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Development of a multi-factorial model to assess the sustainability of irrigation wastewater reuse: application to case studies in Sicily

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Abstract. The reuse of wastewater is a non-conventional water resource that is an essential measure for climate change adaptation. This research introduces an index based on a holistic methodology to evaluate the techno-economic, water-related, and environmental sustainability of wastewater reuse for agricultural applications. The development of the model is structured in the following phases: estimate of preliminary reuse factors, assessment of screening factors, selection of appropriate treatment schemes, assessment of cost factors. The first phase is fundamental to calculate annual reusable volume and the water level stress index (LWSI). Screening factors include desertification tendency, BOD, nitrogen, and phosphorus loads in water bodies, ecological sensitivity of the area, nitrate vulnerability, organic carbon and heavy metal content in soils, and the risk of aquifer contamination. The treatment schemes are selected based on the presence of a storage reservoir and on the nitrate vulnerability of the area. Cost factors include costs of upgrading supply network, pumping system and monitoring soil. The model also includes the calculation of the economic benefit. The model is applied to 101 wastewater treatment plants in Sicily. The obtained results reveal high sustainability indexes attributed to the rising of market prices, which in turn increased the direct economic benefit associated.

Keywords: sustainability index, water level stress index, screening factors index, cost curves, annual reclaimed volume.

1. Introduction

Reusing wastewater represents an alternative water source that plays a crucial role in adapting to the impacts of climate change. These effects are especially pronounced in the Mediterranean region, where climate change combined with population growth is projected to raise irrigation demand by 74%, putting even greater pressure on already scarce water resources (Fader et al., 2016). This study presents an index developed through an integrated methodology to assess the sustainability of wastewater reuse in agriculture, considering techno-economic, water-related, and environmental aspects. The developed Sustainable Water Reuse Index (SWRI) is the output of a multi-factorial model that can be used as a Decision Support System (DSS) to prioritize reuse projects by the Political Authority.

2. Methodology, results and validation

2.1. Development of the model

The model is developed through a structured sequence of phases, including the estimation of preliminary reuse parameters, evaluation of screening criteria, identification of suitable treatment schemes, and cost-benefit economic analysis (Roccaro & Vagliasindi, 2007). The first phase enables the calculation of the annual reusable volume and the LWSI, by combining, respectively, data on WWTPs in the current state and future scenario, and data on the characteristics of the irrigation districts. Regarding second phase, screening factors considered are: desertification tendency, BOD, nitrogen, and phosphorus loads in water bodies, ecological sensitivity of the area, nitrate vulnerability, organic carbon and heavy metal content in soils, and the risk of aquifer contamination. The Screening Factors Index (SFI) is determined through a ranking-based approach, by aggregating the scores of all considered factors. The risk analysis was carried out in accordance with the JRC (*Technical Guidance Water Reuse Risk Management for Agricultural Irrigation Schemes in Europe, Maffettone & Gawlik*), WHO guidelines (*Sanitation Safety Planning: Manual for Safe Use and Disposal of Wastewater, Greywater and Excreta, 2015*; *Guidelines for the Safe Use of Wastewater, Excreta and Greywater. Vol. 1, Policy and Regulatory Aspects, 2007*) and Directive 3019/2024 about UWWTPs, as well as EU Regulation 2020/741. The risk analysis was carried out using the semi-quantitative method. The outcomes of the analysis were used to select the treatment schemes identified in previous studies (Roccaro et al, 2011; Roccaro et al. 2011; Roccaro et al. 2007). For last phases, cost factors include costs of upgrading supply network and WWTP, pumping system and monitoring soil. An analysis of the market is conducted for pipelines and associated pumping plant. For the estimation of WWTPs upgrade costs, cost curves from previous studies are used (Roccaro et al. 2011; Roccaro et al. 2010; Roccaro et al. 2011; Roccaro et al. 2007), while the calculation of soil monitoring costs is based on the selection of a sampling frequency. By combining crops prices data with information from irrigation districts, the direct economic benefit is calculated. This was then added to the indirect benefit from water freed up for civil uses, thus obtaining the total economic benefit. The following section presents the equation for calculating the SWRI.

$$\mathrm{SWRI} = (1 + \mathrm{LWSI} + \mathrm{SFI}) * \left(\sum \mathrm{B_i} - \sum \mathrm{C_i}\right)$$

2.2 Results and discussion

The model is applied to 101 wastewater treatment plants across Sicily. The resulting analysis shows elevated sustainability indices, largely driven by the increase in market prices, which enhances the direct economic benefits linked to the additional annual volume of reclaimed water introduced. The application also highlights that the most significant cost factors are related to transport and pumping, especially in the presence of steep negative elevation differences from the supply point. This underscores the importance of the geographical positioning of treatment plants relative to irrigation districts. At the same time, the model's compliance with regulations and guidelines on agricultural reuse ensures a high level of protection for the environment, the agricultural sector, and human health.

2.3 Validation of the model and conclusions

The sensitivity analysis is carried out in several ways: by setting increasingly higher SWRI thresholds and performing annual water balances for WWTPs meeting those requirements; by building a correlation matrix; by applying the AOT analysis; and by calculating both the initial investment and the 30-year economic return. In the first case, the higher the threshold, the less the regional water deficit is mitigated, as fewer and smaller plants are able to meet increasingly demanding SWRI levels. This highlights the greater feasibility and cost-effectiveness of reuse projects in decentralized systems serving small communities, especially when the index increases significantly. The correlation matrix revealed a strong relationship with the techno-economic analysis component. This correlation is clearly demonstrated by the SWRI interpolation line constructed as a linear function of variable $\sum B_i - \sum C_i$. The AOT analysis confirms the results of the correlation matrix while also showing the model's robustness as the sensitivity index shifts from its minimum to maximum value. The sustainability index provides a multidisciplinary perspective for the practical implementation of wastewater reuse projects in agriculture. It relieves the Policy Authority from evaluating technical aspects, as through a single value expressed in €/m³ (that is measure unit of SWRIs obtained), it enables the identification of which reuse projects are more urgent and should be prioritized over others.

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