An Alternate Design Approach for the Control of Instream Erosion Potential in Urbanizing Watersheds

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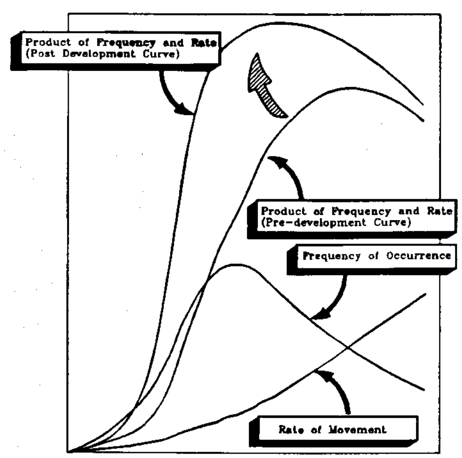
I. INTRODUCTION

Case studies have demonstrated the potentially adverse effects of uncontrolled urban storm water runoff on stream channel form. The concepts of detention and retention were employed in the form of Best Management Practices (BMPs) to mitigate these impacts through the reduction of flow rates by storage routing effects. Studies have shown that stormwater control facilities designed using current techniques may be ineffective or may aggravate erosion hazard in some instances (McCuen, 1979; Lorant, 1983, 1988). These and other studies suggest that the criteria upon which current design techniques are based may not adequately meet the intent of Stormwater Management (SWM) practice. The challenge then, is to develop criteria and ultimately a design procedure which more adequately deals with the instream erosion issue.



PROBABLE ALTERATION OF LEOPOLD ET AL.'S (1964) EFFECTIVE WORK CURVE — Figure 1

Current design practice is based on criteria developed from studies of non-urban stream channel systems. In an influential study, Leopold et al. (1964) demonstrated that "effective work" achieved an absolute maximum at bankfull stage that was in accord with a flood recurrence interval (RI), of 1:1.5 to 1:2 years (Figure 1). However, numerous studies have shown that the hydrologic and sediment regimes in urban systems are altered from their pre-development state. MacRae and Rowney (1992) demonstrated that under urban conditions the absolute maximum on the effective work curve increased in magnitude and shifted to flows of 1:0.5 to 1:1.5 year return period (Figure 1). These events occur more frequently than previously considered and they are not specifically addressed in current design practice.

Heterogeneities in boundary material composition and bank structure may also have implications on design practice. The apparent significance of the "least resistant bank toe stratigraphic unit" (MacRae and Rowney, 1991), suggests that the use of a one-dimensional representation of the stream channel, as used in current design practice, may not adequately characterize the resistance of the channel to scour and subsequently, its response to a change in erosion potential.

II. INDEX OF INSTREAM EROSION POTENTIAL

A two-dimensional index of scour potential is proposed to account for heterogeneities in boundary material composition and bank structure (MacRae, 1991). The index is applied on a multi-event basis to address the affect of the non-uniform increase in flow frequency following urbanization. Based on shear stress concepts and a comparative pre- versus post-development approach, the index has the general form,

$$\Delta(E_S)_P = [(E_S)_{POST} - (E_S)_{PRE}]_P \qquad (1)$$

where (ΔE_S) is the change in instream erosion potential at point P about the channel perimeter and the subscripts PRE and POST refer to the pre- and post-development condition respectively. Assuming the pre-development channel represents a stable state, then a non-zero value of the index would represent a change in the potential for channel deformation at point P about the channel perimeter.

The functional form of Eqn. (1) may be written as,

$$(\Delta E_S)_P = \left(\int_0^T [(q_S)_O - (q_S)_I]\, dt\right)_{POST} - \left(\int_0^T [(q_S)_O - (q_S)_I]\, dt\right)_{PRE} \qquad (2)$$

in which q_S is the sediment transport potential and the subscripts I and O refer to the influx and outflux of sediment through a channel reach respectively. The explicit form of the index will depend upon the exact form of the sediment transport relation. When $\Delta(E_S)_P > 0$, erosion of the channel boundary will occur either along the bed (degradation), the bank (basal scour) or both. If $\Delta(E_S)_P < 0$, aggradation of the bed will occur with erosion of the bank ensuing. Finally, $\Delta(E_S)_P = 0$, defines a stable (no scour) scenario. The ability of the index to represent scour potential was demonstrated through a one-to-one correspondence between the rank of the index values with a ranking of depths of degradation. Depths of scour were predicted using a one-dimensional mobile bed model in a trapezoidal channel formed in homogeneous, non-cohesive, sand sized material.

