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Development of EMC-based empirical model for estimating spatial distribution of pollutant loads and its application in rural areas of Korea

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ABSTRACT

An integrated approach to easily calculate pollutant loads from agricultural watersheds is suggested and verified in this research. The basic concepts of this empirical tool were based on the assumption that variations in event mean concentrations (EMCs) of pollutants from a given agricultural watershed during rainstorms were only attributable to the rainfall pattern. Fifty one sets of EMC values were obtained from nine different watersheds located in the rural areas of Korea, and these data were used to develop predictive tools for the EMCs in rainfall runoff. The results of statistical tests of these formulas show that they are fairly good in predicting actual EMC values of some parameters, and useful in terms of calculating pollutant loads for any rainfall event time span such as daily, weekly, monthly, and yearly. This model was further checked in for its field applicability in a reservoir receiving stormwater after a cleanup of the sediments, covering 17 consecutive rainfall events from 1 July to 15 August in 2007. Overall the predicted values matched the observed values, indicating the feasibility of this empirical tool as a simple and useful solution in evaluating timely distribution of nonpoint source pollution loads from small rural watersheds of Korea.

Introduction

For many years, nonpoint source pollution in rural areas has been identified as a significant cause of surface water quality degradation and has been studied widely in the world (USEPA, 2003; Liang et al., 2008; Ongley et al., 2010; Gil and Im, 2014; Lee et al., 2010). For instance, agricultural sources are responsible for impairment of more than one-half of the rivers and lakes in the United States (USEPA, 2003; Rowny and Stewart, 2012). The causes and processes involved in the problems of nonpoint source pollution are complicated and vary from area to area; these include precipitation, soil erosion, agricultural drainage, the influence of topography, and types of land use (Novotny and Olem, 1994; Lai et al., 2011; Guo et al, 2014). To aid in estimating nonpoint pollution loads in rural areas, efforts have been made to develop predictive models and to produce some detailed models which have been successfully applied to specific sites. Regarding complexity, the estimating methods are grouped into three general categories: (1) simple methods; (2) mid-range models; and (3) detailed models (USEPA, 2003; Shen et al., 2012).

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Simple methods are used to provide quick and easy identification of critical pollutant sources in a watershed, which are widely used for nonpoint source pollution management in small rural watersheds due to their simplicity and practicality (Shrestha et al., 2008; Shen et al., 2012). Nevertheless, they are typically derived from empirical relationships between physiographic characteristics of watershed and pollutant export, and focus on continuing monitoring efforts. Accordingly, the output is in mean annual values or storm loads, and the predictive results are rough and have low transferability to other regions due to empirical details. In addition, simple methods consider few detailed representations of pollutant transport within and from the watershed.

On the other hand, detailed watershed models feature costly and time-consuming efforts to provide quantitative estimates of pollutant loads while providing a range of management alternatives. For a more accurate estimation of nonpoint source pollutants, comprehensive models have been developed. The Hydrological Simulation Program-Fortran, Soil and Water Analysis Tools, and Better Assessment Science Integrating Point and Nonpoint Sources are examples of models used in watershed management to simulate nonpoint pollutant transportation under various hydrological conditions (Nasr et al., 2007; Zhang et al., 2010; Chen et al., 2013). Incorporated with the geographic information system, these detailed models cover a range of variations in complex physical, chemical, and biochemical processes, and help estimate the effects of agricultural management measures and practices (USEPA, 2003). Conversely, these integrated and detailed models are complicated and require considerable time and expenditure for data collection and model application, which also need professional training for the model calibration and application.

Mid-range watershed models are generally midway between the cost, complexity, and accuracy of simple methods and detailed watershed models, supplying qualitative estimates of management alternatives (USEPA, 2003). Regarding mid-range models, the Agricultural Nonpoint Source (AGNPS) model or Annualized Agricultural Nonpoint Source (AnnAGNPS) were widely used and were validated for different conditions ranging from agricultural to forest areas, and can be used to simulate runoff, sediments, and chemical transport from a single storm event (Cho et al., 2008). Although AGNPS is a distributed model in the sense that watershed geometry is represented by uniformly distributed cells, its components are primarily empirical and lumped. For example, the AGNPS model uses the curve number and universal soil loss equation in estimating runoff and erosion from agriculture land (Cho et al., 2008; Shrestha et al., 2006; Polyakov et al., 2007). Still its application is restricted if detailed information is lacking because a large number of input parameters are necessary (Shen et al., 2012).

Therefore, developing a simple predictable model for general application in a small rural area would make the management of nonpoint pollution convenient and efficient (Donigian and Huber, 1991; Brezonik and Stadelmann, 2002). Here we seek to establish a useful empirical model through the compilation and analysis of EMC data sets obtained from different watersheds. The empirical tool presents a simple and understandable approach or concept based on the assumption that variations in event mean concentrations (EMCs) of pollutants from a given agricultural watershed during rainstorms were only attributable to the rainfall pattern. EMCs represent the concentration of a specific pollutant contained in stormwater runoff coming from a particular land-use within a watershed, are generally calculated from local storm water monitoring data. It is worth noting that EMCs of pollutants could vary over wide ranges in different agricultural watersheds due to other impact factors in addition to rainfall events, *e.g.*, topography, land use, climate, and agricultural management. Therefore, collection of site-specific EMCs of pollutants driven by rainfall events in different agricultural watersheds is the basic work for the development of empirical prediction tools.

However, obtaining the necessary data for calculating site-specific EMCs can be cost-prohibitive, and researchers or regulators often use values that are already available in the literature. If site-specific figures are unavailable, regional or national averages can be used, although the accuracy of these data is questionable. Due to the specific climatological and physiographic characteristics of individual watersheds, agricultural and urban land uses could exhibit a wide range of variability in nutrient export. Therefore, we have three objectives in this research: (1) to statistically characterize EMCs and loads in nine small different rural watersheds distributed in Korea; (2) to develop a predictive equation describing runoff volumes, loads, and EMCs using easily-measurable physical parameters such as watershed and rainfall in Korea; and (3) to examine the utility of the proposed model based on a comparison between the predicted and observed values in a reservoir.

1. Model development

The most important variable for a predictive model is EMC during the rainfall event, defined as (Ellis, 1986):

$$\mathrm{EMC} = \frac{\text{Total load}}{\text{Total runoff volume}} = \frac{\sum\{Q_i \times C_i \times \Delta t\}}{\sum\{Q_i \times t\}} \quad (1)$$

where, EMC (mg/L) is event mean concentration of a particular event, Q_i (m^3/hr) is discharge during time interval Δt (hr), C_i (mg/L) is concentration of pollutant during time interval Δt.

If the EMCs from the rainfall events are available, the pollutant load can be estimated based on the simple method, described as:

$$L = \mathrm{EMS} \times C \times R \times A \times f \quad (2)$$

where, L (kg) is nonpoint source load of pollutant in the nth rain event, R (mm) is rainfall depth, C (dimensionless) is runoff coefficient, A (ha) is area of the watershed, f is conversion constant (0.01).

Nonetheless, EMC has a wide variability due to specific climatological and physiographic characteristics of individual watersheds, land uses, and seasonal changes. Even in the same watershed, the EMC range changes significantly with diverse rainfall patterns. For that reason, we focused on finding a relationship among the main influence factors including the characteristics of watershed, rainfall information, and flow parameters. The general description can be expressed as:

$$\mathrm{EMS} = f(\mathrm{LANDUSE},\ \mathrm{SLOPE},\ \mathrm{RAINFALL},\ \mathrm{ADD}\ldots) \quad (3)$$