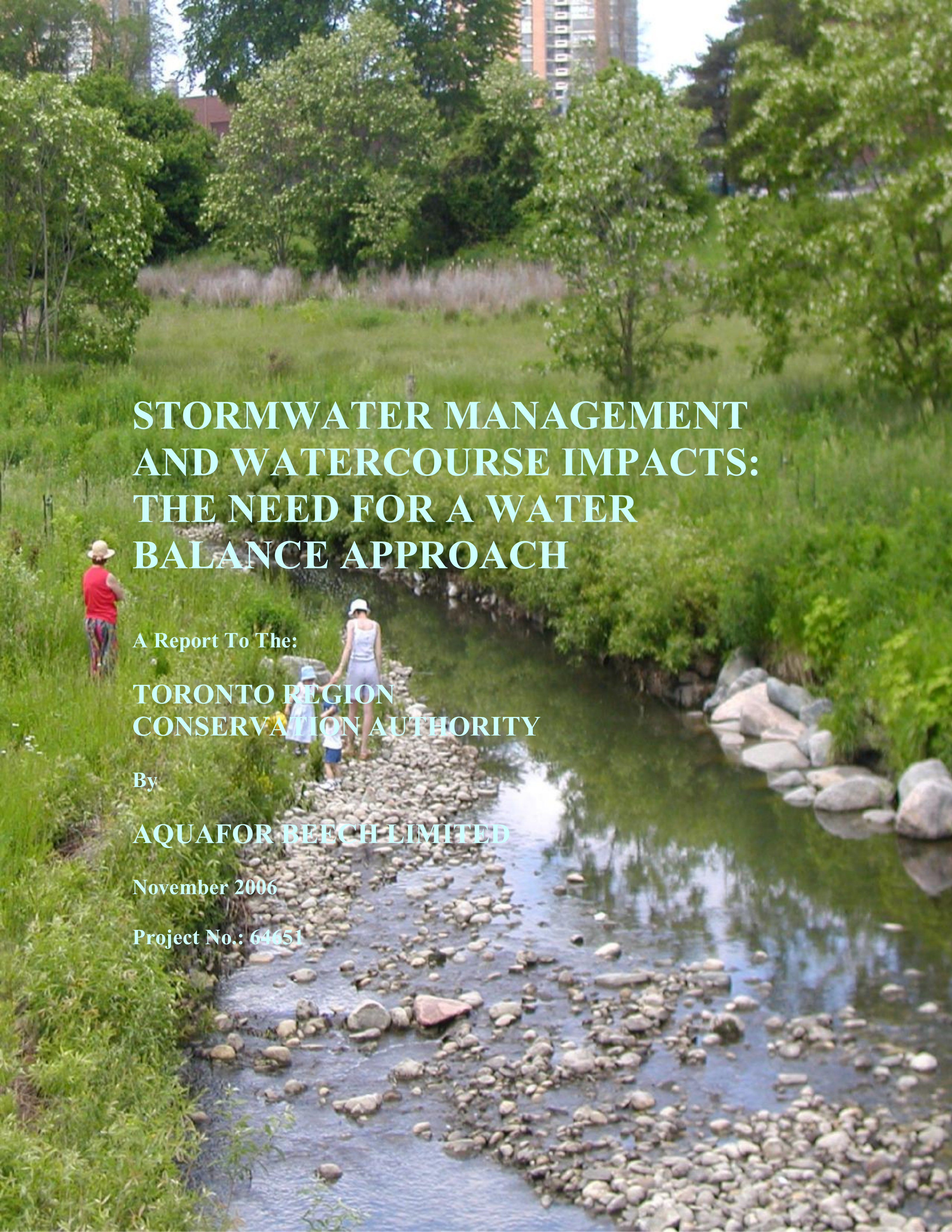

STORMWATER MANAGEMENT AND WATERCOURSE IMPACTS: THE NEED FOR A WATER BALANCE APPROACH

A Report To The:

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EXECUTIVE SUMMARY

Urban development alters the composition of surface materials by introducing significant areas of asphalt, concrete and other impervious surfaces over previously porous soils. The impervious materials prevent rainfall from soaking into the ground thereby increasing the amount or volume of rainfall that flows into nearby watercourses. In addition the drainage system is enhanced through swales, curbs and gutters, catchbasins and stormsewers such that these flows are drained as quickly as possible to the watercourse. The result is an increase in flow magnitude and duration in the watercourse. This impact is referred to as *hydromodification*.

Commensurate with the change in flow rate and volume, urbanization results in alteration of the physical characteristics and mass of sediments delivered to the watercourse. Following disruption of the soils during the active construction phase, which results in an increase in sediment inputs to the watercourse, the landscape is stabilized as lawns or paved areas are established and the sediment yield declines significantly relative to pre-development agricultural conditions. This impact is referred to as alteration of the sediment-regime.

The quality of stormwater runoff is also altered by urban development and the human activities that take place in urban areas which contribute to the pollution of runoff and the resulting degradation of water quality in urban streams.

Channels adjust their shape to maintain a balance between the forces exerted on the boundary by flowing water and the sediment load they transport downstream. When the flow and sediment regimes are altered, the channel responds by adjusting its form through erosion of the bed and bank materials. The resultant loss of property and riparian vegetation decline in aesthetic and recreational value and damage to infrastructure are well documented. When channel instability is coupled with an increase in pollutant loadings and increased water temperatures the stress on aquatic habitat can be acute.

The management of stormwater from urban areas was first introduced in Ontario for mitigation of flood concerns in the mid 1950's. The concept was expanded to include water quality in the 1960's and channel erosion concerns in the 1970's. The principle tool used in the management of these issues was detention of storm flows in ponds. The inflow hydrograph of a pond has a very high peak flow rate but short duration relative to the outflow rate. This process is referred to as routing. Pond drainage may take hours to days depending on the magnitude of the event and the degree of routing applied to the inflows.

The amount of routing required to control erosion potential in the watercourse has evolved since the 1970's with our increasing understanding of channel form and process and how ponds impact watercourses. Although the management of channel erosion has improved with these modifications, ponds still do not meet the intent of stormwater management in terms of preservation of channel form and protection of aquatic ecosystems. Further investigations have identified several deficiencies with current design practice.

Current pond design practice relies on the control of the outflow rate to mitigate the increase in erosion potential in the receiving channel associated with hydromodification. The hydraulic performance of the pond outlet structure, which governs the release of flows from the pond, is designed using the concept of a "duration standard" to define a critical flow (i.e., force required to entrain and transport the mean or average particle size fraction of the bed sediments). It is assumed that flows released below the critical flow lack the energy required to transport sediment or erode the channel boundary. Following

this argument, the excess volume of stormwater runoff generated following urbanization can be released to the receiving channel without increasing erosion hazard provided it is below the critical flow.

Ponds based on the "duration standard" design approach have been shown to successfully reduce erosion potential for particles greater or equal to the mean particle size fraction as they are designed to do. However, even if duration standard ponds are utilized, sediment transport potential for particles finer than the mean particle size fraction increases dramatically due to the increase in frequency of minor flow events following urbanization, and results in the selective removal or winnowing of these particles. This alteration in the composition of the bed sediments impacts the stability of the substrate materials with associated geomorphic and biological ramifications, especially at the meso- and microscale channel forms. The problem relates to the lack of control of flows below the critical flow rate by detention ponds using a duration standard.

Another complicating factor is that ponds are designed for specific development projects in isolation of other developments. Consequently the extended duration of the outflow from one pond coincides with the outflow from the next downstream pond. The constructive interference effect associated with overlapping hydrograph recession limbs increases erosion potential for particles of all sizes and in particular for grains smaller then the mean particle size fraction.

Research over the last decade in particular has advanced the understanding of the relationships between channel form and aquatic organisms. Benthic macro-invertebrates (organisms that inhabit the bed materials) are affected by changes in water quality, flow rate and the composition and mobility of the bed materials. While ponds do provide water quality treatment they also alter the "natural" flow patterns in the receiving watercourse. Exposure to higher flow velocities over longer durations increases stress on these organisms and limits the region of the bed suitable for colonization of some species. This is a recognized consequence of current stormwater management practice.

The alteration of the flow regime also contributes to destabilization of the lower bank zone where the accumulation of weathered soil protects underlying bank materials and provides a medium for germination of seeds. The increase in frequency of occurrence and duration of minor flow events remove the weathered materials, resulting in an increase in bank erosion and susceptibility to failure during high flow events. In southern Ontario, particularly the Greater Toronto Region many channels are worn into deposits comprised predominantly of silt and clay sized materials. Bank erosion in these watercourses introduces large quantities of very fine-grained material into the channel which offsets, in part, the increase in sediment transport potential associated with hydromodification of these particle size fractions in the faster flowing reaches. In lower gradient reaches these sediments may be deposited burying coarser materials and impacting benthic macro-invertebrate habitat. Very fine-grained sediments can also be deposited in gravel spawning beds. The fines get drawn down into the gravels where they plug up the spaces between the larger particles increasing mortality in the eggs and hatchlings.

The selective removal of particles smaller than the mean grain diameter alters the composition of the bed sediments and weakens sediment structures. The weakened structures are more susceptible to failure during flow events exceeding the critical flow, leading to an increase in mobility of the larger bed particles, which in turn, leads to increased mobility of smaller particles due to a decline in the sheltering factor. The increase in mobility of the larger particles has ramifications on channel form at all scales (i.e., especially at micro- and meso- scales; e.g., destabilization of riffle line can create a micro-knickpoint, leading to alteration of riffle forms). Macro-invertebrate aquatic habitat is directly affected by alterations in micro and mesoscale channel form (e.g., Mortality increases due to burial, crushing and exposure to predation as well as a loss of habitable area. The decline in these organisms impacts the fish community as does the loss of pool volume and burial or erosion of spawning areas).