Determination of the index at points about the channel perimeter defines a two-dimensional measure of the potential for channel deformation. An aggregate measure of the change in scour potential would yield,

$$(\Delta E_S)_{AGG} = \int_0^{L_x} |\,(\Delta E_S)_P\,|\, dz \qquad (3)$$

where $\Delta(E_S)_{AGG}$ is the aggregate change in scour potential about a channel cross-section, L_x is the length of wetted perimeter, and z is the transverse cross-sectional axis. The absolute value of $\Delta(E_S)_{AGG}$ is used to encompass the special case of aggradation of the bed combined with erosion of the banks.

III. EVALUATION OF CURRENT DESIGN PRACTICE

The scour index was incorporated into QUALHYMO, a continuous hydrologic simulation model (Rowney and MacRae, 1991). The model was then used to evaluate two of the most commonly applied current design procedures: the "zero runoff increase" (ZRI) concept; the "over control" approach. The ZRI method is a hydrologic approach where the post-development 1:2 year peak flow rate is reduced using detention storage to the pre-development flow rate. It is a one-dimensional, discrete event approach with no consideration of boundary material characteristics. The OC method, initially proposed by Whipple et al., (1981), provides detention storage in addition to that required by the ZRI technique to reduce aggregate erosion to pre-development levels. This method also uses a one-dimensional, discrete event approach although it does account for sediment characteristics averaged over the cross-section.

McCuen and Moglen (1988) demonstrated the OC approach by reducing the peak outflow rate from a control pond until the post-development sediment transport rate, as measured by unit width bed transport potential, approached the pre-development level. For their specific case study, this represented an 85 percent reduction of the 1:2 year pre-development peak flow rate. Storage in addition to that required for ZRI control is necessary to obtain the additional reduction in peak flow rates hence the term "over control" (OC). The OC approach was evaluated using the proposed index for 50 to 90% reductions in the 1:2 year pre-development peak flow rate.

Both techniques were tested using a trapezoidal channel formed in uniform, non-cohesive materials and a channel formed in stratified, cohesive materials. Figures 2 and 3 present the transverse distribution of the index for these control philosophies for channels formed in very soft and firm cohesive boundary materials respectively. Table 1 presents a summary of the value of $(E_S)_P$ for the mid bed and bank toe regions as a ratio (R) of post- to pre-development conditions for materials formed in very soft to stiff cohesive boundary materials.

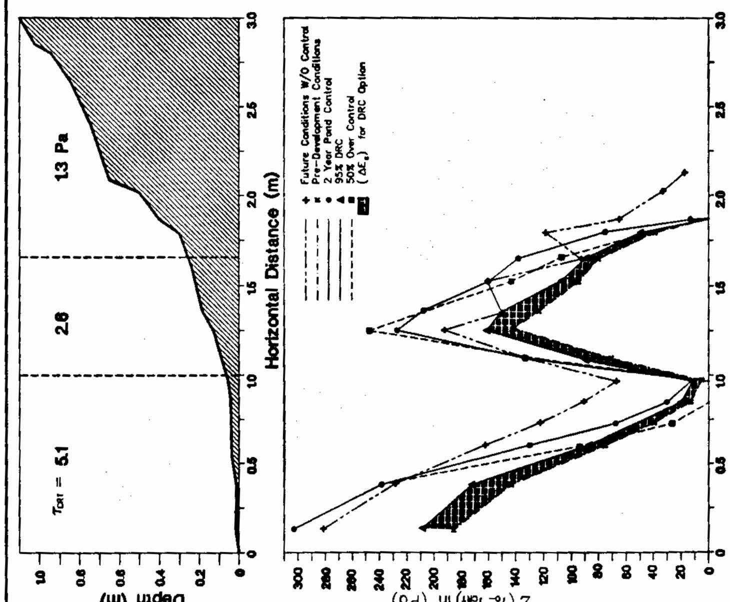
TABLE 1: Pre- Versus Post-Development Ratio (R) of $((E_S)_P)_{BED}$ and $((E_S)_P)_{TOE}$

