Modulating Storm Drain Flows to Reduce Stream Pollutant Concentrations

Walter Frick, Debra Denton

Abstract

Pathogen and toxic chemical concentrations above the chemical and toxicity water quality standards in creeks and rivers pose risks to human health and aquatic ecosystems. Storm drains discharging into these watercourses often contribute significantly to elevating pollutant concentrations during wet weather, especially following extended periods of dry weather over which pollutants accumulate, or after seasonal pesticides applications that cause high concentrations in retention structures and flood control basins drained by the storm drains. In many instances the discharges from the storm drains are controlled by pumps that run intermittently in response to water level elevations in the retention basins. These pumps usually run at full volume, modulated only in stepwise fashion when more than one pump serves the overflow structure. The on-off mode of operation is insensitive to conditions in the ambient flow or the effluent. Modulating storm drain flows can ameliorate the impact of pathogens or toxic residues found in the storm drain effluent by controlled and optimum mixing of the effluent and ambient streams. Plume models simulating the mixing process in real time based on continuously measured stream levels and storm drain volumes, together with variable flow pumps, could be used to blend the effluent with the receiving stream in a way that mitigates the impact of the storm drain on the environment. The Visual Plumes model is used on a storm drain discharging to urban Arcade Creek in Sacramento, California to demonstrate the potential benefits that may be realized by implementing this strategy.

Keywords: storm drain, diazinon, Visual Plumes, pollutant concentration, flow rate

---

Frick is a Research Oceanographer, Ecosystems Research Division, U.S. Environmental Protection Agency, Athens, GA 30605. E-mail: frick.walter@epa.gov. Denton is an Environmental Scientist, Region 9, U.S. Environmental Protection Agency, San Francisco, CA, 95814.

Introduction

The development of Total Maximum Daily Loads (TMDLs) for a particular water body depend on the location of point sources, available dilution, water quality standards, non-point source contributions, background conditions, and in-stream pollutant reactions and pollutant toxicity (USEPA 1991). To establish a TMDL, both the upstream and downstream boundaries of the water body and the critical flow conditions must be defined. Critical conditions are stream flow, pollutant loading, and water quality conditions that result in no acute or chronic concentrations exceeding the chemical-specific water quality standard or the toxicity water quality standard.

Thus development of TMDLs implies that the effects of merging streams, including storm drains bearing their respective pollutant loads, can be adequately characterized. It goes without saying that pollutant concentrations undergo changes at stream confluences, adjusting in conformance with mass balance that, given sufficient fetch, approaches a new fully mixed state defined by

$$C_f = \frac{C_a Q_a + C_{SD} Q_{SD}}{Q_a + Q_{SD}} \qquad (1)$$

where C is concentration, Q is flow, and the subscripts *a, f,* and *SD* refer to the ambient receiving stream upstream of the confluence, the confluent stream, and the storm drain respectively.

The storm drain could be a combined sewer overflow, or CSO, an "event during which excess combined sewage flow caused by inflow is discharged from a combined sewer, rather than conveyed to the sewage treatment plant because either the capacity of the treatment plant or the combined sewer is exceeded" (Washington State Department of Ecology 1994). The content of the water and intermediate storage, if any, remain undefined. CSOs imply loss of control, and, therefore, this work addresses a broader range of outfalls, including storm drains.

Addressed herein are structures found in urbanized areas that discharge accumulated wastewater from storm water retention basins to streams or channels by means of a pump intermittently pumping at a steady rate, or several pumps operating in stepwise fashion.

The model storm drain described herein discharges to a small watershed (88 km^2) in Sacramento, California. Arcade Creek is an urban perennial stream with a mean dry weather flow of 0.50 cfs (0.014 m^3s^{-1}) with storm event flows reaching 500 – 700 cfs (14.2 – 19.8 m^3s^{-1}) within a few hours following rain because of limited opportunities for watershed infiltration. The watershed drainage area comprises 79% urban, 19% agricultural, and 2% barren lands according to the land-use classification of Anderson et al. (1976). Approximately ten miles of Arcade Creek are 303(d) listed for chlorpyrifos, two organophoshates, and diazinon, an organophosphorus insecticide.