Consequently, the geomorphic and biotic impacts associated with hydromodification and current pond design practice are significant. Modelling studies of sediment transport and erosion potential in Ontario and a number of jurisdictions in Australia and the United States have identified the need to minimize erosion potential associated with the increase in runoff volume attributed to minor runoff events. Reduction of the “duration standard” was examined as one possible mitigation strategy. However the size of the ponds required to achieve the desired level of control made this option impractical. .

Presently, progressive jurisdictions are developing water balance approaches to stormwater management for urban development to mitigate the geomorphic and biotic impacts that result from current practice. Such approaches, often referred to as ‘Low Impact Development”, utilize best management practices to infiltrate or evaporate water and minimize increases in runoff volume. Studies performed considering Ontario conditions suggest that source controls to remove runoff approximately equal to a 15 mm depth of precipitation over the upstream drainage area, in addition to end-of-pipe extended detention ponds, may be required to reproduce the predevelopment erosion potential and avoid negative watercourse impacts over the continuum of flow events. Other benefits of water balance approaches include minimization of the alteration to the “natural” flow regime, maintenance of groundwater levels and reduction in the generation of pollutant loadings. These measures represent a significant step toward realizing the intent of stormwater management, that is to accommodate land use change in the form of urban landscapes will protecting the receiving watercourses and their aquatic ecosystems.

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GLOSSARY OF TERMS

Active Channel	The channel that conveys flows during periods between rainfall events. During wet weather periods the active channel is typically able to contain minor rainfall-runoff events up to events having a return period of 1 to 2 years. In a stable channel of meander-pool-riffle morphology events that exceed the capacity of the "active" channel are conveyed through the floodplain channel.
Aggradation	The process by which sediment or other material accumulates and builds up. In river landforms, aggradation often occurs because of the channel's inability to transport its sediment load. See degradation.
Bankfull Flow	Flow that fills channel to top of bank. The term is strictly applicable only to equilibrium channels and corresponds to the critical channel forming flow that has a recurrence period of ~ 1.5 yrs. In a non-equilibrium channel, the bankfull stage may be below the top of bank.
Benthic Macro-Invertebrate	An animal lacking a backbone or internal skeleton which lives on or near the bottom of a body of water (for example, crayfish, mayflies, and nymphs). Because they spend their entire lifecycle in water, they are good indicators of the health of that water body.
Biota	The entire compliment of species of organisms, plants and animals, living within a region or environment.
Conveyance Control	Stormwater transport systems that are generally located within the road right of way. These facilities promote infiltration, reduce pollutant loadings, and cool stormwater runoff prior to discharging to the stream
Critical Flow	This refers to a quantified flow rate above which erosion of the boundary materials may be anticipated. The rate will vary depending on the grain size of interest, and channel characteristics (slope etc.)
Degradation	In fluvial systems, refers to the process of erosion or wearing down of the channel bed
Detention	Refers to the holding back or temporary storage of stormwater runoff prior to release to the receiving watercourse.
Dominant Discharge	Historically referred to as the bankfull flow, the dominant discharge is that event which performs the most work on the channel as measured by the amount of sediment moved. In non-urban channel systems the dominant discharge is in accord with flows of *recurrence interval* of 1.0 to 2.0 years (average value 1.5 years). In urban watersheds the average value declines to 1.0 year or less depending upon the degree of impervious cover.
Effective Work	Refers to the flow event which, over a hydrologic cycle or hydrograph is responsible for the most sediment transport.

End-of-pipe Control	These are measures that occur at the end of a stormwater flow conveyance system. These facilities are utilized for erosion, quantity and quality control applications
Evaporation	The diffusion of free-standing water (i.e. from rivers and other water bodies) into the atmosphere. It does not incorporate transpiration losses from plants.
Extended Detention	The temporary storage of stormwater runoff often in a reservoir or pond, in order to minimize the potential for downstream erosion and flooding
Groundwater	All subsurface water in a liquid, solid or gaseous state, provided that it is not chemically bound with the minerals present.
Infrastructure	The basic engineered systems of a community's population that support economic activity, including roads, utilities, water, drainage, and sewage systems.
Infiltration	The process by which water percolates into the soil surface.
Interception Storage	In hydrologic terms, rainwater caught by plants (before reaching the ground surface) at the onset of a rainstorm.
Macroscale	Fluvial forms having dimensions of the width of the floodplain including pool length, riffle length, meander wavelength, radius of curvature, and sinuosity.
Mean Particle Size	The mean particle size fraction is that particle for which 50% of the particles in the bed material are finer by mass.
Meander	A bend in a sinuous watercourse resulting from the processes that control channel form.
Mesoscale	Fluvial forms having dimensions in the order of the width of the active channel including hydraulic geometry variables of depth, width, hydraulic radius, wetted perimeter and cross-section area.
Microscale	Fluvial forms having dimensions of vortices and turbulences associated with logs, boulders, sediment structures such as dunes, ripples, and imbricate structures or other obstructions which create hydraulic discontinuities in the flow field.
Morphology	The structure or physical form of a feature or landform that may also provide insight to the processes responsible for its creation
Particle Size	The dimensions of a sediment particle as defined by the length of its longest axis, intermediate axis and shortest axis. Typically, intermediate axis length is used to define particle size. Particle size may refer to an individual particle or a mass of particles.

Physical Characteristics (sediment)	The size, shape, and density of individual sediment particles. These characteristics (especially size) are important for defining the ability of a given flow to erode, transport and deposit sediment.
Pond	A constructed impoundment for the detention of stormwater runoff usually located at the outlet of a stormsewer system. Outflow from the pond is governed by an outlet structure. The hydraulic performance of the outlet structure is referred to as a rule curve which specifies the release rate for any given depth of storage in the facility.
Pool	A topographical low in a river channel caused by the scour that typically occurs during bankfull flow stage. Once formed, pools are relatively stable and frequently form in the bends of regularly meandering channels. (See riffle)
Pool Volume	The volume of the permanent pool, which, for a stormwater facility is typically determined, based on drainage area or runoff volume.
Recurrence Interval	The expected frequency of occurrence in years for a discharge of a particular magnitude. Also called return period.
Response Time	The time required for a fluvial feature to respond to an alteration in the driving mechanism controlling the form of that feature.
Retention	Refers to the portion of a stormwater pond which retains rainfall runoff in a permanent pool of water. This provides a water quality benefit by allowing contaminants to settle.
Riffle	A topographical high in a river channel caused by deposition. Riffles tend to form at inflection points between channel bends. (See pool)
Riffleline	This refers to the larger materials in a riffle, that often span the channel – diagonal or perpendicular to the banks – and which are key stones within the riffle's structure.
Rural Profile	Refers to the roadside ditch or grassed swale typically found along rural roads and many suburban neighborhoods constructed prior to the 1960's.
Sediment/Flow Regime	The seasonal variations in river discharge and sediment transport as dictated by precipitation, temperature, evapotranspiration and drainage basin characteristics.
Sediment Yield	The total mass of particulate material reaching the outlet of a drainage basin within a given timeframe. Often expressed in tons $km^{-2}yr^{-1}$
Source Control	Lot or site level measures taken to retain or detain stormwater flows at the point of generation prior to entry into the stormwater flow conveyance system. These promote ground infiltration and mitigate stormwater overflow.

Specific Stream Power	A measure of the energy available to a watercourse to perform work through erosion of the channel boundary and transport of sediment. Specific stream power is defined as the product of gravity, specific weight, channel gradient and flow rate divided by channel width or the product of boundary shear stress and mean flow velocity.
Storativity	A measure of the amount and rate at which *surface water* is generated and drained off a site or basin.
Stormwater	The proportion of precipitation occurring as rainfall runoff in an urban environment and conveyed through the stormwater conveyance system to a receiving channel.
Stream Competence	The ability of a stream flow to mobilize sediment of a given size
Substrate	Substrate refers to the loose sediments transported by the channel that are deposited on the bed over the substratum or intact (undisturbed) boundary materials.
Substratum	Alluvial sediments under a stratum of surface materials referred to as the substrate.
Surface Water	water which is stored or flows above the surface of the land, including rivers, streams, lakes and ponds.
Time of Concentration	The time required for rainfall runoff from the most distant part of the basin to travel to a selected location on the main channel.
Turbidity	Cloudiness in a fluid caused by the suspension of fine grained material.
Transpiration	That portion of precipitation, surface or groundwater runoff absorbed by plants and animals and released in vapor form back to the atmosphere.
Water Balance	The water balance or water budget of an area over a period of time represents the way in which precipitation falling within that time period is partitioned between the processes of evaporation, transpiration, infiltration, and runoff, taking account of changes in water storage.

1.0 INTRODUCTION

Precipitation that falls onto the ground either flows over land as surface runoff which makes its way directly to a watercourse, soaks into the ground as *infiltration*, or is retained on plant leaves and other surface materials as *interception storage*. Rainfall retained as interception storage is returned to the atmosphere through *evaporation* and never contributes to runoff. A portion of the waters infiltrating the soil recharges deep *groundwater* reserves and the remainder is stored near the ground surface where it is depleted through *transpiration* by plants. Some groundwater migrates laterally and is intercepted by valleys, ravines or the banks of watercourses where it emerges to become surface flow. This groundwater discharge maintains flow in the channel during periods between precipitation events and consequently it is a very significant factor in the determination of habitat value.

The proportion of precipitation occurring as surface runoff versus infiltration and how rapidly the surface runoff is delivered to the watercourse determines, when combined with the slope of the watercourse, the energy the watercourse has to perform work. The work it performs is used to shape the channel and transports sediments downstream. The resulting shape of the channel is one in which the ability of the watercourse to perform work is balanced by the supply of sediment and sediment *physical characteristics* e.g. the size of the particles as well as the resistance of the bed and bank materials in which the channel is formed. The shape of the channel and the size and mobility of the sediments transported by the watercourse are the primary factors determining habitat features and stability. Consequently the shape and size of the channel and associated habitat features are in balance with flow and sediment supplied to the watercourse.

