Differentiation of Mass and Flow Limited Rainfall-Runoff Events for Overland Flow from Small Urban Catchments

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ABSTRACT

Water quantity and quality are coupled phenomena in urban rainfall-runoff. These rainfall-runoff quantity and quality relationships have been significantly altered by the built environment and associated anthropogenic activities. Understanding the relationship between quantity and quality of urban overland flow for a given catchment facilitates development of in-situ wet weather control. One aspect of this relationship for a given catchment is the differentiation between mass and flow-limited event delivery for water quality indices. While there have been many incarnations of mass-limited behavior, such as the much-maligned mass-based first-flush, there have been fewer investigations for differentiating mass limited behavior from flow-limited behavior. The concept of a first-flush can be shown to be one limiting form of such coupled phenomena for small urban catchments, a mass-limited phenomenon. While the common assumption of mass-limited behavior is generally implicitly assumed for urban catchments (generally irrespective of size), this study illustrates that such behavior is only one limiting form of quantity-quality phenomena. This study examines such limits of transport in urban rainfall-runoff and differentiates between coupled quantity and quality behavior in order to classify rainfall-runoff events. Results from two small urban catchments are examined, a fully-paved catchment in Baton Rouge, Louisiana and a fully-paved catchment in Cincinnati, Ohio. Both sites were urban, paved, and transportation land use and the upper end of the watershed. Results indicate that the derived physical-based differentiation criteria are able to fit experimental data from these two different sites. Results are useful for mass delivery differentiation, physical understanding and for use in models such as SWMM.

KEYWORDS


INTRODUCTION

The quantity and quality relationship of rainfall-runoff in urban areas has been significantly changed by both the impervious built environment and anthropogenic activities. For example, the combination of pavement and automotive transportation in the urban environment has a significant impact on the relationship between quantity and
quality. Impervious pavement functions as an efficient water quantity conveyance surface for transport of water quality constituents as compared to more pervious pre-
constructed conditions such as soils and vegetation. Impervious pavement cover conditions also significantly alter the relationship between rainfall and runoff. This altered relationship between rainfall and runoff results in increased peak flow, increased runoff volume, reduced infiltration, reduced evaporation and reduced depression storage. Especially if the pavement is asphaltic, there is an increase in urban temperatures and runoff temperatures.

Common water quality indices associated with urban rainfall-runoff include a wide gradation of particulate matter, ranging from colloidal (< 1 μm), suspended (~ 1 to 25 μm), settleable (~ 25 to 75 μm), sediment (~ 75 to 4750 μm), and gross solids (>4750 μm). It is becoming more common to measure this material in terms of an aggregate mass measurement such as suspended sediment concentration (SSC) (Gray et al. 2000), that recognizes the problems associated with the application and use of total suspended solids (TSS) given the complexity of rainfall-runoff. These water quality indices also include measurement such as the total dissolved solids (TDS) (that potentially overlaps the larger colloidal fraction based on operational method. Most of this particulate matter is anthropogenic; however depending on the land use and season, there can be an important biogenic fraction. Given the largely inorganic nature of most particulate matter in urban rainfall-runoff (on a gravimetric basis) and the potentially inhibitory nature of rainfall-runoff, chemical oxygen demand (COD) methods, for example, APHA 1998, are used for oxygen demand considerations. Challenges to such methods occur because of the wide gradation of particulate matter that can exert an ultimate COD and current COD methods are more amenable to the dissolved and suspended fractions of COD in rainfall-
runoff; given that the settleable, sediment and gross solids are much more challenging to representatively sample and analyze, whether for COD or other water quality parameters. Other common water quality concerns include nutrients (N, P), a wide range of toxics including metals and organic compounds. These water quality parameters also dynamically partition between dissolved and particulate phases and distribute across the wide range of particle size gradations. This distribution is a function of total surface area and total surface charge (as opposed to specific surface area) and indicates that pollutant loads are associated with the fraction of the gradations which contributes the highest total surface area and total surface charge. In addition, neutrally-buoyant pollutants, there is trash, litter and floatables; all of which contribute to this complex, dynamic and heterogeneous mixture that is transported under unsteady conditions during a wet weather event.

