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Evaluation of source water protection strategies: A fuzzy-based model

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A B S T R A C T

Source water protection (SWP) is an important step in the implementation of a multi-barrier approach that ensures the delivery of safe drinking water. Available decision-making models for SWP primarily use complex mathematical formulations that require large data sets to perform analysis, which limit their use. Moreover, most of them cannot handle interconnection and redundancy among the parameters, or missing information. A fuzzy-based model is proposed in this study to overcome the above limitations. This model can estimate a reduction in the pollutant loads based on selected SWP strategies (e.g., storm water management ponds, vegetated filter strips). The proposed model employs an *export coefficient* approach and account for the number of animals to estimate the pollutant loads generated by different land usages (e.g., agriculture, forests, highways, livestock, and pasture land). Water quality index is used for the assessment of water quality once these pollutant loads are discharged into the receiving waters. To demonstrate the application of the proposed model, a case study of Page Creek was performed in the Clayburn watershed (British Columbia, Canada). The results show that increasing urban development and poorly managed agricultural areas have the most adverse effects on source water quality. The proposed model can help decision makers to make informed decisions related to the land use and resource allocation.

1. Introduction

Protection of water supplies is a main priority and an integral part of Canada's Science & Technology Strategy. However, increasing urbanization and emerging environmental issues are making water protection more challenging: both point pollution sources (PPS) (e.g., municipal and industrial discharges) and nonpoint pollution sources (NPS) (e.g., agricultural runoff and storm water) are increasing. Water sources for large cities like Toronto, Ottawa and Vancouver are comparatively well managed and adequate treatment is generally available to ensure 'reduced risk' to consumer health. However, for small and rural communities (SRC), achieving the same level of reduced risk under limited information and budgeting constraints is demanding (Timmer et al., 2007). Properly executed source water protection (SWP) strategies coupled with conventional water treatment can prove effective in ensuring safe drinking water supplies. Likewise, in the wake of the Walkerton inquiry, a multi-barrier approach is now recommended in Canada to ensure safe drinking water from source to tap, starting with SWP (O'Connor, 2002).

The goal of SWP is to provide protection against potential pollution or refine contaminated water if it is economically feasible. Protecting water at the source is always a preferred option (preventive action), compared to subsequent expensive water treatment technologies (mainly corrective action) (Wilsenach et al., 2003). Although source water generally refers to both ground and surface waters, this paper focuses on the latter. Strategies for SWP refer to watershed-based protection strategies that reduce contaminated water entering receiving water bodies.

Various SWP strategies have been implemented worldwide. Two major categories of SWP strategies include implementing low impact development (LID) activities and adopting best management practices (BMPs) (management of industrial, municipal and agricultural areas). Numerous studies have reported the benefits of SWP in terms of contaminant reductions in receiving water bodies (Arora et al., 2003; Borin et al., 2010; USEPA, 2000). In the most cases, organizations and authorities at the federal, provincial and municipal levels should coordinate efforts to make SWP programs effective and efficient.

Decision support tools can be very useful in making informed decisions related to the implementation of SWP strategies that

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can preserve and ultimately improve the quality of the water at source. A number of watershed decision models, such as AGNPS (Agricultural Nonpoint Source Pollution Model), GISPLM (GIS Based Phosphorus Loading Model) and WARMF (Watershed Analysis Risk Management Framework), provide a process for the calculation of pollutant loads based on land use, soil properties, precipitation patterns, vegetation type and related environmental factors (Chen et al., 2003; Walker, 1997; Young et al., 1987). These models are based on complex mass balance and empirical relationships (e.g., universal soil loss equation) and cannot handle water quality issues such as microbes, nutrients, organic matter, toxic substances and the aesthetics of water (Young et al., 1987). Export coefficients (land use-based pollutant export to the source water) (Lahlou et al., 1998) and counting animals[1] (ASAE, 2003[2]) provide a simpler, but pragmatic, approach that can be integrated easily with water quality assessment calculations.

Various methods for quality assessment of surface waters have been reported in the literature (e.g., Banerjee and Srivastava, 2009; Rajankar et al., 2009; Sedeno-Diaz and Lopez-Lopez, 2007). These studies propose a water quality index (WQI) based on selected water quality parameters. However, for water quality assessment at source, changes in WQI values have never been used as surrogates to estimate the impact of implementing SWP strategies.

Soft computing methods such as fuzzy logic can handle complex interrelations, redundancy, non-linearity and experts' opinions in the analysis. In the past, fuzzy-based methods have been used for water quality management (Icaga, 2007; Li et al., 2009; Ocampo-Duque et al., 2006). This paper will present a model that can predict the reduction in pollutant loads by implementing SWP strategies using a soft computing approach that can handle limited data and complex situations such as redundancy and interconnection among the parameters. Islam et al. (2011) have reviewed different SWP strategies, available models and necessary factors to develop a fuzzy-based decision model. This paper is a continuation of previous work undertaken by us and proposes a model using soft-computing methods (fuzzy-rule based approach) along with mass-balance and assessment of water quality with WQI. The paper basically presents the formulation and an in-depth discussion of the model using the case study of Page Creek in the Clayburn watershed, British Columbia (Canada).