A *water balance* is a way of accounting for what portion of precipitation occurs as surface runoff versus infiltration or interception, how much water is returned to the atmosphere through evaporation and transpiration or supplied to the watercourse through groundwater discharge. The portion of precipitation accounted for in each of these components of the water balance is determined by a number of factors which can be broadly classified as climate, vegetation and geology. Climate refers to long term trends in meteorological conditions typically measured in units of decades to thousands of years. Although there may be short-term changes to the water balance as a result of climate variations, over the long term the water balance is constant, providing vegetation and geology are not altered. Since the water balance ultimately determines the watercourse flow, the form of the channel adjusts to and is intimately related with the water balance.

Changes in land use from natural cover, such as clearing forests for cultivation or conversion of rural lands to urban development forms, alters the infiltration characteristics of the soils and their erosion potential. Consequently land use change can lead to a significant and sometimes radical alteration in the prevailing sediment-flow regime. Much of southern Ontario and particularly the Greater Toronto Area was converted from forest to agriculture in the late 18th and early 19th Centuries as a result of European settlement. The transformation of a forested landscape to active cultivation increases both the volume of sediment and water delivered to receiving watercourses. However, the increase in *sediment yield* is significantly greater then the increase in flow rate and volume resulting in *aggradation* or the accumulation of sediment in the watercourse. An aggrading environment will de-stabilize the watercourse if it persists. Many southern Ontario watercourses became unstable as a result of this aggradation following forest clearing and adjusted their *morphology* in order to re-establish the balance between form and the new prevailing sediment-flow regime.

In the latter half of the 20th century, much of the agricultural land in the Greater Toronto Area was subject to urban development as a result of rapidly increasing population growth. Following transformation to urban landscape sediment loads decline to near forested yields while runoff volume increases dramatically. Drainage efficiency also increases, which means surface runoff takes less time to reach the watercourse. The combined effect of larger runoff volumes and increased drainage efficiency is an increase in peak flow rate and the duration of high flows in the watercourse. These changes in the flow regime are referred to as hydromodification. As a result of the hydromodification associated with urbanization, the watercourse switches from sediment dominated to an erosion dominated environment with significantly more energy available to perform work through erosion and sediment transport. Since sediment yield to the channel from upland areas is greatly diminished the excess energy is expended through erosion of the channel bed and bank materials.

The physical stress resulting from increased erosive energy is manifested through systemic destabilization of the watercourse resulting in channel enlargement and associated loss of property, damage to *infrastructure* as well as *degradation* of habitat and aesthetic value and decline in recreation potential. Such impacts can be observed on many urban and suburban watercourses in the Greater Toronto Area and throughout southern Ontario. When coupled with a dramatic increase in water borne pollution such as litter, heavy metals and nutrients, plus increases in stream water temperature, these changes in the sediment-flow regime place considerable stress on the channel and associated *biota.*

The management of *stormwater* runoff was conceived as a means to allow land use change, specifically urban development, to occur while mitigating the affects on the receiving channel associated with hydromodification. While significant progress has been made in this regard, it is increasingly apparent that current stormwater management practices do not provide sufficient mitigation in terms of channel stability and the preservation of aquatic habitat to meet the intended purpose. This paper examines studies reported in the literature concerning the design concepts and performance of current measures for the management of stormwater runoff such as *pond*s in light of new developments in the understanding of the dependency of channel form and process on the hydrologic water balance and the relationship between channel features and habitat. Literature studies are supported by findings from studies of the effects of hydromodification on streams on the Greater Toronto Area. Other impacts from urban modification to the hydrologic water balance, such as decreased water quality, alterations to the groundwater regime and reduced stream baseflow are acknowledged but are not specifically discussed in this document.

The first section of the document deals with current stormwater management practice which relies primarily on ponds to detain stormwater with limited if any reduction in runoff volume. Erosion potential in the receiving watercourse is managed through controlled release of the excess stormwater runoff volume below a threshold referred to as the *critical flow* rate. It is assumed that flows at or below the critical flow lack the competence to erode the channel boundary and entrain the loose sediments on the bed. The method for determination of the critical flow is typically based on the *mean particle size* fraction, the particle for which 50% of the bed material is finer by mass. Observations for non-urban watercourses having a wide range of *particle size* factions indicate that particles smaller than the mean grain diameter are sheltered by the larger particles (Church, 2006). This suggests that selection of the mean particle size fraction for the determination of the critical discharge may have a geomorphic basis. However the assumption that observations for non-urban watercourses can be applied to urban systems is challenged and impact of current stormwater management practices on watercourse geomorphology is considered. The linkages between *microscale* elements, channel stability and measures of habitat value are presented. These linkages provide a basis for explanation of the failure of ponds to satisfy the intent of stormwater management using current design practice. They also provide insight into possible mitigation strategies.

Alternate stormwater management approaches are considered for mitigation of the increase in erosion hazard. These include adopting a lower critical flow rate for design of the pond. Another mitigation option considered was the reduction of runoff volume with the objective of maintaining the pre-development water balance. The limitations and merits of these approaches are discussed with respect to the need reproduce erosion potential for a wide range of particle size fractions over a continuum of runoff events. The management approach that most closely meets this design objective is considered to be the preferred approach and the most consistent with the intent of stormwater management.

2.0 HYDROMODIFICATION

It is important to understand how the sediment-flow regime of a watercourse is altered by current stormwater management practices so that appropriate mitigation strategies can be formulated. This section addresses changes to the flow regime; alteration of the sediment-regime is discussed in **Section 3**.

When rural lands are urbanized, porous soils are replaced with impervious materials such as concrete and asphalt which yield high runoff during precipitation. Marsalek (1991) summarized the change in hydrologic parameters as a function of impervious cover (Figure 1) which can also be described as a change in watershed *storativity* characteristics (McCuen, 1985)

With urbanization, surface drainage efficiency is enhanced, resulting in a significant shift in the hydrologic budget toward a regime with high runoff yield and a rapid flow response. Hollis (1975) observed that rare flood flow peaks such as the 100-year event increased by a factor of 1.5 at a total watershed imperviousness of 30%. In contrast, events occurring on average once in 2 years or annually, increased by factors of 3.3 to 10.6 respectively at a watershed imperviousness of 30%.

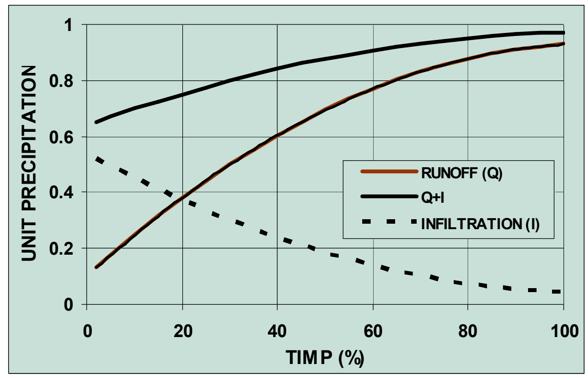

Fig. 1. Change in Hydrologic Budget Parameters (Marsalek, 1991). The increase in runoff volume coupled with improvements in drainage efficiency translates into an increase in the frequency and magnitude of peak flows to the receiving channel for the entire spectrum of flow events experienced by the watercourse (Leopold, 1967). The impact on the hydrologic regime is non-uniform.

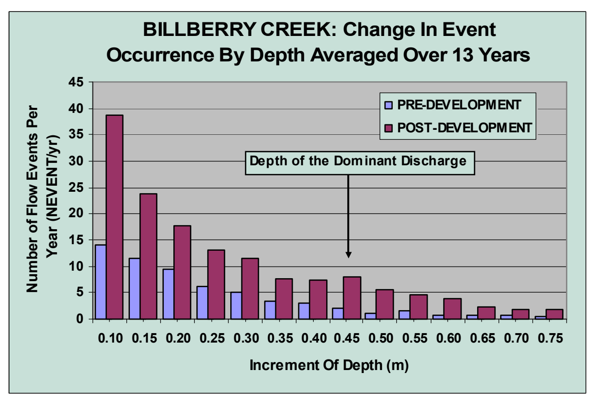

Fig. 2. Increase in number of events by depth in the channel for Billberry Creek near Ottawa Ontario (MacRae and Rowney, 1992).

In stable channels with *meander-pool-riffle* morphology, the shape of the *active channel* was found to be in accord with flow events in the 1-2 year range of recurrence. These events were described as channel forming events, often referred to as the dominant or bankfull discharge (Wolman and Miller, 1960; Leopold et al, 1964; Leopold, 1967; and Dunne and Leopold, 1978).

MacRae (1991) and Bledsoe (2002) found that the greatest increase in erosion potential following urbanization was associated with minor flow events or sub-*bankfull flow*s having depths less than that associated with the *dominant discharge*. That is, even through there is a lower sediment transport potential associated with sub-bankfull flow events, there is a large increase in the number of these events within a year relative to 1:2 year event (i.e., bankfull or dominant discharge). Figure 2 demonstrates how the number of flow events, by water depth, increases between pre and post development conditions for Billberry Creek which is near Ottawa.

3.0 ALTERATION OF THE SEDIMENT REGIME

Osterkamp (1972) considers change in the flow-regime of meander-pool-riffle channels to be the most important factor controlling channel erosion. Alteration of the *sediment regime* can not be ignored, however, and in some instances may replace flow as the controlling factor of channel erosion. Indeed changes in sediment yield following European settlement have played a significant role in determining current channel form of watercourses situated within the Greater Toronto Area and across southern Ontario

Watercourses in southern Ontario have experienced a significant alteration in the sediment regime since settlement of the region in the 1790's. Clearing of forests from tablelands occurred primarily in the early 1800's (Richardson and Barnes, 1956) with the remainder of the conversion being completed by the late 1800's. Active cultivation and clearing practices resulted in significant increases in soil erosion and hence sediment loadings to watercourses. Sediment loadings remained elevated well above yields under forested conditions through the years of active cultivation.