Accretion of constituents associated with such indices and measurements result from vehicular-pavement interaction, deposition and leaching of deposited anthropogenic materials and infrastructure, and maintenances practices (Brown 1978; Sansalone and Buchberger, 1997, USEPA 1995, Yu et al 1994). This dry deposition material is entrained in runoff and transported to sewer systems and some fraction thereof transported to receiving waters.
METHODOLOGY

Increasingly attention has been focused towards defining the delivery of rainfall-runoff constituent loadings. In addition, common rules of thumb (such as a first flush) regarding constituent delivery have been re-invigorated using concepts such as water quality volumes (WQV). Such concepts (whether utilizing concentration or mass) are intended to optimize volumetric-based capture criteria for unit operations and process BMPs intended while providing receiving water quality benefits. Whether identified as a first-flush or a WQV, the basis of such concepts is similar; a disproportionate delivery of constituent loads early in the event in order to define a treatment volume or volumetrically-size a BMP. For example, a common first-flush or WQV definition is the capture and treatment of the first ¾ inch of rainfall. The operative words in this definition are “first”, implying a temporal distribution, “3/4 inch”, implying a fixed depth, and “rainfall” (as opposed to runoff). While many such definitions may differ with respect to specifies the conceptual basis for each is the same; an initial (i.e. disproportionate) delivery of constituent load that is transported by a singular value of a hydrologic component depth. While it is clear that the specification of rainfall or runoff can make a significant difference under conditions where infiltration, evaporation (and evapotranspiration) or depression storage may occur; this specification can also be important in impervious paved catchments where anthropogenic abstractions such as traffic or unintended losses through infrastructure surfaces alter the rainfall-runoff relationship. While these differences in specifics have led to historical latitude of interpretations, first-flush definitions can be grouped into a mass (load) or concentration basis (Gupta and Saul 1996).

A concentration first flush indicates a disproportionately high constituent concentration during the rising limb of the runoff hydrograph or the early portion of the runoff hydrograph (Sansalone and Cristina 2003). A common basis of a first flush is the occurrence of a significant concentration peak for a constituent of interest at the beginning of storm event. It should be noted that this behavior is variable between constituents, variable for constituent phases and variable depending on the method of measurement. It should be noted that studies have concluded that from the treatment point of view, definitions based only on concentration may be inadequate. For example, Wanielista et al. pointed out that increases in mass at lower concentrations might be more detrimental to receiving waters than lower flows with higher concentrations and those first flush definitions based on concentration could mislead designers of treatment controls (Wanielista et al. 1977). Unless the specific focus is acute toxicity, first-flush specifications based on constituent specification are generally inadequate.

While a concentration-based first flush definition was first proposed, first flush definitions based on mass have received much attention and the literature is replete with mass-based first flush (MBFF) examinations (Sansalone 2004; Cristina and Sansalone 2003; Sansalone et al 1997; Sansalone 1998). A basis of mass indicates a disproportionately high delivery of constituent mass during the rising limb of the runoff hydrograph or the early portion of the runoff hydrograph (Sansalone and Cristina 2004).
The first flush phenomenon based on mass that is the focus of this paper can be identified based on the relationship between the cumulative mass curve and the cumulative runoff volume curve (Sansalone et al 1998, Cristina and Sansalone 2003, Sansalone and Cristina 2004). A first flush based on constituent mass can generally be modeled using a first-order exponential. This first flush behavior represents one limiting behavior of transport from small urban catchments and is classified as a mass-limited transport. Such a classification infers a limiting relationship between hydrology and mass transport. In a mass limited relationship the hydrologic intensity transports constituent mass and can be modeled by a first-order exponential. A plot of cumulative mass as a function of cumulative volume for a mass-limited event yields an asymptotic profile for a constituent. However, events and constituent phases do not always behave in a mass-limited fashion. The other limiting behavior is a flow-limited condition. While a mass-limited first flush behavior represents one limiting behavior of transport from small urban catchments, the other limiting transport is a flow-limited behavior (Sansalone et al 1998, Cristina and Sansalone 2003). Such a classification infers a unique limiting relationship between hydrology and mass transport that is not disproportionate or initial. In a flow-limited relationship the hydrologic intensity transports constituent mass in a linear manner and can be modeled by a linear function in contrast to a first-order exponential. A plot of cumulative mass as a function of cumulative volume for a mass-limited event yields an linear profile for a constituent or constituent phase.