During wet weather events there are times when Arcade Creek is flowing with pollutant concentrations that do not exceed the diazinon water quality criteria upstream of the storm drain discharge but do exceed the criteria downstream of it. In such cases the mass balance is such that the higher concentration of the storm drain effluent produces plumes of elevated concentrations in the receiving stream. If the storm drain water exceeds a threshold concentration, the receiving stream will not have sufficient water to dilute the plume below the criterion concentration even after full mixing. In such an event the stream will exceed criteria concentrations between that point and the next confluence, and even farther, unless decay, absorption or other process or strategy reduces concentrations below criterion level.

One strategy to meet water quality criteria in the receiving stream would be to moderate the flow rate serving the retention basin and storm drain. If conditions allow, the storm drain flow rate would be reduced to prevent exceeding the criterion concentration on an average basis. There will be a plume of elevated concentrations but the criterion pollutant isopleth will form a closed contour relatively close to the storm drain source instead of growing until it exceeds the criterion across the entire cross-section of the stream. Examples based on conditions generally describing a stream such as Arcade Creek are presented below to demonstrate the overall concept. Both storm drain and ambient variables are changed slightly for illustrative purposes.

Site Description

In connection to previous work (Denton 2001), three creek sampling sites were established. Downstream Site A is located adjacent to the existing USGS gaging station (No. 11447360), near Interstate 80 and Watt Avenue in Sacramento, and is 7.72 km upstream of the Natomas East Main Drain. Site B is located 1.84 km upstream of Site A. Site C is located 2.96 km upstream of Site A. The storm drain (SD) is located 0.50 km upstream of Site B. The USGS gaging station located on the creek provides an historic hydrologic context for the data collected during the study.

Methods

Diazinon and water chemistry

Water samples were collected from Sites A (1.8 km downstream of Site B), B (in between Sites A and C and slightly below the storm drain), and C (2.9 km upstream of Site C) in Arcade Creek during a twelve-month period (August 2000 through July 2001) to characterize the spatial and temporal concentrations of diazinon. Sampling events consisted of (bi-weekly) dry weather baseline values and storm events (n = 4). The storm events included both fall and winter events. Stream flow and stage data and general water quality measurements were collected in the field at each sampling event. Rainfall data were obtained from Gage #16 at American River College within the Arcade Creek watershed and used to determine precipitation amounts for the storm events. Such information was used to establish stream flows or other information indirectly.

Diazinon concentration reduction strategy

An examination of Eq. 1 may be used to explain the simple concentration reduction strategy. If C_{SD} is greater than the criterion concentration but C_a is below it, then there will be a threshold storm drain flow rate, $Q_{critical}$, at which the fully mixed concentration will be equal to the criterion concentration.

$$Q_{Critical} = Q_a \frac{C_a - C_{criterion}}{C_{criterion} - C_{SD}} \qquad (2)$$

where $C_{criterion}$ is the diazinon water quality criterion.

If this flow rate is exceeded by the storm drain pump then, downstream of the confluence, where the contributions of both streams are fully mixed, the diazinon criterion will be exceeded. However, if the pump is metered to reduce the flow below the critical flow rate, the receiving stream will exceed the criterion concentration only in a relatively small mixing zone. That is the basis for the simple strategy outlined herein. It can be achieved without using the Visual Plumes model. However, the model can be used to further analyze plume concentration patterns to not only simply meet the fully mixed criterion concentration but, for example, to provide a passage at the confluence in which the criterion concentration is met. The approach applies to suitably designed retention basins.

Estimating concentration contours beyond the stream dilution limit

When using plume models such as Visual Plumes UM3 it is important to understand that the streamflow constrains the amount of dilution that can occur. This is effectively what Eq. 2 states. When this limit is reached UM3 issues a stream-limit statement informing the user that beyond that point additional dilution is not supported by actual events. However, it continues the simulation as if additional diluting water were available. This feature of the model can be exploited to give further estimates of how the concentrated portion of the plume might continue to become more uniform downstream. This approach is similar to the reflection technique used in the PDS surface plume model (Davis 1999).

