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Cost-effectiveness analysis for sustainable wastewater engineering and water resources management: a case study at Minho–Lima river basins (Portugal)

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ABSTRACT

A cost-effectiveness integrated methodology applied in a water resources management and sanitation project in Minho and Lima's region (Portugal) is presented. First, environmental objectives and programmes of measures (PM) are established and priorities are identified using a cause–effect assessment matrix and a global effectiveness index. Aiming to achieve more demanding goals, some complementary actions are considered, including "decentralized low-energy wastewater treatment plants construction". A geographic information system was used to select potential implementation sites, and suitable treatment processes for each location are identified. The centralized and decentralized wastewater treatment plants combination is promising, achieving a cost-effectiveness attendance of €1510/equivalent-inhabitant in Minho–Lima river basins.

Keywords: Cost-effectiveness analysis; Sustainable wastewater treatment; Water economics; Water Framework Directive (WFD)

1. Introduction

European Water Framework Directive (WFD) establishes a structure for action in the water policy domain, stipulating that water-uses economic analysis must contribute to an appraisal of the most cost-effective combinations of measures required under Article 11 [1]. Therefore, environmental and resource costs and benefits information is needed to design cost-effective measures. Meanwhile, there is a lack of clear specifications and methodologies lack to perform cost-effectiveness assessments at the European level [2]. Therefore, the interregional European project "AQUA — Preliminary Studies for the Water Framework Directive Implementation at the Minho–Lima River Basins" was focused on water services cost recovery and practical cost-effectiveness methodologies in order to support strategic priorities towards water resources protection and sanitation goals. In that regard, the potential of energy-saving and small-scale wastewater treatment plants, as complementary actions, was analyzed considering their feasibility in rural areas [3]. Indeed, despite the significant efforts carried out by the local water company, levels of wastewater drainage and treatment are still below the aimed level, mostly because of the dispersed settlements at the Minho and Lima region [4]. Furthermore, several water bodies risk failing good ecological status achievement, within the WFD timescale goals, and all measures that can contribute to overcome derogations should be assessed. Therefore, this communication presents a cost-effectiveness integrated methodology simplified scheme applied as a first screen in the context of Minho and Lima water resources management and sanitation goals (Fig. 1).

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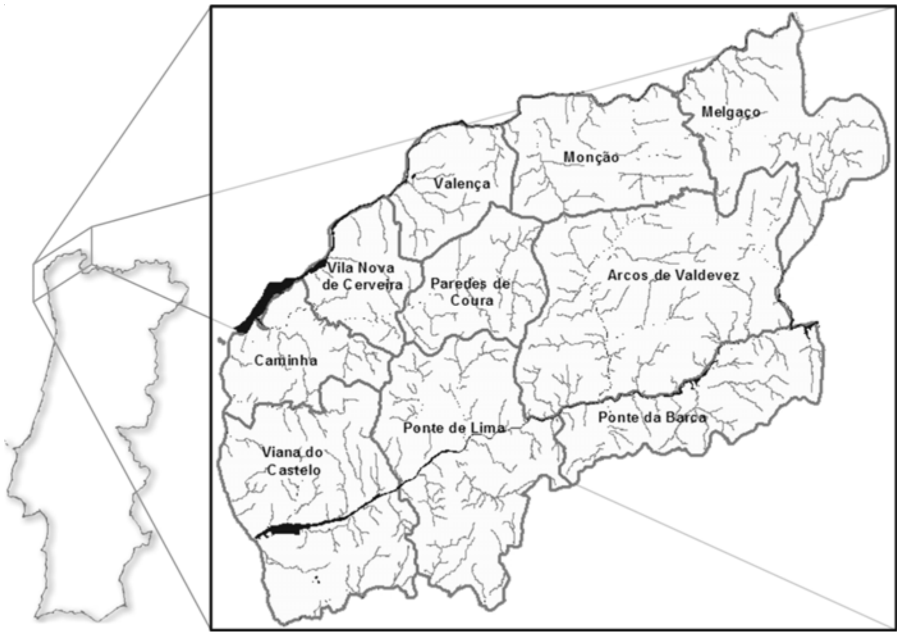

Fig. 1. Minho–Lima river basin study area (Portugal).

2. Methodology

This study comprises three interrelated tasks:

(1) Characterization of Minho–Lima river basins and water use trends (considering future scenarios of wastewater treatment levels);
(2) Definition of strategic and operational objectives addressing key thematic areas taking into account a set of environmental indicators according to a Pressure-State-Response model;
(3) Definition of a programme of measures (PM) based on the existing river-basin management master plans and focused on relevant actions for attaining WFD goals.

