Environmental Pollution 159 (2011) 1932–1940

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Urban nonpoint source pollution buildup and washoff models for simulating storm runoff quality in the Los Angeles County

Long Wang [a], Jiahua Wei [a], Yuefei Huang [a,*], Guangqian Wang [a], Imran Maqsood [b]

[a] State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, China
[b] Faculty of Engineering and Applied Science, University of Regina, Regina SK S4S 0A2, Canada

ARTICLE INFO

Article history:
Received 11 September 2010
Received in revised form
8 March 2011
Accepted 10 March 2011

Keywords:
Buildup model
Nonpoint source pollution
Storm runoff
Urban
Washoff model

ABSTRACT

Many urban nonpoint source pollution models utilize pollutant buildup and washoff functions to simulate storm runoff quality of urban catchments. In this paper, two urban pollutant washoff load models are derived using pollutant buildup and washoff functions. The first model assumes that there is no residual pollutant after a storm event while the second one assumes that there is always residual pollutant after each storm event. The developed models are calibrated and verified with observed data from an urban catchment in the Los Angeles County. The application results show that the developed model with consideration of residual pollutant is more capable of simulating nonpoint source pollution from urban storm runoff than that without consideration of residual pollutant. For the study area, residual pollutant should be considered in pollutant buildup and washoff functions for simulating urban nonpoint source pollution when the total runoff volume is less than 30 mm.

1. Introduction

Urban storm runoff can result in significant water quality problems, including direct pollution of receiving waters, impairment of water treatment processes due to extreme fluctuations in raw intake water quality, and reduction of sewer system efficiency (Deletic and Maksimovic, 1998). Typical pollutants found in urban storm runoff include suspended solids, fecal coliform, nutrients, chloride, and heavy metals such as aluminum, lead, copper, and zinc (Tsihrintzis and Hamid, 1997). These pollutants impose considerable physical, chemical, and biological stresses on receiving waters which consequently pose risks to aquatic life and human health (Field et al., 1998).

For eliminating and controlling water pollution from urban storm runoff, Best Management Practices (BMPs) have been paid much attention by researchers and stakeholders. However, a better understanding of the processes behind urban runoff and pollutant generation is necessary to improve BMPs. Many urban nonpoint source pollution models, such as STORM (USACE, 1974), HSPF (Johanson et al., 1980), DR3M-QUAL (Alley and Smith, 1982), SWMM (Huber and Dickinson, 1988), and SLAMM (Pitt, 1998) have been developed and applied effectively in modeling urban stormwater quality. In these urban nonpoint source pollution models, pollutant buildup and washoff modules are the core components.

In most buildup and washoff models, antecedent dry days and total runoff volume are the two primary and important variables. Previous studies have been undertaken to investigate the relationship among pollutant washoff load, antecedent dry days and total runoff volume. Sartor and Boyd (1972) found a weak exponential relation between solids amount accumulated on an asphalt surface and antecedent dry days. Deletic and Maksimovic (1998) found no correlation between event mean concentration of suspended solids and antecedent dry days, but suggested that solids buildup process should not be completely ignored in water quality modeling of storm runoff. They also found that washoff load of suspended solids was strongly related to total runoff volume. Charbeneau and Barrett (1998) tried to build relation between TSS load and antecedent dry days in eight catchments, and found no significant correlation. However, they found that correlation existed between TSS washoff load and total runoff volume. Most researchers agree that total runoff volume is a suitable variable for building pollutant washoff models but there is still an argument about whether antecedent dry days is a suitable variable for building pollutant buildup models.

Models for simulating pollutant buildup and washoff load can be significantly different in terms of their variables, assumptions, and complexity (Charbeneau and Barrett, 1998). The most widely used models for calculating urban nonpoint source pollution were the

* Corresponding author.
E-mail addresses: wanglong08@mails.tsinghua.edu.cn (L. Wang), weijiahua@mail.tsinghua.edu.cn (J. Wei), yuefeihuang@tsinghua.edu.cn (Y. Huang), dhhwgq@tsinghua.edu.cn (G. Wang), imran@iseis.org (I. Maqsood).

0269-7491/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envpol.2011.03.019

exponential buildup and washoff functions (Chen and Adams, 2006). To develop these models, two kinds of assumptions were made. One is that pollutant is completely washed off by storm runoff from the previous rainfall event and there is no residual or initial pollutant on the catchment surface. Another one is that there is always a residual or initial pollutant available on the catchment surface after the previous storm runoff event. Charbeneau and Barrett (1998) presented two types of pollutant buildup functions based on the two assumptions but without any functions evaluation and application. Shaw et al. (2010) evaluated a traditional urban pollutant buildup/washoff model and a model assuming a constant pollutant amount available for washoff because they also observed a limited relationship between event load and antecedent dry days. They concluded that pollutant buildup models could be simplified if pollutant buildup between storm events is rapid or pollutant washoff during storm events is small. Sutherland and Jelen (2003) noted that the first assumption was unreasonable with evidence of pollutant buildup data collected by Sartor and Boyd (1972). They also noted that data on pollutant accumulation collected by Pitt (1985) subsequent to Sartor and Boyd's work clearly indicated that most rain events were not very effective at reducing accumulated street dirt. Therefore, they concluded that storm related washoffs that remove all accumulated street dirt appear to be quite rare and that a residual accumulation always exists.

