

# Defining Hydrologic Mitigation Targets for Stormwater Design in Auckland

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# Defining Hydrologic Mitigation Targets for Stormwater Design in Auckland

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## Executive Summary

In order to improve the level of receiving water protection in the Auckland region, the Auckland Council promotes the implementation of LID to manage stormwater runoff from developed or redeveloped sites. One of the main technical objectives of an LID approach can be summarized as mimicking the pre-development runoff hydrograph, including flow rates, total runoff volumes, and runoff timing. Two main aspects of design to protect receiving environments from hydrologic impacts are addressed herein: 1) expanding Auckland's hydrologic control objectives to better align with international best practice for LID; and 2) developing quantitative procedures and tools for stormwater design professionals. Design for water quality treatment is not specifically addressed.

A historical perspective on the evolution of international stormwater management guidelines as they pertain to controlling, mitigating, or reducing the effects of post-development conditions on the runoff hydrograph, and thus receiving water impacts, is presented. Current conventional stormwater management design largely originates from work by Leopold et al. (1964) that empirically determined that the bankfull discharge for most streams has a 1–2 yr recurrence interval. Subsequent study has shown that the relationship between channel-forming discharges and return periods for storm events is not well-defined (Ward et al., 2008, Shields et al., 2003), and may have significant error for urbanising watersheds where land use change forces changes in hydrology and geomorphology (Shields et al., 2003). Further studies suggest that control of the runoff hydrograph from developed areas for storms smaller than the 2-yr event is required; the largest relative changes to natural hydrologic regimes (infiltration losses, runoff volume and flow peak increases, and increased frequency of runoff occurrences) occur from smaller events which thus cause impacts almost every time it rains. Design for stormwater management should address changes to runoff volumes, groundwater recharge, evapotranspiration, and hydrograph timing in the post-development condition in addition to peak flow mitigation.

Auckland's current guidelines for stormwater control address or are consistent with many of the internationally recognized paradigms. However, newer research and international policies suggest expansion of historic hydrologic mitigation approaches in Auckland is warranted. In order to better align with international approaches to maintain pre-development hydrology, as an initial step the main suggestion is to consider on-site retention (volume control) of up to the 90<sup>th</sup>-95<sup>th</sup> percentile design storm event. This control should be implemented *in addition to* conventional hydrologic mitigation goals of peak flow controls for 2yr, 24-hr ARI and larger events and should also account for site-specific conditions such as in-situ soils and coastal receiving environments. An on-site retention requirement of this type likely implicitly incorporates the current 34.5 mm extended detention requirement, and may prove to be more stringent.

Calculation of retention and/or flow mitigation potential for bioretention, living roofs, permeable pavement, and grassed swales is given for a variety of conditions. These calculations contribute to device sizing, and can be incorporated into forthcoming device design guidance under development by Auckland Council. Devices could be integrated into catchment or sub-catchment design to maintain pre-development hydrology.

The recommendations for hydrologic controls are limited to a desktop study of existing information. Areas of further research are identified as improving the understanding of the influences of development on Auckland's specific receiving environments, the influences of site constraints on LID

implementation, modelling the effects of devices on runoff hydrology, and developing locally calibrated continuous simulation techniques.

The solutions considered herein are focussed on device design as elements of LID. This is not intended to suggest that stormwater devices should be considered a panacea. LID relies on a combination of structural devices, source controls, and very importantly, land-use planning for a catchment-wide approach to minimizing the effects of development on receiving environments.

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## Definitions

AC	Auckland Council
AEP	Annual Exceedance Probability
ARC	Auckland Regional Council
ARI	Average Recurrence Interval
BMP	Best Management Practices
CN	Curve Number
DRC	Distributed Runoff Control
ESD	Environmental Site Design
GD	Guideline Document
IC	Impervious Cover
ICMP	Integrated Catchment Management Plan
LID	Low Impact Design, Low Impact Development in references from the USA
MS4	Municipal Separate Storm Sewer System
NSCC	North Shore City Council
NPDES	National Pollutant Discharge Elimination System
SCS	Soil Conservation Service
TP	Technical Publication
TR	Technical Report
WCC	Waitakere City Council
WQSD	Water Quality Storm Depth
WQV	Water Quality Volume
WSUD	Water Sensitive Urban Design



# 1.0 Introduction

Auckland Council provides stormwater management design guidance to protect Auckland's aquatic receiving environments. The preferred approach for stormwater management is through low impact design (LID). The current guideline published by the Auckland Regional Council (ARC) Technical Publication (TP)124 "Low Impact Design Manual for the Auckland Region" (Shaver, 2004) sets out philosophical, conceptual and qualitative LID guidance.

TP124 is in the process of being updated, the replacement guideline document (GD) will be entitled "GD04 Auckland Council Guideline for Water Sensitive Design". Implementation of TP124's objective is partially through integration of structural (built) devices that capture and treat runoff, or that prevent or minimize runoff generation or contamination (source controls). Design of devices is currently addressed in TP10 "Stormwater devices design guidelines manual" (ARC, 2003), which also relies on TP108 "Guidelines for Stormwater Runoff Modelling in the Auckland Region". As with TP124, TP10 and TP108 are also under revision as GD01 "Auckland Council Guideline for Stormwater Best Practice" and GD02 "Auckland Council Guideline for rainfall – runoff modelling", respectively. Auckland Council is currently producing a series of technical reports each of which focusses on the design of individual stormwater devices, and which will cumulatively contribute to GD01.

## 1.1 Hydrologic objectives for LID stormwater management

At present, GD04 (Draft) carries forward quantitative stormwater mitigation objectives from the TP10 (ARC, 2003) using a design storm approach (calculations based on isolated rainfall events). For typical sites, TP10's mitigation objectives are summarised as:

- *Peak flow* control to predevelopment levels for 50% annual exceedance probability (AEP) and *less frequent* events (equivalent to a 2-yr annual recurrence interval (ARI) event or less frequent)
- Water quality control for runoff generated from 1/3 of the 2-yr, 24-hr rainfall event
- Stream erosion control by controlled or extended flow release of the runoff generated from 34.5 mm of rainfall

On the other hand, design advice presented in overseas LID guidance is setting quantitative goals pertaining to:

- Controlling *hydrology* from *frequently occurring* storm events
- Water balance approach to maintain pre-development conditions
- Water quality control
- Matching flow duration curves between pre- and post-development conditions

The clear distinction between TP10 and international LID best practice is defining the level of hydrologic control between pre- and post-development to be designed into a site, whether it is for new development (greenfield) or re-development (brownfield). An ever-growing body of evidence indicates that the majority of ecosystem impacts are the result of cumulative damage from "every day" rainfall events. Significant changes to natural hydrologic regimes (infiltration losses, runoff volume and flow peak increases, and increased frequency of runoff occurrences) occur from smaller events which thus cause impacts almost every time it rains.

Design of LID stormwater management systems at a catchment or sub-catchment scale therefore incorporate quantifiable objectives such as peak flow *and* volume control (retention) to pre-development conditions for storms such as the 6-month to 1-yr return frequency event, where a design storm approach is used. Timing and method of release are also often addressed. On-site mitigation measures using infiltration, evapotranspiration and rainwater harvesting and reuse are useful to achieve objectives. The use of flow duration curves integrates multiple hydrologic objectives in a single computational process using continuous simulation. Often the mechanisms for controlling peaks, volume, and timing also address water quality objectives.

An LID scheme does not supersede conventional stormwater management requirements (e.g. in terms of TP10 (ARC, 2003) requirements: 2-yr, 10-yr, 100-yr peak flow control and/or 34.5 mm extended detention and/or water quality treatment). In several jurisdictions overseas, LID controls are implemented *in addition to* design for conventional management. Implementation of LID at the site scale does not preclude satisfying Auckland Council or catchment management plans (CMP) requirements for peak flow control for the 2-yr, 10-yr, 100-yr, 24-hr events, extended detention, or water quality treatment. It has been shown that adequately designed on-site LID controls can account for water quality requirements and/or lead to reduced size of conventional end-of-pipe devices (e.g. ponds) for flood control further downstream (i.e. smaller regional ponds) when devices are operating in series. Expanding design considerations of LID devices to quantitatively include their effects on hydrology should promote more holistic catchment management.

From an engineering perspective, the runoff hydrograph is perhaps the most important parameter to begin the design process when using a design storm approach. An outstanding question that impedes implementation of full-scale LID in the Auckland Region is: what is the appropriate runoff hydrograph upon which to base design for LID systems? In other words, what is a frequently occurring, “everyday” runoff event in Auckland? These are technical questions that require quantitative answers to aid Auckland’s design and engineering community in LID implementation.

An LID approach to development begins with land-use and its arrangement (affecting the quantity of runoff generated and the timing of the hydrograph). If pre-development conditions cannot be maintained by minimising (as best as possible) changes in land use and hydrograph timing, then distributed devices throughout the drainage area are required to control hydrology. Each of these design elements will influence the runoff hydrograph. From the very beginning of the design process, a runoff hydrograph is needed for assessing effects, and subsequently for sizing on-site devices.

