Stream Erosion Potential and Stormwater Management Strategies

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Abstract: Hydrologic and sediment transport modeling were used to examine the effectiveness of typical stormwater management policies in reducing the potential for stream-channel erosion. Two bedload functions and three total-load transport relationships were applied to 8 mm gravel and 0.5 mm sand bed materials to compare the performance of the relationships in estimating detention requirements across modes of sediment transport. The various sediment-transport relationships yielded widely diverging estimates of sediment-transport capacity and yet suggested detention volume requirements that agreed within 20%. Detention design for control of cumulative sediment load required a detention storage volume 61% greater than a peak control detention facility and resulted in an altered temporal distribution of sub-bank-full shear stress. Design of stormwater facilities based on time-integrated sediment-transport capacity may inadvertently result in channel instability and substrate changes unless the approach accounts for the frequency distribution of sub-bank-full flows, the capacity to transport heterogeneous bed and bank materials, and potential shifts in inflowing sediment loads.

DOI: 10.1061/(ASCE)0733-9496(2002)128:6(451)

CE Database keywords: Stormwater management; Channel stabilization; Stream erosion; Sedimentation; Bed loads; Land usage.

Introduction

Streams dynamically adjust over time to the temporal sequence of sediment and water flows delivered from the upstream watershed. In urbanizing watersheds, increased runoff coupled with a decline in watershed sediment yield frequently results in channel enlargement through incision and/or bank erosion. Such erosion may degrade stream integrity via altered channel morphology, planform, and bed material; increased suspended sediment loads; and loss of riparian habitat and may ultimately contribute to declines in sensitive aquatic biota (Waters 1995).

Management of altered watershed storage, runoff, and sedimentation processes during urbanization usually occurs in the absence of a comprehensive regional strategy and without application of geomorphic principles (McCuen and Moglen 1988). The ‘‘peak shaving’’ approach of maintaining the peak flow of the 2- to 10-year storm event typically achieves a peak-flow magnitude that approximates the predevelopment flow rate but increases the duration of in-bank flows. For example, MacCrae (1997) found that the hours of exceedence of morphologically significant midbank flows increased by 4.2 times after 34% of a 21 km^2 basin had been urbanized. An increased prevalence of midbank flows resulted in elevated sediment yields from bed and bank erosion and a threefold increase in predevelopment bank-full cross-sectional area, despite the installation of upstream stormwater management facilities.

Mitigating channel instability and aquatic ecosystem impacts necessitates the application of geomorphic principles in stormwater management. To account for the undesirable effects of increased flow duration, McCuen and Moglen (1988) proposed a multicriterion approach to stormwater policy that requires the cumulative, postdevelopment bedload transport volume to not exceed the predevelopment amount for the 2 year recurrence interval. Comparisons of various bedload equations suggested that computation of detention requirements was not sensitive to selection of a transport relationship. The approach did not explicitly include an assessment of transport potential across size fractions, modes of sediment transport, and shifts in the distribution of sub-bank-full shear stress.

The objectives of this study were to (1) conduct preliminary modeling to examine the effectiveness of typical stormwater management policies in reducing stream channel erosion potential; (2) compare the level of storage necessary to reduce channel erosion across sand and gravel particle sizes; (3) compare estimated channel erosion potential and detention storage requirements using different sediment-transport relationships; and (4) explore the compatibility of flood control, water quality, and channel stability criteria in multiobjective stormwater planning.

Methods and Approach

A computer model was developed to simulate the hydrologic and hydraulic processes associated with varying levels of watershed development and stormwater controls. Procedures used in the model, which included synthetic hydrograph formulation, weir and orifice equations, and the continuity principle (storage indication method) for modeling the passage of a flood wave through a detention facility, were consistent with standard practice tech-

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Note. Discussion open until April 1, 2003. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this technical note was submitted for review and possible publication on January 17, 2001; approved on July 23, 2001. This technical note is part of the ***Journal of Water Resources Planning and Management***, Vol. 128, No. 6, November 1, 2002. ©ASCE, ISSN 0733-9496/2002/6-451–455/$8.00+$.50 per page.

niques for urban stormwater design (Malcom 1989). The model was developed using existing land-use conditions and flow data from a flood analysis and geomorphic study of the Mail Creek watershed (3.9 km^2) located just inside the southern boundary of the city limits of Fort Collins, Colorado (Lidstone and Anderson, Inc. 1993). The watershed is rapidly urbanizing with approximately 50% medium-density development, 20% high-density development, and approximately 30% undeveloped land use. Ultimate buildout conditions are expected to result in over 50% impervious cover in the watershed.

