Matching the critical portion of the flow duration curve to minimise changes in modelled excess shear

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Abstract Hydrologic and hydraulic modeling in the USEPA Stormwater Management Model (SWMM) were used to examine the effectiveness of typical stormwater management practices in reducing the potential for stream erosion. Fifty-year continuous simulations were used to produce flow duration curves and stream erosion rates for a variety of critical shear stress values representative of both cohesive and non-cohesive sediments. An excess shear stress erosion potential index was used to evaluate changes in erosion between undeveloped conditions of a 10 hectare watershed and four variations of post-development stormwater control. Evaluation of flow duration curves showed that when development takes place, the duration of mid- to low-range discharges increase significantly, especially when detention practices are applied. In channels with low entrainment thresholds for bed and bank materials, e.g. sands and highly erodible clays, the significant increase of the duration of mid- to low-range discharges results in erosion potential index values greater than two regardless of the detention practices used. Overcontrol detention resulted in erosion potential index values of less than one, indicating a loss of erosion potential for bed materials such as most gravels (d₅₀ > 6 mm) and resistant clays that have critical shear stress values greater than four Pa.

Keywords Continuous simulation; flow duration; modeling; shear stress; stormwater management; stream erosion

Introduction

Urbanisation of a watershed increases impervious areas, and consequently increases stormwater runoff. Peak-flow increases from two- to more than 50-fold typify the changes brought by urbanisation on flood peaks (Hollis, 1975; Roesner et al., 2001) and flow exceedance frequencies have also been shown to increase dramatically when development of a watershed is left uncontrolled (Nehrke and Roesner, 2004). Durations of flows also increase when uncontrolled development takes place; however, Nardi and Roesner (2003) showed that the addition of extended detention best management practices produced an increase in the flow duration curve above that of uncontrolled development. Unless volume reduction controls are implemented when urbanisation takes place (i.e. infiltration basins), the total duration of flows will lengthen, with or without stormwater controls, due to the increase in overall quantity of stormwater.

When stormwater is left uncontrolled or is controlled inadequately, increases of the magnitude and duration of runoff cause downstream flooding, accelerate channel erosion, and impair aquatic habitat (Roesner et al., 2001). Increases in the magnitude and duration of stormwater runoff that accompany uncontrolled development allow a stream to carry more sediment than it could prior to watershed development. When a watershed cannot supply the stream with the volume of sediment it has the capacity to carry, channel degradation may occur in the form of incision, lateral migration or a combination of both (Bledsoe, 2002).

Many municipalities and agencies require some level of stormwater control when development or redevelopment takes place within their jurisdiction. The intent of these
practices ranges widely: from flood prevention to protection of water quality (Center for Watershed Protection, 2004). Currently, few municipalities require design of stormwater controls specifically to minimise stream channel degradation. This study examines an alternative method for designing stormwater controls to minimise the potential for stream channel degradation by matching the critical portion of the flow duration curve and identifying the stormwater management scenarios that have an erosion potential index closest to one.

Methods
A six-step approach was employed for this study, primarily using programs contained in Version 44 h of the USEPA Stormwater Management Model (SWMM) suite of tools. (1) continuous precipitation data were processed by SWMM Rain for use in SWMM Runoff; (2) SWMM runoff generated surface runoff based on local precipitation data (continuous and event-based), land use and topography; (3) SWMM Extrann routed event based flows through the drainage system and stormwater basins, creating stage-discharge relationships for use in SWMM Transport; (4) SWMM Transport routed continuous and event-based flows through the drainage system and stormwater basins; (5) the SWMM Statistics block generated flow frequency data from Transport; (6) SAS, a statistical analysis/programming package, was used to calculate flow duration curves, erosion rates and erosion potential indices.

Three levels of stormwater control within the developing portion of the watershed were examined in this study, and compared to “Undeveloped” and “Developed Uncontrolled” conditions. The first stormwater control examined, referred to as “Overcontrol”, was based upon detention storage requirements in the City of Fort Collins (1997) for areas where master drainage plans are not yet in place. The Fort Collins regulations require that stormwater runoff be released from developments at a rate not greater than the 2-year historic runoff. The amount of runoff to be detained on-site is the difference between the 100-year runoff under developed conditions and the 2-year historic runoff. The second level of stormwater control examined is referred to as the “Peak Shaving (100 & 10) + BMP” scenario. This scenario combines control of the water quality capture volume (WQCV) with peak shaving practices for stormwater detention that are frequently observed across the United States, control of the 100-year post development runoff rate to the 100-year historic rate, and, control of the 10-year post development runoff rate to the 10-year historic rate. The term BMP represents best management practice, which in this study is the control of WQCV. A WQCV is computed as the product of the mean runoff event and a drawdown coefficient, resulting in the capture of 70–90% of all runoff-producing events in their entirety. The WQCV in this study was calculated using the method described by the Denver Urban Drainage and Flood Control District (UDFCD, 1999). The third level of stormwater control examined is referred to as the “Peak Shaving (100) + BMP” scenario. As in the second scenario, the detention in this scenario reduces the 100-year post development runoff rate to the 100-year historic rate; however, the 10-year storm is not controlled.