After the environmental objectives establishment, high-priority measures definition and complementary actions analysis was performed. This analysis is based on an integrated cost-effectiveness scheme, and Fig. 2 illustrates the methodological design of the comprehensive analysis.

Priorities definition was the cost-effectiveness analysis first level. Inquiring of stakeholders and professionals in order to score options, priorities were selected using a cause–effect assessment matrix and a global effectiveness index (EI), adapted from [5]. Several quality elements defined in the Annex V of WFD were considered in the cause–effect assessment matrix, namely biological, hydromorphological, physical-chemical and socioeconomic elements. The global effectiveness index calculation and priorities criteria are presented in Eq. (1) and Table 1.

Table 1
Criteria for global effectiveness index and related priorities

EI value range	Effectiveness assessment	Priority
1<EI<10	Low	1
11<EI<20	Medium	2
21<EI<30	High	3

$$\mathrm{EI} = \sum_{c=1}^{4} \left(\frac{\sum_{i=1}^{n} a_i}{n} \right) \times gr_c \quad (1)$$

where c — quality components ($c=1$: biological elements; $c=2$: hydromorphological elements; $c=3$: physical-chemical elements; $c=4$: socioeconomic elements), a — assessment indicators classification for each quality component; n — number of assessment indicators for each quality component: gr — relevance of each quality component.

In order to achieve more demanding quality goals, additional complementary actions for the high-priority measures were then proposed. In that regard, two sub-methodologies were applied: one based on the analysis of specific cost-effectiveness indicators (targeting the pressures associated with different responses), and an-

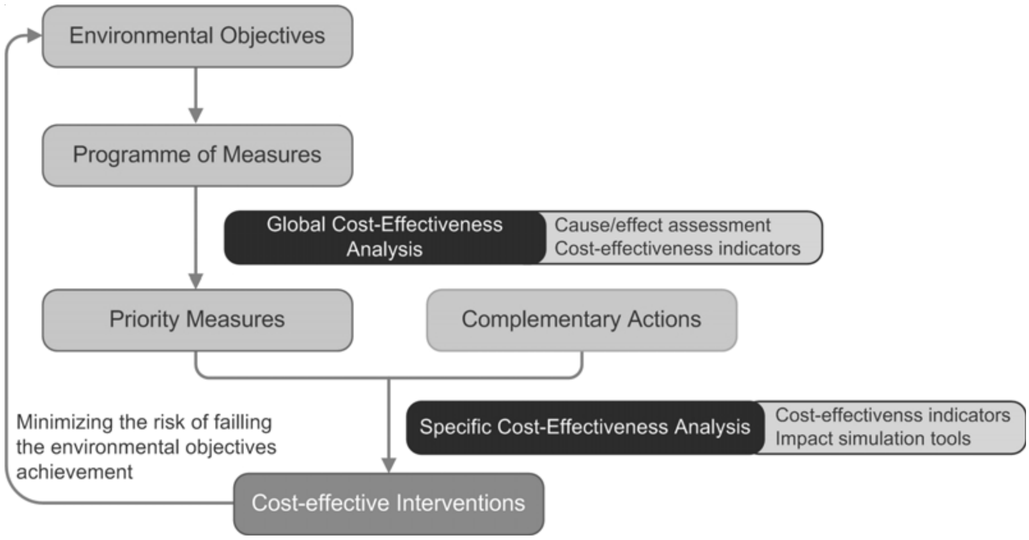

Fig. 2. Integrated cost-effectiveness analysis.

other one based on the environmental impacts assessed by simulation tools [6]. The final step consists of a comparative cost-effectiveness analysis between the PM and the complementary actions value added.

A complementary action "Construction of decentralized low-energy wastewater treatment plants" was assessed in order to increase the wastewater treatment services at rural zones of Minho and Lima's region where centralized wastewaters systems will not be built. A geographic information system was used to cross different characteristics (e.g. climate, water table depth, slope and soil permeability) and sort out a preliminary identification of sites with the best profile for this complementary action, as well as the more appropriate treatment technology to apply in each location. The PM investment requirements were based on the allocated costs derived from the river-basin master plans [7,8]. The estimating costs for decentralized wastewater treatment plants are presented in Table 2, and data from equipment suppliers were also collected for such purpose: €1000 p.e.$^{-1}$ up to 300 p.e.; €750·p.e.$^{-1}$ between 300 and 400 p.e.; €600 p.e.$^{-1}$ between 400 and 500 p.e.; €500 p.e.$^{-1}$ for more than 500 p.e. Finally, a comparative study of the impact of adding up complementary actions to the selected measures was carried out.