Active cultivation began to decline in the 1950's and 1960's, beginning in the former boroughs of Metropolitan Toronto and continuing in the satellite communities located immediately adjacent. In the Town of Markham, for example, cultivation began to decline occurred in the 1960s (Champion, 1979) when land was converted to pasture, scrubland or urbanized. In all communities, the impervious cover increased; in Markham for example, imperviousness was estimated to be 21 percent by 1995 (ABL, 1996) and growing rapidly. Sediment yields from tablelands declined proportionately with a reduction in the amount of land under active cultivation. There were, however, episodes where sediment yields increased dramatically in associated with the construction phase of urban development. The impact to aquatic ecosystems associated with the spike in sediment loadings during active construction phase is well established and prompted municipalities to implement soil erosion control guidelines. Introduction of sediment into the watercourse due to construction activity is relatively short lived; however, the sediment can remain in the channel for decades and contribute to instability and degraded conditions downstream. Sediment yields from the urban land surface have declined to near forested conditions with stabilization of the urban landscape. The change in sediment yield through time as a result of land use change is summarized by Wolman (1960).

The above chronology of change in the sediment regime with land use means that alteration of sediment loadings to the channel can be anticipated regardless of the implementation of measures to control stormwater runoff. Stormwater controls also affect sediment loadings to the receiving channel. For example, ponds are designed as sediment sinks, which further reduce the supply of sediment from tablelands. Ponds are also more efficient at removing coarse particles such as sand and gravel, relative to fine-grained materials such as clay and fine silt. Consequently an alteration in the sediment particle size distribution can be expected with land use change and the implementation of measures for the *detention* of stormwater runoff. The implications on channel form and stability as well as habitat value are considered below.

During the period of land clearing and active cultivation the impacts of increase in sediment loadings exceeds the increase in flow volume and rate by a significant margin. In many instances the watercourse lacks the capacity to transport the sediment supply resulting in the accumulation of sediment in the active channel, a process referred to as aggradation. Over a sustained period of time, aggradation results in a net increase in the elevation of the active channel and its floodplain. The cross-section and plan form geometry of the channel system is also altered to reflect a sediment dominated environment. As an example, sediment deposits associated with land clearing and agriculture in Schneider Creek in Kitchener were observed to be several meters thick along the current active channel (ABL, 2000).

Following urbanization of the watershed the increase in flow rate and volume coupled with the decrease in sediment yield from the tablelands produces a significant increase in sediment transport potential creating an erosion dominated environment. Schneider Creek, which was urbanized without stormwater management, has cut down through the sediments deposited during the post-colonization period exposing a layer of ash, charred logs and cedar stumps that are indicative historic land clearing.

A similar although less dramatic adjustment in channel form was observed in the west Humber River at Highway 7 (ABL, 1996). Land use in the watershed upstream of Highway 7 shifted from active cultivation to pasture and fallow fields. The reduction in sediment yields is significantly greater than the reduction in flow rate and volume. Consequently there has been a net increase in erosion potential. The active channel has begun to downcut into the post-colonization period sediments. The presence of a terrace at locations along the channel indicates that the channel is also reducing in width. This response is characteristic of the "hungry water" syndrome which is a well established phenomenon.

These impacts point to the need to manage stormwater runoff from a sediment transport perspective. More specifically management measures should consider the change in sediment transport competence and capacity relative to changes in the mass of sediment delivered to the channel and the physical characteristics of those sediments.

4.0 CURRENT POND DESIGN PRACTICE

The measures used to mitigate against the impacts associated with hydromodification can be divided into three general groups: *End-of-pipe Controls*, *Conveyance Controls* and *Source Controls*. End-of-pipe Controls refers to facilities such as ponds and constructed wetlands that receive stormwater runoff from relatively large contributing areas such as an entire subdivision. These facilities are usually located at the outfall of a stormsewer system prior to release of stormwater runoff to the receiving watercourse. They are detention-based measures intended to hold or store stormwater runoff and release it in a controlled manner to the receiving channel. Although water losses through evapotranspiration, and in some cases losses through infiltration through the bottom of the pond or wetland occur, these losses are not generally significant in the majority of detention facilities.

Conveyance Controls represent measures built into the structures that route storm flows to the receiving channel or End-of-pipe Control facility. They typically provide detention functions, but may also provide a flow *retention* or volume reduction function (e.g., through infiltration in porous stormsewers). Examples of Conveyance Controls include super pipes, roadside ditches (*rural profile*), vegetated swales and pocket wetlands.

Source Controls are measures that are applied at the lot level, near the source of stormwater runoff generation, prior to collection by the storm sewer conveyance system. Source Control measures can provide a retention function through infiltration and evaporation/transpiration losses as well as detention. Source Control measures include rooftop storage, French drains, porous pavements, rain gardens, porous topsoil, urban forests, biofilters, and cisterns or rain barrels.

Although Source and Conveyance Control measures have been recognized and utilized for some time, stormwater management in southern Ontario has relied primarily on End-of-pipe Control measures in the form of detention ponds. Originally, such facilities were designed for the purpose of attenuating large flood flows. In the 1980's and early 1990's design standards for detention ponds were revised to provide water quality treatment through settling of suspended sediments. More recently (beginning in the late 1990's), ponds began to be designed for the management of increased erosion potential associated with hydromodification. However, there are fundamental problems with the reliance of detention ponds as the basis for the management of hydromodification.

A variety of approaches have been proposed for designing the hydraulic performance of detention pond outlet structures, including the 2 year post to pre-development peak flow shaving approach, over control (McCuen, 1985), 25mm/48 hour or similar *extended detention* criteria, and Distributed Runoff Control (MacRae, 1993) among others. All of these methods are targeted at the protection of mesoscale fluvial features with the intent of minimizing property loss and damage to infrastructure within the riparian zone.

The 2 year peak flow shaving concept was widely applied throughout the 1970's and is based on the premise that truncation of the post-development 2 year flow at the pre-development 2 year flow rate, using a pond, would minimize the increase of erosion potential in the receiving channel. This approach was based on the geomorphic significance of the dominant discharge or channel forming flow (i.e., 1 to 2 year recurrence flow, (Wolman and Miller (1960), Leopold et al., (1964)), see **Section 2** above for further discussion). While the dominant discharge is an important channel modifying flow, Leopold et al, (1964) and Leopold (1967) also noted that the channel was formed by a continuum of flows, which is not addressed by the peak flow shaving approach.

Truncation of the post-development hydrograph at the pre-development 2 year flow rate actually aggravated erosion hazards in most watercourses as it extended the duration of flows above the critical flow at which material is entrained (McCuen, 1985; MacRae, 1991, 1996). This prompted McCuen (1985) to propose the over control approach which reduced the pond outflow rate to 20% of the 2 year peak flow shaving method. However, MacRae (1991) showed that the over control approach provided excessive control leading to channel instability through aggradation in all but highly erodable channel systems.

The problem with these approaches is that they are hydrological based methods that are applied using a single runoff event for design without consideration of the erodability of the channel boundary materials. Distributed Runoff Control (DRC) was proposed by MacRae (1991, 1993) as a means to assess erosion hazard over a continuum of runoff events. The approach was 2-dimensional in that it accounted for the sensitivity of the boundary materials about the entire channel perimeter. The technique could be applied at selected cross-sections along the length of the watercourse, thereby providing a pseudo 3-dimensional approach to assessing erosion hazard. As such, the DRC approach represented a significant enhancement over previous approaches.

A monitoring program was undertaken by Aquafor Beech Limited for Morningside Tributary in Markham prior to, and following, the retrofit of a peak flow shaving facility with Distributed Runoff Control (MacRae 1996). Subsequent monitoring noted that erosion rates were reduced to those associated with stable watercourses of meander-pool-riffle morphology. Field investigations showed that the approach protected the channel in reaches where the channel was well connected to the floodplain during passage of an event having a recurrence of once in 25 years on average. Those reaches where the channel was unstable and incised, however, continued to erode with instability propagating upstream. These observations suggest that ponds even with Distributed Runoff Control are not sufficient in themselves to control erosion in unstable watercourses.

Cover (pers. comm. 2006), citing anecdotal evidence, noted a decline in habitat value in channels downstream of extended detention facilities even in previously stable watercourses. These observations bring into question the validity of end-of-pipe controls as the sole means to control instream erosion potential.

This contention is supported by Booth et al., (2002) who note that end-of-pipe detention ponds, regardless of increasingly conservative design criteria, have proven inadequate in the control of channel erosion. This conclusion is substantiated by US EPA (2004) who cite independent modelling studies throughout the US, including the studies listed below which all confirmed that various detention ponds have failed to provide downstream flood and channel protection:

- McCuen (1979) – Maryland
- Ferguson & Debo (1991), Ferguson (1995) and Hess & Inman (1994) - Colorado, Georgia and Virginia
- Debo & Reese (1992) - North and South Carolina
- Skupien (2000) - New Jersey

Some of the lack of success of end-of-pipe detention ponds can be addressed through deficiencies in actual pond performance relative to the intended effects due to design or construction issues (Booth and Jackson, 1997). However, the discrepancies in the design, construction or operation of end-of-pipe control measures is not sufficient to explain the apparent lack of performance of these measures over so many jurisdictions (US EPA, 2004; Vancouver BMP Guide for Stormwater, 1999; and Minnesota Stormwater Manual, 2005; Cover pers. com., 2006).

Further consideration of the end-of pipe design approaches noted four basic deficiencies as discussed below.

4.1 The "Duration Standard"

Current pond design methods for erosion control are based on the concept of a "duration standard" which assumes the existence of a discharge (i.e., critical discharge) below which no sediment transport occurs, thereby allowing release of increased runoff volumes associated with urbanization without impact (Booth and Jackson, 1997). MacRae (1991) showed that the "duration standard" assumed for the peak flow shaving approach was applicable to channels worn into very resistant materials not commonly found in southern Ontario. The over control approach, on the other hand, underestimated the "duration standard". The lack of success of the Distributed Runoff Control concept and related extended detention methods suggests that the concept of the "duration standard" as currently applied may be invalid. Further detail with respect to the "duration standard' is provided in the remainder of this section.

