Simple mass balance approach for assessment of flood control sumps in an urban watershed: case study of heavy metal loading

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Abstract Levee sump systems are used by many riverine communities for temporary storage of urban wet weather flows. The complex hydraulics and transport of stormwater pollutants in sump systems, however, have not been systematically studied. The objective of this work is to present a case study, utilizing a relatively simple and low-cost methodology, for assessing the hydraulic performance of flood control sumps in an urban watershed. Two sumps of highly variable physical and hydraulic characteristics were selected for analysis. HEC-1 software was used to estimate the flow hydrograph for each outfall to a sump as part of the overall flow balance, resulting in a total runoff hydrograph for a precipitation event. To validate HEC-1 results, a water balance was used to estimate the total runoff using sump operational data. The results suggest that HEC-1 calculation provide a satisfactory estimate of the total runoff and its time-distribution to the sump. The hydraulic model was then used to estimate nonpoint loads of selected heavy metals to the sump and to the river. Although flow of stormwater through a sump system is regulated solely by flood-control requirements, these sumps may function as sedimentation basins that provide purification of stormwater. An example calculation of removal of heavy metals in a sump using a mass balance approach is presented.

Keywords Flood-control sumps; modeling; nonpoint source pollution; stormwater management; urban hydrology; water quality

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Introduction

Many urban flood contour projects involve protection of land in a riverine floodplain by the construction of a system of levees and irregular-shaped drainage ways/basins, called *sumps*. Stormwater is intercepted by the sumps before eventual release to the river by a gravity sluice or pumping over the levees. Unlike conventional stormwater detention basins, sumps are of variable design, irregular configuration, and typically comprised of a complex array of outfalls that make analysis of their hydraulic performance difficult. As a result, obtaining estimates of nonpoint source pollutant loads to the sump and, ultimately, to the river as may be required in permitting practices, is also a formidable challenge. Moreover, although flow of stormwater through a sump system is regulated solely by flood-control requirements and not detention factors as in actual stormwater detention basin, these sumps nevertheless may function as sedimentation basins that potentially provide purification of stormwater. It is well known that stormwater detention basins can provide a significant level of removal of solids and associated pollutants for appropriate design and operating conditions (Urbonas and Stahre, 1993). The treatment capabilities of flood-control sumps, however, have not been systematically studied to date. This work presents a case study with the aim of developing a simple assessment procedure for the hydraulic performance of sumps in an urban watershed that does not require expensive flow monitoring of individual outfalls. The potential for application of the hydraulic model to estimate nonpoint pollutant loads to the sump and to the river for an event is illustrated using stormwater data for three heavy metals. Using this approach, together with mass balance considerations, a sample calculation of pollutant removals in a sump is presented.

The current study considers the sump system of the city of Dallas, Texas along the Trinity River. The system consists of nine designated sump areas, one for every drainage basin that was cut off by the levees (Forest and Cotton, 1973). Two sump areas are designated as C and D were selected for detailed analysis. These two sumps, both drained by pumping stations consisting of high and low rate pumps, represent variable land use distribution and extremes in terms of drainage area and storage capacity. Drainage areas are 3.15 versus 6.90 km^2 for C and D, respectively; while storage capacities are 2.36×10^5 and 1.62×10^6 m^3, respectively. Sump C basin has a more narrow shape with steep sides, giving the appearance of a "flashy" flow-through system, and is mostly free of water during dry periods. Conversely, the Sump D basin in the vicinity of the pumping station resembles a lake with more gradual slopes and retained water during even extended dry periods.

Methods

In order to understand the hydraulic performance of the sumps and make subsequent estimates of nonpoint source pollutant loads to and from the basins for stormflow events, a time variable hydraulic model is required in the form of a flow balance. The most difficult terms to estimate in the flow balance are the inflows, consisting of a large number of stormwater outfalls to a given sump. Sump C has 14 outfalls, including a drainage area directly connected to the sump itself, and Sump D contains 33. Since continuous flow monitoring of the outfalls of each sump would involve extraordinary effort and expense, a flow estimator was selected to estimate the flow hydrograph for each outfall as part of the flow balance for the sump. HEC-1 software developed by the U.S. Corps of Engineers was chosen for this purpose, using drainage characteristics derived from drainage locator maps, land use information, and rainfall data for an individual event (Hydrologic Engineering Center, 1985). A hydrograph of total runoff to the sump was then derived by real-time superposition of the hydrographs of the individual outfalls.