A criterion that most appropriately classified a rainfall-runoff event as either mass-limited or flow-limited was examined. The criterion was on the basis of both hydrographs and pollutographs derived from rainfall-runoff water quality and quantity analysis data from two similar urban catchments. One instrumented catchment was located in urban Baton Rouge, Louisiana and was typical of small urban paved catchments with traffic loads in an NPDES Phase II municipality. Runoff is generated from a 544-m² section of Portland cement concrete (PCC) pavement and collected from the lower expansion joint. The pavement catchment is 12.2-m wide by 44.6-m long, with a tangential slope of 2.0%. All rainfall that generated overland flow was captured by a hydraulically short and steep conveyance system from which all flow volume and constituent mass was captured and sampled through full cross-sectional flow sampling. The other instrumented catchment was located in urban Cincinnati, Ohio. Runoff generated from a 300-m² section of asphalt pavement is collected at the edge of the pavement. The pavement catchment is 20-m wide by 15-m long, with a transverse slope of 2% across the length of the asphaltic pavement and a longitudinal slope of 0.04%. All rainfall that generated overland flow was captured from the 300-m² area at the edge of the pavement in an epoxy-coated flume from which all flow volume and constituent mass was captured and sampled through full cross-sectional flow sampling. Samples were replicated for each sampling time, and TDS, suspended, settleable, sediment and SSC analyses were replicated for each sample replicate. This paper focuses on TDS and SSC results. The differentiation results were compared with those resulting from statistical methods including Logistic Regression Analysis (LA) and Discriminant Analysis (DA) which were based on hydrologic data parameters. Multiple-linear regression approaches were utilized to predict parameter coefficients first-order \( k_1 \) and \( M_0 \) in mass-limited events.
RESULTS AND DISCUSSION

The differentiation criteria for mass-limited events and flow-limited events, based on the evaluation of the relationship between cumulative volume and cumulative constituent mass can be stated as a) If the cumulative constituent mass versus cumulative volume curve follows an exponential pattern, the event would be mass-limited; b) If the cumulative constituent mass versus cumulative volume curve follows a linear pattern, the event would be flow-limited. Each of the 28 events from Baton Rouge site and 14 events from Cincinnati site during the time period of 1995 to 1997 were classified as mass-limited or flow-limited according to the proposed criteria. The classification results were compared with those from Logistic Regression and Discriminant Analysis. The classification accuracies of six constituents such as TSSC were shown in Table 1.

Table 1 – Table 1 provides a summary for the classification accuracy of Discriminant Analysis (DA) and Logistic Regression (LA) differentiating mass-limited or flow-limited behavior for SSC, the volatile fraction of SSC (VSSC) and TDS.