Watershed characteristics and hydrologic modeling
The study area is located south of Fort Collins, Colorado, USA, and is a subbasin within the Fossil Creek Watershed. The climate in Fort Collins is semi-arid, and the average annual precipitation is 368 mm. Precipitation is spatially variable, and often occurs at high intensities, for a limited duration. The resulting flow regime is flashy, and typically includes a sharply peaked runoff hydrograph. Land use in the study area currently consists of 10 ha of pastureland, assumed to be 5% impervious. Potential development within
the watershed was simulated by converting the pastureland to a medium-density residential subdivision. Representative lot sizes were modelled after typical existing residential subdivisions in the vicinity of the study area. Average lot sizes in the simulated subdivision were 0.15 ha, with 27 m of frontage. The study area was divided into seven subbasins, with an average imperviousness of 25%. Under “Undeveloped” (current) conditions, runoff from the study area travels overland to a grassed swale. Under “Developed” conditions, runoff from each subbasin was modelled to travel overland to respective gutters and swales. SWMM Runoff was used for the hydrologic modelling and generated runoff hydrographs for the 2-, 10-, and 100-year design storms, as well as the 50-year continuous precipitation record.

Flow routing and stormwater controls
Downstream flow routing and stormwater detention were modelled using SWMM Extran and SWMM Transport. The downstream channel was modelled as triangular, with side slopes of 4:4, a bed slope of 0.005, and a Manning n of 0.04. Stormwater detention ponds and outlets for the study area were sized in SWMM Extran, using simulations of the 100- and 10-year design storms. Trial and error was used to design appropriate detention volumes as well as orifice outlet sizes and inverts. Detailed information about the detention pond and outlet sizes can be found in Rohrer (2004). Detention pond stage-discharge data generated by SWMM Extran were used to establish relationship equations. These equations were used as input for SWMM Transport, which is not able to calculate detention pond discharge using orifice equations. Simulations in SWMM Transport were then run using the 50-year surface runoff hydrograph generated by SWMM Runoff.

Erosion potential analysis
Incipient motion occurs when the fluid flow around a sediment particle exerts a force that is greater than the resisting force of the particle weight. This condition can be evaluated by comparing a calculated shear stress in the channel to a critical shear stress value for the bed material examined. Boundary shear stress, \( \tau_o \), is calculated as:

\[
\tau_o = \gamma R_h S_f
\]

where \( \gamma \) is the unit weight of water, \( R_h \) is the hydraulic radius of channel, and \( S_f \) is the energy gradient in the channel. Channel erosion is a function of the erodibility of the bed and bank materials and excess shear stress. Erosion rates can be estimated using an excess shear equation described by Foster et al. (1977):

\[
e = k(\tau_o - \tau_c)^A
\]

where \( e \) is the erosion rate, \( k \) is an erodibility or detachment coefficient, \( \tau_c \) is the critical shear stress, and \( A \) is an exponent with an average value of 3/2. For the erosion rates calculated in this study, \( k \) was assigned a value of 1.0 for simplicity. For granular (non-cohesive) materials, \( \tau_c \) can be estimated using the Shields criteria:

\[
\tau^* = \tau_c / (\gamma_s - \gamma) d
\]

where \( \tau^* \) is the critical dimensionless shear stress, \( \gamma_s \) is the unit weight of sediment, \( \gamma \) is the unit weight of water, and \( d \) is the representative particle diameter. It is more difficult to estimate the erosion resistance of cohesive materials. Various studies on the erodibility of cohesive materials have shown that numerous soil properties influence erosion resistance, including antecedent moisture, clay mineralogy and proportion, density, soil structure, organic content and pore and water chemistry (Grissinger, 1982). Erodibility
coefficients and critical shear stress values for cohesive sediments can be estimated by \textit{in situ} jet-testing using the methods described by Hanson and Cook (2004). As suggested above, the potential for erosion in a channel can be quantitatively evaluated as the difference between calculated shear stress and critical shear stress. Bledsoe (2003) described an index which estimates an increase or decrease in erosion potential by calculating a ratio of post-development to pre-development “work” on a channel. This “work” on a channel can be estimated using erosion rates. For this study, an overall erosion potential index was calculated as a ratio of the sum of excess shear values raised to the 3/2 power, $e$, for each time step modelled using continuous simulation. This index uses a simple finite-difference approximation to estimate the time-integrated sediment transport capacity over the duration of the continuous flow record:

$$E = \frac{\sum_{t=0}^{T} e_{\text{post}}}{\sum_{t=0}^{T} e_{\text{pre}}}$$

where $E$ is the instream erosion potential, $e$ is the erosion rate at time $t$, $T$ is the length of the continuous simulation (50 years), and \textit{pre} and \textit{post} represent pre- and post-development conditions, respectively.

**Results and discussion**

Without reproducing the pre-development hydrologic regime by matching historic infiltration and evapotranspiration rates, a post-development flow duration curve cannot be the same as the pre-development flow duration curve in its entirety because the total volume of stormwater runoff increases when development takes place. The inability to match the full duration curve does not mean that erosion potential due to changes in flow in the stream has to increase, however, so long as the critical portion of the flow duration curve is matched. The critical portion of the flow duration curve can be described as the duration of flow magnitudes above which stream bed or bank erosion occurs in the channel. A threshold discharge can be calculated through the use of a critical shear stress estimate for the bed and bank materials in the channel. If the duration of flows above the threshold remains the same pre- to post-development, no increase in erosion potential, as defined in this paper, takes place. It is important to note, however, that changes in sediment supply to the stream channel, such as those that occur due to development, will also affect the potential for erosion in the stream channel.

**Figure 1** displays the percent of time discharges are equalled or exceeded over the 50-year simulation for undeveloped conditions and each post-development level of stormwater control examined. In this figure, 1% represents 1% of the 50-year simulation period, or approximately 183 days; 10% represents 1,826 days (5 years); 0.1%, 18.3 days, etc. Figure 1 shows that when development takes place without any type of stormwater control, the discharges are greater in magnitude than “undeveloped” conditions for approximately 5.2%, or 949 days (2.6 years) of the overall time period examined. The magnitude and duration of discharges in the “Peak Shaving (100) + BMP” scenario are approximately the same as the “Undeveloped” scenario for the largest discharges, for 3 hours of the total duration. The duration of discharges in the “Peak Shaving (100 & 10) + BMP” scenario are less than those in the “Undeveloped” scenario between 0.43 and 0.26 cm, which is the maximum discharge rate for the 10-year storm. Beyond this point, “Peak Shaving (100 & 10) + BMP” discharges are greater in magnitude that the “Undeveloped” discharges until convergence with the “Undeveloped” discharges for the remaining 16.8% of the time. “Overcontrol” discharges are less than “Undeveloped” discharges for 19 hours.
The critical portion of the flow duration curve varies depending on the critical shear stress of the stream bed and bank material to be protected. In channels with low sediment entrainment thresholds, e.g. sands, fine gravels and highly erodible clays with critical shear stresses less than one Pa, the rate of discharge required to entrain particles is so small that the flow duration curve should be controlled in its entirety. For stream bed and bank materials with higher entrainment thresholds, e.g. gravels and resistant clays, the critical discharge value, $Q_c$, can be estimated by first identifying $\tau_c$; then using the shear stress equation to calculate the hydraulic radius value necessary to initiate particle movement; and lastly, using the Manning equation to calculate the critical discharge value. The duration of post-development discharges above the critical value should be restricted to the duration of the pre-development discharge. For example, if $\tau_c$ for the stream in the study area presented in this paper is 7 Pa, the $y_c$ is 0.29 m, and $Q_c$ is 0.167 cm and the flow duration curve above this value should be matched to the extent possible.

Using the methods described in the previous section, erosion potential was evaluated for a variety of critical shear stress values, ranging from 0.2 to 10 Pa, and are presented in Figure 2. In Figure 2, erosion potential values less than one indicate a decrease in erosion rates pre- to post-development, and erosion potential values greater than one indicate an increase in erosion rates. Erosion potential values equal to one indicate no change in erosion rates. Figure 2 demonstrates what was difficult to discern in Figure 1: the use of stormwater detention increases durations of the discharges that entrain sediment with shear stress values less than 0.7 Pa. When $\tau_c$ is between 0.2 and 0.7 Pa, the calculated erosion potential is larger when stormwater controls are in place than when stormwater is left uncontrolled. These results indicate that detention may exacerbate erosion in a stream channel above what might occur if the stormwater were left uncontrolled. This increase in erosion potential suggests that a reduction in the total volume of runoff, through the use of infiltration, for example, may provide a better method for stormwater management for watersheds that drain to fine grained non-cohesive or erodible clay streams.