At present, most on-site or LID devices such as bioretention cells (rain gardens), pervious paving, living (green) roofs, grassed swales, and rain tanks are not actually designed or sized for a particular level of flow or volume control (which is the one of the intents of an LID approach). Briefly, the design approaches tend to consider:

1. Bioretention cells are usually sized to treat the water quality volume (WQV); while studies show significant hydrologic control (Hinman, 2010, Hunt et al., 2006, Liao et al., 2010) is an added benefit rather than a design intent. Due to potentially harmful impacts to the vegetation and water quality treatment performance, bioretention cells should not be designed to manage 2-yr or greater flows, but it may be feasible to modify the size to provide hydrologic control for the “everyday event” without compromising water quality treatment and vegetation health.

2. Pervious paving design procedure has been the subject of significant debate locally, with the Auckland Regional Council (ARC), North Shore City Council (NSCC), Waitakere City Council (WCC), and the concrete industry attempting to pool resources to establish design procedures for stormwater control. Since the amalgamation of the Auckland legacy councils, Auckland Council is revising the current design approach (Worth and Blackbourn, 2013 Draft). The draft approach compares the basecourse depth required to support the structural loading or full storage of the WQV. Whichever depth is greater is used for design. The document sizes underdrains based on the predevelopment hydrologic regime, where sites cannot exfiltrate to surrounding soils.
3. Living (green) roof design has been established for Auckland (Fassman et al., 2010b, Fassman et al., 2010a). In the proprietary markets that have developed in the USA, living roof design is not typically based on ensuring a particular level of flow control. Rather, the living roof specification is determined based on structural loading and/or substrate depth (presumed) for vegetation health. Rules of thumb are often applied for crediting stormwater control. Research in Auckland has developed standardised testing methodology for substrates to deliver a minimum level of stormwater retention (volume control) (Fassman and Simcock, 2012) . The design is based on fully retaining the 90-95<sup>th</sup> percentile design storm event (Fassman-Beck and Simcock, 2013).
4. Grassed swales are designed for flow conveyance and contaminant removal. A minimum residence time of 9 min is recommended to promote water quality treatment. The high flow conveyance capacity is designed to pass the design storm used for local stormwater infrastructure sizing at the site, without causing erosion or nuisance flooding. While the literature provides evidence of hydrological benefit of swales, there is currently no accepted method for quantifying this effect in terms of stormwater quantity control (Paterson and Hellberg, 2012)
5. Rain tanks sizing allows for mitigation of multiple stormwater management objectives through the use of multiple outlets. In draft advice to the Auckland Council, recommended design procedures aim to meet some or all of the following stormwater management objectives (Patterson, 2013 Draft):
  - a. Extended detention storage;
  - b. Peak flow attenuation of the 2 year ARI rainfall event;
  - c. Peak flow attenuation of the 10 year ARI rainfall event; and
  - d. Retention and reuse of rainwater to provide stormwater quality and quantity credits for downstream devices.

The effectiveness of LID at the lot-scale in protecting the receiving environment depends on appropriate design to address hydrologic mitigation otherwise induced by development. Furthermore, uptake of LID should improve if design objectives and calculation procedures are clarified in the local context.

## 1.2 Objectives and Scope

Specific quantitative (computational) technical direction is required to translate TP124's objectives into site design with meaningful prediction for stormwater management outcomes. This report is intended to expand the quantitative design approach for LID devices in the Auckland region. Two main aspects of design are addressed herein: 1) expanding Auckland's hydrologic control objectives to better align with international best practice for LID; and 2) developing quantitative procedures and tools for stormwater design professionals, e.g. engineers.

The study provides recommendations to be implemented within Auckland's existing stormwater design framework. It is limited to a desktop study of existing information, relying on an international literature review, and considers only a design storm approach in order to facilitate immediate adoption. Design tools consistent with hydrologic modelling guidance from TP108 (ARC, 1999) and/or GD02 (Auckland Council, 2010) are intended to supplement guidance for LID devices in terms of hydrologic effects only. They do not replace the design guidance in TP10 (ARC, 2003), GD01, or Auckland Council technical reports updating design of individual devices. This report does not investigate suitability of LID implementation for specific sites, nor does it specifically address water quality treatment.

## 2.0 International literature review: hydrologic design objectives

A survey of academic literature is presented to provide some historical context on the evolution or genesis of stormwater management approaches across international jurisdictions. Government policy, regulations, and/or guidance documents are also reviewed, in an attempt to identify common hydrologic design objectives often resulting from the historical literature.

In addition to water quality impairment from pollutants such as total suspended solids (TSS), nutrients and heavy metals, urban development has been linked to hydromodification of receiving waters. The US EPA (1993) has defined hydromodification as the "alteration of the hydrologic characteristics of coastal and non-coastal waters, which in turn could cause degradation of water resources." Hydromodification is exhibited as channel erosion and instability, resulting in negative consequences for aquatic habitat, and potential infrastructure and property damage. Evidence in the literature shows that marked alteration of channel forming flow processes is associated with declining ecological health, or degradation of the physical channel attributes required for normal ecological functioning (Gippel, 2001). LID principles of restoring pre-development hydrology aim to address hydromodification as one aspect of receiving water protection.

A review of Auckland regional and international stormwater management manuals and related documents was undertaken to explore the concept of detention to minimise channel erosion. The literature review investigates causes of stream erosion and summarises regulatory approaches for mitigating erosion potential, both with respect to urban runoff.

The following sections are intended to:

- Clarify understanding of the intent behind ARC (2003) design guidance on stream erosion protection (channel erosion control, aka "extended detention requirements").
- Define causes of stream channel erosion and their relationship to flow magnitudes and storm events with specific average return intervals (ARI events).
- Provide historical context and evolution of stormwater management approaches to minimise channel erosion.
- Compare causes of channel erosion with LID objectives for stormwater management.

### 2.1 ARC (2003) policy regarding stream erosion protection

In order to protect the physical structure of the receiving stream, ARC specifies an erosion control requirement of detaining runoff from the first 34.5 mm of rainfall and release over a 24 hour period (ARC, 2003). The 34.5 mm requirement is a rainfall-based approach, thus acknowledging the variation of potential impacts associated with different types of land use. For example, the volume of runoff generated from 34.5 mm of rainfall over an industrial area with high imperviousness will be significantly greater than the volume of runoff generated from 34.5 mm of rainfall over a single family low density residential development, and thus the impacts to the receiving stream are likely to be different. The volume of runoff to be stored for extended detention from the 34.5 mm of rainfall is calculated based on the entire site area, regardless of predevelopment conditions.

The original document which led to the 34.5 mm requirement has not been reviewed herein, as the validity or justification of it was reviewed by the ARC in 2008 (Shaver, 2008, Teal, 2008). These reviews took the form of discussion papers, which are included as an Appendix A of this report.

Shaver's discussion paper documents the ARC's quest to find a simple, regionally appropriate method to provide stream channel erosion protection from stormwater runoff. Development of the method started with a desktop study, the results of which were attempted to be verified with a field study by NIWA. Despite the field study and subsequent additional desktop work, the ARC was unable to justify nor refute or invalidate the 34.5 mm requirement. It was also observed that the erosion process is quite complicated, and a regional rule might not be appropriate.

The Teal report compares the 34.5 mm requirement with erosion control policies from three jurisdictions in the western United States (San Diego, San Francisco Bay Area, and Washington State). Determination of shear stress appears to be theoretically the most robust or direct method for assessing erosion potential. The report concludes that without determining the shear stress within a stream specifically, there does not appear to be a simple, agreed upon approach for mitigating erosion potential. Again, the report does not recommend changing the current ARC rule based on current knowledge, but does suggest an investigation into how the rainfall standard for erosion control relates to effective shear stress in the channel.

The 34.5 mm requirement aims to prevent accelerated downstream channel erosion as a result of increases in impervious areas. The 24 hour drain down requirement is designed to separate the site runoff from the catchment runoff. Since most Auckland storms have a duration of about 6 hours, detention and release over 24 hours would retard site runoff so that peak runoff from unattenuated parts of the catchment has passed before the majority of the volume stored in the extended detention area is released (Shaver, pers.comm).

The 2-yr and 10-yr event requirements are primarily for flood protection with a secondary goal of protecting the amenity value of streams from "flashy", high run-off rates which cause "out of bank" destabilisation (Shaver, pers comm).

Without reproducing each of the sources of information, conclusions are summarised as:

The 34.5 mm design storm may not be appropriate on a catchment specific basis.

The stream erosion studies undertaken to date have been inconclusive for scientifically justified region-wide policies.

As the ARC's documentation appeared somewhat inconclusive, a literature review of academic and additional regulatory approaches has been undertaken herein to further investigate relationships between stormwater runoff and stream erosion, and design approaches for controlling these impacts. No challenge is made to the fact that uncontrolled stormwater runoff from urbanizing areas carries the potential for stream erosion and habitat degradation. What is being explored is the basis for design to mitigate or prevent those impacts.