<table>
<thead>
<tr>
<th>Classification Accuracy</th>
<th>SSC</th>
<th>VSSC</th>
<th>TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DA</td>
<td>LA</td>
<td>DA</td>
</tr>
<tr>
<td>Baton Rouge</td>
<td>82%</td>
<td>93%</td>
<td>85%</td>
</tr>
<tr>
<td>Cincinnati</td>
<td>93%</td>
<td>100%</td>
<td>93%</td>
</tr>
<tr>
<td>Both</td>
<td>/</td>
<td>95%</td>
<td>/</td>
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</tbody>
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It is important to emphasize different constituents, and different constituent phases yield different transport behavior. As an example, results for a 31 May 2001 event are illustrated for SSC, VSSC and TDS. These results are summarized in Figure 1. It is expected that the interactions between hydrology and mass delivery of constituent are different with respect to different constituents indices examined, SSC, VSSC and TDS. This is in fact the case. In addition, if the constituents are examined based on particle size class; for example suspended or settleable or sediment, differing behavior is possible and in fact likely within each event. One can examine these particle classes even more fundamentally based on particle size and illustrate a distribution of behavior that can be classified as either flow-limited or mass-limited based on particle size for a given rainfall-runoff events.

Multiple linear regression on $k_1$ (the first-order transport coefficient for mass-limited events) was performed for the two experimental sites separately and the results for Baton Rouge site are shown in graphically in Figure 2. The solid line represents a perfect prediction and the distance of the predicted point away from the line is a measure of the prediction error. Results indicate a good prediction capability. Analysis of covariance was also performed on $k_1$ for both Baton Rouge site and Cincinnati site. Results indicate that the multiple linear regression lines from two sites are parallel but with different intercepts. Results indicate that the classification rules derived from both sites are
feasible in differentiation of mass delivery (and determination of a first-flush) for rainfall-runoff events for small urban watersheds. Results have significant implications for decision-making with respect to volumetric capture and water quality volume (WQV) determinations. Results also suggest that common rules for WQV can significantly underestimate delivered loads and that event-based WQV are never known a-priori.

Figure 2. Classification of Mass-delivery, based on constituent indices and phases, for the 31 May 2001 event in Baton Rouge LA illustrating the differing behavior of constituents within an event.
In Figure 3 the parameter is the first-order $k_1$ in $\Delta M_T = M_0(1-e^{-k_1T})$. $\Delta M_T$ is the cumulative constituent mass delivered [M]; $V_T$ is the cumulative volume [L$^3$]; $M_0$ is the constituent mass on the surface at the beginning of the rainfall-runoff event [M]; $k_1$ is the first-order coefficient [L$^{-3}$], physically indicating the mass decrease rate for unit flow rate.
and unit constituent mass remaining on the watershed surface; SSC – suspended sediment concentration; VSSC – volatile suspended sediment concentration; TDS - total dissolved solids; Each data point represents a single event. Events classified as mass-limited in Baton Rouge site are plotted.

CONCLUSIONS

There are several important conclusions of this study. First and most importantly; the occurrence of a first-flush based on mass is generally not known a-priori. Technology may eventually result greater prediction capability at a temporal and spatial scale appropriate for smaller urban catchments (< 10 acres) but not as of 2006. Existing first-flush concepts do not capture the hydrologic and load transport relationships of urban rainfall-runoff behavior. First-flush guidance based on concentration is generally not appropriate for load-based decisions. As a result, guidance, regulation and design based on such first-flush concepts are often inadequate for load-based delivery, capture and treatment considerations. Secondly, constituents and constituent phase transport behavior is markedly different within an event as illustrated when comparing SSC to TDS. There is a clear physical basis for this, but this differing behavior within an event illustrates the complexity of rainfall-runoff quality and quantity. This complexity has a significant impact on the performance of unit operation and process BMPs or low impact development (LID) systems or sustainable urban drainage (SUD) systems. Finally, despite such complexity, events and constituent phase transport behavior can generally be classified as either mass-limited (first-order transport, \(k_1\)) or flow-limited (zero-order, \(k_0\)) based on volume. When \(k_1\) or \(k_0\) results are determined for a catchment and constituent, or constituent phase, or constituent class (suspended, settleable, sediment); such results find good applicability in simulation models such as SWMM which can examine the rich complexity of urban drainage conditions, loadings and management controls for quantity and quality. Finally, urban rainfall-runoff quantity and quality are coupled phenomena; and there must be an increasing level of hydrologic restoration in our urban environments for our management objectives to be sustainable for these phenomena.

REFERENCES


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