Figure 2 also shows that as the $\tau_c$ values increase, stormwater management practices create erosion potentials closer to the ideal value of 1.0. The erosion potential values of zero for the “Overcontrol” scenario demonstrate that no erosion occurs in this scenario if
the \( \tau_c \) is greater than 4. Using the example of \( \tau_c = 7 \) Pa, Figure 2 shows that the “Peak Shaving (100 + 10) + BMP” scenario results in an erosion potential value closest to one, indicating that this type of stormwater control may be most appropriate to minimize changes in stream erosion potential when urbanisation of the watershed takes place.

Erosion potential in the study reach was also evaluated for a grain size distribution consisting of \( d_{16} = 0.505 \) mm (coarse sand), \( d_{50} = 3.29 \) mm (very fine gravel), and \( d_{84} = 12.3 \) mm (medium gravel). Erosion potential was calculated for individual grain sizes and for the composite grain size distribution. For the composite grain size distribution analysis, average erosion rates for each time step were calculated using the \( d_{16} \), \( d_{50} \), and \( d_{84} \) values as well as estimates of the \( d_{33} \) and \( d_{57} \) values obtained through interpolation. Table 1 summarises the erosion potential index calculated for each diameter, as well as for the composite grain size distribution. The erosion potential values for each diameter correspond to those for similar \( \tau_c \) values presented in Figure 2. This Table shows that as \( \tau_c \) values increase, the erosion potential increases when stormwater is left uncontrolled. Conversely, as \( \tau_c \) values increase, erosion potential decreases when stormwater controls are implemented. When the grain size distribution is considered as a whole, the erosion potential is smallest when stormwater is left uncontrolled, similar to the differences between stormwater management scenarios observed for the \( d_{16} \) grain size. This is because of the significant contribution the smaller grain sizes make to the overall erosion rate. Figure 3 shows the cumulative sediment load contributed by each class. For each scenario evaluated, the contribution of the \( d_{16} \) grain size is an order of

**Table 1** Erosion potential for representative grain size distribution

<table>
<thead>
<tr>
<th>Scenario</th>
<th>( d_{16} = 0.51 \text{ mm} )</th>
<th>( d_{50} = 3.3 \text{ mm} )</th>
<th>( d_{84} = 12.3 \text{ mm} )</th>
<th>Full distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed Uncontrolled</td>
<td>3.12</td>
<td>9.71</td>
<td>24.54</td>
<td>3.86</td>
</tr>
<tr>
<td>Overcontrol</td>
<td>4.75</td>
<td>4.50</td>
<td>0.00</td>
<td>4.80</td>
</tr>
<tr>
<td>Peak Shaving (100 + 10) + BMP</td>
<td>5.24</td>
<td>2.35</td>
<td>0.60</td>
<td>4.98</td>
</tr>
<tr>
<td>Peak Shaving (100) + BMP</td>
<td>5.24</td>
<td>2.8</td>
<td>1.14</td>
<td>4.96</td>
</tr>
</tbody>
</table>
magnitude higher than the $d_{50}$ grain size for the full sediment load. Overall, significantly more of the fine grain material is transported than the coarse grain material, giving it more weight in the calculation of the erosion potential for the full distribution of grain sizes.

Results from this study show that erosion index values are highly sensitive to the critical shear stress values required to initiate erosion. Selection of the stormwater controls best suited to minimise changes in erosion potential requires the identification of these critical shear stress values. Identification of these critical shear stress values requires field evaluation through the use of sieve analysis or direct measurement of erodibility through the use of methods such as jet-testing.

Conclusions
This work demonstrates that the SWMM model can be used to look at the hydraulic impact of various stormwater control scenarios to estimate erosion potential in urban receiving waters. In stream channels with non-cohesive fine grained sediments, or with erodible clays, stormwater management practices may exacerbate erosion potential above what would occur if stormwater were left uncontrolled. In these cases, a reduction of the overall increase in runoff volume through the use of infiltration or increased evapotranspiration opportunities may be warranted. Regardless, erosion potential should be evaluated before stormwater control recommendations are made.

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References