## **2.2 Characteristics driving stream erosion: bankfull flow and effective discharge**

Key characteristics driving stream channel erosion are *bankfull flow* and *effective discharge*. Changes in bankfull flow have been observed following extensive urbanisation (Booth and Jackson, 1997, Hammer, 1972), with implied resultant channel instability and changes in bankside vegetation (Hey,

2006). The discussion herein applies to natural stream channels subject to fluvial processes. Constructed channels, ditches, or other artificial drainage systems are excluded.

The terms are described by Ward et al. (2008):

- *Bankfull discharge* is a range of flows that is most important in forming a channel, floodplains (benches), and banks. It is often related to the amount of water flowing in a stream that fills the main channel and begins to spill onto the active floodplain. Measurements of stream channel geometry are usually needed to determine the bankfull geometry and associated discharge capacity according to Manning's equation and the continuity equation. Actual measurement is difficult in unstable streams (Hey, 2006, Shields et al., 2003).
- *Effective discharge* is the amount of water that transports the most sediment over the long term. It is usually determined by plotting the sediment discharge against various flow rates over the long term. The maximum value in the plot is the effective discharge. The Wolman-Miller model for geomorphic work is usually used to determine sediment movement. Stream discharge data is also needed or must be estimated to determine a frequency histogram. Seasonal effects may be important in determining effective discharge, recognising that small flows may be capable of transporting large sediment masses, and vice versa depending on the particular stream, season, and other factors. The concept links sediment load with channel geometry.

Often, the terms *bankfull flow* and *effective discharge* are considered to be synonymous (Hey, 2006, Leopold et al., 1964). Either, or both, may be considered a "channel-forming discharge". However, Shields et al. (2003) define the channel-forming discharge more generally as a single discharge that given enough time, would produce the width, depth, and slope equivalent to those produced by the natural hydrograph for a given alluvial channel geometry. This concept is claimed valid for streams in humid regions and perennial streams in semi-arid regions (Biedenharn et al., 2001, Soar and Thorne, 2001). The notion of bankfull or effective discharge underpins the well known stream restoration scheme called the Rosgen Method (but is not the only variable in design) (Hey, 2006, Shields et al., 2003, Rosgen, 1994).

Current (non-LID) stormwater management design largely originates from work by Leopold et al. (1964) that empirically determined that the bankfull discharge for most streams has a 1–2 yr recurrence interval. Subsequent study has shown that the relationship between channel-forming discharges and return periods for storm events is not well-defined (Ward et al., 2008, Shields et al., 2003), and may have significant error for urbanising watersheds where land use change forces changes in hydrology and geomorphology (Shields et al., 2003). For various streams in Ohio (USA), bankfull discharges were found to be associated with less than 1-yr to 5-yr ARI. In terms of effective discharges for the same streams, the ARI was found to be ~0.45–1.3 yrs. MacRae (1991) demonstrated that the greatest increase in erosion potential was associated with moderate flow events with less than 1.5 yr ARI. MacRae and Rowney (1992) later demonstrated that under urban conditions the maximum effective work in a stream increased in magnitude and shifted to flows of 0.5–1.5 yr ARI. Another study found that events that shape in-channel features occurred 14–30 times per year, and did not equate with bankfull conditions (Gippel, 2001). Bankfull or overbank flood occurs every 1.7 to 21.1 months across the Rouge River Watershed, Michigan (Alliance of Rouge Communities, 2011). There is evidence to suggest that bankfull flows occur more frequently as basin area decreases and slope increases (Gippel, 2001).

Results give rise to advising caution in using a return period as a stand-alone metric in determining bankfull characteristics (Ward et al., 2008). It is clear however, that channel forming discharges generally may occur or be exceeded several times a year for humid or semi-humid regions (Ward et al., 2008). Shields et al. (2003) warn that any estimate of a channel forming flow which exceeds a 1-3 yr return interval should be questioned, and that more than one of bankfull discharge, effective discharge, and ARI flows should be considered with respect to determining channel-forming flows. Ultimately, in order to address erosion problems in receiving waters, it is important to understand the frequency of the erosive small storm events and take actions to reduce the frequency of these events (Alliance of Rouge Communities, 2011).

Regional curves for bankfull discharge have been determined in areas of the USA and UK. Shields et al. (2003) indicate that regional relationships are best applied to channel networks with large data sets that include stable sites. An underlying assumption is that future hydrology will be similar to past, as it is a purely empirical method, and thus may result in error in urbanising watersheds. Significant variation from regional values has been observed for site-specific data (Hey, 2006, Ward et al., 2008). Hey (2006) suggests development of curves based on stream type and bank vegetation density, rather than by regional clustering. These observations were confirmed locally by ARC studies (see Section 2.1), which documented challenges associated with measuring shear stress in local streams, and defining regionally-appropriate rules.

In streams, the shear stress that causes scour and erosion is related to the depth of flow and the slope of the channel bed (Ward et al., 2008). To maintain stability, a river needs to transmit the incoming sediment load without net erosion or deposition (Hey, 2006, Shields et al., 2003). In the Rosgen method, calculations are made to ensure that the river can transport the largest stone represented in the bed material at bankfull flow, implying that the river will just transmit the incoming bed load material up to and including this critical size. This idea implies defining a critical shear stress for the particle size of interest. To estimate erosion potential in a specific stream, therefore, site specific bed-load characterisation is useful (Shields et al., 2003).

Flows greater than the effective discharge should not cause erosive forces where floodplains are preserved. Flow, velocity, and shear stress in the main channel are maintained at or near effective discharge conditions when streams are allowed to overtop and spread across the floodplain when flow exceeds the effective discharge (Ward et al., 2008). In terms of designing for stormwater management, investigation of shear stress duration curves with respect to flow-duration relationships for a particular stream suggest that as long as the critical portion of the shear stress duration curve can be matched between pre- and post- development, no net increase in erosion potential takes place (Rohrer and Roesner, 2005).

In summary, the literature indicates:

1. Erosion in natural streams is driven by channel-forming flows, which are often defined as either *bankfull flow* or *effective discharge*.
2. Regional values for channel forming flows are unlikely to accurately reflect conditions at a particular site.
3. Channel-forming flows are not related to a single average return interval discharge.
4. Site-specific analysis would be required to accurately estimate erosion potential in a stream, and thus design measures to mitigate effects.
5. Where flood plains exist, flows in excess of the channel forming flows (typically 0.3–2 yr ARI) are unlikely to cause any additional erosion once bankfull flow is reached.



## 2.3 Targeting rainfall events for a hydrologic basis to stormwater device design

Historically, stormwater management has focussed on control of larger, more infrequent, rainfall events such as the 2-yr, 24-hr ARI event for erosion control and flood mitigation. Recent studies are demonstrating that the typical “one-size-fits-all” management approach of peak flow control with retention or detention ponds has not been entirely effective, pointing to a need for improved management strategies and tools for mitigating the impacts of hydromodification (Bledsoe et al., 2012). Academic literature (Section 2.2) suggests that channel forming flows are not necessarily linked to a particular design storm event, rather a range of flow conditions which are likely encountered several times per year, which may be more frequent than the 2-yr, 24-hr ARI event (specific citations range from approximately 4 mo to 2 yr). The duration of flow and frequency of occurrence is just as important as the magnitude of flow in creating channel erosion. Site-specific investigation of channel forming flows, including bankfull discharge and effective discharge, are the best indicators of the erosion potential, according to Section 2.2. Regional rules for managing erosion potential based on limited site-specific investigations are not recommended.

Figure 1 has been reproduced amongst LID literature (Chesapeake RC, 1996, Prince George's County DER, 1999). While still somewhat qualitative, the figure suggests that channel erosion is a result of storms greater than approximately 0.35 yr (4 mo) ARI. The distribution of rainfall events is divided into four classes by recurrence intervals as shown in Figure 1. The first two classes are the most frequent rainfall events, which are targeted for water quality control, ground water recharge and (to some extent) channel erosion control. Storms sized in zones three and four are water quantity storms, for which the control objectives are around channel erosion and flood control (Chesapeake RC, 1996). Some stormwater management references suggest that medium storms with the recurrence interval of 6-mo to 2-yr are the critical storms that determine the size and shape of the receiving streams, despite the more specific considerations of bankfull or effective discharge as discussed in Section 2.2 (McCuen, 2005, US EPA, 2004, Roesner et al., 2001).

Similar to Figure 1, the Vermont Stormwater Management Manual (Vermont ANR, 2002) identifies that effective stormwater management must include both water quality and water quantity controls, and presents rainfall event ranges to demonstrate the proportion of rainfall contributing to each parameter of concern (groundwater recharge, water quality, channel protection, and flood protection). The intended approach is to manage the entire frequency of rainfall events anticipated over the life of the stormwater management system, ranging from the smallest, most frequent events that produce little runoff, but make up the majority of individual storm events and are responsible for the majority of groundwater recharge, up to the largest, very infrequent events that can cause catastrophic damage (Vermont ANR, 2002).

