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Modeling a phosphorus credit trading program in an agricultural watershed

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ABSTRACT

Water quality and economic models were linked to assess the economic and environmental benefits of implementing a phosphorus credit trading program in an agricultural sub-basin of Lake Okeechobee watershed, Florida, United States. The water quality model determined the effects of rainfall, land use type, and agricultural management practices on the amount of total phosphorus (TP) discharged. TP loadings generated at the farm level, reaching the nearby streams, and attenuated to the sub-basin outlet from all sources within the sub-basin, were estimated at 106.4, 91, and 85 mtons yr^{-1}, respectively. Almost 95% of the TP loadings reaching the nearby streams were attributed to agriculture sources, and only 1.2% originated from urban areas, accounting for a combined TP load of 87.9 mtons yr^{-1}. In order to compare a Least-Cost Abatement approach to a Command-and-Control approach, the most cost effective cap of 30% TP reduction was selected, and the individual allocation was set at a TP load target of 1.6 kg ha^{-1} yr^{-1} (at the nearby stream level). The Least-Cost Abatement approach generated a potential cost savings of 27% ($1.3 million per year), based on an optimal credit price of $179. Dairies (major buyer), ornamentals, row crops, and sod farms were identified as potential credit buyers, whereas citrus, improved pastures (major seller), and urban areas were identified as potential credit sellers. Almost 81% of the TP credits available for trading were exchanged. The methodology presented here can be adapted to deal with different forms of trading sources, contaminants, or other technologies and management practices.

1. Introduction

Nutrient over-enrichment of freshwater lakes, streams, and reservoirs is a rapidly growing environmental problem, severely impacting freshwater resources worldwide. Many of the world's freshwater lakes suffer from eutrophication including Lake Erie and Lake Okeechobee (United States), Lake Victoria (Tanzania/Uganda/Kenya), and Tai Lake (China), among others. The rise in eutrophic events is generally attributed to the rapid increase in intensive agricultural practices, industrial activities, and population growth which have increased nutrient flows into the environment.

Lake Okeechobee, the largest lake in the southeastern United States (1890 km^2), is located in the center of the greater Florida Everglades ecosystem. It constitutes a critical link between lakes and rivers to the north, wetlands and bays to the south, and estuaries to the east and west. The environmental health of the Lake has been degraded as wetlands and natural habitats in the Lake Okeechobee watershed have been replaced with farms, urban areas, and dairy operations. Excessive phosphorus loadings from these diverse sources – including agriculture and livestock, municipal and industrial wastewater discharges, and urban stormwater runoff – have been identified as the leading causes of the Lake's impairment (FDEP, 2001). In order to protect the Lake and its designated uses (e.g., drinking, fishing, recreation, irrigation), a phosphorus Total Maximum Daily Load (TMDL) for it was adopted in 2001. This TMDL establishes an annual target load of 140 mtons of total phosphorus (TP) to Lake Okeechobee, including atmospheric deposition (35 mtons) and the sum of all TP-bearing surface water inputs to the Lake (105 mtons) (Zhao et al., 2012). Watershed projects, along with on-site agricultural and urban Best Management Practices (BMPs), are being implemented to reduce TP transport from uplands and capture runoff during high rainfall periods. BMPs are individual or combined management practices

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usually classified into management or structural practices. Management practices, such as efficient use of fertilizers, are owner-implemented BMPs. Structural practices involving the construction of more capital-intensive BMPs, are generally divided into typical practices (i.e., erosion control, etc.) and alternative practices (i.e., edge-of-farm stormwater retention/detention, etc.) (FDACS, 2011; SWET, 2006). Despite the high number of acres enrolled in the BMP program, a large percentage of the lands have neither reached the full level of typical/owner BMP implementation, nor have adopted more efficient alternative BMPs. This is mainly due to lack of funding and to the high costs associated with more advanced and efficient chemical treatments (FDACS, 2011). Consequently, the establishment of innovative economic incentives is essential to drive landowners to implement BMPs to their full extent.

Water quality trading programs have emerged as a promising alternative to assist in meeting nutrient water quality standards at an overall lower cost (Corrales et al., 2013; Kardos and Obropta, 2011). Studies conducted for the Great Miami River Watershed Trading Pilot program and for the Long Island Sound Nitrogen Credit Exchange reported cost saving estimates of \$314–\$385 million (Kieser and Associates, 2004) and \$200 million (CTDEP, 2010), respectively for each program. Trading allows one polluting source to meet its regulatory obligations by using pollution reductions achieved by another source with lower abatement costs (King and Kuch, 2003). The latter, in turn, obtains revenue for their efforts in reducing pollution. Because trading programs are expected to reduce the overall cost of complying with water quality goals, environmental agencies have recently focused their effort on this type of programs over traditional Command-and-Control approaches for water pollution control. Command-and-Control approaches are generally cost-inefficient and consist of implementing technologies that agencies deem to be most effective for controlling the amount of pollutant that may be emitted by pollution sources, with violators facing rigid financial penalties (Field and Field, 2006; Mariola, 2009; Paniccia, 2002).

