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Effects of Land Use, Stormwater Management, and Channel Materials on the Channel Morphology of Apple Creek, WI

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Abstract

Computer modeling has shown that detention ponds, although ubiquitous, are ineffective at preventing channel erosion. To test these results, five reaches of Apple Creek under different land use and stormwater management scenarios were monitored for six years. Results indicate that channels draining developed basins without stormwater management enlarged the most. Channels with stormwater management and comparable levels of development changed very little. These results are contrary to previous field studies, which revealed channel enlargement downstream of detention ponds. The Apple Creek reaches downstream of detention ponds are more cohesive than those without detention ponds, which could explain their relative stability.

Introduction

The effects of urbanization on hydrology and channel morphology are well documented. Urbanization increases the amount of impervious surface area and leads to an increase in the volume, peak rate, and frequency of runoff (Leopold, 1968; Hollis, 1975; Neller, 1988; Booth, 1990 and 1991; Glazner, 2001). Alterations to the hydrologic regime of the catchment can initially increase the frequency and magnitude of overbank flows, and eventually elicit changes in channel morphology including incision, widening, or a combination of both (Hammer, 1972; Morisawa and LaFlure, 1979; Nanson and Young, 1981; Booth, 1990 and 1991, Bledsoe and Watson, 2001). Such morphologic changes can diminish aquatic and riparian habitat (EPA, 1997a). In response to downstream flooding and the documented changes in channel morphology and habitat, stormwater management was introduced.

Stormwater management practices initially focused on flood control through improved conveyance systems (e.g. curb and gutter, pipe, and concrete channel). Effective as these hard-engineering treatments were at preventing flooding, they did little to protect the integrity of the receiving channels. To protect these areas, hydrologists and civil engineers realized that the overall volume of runoff and, in particular, the peak discharge needed to be reduced (Leopold, 1968). An early design criterion was the peak shaving technique. Peak shaving requires that the post-development peak discharge for a particular event (commonly the 2-year recurrence interval flow) be maintained at a level equal or less than the pre-development peak rate. In the past fifteen to twenty years, retention and detention pond designs were altered and improved to address water quality issues as well. As a result, a host of new best management practices (BMPs) (e.g. vegetated swales, biofilters, infiltration basins etc.) have been introduced (Schueler, 1987), and in some cases required by governmental agencies, to mitigate polluted urban runoff. However, assessing the effectiveness of any BMP is problematic (EPA, 1997b and 2002; FWHA 2000; Strecker et al., 2004).

Although there are many studies dealing with the effectiveness of BMPs on water quality parameters (e.g. EPA/ASCE BMP Database), there are very few studies that address the effectiveness of BMPs on mitigation of erosive discharges and protection of downstream channel integrity. A number of modeling efforts (e.g. McCuen and Molgen, 1988; MacRae, 1993; Bledsoe, 2002) have demonstrated that the common practice of peak shaving is ineffective at mitigating erosive discharges. However, only two field studies (Lee and Ham, 1988; MacRae, 1996) have been conducted to verify the model predictions. Here a third field study that documents morphological changes in reaches with and without stormwater management is presented.

Methods

Study Site

Apple Creek is a 117 km^2 tributary to the lower Fox River in NE Wisconsin. The creek is classified as a warm water sport and forage fishery by the Wisconsin Department of Natural Resources (WDNR), and was identified as a priority watershed in 1994. Roughly 25% of the basin is developed and the majority of this development is in the headwater reaches located in northern Appleton, Wisconsin. Development has steadily progressed over the past ten years and by 2020 most of the study area (save for a regional park and athletic fields) will be developed (City of Appleton Planning Department, 2005).

This study focuses on the southwestern headwater and lowland reaches of Apple Creek (Figure 1). These reaches flow through the moderately fine grained to medium textured soils of the Winneconne-Manawa association (Soil Conservation Service, 1978). As part of the Lake Winnebago-Green Bay Lowland physiographic region, a layer of pinkish, clay from glacial Lake Oshkosh underlies this area (Martin, 1932). The thickness of soil overlying the clay varies in depth from several meters in the uplands to less than a few centimeters in the river channels. The topography is generally flat near the Duck Creek, Ballard Road, and Holland Road cross sections, whereas the Plamann Park and Stone Chimney reaches drain rolling hills (Figure 1).

Land use in the study area is a mixture of developed land (e.g. institutional, commercial, residential, and transportation land uses) and undeveloped land (e.g. recreational and agricultural land uses). Most of the development is in the southwestern portion of the Apple Creek watershed with smaller areas of development in the north and southeast regions of the drainage basin (Figure 1). The northwestern and eastern sections are still under active agriculture, but are slated for development within the next 15 years (City of Appleton Planning Department, 2005). Two regional stormwater detention ponds were installed by the City of Appleton in cooperation with the 1997 WDNR Priority Watershed Plan. Ballard Road Pond (constructed in 1996) was built to treat runoff from existing development to the west, whereas Holland Road Pond (constructed in 1998) was built to accommodate future development as it moved eastwards (Figure 1). Both ponds were designed to maintain the pre-development 2-year peak discharge and to mitigate polluted urban runoff. The ponds consist of in-line treatment with a smaller fore bay separated from a larger storage bay by a weir. This design effectively traps sediment and reduces nutrient input to downstream reaches (Nelson, 2003).