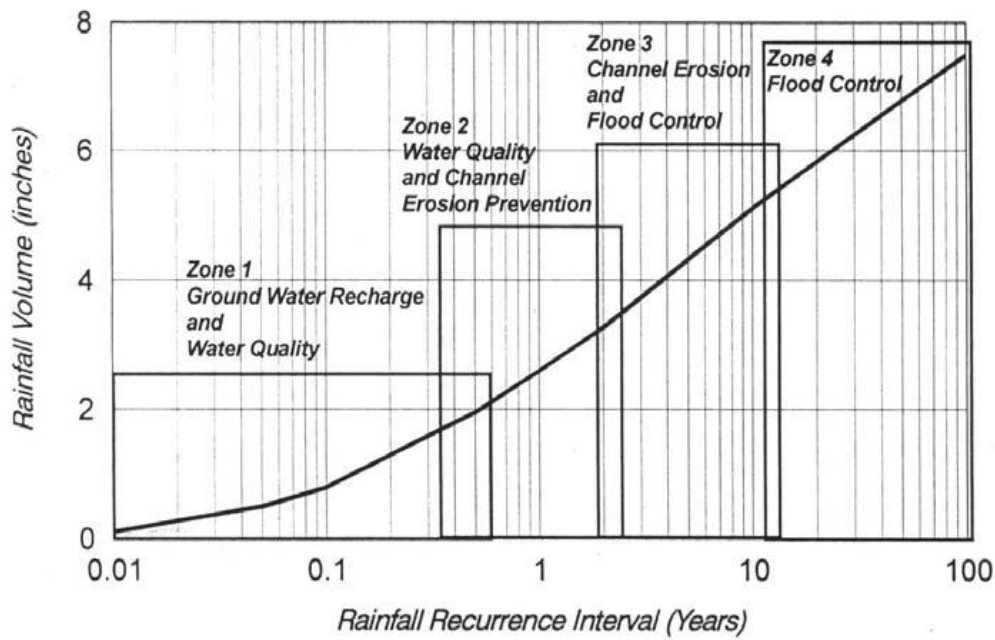


Figure 1 Stormwater control points along the rainfall frequency spectrum (Chesapeake RC, 1996)

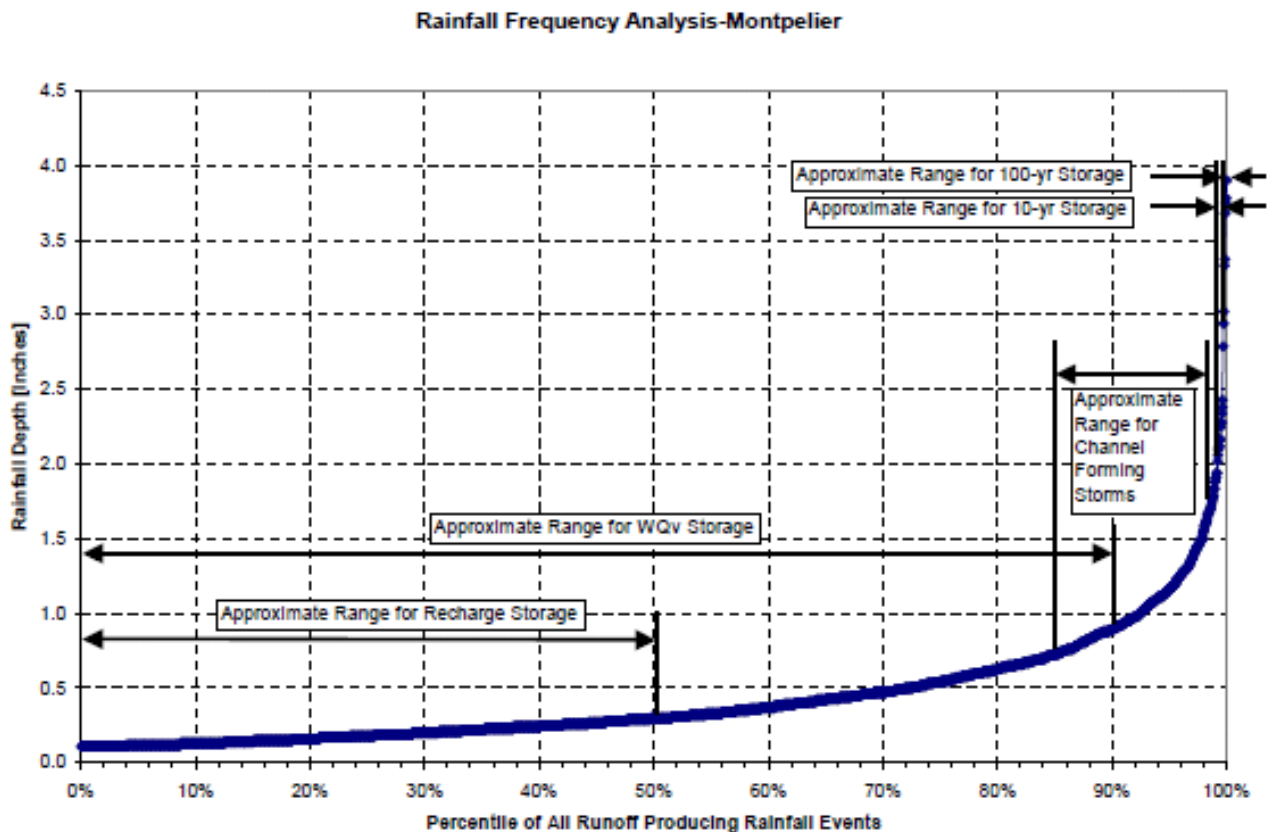


Figure 2 Rainfall event ranges for sizing stormwater treatment practices to meet treatment standards for water quality, channel protection, groundwater recharge, overbank flood protection and extreme flood control (Vermont Agency of Natural Resources, 2002)

Hydromodification refers not only to erosion, but also changes to the overall flow regime. It is interesting to note that both Figure 1 and Figure 2 identify that the more frequent events (ARI <1-yr and 50<sup>th</sup> percentile event, respectively) are important for groundwater recharge. Groundwater recharge is one of the key hydrologic functions provided by a natural landscape that is often significantly compromised by urbanisation, and ultimately is off-set by increased surface runoff. Hamel et al. (2013) recognize that stream baseflow in peri-urban catchments reflects complex interactions between physiographic and anthropogenic influences; mimicking pre-development hydrology should perhaps not rely on a single measure of post-development hydrology (Cizek and Hunt, 2013).

**2.3.1 Peak flow control approach**

Historically, control of channel erosion has been focused on restricting the post-development peak discharge for the 2-yr event to the pre-development level (Leopold et al., 1964, US EPA, 2004, Brown and Caraco, 2001). This method evolved largely in response to observations by Leopold et al. (1964) that bankfull rainfall events have a 1–2 yr ARI and are responsible for channel forming discharges. The approach of peak flow control of 2-yr and 10-yr events combined with demonstration of non-erosive channel velocities is still used in many jurisdictions. MacRae (1991) suggested that the 2-yr peak flow control approach was adequate for channel protection for geomorphically robust channel systems (i.e., rock beds or banks), but inadequate for more sensitive channel environments.

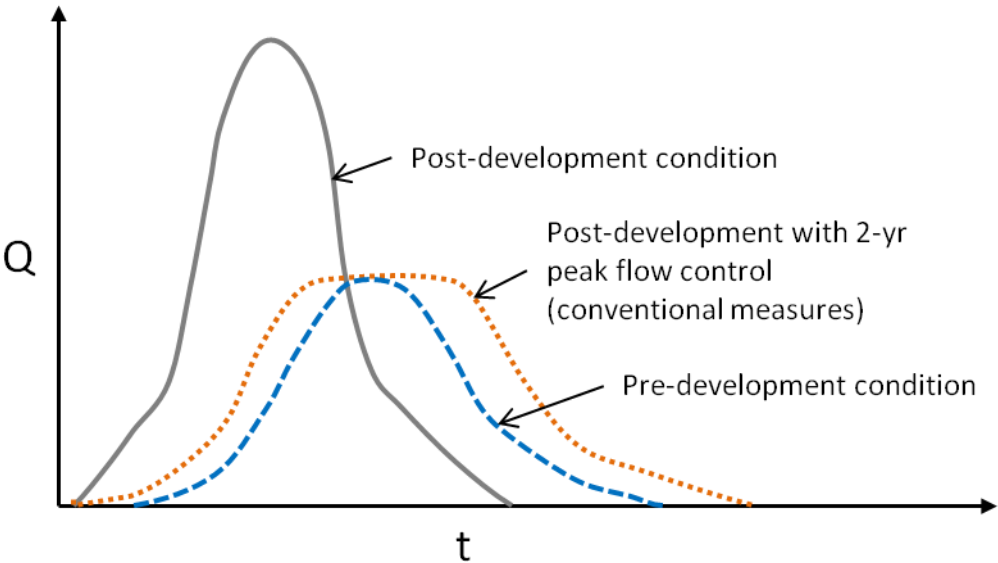


Figure 3 Post-development hydrograph response to conventional control measures

In a catchment designed with 2-yr peak flow control, Bledsoe (2002) found that the duration of flows exceeding the critical shear stress for mobilisation of coarse gravel was over 50% greater than in predevelopment conditions. MacRae (1996, 1993) documented that peak flow control of the 2-yr event causes channel expansion by up to three times the pre-development condition, depending on the sensitivity of the receiving channel (e.g., rock-lined or armoured channels do not show the same response), and that the duration of morphologically significant flows increased by a factor of 4.2 with

increased urbanisation. The increased prevalence of mid-bank flows resulted in elevated sediment yields from bed and bank erosion and channel expansion.

