A Modelling Analysis of Urban Stormwater Flow Regimes and their Implication for Stream Erosion

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Stream erosion is a major issue in stormwater management. The objectives of this research are to investigate by means of computer modelling: (a) the flow-duration characteristics of a receiving stream before and after urbanization; (b) the implication of flow regime changes on stream erosion potential with and without control measures (e.g., extended detention basins and source control); and (c) the maximum degree of urbanization, for which stream erosion may be unavoidable regardless of the stormwater control measures applied. The U.S. EPA Stormwater Management Model was used in the analysis of flow-duration characteristics of a small northern Ontario watershed. It was found that flow-duration characteristics of the stream could change significantly after urbanization. Although no stream erosion was modelled in this investigation, the change in flow regimes after urbanization may indicate potential stream bed and/or channel erosion. Extended detention basins with short detention times (24-h) could control flow-duration characteristics at low flow rates better than those with long detention times (48-h). Both extended detention basins and source control measures should be applied in order to bring the flow duration curve after urbanization back to its original position. If the watershed were to be urbanized beyond 40% of imperviousness, it may not be possible to bring the flow duration curve back to its original position in spite of the various source control measures and detention basins used. The optimal location of detention ponds for erosion control depends upon the range of flows, which control the stability of the stream.

Key words: computer modelling, stream erosion, urban stormwater, flow duration curves, extended detention basins, source controls

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Analysis of Stream Erosion Using Flow-Duration Characteristics

Flow-duration curves have a long history in the field of water resources engineering (Vogel and Fennessey 1995). They have been used to solve problems in water quality management, river and reservoir sedimentation, in-stream flow methodologies and water-use planning. A flow-duration curve is the complement of the cumulative distribution function of stream flow. It represents the relationship between the magnitude and frequency of daily, weekly, monthly or even a longer period of time of stream flow for a particular watershed. On a flow-duration curve, discharge, $Q$, is plotted against exceedance probability, $p$. A flow-duration curve shows all flow rates at a constant time interval over a particular period of time.

Stream erosion is a continuous process where sediments are removed and deposited by stream flows of all magnitudes. A stable stream has a unique balance between sediments and flows. When a watershed is urbanized, both sediments and flows in the watercourse can change significantly. In order to determine the impacts of urbanization on stream erosion potential, both sediment and flow characteristics should be analyzed. Unfortunately, sediment characteristics may not be available during the preliminary planning stage. However, flow characteristics before and after urbanization can be simulated by calibrated hydrologic models. If the flow characteristics are altered significantly after urbanization, it is anticipated that the stream may erode or aggrade. The following case study demonstrates how a hydrologic model can be applied to evaluate the implication of flow regime changes on stream erosion at the preliminary planning level.

Development of a Hydrologic Model for Flow Duration Simulation

The analysis of flow duration curves in this research study is based upon long-term runoff simulation of a rural watershed in northern Ontario using a hydrologic model termed Integrated Storm Water Management Simulator (ISWMS). It is a shell program of the U.S. EPA Stormwater Management Model, SWMM (U.S. EPA 1988), produced by Greenland International Consulting Inc. and Ryerson University. The ISWMS is a proprietary software of Greenland International Consulting Inc. (http://www.grnland.com/iswms.php). Other hydrologic models (e.g., PC-SWMM or XPSWMM, HSPF) can also be used to simulate runoff flow regimes in urban areas. By assuming a constant baseflow, runoff flow duration curves were used to assess the change of flow regimes, which in turn may cause potential stream erosion after urbanization.

The watershed characteristics, precipitation and stream flow data (March 1 to May 31, 2000) used in model calibration were provided by Greenland International Consulting Inc. It is important to understand that the measured data only represent the spring and early summer conditions and any recommendations are limited by the short data available in this study. The rural watershed is within a marshy area and consists of a variety of vegetation community types, but it is not considered to be a fish habitat based on site investigations. The marsh is sustained by intermittent overland runoff from the watershed.