To attempt to validate HEC-1 results, a water balance was used to estimate the total runoff hydrograph using available sump operational data. The water balance is:

$$V_{R,t} = V_{P,t} \pm \Delta V_t \qquad (1)$$

where $V_{R,t}$ is the storm runoff to the sump during a prescribed time interval, t; $V_{P,t}$ is the volume of water pumped from the sump to the river in the time interval; and ΔV_t is the change in volume of water in the sump during the time interval. The status of high- and low-flow pumps is continuously monitored during an event as part of a SCADA network, enabling calculation of $V_{P,t}$. Continuous data on sump elevations are also available for calculation of ΔV_t using volume-elevation relationships developed for Sumps C and D, respectively. The latter derive from digitization of contour maps resulting in an explicit, fitted polynomial relationship between sump water elevation and the corresponding volume. In the case of very high flow events, Sump D may receive flows from one or even two neighboring sumps. These sumps have connecting sluiceways to the river but no pumping stations. If river levels exceed sump elevations, stormwater passes from these neighboring sumps to Sump D through connecting rated gates. Using the relevant structural elevations and the continuously provided river elevations from the monitoring network, this flow contribution was incorporated into HEC-1 calculations in the form of additional outfall areas. Additional water gain in the form of backwater flow from the river to the sump through the main sump-levee-river sluiceway was also estimated using these data and was observed in a few high-flow events. In such cases, a term for this miscellaneous water gain to the sump is added to the righthand side of Eq. 1 with a negative sign to compensate for the inclusion of this quality of water in ΔV_t.

Implementation of HEC-1

The HEC-1 model was calibrated and implemented according to a weighted-average curve number (CN) approach, where CN is an index of the infiltration capacity of a specific coil-cover condition. A relatively large runoff event at the beginning of the study period, and during what could be considered as "average" antecedent moisture conditions, was chosen for the calibration step. For a given sump, a CN was assigned to each sub-drainage area based upon land use, soil type, vegetation, etc. as prescribed in the HEC-1 user manual. Proportional adjustments were made in the CN values to obtain a best fit of the data in terms of total runoff from the sump over the time period of the event. From this result, a weighted-average CN for the sump was calculated to represent the average antecedent moisture condition for the sump (Corbit, 1989; Gupta, 1989). By this methodology, the average CN for Sump C was considerably higher than that of Sump D (93 versus 77) owing to the higher degree of development as well as the generally steeper slopes in the basin drained by Sump C. the curve numbers thus established were used to model the runoff for subsequent storms with adjustments only for antecedent moisture conditions according to published curve number tables and: (a) Category I: dry soil condition but not to the wilting point (CN_C = 83, CN_D = 59); (b) Category II: average conditions as given above; and (c) Category III: saturated soil due either to heavy rains or light rainfall combined with low temperatures within the previous five days (CN_C = 98, CN_D = 89).

Not all of the events analyzed are common between the two target sumps due to malfunctioning of either the rain or sump-level gages during an event for a sump area. Of the 22 storms analyzed for Sump C and 21 for Sump D, 14 were common events. Two of the common events, during late Summer of 1995 and Fall of 1996, were beyond the dry condition with no antecedent rainfall for 42 and 32 days, respectively. There was notable cracking of soil, wilting of a portion of unwatered vegetation, and almost no ponded water even in Sump D during these two events. Selecting a CN for this condition is rather arbitrary. For Sump C, the weighted CN used above for dry conditions (83) was considered as the starting or average value (i.e. revised Category II) value, and the corresponding Category I value of 67 from the tables used to represent this extremely dry condition. By a similar strategy, a CN = 59 was used for Sump D.