In model results by the US EPA (2004), detention basins designed using large storms (2–100 yr ARI) had virtually no attenuating effect on peak flow for a more typical rainfall event. Approximately 97% of the annual rainfall volume was neglected as the events modelled in the study were much less than the intensity of a 2-yr storm. Although detention basins can be designed to limit peak flow rate levels to predevelopment levels for a range of events, their design objectives nonetheless fail to address the increase in volume of runoff (US EPA, 2004). Two-year flow control may exacerbate channel degradation, as increased volume in post-development runoff results in channel banks exposed to erosive flows for longer durations (Figure 3) and more frequently than in the pre-development state (US EPA, 2004, Brown and Caraco, 2001, MacRae, 1991, MacRae, 1993, MacRae, 1996).

Stricter methodologies have been developed in response to literature demonstrating that peak flow control of 2-yr event is inadequate to control downstream channel impacts. An initial move was to restrict the post-development peak flow rate to 50% of the predevelopment peak for the 2-yr, 24-hr design storm, i.e. “over control” of the 2-yr event (Washington SDE, 2011, Idaho DEQ, 2005). The post-development peak flow rates for the 10-yr and 100-yr 24-hr events are maintained at the pre-development level (Washington SDE, 2011, Idaho DEQ, 2005). Another approach is to control the 2-yr post-development flow rate to the 1-yr pre-development rate (Brown and Caraco, 2001). However, MacRae (1993) indicates that over control of the 2-yr event may either degrade or aggrade the channel depending on the bed and bank material; it is still not fully capable of protecting stream channels from erosion (Brown and Caraco, 2001).

The limitations of this approach may be partly attributed to the observations that channel forming flows are not necessarily associated with a particular return period event (Ward et al., 2008, Shields et al., 2003), and that the duration of flows above a critical magnitude exacerbate sediment transport (Bledsoe, 2002, MacRae, 1993, MacRae, 1996).

### **2.3.2 Distributed runoff control**

The distributed runoff control (DRC) approach was developed as an alternative solution to “over control”. DRC is a method of channel protection that accounts for the geomorphology of downstream channels, which was developed by MacRae (1993) and adopted by the Ontario (Canada) Ministry of the Environment in the Stormwater Management Planning and Design Manual (Brown and Caraco, 2001, Ontario MoE, 2003). The DRC hydrograph attempts to mimic the predevelopment hydrograph for the area above the critical discharge for effective work ( $Q_{CRT}$ ).  $Q_{CRT}$  is also known as the geomorphically significant flow that is capable of moving sediments and bed load. These definitions are reminiscent of the previous discussion on channel forming flows.

The DRC approach adjusts the storage volume for a 2-yr peak flow control pond with considerations of the USA Soil Conservation Service (SCS) hydrologic soil group and soil porosity. Erosive thresholds are established for the downstream channel depending on the composition of both the bed and bank materials. The types and sizing of stormwater devices are then determined and constructed with consideration of the stream thresholds. The DRC approach controls the in-stream channel erosion potential for the range of flows exceeding the critical flow up to the bankfull stage with the highest level of control focused on flows in the mid-bankfull range (Ontario MoE, 2003). The criteria states that channel erosion is minimised if the erosion potential of the channel boundary materials is

maintained at the predevelopment conditions over the range of available flows, and such that the channel is just able to move the dominant particle size of the bed load (Brown and Caraco, 2001). As a result, the magnitude and duration of flows is the same as in the predevelopment condition (Figure 4). The criteria are reminiscent of the ideas behind the Rosgen method for stream restoration to stable stream environments. However, the DRC approach is difficult to apply due to the requirements of complex field assessments and modelling to determine the hydraulic stress and erosion potential of bank materials. Detailed site-specific assessments are required for adequate design.

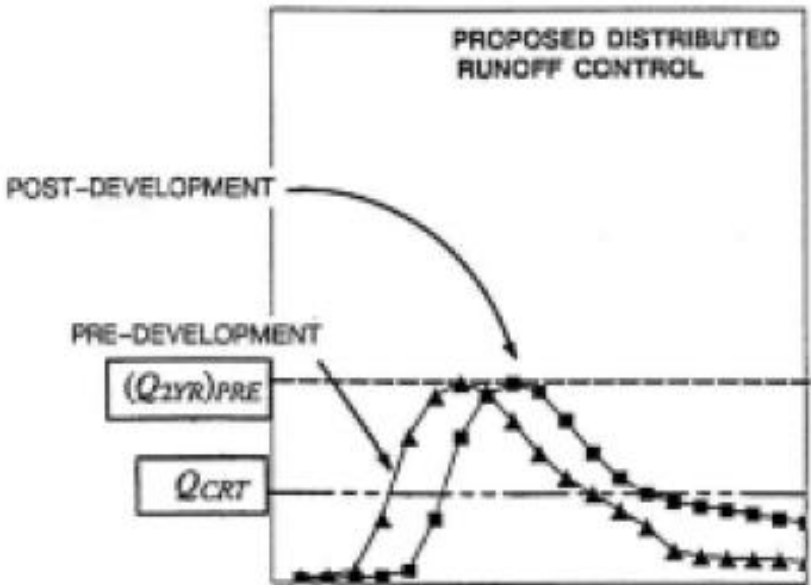


Figure 4 Distributed runoff control vs. predevelopment hydrograph (MacRae and Rowney, 1992)

### 2.3.3 Extended detention

Extended detention is a method intended to reduce the frequency, magnitude and duration of post-development bankfull flow conditions, by detention and release of runoff in a gradual manner thus minimising the exceedance of critical erosive velocities (i.e. critical shear stresses) in the downstream channel. The USA states of Maryland, Georgia, and Vermont<sup>1</sup> adopt requirements of 12–24 hr extended detention of the 1-yr, 24-hr storm event (Atlanta RC, 2001, Maryland DE, 2009, Vermont ANR, 2002), which is similar to the ARC 34.5 mm requirement, noting the smaller storm magnitude compared to Auckland’s requirements. The shorter duration (12-hr) is specified in Vermont where sites discharge to cold water fish habitats. Additional requirements of erosion prevention measures such as energy dissipation, velocity control and stream bank stabilization, and the establishment of riparian stream buffer, are specified in the Georgia manual (Atlanta RC, 2001), although Shields et al.

<sup>1</sup> Online documentation detailing the development of Vermont’s stormwater design standards show strong dependence on Maryland’s approach. While the Maryland manual has more recently been updated, the details channel erosion protection were the same in older documentation (e.g., when Vermont’s manual was written).

(2003) state that bank protection is ineffective if stream bed degradation is occurring. The volume of runoff for extended detention of the 1-yr, 24-hr storm is also known as the channel protection storage volume ( $C_{pv}$ ), which is roughly equivalent to the required volume for peak flow control of 5 to 10-yr storms (Brown and Caraco, 2001, Maryland DE, 2009, Atlanta RC, 2001).

Modelling based on a Maryland site demonstrated that extended detention of 1-yr 24-hour storm significantly reduced the erosive velocities for critical smaller storms and approximated the DRC approach for storms <50 mm in 24 hrs (Brown and Caraco, 2001). The advantage of the extended detention approach over the DRC is that it is relatively easy to apply and it does not require extensive field measurements. Therefore, a stormwater mitigation strategy that incorporates on-site source control to pre-development conditions for the 1-yr, 24-hr ARI storm for volume, peak flow, and timing is likely to provide significant protection from channel erosion downstream.

In contrast Argue et al. (2012) state that extended detention alone is inadequate. Although it accounts for peak flow control, no volume control is demonstrated and durations of selected flow rates are increased thus increasing potential for erosion. There are multiple potential problems with extended detention as a water quality management practice, including the fact that receiving stream dynamics are generally based on balances of much more than just discharge rates (Western Australia DoE, 2009).

The key determinant to successful implementation of an extended detention control measure is definition of the allowable release rate. If the specified release rate, such as the peak flow from the 1-yr, 24-hr ARI event, is greater than the flow velocities responsible for channel erosion then the extended detention device will be inadequate for the prevention of hydromodification.