Figure 1 shows the discretization of the ISWMS model. The hydrologic model has nine subcatchments within the marshy area. Each subcatchment has its own set of model parameters. The calibration process determined the appropriate model parameters which could produce a simulated runoff flow duration curve similar to that derived from field measurement. Stream flows were measured at Node #733 (Fig. 1). The total runoff volume from March 1 to May 31, 2000, was calculated by subtracting an assumed constant baseflow and integrating the product of runoff rate and its time increment. Using the precipitation data recorded in the watershed from March 1 to May 31, 2000, the ISWMS model was used to simulate runoff over the 3-month period. During the iterative process of calibration, the ISWMS model simulated many time steps with no runoff. These zero runoff time steps caused the simulated runoff flow duration curve to deviate significantly from the measured runoff flow duration curve even though the total runoff volume was matched. Thus, an iterative calibration process was needed to match both the total runoff volume and the number of zero runoff time steps. In the beginning of the calibration process, an assumed constant baseflow was subtracted from the measured stream flows and the total runoff volume over three months was calculated. The ISWMS model was then calibrated by comparing the simulated and measured total runoff volume. After the total runoff volume...
was matched, the number of time steps without runoff predicted by the ISWMS model were then compared to the measured zero time steps. If they differed, another assumed baseflow was subtracted from the measured stream flows and the ISWMS model was re-calibrated by matching the number of time steps without runoff. After the number of time steps without runoff was matched, the total runoff volume predicted by the ISWMS model was compared to the measured total runoff volume. If they differed, the whole calibration process was repeated until both the total runoff volume and the number of time steps without runoff were matched. For the case study, the calibration process was completed after three iterations. The exceedance probability of each flow, $P_{\text{exceedance}}$, was computed as:

$$P_{\text{exceedance}} = \frac{\text{# of time steps where the flow is greater than a certain value}}{\text{total time steps}}$$  \hspace{1cm} (1)

Figure 2 shows the good agreement between the measured and simulated flow-duration curves after three iterations of calibration. The calibrated hydrologic model was then used to simulate long-term flow duration curves of the watershed. It is important to recognize that the long-term simulation is based on a relatively short calibration period. Thus, the analysis of flow regime change and its implications for potential stream erosion should be considered as a preliminary evaluation.

**Simulation of Long-Term Flow-Duration Curves**

For both the calibration and long-term simulation of the runoff flow regimes, the Horton’s equation was used as the infiltration model. Twenty-seven years of hourly rainfall data (from April to October) at a nearby Meteorological Services of Canada station was used in the long-term simulations. The pre-development long-term runoff flow duration curve (i.e., the “original” curve in Fig. 3) was derived from the simulated runoff hydrographs.

In order to simulate the flow-duration curves for different degrees of urbanization, the percentage of imperviousness, WWT (%), of each subcatchment was adjusted from 20 to 40%, except in subcatchment #5. Since subcatchment #5 represents the wetland area, most of the rainfall becomes runoff. Figure 3 shows the long-term flow duration curves of 20, 30 and 40% of imperviousness. It is noted that the “urbanized” flow duration curves are shifted from the “original” curve as more runoff is expected. Thus, flows may change over the entire range of exceedance probability as imperviousness increases. Unless appropriate stormwater management practices are used, the stream may experience the same flows at a higher frequency after urbanization. As a result, there is a potential that the stream may erode at a higher rate.

**Analysis of Control Measures for Urban Stream Erosion**

Urbanization tends to contribute to erosion of banks and beds of streams. Detention basins may be designed to reduce erosion in addition to flood and pollution control (McCuen and Moglen 1988; Whipple 1992). After the post-development runoff flow duration curves were developed for the rural watershed (Fig. 4), three scenarios were examined: (1) an extended detention basin was added to each subcatchment except subcatchment #5, the wetland; (2) two extended detention basins were added downstream of subcatchments #1 to #5 and #6 to #9; (3) an extended detention basin was added downstream of all the subcatchments. The extended detention basins were used to bring the flow duration curves after urbanization back to those before urbanization as close as possible without significant flooding.

According to the Ontario Ministry of Environment’s stormwater guidelines (Ministry of the Environment 2003), both extended detention basins and source control measures (e.g., downspout disconnection, stormwater gardens and infiltration trenches) are recommended.
for erosion control. Figure 4 shows the recommended storage size (in mm over the watershed area) of extended detention basins with different percentages of impervious area and source control (SC) measures (in mm over the watershed area). In this research, the outlet orifices of extended detention basins were sized for 24- and 48-h detentions and source control measures were limited to capturing 5.0 mm of rainfall.

Figure 5 shows the flow duration curves at 20% imperviousness with and without an extended detention basin at the watershed outlet and source control measures. Both the 24-h and the 48-h curves indicate that runoff greater than 0.1 m³/s can be controlled using the extended detention basin. Additionally, the 24-h detention may be slightly better than 48-h for low runoff flow control since it overlaps the 48-h curve in the low exceedance flow region (less than 0.05 m³/s). For higher runoff flows (greater than 0.05 m³/s), the 48-h detention is better than the 24-h. Similar observations were made for 30 and 40% imperviousness.

