Journal of Environmental Management 205 (2018) 73–84

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Development of urban runoff model FFC-QUAL for first-flush water-quality analysis in urban drainage basins

Sungchul Hur [a], Kisung Nam [b,*], Jungsoo Kim [c], Changjae Kwak [d]

[a] Department of Water Resource, Isan Corporation., Ltd., 14066, Anyang, South Korea
[b] Supervision Department, Dohwa Engineering Corporation., Ltd., 06178, Seoul, South Korea
[c] Department of Civil Engineering, Bucheon University, 14635, Bucheon, South Korea
[d] Department of Disaster Research, National Disaster Management Research Institute, 44538, Ulsan, South Korea

ARTICLE INFO

Article history:
Received 31 March 2017
Received in revised form
21 September 2017
Accepted 21 September 2017

Keywords:
Washoff equation
Pollutants
Peak flow
Peak concentration

ABSTRACT

An urban runoff model that is able to compute the runoff, the pollutant loadings, and the concentrations of water-quality constituents in urban drainages during the first flush was developed. This model, which is referred to as FFC-QUAL, was modified from the existing ILLUDAS model and added for use during the water-quality analysis process for dry and rainy periods. For the dry period, the specifications of the coefficients for the discharge and water quality were used. During rainfall, we used the Clark and time—area methods for the runoff analyses of pervious and impervious areas to consider the effects of the subbasin shape; moreover, four pollutant accumulation methods and the washoff equation for computing the water quality each time were used. According to the verification results, FFC-QUAL provides generally similar output as the measured data for the peak flow, total runoff volume, total loadings, peak concentration, and time of peak concentration for three rainfall events in the Gunja subbasin. In comparison with the ILLUDAS, SWMM, and MOUSE models, there is little difference between these models and the model developed in this study. The proposed model should be useful in urban watersheds because of its simplicity and its capacity to model common pollutants (e.g., biological oxygen demand, chemical oxygen demand, *Escherichia coli*, suspended solids, and total nitrogen and phosphorous) in runoff. The proposed model can also be used in design studies to determine how changes in infrastructure will affect the runoff and pollution loads.

1. Introduction

Recently, nonpoint pollutants have been reduced by the conversion of technology-based control to water-quality-based control in Korea. In spite of some difficulties in measurement and observation, water-quality-based control can maintain fairness among polluters and consider stream situations. In the United States of America (USA), the total maximum daily load (TMDL) system has already been introduced under the direction of state governments and the Environmental Protection Agency (EPA), and the TMDL that can satisfy an environmental standard even in the worst situation has been calculated and is being observed in all 50 states. Japan has also introduced a TMDL system. However, the permissible load is calculated according to the environmental standards in the USA, and accordingly, the size of the reduction is determined. In Japan, the size of the reduction is determined on the basis of the technology level. An attempt to achieve a target water quality for public water is referred to as wastewater discharge control in Germany and as a watershed management system in the United Kingdom (UK) and France. In order to reduce nonpoint pollution sources in the urban watershed, it is very important to analyze the water quality of the initial pollution.

Pollutants flushed out by the surface runoff during storm events can be a large contributor to the receiving-water-quality problems in urban areas (Behera et al., 2006; Richardson and Tripp, 2006). The first flush is the concept that pollutants exist in higher concentrations at the beginning of a storm runoff event than in the later parts of the storm (Kayhanian and Stenstrom, 2005). The flush effects have been extensively investigated to determine whether the pollutants are at higher concentration levels in certain periods of a storm event. The first flush effect can be defined as a

---

* Corresponding author.
E-mail addresses: drgei@isg.kr (S. Hur), nk1314@hanmail.net (K. Nam), hydroguy@naver.com (J. Kim), water203@korea.kr (C. Kwak).

https://doi.org/10.1016/j.jenvman.2017.09.060

phenomenon in which a greater proportion of pollutant loads are washed off during the beginning of a rainfall event than in other periods (Lee et al., 2002; Sansalone and Cristina, 2004). In most cities in Korea, sanitary waste and stormwater are combined in the same sewer system. Therefore, a significant amount of pollution entering the sewage treatment plant is from street washoff during rainstorms (Kim et al., 2012). Since 1990, the water quality has been significantly improved by expanding the treatment capacity of the sewage treatment plants in the city and strengthening the water-quality standards (Park et al., 1998; Kim et al., 2004). However, these previous efforts were mainly focused on reducing the contaminant loading from point sources. The nonpoint pollutants flushed out by the surface runoff are difficult to predict and cope with owing to the unclear cause of occurrence, the inflow route, and the intermittent flow into rivers during rainfall. The pollutant mass from nonpoint pollution sources increased year-by-year owing to population concentration and the progress of urbanization. Therefore, it is necessary to analyze the changes in the loading and concentration of a nonpoint source during the initial rainfall.