## **2.4 Use of LID for stormwater mitigation**

The regulatory approaches to stream channel erosion control described in Section 2.3 adopt and rely on minimum control measures that do not fully address the change in pre-development hydrology. Additional problems related to these approaches are water quality, thermal impacts, reduced ground water recharge, and reduced stream base flows.

The US National Research Council noted that conventional stormwater management focuses on flood control to protect life and property from extreme rainfall events but does not adequately address the water quality problems it causes (US NRC, 2008). Conventional approaches focus on strategies for detention and/or diversion of water away from developed areas, ultimately releasing it to local receiving waters.

One important fundamental change in stormwater control measure design philosophy has come about because of the recent understanding of the roles of smaller storms and of impervious surfaces. Conventional end-of-pipe systems ignore smaller, more frequent rainfall events, which cities are becoming challenged to handle due to increased urbanisation. If extreme events are the only design criteria for stormwater control measures, the vast majority of the annual rainfall will go untreated or uncontrolled, as it is smaller than the minimum extreme event (US NRC, 2008).

The emerging goal of stormwater management is to mimic, as much as possible, the hydrological and water quality processes of natural systems as rain travels from the roof to the stream through combined application of a series of practices throughout the entire development site and extending to the stream corridor. The philosophical basis for impact reduction is to avoid exposing receiving waters to impact sources or to otherwise minimise that exposure. The concept embraces both water

quantity and quality impact sources and specifically raises the former category to the same level of scrutiny as traditionally applied to water quality sources (US NRC, 2008). The LID approach to impact reduction, where direct focus is on reducing the loss of aquatic ecosystem function, fundamentally contrasts with the current system (US NRC, 2008). What are primary concerns in the existing system (e.g., discharge concentrations of certain chemical and physical substances) are still important, but more as a means toward realising functional objectives, not as endpoints themselves.

LID approaches aim to keep post-development increases of runoff volumes out of receiving waters entirely, eliminating associated pollutant loads and protecting against separated or combined sewer overflows and hydromodification results such as channel erosion. When rainfall is retained, it can also provide critical recharge and base flow functions.

Hydrograph timing is a clear issue with respect to minimising erosion potential. Peak flow control via detention does not eliminate runoff but simply delays it, while the increased volume of runoff from post-development remains the same and thus duration of erosive flow velocities is lengthened. There is a possibility of creating even greater peak flows when the post-development flows from different tributaries converge in the main stream (US EPA, 2004, Ferguson, 1998). With specific respect to stream erosion, a study in California determined that ephemeral and intermittent streams were highly sensitive to changes in flow associated with increased impervious area, but also demonstrated increased susceptibility to channel enlargement due to extended durations of high flows (Coleman et al., 2005), similar to findings by Bledsoe (2002) and MacRae (1993, 1996). Management recommendations in the California example included limiting effective impervious cover (the extent of impervious cover directly connected to a stream), design to “match” hydrographs for a range of return periods of 1–10 yr rainfall events, and establishing buffer zones and maintaining setbacks to allow for channel movement (Coleman et al., 2005).

A report investigating relationships between urbanisation (namely increase in runoff volume, decrease in runoff lag time, and flashier flow regime) and detrimental impacts to stream ecology identified an eight step process to determine effects of urbanisation on receiving water health (WERF, 2007). The process aimed to assist in the development of urban runoff management rules and design criteria with some assurance that the resulting development will minimise negative impacts on the receiving stream ecology. The protocol focused on minimising change to the hydrologic regime of runoff in the urbanised state from that in the pre-development state. The full hydrologic spectrum of runoff was considered, from small storms that transport most of the pollutant load to the 100-year event. This was done by considering how both the peak-flow frequency curve and the flow-duration curve are modified by urbanisation, and how different runoff control strategies change those two curves compared to the pre-development curves. It was concluded that “full spectrum control” significantly reduces the erosive work that occurs in the stream channels of urbanised watersheds (WERF, 2007). Although not studied explicitly, the report surmises that implementation of stormwater management practices that reduce the overall volume of runoff through infiltration or evapotranspiration will aid movement towards a more natural hydrologic flow regime that will allow for healthier receiving waters (WERF, 2007).

Specific sources of increased channel erosion as described in the current literature review are remarkably similar to the qualitative language proposing using an LID approach for better receiving environment protection. Advocates of LID suggest that the majority of environmental impacts from urban stormwater runoff are the cumulative result of frequently occurring runoff events. Channel erosion literature points to the sources of increased erosion potential (increased peak flow, volume, and duration of elevated flows for bankfull events—often associated with flows from 6-month to 2-yr

ARI); while LID literature points to solutions and management schemes to address all of these problems. Fundamental to the LID scheme is distributing controls throughout the landscape to manage hydrology on-site, before runoff aggrades in a significant point of discharge.

Argue et al. (2012) maintain it is possible to ensure the preservation of environmental values in natural waterways within the scope of current quality oriented LID guidelines. The key requirements are to ensure post development stormwater runoff enters receiving waters in harmony with the receiving waters' channel forming flow (at each point of entry) in terms of frequency (ARI), peak flow, and hydrograph volume. Environmental flows should be as close to those of the original pre-development catchment as possible, and the floodplain should be managed so that intermittent entry of flood waters can occur without threatening life or causing serious damage to property or prolonged interruption to services (Argue et al., 2012).

However, these characteristics are unique to each waterway and within reaches of an individual waterway in terms of conveyance capacity (channel roughness, geometry and bed slope), erodibility, contributing catchment properties (area, land use, runoff characteristics, climate, etc.), and biodiversity. It is impractical to identify all characteristics for all receiving waters in a region, therefore simplification is necessary. Argue et al. (2012) suggest two key stormwater design criterion for preservation of environmental values in receiving waters. The first is to ensure peak flows do not exceed bankfull or channel forming flow rates. Peak flow control is insufficient alone, as conventional detention techniques still result in erosion due to the extended nature of the hydrograph compared to pre-development conditions. Thus, criterion two is preservation of the channel forming hydrograph volume. The design storm hydrograph volume in the developed catchment should be as close to possible to that estimated for catchment pre-development. Phrasing allows for the fact that achieving identical runoff hydrographs for pre- and post-development is very difficult in practice. Argue et al. (2012) recommended focus on correspondence of hydrograph peak flows and acceptance of differences in hydrograph volumes.

#### **2.4.1 International examples of LID regulation with specific design information**

Based on the literature, it is apparent that small, frequently occurring rainfall events dominate catchment hydrologic parameters typically associated with water quality management issues. These small storms are responsible for most annual urban runoff and groundwater recharge. Likewise, with the exception of eroded sediment, they are responsible for most pollutant wash off from urban surfaces. Therefore, the small storms are of most concern for the stormwater management objectives of ground water recharge, water quality resource protection and control of thermal impacts (US EPA, 2004).

Many jurisdictions overseas have been developing regulations with the performance requirement to limit hydromodification, including the volume of stormwater runoff and runoff timing. Terminology is not always consistent, but mitigation objectives are reminiscent of the general LID philosophy. Within the literature, the general concept of LID may be presented as water sensitive urban design (WSUD, commonly used in Australia), sustainable drainage systems (SUDS, commonly used in the UK), green infrastructure, environmental site design, sustainable site design, or better site design (used relatively interchangeably throughout the USA). Regardless of the terminology, the principles reflect a water balance approach to stormwater management with a focus on source control using measures such as top soil amendments, infiltration, evapotranspiration and water harvesting and reuse. The term LID is used herein to reflect the entire suite of nomenclature.



Table 1 identifies the hydrologic basis of design for a variety of international jurisdictions, organised by country. Jurisdictions have been included based upon their promotion of LID technology through relevant regulations and guidance, reflecting a progression in current stormwater management approaches from conventional methods.

In addition to Table 1, the USEPA has published a document summarising the post-construction stormwater standards for all 50 US states and the District of Columbia (US EPA, 2011). Inclusion of every state is outside the scope of this literature review, particularly as the predominant focus has been to identify the regulatory means adopted by states and cities promoting LID, however the reference is included for completeness.

A number of studies not presented in Table 1 do not specifically designate a hydrologic basis of design, but encourage the use of non-structural controls and design strategies such as LID (Argue, 2008, US NRDC, 2011, Alliance of Rouge Communities, 2011, Mahoney, 2009, US EPA, 2010a).