![Fig. 4. Design of storage size (Ministry of the Environment 2003).](image)

The probability of low runoff is much greater than that of large runoff. Since the duration of detaining water in a 24-h extended detention basin is shorter than that in a 48-h extended detention basin, the available storage volume in the 24-h detention basins is usually larger than the 48-h detention basins. Under back-to-back storm conditions, the probability of using the flow divider system for the 24-h detention basins is less than that for the 48-h detention basins. Therefore, the 24-h detention basins are better than the 48-h detention basins for low flow control. For larger storms, longer detention times usually provide a better control of the flow duration characteristics. Thus, the 48-h flow duration curves are better than the 24-h curves at higher exceedance flows.

As source control is increased, the 24- and 48-h flow duration curves are closer to the pre-development flow duration curve (Table 1). When the percentage of imperviousness is high (e.g., 30% or higher), the distance between the 24- and 48-h curves and the pre-development curve is much larger than in the cases with a lower percentage of imperviousness. These findings are expected as more runoff is anticipated as the percentage of imperviousness increases. When the watershed is urbanized beyond 40% of imperviousness, the extended detention basin and source control cannot control both low flows and high flows.

Figure 6 compares the flow duration curves of various storage systems at 24-h detention for 40% imperviousness and source control of 5 mm. Extended detention basins are assumed at three different locations: (1) local control at each subcatchment; (2) regional control for subcatchments 1 to 5 and subcatchments 6 to 9; and (3) regional control for all subcatchments at the downstream end of the watershed. It was found that regional control at location 2 provided better control performance than at location 3 when the exceedance flow is greater than 0.07 m³/s. Local control at each subcatchment generally performs best when the exceedance flow is less than 0.09 m³/s. These results indicate that the optimal location of detention basins is dependent on the flow regimes which affect stream erosion.

![Fig. 5. Flow duration curves for 20% impervious area and source control = 5 mm.](image)

**Table 1.** The exceedance flows, for which the 24- and 48-h flow duration curves are close to the pre-development curve

<table>
<thead>
<tr>
<th>24-h Detention time (m³/s)</th>
<th>48-h Detention time (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% WWT, SC = 0</td>
<td>0.16</td>
</tr>
<tr>
<td>20% WWT, SC = 3.8</td>
<td>0.15</td>
</tr>
<tr>
<td>20% WWT, SC = 5</td>
<td>0.14</td>
</tr>
<tr>
<td>30% WWT, SC = 0</td>
<td>0.21</td>
</tr>
<tr>
<td>30% WWT, SC = 3.8</td>
<td>0.18</td>
</tr>
<tr>
<td>30% WWT, SC = 5</td>
<td>0.16</td>
</tr>
<tr>
<td>40% WWT, SC = 0</td>
<td>0.33</td>
</tr>
<tr>
<td>40% WWT, SC = 3.8</td>
<td>0.25</td>
</tr>
<tr>
<td>40% WWT, SC = 5</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Conclusions and Recommendations

From the simulation results of the ISWMS model, it is found that flow regimes of the watershed can change significantly after urbanization. Extended detention basins with long detention time (48-h) provide better control of flow-duration characteristics at higher flow rates than those with short detention time (24-h). Conversely, extended detention basins with short detention time (24-h) control flow duration characteristics at lower flow rates better than those with long detention time (48-h). The required detention time of extended detention basins for stream erosion control should be governed by the range of flows which determine the stability of a stream. As most stream erosion occurs at high flows (Whipple et al. 1981; Galay 1983), detention basins with long detention times should be used for erosion control. For the case study, further stream evaluation is necessary to determine other erosion control factors such as bed load, and the presence of large rocks, cohesive material, roots and vegetation.

Source control measures complement extended detention basins for erosion control. As source control increases, extended detention basins can restore a larger range of flow characteristics back to their pre-development stage. Both extended detention basins and source control measures must be applied in order to bring the flow duration curve back to its original position. If a watershed is urbanized beyond 40% of imperviousness, it may be impossible to restore the flow duration curve back to its original position even though control measures are used. For this situation, bio-engineering and/or structural control measures such as armoring may be necessary to stabilize the stream after urbanization.

It is generally recognized in flood control that local controls at individual subcatchments are ineffective. For the case study addressed here, local detention basins may reduce stream bed erosion at low flow rates, while regional detention basins may reduce streambank erosion at high flow rates. Thus, it is important to take erosion control into consideration when designing stormwater management facilities.

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References


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