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Analysis of the efficacy and cost-effectiveness of best management practices for controlling sediment yield: A case study of the Joumine watershed, Tunisia

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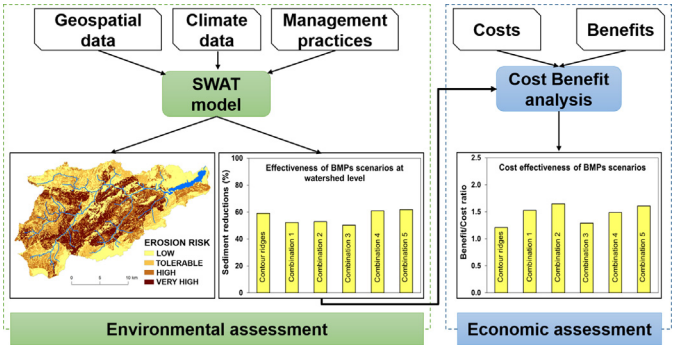
HIGHLIGHTS

- Soil erosion affects agricultural productivity and sustainable use of surface water resources.
- The efficacy and cost-effectiveness of Best Management Practices (BMP) is evaluated.
- Various BMP scenarios (applied individually and in combination) are evaluated.
- Combinations of BMPs scenarios are the most cost-effective at reducing sediment yield.
- The success of future conservation and management programs can be ensured.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil erosion can be reduced through the strategic selection and placement of best management practices (BMPs) in critical source areas (CSAs). In the present study, the Soil Water Assessment Tool (SWAT) model was used to identify CSAs and investigate the effectiveness of different BMPs in reducing sediment yield in the Joumine watershed, an agricultural river catchment located in northern Tunisia. A cost-benefit analysis (CBA) was used to evaluate the cost-effectiveness of different BMP scenarios. The objective of the present study was to determine the most cost-effective management scenario for controlling sediment yield. The model performance for the simulation of streamflow and sediment yield at the outlet of the Joumine watershed was good and satisfactory, respectively. The model indicated that most of the sediment was originated from the cultivated upland area. About 34% of the catchment area consisted of CSAs that were affected by high to very high soil erosion risk (sediment yield >10 t/ha/year). Contour ridges were found to be the most effective individual BMP in terms of sediment yield reduction. At the watershed level, implementing contour ridges in the CSAs reduced sediment yield by 59%. Combinations of BMP scenarios were more cost-effective than the contour ridges alone. Combining buffer strips (5-m width) with other BMPs depending on land slope (> 20% slope: conversion to olive orchards; 10–20% slope: contour ridges; 5–10% slope: grass strip cropping) was the most effective approach in terms of sediment yield reduction and economic benefits. This approach reduced sediment yield by 61.84% with a benefit/cost ratio

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of 1.61. Compared with the cost of dredging, BMPs were more cost-effective for reducing sediment loads to the Joumine reservoir, located downstream of the catchment. Our findings may contribute to ensure the sustainability of future conservation programs in Tunisian regions.

1. Introduction

Soil erosion by water is one of the main factors negatively affecting agricultural productivity and the sustainable use of surface water resources (Kefi et al., 2011). Heavy precipitation, low vegetation cover, topography, and intensive agriculture practices are the main causes of soil erosion (Pimentel and Burgess, 2013). This erosion process has numerous onsite and offsite impacts that affect the socio-economic, environmental, and sustainable development of many developing countries (Ananda and Herath, 2003). Onsite impacts include reductions in soil fertility, crop productivity, and nutrients. Offsite impacts include reduction in reservoir storage capacity, increased flood risk, eutrophication, and water quality degradation because of the discharge of sediments and pollutants (Moss, 2008; Boardman et al., 2009). Best management practices (BMPs) have been widely used to limit soil erosion impacts, control nonpoint source (NPS) pollution and improve agricultural productivity. BMPs can be structural, such as contour ridges, hill ponds and grassed waterways; or agronomic, such as no-till farming systems, afforestation, residue management, crop rotation, and strip cropping.

The Mediterranean region is particularly prone to erosion because basin sediment yield is greater in the environments of this region than in many other environments worldwide (Woodward, 1995). In this region, reservoir sedimentation is of particular interest because of its negative impact on the development of existing and future water resources and the large capital investments required to address reservoirs that have experienced high siltation prematurely. In Tunisia, one of the developing countries within the Mediterranean basin, about 19 million m^3 of reservoir storage capacity is lost annually because of sedimentation (Sarraf et al., 2007), corresponding to a loss of about 1% of the storage capacity of reservoirs every year (Ben Mammou and Louati, 2007; Irie et al., 2011). The cost of replacing this lost capacity was estimated at about 13 million USD based on the least expensive restoration options, such as the construction of new reservoirs. Moreover, the cost in terms of lost crop productivity was estimated to be 29.3 million USD (Sarraf et al., 2007).