3. Results and discussion

Combining WFD goals and water utilities perspectives, Table 3 presents the multi-criteria results arising from the cause–effect matrix and global effectiveness index application. Those results allowed the identification of five "high priority measures" for which complementary actions were defined. Focusing the analysis on the *pollutants discharges assessment and control*, a complementary action regarding the *construction of 10 decentralized*

Table 2
Cost functions for decentralized wastewater treatment systems

Technology	Cost function		Optimized range (p.e.)	Removal rate (%)		
	Construction and equipment	Operation		BOD_5	TSS	P
Slow-rate irrigation systems	$y = 32.6\ e^{-0{,}0025x}$	$y = 5.0\ e^{-0{,}0019x}$	0–500	90–95	90–95	75–85
Peat filters	$y = 333.1\ e^{-0{,}0002x}$	$y = 13.2\ e^{-0{,}0002x}$	1000–2000	80–85	95–99	10–30
Aerated lagoons	$y = 131.5\ e^{-0{,}00006x}$	$y = 20.1\ e^{-0{,}00003x}$	1500–12000	80–95	70–90	40–60
Constructed wetlands	$y = 371.3\ e^{-0{,}001x}$	a.d.	150–800	98	99	81

Investment costs: y – Investment cost/Equivalent population (€·p.e.$^{-1}$); x – Population (p.e.).
Operation costs: y – Operation cost/ Equivalent population (€·p.e.$^{-1}$); x – Population (p.e.).

Table 3
Cause–effect matrix for environmental decisions at Minho–Lima river basins

	Biological elements			Hydro-morphological elements		Physico-chemical elements				Socioeconomics			Effective-ness index	Priority classifica-tion
Measures	Aquatic flora	Benthic inverte-brates	Fish	Water regula-tion	Riparian zone structure	Oxygena-tion conditions	Salinity	Nutri-ents	Prioritary sub-stances	Water needs	Effective water usage	Costs recov-ery		
Control of wastewater discharges	●●●	●●●	●●●	○	●●●	●●●	●	●●●	●●●	●●	●	●●●	23	3
Prevention of diffuse pollution	●●●	●●●	●●●	○	●●●	●●	●●	●●●	●●●	●●	●	●●	22	3
Selection of WWTP sludge disposal sites	●	●	●	○	●	●	○	●●	●●	○	○	●	8	1
Definition of ecological flows	●●	●●	●●●	●●●	●●	●	○	○	○	○	○	○	8	1
Recovery of fish populations	●●	●	●●●	●●●	●	●	●	●	●	○	○	○	9	1
Restoration of riparian zones	●●●	●	●●	●●	●●●	●	●	●	●	○	○	○	10	1
Protection of water abstraction points	○	○	○	○	○	○	○	○	●●	●●●	●●	●	10	1
Water supply services improvement	○	○	○	●●●	●	●●●	●●●	●●	●●	●●●	●●●	●●●	22	3
Minimization of losses in the water supply systems	○	○	○	●	○	○	●●●	○	○	●	●●●	●	9	1
Valorization of fluvial beaches	●	●	●	●	●	○	○	○	○	○	●	●●●	8	1
Delimitation of the water domain	●	●	●	●●	●●	●	●	●●	●●	●	●●	○	13	2
River banks conservation	●●	●	●	●●●	●●	○	○	●	●	○	○	○	7	1
Droughts prevention	●	●	●	●	●	●	○	○	○	●●●	●	○	9	1
Floods prevention	●	○	●●	●●●	●●	○	○	○	○	●	●●	●	10	1
Prevention and minimization of accidental pollution effects	●●	●●	●●	○	●●	●	○	●●	●●●	○	●	●	12	2
Water management costs recovery	○	○	○	○	○	○	○	○	○	○	●●●	●●●	8	1
Better integration of river-basin management (including transboundary relations)	○	○	○	●●●	○	●	○	●●	●●	●●	●	○	9	1
Surface water monitoring	●●●	●●●	●●●	●	●●	●●	●●	●●	●●●	●●	●	●●	21	3
Groundwater monitoring	○	○	○	●●	○	●	●	●	●●	●●●	●●	●●●	15	2
Ecological monitoring of aquatic ecosystems	●●●	●●●	●●●	●●	●●●	●●●	●●	●●●	●●●	○	●	●●	21	3
Water information and public participation	●	●	●	●●	○	○	○	○	●	●●	●●●	●●	13	2
Educational programs for water resource protection	○	○	○	○	○	○	○	○	●	●●	●●●	●	9	1

○ – very low impact, ● – low impact, ●● – medium impact, ●●● – high impact.
Priority classification: 1 – low priority; 2 – medium priority; 3 – high priority; g – high priority measure.