Results and discussion

HEC-1 runoff hydrographs

Bar charts comparing HEC-1 calculations of total runoff and water balance calculations deriving form Eq. 1 for Sumps C and D are presented in Figures 1 and 2, respectively. There is no evident bias in terms of either model-estimated or measured runoff being consistently higher than the other. A least squares linear regression of ratio plots of total runoff from HEC-1 estimates versus water balance calculations yields slopes of 0.95 and 1.02 for Sumps C and D, respectively. Correlation coefficient values are 0.90 in each case. The average relative percent difference (RPD) between HEC-1 and water balance values of total runoff is ~15% in the case of Sump C and ~25% for Sump D. Much of this difference is contributed from the relatively smaller runoff events. For instance, the largest relative percent difference event for Sump D was 85%, deriving from HEC-1 and water balance total runoff of 9,350 versus 23,120 m^3, respectively. As indicated in Figure 2, total runoff to Sump D for the events studied was as high as nearly 700,000 m^3.

Figures 3–5 depict composite HEC-1 runoff hydrographs using the displayed rainfall record against water balance calculations for a few selected events. As indicated, HEC-1 provided a good estimate of the time of peak flow relative to the rainfall record, even in cases of

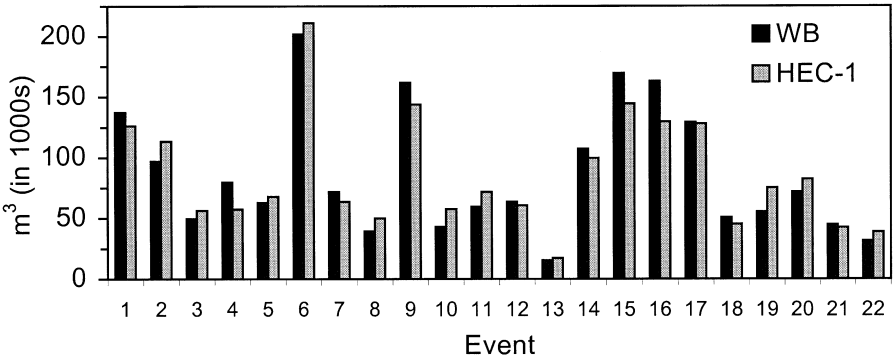

Figure 1 Total runoff to Sump C comparing HEC-1 model simulations to water balance calculations (WB) based on water level and pumping data for 22 events

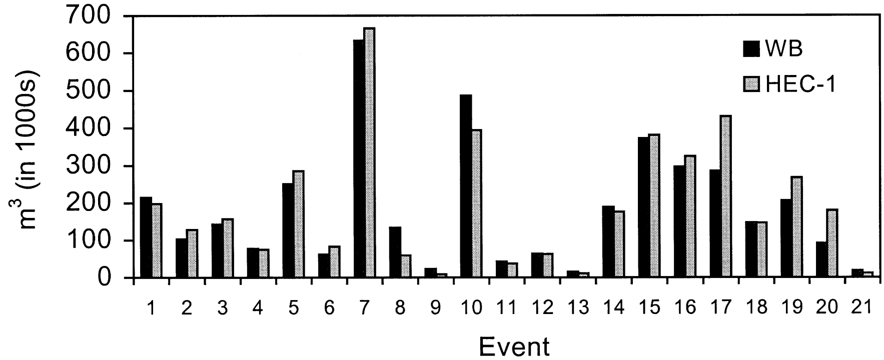

Figure 2 Total runoff to Sump D comparing HEC-1 model simulations to water balance calculations (WB) based on water level and pumping data for 21 events

