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Using fuzzy logic analysis for siting decisions of infiltration trenches for highway runoff control

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HIGHLIGHTS

- We assess the site feasibility of infiltration trenches using a fuzzy logic analysis.
- We compare the performance of fuzzy logic and one of the popular overlay analyses.
- The fuzzy logic analysis provides flexibility in developing a site suitability map.
- The new index map is then combined with the intrinsic groundwater vulnerability map.
- The specific locations of infiltration trenches are determined at the sub-basin level.

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ABSTRACT

Determining optimal locations for best management practices (BMPs), including their field considerations and limitations, plays an important role for effective stormwater management. However, these issues have been often overlooked in modeling studies that focused on downstream water quality benefits. This study illustrates the methodology of locating infiltration trenches at suitable locations from spatial overlay analyses which combine multiple layers that address different aspects of field application into a composite map. Using seven thematic layers for each analysis, fuzzy logic was employed to develop a site suitability map for infiltration trenches, whereas the DRASTIC method was used to produce a groundwater vulnerability map on the island of Oahu, Hawaii, USA. In addition, the analytic hierarchy process (AHP), one of the most popular overlay analyses, was used for comparison to fuzzy logic. The results showed that the AHP and fuzzy logic methods developed significantly different index maps in terms of best locations and suitability scores. Specifically, the AHP method provided a maximum level of site suitability due to its inherent aggregation approach of all input layers in a linear equation. The most eligible areas in locating infiltration trenches were determined from the superposition of the site suitability and groundwater vulnerability maps using the fuzzy AND operator. The resulting map successfully balanced qualification criteria for a low risk of groundwater contamination and the best BMP site selection. The results of the sensitivity analysis showed that the suitability scores were strongly affected by the algorithms embedded in fuzzy logic; therefore, caution is recommended with their use in overlay analysis. Accordingly, this study demonstrates that the fuzzy logic analysis can not only be used to improve spatial decision quality along with other overlay approaches, but also is combined with general water quality models for initial and refined searches for the best locations of BMPs at the sub-basin level.

1. Introduction

Management of diffuse pollution is of primary concern for the protection of the nation's water resources (EPA, 1994). Potential sources of diffuse pollution are widely distributed over watersheds, where their cumulative loads at major outlets extensively impair both surface water and groundwater quality (Schreiber et al., 2001). Examples of such pollution include leaching and runoff losses of fertilizers, manure, and pesticides from agricultural land (Novotny, 1999; Radcliffe et al., 2009) as well as surface runoff of suspended solids, organic matters, and metals from highways and urban areas (Kim et al., 2005; Ki et al., 2011; Lee et al., 2012). The current Total Maximum Daily Loads and National Pollutant Discharge Elimination System Permit Programs in the United States (US) entail establishing appropriate mitigation strategies for diffuse pollution control (Fang et al., 2005; Radcliffe et al., 2009).

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Best management practices (BMPs) are often implemented as effective measures for reducing diffuse pollutant loads, and restoring impaired waters to an acceptable level (Schreiber et al., 2001; Radcliffe et al., 2009; Lee et al., 2012).

Large uncertainties are expected to arise in assessing the performance of BMPs, as different studies have shown wide variations of pollutant removal efficiency (EPA, 1999). The efficiency of BMPs is strongly affected by several factors such as watershed characteristics (e.g., runoff and soil properties; Wu et al., 2006), design features (e.g., types, dimensions, and different combinations; Kaini et al., 2012), and geographic locations (e.g., topography and proximity to streams; Lee et al., 2012). Various models to simulate watershed hydrology and water quality such as SWAT (Kaini et al., 2012), HSPF (Wu et al., 2006), MIKE (Zhao et al., 2012), and SUSTAIN (Lee et al., 2012) have been used to quantify the different effects of these factors on the efficacy of the BMPs. Combining optimal search techniques (e.g., scatter search and genetic algorithms) with these models will yield cost-effective solutions that attenuate both runoff and pollutant loads, in terms of applicable BMP types (or their combinations), design features, and potential locations (Kaini et al., 2012; Lee et al., 2012). However, the existing methods (excluding SUSTAIN) rarely examined the site eligibility of selected locations based on the site selection criteria (i.e., geographic factors) recommended by the US Environmental Protection Agency (EPA) and individual states (EPA, 1999; HDOT, 2007). In particular, earlier studies have focused on meeting water quantity and quality goals around hotspot areas rather than a practical implementation of BMPs in the field, e.g., where to exactly locate it "within a given sub-watershed" to satisfy the site suitability criteria, low pollution potential to surrounding areas, site accessibility, etc.