Four hydrologic scenarios based on a 2-year, 2-h design storm for the Fort Collins area were considered. Since the effective or bank-full discharge of many streams is estimated to have a recurrence interval of approximately 1 to 2 years, a single 2-year event was used to examine erosion potential throughout this analysis. Model parameters (Soil Conservation Service curve numbers) were adjusted to represent predevelopment, existing, and ultimate-buildout land uses without stormwater detention controls.

In addition to pre- and postdevelopment conditions, two stormwater management scenarios were simulated using the model. In the first scenario, the postdevelopment hydrograph was routed through a stormwater detention facility designed to simply reduce the postdevelopment peak discharge to match that of the predevelopment hydrograph. This approach is hereafter referred to as "peak control detention." In the second stormwater management scenario, the postdevelopment hydrograph was routed through a detention facility that resulted in a cumulative sediment transport capacity over time that approximated that of predevelopment conditions as described by McCuen and Moglen (1988). This approach is hereafter referred to as "erosion control detention." Although precise modeling of existing and projected watershed hydrology was not an objective of this study, the estimated hydrologic conditions provide an adequate and generic context for examination of relative erosion potential associated with differing stormwater management strategies.

Input-channel geometry data represented an average channel section derived from cross-section surveys published in the City of Fort Collins's geomorphic assessment conducted in 1991. Channel geometry was approximated as rectangular in the analyses. Material comprising the bed and banks was characterized in 1991 by taking four bed-material samples and 12 bank-material samples at representative locations along the study reach (Lidstone and Anderson, Inc. 1993). The bed material consisted almost entirely of sands and gravels, with the majority of each sample being composed of gravel. Limited quantities of cobbles and small boulders were also present in the bed material. The lower bank unit had the highest content of clay (10 to 20%). The midbank unit—stratified alluvial deposits—typically contained less than 10% clay fraction material. Model runs were conducted for both 8 mm gravel (d_{50}) and 0.5 mm sand (d_{10}) bed material.

To determine the erosive potential of the different hydrologic scenarios, five sediment transport relationships were used in the model for the two bed-material sizes. The sediment-transport relationships utilized were the Einstein-Brown bedload function (Brown 1950), the Meyer-Peter/Müller (1948) bedload function, the Bagnold (1966) total-load relationship, the Engelund/Hansen (1967) total-load relationship, and the Shen/Hung (1972) total-load relationship as described in Julien (1995). Although the relationships for computing the total sediment-transport capacity are inappropriate for particle sizes that are transported exclusively as bedload (for example, 8 mm gravel), erosion potential indices were computed for both particle sizes using the five sediment transport relationships for comparative purposes. Model algorithms for computing sediment-transport capacity and bedload discharge were verified using data published by Julien (1995).

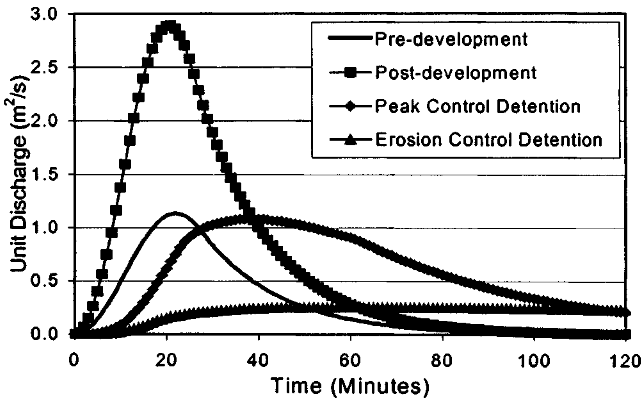

Fig. 1. Estimated Mail Creek unit discharge (2 year). Erosion control detention based on Meyer-Peter and Müller relationship using 8 mm gravel