Channel Surveys

Cross sections were surveyed at six reaches each with a different combination of land use and stormwater management. Each cross section is representative of the channel, bank, and vegetative conditions along an approximately 100-meter reach of river. Straight reaches were chosen to facilitate comparison between similar geomorphic units. One meandering reach (Stone Chimney) was also chosen so that migration dynamics could be investigated. The margin of error associated with the surveys is small (+/- 0.5 cm).

From the cross sectional surveys, width and area were determined using WinXSPRO (Hardy, et al., 2005), whereas changes in thalweg elevation were determined by comparing cross sections using a common datum. These morphologic parameters are based on what is defined here as the channel filling stage. The channel filling stage is marked by the first major break in slope where water flows out of the channel. The same stage was used each year for a consistent basis of comparison.

A monumented cross section on a reach downstream of Ballard Road pond (BR) was established in 2000, the Holland Road pond (HR) reach was established two years later in 2002. Both of these sites are located in broad (>1km), low gradient alluvial valleys. Ballard Road section flows through a narrow wooded corridor bounded by agricultural fields, whereas the HR floodplains are in a mixture of grasses, corn, and soy. An additional reach along Duck Creek (DC) was surveyed in 2002 to serve as a basis of comparison to watersheds that were mainly agricultural (Table 1). Replicate surveys of this section were not preformed.

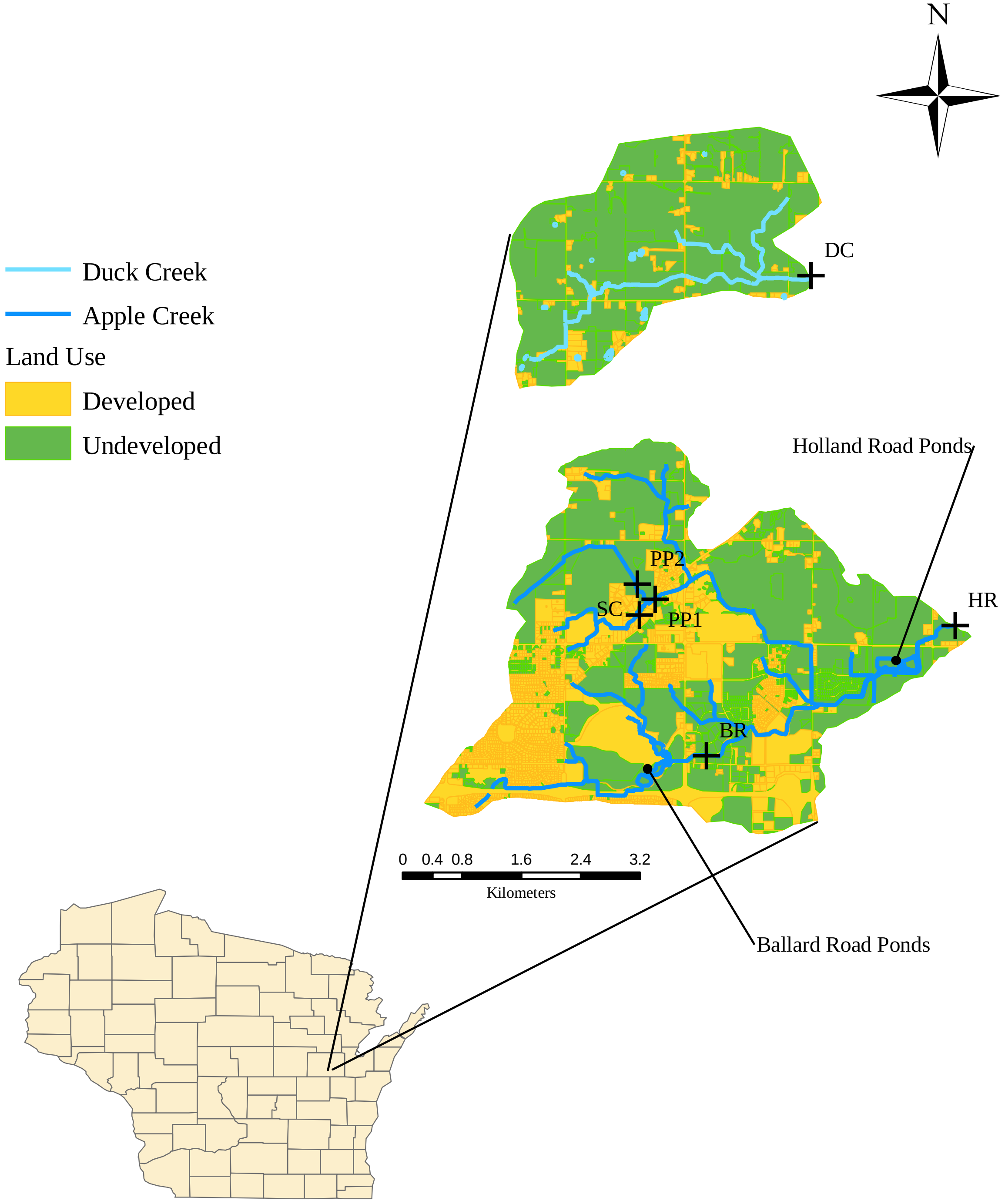

Figure 1: Land use pattern for 2003 in the Apple Creek study area. The detention ponds at Ballard Road and Holland Road are shown along with the five study sections, Plamann Park 1 (PP1), Plamann Park 2 (PP2), Stone Chimney (SC), Ballard Road (BR), and Holland Road (HR). Flow direction is to the northeast. Duck Creek (DC) is directly to the north and flows easterly.