The US Environmental Protection Agency's Storm Water Management Model (EPA SWMM) has effective performance for simulating the stormwater quality and quantity. It is a widely used water-quality model that has the capacity for both single-event and continuous simulation in the prediction of flows and pollutant concentrations. Many researchers have applied the model to assess the runoff and loads with calibration and verification (Tsihrintzis and Hamid, 1998; Koo, 2005; Temprano et al., 2006; Hong et al., 2009; Lee et al., 2010; Chow et al., 2012; Ouyang et al., 2012; Rosa et al., 2015). The model is constructed to be able to model the watershed under various conditions, which is somewhat complicated in terms of the generation of the input conditions and the utilization of the user. Therefore, it is necessary to develop a model capable of a simple outflow and water-quality analysis.

Han and Delleur (1979) utilized the existing Illinois Urban Drainage Area Simulator (ILLUDAS) model to develop the Drainage Quality (DRAINQUAL), which could conduct a continuous simulation and water-quality analysis, and demonstrated that the addition of DIRT, which is a water-quality subroutine within the Storage, Treatment, Overflow, Runoff Model (STORM), enabled the results for the biological oxygen demand (BOD) and suspended solids (SS) to predict the water quality more accurately than STORM. Noel and Terstriep (1982) considered the spatial change caused by the surface runoff and precipitation loss and developed Q-ILLUDAS, which reflected the arrival time of the surface runoff obtained from a kinematic-wave model. It turned out that the shapes of the hydrograph and its peak portion were close to the measurements. Terstriep and Lee (1989) combined a geographic information system (GIS) interface with ILLUDAS to develop AUTO_QI, which could simulate the discharge and water quality. In this model, the linear accumulation of pollutants and exponential washoff equations were used for the water-quality calculation module, and it was assumed that the washoff reduction factor and basic concepts were the same as those in the Storm Water Management Model (SWMM). Additionally, a user could consider the characteristics of the applied region, and the event mean concentration (EMC) could be determined by dividing the total washoff load by the runoff volume according to the type of rainfall event. Bang et al. (1997) constructed, calibrated, and verified the ILLUDAS-POLL model, which can predict the water quality of combined sewer overflows (CSOs) to calculate the basic unit of runoff loadings in urban areas. Hossain et al. (2010) developed a model that continuously simulates the accumulation and washoff of water-quality pollutants in a catchment. The developed model provided an excellent representation of the field data, demonstrating the simplicity and effectiveness of the proposed model. Wang et al. (2011) developed two urban pollutant washoff load models derived using the pollutant buildup and washoff functions. The developed models were calibrated and verified with data observed from an urban catchment in Los Angeles County. Miguntanna et al. (2013) confirmed that the composition of the initially available nutrients in terms of their physical association with solids and chemical speciation determines the washoff characteristics. Maruejouls et al. (2013) developed a new dynamic retention tank model and found good agreement between the observed and simulated data for the total suspended solids and total chemical oxygen demand. Xue et al. (2015) developed a model that is typically efficient for simulating the water-quality response to nonpoint loadings from urban drainage systems.

This study is mainly focused on model development for the urban area in Korea. It aims to analyze the influential factors influencing the runoff and nonpoint pollutant loads in the urban watershed and to provide a runoff and water-quality model that can provide basic data on the management of nonpoint-source pollutants during the initial rainfall. It will estimate the EMCs and mass loads and finally use these results to evaluate the practiced sampling campaigns.

2. Development of the water-quality model

It is important to predict and analyze the effects of the first flush on the river discharge and water quality in urban drainage systems. However, the load characteristics vary greatly because of insufficient field data, the uncertainties in pollutant routes, the intermittency, and the rainfall and basin conditions. Consequently, it is essential to develop an appropriate analysis technique and model. For this reason, a water-quality model was developed to calculate the nonpoint pollution load and concentration caused by the first flush, and the applicability of the model was evaluated by comparison with the SWMM (James et al., 2003) and Modeling of Urban Sewer (MOUSE; Danish Hydraulic Institute, 2003) model.

The ILLUDAS model was developed at the University of Illinois and can simulate actual measurements with less input data in comparison with other models (SWMM and MOUSE), but it is applicable only to runoff simulation. The Flood-Free City Quality (FFC-QUAL) model proposed in this study was developed by adding a water-quality module to the existing time–area curve method, which is a model for analyzing the urban runoff and water quality affected by the nonpoint pollution load during the first flush. When calculating the water quality, the pollutant accumulation is simulated by one of four equations (daily pollutant accumulation, power–linear, exponential, Michaelis–Menton). The washoff, which occurs during rainfall/runoff as a result of the raindrop effect, erosion, or the flushing of pollutants from impervious surfaces, is calculated by the exponential washoff equation. In comparison with the existing models (SWMM and MOUSE), the proposed model can simulate actual measurements more closely with less input data and also analyze the water quality in terms of as many as six items (the SS, BOD, chemical oxygen demand (COD), total nitrogen (TN), total phosphorous (TP), and *E. coli*).

2.1. Runoff analysis theory

In the developed model, since the ILLUDAS and SWMM algorithms are applied for the runoff analysis, the time–area curve is used to calculate the runoff in impervious, pervious, and indirectly connected impervious areas, and the calculated results are utilized as input data for the pipe inlet. The storage equation is also applied to track the flow within pipes, thereby drawing a runoff hydrograph at the final runoff portion.