To combat these issues, the Tunisian government has applied considerable resources to the implementation of BMPs through institutional and legislative measures, and has adopted two national management strategies for soil and water conservation and agricultural development, from 1990 to 2011. During this period, about 1,500,000 ha of agricultural land were managed by BMPs (especially contour ridges), many ponds ($n = 1080$) and structures for flood control and groundwater recharge ($n = 6556$) were constructed, and about 12,500 ha agricultural land was protected against urbanization (Kefi et al., 2011). Although these works contributed to the reduction of reservoir sedimentation and improved agricultural productivity, the Tunisian government has recently engaged in an effort to adopt a new strategy integrating new technical and organizational visions for agricultural land conservation and erosion mitigation. Therefore, the environmental and economic effectiveness of BMPs should be assessed before in-field construction to aid in decision making related to the mitigation of erosion with limited public funds and to ensure the success of future conservation and management programs.

The environmental effectiveness of BMPs in terms of sediment yield and/or NPS pollution reduction can be assessed by several watershed models (Xie et al., 2015), such as Agricultural Policy Environmental eXtender (APEX) (Williams and Izaurralde, 2005), Soil Water Assessment Tool (SWAT) (Arnold et al., 1998), Agricultural Nonpoint Source (AGNPS) (Young et al., 1989), Annualized Agricultural Nonpoint Source (AnnAGNPS) (Bingner and Theurer, 2005), and Hydrological Simulation Program–FORTRAN (HSPF) (Bicknell et al., 2001). Among these models, SWAT has been adopted widely because of its robust algorithms for simulation of the hydrologic system, sediment transport, and NPS pollutant transport, as well as its comprehensive database on agricultural management practices (Arabi et al., 2008; Parajuli et al., 2008; Yang et al., 2010; Tuppad et al., 2010; Betrie et al., 2011; Zhang and Zhang, 2011; Dechmi and Skhiri, 2013; Ramos et al., 2015). Most previous studies of these topics carried out in the Tunisian region have focused mainly on assessing the environmental effectiveness of individual BMPs, such as alternative scenarios of land-use management (Bouraoui et al., 2005), contour ridges (Abouabdillah et al., 2014; Ben Khelifa et al., 2016), and filter strips and fertilizer reduction (Aouissi et al., 2014). However, none of these studies assessed the environmental effectiveness of combinations of BMPs scenarios or the economic effectiveness of BMPs.

Economic assessment generally has been conducted by combining modeling and economic approaches. Thus, many studies have focused on using this strategy to investigate the cost-effectiveness of BMPs in terms of NPS pollutant reduction and/or sediment yield reduction (Srivastava et al., 2002; Arabi et al., 2006; Yang et al., 2010; Panagopoulos et al., 2011; Grimaldi et al., 2015; Smith et al., 2014) and a few studies have assessed the benefit/cost ratio of BMPs (Zhou et al., 2009; Liu et al., 2014). However, none of these studies focused on the cost effectiveness of the use of contour ridges, which has been adopted widely in Tunisian regions as a soil conservation and water harvesting measure. Additionally, previous studies have consistently not considered an appropriate discount rate that would make costs and benefits with different timescales comparable, which may have led to substantial underestimation of the true costs and benefits of BMPs. Such an economic parameter is critical for determining whether a public investment project for the implementation of BMPs is socially desirable, especially in developing countries where discount rates are high (8–15%) (Zhuang et al., 2007).

Contrary to worldwide progress on the subject, the economic effectiveness of BMPs has not yet been addressed in studies of Tunisian regions. Although the above-mentioned studies have provided a valuable list of BMPs with information on their cost effectiveness and potential benefits, referring to these findings to select the most cost-effective BMP scenario for use in Tunisian catchments cannot be considered because the impacts of BMPs are site specific and influenced greatly by geomorphological conditions, climatic conditions, and landscape characteristics, such as soil, land use, and agricultural management practices. Therefore, assessment of the cost effectiveness of BMPs in Tunisian regions may have interesting application potential. In this study, the environmental and economic effectiveness of various BMP scenarios was assessed to identify the most cost-effective BMP scenario for the control of sediment yield. A discount rate of 10% was considered to make the costs and benefits of BMPs with different timescales comparable. The Joumine watershed, a cropland-dominated watershed in northern Tunisia, was chosen as the study case. The results of the present study provide important information to aid decision making related to the reduction of sediment yield at an affordable cost and to ensure the success of future conservation strategies in Tunisian regions.