Table 1: Sub-basin characteristics of Apple Creek. Shading represents cross sections under stormwater management.

Reach	DA [km^2]	Percent Developed*	SWM	Initial Width** [m]	Initial Area** [m^2]
Plamann Park 1	3.18	26.0	No	3.31	1.90
Plamann Park 2	1.83	7.03	No	1.87	0.57
Stone Chimney	1.23	56.6	No	1.62	0.46
Ballard Road	4.83	65.2	Yes	9.17	4.51
Holland Road	19.5	39.4	Yes	12.35	7.33
Duck Creek	8.91	5.0	No	10.35	5.48

*Developed area includes residential, urban, commercial, transportation, and communication and utilities land use classifications.

** Plamann Park 1 and 2, Stone Chimney, and Ballard road were initially surveyed in 2000. Holland Road and Duck Creek were initially Surveyed in 2002.

Three additional cross sections were established in 2000 (Table 1; Figure 1). Plamann Park 2 (PP2), which drains a partially forested area and farmland, is only about 7% developed. In contrast, Stone Chimney (SC) and Plamann Park 1 (PP1) are about 8 and 4 times more developed respectively. Stone Chimney has roughly the same amount of development as BR, albeit a significantly smaller drainage area. PP1 and PP2 cross sections were located in straight reaches, whereas SC is on a meander bend. PP2 and SC both drain relatively narrow (100 m), wooded alluvial valleys. PP1, which is downstream of the PP2 and SC tributaries, widens out into a wider valley (~300 m) covered in tall grasses.

At each cross section, samples of the bed and bank materials were collected and sediment size distributions were determined. Pebble counts of 100 particles (Wolman, 1954; Leopold, 1970) were conducted on surficial bed material. Due to the small size of the particles at most sites, replicate bulk samples of bed material were taken to the lab and sieved. Bank material was characterized in the field on the basis of color, texture, and moisture. Field textural classifications were verified in the lab using sieving and the hydrometer method to separate out the proportions of sand, silt, and clay (Day, 1965).

Results

Cross sectional changes

Changes in channel size and shape can be ascertained by simple visual investigation and measurement of channel dimensions. First, consider the three sites that were not under stormwater management. Both the Stone Chimney (SC) and Plamann Park 1 (PP1) cross sections enlarged in width and cross sectional area over the 6-year study period (Figure 2; Table 2), but their mechanisms of enlargement differ. Stone Chimney, which is located on a meander bend, is actively enlarging. The lateral migration and cut bank erosion is not balanced by deposition on the inside bank. At Plamann Park 1, the thalweg elevation decreased by 16 cm, indicating net bed degradation. In addition to bed degradation, the left bank at PP1 failed via a slump between 2000 and 2002. The slump seems to be diverting water into the right bank, causing further erosion.

Unlike PP1 and SC, the drainage basin of Plamann Park 2 (PP2) is relatively undeveloped (Figure 1; Table 1). As one might expect, this reach has changed less than those under more development (see for example PP1 and SC in Figure 2; Table 2). Erosion of the left bank has led to channel widening, but the overall channel area has increased only by 14% due to sediment deposited at the right bank toe. In contrast, PP2 and SC increased in area by 34% and 80% respectively.

The reaches downstream of detention ponds, Ballard Road (BR) and Holland Road (HR) (see Figure 3), have changed little over the course of the study despite having developed watersheds (65% and 39% respectively). From 2000 to 2006, BR did not significantly change in width, and only increased in area by 0.2 m^2 (about 5%). The apparent contraction in width in 2002 is due to the precision of the survey