Determination of the "duration standard" is generally based on mean particle size fraction. This metric was selected as representative of the sediment transport characteristics of the fluvial system based on the strength of relationships relating mean particle size and Manning's 'n' value (Strickler, 1923; Limerinos, 1991). Further, the mean particle size fraction is commonly used in sediment transport equations (Shields (1936), Mavis and Laushey (1949), Lane (1957), Engelund (1967), and Vanoni (1977)). Finally, the mean particle size fraction is one of the key variables used to predict the dimensions of hydraulic and plan form geometry parameters.

By definition, bed *substrate* is composed of a range of particles 50% of which are finer than the mean particle size fraction. These finer particles vary from very fine-grained sediments (clays, silts and fine sands) to medium sand and coarse gravel depending upon the physical characteristics of the sediments supplied to the watercourse and its sediment transport competence.

Critical discharge is defined as the flow required to entrain the mean particle size fraction in the bed materials. It is contended with the duration standard approach that discharges lower than the critical discharge would not result in significant sediment transport or bank erosion and hence limit changes to channel geometry. In other words it was argued that protection of the mean particle size fraction was sufficient to maintain the integrity of the channel. This position was supported based on observations of *stream competence*. In his study, Church (2006) noted a difference in hydraulic requirements to lift particles for entrainment between closely packed population of grains of similar size and the usual mixtures of sediments on stream beds. The rationale provided by Church (2006) for this phenomenon is the protection afforded to smaller particles by larger grains, so that once the larger grains begin to move, all grains may be entrained.

The importance of microscale bed features in the channel in determining channel form and stability was not explicitly addressed by the duration standard approach for several reasons. First of all, the importance of microscale features in the determination of channel form and stability was not well understood. Secondly bed sediments are difficult to characterize because of the high spatial and temporal variability of these materials. Finally, as noted above, the sheltering factor provided by larger grained particles restricts the mobility of the smaller grains.

The design of detention ponds using the mean particle size fraction to determine the critical discharge means that little if any control is applied to flows associated with minor runoff events. Minor events are defined as any flow event having a peak flow rate less than the critical discharge. However, minor flow events have the competence to move particles finer than the mean particle size fraction if these particles are available for entrainment and transport. Following urbanization, the frequency of minor flow events increases by an order of magnitude and the duration of flows below the critical flow is magnified by the truncation of the hydrograph by detention ponds (Fig. 3). The result is a significant increase in the sediment transport potential for sediments finer than the mean particle size fraction.

Modelling studies of sediment transport and erosion potential in Ontario and a number of jurisdictions in Australia and the United States have identified the need to minimize erosion potential associated with the increase in runoff volume attributed to minor runoff events. Reduction of the "duration standard" was examined as one possible mitigation strategy. However, the size of the ponds required to achieve the desired level of control made this option impractical (Washington, 2004; Booth and Jackson, 1997).

Wolman and Miller (1960) developed a method for assessing the ability of a watercourse to perform work referred to as the "*Effective Work*" curve. One form of this curve is a plot of the product of sediment transport potential for any event and frequency of occurrence on the y-axis against flow rate or the likelihood that an event of known magnitude will occur on the x-axis. Cover et al, (2006) showed, using the Effective Work concept, that sediment transport potential for particles finer than mean particle size fractions increases significantly following urbanization with stormwater ponds for extended detention erosion control using Poole Creek near Ottawa as a case study (Fig. 4).

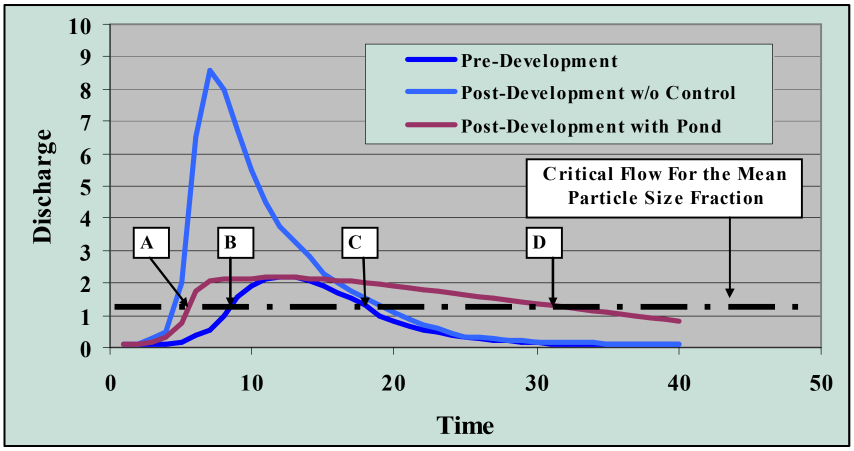

Fig. 3. Illustration of the Effect of Pond Routing On The Post-Development Hydrograph in Comparison With the Pre-Development Hydrograph and the Critical Flow Based on the Mean Particle Size Fraction. Note that the period for which the pre-development flows exceed the critical flow is between points B and C. Following implementation of the Pond this period increases to points A and D with a proportionate increase in the ability of the watercourse to perform work.

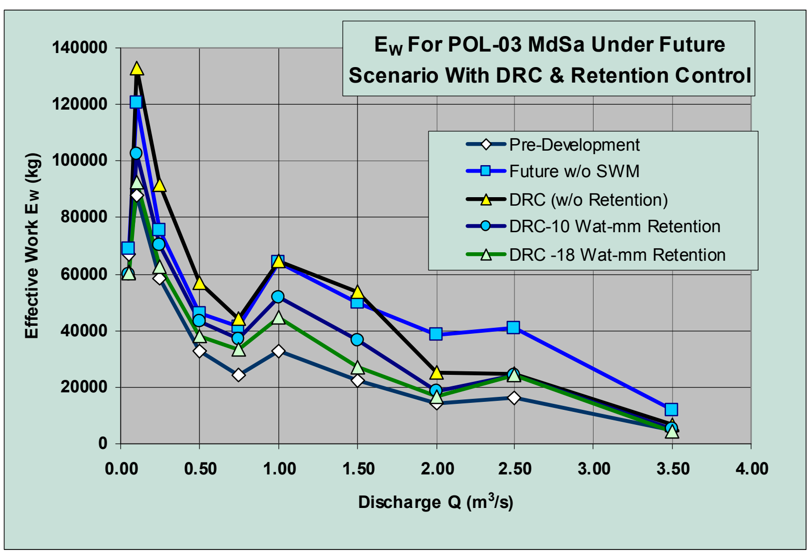

Fig. 4. Particle mobility for medium sand (MdSa assuming a "duration standard" based on the mean particle size fraction (ϕ_{50} = 35 mm (minimum range for coarse gravel)) and selected SWM alternatives (Cover et al., 2006). Note that SWM refers to Stormwater Management, DRC is the acronym for Distributed Runoff Control, Watt-mm Retention represents the volume of runoff measured in millimetres spread uniformly over the area of the watershed assigned to retention using Source Control.

4.2 Overlapping Hydrograph Recession Limbs

Individual ponds designed using the extended detention concept extend the hydrograph recession limb for periods which typically exceed the *time of concentration* for most urban catchments (Fig. 5). Consequently the flow contributed from a pond located within the most distal part of the basin will create a constructive interference effect with the hydrograph recession limb associated with all downstream ponds (Fig. 5).

Current design and approval practice deals with ponds in an isolated or development by development basis rather than integration over an entire watershed. This means that the "duration standard" used to design the most downstream pond may be exceeded upon completion of the next upstream pond. To correctly design and implement detention ponds based on a "duration standard", the cumulative effect of runoff from all past and future developments and the associated ponds within the watershed must be accounted for.

Using a watershed based approach, modelling studies indicate that the degree of control by detention ponds over excess runoff volume to accomplish implementation of a "duration standard" based strategy must increase from negligible control in the downstream portion of the watershed to significant over control in the headwater regions compared to what would be provided were the ponds designed in isolation (ABL, 1999).

Modelling undertaken for Burndenet Creek (Aquafor, 2005) showed that if stormwater management ponds would be 50% oversized compared to a typical duration standard approach, positive effects would be realized in upstream channel sections, but negligible benefit would be noted downstream. This is due to the constructive interference associated with overlapping recession limbs from outfalls of successive ponds. Therefore, there is a cumulative downstream effect that causes an increase in flow volume above the duration standard which is a result of urbanization.

4.3 Reproduction of the Natural Flow Regime

Konrad and Booth (2005), using an analysis of long-term stream flow data on eight urbanizing and five reference streams identified four changes to the flow regime in urban watercourses:

- Increased frequency of elevated flows;
- Redistribution of water from baseflow to storm flow;
- An increase in daily variation in stream flow; and,
- Reductions in low flow.

Modern detention ponds are implemented under the premise that they can reproduce erosion potential but with the implicit understanding that they do not reproduce the "natural" or pre-development stream flow pattern (Konrad and Booth, 2005).

Booth et al. (2002) noted that seasonal and storm flow patterns associated with Storm water management ponds are substantially different from those to which native biota are adapted. Hydrologic change influences the whole range of environmental features that affect aquatic organisms, including a change in the ambient temperature in the receiving channel due to warming of detention pond effluent, alteration of the flow regime (particularly sustained high flow velocities), water quality, biotic interactions and food sources. Consequently some impact on channel form and aquatic habitat can be anticipated simply due to the inability of ponds to reproduce the "natural" flow regime.

4.4 Frequency of Inundation of the Lower Bank Zone

The increase in frequency and duration of sub-bankfull flows resulting from urbanization may make channel banks more susceptible to failure during events of higher magnitude. Andrews

(1977) noted that minor flow events strip away the thin veneer of weathered materials exposing the intact underlying bank sediments to further weathering. These flows also remove seeds and seedlings that would otherwise increase bank stability through root binding and protect the bank materials from direct impingement by the sediment-flow mixture conveyed by the channel. The increase in the frequency and duration of flows in the lower bank region is accentuated by the use of detention ponds for erosion control, which exacerbate these effects.