Unless the concentration isopleth to be contoured is equal to the ambient concentration, the concentration isopleth will be narrower than the width of the turbulent plume itself. Thus, when the stream limit is reached, the concentrated core of the plume will typically occupy only a fraction of the stream width. In the plume fringes, in other words along the banks, the concentrations often will be less than the contoured criterion concentration. As the plume material continues to flow downstream a mixing process similar to the one used in the model will result in the centerline concentration decreasing as the bank concentrations increase. Eventually, if sufficient fetch is available and there are not radical changes in stream conditions, a uniform concentration is reached. If the ultimate uniform concentration is higher than the contoured concentration, the ultimate contours will conform to the banks. Otherwise the contour may broaden briefly before ultimately closing as the width of the concentrated core reaches zero.
Visual Plumes UM3 may be used to estimate the contours of the criterion concentration beyond the stream dilution limit by assuring that the mass of pollutant in the plume element remains constant beyond that point. The model entrainment equation then may simulate the continued carrier fluid mixing process on which the appropriate concentration profile is simply superimposed so that the in-stream portion of the pollutant mass remains constant. The carrier mass, i.e., the water in the in-bank portion of the model plume element, is also constant beyond this point, as it must be. It is then simply a matter of solving for the width of the contour to continue to plot the stream core beyond the point of the stream dilution limit being reached. This procedure depends on being able to integrate the concentration profile across the stream, or, across the plume, if it is narrower than the stream.

Plume profiles

It is convenient to express concentration profiles in terms of the relative radius, f,

$$f = \frac{r}{b} \qquad (3)$$

where b is the radius of the plume. Upon growing to fill the water column depth the plume becomes a two-dimensional problem, in which case r and b become the relative and full width of the plume.

There are several profiles in common use, including the Gaussian and the 3/2 power profiles (Kannberg and Davis 1976). The former distribution extends to infinity, making it necessary to associate a statistic with the plume boundary. The latter is associated with flux-averaged concentrations. For the material element used in the Visual Plumes UM3 model a third profile, $g(f)$, is adopted, where

$$g(f) = 1 - f^2 \qquad (4)$$

The peak-to-mean ratio for this profile, k, for radial symmetry is 2.0. For a reflecting one-dimensional distribution $k = 1.5$. These are consistent with peak-to-mean ratios calculated from experimental data (Tian 2002).

Several related equations are used to apply this profile to the problem of determining specific concentration isopleths in the Visual Plumes UM3 model.

Results

Diazinon

Throughout the study period, all 137 samples collected were above draft USEPA diazinon acute and chronic criteria of 100 ng/L (USEPA 2000). The 10th percentile values of diazinon concentration for Site A, B, C and storm drain (SD) were 201, 216, 204 and 150 ng/L, respectively. The 90th percentile values of diazinon concentration for Site A, B, C and storm drain were 830, 836, 773 and 2415 ng/L, respectively.

The first winter storm event (Table 1) yielded the highest concentrations of diazinon from the storm drain (maximum = 4,800 ng/L), and concentrations remained high in consecutive sampling days. The second winter storm event yielded lower diazinon concentrations with a maximum of 1,300 ng/L, and concentrations decreased more quickly compared to the first sampling event.

The highest diazinon concentrations occurred during the rising limb of the hydrograph (Fig. 1) and in the first few days following the first fall and winter storm events. Diazinon concentrations were generally high during storm events (Fig. 2). However, there are a few diazinon concentration peaks during low or base flows (e.g., 11/17/2000 and 04/02/2001). Typically, higher diazinon concentrations occurred during winter storm events, which may have included both agricultural (i.e., offsite-movement from agricultural fields) and urban use components (Table 1).