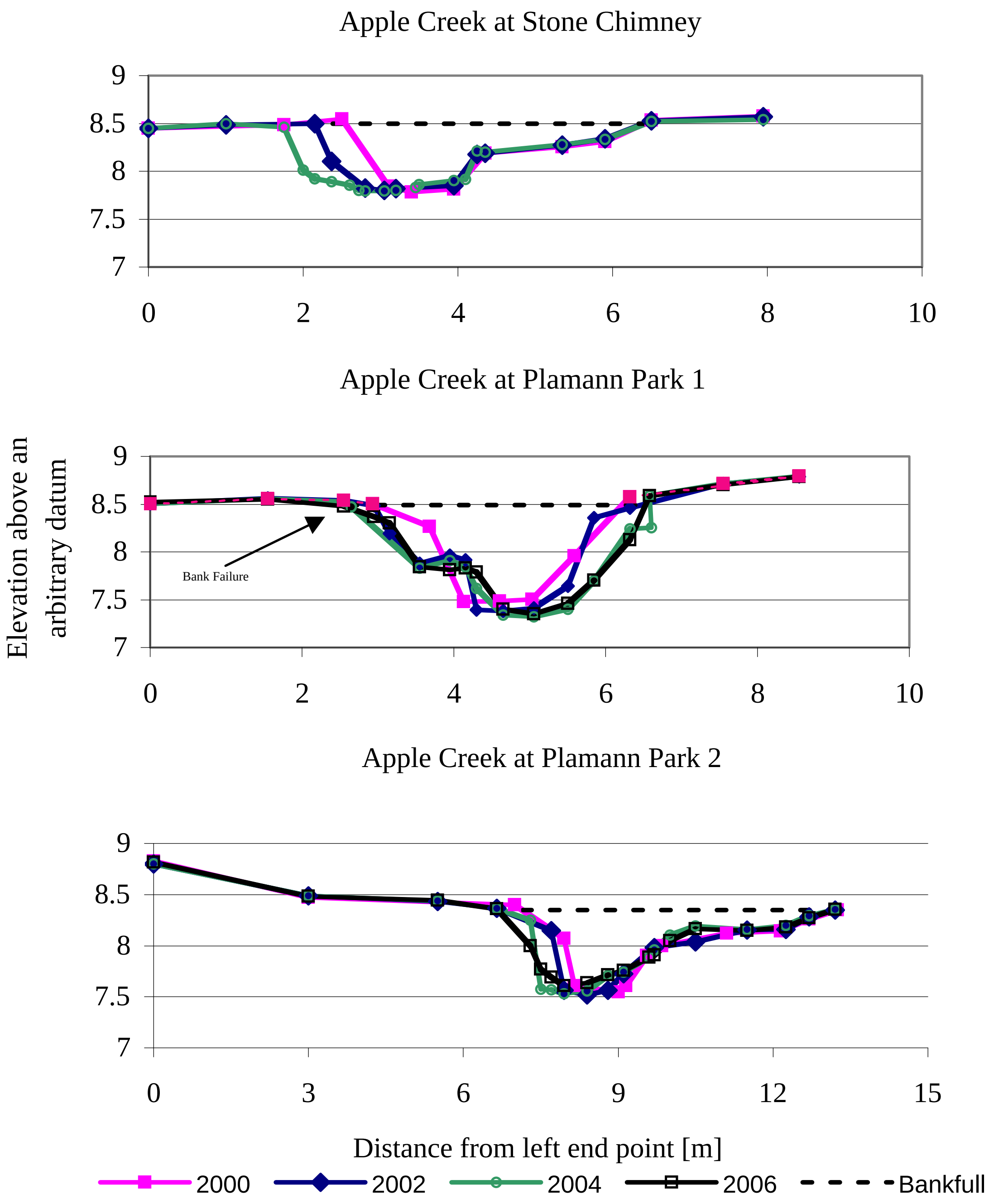

Figure 2: Geomorphic surveys of the three reaches without stormwater management for 2000 (solid squares), 2002 (solid diamonds), 2004 (open circles), and 2006 (open squares). The dashed horizontal lines delineate the channel filling stage, which is used to determine the channel dimensions. The thickness of the lines approximates a survey precision of +/- 0.5 cm. Note the different horizontal scales for each section. View is looking downstream.

Table 2: Percent change in channel dimensions of the study sections based on topographic surveys. Shading represents cross sections under stormwater management.

Cross Section	Drainage area (km^2)	Width 2000-2002	Width 2002-2004	Width 2004-2006	Total Change in Width	Area 2000-2002	Area 2002-2004	Area 2004-2006	Total Change in area
PP1	3.06	-0.60	19.45	1.02	19.94	5.79	37.81	-8.30	33.68
PP2	1.40	19.25	2.24	8.77	32.62	10.53	-1.59	4.84	14.04
SC*	1.11	25.31	40.89	No Data	76.54	23.91	45.61	No Data	80.43
BR	5.21	-4.91	4.70	0.44	0.00	-5.54	10.56	0.64	5.10
HR**	19.5	No Data	-0.65	1.06	0.40	No Data	-1.09	-1.52	-2.59

*No survey was conducted at Stone Chimney in 2006.