Spatial overlay analysis in a geographic information system (GIS) has been successfully applied to site suitability analysis and risk/vulnerability assessment (Bojorquez-Tapia et al., 2009; Chen et al., 2010). Landfill site selection (Sener et al., 2010), habitat suitability evaluation (Gillenwater et al., 2006), landslide risk assessment (Ghosh et al., 2011), and groundwater vulnerability analysis (Panagopoulos et al., 2006) are a few illustrative examples of typical overlay approaches. In the overlay analysis, multiple thematic layers associated with the site selection criteria (i.e., geographic factors) are combined in a single index map based on a relative ranking system. In the output map, areas of environmental interest are illustrated with a numerical index, which is computed from both weights of each thematic layer and ratings of each attribute range in the relative ranking scheme. Numerous methods (e.g., different overlay methods or coupling overlay analysis with other statistical methods) have been suggested to mainly revise the weight and rating values of thematic layers, thereby improving the accuracy of the overlay analysis (Panagopoulos et al., 2006; Bojorquez-Tapia et al., 2009). However, there appears to be an inherent weakness in the proposed methods as long as the weights are subjectively determined by the preferences of the analyst and/or the attributes of a given layer are classified by a limited number of (discrete) rating scales (Alvarez-Guerra et al., 2009). In addition, different types of sensitivity analyses have been used interchangeably for spatial overlay analyses (Chen et al., 2010; Huan et al., 2012). Common methods for assessing changes in the output map involved eliminating one thematic layer at a time from the analysis (Huan et al., 2012) as well as modifying the weight, rating, or both, assigned for thematic layers (Chen et al., 2010). Yet, more research is needed to examine what methods are most appropriate.

In this study, a fuzzy logic analysis is used to overcome the major drawbacks of well-accepted overlay analyses (i.e., the subjective weightings and discrete ratings) in developing the index map (Joss et al., 2008; Raines et al., 2010; Caniani et al., 2011). The fuzzy logic analysis was applied to a site evaluation in locating infiltration trenches at eligible areas (on the island of Oahu, Hawaii, USA), where a two-tier approach was used to initially screen candidate sites and then determine the most suitable locations among them. This study uses the fuzzy logic analysis to (1) identify the difference between fuzzy logic and one of the popular overlay analyses, (2) determine the best locations for infiltration trenches that meet the site selection criteria with low groundwater pollution potential, and (3) assess the effect of each thematic layer on index map development. Using the fuzzy logic method that requires minimal prior knowledge on the weighting and rating values of the selected thematic layers, this study aims to provide greater flexibility in developing the composite index map over other overlay analyses. Thus, the proposed method, along with other approaches, can be used to support existing hydrologic and water quality models in identifying the best possible solutions to the BMP placement issue at both theoretical and practical levels.

2. Materials and methods

2.1. Thematic layers—including recommended criteria

Site suitability and groundwater vulnerability maps in locating infiltration trenches on the island of Oahu, Hawaii, USA, were developed using seven thematic layers for each approach. Table 1 shows fourteen thematic layers used for site selection and groundwater pollution analyses, where the data layers indicated by an asterisk (*) represent identical maps (i.e., A1 = B5 and A3 = B1). The thematic layers necessary for both analyses were obtained from a variety of sources available at the national and state levels (e.g., US Geological Survey and Source Water Assessment and Protection Program in the Hawaii State Department of Health), as shown in Table 1. The data layers used to assess the site suitability potential in this study (A1–A7) were similar to those of SUSTAIN, which has been recently released by the US EPA to provide an integrated analysis for BMP performance in various watershed scales (Lee et al., 2012). For example, the urban land use layer that provided information on the building boundaries and the impervious areas in SUSTAIN was not considered in our site suitability analysis, whereas the data layer representing the well locations (A6) was added to minimize the risk of water supply contamination. The thematic layers to examine the groundwater pollution potential were the same as those in the standard DRASTIC methodology recommended by the US EPA (B1–B7; Aller et al., 1987).

In the site suitability analysis, a topography layer (A1) was used to identify suitable locations as the installation of infiltration trenches on steep slopes was not possible (see Table 2). A land use and land cover (LULC) map (A2) was used to remove unsuitable sites for infiltration trenches (i.e., Open Water, Woody Wetlands, and Emergent Herbaceuous Wetlands). The hydrologic soil group (HSG) layer (A4) was employed to indentify suitable soils for infiltration systems (i.e., Classes A, B, and C in order of good water infiltration). Like the layer associated with public wells (PW, A6), the layers of depth to water (DW, A3) and streams (A5) were used to determine the minimum setback distances (i.e., 1.22 m and 30.48 m, respectively) needed to protect water resources; the longer the better. Conversely, the layer of roads (A7) was employed to define the maximum buffer zone distance (i.e., 8000 m) within which infiltration trenches should be implemented; the shorter the better.

However, a loose set of criteria was applied in some data layers, largely due to the limitations of finding available land in implementing infiltration trenches on Oahu Island (see criteria for topography and HSG layers in US EPA, Hawaii, and this study in Table 2). For example, the US EPA recommended areas of less than 5% slope as suitable sites (EPA, 1999), whereas this study used the topographic criterion as less than 45% slope (approximately 70% of the areas on Oahu would be eliminated from analysis if the US EPA guideline of 5% were applied). Due to the same reason, the hydrologic soil group D was only excluded from the analysis. Depending on the criteria established, some areas were, therefore, excluded from the analysis that determined suitable locations for infiltration trenches. After two basic spatial data types (i.e., raster and vector layers) were initially retrieved from the sources, raw