Diazinon concentrations were converted to mass loads to express a load to the creek in kg/day. Not surprisingly, streamflow (cfs) and mass loading (kg/day) of diazinon in the creek yielded a good correlation (Fig. 3, $R^2 = 0.71$). Data point (a) was the first winter storm event with a high flow (651 cfs) and a high diazinon concentration (1200 ng/L), whereas the data point (b) was the second winter storm event with a high flow (561 cfs) and a lower diazinon concentration (240 ng/L).

At the storm drain flow rates were estimated from the sump pump rating curve, pipe discharge assembly, and time period during which each of the two sump pumps was operating. Each pump delivered approximately 2000 gpm (0.126 m^3s^{-1}) to Arcade Creek when running. Storm drain mass load ratios were calculated for three different storm dates (February 11, 12, and 19, 2001) when the concurrent flow rates and diazinon concentrations were known for both the storm drain and the creek. The contribution of diazinon from the storm drain ranged from 0.67 to 17.8% of the diazinon load in Arcade Creek.

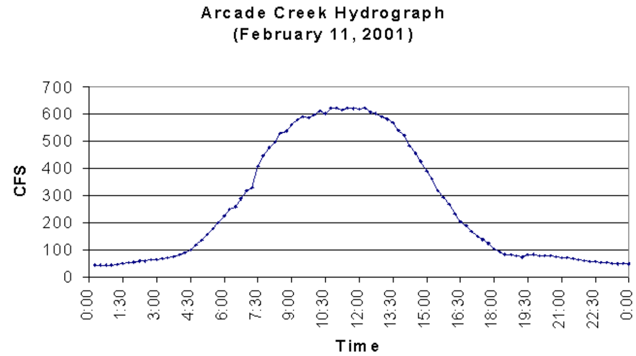

Figure 1. Arcade Creek hydrograph for 2/11/01.

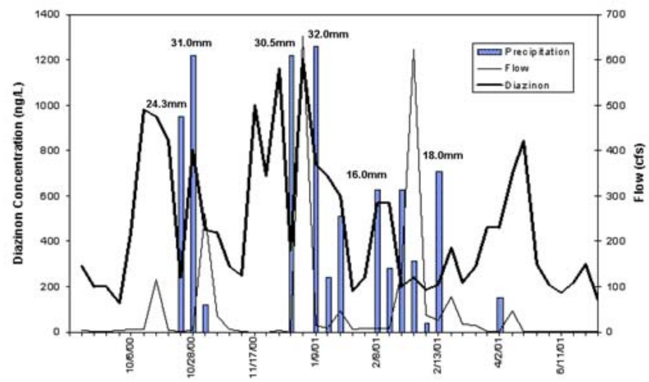

Figure 2. Diazinon concentration, flow, and precipitation at Site A. Note: Site A is the location of a USGS gaging station No. 11447360.

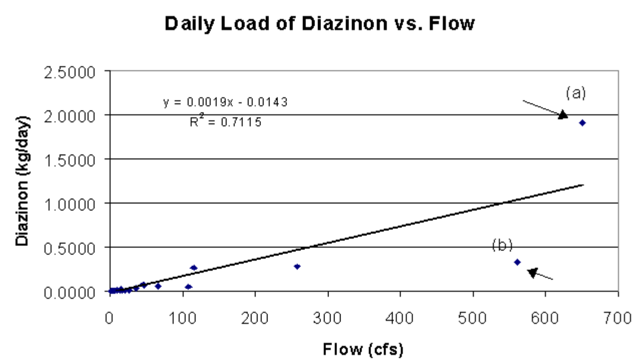

Figure 3. Mass loading of diazinon vs. flow (August 2000 - July 2001).

Model sensitivity run

Several realistic hypothetical cases are developed to show the sensitivity of plume area exceeding the criterion value to variations in flow. The results are shown in Fig. 4. Plumes (a) through (d) correspond to storm drain flows of 0.233, 0.243, 0.253, and 0.116 m^3s^{-1}, approximately one (0.116) or two pumps pumping at once.

