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Stormwater pollutant runoff: A stochastic approach

Edoardo Daly *, Peter M. Bach, Ana Deletic

MONASH Water for Liveability, Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia

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ABSTRACT

Since stormwater wash-off of pollutants in urban areas is largely affected by environmental variability, it is very difficult to predict the amount of pollutants transported by stormwater runoff during and after individual rainfall events. We investigated the addition of a random component into an exponential wash-off equation of total suspended solids (TSS) and total nitrogen (TN) to model the variability of runoff pollutant concentrations. The model can be analytically solved to describe the probability distributions of TSS and TN concentrations as a function of increasing runoff depths. TSS data from six Australian catchments and TN data from three of these catchments were used to calibrate the model and evaluate its applicability. Using the results of the model, its potential use to determine the appropriate size of stormwater treatment systems is discussed, stressing how probabilistic considerations should be included in the design of such systems. Specifically, stormwater depths retained by a treatment system should result from a compromise between the recurrence of specific runoff depths and the probability to discharge a target pollutant concentration when such a runoff depth is exceeded.

1. Introduction

Stormwater represents a large, diffuse source of pollution in urban environments, and its direct discharge into water bodies is one of the main causes of urban waterways degradation [1,2]. Most of the efforts for stormwater management aim at controlling or reducing the effect that this diffuse source of pollutants might have on receiving water bodies. Stormwater treatment systems mostly rely on the collection of a certain amount of runoff volume that can be either retained (e.g., in the case of infiltration trenches and porous pavements) or treated before being discharged in receiving waters (e.g., in the case bioretention systems and constructed wetlands) [3]. Effective design of stormwater treatment systems thus depends on their ability to reduce pollution concentrations, but even more on the volumes of runoff that they can treat.

Because of the large variability in both runoff volumes and pollutants generated by different rainfall events, empirical approaches are often used to guide the design of stormwater treatment systems. For example, in many states in the USA, a commonly adopted criterion is the collection and treatment of a fixed depth of runoff, often half-inch [4]. Other approaches are based on the collection of a percentage of runoff generated by design storms or by a percentage of removal rates of certain pollutants [4]. In Australia, standards are based on prescribed reduction in the annual load (volume and concentration product) of key pollutants [5].

Most of the criteria for sizing stormwater treatment systems are founded on the first-flush assumption, according to which the peak concentrations of pollutants appear during the initial stages of runoff flow [6]. However, many studies have discussed the ambiguity of the first-flush phenomenon, whose occurrence might depend on how it is defined. Different, and rather arbitrary, definitions can be found in the literature [6,7] and they can lead to different designs of treatment systems. Additionally, many experiments observed the first flush in only a small part of the sampled events [8] and often, when the first flush was observed, substantial pollutant loads were also detected throughout the entire duration of runoff events [9,10]. These differences between events have been attributed to many environmental factors, such as catchment area, land use, rainfall intensity, runoff volumes and antecedent dry weather period. Different studies showed contrasting results with some of these environmental variables appearing to be of key importance in some catchments, but not influencing pollutant runoff concentrations in others [9,11,12]. Furthermore, the dynamics of different types of pollutants are driven by different mechanisms, thereby making certain environmental variables more or less important depending on the chemical of interest [9,13].

Given the complexity of pollutant accumulation and transport in urban environments and their interaction with runoff flows, the modelling of stormwater runoff quality is very challenging.

* Corresponding author at: Department of Civil Engineering, 23 College Walk (old Bld 60), Monash University, Clayton, VIC 3800, Australia. Tel.: +61 3 990 54979.
E-mail address: edoardo.daly@monash.edu (E. Daly).

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Empirical regressions between concentrations and environmental variables, such as rainfall intensity and runoff volumes, are available [14,15] as well as deterministic, process-based models for sediment wash-off [14,16] and coupling of sediment deposition, wash-off and transport by runoff [17,18]. These models, however, do not account for the variability that characterises pollutant generation and transport in different runoff events. This variability is partially taken into account in probabilistic models of stormwater quality, where probability distributions of rainfall are transformed into distributions of pollutants using a derived distribution approach [19]. More recently, stochastic approaches have been proposed to determine the value of parameters in models of first flush (e.g., [20]).

The aim of this work is to present a model that can address the variability observed in the concentration of pollutants in stormwater runoff, focussing on total suspended solid (TSS) and total nitrogen (TN). The model relates stormwater runoff volumes to pollutant concentrations. As surface runoff volumes increase, TSS and TN concentrations have been observed to experience fluctuations, which vary in different storm events [7,21]. These fluctuations, which are associated with various sources of environmental variability and difficult to be accounted for deterministically, are embedded in the model via a multiplicative noise and a distribution of concentrations at the start of runoff events. The stochastic model, presented in Section 2 and applied to several urban catchments in Section 3, is used to discuss possible criteria for the design of stormwater treatment systems based on probabilistic considerations (Section 4).