Table 1 Stormwater regulations for a selection of international jurisdictions

Jurisdiction	Reference	Requirement for LID <sup>1</sup>	Groundwater recharge	Water Quality Volume	Channel Protection/ Erosion Control/ CSO prevention
<b>USA</b>					
California	(California EPA, 2009)	Required	<p><u>Volume control option:</u> Control either 85% of 24-hr storm runoff event or the volume required to capture 80% or annual runoff</p> <p><u>Flow control option:</u> 10% of the 50-yr peak flow rate, or runoff produced by a rain event equal to at least two times the 85<sup>th</sup> percentile hourly rainfall intensity, or runoff resulting from a rain event equal to at least 5.1 mm hr<sup>-1</sup> intensity</p>		
California (Santa Monica)	(City of Santa Monica, 2012)	Required for new and redevelopment projects	Manage 19.1 mm onsite through infiltration or treatment and release (~80% of rainfall events annually)		
Georgia	(Atlanta RC, 2001)	Requirement to preserve natural drainage systems and reduce generation of additional runoff	Maintain annual GW recharge rates to the MEP <sup>2</sup>	Treat runoff from the 85 <sup>th</sup> percentile storm (the first 30.5 mm of rainfall from a site)	24-hr extended detention of the 1-yr, 24-hr return frequency rainfall event
Illinois (Aurora)	(Kane County, 2001)	Use of natural drainage systems encouraged	Manage first 19.1 mm rainfall onsite, no direct connection to downstream areas allowed		
Illinois (Chicago)	(City of Chicago, 2012)	Recommended	Manage 12.7 mm runoff onsite or reduce the prior imperviousness of the site by 15%		Maximum allowable release rate is 4.2 L s <sup>-1</sup> or 7.1 L s <sup>-1</sup> dependant on site size
Kansas (Lenexa)	(MARC & APWA, 2008)	Use LID treatment train approach to the MEP	Capture and treat 34.8 mm (equivalent to 90% of the average annual stormwater runoff volume of all 24-hour storms)		
Maryland	(Maryland DE, 2009)	Implement to the MEP	Maintain existing groundwater recharge rates	Catch and treat runoff from 90% of the average annual rainfall (22.9 mm or 25.4 mm dependant on location)	24 hr extended detention of post developed 1-yr, 24-hr storm event
Maryland (Prince George's County)	(Prince George's County DER, 1999)	Recommended	Maintain predevelopment hydrology: design storm is the greater of the rainfall at which direct runoff begins from a catchment of woods in good condition, with a modifying factor of 1.5, or the 1-yr, 24-hr ARI event; $P = \max(P_{\text{wood}}, P_{(1\text{-yr}, 24\text{-hr})})$		
New York (New York)	(New York DEC, 2012)	Required to make "best efforts" to meet goals	Goals are staged: control the stormwater generated by 25.4 mm of precipitation on 1.5% of impervious surfaces citywide in combined areas by 2015 (on 4% of impervious areas by 2020, on 7% of impervious areas by 2025, and on 10% of impervious areas by 2030)		
North Carolina	(Idaho DEQ, 2009)	To minimise impervious surfaces and to treat stormwater runoff using BMPs	<p><u>Sites draining to saltwaters:</u> capture of runoff from the 38.1 mm storm, for "shellfishing" and "outstanding resource" waters the greater of 38.1 mm storm or pre/post difference for the 1-year, 24-hour storm</p> <p><u>Sites draining to freshwaters:</u> capture of runoff from the 25.4 mm storm</p> <p><u>All sites:</u> No increase in peak flow leaving the site from the predevelopment conditions for the 1-year, 24-hour storm</p>		
Oregon (Portland)	(Atlanta RC, 2008)	Required for new and redevelopment projects to the MEP	Infiltrate onsite to the MEP	Capture and treat 80% of the annual average runoff volume	<p><u>Ultimate discharge to a surface water body:</u> detain 2-yr post-development peak to ½ the 2-yr pre-development peak, and 5-yr, 10-yr, and 25-yr post-development peaks to equivalent pre-development rates</p> <p><u>Discharge to a combined sewer:</u> detain the 25-yr post-development peak to the 10-year pre-development peak</p>
Pennsylvania (Philadelphia)	(Philadelphia WD, 2009)	Required, post-development peak runoff rates must match pre-development conditions	The first 25.4 mm of precipitation over directly connected impervious cover must be recharged. (equiv. to 80-90% of runoff on an annual basis) Where recharge is not feasible, remaining volume is subject to an acceptable water quality practice.		The 1-yr, 24-hr storm must be detained and slowly released over 24–72 hrs at a maximum rate of 6.8 L s <sup>-1</sup> per acre
Pennsylvania (Pittsburgh)	(City of Pittsburgh, 2007, City of Pittsburgh, 2010)	Required for new and redevelopment projects to the MEP	Manage the first 25.4 mm of runoff onsite Do not increase the post development runoff volume for all storms ≤ 2 yr 24 hr duration rainfall. Publicly subsidised projects, manage all runoff from ≤95 <sup>th</sup> percentile storm (38.1 mm)		Do not increase peak rate of runoff for 1-, 2-, 10-, 25-, 100-year storms (minimum) pre-development to post-development

Jurisdiction	Reference	Requirement for LID <sup>1</sup>	Groundwater recharge	Water Quality Volume	Channel Protection/ Erosion Control/ CSO prevention
Tennessee (Nashville)	(Nashville and Davidson County MG, 2012)	Recommended, identifies future requirement for use to MEP	Capture and use the first 25.4 mm of rainfall per day (equiv. to 80% of average annual rainfall)		
USA Dept. of Defence	(USA DoD, 2010)	All Dept. of Defence construction must maintain predevelopment hydrology and prevent any net increase in stormwater runoff	Total volume of rainfall from 95 <sup>th</sup> percentile storm is to be managed on site, or the required water quality depth as defined by the State or local requirements, whichever is more stringent. First flush WQV defined by the local regulatory agency, generally taken as the first 25.4 mm of rainfall, in localities with sensitive coastal or reservoir watersheds, may be taken as first 38.1 mm of rainfall		
Vermont	(Vermont ANR, 2002)	Identified as an option	Recharge volume as a multiplier of impervious area (i.e. SCS soil group type A: 10.2 mm x impervious area)	Catch and treat runoff from 90% of the average annual rainfall (22.9 mm)	12-24 hr extended detention of post developed 1-yr, 24-hr storm event
Virginia	(Virginia DCR, 2004)	-	-	Detain the first 12.7 mm rain to fall over impervious surfaces	24 hr extended detention of the 1-yr, 24-hr event
Washington (Seattle)	(Seattle PU, 2009)	Implement to the MEP for new and redevelopment projects	Onsite treatment of the daily runoff volume at or below which 91% of the total runoff volume occurs		Match post-development discharge flow rates and durations to pre-developed forest condition for the pre-developed range from 50% of 2-yr ARI event to the 50-yr ARI. The post-development 25-yr ARI flows $\leq 11.3 \text{ L s}^{-1}$ per acre; and 2-yr ARI flows $\leq 4.2 \text{ L s}^{-1}$ per acre.
Washington (Western)	(Washington SDE, 2011)	Required for new and redevelopment projects	WQ flow rate at or below which 91% of the runoff volume will be treated; the runoff volume must pass through the treatment device at or below the approved hydraulic loading rate for the device		<u>LID performance standard</u> : match developed discharge durations to pre-developed (pre-European) durations for the range of pre-developed discharge rates from 8% of 2-yr flow to 50% of 2-yr flow <u>Flow control standard</u> : match developed discharge durations to pre-developed durations for the range of pre-developed discharge rates from 50% of 2-yr flow up to the full 50-yr flow
Washington, D.C.	(Western Australia DoE, 2009)	Required for new and redevelopment projects	On-site retention of the 90 <sup>th</sup> percentile volume, or 30.5 mm		
Wisconsin (Milwaukee)	(Milwaukee MSD, 2010, Milwaukee MSD, 2012)	Identified in guidance manual for new and redevelopment, recommended in Strategic Objectives	Limit post-development runoff volumes to existing condition runoff during the critical time period <sup>3</sup> ; outflow volume must be maintained in both the 100-yr and 2-yr ARI events. Strategic objective to use LID to capture the first 12.7 mm by 2035		Limit site outflows to a release rate of $14.2 \text{ L s}^{-1}$ per acre for the 100 yr ARI event and $4.2 \text{ L s}^{-1}$ per acre for the 2 yr ARI event
<b>Canada</b>					
Ontario (Toronto)	(Toronto Water, 2006)	On-site control to the MEP to match annual developed runoff volumes to pre-development (current) conditions	On-site retention of 5 mm (equiv. to ~50% of annual average 24-hr rainfall volume) through infiltration, evapotranspiration and rainwater reuse		Control post development peak flows to pre-development levels for all storms up to and including the 100 yr storm Large sites, typically onsite detention of 25 mm with $\geq 24$ hrs release Detain post-development runoff from a 30 mm storm for $\geq 24$ hrs for Tributary "B" of the little Rouge Creek (Rouge River watershed) Detain post-development runoff from a 33 mm storm for $\geq 48$ hrs for the Morningside Tributary (Rouge River watershed)