**No survey was conducted at Holland Road in 2000.

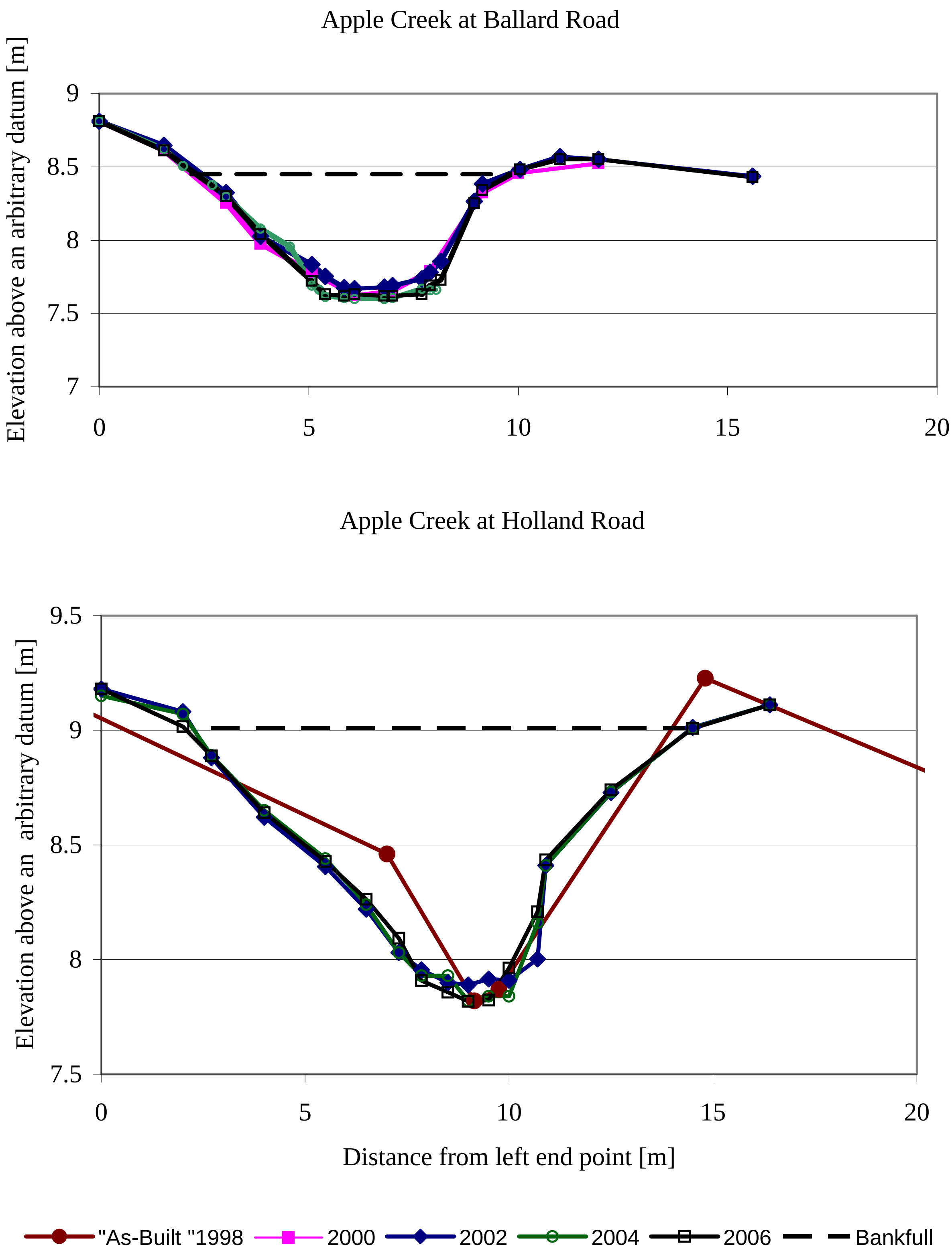

Figure 3: Geomorphic surveys of the two reaches with stormwater management for 2000 (solid squares), 2002 (solid diamonds), 2004 (open circles), and 2006 (open squares). Survey data from a floodplain study in 1998 is shown as solid circles. The dashed horizontal lines delineate the channel filling stage, which is used to determine channel dimensions. The thickness of the lines approximates a survey precision of +/- 0.5 cm. Note the different vertical scale for each section. View is looking downstream.

technique, which is approximately +/- 0.5 cm. On gentle bank slopes like the left bank of BR, a 1 cm difference in elevation can result in a 10-20 cm difference in width. The thalweg elevation at BR dropped slightly (3 cm), and Figure 3 shows some erosion at the toe of the banks. Thalweg elevation also decreased (8 cm) at HR from 2002 to 2004, but the width and area changed little (Table 2).

Historical Analysis

Most of Apple Creek and surrounding watersheds had been under agriculture for at least 100 years prior to development. Unfortunately, historical information on channel form is lacking. The headwater reaches are too small for aerial photograph analysis at the scales available and no surveys prior to a 1998 floodway study are available. Nonetheless, a stream to the north (Duck Creek) that is almost entirely under agriculture can provide some indication of channel form prior to development. Duck Creek (DC) is a good analog because it is a low gradient, alluvial stream with broad valleys, runs through the same physiographic province, has similar soils, and the same climate as Apple Creek. The only significant difference is the land use – Duck Creek has very little development in its watershed beyond transportation. The drainage area of Duck Creek falls between that of HR and BR, as does its width and depth. When width is plotted against drainage area a well defined (r^2=0.98) power function relation exists between the HR, BR, and DC reaches. This indicates that HR and BR are sized consistently with agricultural reaches in the area and that HR and BR probably did not adjust appreciably to development prior to the construction of the detention ponds.

A nearby reach from a 1998-99 floodway study for the City of Appleton was also compared to our measured sections (Figure 3). The floodway cross section cannot be used to quantify changes in width, depth, or area because it does not correspond exactly with the cross sections established for this study, and lacks sufficient detail. Nonetheless, the floodway drawings indicate that the channel width and depth near Holland Road in 1998 were within 10% of the values for the initial surveys taken in 2002. This comparison suggests that the HR channel did not enlarge substantially after construction of the ponds. Riparian vegetation along the BR reach provides further evidence for relatively stable channels. Here, there is a 5 m buffer of 15 to 20 year old trees and little evidence of bank undercutting.

Channel Materials

Sediment analysis of the five study sites was conducted using a variety of field and lab techniques. Upstream of the detention ponds (PP1, PP2, and SC) the average bed sediment size is less than 0.7 mm (Table 3), a fine-grained sandy bed. The depth to the underlining cohesive glacial clay layer ranged between 0.13 and 0.15 m (Table 3). The bank materials for each of the three sites contain between 30 to 99% sand, 1 to 29% silt, and 0 to 20% clay (Table 4). Moreover, the toe at each of the three locations contains less than 10% clay.

Downstream of the detention ponds the D_{50} ranged between 0.50 mm at Ballard Road to 5.00 mm at Holland Road (Table 3). At BR and HR, the glacial clay layer was 0.04 m below the streambed, on average. Compared to the three upstream locations, the banks at Ballard Road and Holland Road contained less sand and more clay (Table 4). The banks at Ballard Road varied between a silt loam and a loam (Table 4). At Holland Road, the banks were classified as a sandy loam or a loam. The toes at both downstream locations contain more than 10% clay (Table 4).

Table 3: Bed sediment characteristics for the Apple Creek study sites. Bed thickness is the depth to the glacial lake clay layer. Shading represents cross sections under stormwater management.