Other model input conditions
Effective creek width, 10 m
Average flow depth, 3 m
Arcade Creek flow, 17 ms^{-1}
Arcade Creek diazinon concentration, 90 ng/L
Storm drain diazinon concentration, 800 ng/L
Depth to storm drain centerline, 2.7 m
Effective port diameter, 0.4 m
Isopleth (solid contours) concentration, 100 ng/L
Isopleth (dashed contour) concentration, 95 ng/L

Table 1. Winter storm event diazinon concentrations for storm drain

Storm date	Time interval	Diazinon ng/L)
01/09/2001 (1st winter event)	0-6 h 7-12 h 13-18 h 19-24 h	3 000 2 300 4 600 4 800
01/10/2001	0-6 h 7-12 h 13-18 h 19-24 h	2 700 3 100 4 500 2 600
01/11/2001	0-6 h 7-12 h 13-18 h 19-24 h	3 100 2 100 1 600 2 000
02/10/2001 (2nd winter event)	0-6 h 7-12 h 13-18 h 19-24 h 24h composite	1 300 1 100 800 740 690
02/11/2001	0-6 h 7-12 h 13-18 h 19-24 h 24h composite	360 390 320 280 400
02/12/2001	0-6 h 7-12 h 13-18 h 19-24 h 24h composite	580 370 400 570 630
02/13/2001	0-12 h 13-18 h 19-24 h 24h composite	440 410 450 450
02/19/2001 (3rd winter event)	0-6 h 7-12 h 13-18 h 19-24 h 24h composite	1 200 1 200 1 100 1 200 1 100
02/25/2001	0-6 h 7-12 h 13-18 h 19-24 h 24h composite	1 200 1 900 1 600 1 700 1 600

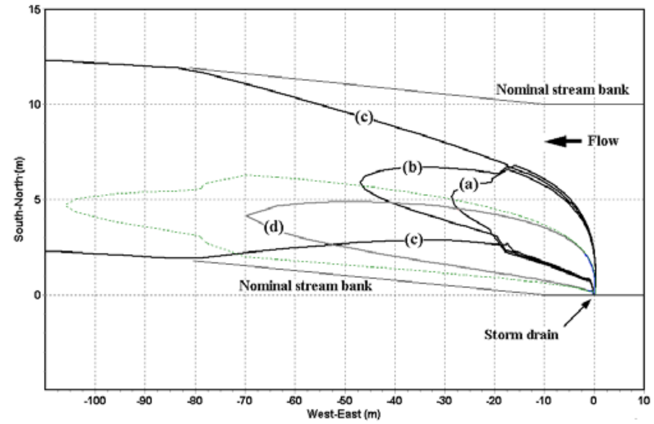

Figure 4. Simulated plumes--solid isopleths define the 100 ng/L ambient diazinon criterion concentration. Storm drain flows are (a) 0.233, (b) 0.243, (c) 0.253, and (d) 0.116 m^3s^{-1}, respectively. The light dashed isopleth, 95 ng/L concentration, part of Plume (d), shows how concentrations further decrease under these conditions.

Based on flow of 17 m^3s^{-1} (600 cfs) in Arcade Creek (near the upper range of wet weather flow rates) and using Eq. 2, the critical storm drain flow is computed to be approximately 0.243 m^3s^{-1}.

Plumes (a) through (c) illustrate the extreme sensitivity of the plume area in excess of the diazinon criterion to small fluctuations in storm drain flow as the flow approaches and then exceeds the critical storm drain flow. In theory even smaller increments in flow would illustrate the observed sensitivity to flow greater than the critical flow, however, the time step used UM3 is too large to show it.

By reducing the flow rate by a factor of two, perhaps by shutting off one of two pumps, the plume area in Plume (d) (Fig. 4) is produced. While it is somewhat larger in area than Plume (a), it is nearer to one bank and rapidly dilutes further as shown by the dashed 95 ng/L concentration isopleth. Plume (d) bends into the current more rapidly due to a reduction in discharge velocity. In this case the criterion can be safely met outside the plume's mixing zone.