2. Proposed model

We adopt the often used exponential decay of pollutant concentrations, C, as a function of runoff volume, V, as observed in [21]; accordingly, one can write

$$\frac{dC}{dV} = -kC, \tag{1}$$

where k is a parameter dependent on catchment characteristics. Eq. (1) is simplified and does not account for the large number of processes involved in the pollutant transportation by stormwater runoff. To include some information on the natural variability that influences the function $C(V)$, we assume that the parameter k is not constant, but is subjected to fluctuations dependent on environmental variability due to, for example, the length of the dry period before an event, the intensity of an event and soil spatial variability within the catchment. We assume that the parameter k can be written as the sum of an average value, $\bar{k}$, and stochastic fluctuations, k', which we consider to be normally distributed with average 0 and variance σ^2. This model for the fluctuations k' is simplified and it is derived from a more realistic description of random fluctuations discussed in detail in Appendix A.

Eq. (1) can thus be written as

$$\frac{dC}{dV} = -(\bar{k} + \sigma\xi(V))C = -\bar{k}C + \sigma\xi(V)C, \tag{2}$$

where $\xi(V)$ is a Gaussian noise, with $\langle\xi(V)\rangle = 0$ and $\langle\xi(V)\,\xi(U)\rangle = \delta(V-U)$. With the assumption that $C(V=0) = C_0$ and using the Stratonovich interpretation of Eq. (2) [22], the probability density function (PDF) of C can be derived as [23] (see Appendix B for details)

$$p(C, V|C_0) = \frac{1}{\sqrt{2\pi\sigma^2 V}C} \exp\left(-\frac{(\ln C - \ln C_0 + \bar{k}V)^2}{2\sigma^2 V}\right), \tag{3}$$

which is a log-normal distribution.

It is reasonable to assume that the value of the initial concentration, C_0, is not constant, but it is a variable characterised by its PDF, $p(C_0)$. Therefore, to obtain how the PDF of C varies with V, we need to calculate the integral

$$p(C, V) = \int_0^{+\infty} p(C, V|C_0)p(C_0)dC_0. \tag{4}$$

The average of C can thus be calculated as

$$\langle C\rangle = \langle C_0\rangle \exp\left[-V(\bar{k} - \sigma^2/2)\right], \tag{5}$$

and the second moment as

$$\langle C^2\rangle = \langle C_0^2\rangle \exp\left[-2V(\bar{k} - \sigma^2)\right]. \tag{6}$$

Specifically, if C_0 is assumed to be log-normally distributed, i.e.,

$$p(C_0) = \frac{1}{\sqrt{2\pi\sigma_0^2}C_0} \exp\left(-\frac{(\ln C_0 - \ln \mu)^2}{2\sigma_0^2}\right) \tag{7}$$

one obtains

$$\begin{aligned}\langle C_0\rangle &= \mu \cdot \exp\left(\sigma_0^2/2\right)\\ \langle C_0^2\rangle &= \mu^2 \cdot \exp\left(2\sigma_0^2\right),\end{aligned} \tag{8}$$

and the PDF $p(C, V)$ can be derived in closed form as

$$p(C, V) = \frac{1}{\sqrt{2\pi(V\sigma^2 + \sigma_0^2)}C} \exp\left(-\frac{(\ln C - \ln \mu + kV)^2}{2(V\sigma^2 + \sigma_0^2)}\right), \tag{9}$$

with cumulative density function (CDF)

$$P(C, V) = \frac{1}{2}\left(1 + \mathrm{Erf}\left(\frac{kV - \ln \mu + \ln C}{\sqrt{2(V\sigma^2 + \sigma_0^2)}}\right)\right), \tag{10}$$

where Erf is the error function [24].

Eqs. (9) and (10) will be used to describe the evolution of the statistics of pollutant concentrations for increasing runoff volumes.

3. Model application and testing

3.1. Methods

3.1.1. Catchments and data description

Discrete water quality data were collected from six urban catchments around Melbourne, Australia. Table 1 provides a summary of key catchment characteristics and the available data set for each catchment. Further information can be found in Francey et al. [25]. All catchments have separate stormwater and wastewater systems; however, the presence of septic tanks at Narre Warren might have caused possible cross connections at this site. The model was applied for assessment of TSS and TN concentrations, since these pollutants are very different in nature: while TSS is a physical parameter that explains total level of suspended material in water, TN is mainly in dissolved form [26]. TSS and TN concentrations were measured in samples obtained at increasing flow-weighted intervals with an auto-sampler having a maximum capacity of 24 bottles. Doppler-based flow metres recorded flow rates every minute.

Preliminary analysis conducted on the data is described in detail in [7,21], so we report here only a brief summary on data preparation. For each catchment, the runoff volumes were divided by the catchment area to obtain an equivalent runoff depth. The concentrations measured at different runoff depths during each event were linearly interpolated; these interpolated series were then re-sampled at 2 mm intervals of increasing runoff depths. Each event thus resulted in a trajectory of concentrations changing as a function of runoff depths. The ensemble of available trajectories was used to generate empirical distributions of pollutant