Cross Section	Bed d_{50} [mm]	Bed Thickness [m]
PP1	0.31	0.13
PP2	0.66	0.15
SC	0.30	0.15
BR	0.50	0.05
HR	5.00	0.03

Table 4: Texture of bank material for the five study reaches within the Apple Creek drainage basin. In each case, Layer 3 covers the mid to lower bank portion of the channel. Shading represents cross sections under stormwater management.

Location	Depth below surface [m]	Percent sand	Percent silt	Percent clay	Textural Classification
PP1					
Layer 1	0.00-0.29	54	40	6	Sandy Loam
Layer 2	0.29-0.37	46	36	19	Loam
Layer 3	0.37-1.06	99	1	0	Sand
PP2					
Layer 1	0.00-0.15	78	17	5	Loamy Sand
Layer 2	0.15-0.30	69	24	7	Sandy Loam
Layer 3	0.30-0.85	99	1	0	Sand
SC					
Layer 1	0.00-0.14	30	50	20	Silt Loam
Layer 2	0.14-0.43	34	61	5	Silt Loam
Layer 3	0.43-0.78	63	29	8	Sandy Loam
BR					
Layer 1	0.00-0.28	35	59	6	Silt Loam
Layer 2	0.28-0.37	43	39	8	Loam
Layer 3	0.37-0.9	50	35	15	Loam
HR					
Layer 1	0.00-0.27	60	32	8	Sandy Loam
Layer 2	0.27-0.55	59	32	9	Sandy Loam
Layer 3	0.55-1.02	43	34	24	Loam

Discussion

Of the five reaches investigated, the two that changed the most (PP1 and SC) drained watersheds at least 25% developed and were without stormwater management. Two sections (HR and BR) with a similar (or greater) proportion of development than PP1 and SC exhibited no more change in cross sectional area than the section at PP2, which is only 7% developed (Tables 1 and 2). Based upon these results it is tempting to conclude that the Apple Creek detention ponds have been successful in mitigating erosive discharges. However, others have argued that reducing the peak-flow rate to match predeveloped conditions, (peak shaving) is insufficient for the protection of downstream channel integrity (Brown and Caraco, 2001). Moreover, the relatively large agricultural channels and resilient channel materials that comprise the reaches downstream of the ponds likely play a role in channel stability.

Effects of Stormwater Management

McCuen and Molgen (1988) noted that most peak shaving is done on the basis of a hydrologic control rather than a hydraulic control. Hydrologic control entails matching the post-development peak flow rate of a particular recurrence interval (commonly the 2-year, 24-hour event) to the pre-development peak flow rate. If these peaks are matched, the duration of the peak and near peak discharges must be greater to accommodate the large volume of runoff due to urbanization (Glazner, 2001). The duration of more frequent flows also increases. MacRae (1996) observed that the hours of exceedence of mid-bankfull flows increase 4.2 times downstream of a stormwater management (SWM) facility where 34 percent of the basin had been developed. Because these mid-bank to bankfull flows are capable of transporting sediment, the channels enlarge even with SWM in place.

The selection of the 2-year event as the basis for hydrologic design was prompted by the recognition that the effective discharge (e.g. that which moves the most sediment over time) for naturally adjusted alluvial channels may be coincident with the bankfull discharge (Andrews, 1980). In many cases, the bankfull discharge was believed to be equivalent to the channel forming discharge and was shown to occur approximately every 1.5 to 2 years (Wolman and Miller, 1960 and Emmett and Wolman, 2001), though others have shown a wide variety of bankfull return periods (Pickup and Warner, 1976 and Williams, 1978). Channels, however, carry a range of discharges, some of which, although below the bankfull level, may exceed the critical shear stress of the bed and bank materials. Increasing the frequency and duration of these flows may leave the channel even more prone to erosion than before SWM was in place (McCuen, 1979; Moglen and McCuen, 1988; MacRae and Rowney, 1992; MacRae, 1996; Bledsoe, 2002).

A related factor that adds to the potential for channel enlargement downstream of detention ponds is that “in-line” stormwater detention ponds, like the Ballard Road and Holland Road ponds, disrupt the sediment supply to downstream reaches. This phenomenon is analogous to what has been observed downstream of dams where a reduction in sediment supply caused channel enlargement (Williams and Wolman, 1984). Lane (1955) and Schumm (1969) have argued that a decrease in bed load without a corresponding reduction in discharge leads to bed degradation. Erosion is exacerbated if water supply increases while sediment supply is reduced.

Although few in number, field observations generally agree with the modeling studies. In a 1985 survey of streams in Surrey, British Columbia, Lee and Ham (1988) noted that urban stream channels downstream of stormwater detention ponds were wider than rural streams, yet slightly narrower than urban streams without SWM. A follow up survey in 1988 showed that 6 out of 7 channels downstream of SWM facilities continued to widen, such that their average widths exceeded even those of the urban channels without SWM. MacRae (1996) compared abandoned channel scars with active channels downstream of stormwater management ponds along Morningside Tributary in Markham, Ontario. The existing channels enlarged 1.29 to 2.94 times the abandoned channels in just two years. In contrast, the results reported here show that the reaches downstream of the detention ponds at Ballard Road pond and Holland Road pond have changed little over the past six years. Thus, the question arises: why have channels downstream of detention ponds changed little here, when elsewhere they have enlarged substantially?