To facilitate comparison of the pre- and postdevelopment erosive power of streamflows under different management scenarios, an erosion index referenced to predevelopment conditions was developed. This index, which is similar to the approach suggested by MacRae (1993), uses a simple finite-difference approximation to estimate the time-integrated sediment-transport capacity over the duration of the flow event:

$$E=\frac{\sum_{t=0}^{T} q_{s_{\text{post}}}}{\sum_{t=0}^{T} q_{s_{\text{pre}}}} \tag{1}$$

where E is the instream erosion potential; q_s is the unit sediment-transport capacity at time t; and "post" and "pre" represent post- and predevelopment conditions, respectively. The index allows comparison of sediment-transport relationships to determine if they suggest comparable levels of storage necessary to reduce erosion potential to approximate that of predevelopment conditions over the 2 year event. A time increment of 1 min ($T=120$ in 2 h) was used for all model computations.

Results and Discussion

The four hydrographs representing predevelopment, postdevelopment, and postdevelopment with peak control detention and erosion control detention are presented in Fig. 1. In the case of peak control, the peak of the postdevelopment hydrograph matches that of the predevelopment hydrograph, but the volume and duration of lower discharges are markedly increased. It is clear from the hydrographs that both stormwater detention facilities substantially extend the duration of lower discharges. From the toe to the midbank level, the duration of flow depth and therefore shear stress increased. To illustrate this phenomenon, the frequency and duration of critical shear stress exceedence was computed for the four scenarios (Fig. 2). The duration of flows exceeding critical shear stress for mobilization of coarse gravel ($16\text{ mm}<d_s<32\text{ mm}$) was over 50% greater than predevelopment conditions for both stormwater management scenarios.

Values of the erosion potential index were calculated for both particle sizes using the various sediment transport relationships (Table 1). The erosion control detention facility required a storage

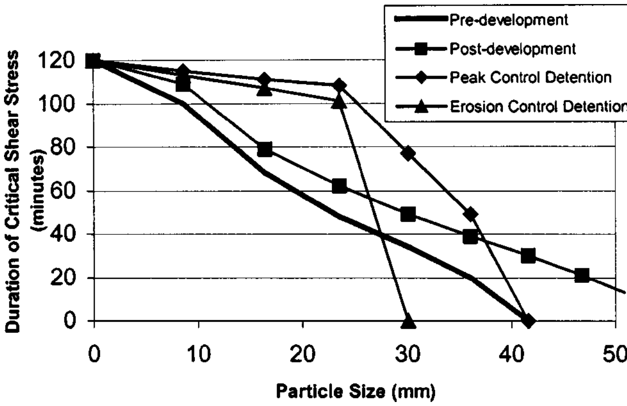

Fig. 2. Frequency and duration of critical shear-stress exceedence computed for four scenarios. Erosion control detention based on Meyer-Peter and Müller relationship using 8 mm gravel

volume 61% greater than the peak control detention facility to reduce the cumulative, postdevelopment erosion potential to a level approximating the predevelopment condition. This additional storage requirement was consistent for both gravel and sand scenarios based on the Meyer-Peter/Müller bedload relationship and the Bagnold total-load relationship, respectively.

For 8 mm gravel, an erosion control detention facility design based on the Meyer-Peter/Müller relationship required 12% more storage than a facility design based on the Einstein-Brown relationship. Although the magnitude of transport predicted by the Einstein-Brown and Bagnold relationships differed by approximately a factor of four, the amount of storage required to achieve the predevelopment, cumulative erosion potential was quite similar. In the case of 0.5 mm sand, an erosion control detention facility design based on the Bagnold relationship required more storage than facility designs based on the Engelund/Hansen and Shen/Hung relationships. A design based on the Shen/Hung approach would require 20% less storage volume. The two bedload equations consistently suggested that additional storage beyond that computed using the Bagnold approach would be necessary to reduce the cumulative sediment transport of 0.5 mm sand to predevelopment levels. These results reflect the inherent differences in the total-load relationships across flow magnitudes.