Discussion

Plume sensitivity to critical flow fluctuations

The plume area is extremely sensitive to storm drain flow near critical flow due to the fact that center of the plume typically has concentrations well in excess of the 100 ppb criterion concentration when the outer edges of the plume, reach the banks of the creek and available diluting water is fully incorporated into the plume. After this point the plume is no longer diluted further but continues to mix laterally, a process that raises concentrations at the banks to the benefit of decreasing concentration at the plume centerline. In effect, the banks act as reflecting surfaces, reflecting back to the center of the plume material that would otherwise spread laterally in width-unconstrained receiving water. At significantly lower flow, the mixing zone area of the plume (d) is comparatively small and could be easily avoided by sensitive species capable of avoiding such concentrated regions.

Conclusion

As watershed hydrologic processes and conditions such as chemical processes (dry vs. wet weather inputs), background receiving water chemical concentrations, plume morphology, and dynamics of the storm hydrograph are better understood, water quality managers will be able to control and reduce the receiving stream chemical concentrations to specified criteria by varying storm drain flows (thereby controlling the mass of chemical inputs) until the criteria are met. In addition, managers could detour peak flows to treat chemical contaminants via best management practices (BMP), such as wetlands, until the chemical of concern is below the levels that cause acute and chronic toxicity to aquatic organisms. This is important because, as the TMDL is developed for diazinon and limits on its use become necessary, there will be alternative pesticides that will replace diazinon and it will be paramount to have the ability to reduce drain stormflow (thereby reducing mass loading) and to have BMPs to reduce pesticide concentrations before discharge into the aquatic environment.

This analysis demonstrates the utility of the Visual Plumes UM3 model in characterizing the appropriate mixing zone size for urban storm drains and diagramming the chemical concentration isopleths to estimate the location and size of stream plumes that may be exceeding criteria. If the size of the isopleth of concern is limited in space and time, then aquatic organisms may still pass upstream as necessary. For example, referring to Fig. 4, they would find the low concentration region in the vicinity of the flow arrow. Managers must check with the appropriate regulatory authority regarding their state's mixing zone allocation, if allowed and not restricted due to the presence of sensitive spawning grounds or threatened and endangered test species.

Acknowledgments

We are grateful to Drs. Brenda Rashleigh, David Young, Don Baumgartner, Anne Sigleo, and Candida West for manuscript review. This paper was reviewed in accordance with the U.S. Environmental Protection Agency review policies and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. EPA.

References

Anderson J.R., E.E., Hardy, J.T. Roach, and R.E. Witmer 1976. A land use and land cover classification system for use with remote sensor data. USGS Professional Paper 964, U.S. Geological Survey.

Frick, W.E., P.J.W. Roberts, L.R. Davis, J. Keyes, D.J. Baumgartner, and K.P. George 2003. Dilution models for effluent discharges, 4th Edition, Visual Plumes. EPA/600/R-03/025. ERD/NERL, U.S.EPA, Athens, GA.

Davis, L.R. 1999. Fundamentals of environmental discharge modeling. CRC Press, Baton Raton, FL.

Denton, D.L. 2001. Integrated toxicological and hydrological assessments of diazinon and esfenvalerate. Ph.D. Dissertation. University of California, Davis.

Kannberg, L.D., and L.R. Davis 1976. An experimental/analytical investigation of deep submerged multiple buoyant jets. USEPA Ecological Research Series, EPA/600/3-76-101, USEPA, Corvallis, OR.

Tian, X. 2002. 3DLIF and its applications to studies of the near field mixing in wastewater discharges. Ph.D. dissertation, Georgia Institute of Technology, July 2002.

United States Environmental Protection Agency. 1991. Technical support document for water quality-based toxics control. EPA/505/2-90-001. Office of Water, Washington, DC.

United States Environmental Protection Agency. 2000. Ambient aquatic life water quality criteria, diazinon. Office of Science and Technology, Washington, DC.

Washington State Department of Ecology 1994. Water quality program permit writer's manual. Washington State Department of Ecology Publication 92-109, Gary C. Bailey, project leader.