METHOD	VERY SOFT	SOFT	FIRM	STIFF
ZRI	1.64	1.51	1.74	2.06
	1.55	1.45	1.64	3.12
OC (50%)	1.64	1.29	1.12	0.06
	1.69	1.50	1.57	2.12
DRC	1.14	1.02	1.19	1.22
	1.10	1.05	1.17	2.12

The ZRI method failed to prevent a significant increase in the potential for downcutting $((R_{BED}) > 1)$, and undercutting $(R_{TOE} > 1)$. Erosion hazard increased with respect to the no-control scenario in channels formed in very soft to soft, cohesive boundary materials, and there was no significant improvement over post-development flows without SWM controls for a channel formed in firm boundary materials.

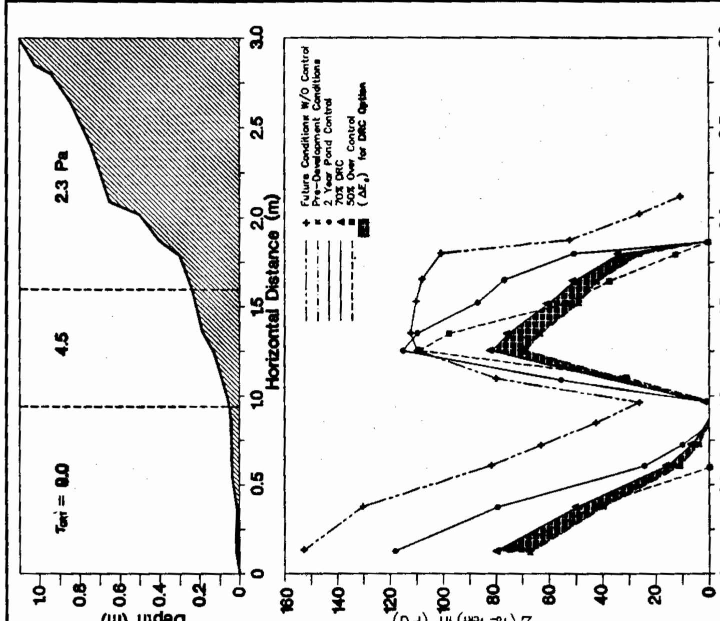
These results are consistent with observations of channel enlargement in seven streams in Surrey B.C. under 1:5 year SWM control (Lee and Ham, 1988). McCuen (1979), noted that while post-development outflow rates were controlled to pre-development levels the duration of high flows increased several fold. This increase in the duration of high flows translated into a higher sediment transport capacity which would likely increase scour potential and hence channel instability.

The OC method also failed to prevent an increase in the potential for downcutting or undercutting in very soft to soft, cohesive boundary materials, (the lowest values of $(\Delta E_S)_{AGG}$ were obtained with a 50% reduction in the 1:2 year pre-development peak flow rate). It significantly reduced the potential for downcutting and undercutting for channels formed in firm, cohesive boundary materials although the potential undercutting was still elevated above the pre-development condition. This reflects the poor reproduction of the transverse distribution of the index due to the alteration in flow geometry in the receiver downstream of the OC storage facility for those flows that exceed the erosion threshold. For channels formed in stiff, cohesive boundary materials the OC method produced aggrading conditions. At 90% reduction the OC approach resulted in aggrading conditions for all channel types except those formed



TRANSVERSE DISTRIBUTION OF EXTAU ABOUT AN ELLIPTICAL CHANNEL SEMI-PERIMETER FOR SELECTED SWM STORAGE ALTERNATIVES IN VERY SOFT CLAY

Figure 2



TRANSVERSE DISTRIBUTION OF EXTAU ABOUT AN ELLIPTICAL CHANNEL SEMI-PERIMETER FOR SELECTED SWM STORAGE ALTERNATIVES IN FIRM CLAY

Figure 3

in very soft, cohesive boundary materials.