The adoption of a stormwater policy that includes sediment-transport capacity as a criterion requires the selection of an appropriate sediment-transport estimation method or model. McCuen and Moglen (1988) compared four bedload equations to estimate the level of detention needed for reducing cumulative erosion potential to predevelopment conditions. Although the equations provided estimates of bedload transport that differed by as much as a factor of 20, the differences in required storage volumes differed by less than 15%. This study generally supports those findings, although the total-load equations of Bagnold and Shen/Hung applied to 0.5 mm sand resulted in erosion control detention requirements that differed by 20%. Differences in computed storage requirements would be much greater if a total-load equation was inadvertently applied to material that moves as bedload. In the case of medium sand, the bedload equations were more conservative and suggested a greater detention volume requirement relative to the total-load equations.

Design criteria that do not account for the nonuniform increase in shear stress (Fig. 2) or stream power may increase the geomorphic work associated with moderate flow events. The peak control detention facility failed to prevent a significant increase in the erosion index. The greatest increase in erosion potential was associated with depths less than about 70% of the bank-full depth. The durations of flows at or below bank-full stages are probably more important than the magnitude of floods in controlling bank erosion (Richardson et al. 1990), and these flows could have a large impact on boundary materials in the toe region.

This finding is consistent with field observation of accelerated bank undercutting following urbanization and points to the importance of bank conditions in determining channel response. The erosion control detention method proposed by McCuen and Moglen (1988) also redistributed the duration of flows around the channel perimeter and substantially altered the temporal distribution of shear stress that occurred under predevelopment conditions.

An implication for maintenance of channel stability is to recognize the disproportionate increase in moderate flow events associated with standard stormwater controls and to account for the temporal distribution of shear stress or stream power at limiting points on the channel boundary (MacRae 1997; Bledsoe and Watson 2001). The variability of bank stratigraphic units in the Mail Creek watershed underscores this point. The duration of various levels of critical shear stress depicted in Fig. 2 could prove useful in comparing differing management scenarios in a variety of contexts. The erosion index and graphical approaches could be extended beyond analyses of single events to more robust continuous simulations of pre- and postdevelopment flow regime and sediment-transport potential across bed materials and bank conditions. A simple erosion index such as the one presented here could also be applied by bed material size fraction and utilized in risk-based models of channel stability.

Table 1. Values of Erosion Potential Index Computed as Ratio of Cumulative Sediment Transport Potential for 2-Year Flow Event Relative to Predevelopment Conditions

	EROSION POTENTIAL INDEX (*E*) RELATIVE TO PREDEVELOPMENT CONDITIONS							
	8 mm Gravel				0.5 mm Sand			
Sediment transport relationship	Pre	Post	PCD	ECD	Pre	Post	PCD	ECD
Einstein-Brown bedload	1.0	2.2	2.1	0.7	1.0	1.5	1.7	1.3
Meyer-Peter/Müller bedload	1.0	1.7	1.9	1.0[a]	1.0	1.5	1.7	1.3
Bagnold total load	1.0	2.4	2.1	0.7	1.0	2.9	2.1	1.0[a]
Engelund/Hansen total load	1.0	4.8	2.3	0.3	1.0	4.9	2.3	0.7
Shen/Hung total load	1.0	5.9	2.3	0.2	1.0	6.3	2.3	0.6

Notes: Pre = predevelopment; Post = postdevelopment; PCD = peak control detention; and ECD = erosion control detention.

[a]Denotes sediment transport relationship used to compute volume required for erosion control detention at the respective particle sizes.

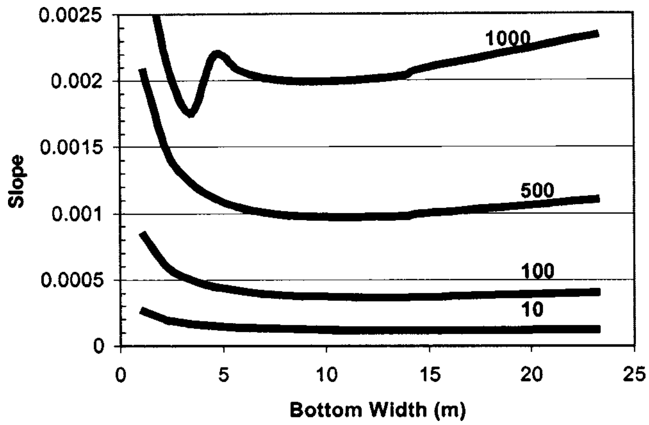

Fig. 3. Analytical stable channel solutions for sand-bed channels with different inflowing sediment concentrations. Solutions based on trapezoidal channel with 2:1 (H:V) bank angles, the Brownlie (1981) depth predictor and sediment-transport equations, $Q = 10\ m^3/s$, and $d_s = 0.5$ mm. Note that upper curve depicts shift to upper regime bedforms at smaller widths occurring at that transport capacity