intermittent rainfall such as illustrated in Figures 4 and 5. A suitable prediction of the ongoing rise and fall in runoff was also achieved for most events. In general for the 40-plus events analyzed, HEC-1 simulations were better in instances of large "spikes" of rainfall rather than for periods of extended rainfall of low intensity (Smith *et al.*, 1999). The overall corroboration of results of the two modeling schemes suggests that HEC-1 can be a useful tool for estimating total stormwater runoff and its time distribution to levee sumps comprised of a complex array of numerous drainage outfalls spanning variable land areas and uses. An important implication is that the hydraulic characteristics and performance of the sumps can be assessed and understood without difficult and costly field measurements of runoff for individual outfalls to the sump, except as may occasionally be required for verification purposes. HEC-1 simulations can be employed as an integral component of a total sump operation management model and for estimating pollutant loads to a sump. Together with the water balance model (Eq. 1), the impacts of operational parameters such as pumping rates and timing on overall sump hydraulics can be studied. For example, the model can facilitate the design of an alternative pumping strategy during higher-flow events to achieve a better balance between river and sump levels and thereby reduce the quantity of backflow to the sump with corresponding reductions in pumping and energy requirements. Furthermore, as demonstrated in the following section, the models can be used to estimate nonpoint pollutant loads to the sump and from the sump to the river. With sufficient pollutant data, the utility of the sumps for removing pollutants as a result of temporary detention can also be assessed, in addition to removal rate constants for specific pollutants. Once this is achieved, the hydraulic model can be invoked to examine the sensitivity of pollutant removals to various management alternatives.

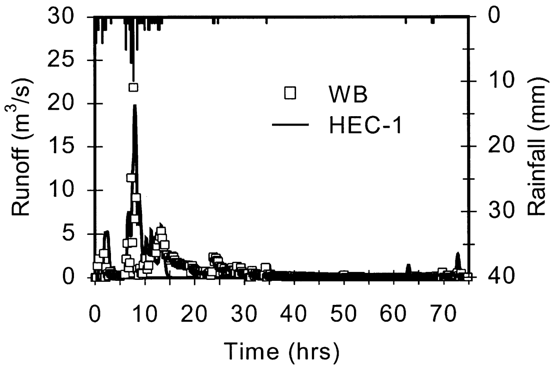

Figure 3 Total runoff hydrograph to Sump C comparing HEC-1 model simulations to water balance calculations (WB) – Event 6

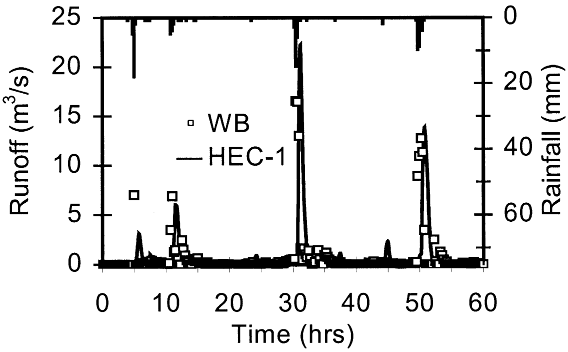

Figure 4 Total runoff hydrograph to Sump C – Event 2

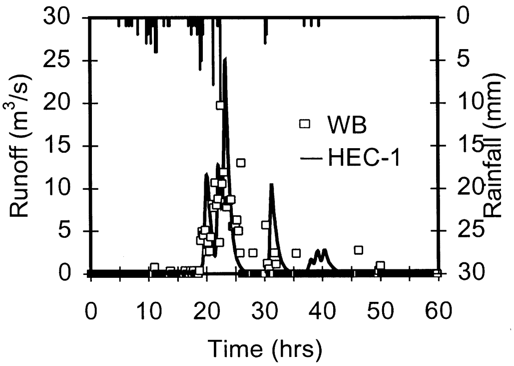

Figure 5 Total runoff hydrograph to Sump D – Event 19

Nonpoint pollutant analysis

Important issues related to nonpoint pollutant transport in levee sump systems are: (1) what quantity of urban stormwater pollutants enter the sumps due to runoff during a specified event? (2) what quantity of pollutants are subsequently transported to the receiving body, in this case the Trinity River? and (3) based on the above, what quantity of pollutants is being retained in the sumps, i.e., effectively removed from the water and, presumably, transferred to the sediments? Resolving these issues requires extensive stormwater quality data, a challenging and expensive undertaking given the complexity of sump systems.