2. Model development

Four important SWP strategies, vegetated filter strips (VFS), storm water management (SWM), fencing (Fen) and pollution control by agricultural practices (PCAP) were identified by Islam et al. (2011). SWM (also referred as LID) is efficient in controlling pollutant loads by equalizing and storing polluted water for a limited time; VFS aims at controlling and infiltrating pollutants, as well as slowing down rapid runoff by vegetation; and PCAP refers to agricultural practices (e.g., cover crop, crop rotation) and soil properties to control pollutant (basically nutrients) holding capacity. Fencing is a physical barrier to keep the livestock away from source waters. Interested readers can consult Islam et al. (2011) for more details. However, following is some brief background information for the proposed framework (Fig. 1) involving the following components: 1) *Component 1*: Estimation of reduced pollutant loads: initially calculates land use pollutants with an export coefficient or number of animals and then reduces pollutant loads (using selected SWP strategies), 2) *Component 2*: Estimation of pollutant concentration at source, and 3) *Component 3*: Estimation of the water quality index (WQI).

2.1. Reduced pollutant loads

2.1.1. Land use pollutants

The export coefficient (EC) concept is widely used to estimate the potential for pollutant loads based on soil erosion and runoff from different land uses (Loehr et al., 1989; Beaulac and Reckhow, 1982) such as agricultural, forests, pasture, livestock, roads/highways (urban type 1) and commercial areas (urban type 2). Generally, EC (estimated in terms of CFU/ha for coliforms and in kg/ha/yr for other pollutants) is used for total suspended solids, total nitrogen and total phosphorous. Table 1 provides EC values for different land uses (USEPA, 2001). It should be noted that the EC value for a specific land use can vary, depending on the local topography and precipitation.

Common formulation to estimate the concentration (mg/l) of a water quality parameter (pollutant) is given as following (USEPA, 2001):

$$C = R \times \frac{\sum_{i=1}^{n} \mathrm{EC}_i \times A_i}{\sum_{i=1}^{n} k \times P \times A_i} \quad (1)$$

where, C = pollutant concentration (mg/l) (for coliform CFU/l), EC_i = export coefficient for ith land use (kg/ha/yr) or (Kg/ha/month), A_i = area of the ith land use (ha), k = runoff coefficient representing the amount of precipitation after infiltration (unitless), depending on rainfall, runoff (%), P = yearly/monthly total precipitation (mm) and R = conversion factor (100).

For fecal coliforms (FC) and total coliforms (TC), the average site specific concentration for different land use or expert-based event mean concentration (EMC) can be obtained directly from studies by USEPA (2001) and Mishra et al. (2008). Since precipitation patterns can vary significantly in the reported studies, the monthly precipitation ratio (i.e., the ratio of the precipitation of the area under study to the precipitation of the reported study area) can be used to convert monthly concentration from reported data to the monthly concentration of the current study area.

For pollutants generated from manure in pasture and livestock, the ASAE (2003) approach can be used to calculate the monthly or yearly load in terms of kg/month or kg/year. ASAE (2003) provides reports for total generated manure expressed in terms of kilograms of total solids, total nitrogen (TN), total phosphorus (TP), 5-day biochemical oxygen demand (BOD_5), fecal coliforms (FC), total coliforms (TC) and lead (Pb) per/(1000 kg body weight of animal-day) or for coliforms (CFU/1000 kg body weight of animal-day). The average weights of different livestock have also been reported. Fresh manure usually contains 88%–92% water for non-poultry-based livestock and 73%–75% for poultry-based livestock (Ohio Livestock Manure Management Guide, 2006). Therefore, the equation for estimating the concentration of manure generated was developed using the ASAE (2003) formulation combined with a runoff equation as follows:

$$C_{\mathrm{WQP}} = S \times \frac{\sum_{m=1}^{n} G - \mathrm{WQP}_m \times \mathrm{BW}_m \times \mathrm{MMF}_m \times \mathrm{ND}}{k \times P \times A_P (or\ A_L)} \quad (2)$$

where, n = number of livestock types, C_{WQP} = concentration of water quality parameters (WQP) or pollutants (mg/l), BW_m = average body weight (kg) of the mth livestock type (ASAE,

[1] Animals located in the watershed can be sources of various pollutants (microbial, nutrients, suspended solids, etc.) indirectly for source water because of runoff transporting animal waste and/or directly if they have access to the source water.

[2] ASAE: American Society of Agricultural Engineers.