	28
Cattle farming	883	999	10901	360	120
Diffuse Pollution	-	-	-	1795	143
Total	23394	64124	39381	4009	623

Note: BOD5 = Five Day Biochemical Oxygen Demand; COD = Chemical Oxygen Demand; TSS = Total Suspended Solids; N = nitrogen; P = phosphorus.

Point and diffuse source water pollution in the Vouga catchment, is related to domestic, industrial and agricultural activities (Table 2; MAOT/INAG, 2000). While CBO5, CQO and SST pollution originates, predominantly, from domestic and industrial sources, N and P pollution originate, almost equally, from domestic and agricultural sources.

Diffuse source N pollution accounts for almost 50% of total N pollution, and is exclusively related to agricultural activities.

According to the MAOT/INAG (2000), pollution generated by industry originates from the slaughter of animals, dairy production, vineyards, and paper and textile industries – pollution from agriculture originates from animal (pig and cattle) and crop (maize, potato, fodder and fruit trees) production. Measurements indicate that N water pollution occurs irregularly throughout the year, though is more pronounced during the wet months after fertilizer application (MAOT/INAG, 2000). This reinforces the need to specifically assess how the use of BAPs can reduce DIN delivery to the coast and, thus, mitigate the negative impacts of DIN water pollution on the receiving coastal ecosystems as well as the communities that depend on these ecosystems for their income generation.

Using information from the Food and Agriculture Organization of the United Nations (FAOSTAT, 2010), we calculated for each of the identified agricultural land use categories (see Table 1) the nitrogen application rate, crop yield and gross margin (Table 3). Note that for Category I (annual crops) we considered the weighted average values for corn, potatoes, barley and vegetables, for Category II (permanent crops) we considered the values for vineyards, and for Category III (heterogeneous agriculture) we considered the weighted average values for maize, barley, fodder and grain.

Nitrogen (N) application rates are highest for Category I (110 kgN/ha), followed by Category III (85.3 kgN/ha) and Category II (50kgN/ha). For the Vouga catchment, total N applied per year is largest for Categories III (~5900 tN/yr) and I (~3350 tN/yr), due to their largest production area as well as N application rates. Total N applied per year is lowest for Category II (~570 tN/yr), due to its small production area as well as relatively low N application rates.

Table 3. Agro-economic data regarding diffuse pollution sources in the Vouga catchment (CLC, 2006; FAOSTAT, 2010).

Category	Area	N applied		Agricultural production				Agriculture income
	1000ha	kg/ha	t/yr	Yield kg/ha	Production t/yr	Price €/t	Value m€	m€
I	30.5	110.0	3,352.7	6020	183,475	208.8	38.3	23.0
II	11.5	50.0	572.6	3921	44,907	969.2	43.5	26.1
III	69.3	85.3	5,905.8	3431	237,667	148.5	35.3	21.2
Total	111.3		9,831.1				117.1	70.3

Total production levels are largest for Category III (237,667 t/yr), followed by Categories I (183,475 t/yr) and II (44,907 t/yr) – thereby noting that Category I and III represent a mix of crops. Using corresponding crop prices and taking in account that production costs represent about 40% of the total production value (Productivity Commission, 2003), it is shown that agricultural income (i.e. production value minus production costs) presents a fairly homogeneous distribution across the different categories (between 21 and 26 m€/yr). Total agricultural income in the Vouga catchment equals about 70 million Euros per year.

Estimating water pollution abatement cost functions – a literature review

There are several approaches that relate land use models with hydrological, ecological and/or agronomic models to consider the externalities associated with agricultural production (see Nelson, 2002; Elofsson et al., 2003, Janssen & Van Ittersum, 2007). These approaches can be divided into three classes (Roebeling et al., 2009b):

1. Approaches that relate the location of land use and associated biophysical conditions to agricultural-economic production potentials, though that either ignore or fail to account for spatially explicit environmental impacts (see Yiridoe & Weersink, 1998; Rounsevell et al. 2003; Hajkowicz et al., 2005);
2. Approaches that relate the location of land use and associated biophysical conditions to environmental impacts, though that either ignore or fail to account for spatially explicit economic impacts (see Prosser et al. 2001; Neitsch et al., 2002, 2005, Lu et al., 2004);
3. Approaches that integrate economic models with hydrological and/or agronomic models to explore opportunities for cost-effective water quality improvement through, for example, land use and management practice targeting (see Khanna et al. 2003; Yang et al 2004, 2005; Roebeling 2009a, 2009b).