Question 2 above was the easiest to address, and a program was designed to collect concentration data for the target pollutants at the pumping station to correspond to the pumping hydrograph (which yields the volume of water pumped to the river as a function of time) for an event as described in the water balance calculations. The heavy metals lead (Pb), copper (Cu), and zinc (Zn) are nonpoint pollutants of concern in the areas drained by Sumps C and D, and were chosen as the target pollutants for this example. Sampling equipment was mounted next to the outlet gates of both pumping stations, which also correspond to the deepest portion of the main sump basins. Details of the design of the sampling stations as well as sampling and analytical procedures were described previously (Smith, 1996). Sump outlet concentration data for Pb, Cu, and Zn in sumps C and D for a corresponding event are presented in Figures 6 and 7, respectively. As indicated, values tend to peak early in the event corresponding to the runoff (Figures 6 and 7 depict the same event as the example hydrograph of Figure 3). For all events in which complete sampling data was obtained, measured values were all less than single grab limits (e.g., 1.5 mg/L for Pb; 2.0 mg/L for Cu) and even less than daily average limits (1.5 mg/L for Pb; 2.0 mg/L for Cu) (EPA, 1993). Moreover, the reported values are for total metals which may be substantially greater than dissolved or bioavailable metals (Paulson and Amy, 1993). The data are not continuous, implying that the time-concentration relationship is not precise and that peak concentrations may not have been captured. Nevertheless, a time-interval method incorporating the concentration data with the pumping hydrograph enabled estimation of the mass of pollutants transferred to the river *via* pumping, M_{pump}. Values for Pb, Cu, and Zn for this event are listed in Table 1.

To determine the quantity of pollutants entering the sump due to runoff, similar time-interval calculations had to be performed for every drainage area in the sump, using the HEC-1 generated hydrograph for the area together with corresponding sump inlet time-concentration information. Just as measuring flows in all the individual sump inlets is prohibitively expensive and, in some cases, access prohibited, so the same applies to stormwater sampling and analysis. The approach to this problem was to select a limited number of strategic locations for installation of sampling stations. Criteria for selection of the stations included size of the drainage area, distribution of sampled areas throughout the total sump area, land use, and amenability of the site to construction of an autosampling station. For instance, because several individual drainage sumps are interconnected, the resulting stations represented 58% and 74% of the total drainage areas of Sumps C and D, respectively. Concentration data for sampled outlets was then assigned to adjacent unsampled areas in order to calculate total load estimates to the sump, M_{load}, according to:

$$M_{load} = \sum_{i=1}^{N}\left[\sum_{j=1}^{\tau}\left(C_{i,j} \times R_{i,j}\right)\right] \tag{2}$$

where i refers to an individual outfall, N is the total number of outfalls for the sump, j is a time interval during the storm event, τ is the total number of time intervals, C is the concentration of pollutant, and R is the corresponding runoff for the outfall. As noted previously, during high flow events a significant quantity of backflow from the river to the sump occurs through the main sump-levee-river channel. Pollutant concentrations in the backflow have to be estimated and were assumed to correspond to the values at the pumping station for the reasons elaborated in a previous publication (Smith, 1996).

Using the above quantities, the removal of pollutants in a sump may be estimated from a mass balance. For a given pollutant, the mass removed in the sump, M_{sump}, can be expressed as:

$$M_{sump} = M_o + M_{end} + M_{load} + M_{pump} + M_{back} \tag{3}$$

where M_o and M_{end} are the mass in the sump at the beginning and end of the event, M_{back} is the