Flow conditions which result in either degradation or aggradation represent unstable channel states. Degradation results in bed downcutting and bank undercutting. Aggradation results in sedimentation patterns which may be equally disruptive of the physical channel environment and the associated ecosystem. The preferred design approach should attain a balance between "under control" resulting in degradation and "over control" causing aggradation.

IV: DISTRIBUTED RUNOFF CONTROL

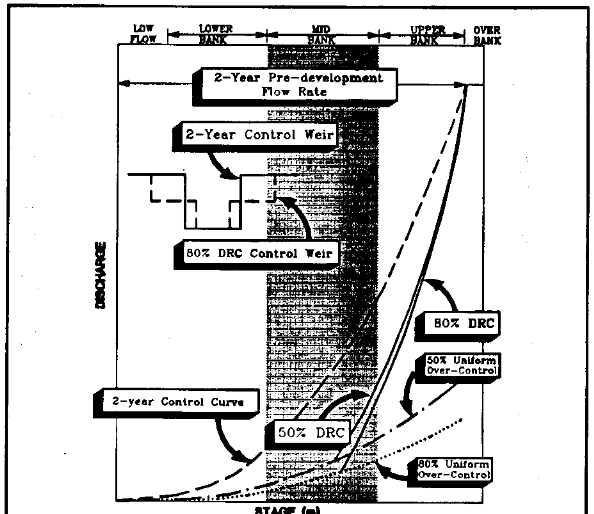
A philosophy for the control of instream erosion potential is proposed predicated on the assumption that change in instream erosion potential will be minimized if the magnitude and transverse distribution of ΔE_S is held constant with pre-development conditions $((\Delta E_S)_{AGG} \approx 0)$. This technique recognizes the contribution of the range of moderate to bankfull flow events for the determination of channel form and distributes the degree of storage control by stage in proportion to the non-uniform increase (post- minus pre-development) in scour potential. The proposed technique is referred to as "Distributed Runoff Control" (DRC) because of the non-uniform distribution of storage by stage.

Three critical zones on the DRC curve (Figure 4), may be defined as follows:

i) low to mid bank flows: the degree of control is independent of erosion objectives because shear forces are less than the threshold for scour of the least resistant stratigraphic unit;

ii) mid bank flows: the degree of control follows the OC curve to the stage of maximum effective work; and,

iii) upper bank flows: the degree of control decreases to the ZRI control level at bankfull stage.



STAGE-DISCHARGE CURVES FOR SELECTED SWM DETENTION CONTROL METHODS Figure 4

Spillage of flows onto the floodplain serves as a natural limit to the magnitude of shear forces acting on the bed which means that the control of flows in excess of bankfull stage is not required.

Although pre-development flows are not reproduced in all aspects, the DRC approach does reproduce the 1:2 year pre-development hydrograph for flows above the erosion threshold defined for the least resistant stratigraphic unit. Figures 2 and 3 show that in comparison to current methods the DRC approach provided the closest reproduction of the magnitude and transverse distribution of the scour index. The comparison is summarized in Table 1 which shows that the DRC technique consistently provides the highest degree of control of instream erosion potential over the range of channel boundary materials examined in this

study.

V. CONCLUSIONS

New criteria for the design of SWM facilities for the control of instream erosion protection has been proposed. These criteria state that the change in erosion potential associated with an alteration in the hydrologic regime will be minimized if the magnitude and transverse distribution of an erosion index is maintained at pre-development levels. This assumes that the pre-development case represents a stable channel system. An index of scour potential is also proposed based on a pre- versus post-development comparison of sediment mass balance at a point about a channel perimeter. Temporal characteristics of the flow field were incorporated into the index through integration with respect to time. Transverse variations in boundary material resistance to scour was addressed by integrating the index across the wetted perimeter.

Evaluation of current design practice indicate that these control techniques may not satisfy the intent of Stormwater Management. An alternate design procedure was proposed based on maintaining the pre-development value of the index at a point about the channel perimeter. It follows that the change in scour potential following urbanization is minimized if the transverse distribution of the index is maintained constant with pre-development conditions. Comparison with current design practice shows that the proposed approach most closely satisfied the proposed design criteria under the range of channel forms and material types considered in this research.

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