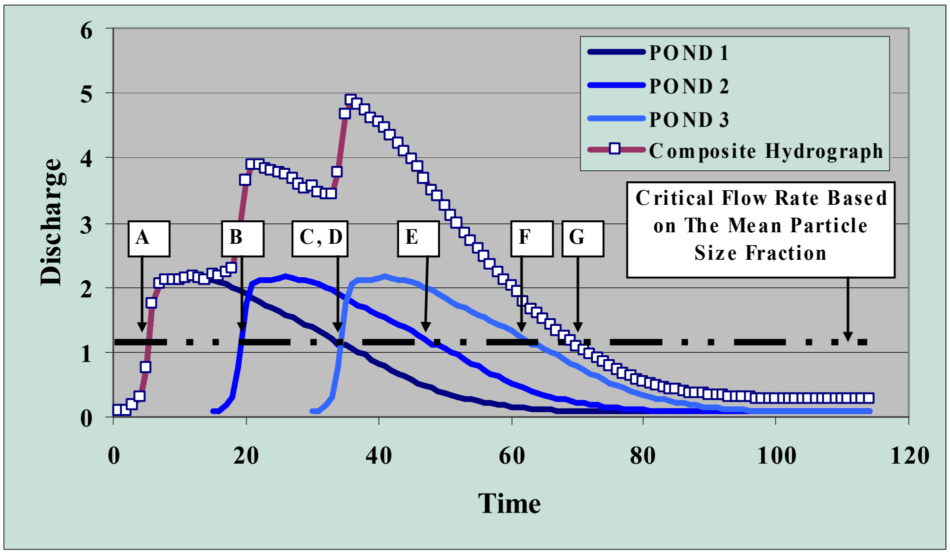

Fig. 5. Impact of Constructive Interference of Multiple Ponds Relative to the Critical Flow Based on the Mean Particle Size Fraction. Note that the duration of exceedance of the critical flow for Ponds 1, 2 and 3 are noted by points AC, BE and DF respectively. However, the combined time of exceedance is between points A and G. Further the magnitude of the composite hydrograph exceeds the peak design flow by a significant margin. The result is higher erosion potential then assessed in the design scenario.

5.0 ALTERATION OF SUBSTRATE PARTICLE SIZE CHARACTERISTICS

Pavlowsky (2004) compared rural and urban streams in the Ozark Plateau Region in southwest Missouri to find that urban streams have shorter inter-riffle spacing, shallower pools and larger bed materials then their non-urban counterparts. Konrad et al., (2005) citing Thoms (1987) and Finkenbine et al., (2000) noted that urban stream beds become coarser in response to the increase in flow magnitude and frequency associated with hydromodification where sediment yields have not increased commensurate with higher flows.

During sustained high flows, small unconstrained particles are moved to more stable positions between larger particles and along channel margins. In urban watercourses, this process exhausts the in-channel supply of sediment readily available for transport and effectively coarsens the particle size distribution of the substrate (Laronne and Carson, 1976; Gomez, 1983; Parker and Sutherland, 1990; Konrad et al., 2005). These observations are consistent with observations reported by Pizzuto et al, (2000) for urban watercourses in Pennsylvania which demonstrated a bimodal particle size distribution in contrast with unimodal distributions in rural streams.

The Effective Work curve analysis reported by Cover et al., (2006) provides a theoretical explanation for the phenomenon of coarsening and the bimodality in the substrate of urban watercourses. As illustrated in Figure 4, sediment transport potential for sediments finer than the mean particle size fraction increase significantly under urbanized conditions despite the implementation of ponds designed using a duration standard. In contrast, through the use of ponds, erosion potential for particles equal to or greater then the mean particle size fraction was controlled to the pre-disturbance condition (Cover et al., 2006). The differential increase in sediment transport potential between sediments finer and coarser then the mean particle size fraction explains the selective removal or winnowing of the unconstrained fine-grained particles from the substrate noted by Konrad et al., (2005). The morphological and biological significance of alteration of the particle size distribution of the bed sediments are discussed in **Sections 6 and 7** below.

6.0 MORPHOLOGICAL ADJUSTMENT ASSOCIATED WITH ALTERATION OF SUBSTRATE COMPOSITION

Watercourse features represent a continuum of forms which, for convenience, may be divided into small scale (microscale), medium scale (*mesoscale*) and large scale (*macroscale*) features (Lewin, 1977). Although the division of any continuum into a finite number of classes has limitations, the spatial scales proposed by Lewin (1977) also have distinct temporal scales governing their formation and destruction which makes them useful in the assessment of fluvial systems.

Microscale elements have *response times* (t_r) from seconds (t_r=10^{-7} years) to less than a year ($t_r \leq 10^0$ years), while mesoscale and macroscale features have response times of one year to decades ($10^0 \leq t_r \leq 10^1$ years) and decades to centuries ($10^1 \leq t_r \leq 10^2$ years) respectively. Changes in the sediment-flow regime associated with urbanization are first manifested in the microscale features (Andrews, 1979) which are significantly more sensitive to hydromodification than mesoscale forms as indicated by their response times.

6.1 Stream Type

The implication on channel morphology and substrate characteristics from alterations to flow regime is complex and variable and depends on Stream Type. Stream Types have been broadly defined as non-shear stress or vegetation dominated, anastomosing, meander-pool-riffle, cascade-pool, braided, step-pool and canyon channel morphologies (Leopold and Wolman, 1957, Schumm, 1972; Gregory and Walling 1973). **Figure 6** shows that Stream Type is related to stream energy as represented by *specific stream power* thresholds (lines of Watts/m^2 after Brookes, 1985). The fact that cascade-pool and braided channels as well as step-pool and canyon Type channels plot in the same region of the graph indicates that a graph based on energy can not be used alone to classify streams. Stream Type is also related to boundary material (Knighton, 1984), composition and characteristics of the sediment load (Church, 2006). Since all three of these factors are instrumental in the determination of channel form, then it follows that all three factors must be considered in the development of a suitable stormwater management strategy.

The classification system proposed in Fig. 6 incorporates, at least qualitatively, the factors of stream energy, boundary material resistance and the physical characteristics of the sediment load. Anastomosing and braided channels represent sedimentation process dominated environments. Cascade-pool, step-pool and canyon systems represent erosion process dominated environments. Meander-pool-riffle systems are more complex because they may include segments dominated by either erosion or sedimentation processes.

Shear stress concepts apply to all channel Types with the exception of vegetation or non-shear stress dominated channels which include vegetated headwater swales and riverine wetlands. Although all of these Stream Types are found in southern Ontario, the channel Type most commonly found in the Greater Toronto Area are of meander-pool-riffle form where the channel is well defined. In headwater areas of these streams a significant length of channel may be classified as vegetation dominated.

Fig. 6 shows that for any unit discharge (discharge per unit width on the x-axis) that channel form changes as slope increases. Commensurate with the increase in channel gradient is an increase in flow energy, which is a measure of the ability of the channel to perform work through erosion of the channel boundary and transport of sediments. Sediment transport potential is described in terms of "competence" and "capacity". Competence refers to the size of the particles that the watercourse can transport for a specified flow while capacity refers to the mass of sediment that can be moved over a given time period.

These concepts can be used to explain differences in channel form between or within Stream Types. Consider for example meander-pool-riffle channels. At the lower end of the energy region for this Stream Type (Fig. 6) the morphology of a channel worn into fine-grained cohesive materials, characteristic of channels in the Greater Toronto Area is dominated by long pools and submerged riffles. The riffles are typically composed of silty sands to fine gravel and are highly mobile. Riffle length varies directly with the mass of sediment carried and proportion of the load in the coarser-grained particle size fractions. However most tend to be short relative to the pools.

As flow energy increases, riffle length increases and exceeds pool length which decreases rapidly with stream energy. The bed materials also become coarser, gravels with some cobbles in a silty sand matrix. The riffles are referred to as emergent because they cause turbulent flow to be visible at the surface and some particles may actually break the surface of the water in some locations. The riffle materials are still within the competence and capacity of the watercourse but flows must attain mid bankfull depths before significant transport occurs. In these systems, channel stability is dependent on the maintenance of the sediment load and consistency in the physical characteristics of the particles to replace those particles transported downstream.

As energy increases further, the bed material becomes coarser, cobbles with some boulders in a sandy gravel matrix. With the exception of the boulders, the majority of the bed materials are within the competence and capacity of the watercourse. If the boulders are sufficient in number they may form imbricate structures such as *rifflelines* that span the width of the active channel bed which has a stabilizing affect on the bed. Riffleline structures in some gravel bed channels may reduce sediment transport rates by orders of magnitude (Church et al., 1998). If the integrity of the riffleline structure is compromised, the riffle materials would be mobilized resulting in channel instability and morphological adjustment.

In summary then, channel form can vary significantly for the same slope and varying discharge per unit width values and is dependent on the sediment supply and physical characteristics of the bed sediments relative to the competence and capacity of the watercourse. It follows that alteration of competence and capacity or alteration of the sediment load and physical characteristics of the bed sediments due to alteration of the sediment-flow regime could de-stabilize the channel and introduce morphological adjustment.

6.2 Removal of Sediment

Pavlowsky (2004) suggested that removal of the fine-grained bed sediments under sustained elevated flows may increase substrate stability under those flow conditions. Along the same lines, Gran and Montgomery (2004) reported an increase in the development of clast structures and bed stability in streams with declining sand input from volcanic sources. While this appears to be contrary to discussions presented above, it is important to recognize that these channels, had experienced a significant disruption in the form of a volcanic eruption that supplied significant quantities of relatively uniformly graded sand sized material to the channel, as a one time occurrence. Consequently these observations refer to unique cases in unstable fluvial systems and are considered to be temporary phenomena and not representative of normal channel conditions.