Despite the fact that many studies assume residual pollutant exists after a storm event, there are numerous others that assume all pollutants were washed off. Deletic et al. (1997) used a pollutant buildup model suggested by Sartor and Boyd (1972) to model storm washoff of suspended solids from two small impervious catchments surfaces in Miljakovac-Belgrade, Yugoslavia and Lund, Sweden. Behera et al. (2006) built analytical probabilistic runoff quality models which were derived using exponential buildup and washoff functions without consideration of residual pollutant. Available field data from an urban catchment located in the Great Toronto Area were used to verify these models. Avellaneda et al. (2009) applied an existing accumulation and washoff model which assumes no residual pollutant on a large asphalt parking lot in the northeastern United States. These studies were carried out in areas with high percentage of impervious surface where pollutants are easily washed off by storm runoff. Only a few studies were undertaken to qualitatively analyze the differences of effectiveness and applicability of pollutant buildup functions based on the two assumptions (Alley and Smith, 1981; Charbeneau and Barrett, 1998). Therefore, it is necessary to quantificationally research whether residual pollutant load should be considered in stormwater quality modeling and on what condition residual pollutant load could be ignored.

In this paper, an improved urban pollutant washoff load model with consideration of residual pollutant load will be developed based on investigating previous urban pollutant buildup and washoff functions. The developed model will be then applied to an urban catchment in the Los Angeles County for illustrating its efficiency and advantages by comparing with previous models without considering residual pollutant load. Lastly, the threshold of total runoff volume will be determined under which residual pollutant load could be ignored for the study area.

2. Urban pollutant buildup and washoff functions

2.1. Pollutant buildup functions

Pollutant accumulation process on a catchment surface may be mathematically represented as a linear, power, exponential, or Michaelis–Menton function of antecedent dry days (Huber and Dickinson, 1988). The exponential function is the most widely used one since it has been used to develop pollutant accumulation models in many approaches on urban surface pollutant accumulation process (Sutherland and Jelen, 1998). In the exponential function, pollutant buildup follows an exponential growth curve that approaches a maximum limit asymptotically, and the pollutant buildup rate can be modeled as follows (Shaheen, 1975):

$$\frac{dB}{dt} = K_0 - K_2 B \tag{1}$$

where B is the pollutant amount per unit area on the catchment surface (mg/m^2); K_0 is the pollutant deposition rate (mg/m^2 d); K_2 is the pollutant removal rate ($1/d$); t is the time (d).

The parameter K_2 accounts for pollutant losses due to wind and vehicles as well as the biological and chemical decay of pollutant (Alley and Smith, 1981). Integration of Equation (1) yields:

$$B = K_1[1 - \exp(-K_2 T)] + B_0 \exp(-K_2 T) \tag{2}$$

where $K_1 = K_0/K_2$ is the maximum pollutant amount per unit area that can accumulate on the catchment surface (mg/m^2); T is the antecedent dry days (day); B_0 is the residual pollutant amount per unit area after the previous storm runoff event (mg/m^2).

Assuming that there is no residual pollutant after the previous storm runoff event ($B_0 = 0$), Equation (2) takes the form as follows:

$$B = K_1[1 - \exp(-K_2 T)] \tag{3}$$

2.2. Pollutant washoff functions

Pollutant washoff occurs during a wet weather period and can be mathematically represented as exponential washoff equation or rating curve washoff approach (Huber and Dickinson, 1988). For the rating curve washoff approach, the rate of pollutant washoff is proportional to the runoff rate raised to some power, and independent on the pollutant amount available for washoff on a catchment surface. This simple approach does not build any relationship between pollutant washoff rate and land surfaces from where pollutants are originated so that users cannot use it to evaluate effectiveness of control practices (Sutherland and Jelen, 1998). Therefore, the rating curve washoff approach is seldom used. In the exponential equation, it is assumed that the rate of pollutant washoff per unit area is proportional to the pollutant amount remaining on the catchment surface, which can be mathematically modeled as (Alley, 1981):

$$\frac{dM}{dt} = -K_4 M \tag{4}$$

where M is the pollutant amount per unit area on the catchment surface (mg/m^2); t is the time (min); K_4 is the pollutant washoff rate (1/min).

Integration of Equation (4) yields:

$$M = M_0 \exp(-K_4 T) \tag{5}$$

where M_0 is the initial pollutant amount per unit area on the catchment surface (mg/m^2); T is the duration of the storm event (min).

Assuming that K_4 varies in direct proportion to the average runoff rate, that is:

$$K_4 = K_3 \overline{R} \tag{6}$$

Equation (5) can be rewritten as:

$$M = M_0 \exp(-K_3 R) \tag{7}$$