The main objective of this study was to assess the economic and environmental benefits of implementing a phosphorus environmental credit trading program, as compared to a Command-and-Control approach. The S-191 sub-basin located within the Lake Okeechobee watershed was selected as a model focus area. A computational methodology coupling a water quality model to an economic model was developed in order to identify P-credits buyers and sellers, determine the optimal credit price, and assess the cost savings of a nutrient credits trading program. A complete trading scenario was detailed to assess the cost-effectiveness of a water quality trading program in the studied sub-basin. The specific objectives included simulating the optimal combination of BMPs to minimize the cost of achieving a specific phosphorus reduction goal, assessing the delivery trading ratios, and estimating the costs savings of a Least-Cost Abatement scenario versus a Command-and-Control approach.

2. Materials and methods

2.1. Study area description

The study area is the S-191 sub-basin located in Taylor Creek/Nubbin Slough Lake Okeechobee sub-watershed in southern Florida, directly north of Lake Okeechobee (Fig. 1a). The sub-basin covers 48,470 ha of a flat landscape with generally poorly drained soils characterized by a low phosphorus retention capacity (Zhao et al., 2012). This investigated area consists of a collection of tributary streams flowing into Lake Okeechobee through the S-191 flow control structure (Fig. 1b). The main tributaries are Taylor Creek, Nubbin Slough, Henry Creek, Lettuce Creek, Mosquito Creek, and Myrtle Slough (Fig. 1b). The annual average rainfall in the investigated sub-basin is 1168 mm (Zhao et al., 2012), and the land use classification is composed of agriculture accounting for approximately 74%, followed by forested areas (11%) and wetlands (9%). Runoffs from farms have been identified as the major source of the TP water quality problem in the S-191 sub-basin (Gale et al., 1993). Even though this sub-basin covers only about 3.5% of the drainage area in Lake Okeechobee watershed, it annually contributed about 34 mtons of TP to the Lake (during the last five years) (SFWMD, 2010), representing 32% of the TMDL. In addition, 99% of this sub-basin's waterbodies have been verified as impaired (USEPA, 2008). Therefore, local authorities have listed this sub-basin as a top priority basin for TP reductions.

The present study used a modeling framework, illustrated in greater detail in Supplemental Fig. S1, integrating a basin-wide hydrology/water quality model and an economic model to assess the cost-benefit of implementing a phosphorus credit trading program in the S-191 sub-basin. The hydrology and water quality model captured the effects of rainfall, land use management practices, and soil characteristics on water flows and phosphorus loads generated and transported within the basin and reaching the Lake. The results of the hydrology and water quality model were then used as input data for the economic model to identify the nutrient management practices, achieving a targeted load reduction at the lowest total cost.

2.2. Hydrology and water quality modeling

2.2.1. Description of the model

The Watershed Assessment Model (WAM) developed by Soil Water Engineering Technology (SWET), Inc. was used in this study to perform hydrology and water quality analysis in the S-191 sub-basin. WAM is a Geographic Information System (GIS) based model that simulates surface and ground water flow and nutrient constituents on a daily basis based on the detailed physical properties of the watershed, underlying hydrogeological system, and land use management practices (SWET, 2011a). WAM has been already calibrated and validated for the northern Lake Okeechobee watershed to characterize the hydrology and water quality of the watershed (HDR, 2004). WAM was also specifically calibrated (calibration period 2002–2004) and validated (validation period 2005–2009) for the S-191 sub-basin, where different Goodness-of-Fit (GOF) statistic measures indicated that the WAM model results closely fitted the observed hydrology and constituent loading data. During the calibration period, the Root Mean Square Error (RMSE), Mean Bias Error (MBE), and the Nash-Sutcliffe coefficient of efficiency (NS) obtained for monthly flows at the S-191 structure were 2.96 $m^3 s^{-1}$, 0.17 $m^3 s^{-1}$, and 0.90, respectively. During the validation period, the RMSE, MBE, and NS obtained for monthly flows at the same structure were 2.45 $m^3 s^{-1}$, 0.25 $m^3 s^{-1}$, and 0.84, respectively. The RMSE, MBE, and NS obtained for monthly TP loadings at the S-191 structure during the calibration period were 7383 kg, 174 kg, and 0.88, respectively and during the validation period, those values were 5345 kg, 1545 kg, and 0.77, respectively (SWET, 2011b).

The WAM model has been used in different studies to assess the nutrient assimilation, and to conduct nutrient and water budgets throughout the Lake Okeechobee watershed (Chebud et al., 2011; SFWMD et al., 2011; SWET, 2011a; SWET and JGH Engineering, 2007; USEPA, 2008). The WAM model provides a spatial representation of nutrient sources and transport processes (McCormick et al., 2011), and allows for the assessment of the effectiveness of current and future management practices in the watershed.