In stable gravel bed rivers of meander-pool-riffle morphology with rifflelines, Cover et al., (2006) rationalized that the removal of fine-grained particles by sustained elevated flows resulting from urban development with detention ponds would render imbricate structures more susceptible to failure during less frequent events of higher sediment transport potential. The removal of fines may result in the shifting or dislocation of riffleline keystone particles. Removal of the fine-grained particles is also likened to disintegration of the mortar in masonry work. The result is a breach in the riffleline structure that anchors the smaller substrate materials and an increase in substrate mobility. This begins to alter the microscale features on the channel bed which compromises the integrity of aquatic habitat. Because micro-scale features are intrinsically linked to meso-scale features, further change begins to occur within the channel, which can lead to destabilization of channel form. For example, wide spread mobilization of riffle substrate materials leads to homogenization of the bed materials as the riffle sediments are spread out, extending the riffle and filling the pool. The morphological consequence is the loss of pool-riffle structure, in particular the loss of pool depth and length (referred collectively as the loss of *pool volume*) (Andrews, 1979).

The removal of the finer-grained particles also reduces the range of particles forming the substrate. Poorly sorted sediments or sediments having a relatively narrow range in particle size fractions are more susceptible to entrainment and transport than well sorted sediment (Church, 1006). These observations support the contention by Andrews (1979) and Cover et al., (2006) that winnowing of the particles smaller then the mean grain diameter increases the sediment transport potential for the larger particles.

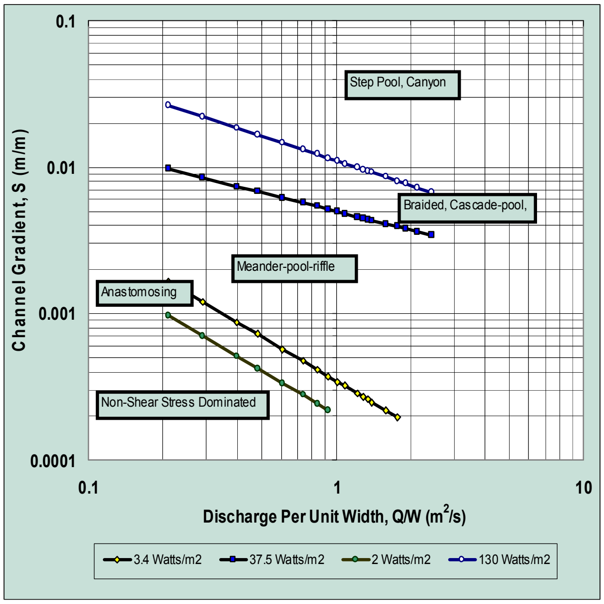

Fig. 6. Specific Stream Power Criteria for Stream Classification (Modified after Brookes 1985) Based on Channels in Southern California and Southern Ontario

Pitlick et al., (2004) using field-based investigations, observed that the substrate becomes more poorly sorted as bankfull shear stress increases. This reflects the greater separation between the grain size distribution for the substrate (surface materials) and *substratum* (the underlying alluvial materials separating the substrate from the parent materials). The ratio of the substrate mean particle diameter to the substratum mean particle diameter increases from 2 in reaches characterized by low boundary shear stress values to 4 in reaches experiencing high boundary shear stress. The coarser substrate materials relative to the substratum sediments is consistent with the winnowing or selective removal of the finer-grained materials that occurs due to extended duration of flows from SWM ponds, above the critical flow required to entrain particles, as suggested by Cover et al., (2006).

As already discussed the increase in the frequency and duration of lower bank inundation results in the stripping of fine-grained products of weathering and the removal of seeds and seedlings from this zone (Andrews, 1979). The removal of sediment undercuts the upper bank and over steepens the slope of the lower bank which can lead to failure. The lack of riparian and bank face vegetation reduces the stabilizing effect of root binding and protection from direct contact between banks and the sediment-flow mixture conveyed in the channel. Increased incidence and duration of lower bank inundation also increases the moisture content of the bank materials and elevates groundwater gradients. Soil moisture acts as a lubricant reducing inter-particulate friction losses making the banks more susceptible to mass wasting while higher groundwater gradients apply force, pushing the bank out toward the channel.

In the Greater Toronto Area, channels draining the glacial tills that cover much of York, Peel and Halton regions have banks composed of fine-grained silts and clayey materials. Increased inundation of these types of bank materials leads to increased risk of bank failure during less frequent higher energy flow events (Andrews, 1979).

Bank failure increases the supply of very fine-grained materials to the channel, which may offset, at least in part, the increase in sediment transport potential for fine materials that is attributed to hydromodification. However, the supply of sands and fine gravels from eroding banks (coarser particles but still smaller then the mean grain diameter, referred to here as the “mid-size” material) is not sufficient to offset the increase in sediment transport potential for these particles. Consequently there is a net loss of these materials from the substrate. Since particles larger than the mean grain diameter are protected by the ponds (i.e., through the duration standard approach) , then the net loss of the mid-sized particles (which are not protected in the duration standard approach) would produce a bimodal particle size distribution as observed by Pizzuto et al, (2000) in urban watercourses of similar morphology in Pennsylvania.

In summary, the above assessment shows that the use of a single particle size fraction in a duration standard approach to stormwater management may not accurately represent the erosion potential of the bed materials over the entire range of particle size fractions. Erosion potential for particles finer than the mean particle size fraction, which is used to determined the duration standard, increases significantly due to the extended duration of the hydrograph recession limb. The protection afforded the smaller particles by the larger ones is not sufficient to prevent winnowing of the finer-grained materials. The loss of fine-grained particles from the substrate renders the larger particles more susceptible to entrainment and transport. As a result, current efforts to manage erosion impacts from urbanization using stormwater detention ponds based on the duration standard concept can cause destabilization of sediment structures. De-stabilization of these structures has negative implications on habitat integrity and channel stability. A more representative calculation of erosion potential requires integration over the entire range of particle size fractions characterizing the bed materials. Further, the impacts of an increase in the duration and frequency of elevated flows on bank erosion must be considered.

Greig et al., (2006) concluded that the calibre, structure and transport dynamics of sediment exert considerable control on channel form and the processes that create and sustain aquatic habitat in all river systems. The relationship between bed material particle composition and mobility and aquatic biota is described in the following Section.

7.0 BIO-GEOMORPHIC RELATIONSHIPS

Harper and Everard (1998) reviewed evidence for the assumption behind the UK's new River Habitat Survey (RHS) that all species of aquatic and riparian organisms depend upon habitats and that higher heterogeneity in the physical habitat supports higher biodiversity in river systems. They find that numerous studies conclude that habitats have distinct biotic assemblages within “functional habitats” and that the link between physical river processes and river biodiversity has been clearly demonstrated.

Modification of physical channel characteristics due to urbanization can have negative impacts on aquatic biodiversity. Results of a study in Lake Ontario tributaries by Stanfield and Kilgour (2006) indicate that low biodiversity is correlated with high percent impervious cover within watersheds. This relationship also exhibits a threshold at 10% impervious cover, after which streams primarily consist of only tolerant aquatic species.

Greig et al., (2006) in a general overview of channel processes stated that physical habitat suitability is a function of substrate type, velocity, depth and bank characteristics. The condition of the substrate, which may be measured in terms of embeddedness, compaction and particle size distribution, plays an important role in defining the quality of various habitat zones. The extended duration of high flow velocities associated with extended detention facilities is another possible stress on aquatic organisms.

Greig et al., (2006) point out that:

- Many freshwater species display preferences for particular grain sizes;
- Alteration to the size and size distribution of substrate materials can affect the presence and quality of riverbed habitats for some species;
- Bed compaction through armoring can reduce bed load sediment supply, can limit scour and particle mobility reducing stable spawning sites and can secure habitat for some species of invertebrates.
- Instream habitats are particularly vulnerable to extreme events, in-channel activities and poor management; and,
- If loadings of fine sediment increase, then the coarse substrate becomes embedded and *benthic macro-*

invertebrate populations decline due to the loss of suitable riverbed habitat.

These sentiments reflect observations by Gurtz and Wallace (1984) based on studies of post logging impacts on macro invertebrates. They conclude that substrate type and channel stability are important factors in determining the direction and magnitude of the response of many aquatic organisms. Sensitivity increases with decreasing substrate size and is greatest for sand beds. Similarly, the physical stability of the river channel tends to decrease with substrate size, being most unstable in sandy environments (Gran and Montgomery, 2004).

The findings simplify the complex nature of the interacting effects of substrate, flow velocity and food on the distribution and abundance of stream invertebrates (Egglishaw 1964, 1969; Minshall and Minshall 1977; Rabeni and Minshall 1977; and, Reice 1980). For example, more taxa responded positively in substrate composed of coarser materials while negatives responses were more common in substrates composed of finer-grained materials. It was rationalized that the larger substrate materials require more energy for transport and consequently are more stable while they also occur in steeper gradient channels of higher velocity with lower probability of deposition of fines. These findings stress the need for channel classification based on boundary material resistance relative to the sediment transport competence and capacity of the watercourse as noted above.

While the higher and lower energy environments are relatively easy to classify the impacts for channels occupying the meander-pool-riffle energy range are more complex. These channels contain reaches of higher and lower gradient that may alternate between erosion and sedimentation dominated environments. Cover et al., (2006) noted that winnowing of the fine-grained sediments may result in coarsening of the substrate in the steeper reaches of Poole Creek but that the loss of this material may also render the coarser particles more susceptible to failure under high flow events. The fine-grained sediments transported out of the steeper gradient reaches constitute sediment inputs to lower gradient downstream reaches.

As noted by Greig et al., (2006) the health of benthic macro-invertebrates and fish communities are closely associated with alteration in the sediment regime, substrate particle size distribution, substrate mobility and the type and stability of sediment structures. An increase in fine-grained sediments transported by the watercourse can invoke a series of stresses on resident biota including direct mortality, reduced reproductive success, and a reduction in the food base (Waters, 1995). The negative effects of substrate changes to aquatic organisms can be generalized as either due to increased fine material deposition or increased coarse substrate mobility.