Because streams adjust to the water and sediment supplied to them, stormwater management efforts targeted at protecting or restoring stream stability should be based on general physical principles rather than referenced to empirically defined equilibrium states (Wilcock 1997). General physical principles clearly indicate that sand-bed channels are particularly susceptible to shifts in the sub-bank-full flow regime. In general, the slope of a sand-bed channel that maintains sediment continuity for a given discharge may decrease by almost an order of magnitude when inflowing sediment concentration is decreased from 1,000 ppm to less than 100 ppm (Fig. 3).

Watershed imperviousness and the sediment-trapping efficiencies of structural best-management practices like those depicted in this study may deplete inflowing bed material loads. Such a reduction in bed material load may act in concert with an increased frequency of moderately sized flows to exacerbate channel instability, especially in mixed- or suspended-load channels. It follows that reproducing the predevelopment flow regime will not necessarily maintain the stability of sand-bed streams if there is a significant, long-term reduction in bed material load.

In contrast to sand-bed streams, the stable slopes of gravel/cobble bed streams are generally much less sensitive to changes in sediment load (Howard 1980; Hey and Thorne 1986). Instead, the slope of a gravel-bed stream is predominantly controlled by moderate to coarse bed material fractions and discharge (Knighton 1998). Stream type and mode of sediment transport are therefore very important considerations in predicting the response of a stream to various land-use and stormwater management scenarios.

As stormwater policies become more focused on both the physical and biological aspects of water quality, it is likely that a multicriterion approach based on flood control, pollutant removal, and maintenance of key geomorphic processes will become more favored. The need for extended detention to remove pollutants from urban runoff and the diametrically opposite trends in delivery of water and sediment from an urbanized watershed are difficult to reconcile. Recognition of multievent changes in the magnitude and duration of flow energy, the heterogeneous nature of channel boundaries, the modes of sediment transport, and the potential response of different stream types are all important aspects of understanding and preventing channel erosion in urbanizing watersheds (MacRae 1997; Bledsoe and Watson 2001).

A promising framework for achieving channel stability and water quality objectives might be to design detention storage to emulate both the shape and magnitude of the predevelopment hydrograph over a range of geomorphically important flows (MacRae 1991, 1993), assess the potential impacts of long-term reductions in sediment delivery on fine-grained systems, and enhance source controls and education efforts for pollutant removal and prevention. In contrast to these analyses, future research should emphasize more robust continuous simulations across stream types and management practices that have not been considered here.

Summary

Analyses of the sediment-transport characteristics associated with standard stormwater management designs suggest that channel instability may result despite reduced postdevelopment peak-flow magnitude and increased storage duration. Various sediment-transport relationships may yield widely diverging estimates of cumulative sediment-transport capacity and yet suggest erosion-control storage requirements that agree within 20%. The selection of a sediment-transport relationship should be based on the predominant mode of sediment transport and the range of conditions used to develop the relationship.

To fully address the potential for channel response, it is necessary to expand standard design approaches to address the temporal distribution of erosive forces relative to both bed materials and bank conditions. Single-event techniques for maintaining the cumulative bedload transport volume, unless modified to account for differential transport by size fractions across a broader range of flow events, may alter predevelopment fluvial processes and affect channel morphology and the quality of instream habitat. Given the sensitivity of fine-grained streams to inflowing bed material load, reproducing the predevelopment hydrograph will not necessarily ensure stability if there is a sufficient long-term reduction in sediment delivery. Thus, stormwater management strategies should be carefully weighed in terms of their long-term geomorphic implications in addition to flood control and pollutant removal functions.

ACKNOWLEDGMENTS

This article was developed as a product under joint sponsorship of the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers. It has not been formally reviewed by EPA or COE. The views expressed in this document are solely those of the writer and neither EPA nor the COE endorse any products or commercial services mentioned in this publication.

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