Historical Conditions

The low gradient, wide-valley reaches (BR, HR, and DC) are somewhat larger than expected as compared to streams from the eastern United States (Dunne and Leopold, 1978). This is probably due to the changes in water and sediment supplied to the reaches during the conversion from forest to agriculture during the 1800s (Jacobson and Coleman, 1986) or through direct dredging of the channels to facilitate drainage. The well-defined power functional relation between drainage area and channel width suggests that these adjustments were complete prior to urbanization and installation of detention ponds. An enlarged channel serves to contain larger flows and focus erosive energies within the channel rather than dissipate them over the flood plain. By this reasoning, the enlarged agricultural channels of HR and BR would be predisposed for further enlargement. However, the nature of the channel materials counteracts this propensity.

The Role of Bed and Bank Materials

Channel erosion occurs by two primary mechanisms, mass failure and fluvial entrainment (Thorne, 1982). Mass failure occurs when the critical bank height is exceeded, often by undercutting the bank toe, or due to increased soil weight and pore pressures within a saturated bank (Darby and Thorne, 1996). Fluvial erosion is the detachment of particles or aggregates from the bed and banks and removal by flowing water (Thorne et al., 1997). Initial detachment of the particles may be caused by subaerial erosion, or the action of fluid shear stress on the boundary materials. In either case, the process of fluvial erosion can be described by the shear stress applied vs. the resistance of the boundary materials. The latter is complex in nature and is influenced by soil properties such as texture, cohesion, bulk density, vegetation/root mass density, soil pore water pressure and chemistry, clay composition, and antecedent moisture conditions (Grissinger, 1982). Entrainment of bed materials is likewise complex; governed by sediment size distribution, distribution of bed forms, channel geometry, and armoring (Middleton and Southard, 1984; Andrews and Parker, 1987; Wilcock and McArdell, 1993; Wilcock et al., 2001).

The bed material for most of the Apple Creek reaches is primarily sand with some gravel. The Holland Road site is predominately gravel. Relatively fine beds such as these can be mobilized even under modest flow events. Because these beds are easily mobilized, the presence of a stable reach suggests that sediment transported out must be replaced from upstream supply. This seems to be the case at Plamann Park 2 where the bed elevation has changed little and erosion of the left bank is nearly balanced by deposition on the right. At Stone Chimney and Plamann Park 1, however, more sediment is evacuated from the channel than is being added. Although the bed has been stable at SC, the channel has enlarged considerably because the point bar is not growing to compensate for the erosion of the cutbank. Plamann Park 1, which is downstream of SC and PP2, is actively enlarging due to down cutting and widening via bank slump (Figure 2; Table 2). Sediment flux from upstream appears to be insufficient to replace the sediment transported out of these reaches by the larger urban runoff.

The bed elevation at Ballard Road and Holland Road has declined slightly in the past few years (Figure 3; Table 2). The ponds effectively trap bed load sediment and there are no tributaries between these reaches and the detention ponds, so any sediment input must come from the short reach between the ponds and the study section. The bed degradation observed here suggests that more sediment is being removed from these reaches than is supplied from upstream. Further bed degradation at the study sections, however, will be limited by the presence of a clay layer beneath the bed. Sediment cores taken in the channels show that the glacial lake clay is between three and five centimeters below the present bed surface at HR and BR respectively (Table 3). This clay is stiff, cohesive, and erosion resistant. Subsequent adjustments in channel capacity will have to come through widening, but this is limited by relatively cohesive lower banks.

In cohesive banks, the amount of silt and clay is recognized as a dominant factor in resistance to fluvial erosion (Wolman, 1959; Schumm, 1960; Ariathurai and Arulanandan, 1978; Allen et al., 1999). Allen and others (1999) noted that soils with the highest fluvial erosion potential had less than 10 percent clay and that fluvial erosion potential decreased with increasing clay content. Therefore, clay content of the lower banks should be a reasonable proxy for erosion resistance.

Textural analysis of bank materials at each of the Apple Creek sections show that HR and BR have a greater proportion of clay than the other reaches (Table 4). Layer 3 at each location corresponds to the unit that makes up the toe and mid portion of the bank. This region is subject to the greatest shear stresses. Both HR and BR have lower units greater than 10% clay content, whereas PP1 and PP2 have no clay and are predominately sand. Stone Chimney has approximately 8% clay, but a larger proportion of sand than HR and BR.

Indicators of bed and bank erosion potential generally support the morphologic changes reported here. The two reaches without stormwater management but with urbanization (PP1 and SC) enlarged the most. These changes were primarily in width and were facilitated by the low resistance of the bed and bank material relative to the forces exerted by mid and channel filling discharges. Plamann Park 2, which is very similar in channel material composition to PP1 and SC, changed less. This is probably because PP2 drains a mixture of forest, park, and agricultural land with relatively little development. Plamann Park 2 likely receives sediment supply sufficient to balance that which is removed by natural transport processes. The reaches downstream of detention ponds and development (HR and BR) changed the least. These reaches have incised a small, but measurable, amount likely due to sequestration of bed load sediment in the ponds. Nonetheless, the resistant bank material has maintained consistent widths.

When channel materials are included, the observations reported here match well with previous field studies. Interestingly, the only channel from the Lee and Ham (1988) survey that had not enlarged was bound by an unstratified, durable silty-clay material (MacRae, 1991). Enlarged channels in the Surrey, British Columbia study consisted of stratified bank materials with a less resistant bank toe. Moreover, the degree of enlargement was well correlated with bank toe resistance (MacRae, 1991). The bed and bank materials along Morningstar Tributary, which enlarged to almost three times its pre-development capacity, were described as silt, cross-bedded sand, and fine gravel overlain by silty-sand (MacRae, 1996). These observations combined with the results of this study underscore the importance of channel materials and strongly suggest that SWM design discharges should explicitly account for the resistance of channel materials downstream.