Catchment-scale water pollution abatement cost functions can be estimated using Class 2 or Class 3 approaches, that adequately assesses the relationship between local water pollution supply (i.e. gross supply of water pollutants to streams and rivers) and end-of-catchment water pollution delivery (i.e. net delivery of water pollutants to the coast). Roebeling et al. (2009a, 2009b) use a Class 3 approach to assess the abatement costs associated with the (spatially-efficient) adoption of BAPs across the catchment. In this study, the Class 2 model SWAT (Neitsch et al., 2005) is used to assess the abatement costs associated with the (non-spatially-efficient) adoption of BAPs across the catchment.

Using SWAT for estimating water pollution abatement cost functions

SWAT (Neitsch et al., 2010) is a catchment scale model that, on the one hand, integrates parameters related to water quality, hydrology, topography, climate, soil and vegetation cover to infer the hydrological balance at the catchment and sub-catchment scale (Nunes et al., 2008) and, on the other hand, includes a crop growth module (CropSys) to determine agricultural production as a function of applied (best) agricultural practices (Caldwell & Hansen, 1993). Hence, SWAT can be used to simulate the environmental (water quality) as well as economic (agricultural production) impacts for a wide range of BAP adoption scenarios – thus allowing to assess the cost-effectiveness of BAP adoption at the catchment scale.

The application of SWAT to the Vouga catchment is supported by its capacity to integrate data (meteorological, soil, hydrology, etc.) and to create homogeneous sub-catchments to simulate possible scenarios (Nunes, 2010). The ability to incorporate time-series data in orders of magnitude of a decade and to calculate water balances for each of the sub-catchments, allows a more objective analysis of the Vouga catchment. This analysis is based on the quantification of impacts from activities, practices and land uses, on the supply of water pollutants to the stream network. The alphanumeric data used in the application of SWAT to the Vouga catchment, include topography (SRTM90 -), land use (CLC, 2006; COS, 2007), vegetation cover (FAOSTAT, 2010), soil type (SROA, 1970), daily meteorology (IM, 2011; SNIRH, 2011) and hydrological (SNIRH, 2010) data, as well as water quality measurements (SNIRH, 2010) (see Caetano, 2007; Jarvis, 2008; Nunes, 2010).

Agricultural land uses considered in this study include annual crops (Category I), permanent crops (Category II) and heterogeneous agriculture (Category III), and considered BAPs relate to a reduction in N-fertilizer application rates. For each

Category I to III and based on data available from the Food and Agriculture Organization of the United Nations (FAOSTAT, 2010; Table 3), we used crop yield values for the period 1991-2008 (kg/ha) and average nitrogen application rates for the period 1999-2000 (kgN/ha). The corresponding production values (€/ha), production costs (€/ha) and gross margins (€/ha), were calculated using average prices for the period 2005-2008 (FAOSTAT, 2010).

Based on scenarios for a stepwise reduction in N-fertilizer application rates and, corresponding, (SWAT-based) estimates for water pollution deliveries (D) and agricultural incomes (π), we estimate diffuse source DIN water pollution abatement cost functions for each of the agricultural land use categories. To this end, and following Roebeling et al. (2009a, 2009b), we plotted the rate of water quality improvement (i.e. $WQI = [D]_{Baseline} - [D]_{Scenario}$) against the associated total water pollution abatement costs (i.e. $WPAC = [\pi]_{Baseline} - [\pi]_{Scenario}$) and fitted the quadratic water pollution abatement cost function:

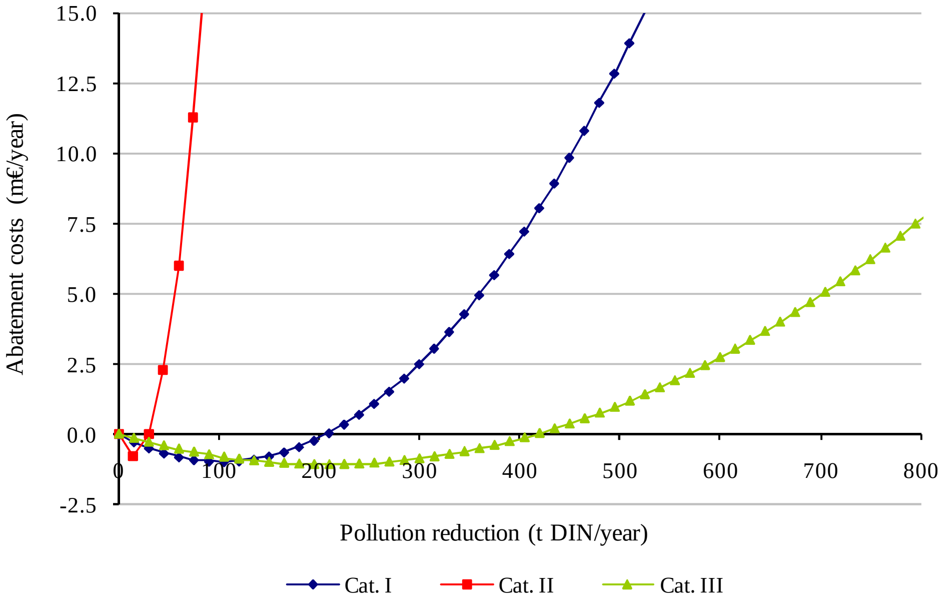
$$WPAC = \alpha_1 WQI + \alpha_2 WQI^2 \qquad (1)$$

where α_1 and α_2 are the linear and quadratic water pollution abatement cost coefficients, respectively.

Water pollution abatement cost functions for the Vouga catchment

Preliminary SWAT results for the Vouga catchment show that the Category I contributes ~610 tones of DIN per year, Category II (permanent crops) contributes with ~105 tDIN/yr, and Category III (heterogeneous agriculture) with ~1080 tDIN/yr. Total DIN delivery from the Vouga catchment is ~1800 t/yr. Overall, Category I contributes with nearly 35% to DIN delivery, although it represents less than 10% of the catchment area. Category II contributes with over 5% to DIN delivery, although it occupies less than 5% of catchment area. Finally, Category III contributes with about 60% and occupies approximately 15% of the area in the Vouga catchment.

Figure 2 – DIN water pollution abatement costs by agricultural category.



Potential opportunities to reduce DIN deliveries are higher in Category I and III, as compared to Category II (Figure 2). A decrease in DIN delivery of up to ~15% results in an increase of 5% and 4% in agricultural income for Category I and III, respectively. Benefits for Category II are, however, limited – less than 3% of agricultural income. While a decrease in DIN delivery of up to ~30% does not result in additional costs, decreases in DIN deliveries above these values come at a significant cost to agricultural producers in the Vouga catchment. For example, a decrease in DIN delivery of 50% implies: for Category I (-305 tDIN/yr) a cost of 2.5 m€/yr; for Category II (-50 tDIN/yr) a cost 2.3 m€/yr, and for Category III (-540 tDIN/yr) a cost of 1.7 m€/yr.

Conclusions and discussion

Using the SWAT model and following the approach developed by Roebeling et al. (2009a, 2009b), DIN water pollution abatement cost functions were estimated for the key agricultural sectors in the Vouga catchment (Central Portugal). The model allowed us to establish an analysis that included the various biophysical and agro-ecological conditions and, in turn, apply an economic component to assess the environmental-economic impacts of best agricultural practice (BAP) adoption. The DIN water pollution abatement cost estimates associated with the adoption of BAPs, allow us to assess the costs related to reduced nitrogen fertilizer application and, hence, establish the relationship between agricultural production and DIN deliveries.

Preliminary SWAT results show that, at the present time, annual crops (Category I), permanent crops (Category II) and heterogeneous agriculture (Category III) contribute, respectively, with ~35% ~5% and ~60% to total DIN delivery from the Vouga catchment, although these categories only occupy 7%, 3% and 15% of the catchment area. Potential opportunities to reduce DIN deliveries are larger in Category I and III, relative to Category II. Reductions in DIN delivery of up to ~15% result in an increase of up to 5% in agricultural income, while a decrease in DIN delivery of up to ~30% does not imply additional costs to agricultural producers. Decreases in DIN deliveries above these values come at significant costs to agricultural producers.

Market-based instruments can be used to encourage the adoption of those BAPs that are, not, profitable from a private-economic but, yes, profitable from a social-economic perspective (Roebeling et al, 2009c). The type of instrument to be used needs to be evaluated based on a consideration of total costs (i.e. abatement costs and transaction costs), given that transaction costs vary considerably between different instruments (Horan & Ribaudo 1999; Kampas & White 2002).

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