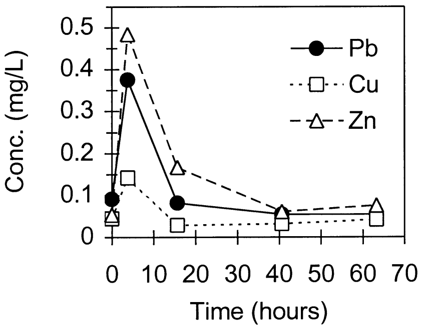

Figure 6 Metal concentrations at Sump C pumping station – Event 6

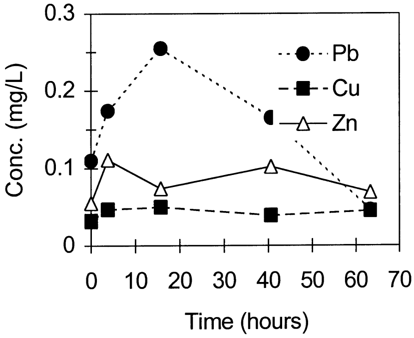

Figure 7 Metal concentrations at Sump D pumping station – Event 7

mass entering the sump via backflow (if applicable), and M_{load} and M_{pump} are as described previously. The challenge of this type of problem is evident when examining the assumptions required to estimate the various quantities. These include: (1) the sump is completely mixed, implying the pollutant concentration in the sump is equal to the pollutant concentration measured at the pumping station; (2) interpolation to obtain pollutant concentration values since this data is not continuous throughout the event; (3) the pollutant concentration measured at sampled outfalls is representative of pollutant loading at unsampled outfalls in the immediate area; and, (4) assumptions for estimating concentration levels for backwater flow.

Table 1 includes the results of pollutant removal calculations using the above approach for the event referred to previously. This is represented as percent removal (%Re), which was estimated as:

$$\%\mathrm{Re} = \left(\frac{M_{sump}}{M_{load} + M_{back}} \right) \times 100\% \tag{4}$$

The event selected for this example was a high-flow event, requiring pumping in both sumps and exhibiting backflow from the river. As such, it also illustrates well the relationship between the hydraulic character of a sump and pollutant removal. As indicated in this instance and in three other events for which complete sampling data was obtained, metal removals in Sump C are very low (essentially zero in this case) which is consistent with the relatively small sump volume and high rate of pumping during the event. In other words, the sump is flushed very quickly, with an estimated water detention time of between 2 and 3 hours, even when considering some backflow from the river. By contrast, Sump D removals are much greater, owing to the large sump volume and detention during the event (detention time in Sump D is ~30–40 hours when backflow water gain is considered). The percent treatment values should not be interpreted as precise given the assumptions inherent in the calculations. Nevertheless, the results illustrate the contrast between the variable hydraulic characteristics of the respective sumps, and suggest that the relatively simple methodologies proposed here provide a rational approach for estimating difficult-to-measure nonpoint source pollutants in urban watersheds.

Table 1 Sump removals of heavy metals for March 1995 event

Sump C	M_{pump}(kg)	$M_{load}+M_{back}$ (kg)	%RE	Sump D	M_{pump} (kg)	$M_{load}+M_{back}$ (kg)	%RE
Pb	87.7	82.3	–7	Pb	145	339	58
Cu	43.6	41.4	–5	Cu	50.4	86.4	41
Zn	174	181	4	Zn	96.8	148.4	32

Attending issues for which the proposed approach may also prove useful include acquiring estimates of stormwater pollutant loads per unit area for specific pollutants, and determining whether these can be meaningfully correlated with system parameters such as the nature of the runoff event and land use patterns for predictive purposes. Reliable models of this form require longer-term sampling and analysis of additional sumps of variable character to verify the principles established in this study.

Conclusions

1. In the absence of flow data for individual outfalls, HEC-1 calculations provided estimates of the total runoff hydrograph to two sumps of highly variable hydraulic character that were validated by a water balance calculation using independent measurements deriving from sump operational data. This information can be used to estimate nonpoint loads of pollutants of concern in urban stormwater drainage, such as heavy metals, to the sumps and to the receiving body.
2. Substantial removals of heavy metals can occur in sumps and can be estimated using the validated flow models together with a simple mass balance approach. As hypothesized, Sump D provided a much higher level of metal removal than Sump C, owing to stormwater detention in Sump D being an order of magnitude higher. From a water quality perspective, therefore, sumps are a better stormwater management practice than simple pumping.

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