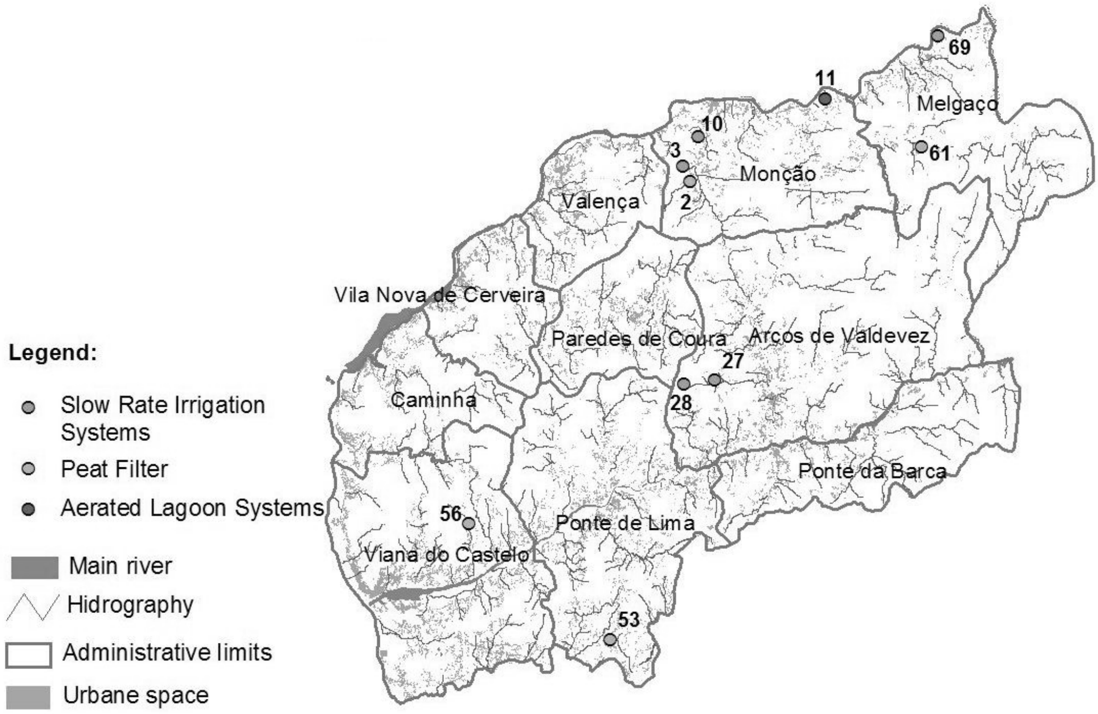

Fig. 3. Potential locations for decentralized low-energy wastewater treatment plants.

low-energy wastewater treatment plants was then set using a cross-comparison between land characteristics and economic criteria. The results are shown in Fig. 3.

The PM implementation without complementary actions will not lead to a substantially different picture in Minho and Lima's region in 2015. Such a business-as-usual scenario will not put significant pressure on the water resources on a regional scale (due to the low population density and rural pattern in the areas without wastewater treatment facilities). However, the absence of secondary treatment near water abstraction wells may raise public health risks due to soil and water contamination. Table 4 presents the effectiveness and cost-effectiveness indicators for the scenarios with and without the complementary action.

A combination of centralized and decentralized wastewater treatment plants allow a cost-effectiveness attendance of €1510/equivalent-inhabitant. Implementation of such sustainable low-energy wastewater treatment plants (as a complement to the centralized wastewater treatment plants) supports a slightly lower cost-effectiveness relationship when compared to the business-as-usual scenario.

4. Conclusion

Cost-effectiveness methodologies can be very useful tools for the PM definition and priorities selection, thus

Table 4
Effectiveness and cost-effectiveness indicators for two scenarios (programme of measures only or with complementary action)

Implementation costs of complementary actions	€126,400,000	
Effectiveness indicators (2015)	(PM)	(PM+CA)
Removal of wastewater organic matter (10^3 kg·year^{-1} BOD_5)	3820 t·y^{-1}	3875 t·y^{-1}
WWTP service upgrade (% of p.e. and p.e.)	61%; 159 826 p.e.	64%; 164 026 p.e.
Cost-effectiveness indicators (2015)	(PM)	(PM+CA)
Removal of wastewater organic matter (€·kg BOD_5 removed)	€3.22·kg^{-1}	€3.17·kg^{-1}
WWTP service upgrade (1000€ per each new inhabitant served)	€1540·inhab^{-1}	€1510·inhab^{-1}

PM: programme of measures; PM + CA: programme of measures plus complementary action.

contributing to a better decision-making process. The present work intended to test a practical cost-efficiency methodology, providing qualitative and quantitative results in a first assessment of measures and complementary actions in Minho–Lima river basins, combining WFD and sanitation goals within the context of a regional water services company. The iterative processes that link economic analyses and pressures and impacts analysis should continue in order to move forward cost-effectiveness methodologies.

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