7.1 Increased fine material deposition

- The area of the stream where flowing water extends down into the gravel is also utilized by aquatic invertebrates. Fine materials may clog the interstitial spaces between streambed gravel, cobble and boulders (Cordone and Kelly, 1961)
- Increased fine sediment in spawning gravels has been show to decrease the survival and emergence of salmonids (Koski, 1966; Tappel and Bjornn, 1983; Lisle; Barnard, 1992; Kondolf, 2000). The highest impact has been show for sediments finer than medium sand (McNeil and Ahnell, 1964).
- Kondolf (2000) reported that when fines exceed 30% of substrate particle size distribution by mass, salmonid emergence and survival is reduced by 50%. Similar findings were reported by Hagar Environmental Science (2003) and (McHenry et al., 1994).
- Increases in the supply of fines in the water column also increases *turbidity*. Turbidity can reduce the feeding

ability of some fish (Sigler et al., 1984; Newcombe and MacDonald, 1991). The longer the duration of high turbidity the greater the stress placed on fish and other aquatic organisms.

- Nutrients associated with increased sediment loadings can increase algal growth contributing to turbidity, the reduction in dissolved oxygen and increased in-stream temperature (Newcombe and MacDonald, 1991).

7.2 Increased coarse substrate mobility

- Some fish, particularly salmonids are very susceptible to changes in sediment mobility associated with a destabilization of imbricate structures noted in coarse substrate.
- An increase in particle mobility resulting in major shifts of the bottom sediments can result in mortality through burial or crushing (Nawa and Frissell, 1993).
- The increase in mobility of the coarse-grained particles also contributes to loss of pool volume, which is important fish habitat (Reeves, 1988; Frissell, 1992; Knopp, 1993; Brown, 1994).

The results of the studies noted above emphasize that aquatic organisms are very sensitive to changes in channel morphology at the microscale level. Cover et al., (2006) demonstrated that current SWM design criteria which are based on duration standards do not adequately mitigate impacts to mesoscale features in receiving watercourses. It is therefore reasonable to assume that these criteria are insufficient to protect resident biota from microscale induced impacts.

There are other biological consequences that may be deduced/hypothesized (speculated on) from the observed changes in hydrologic-sediment regime resulting from the sequence of forested-rural-urban land use change. Some of these are highlighted below:

- Stream margins, that represent important nursery habitats in natural streams, become increasingly hostile environments as a result of the increased frequency of below-bankfull events. As a result, an important habitat niche becomes less productive or may be lost completely;
- As habitats become more homogenous and generally contain less cover for fish, combined with an increase in the magnitude and duration of frequent flows, there is greater potential for fish to be extirpated from entire valley segments and tributaries. There is therefore increased risk that species distributions will be restricted leading to loss of species diversity;
- Discontinuities in the river continuum concept are recognized as areas of increased habitat diversity. These features, such as nick-points, refuge pools, substrate anomalies, gradient breaks, make a significant contribution to total species diversity in a river system. The observed changes in flow-sediment regime may affect habitats in these areas before the rest of the river system, by either degrading them (through aggradation/degradation processes) or making them more hostile environments (to the point where some become fish barriers);
- The coarsening of substrates or winnowing of the fines (less than the D50 particle size) may result in reduced cover for fish, since increased inter-particle flows may prevent some species from utilizing these features as cover. There is some evidence from inventory work in Toronto area streams, that species such as longnose/blacknose dace may be favoured in urban streams over creek chub/bluntnose minnow/white sucker, because of their ability to tolerate higher energy riffle environments;
- The resultant homogeneity in habitats in planform is well documented in urban streams (a shift from meander-pool-riffle morphology to straight-flat-run morphology), however homogeneity can also result in cross-section change a shift from a variable-depth, sediment-bar/pool cross section to a wide, shallow, trapezoidal

shape (Henshaw and Booth, 2000). This type of change can become a fish barrier under low flow conditions and provides little shelter under high flow conditions, leading to elimination of fish and fish habitat;

- In natural streams, there are periodic atypical pool features that are oversized relative to the stream. These serve as refugia for adult fish. Such features are either lost as land use changes or become unstable as a result of aggradation/degradation processes;
- Higher energy streams tend to cycle nutrient more quickly. As a result, there is less opportunity for biota to accumulate nutrients as biomass. The end result in streams is the loss of food chain structure leading to the disappearance of large fish;
- In urban streams, habitat structures such as undercut banks, riffles, LWD tend to be unstable and transitory due to the elevated rate of geomorphic change.

8.0 MANAGEMENT APPROACH

Hydrologically and biologically, there is no truly negligible amount of change in watershed imperviousness as a result of urbanization (Morley, 2000). Any change in basin runoff response will alter the sediment-flow regime, and some impact will occur at some scale in the receiving channel. As the amount of land use change increases, the spatial extent and magnitude of the impact on hydrological and biotic systems increases proportionately. Field data reported by Morley (2000), Kleindl (1995) and May (1996) show a progressive decline in biotic systems with increasing Total Basin Imperviousness (TIMP). If the impact represents a continuum in a spatial context as well as the degree of impact then the question becomes how much change is acceptable, if any, over how much of the channel?

The impact observed on biotic systems is measurable after relatively small changes in Total Basin Imperviousness. The Center For Watershed Protection (2000) in a study of watercourses in Vermont showed a significant decline in the number of benthic sites reporting good or better habitat value where TIMP was between 2% and 6% percent.. A similar decline was observed in the number of sites reporting good or better habitat value for salmonids. The number of sites reporting good or better habitat value for both benthic macro-invertebrates and salmonids declined to zero when Total Basin Imperviousness was within the range of 7% and 11%. Similar results were noted for the West Credit River (ABL, 2000). The need for careful management of stormwater is underscored by the fact that Total Basin Imperviousness for new suburban residential developments can exceed 50%.

Simply stated, one of the most effective ways of minimizing the potential for channel erosion, reduction in water quality loadings and degradation of aquatic habitat in the receiving channel downstream of an urban development is to minimize changes to runoff volume and discharge rate (QUDM, 2006). Priority should be given to methodologies that minimize the change in average annual runoff volume or in other words adopting a hydrologic budget or water balance approach. In so doing the debate about what is an acceptable hydrologic impact can be avoided and the uncertainties associated with an absence of sound geomorphic evidence for the derivation of critical thresholds and incomplete knowledge of aquatic biotic systems can be bypassed. Some impacts can still be expected despite implementation of a hydrologic budget approach as a result of variability in the performance of engineered stormwater management measures that will be required when compared to natural landscapes as well as ongoing impacts to water quality. However, the negative hydrologic effects of urban development will be minimized to the extent possible and the cost and practicality of managing the residual impacts will be significantly improved. In contrast, the massive undertakings required to restabilize and rehabilitate entire creek systems in urban areas that have become physically and biologically degraded once urban impacts have

already occurred, represent a fiscal as well as a technological challenge as is increasingly recognized and experienced by municipalities in the Greater Toronto Area and elsewhere.
In terms of approach, McCuen (2003) noted that the principle of the hydrologic philosophy of smart growth should be to control runoff at the source – not at the end-of-pipe. Various means for the control of stormwater runoff were tested by Cover et al., (2006) as reported in Fig. 4. The methods tested included current end-of-pipe methods as represented by ponds designed using the Distributed Runoff Control approach, Source Control measures for minimizing runoff generation and a combination of Source Control and End-of-Pipe methods The assessment, which was performed using Poole Creek near Ottawa as a case study, demonstrated that:

1. End-of-Pipe control was not sufficient in itself to control erosion potential for a wide range in particle size fractions over a continuum of runoff events;
2. Source Control measures were effective at controlling erosion potential for a wide range in particle size distributions but not for larger runoff events;
3. In order to reproduce pre-disturbance erosion potential over a wide range of particle size fractions over a continuum of flow events, source control runoff reduction measures with an approximate capacity equal to a 15 mm depth of precipitation over the upstream drainage area are required in addition to end-of-pipe measures.

It was concluded from these and other studies (e.g., Holman-Dobbs et al., 2003; Williams and Wise, 2006) that runoff volume reduction, and thus minimization of changes to the hydrologic budget, are required in combination with extended detention rate control to achieve the intent of stormwater management, which is to accommodate urban development while preserving the integrity of the watercourse and associated aquatic ecosystem.

The hydrologic budget as an integrating component of the framework for urban design have been embraced by a growing number of jurisdictions at all levels of government around the world that are investing considerable resources into strategies such as Low Impact Development (LID) that focus on the innovation of development forms and stormwater management measures to maintain the hydrologic water balance. These jurisdictions appreciate the numerous benefits resulting from this approach, including mitigation of physical and habitat impacts to watercourses as described in this paper but also the protection of groundwater resources and discharge to streams, as well as water quality, air pollution, traffic, and social benefits. The need to integrate water sensitive principles into the planning phases of urban development to ensure that the full range of water sensitive techniques is available during design is also increasingly recognized (Bond et al., 2004). Some notable jurisdictions that have advanced water balance approaches such as LID are the State of New Jersey Department of Environmental Protection, the Massachusetts Metropolitan Area Planning Council, the City of Portland, Oregon, Prince George's County, Maryland and the Greater Vancouver Regional District, British Columbia.

9.0 SUMMARY AND CONCLUSIONS

Changes in land use from a natural vegetated condition to agriculture and urban development have altered, and continue to alter, the sediment and hydrologic regime of receiving watercourses. Such changes result in adjustments at the micro, meso and macro scale of channel form, which have implications for exacerbated erosion, increased risk to safety, property and infrastructure, and degradation of aquatic habitat.

Through review of the literature, it is apparent that the hydrologic impacts of urbanization have been studied globally, spanning several continents. Recognition of adverse effects has led to a progression of evolving stormwater management strategies, each of which has attempted to minimize impact of urban runoff on the flow regime of receiving watercourses. While these efforts have resulted in reduction of some impact, research has shown that the current state of practice with respect to stormwater management is not sufficient to mitigate the impacts of land use change and urban development on channel stability and aquatic habitat.

Examination of the premises behind current management strategies clearly reveals the need for a paradigm shift in stormwater management practice. While end-of-pipe solutions have been effective to a degree in reducing flood flow and water quality impacts, current science points to the need for a water balance approach that promotes additional source and conveyance controls to minimize the increase in runoff generation from urban landscapes and reduce impacts to receiving watercourses and the aquatic habitats that they support.

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