The problem with using a simple hydrologic parameter for stormwater detention pond designs has been recognized for over two decades (McCuen, 1979). Surprising, however, is the persistence with which such design criteria are still used by many states.

Stormwater Management Policy

Documents on stormwater policy, guidance, and best management practices were reviewed for 46 states (the contiguous US minus MS and LA which could not be obtained). Additional information and clarification was garnered through email and phone contact with state agency representatives. Of the 46 states covered in the survey, seven use some form of peak-shaving technique based upon the 2-year, 24-hour event. Half of the states surveyed have no statewide regulations beyond the National Pollution Discharge Elimination System (NPDES) Phase II Municipal Separate Storm Sewer Systems (MS4) permit requirements. These states leave it up to the individual localities to establish regulations regarding quantity control. Local regulations can vary from quite stringent to nearly non-existent. This approach is problematic because streams often cross county and municipal boundaries. The actions of one community can affect reaches in downstream localities. Moreover, uncoordinated implementation of SWM plans, even within a single county, can greatly reduce their overall effectiveness (Emerson et al., 2005).

Fourteen of the 46 states have implemented management policies where control of “erosive” discharges are explicitly mentioned. Most of these states use a single hydrologic parameter such as “over control” of the 2-year, 24-hour event, where the post-development peak is shaved an additional 60-90% below the pre-development peak (Whipple et al, 1981; McCuen and Molgen, 1988), or extended detention (for durations of 24 to 48 hours) of the 1-year, 24-hr event for design. While these designs reduce erosion potential, they, like the original peak shaving designs, specify flows without regard for downstream channel materials. The resulting facilities could be larger and more costly than necessary in areas where channel materials are robust.

A number of alternative approaches to stormwater facility design exist that consider the boundary materials of the receiving channel. Erosion control detention, for example, seeks to match the pre- and post-development total sediment transport capacity (Bledsoe, 2002; McCuen and Molgen, 1988). The data and computing requirements are modest for this type of analysis, but these models tend to be one-dimensional and do not account for flows less than bankfull. A relatively new technique that improves upon the former method is distributed runoff control (MacRae, 1993). Here the cross-channel distribution of an erosion index (based upon sediment transport potential) is maintained at pre-development levels over a range of flows capable of transporting sediment. The major drawbacks of this method are the relatively large data and computing requirements. This could be the reason why only Vermont has adopted this approach (although a few municipalities have as well).

A similar approach, which New Jersey employs, is pre- and post-development hydrograph matching for the 2-year event. This may emulate the natural hydrologic condition and limit erosion for this particular return period flow for some stream types, however, the problem of erosive events of smaller and larger recurrence intervals remains. Moreover, it may be difficult in practice to design such a facility because the scarcity of historical stream flow data and the inherent problems of rainfall-runoff modeling make selection of the 2-yr hydrograph problematic. Of course, all of the above methods assume an adequate sediment supply to the downstream channels. This supply is disrupted with the addition of in-line ponds that trap sediment. Few states acknowledge this problem and fewer still make policy accordingly.

The design and intent of stormwater systems has moved away from quantity controls and now focuses primarily on water quality. Many stormwater managers noted that quantity controls are achieved as a beneficial “side effect” to water quality BMPs, so there was no need for additional state regulation. While this may be true for some BMPs like infiltration trenches, other BMPs such as in-line detention ponds may actually exacerbate downstream erosion.

Stream response to changes in water and sediment supply can be complex and are a function of antecedent land use, climate, topography, bed and bank materials, and stream type as well as the magnitude, direction, and timing of the imposed changes. As municipalities try to cope with the new Phase II rules, there is an opportunity to educate local and state stormwater personnel on the complexities of the hydrologic response to stormwater management and the resultant downstream effects. An encouraging model for such localities is the Hydromodification Modeling Plan (SCVURPPP, 2005), which includes stream and watershed assessments and continuous simulation of all erosive events with explicit consideration of the bed and bank erodability as part of the BMP selection. This holistic approach should ensure that BMPs are designed and selected in concert with the receiving channels. Even though such approaches may be expensive and time consuming, restoring degraded habitat and retrofitting failed facilities are even more costly endeavors.

Conclusions

As our population grows and urban and suburban developments expand, the need for effective stormwater management becomes more acute. Today there are a large number of BMPs to improve the quality and control the quantity of runoff. However, the most common BMP is still the detention pond. The goal of this work was to investigate the effectiveness of this common stormwater management technique. The results show that reaches of the Apple Creek drainage basin that were developed, but without stormwater management, enlarged the most. Channels under comparable levels of development but downstream of detention ponds changed very little. In fact, these reaches changed no more and were no larger than predominantly undeveloped reaches in the area. These results are contrary to previous field studies, which generally show channel enlargement downstream of detention ponds. The Apple Creek reaches downstream of detention ponds, however, are more cohesive than those in Markham, ON or Surrey, BC, which likely explains their relative stability.

Research conducted over the past few decades has demonstrated flaws in the use of simple hydrologic design criteria for these detention ponds. Greater consideration given to the integrity of the receiving channels would help guide design criteria and ensure a cost-effective design. Government policy makers and planners have been slow to change these practices, but as more and more localities develop their own regulations there is hope that they will include a provision for the reduction of erosive discharges in order to protect downstream channel integrity.

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