Jurisdiction	Reference	Requirement for LID <sup>1</sup>	Groundwater recharge	Water Quality Volume	Channel Protection/ Erosion Control/ CSO prevention
<b>United Kingdom</b>					
England	(British DEFRA, 2011)	Required for new and redeveloped sites	Surface runoff discharged to the ground where possible Water not infiltrated must be discharged to a surface water body Next alternative is to stormwater reticulation, followed by combined sewer.	Retain onsite the first 5 mm of any rainfall event	<u>Peak flow rate and volume restricted:</u> Peak flow for the 1 yr and 100 yr ARI events $\leq$ equivalent greenfield runoff rates. Runoff volume < greenfield for the 100 yr, 6-hr event or <u>Peak flow restricted:</u> 1 yr ARI flow rate $\leq$ greenfield runoff rate from the site or $2 \text{ L s}^{-1}\text{ha}^{-1}$ ; 100 yr ARI flow rate $\leq$ greenfield mean annual flood for the site or $2 \text{ L s}^{-1}\text{ha}^{-1}$ <u>Both:</u> 100 yr ARI required storage volume calculated using the critical duration event
<b>Australia</b>					
Lower Hunter and Central Coast Region	(Hunter Central Coast, 2007)	Requires "water smart development"	Site discharge index (SDI) $\leq 0.1$ , SDI takes into account source control measures and gives "effective impervious area" Performance standard for stormwater controls: frequent discharge mitigation, complete mitigation of increased runoff from impervious surfaces for rainfall events with a 3 month ARI.		
Southeast Queensland	(Queensland DIP, 2009)	-	0-40% total impervious: manage onsite the first 10 mm of runoff >40% total impervious: manage onsite the first 15 mm of runoff Storage capacity must be restored within 24 hrs of the runoff event.		Limit post-development 1-yr ARI event peak discharge to the pre-development peak
Western Australia	(Western Australia DoE, 2009, Western Australia DoE, 2004)	To maintain the total water cycle balance within development areas relative to pre development conditions	<u><math>\leq 1</math>-yr ARI events:</u> Retain/detain runoff from impervious surfaces generated by up to 1-yr, 1-hr ARI events on-site. Detention systems should preserve the pre-development critical 1-yr ARI peak flow rate and discharge volume for the catchment. <u>1-yr to 100-yr ARI events:</u> Manage runoff from impervious areas for >1-yr, 1-hr ARI events in landscaped retention/detention areas in road reserves, public open space or linear multiple use corridors. Runoff into waterways and wetlands shall be by overland flow paths across vegetated surfaces.		
Notes:					
1. LID = Low Impact Development, may be called Low Impact Design (also LID), Water Sensitive Urban Design (WSUD), Sustainable Drainage Systems (SuDS), Green Infrastructure (GI), Environmental Site Design (ESD) or sustainable site design in some guidelines					
2. MEP = Maximum Extent Practicable, may be Maximum Extent Feasible (MEF) in some guidelines					
3. Critical time period = also critical duration, the duration of a specific event (i.e.: 100 year event) which creates the largest volume or highest rate of net storm water runoff (Post "Q" less Pre "Q") for typical durations up to and including the 10 day duration event.					

## 2.4.2 Summary

Multiple approaches for stormwater management are evident. The main similarity amongst regulations and/or guidance identified in Table 1 is the acknowledgement that peak flow control as an isolated measure is insufficient to protect receiving waters. Better mitigation against hydromodification and water quality impairment is afforded by comprehensive management strategies, such as LID, that consider multiple hydrologic characteristics: flow rate, volume, duration, and timing.

Where LID strategies are adopted, traditional peak flow control is replaced with, or supplemented by, volume control, generally in the form of a WQV that ultimately acts to address hydromodification by limiting changes in flow rate and flow duration within the receiving waters (Queensland DIP, 2009, Philadelphia WD, 2011). Volume control and specifications for groundwater recharge are utilised to protect aquatic biota, limit impacts on receiving water quality (maintain stream channel stability, reduce runoff pollution, and reduce CSOs), and restore natural site hydrology, so as to promote appropriate aquifer levels, recharge and streamflow characteristics (Hunter Central Coast, 2007, Philadelphia WD, 2011, City of Pittsburgh, 2010). Examples demonstrating general requirements for a water balance approach are:

- “...maintain the total water cycle balance...” (Western Australia DoE, 2004)
- “...infiltrate, evapotranspire, or capture and reuse...” (Nashville and Davidson County MG, 2012)
- “...recharge groundwater, restore natural site hydrology, reduce runoff pollution and CSOs” (Philadelphia WD, 2011)
- “...preserve natural drainage systems...” (Atlanta RC, 2001, MARC & APWA, 2008)

A common trend was the restriction to match post development runoff to predevelopment conditions for one, or any combination of, the following (Table 1):

- Peak runoff rates (most common)
  - While the hydrologic control may be written as peak flow, studies have shown that volume control is essential in order to satisfy the control criterion for peak flow (Hinman, 2009)
- Total volume
- Duration or hydrograph timing

Onsite retention of a WQV, or a water quality design depth, was reflected throughout international regulations (Table 1). The WQV to be retained and treated was defined using a variety of methods:

- Capture and treat a percentile rainfall event (“rainfall capture rule”)
  - Typical range from 80<sup>th</sup>–95<sup>th</sup> percentile
  - One exception was the 50<sup>th</sup> percentile (Toronto Water, 2006)
- Capture and treat a specified depth
  - Typical range from 25.4–38.1 mm
  - Often related to a percentile event (80<sup>th</sup>–95<sup>th</sup> percentile)
- Capture and treat the volume associated with an ARI event
  - For example the 3 month ARI event, or all events  $\leq 2$  yr ARI

The term “water quality” covered a wide range of groundwater and surface water pollutants, including water temperature, and emerging contaminants (US NRC, 2008). The National Research

Council (US NRC, 2008) and US EPA (2010a) suggest reductions in stormwater volume and flow will automatically achieve reductions in pollutant loading; identifying that flow itself is responsible for erosion and sedimentation that adversely impact water quality. However, specific design for water quality treatment is still necessary.

The rainfall capture rule is a currently accepted method, commonly used for defining the water quality capture volume. It is based on the long term spectral frequency analysis of daily rainfall depth and is based on the capture of a certain percentile frequency rainfall event. The rainfall frequency spectrum curve gives the percentage of time that a given rainfall depth is equalled or exceeded. In the spectral analysis, the rainfall events which do not produce runoff are eliminated from the analysis (Shamseldin, 2010). The resultant graph typically shows a sharp curvature (knee or inflection point), normally between the 85<sup>th</sup> and the 90<sup>th</sup> percentile rainfall depth. The inflection point is recognised as the volume that captures a significant number of rainfall events (Figure 2) without attempting to treat the small percentage of much larger events that result in large volumes of runoff (Shamseldin, 2010, Guo and Urbonas, 1996). Such events would be expensive to treat, are rare in occurrence, and typically diluted in pollution concentration. Hence, optimization of the device size is implicitly taken into consideration (Shamseldin, 2010, Guo and Urbonas, 1996). Capturing small and frequent rainfall events, in the range of 85<sup>th</sup>–95<sup>th</sup> percentile events, retains a large proportion of the total annual runoff volume, reducing discharge volume and pollutant loads (US NRDC, 2011).

The District of Columbia (2011) state that retention, or volume control, of all rainfall events  $\leq 95^{\text{th}}$  percentile rainfall event is comparable to maintaining or restoring the pre-development hydrology with respect to the volume, rate, and duration of runoff for most sites. The 95<sup>th</sup> percentile has been selected for the mid-Atlantic region as it appears to reasonably represent the volume that is fully infiltrated in a natural condition and thus should be managed onsite to restore and maintain pre-development hydrology for the duration, rate and volume of stormwater flows. The document recognises that the 95<sup>th</sup> percentile volume is not a “magic” number; there will be variation based on site-specific factors when replicating predevelopment hydrologic conditions. However, this metric represents a good approximation of what is protective of water quality on a catchment-wide scale (Columbia DG, 2011). It can be easily and fairly incorporated into standards, and can be equitably applied on a jurisdictional basis.

Many jurisdictions included requirements for groundwater recharge (Table 1), for example:

- Maintain existing infiltration rates (Maryland DE, 2009)
- Recharge calculated as a multiplier of impervious area (Vermont ANR, 2002)
- Infiltration to the MEP (Atlanta RC, 2008, Atlanta RC, 2001, British DEFRA, 2011)

The recharge volume is typically expressed dependant on the climate and soil type of the region, for runoff from impervious surfaces. It is usually identified as a depth for which very little runoff occurs from grass or forested areas, which is why runoff from impervious surfaces is used as the criterion (US NRC, 2008). Groundwater recharge is a significant inclusion to guidance and regulations as it is one of the key hydrologic functions provided by a natural landscape that is often significantly compromised by urbanisation, and typically unaccounted for in conventional stormwater mitigation measures.

Recognizing site limitations, for example sites with hydrologically “tight” in-situ soils, areas with significant in-fill, or brownfields/redevelopment sites with contaminated soils, and in retrofit situations, capture amounts as small as 10 mm are a distinct improvement. Extending stormwater

requirements to redeveloping property also gradually “levels the playing field” with new developments subject to the requirements (US NRC, 2008).

In addition to volume control and groundwater recharge requirements, many international regulations and guidelines included in Table 1 had detention requirements for the purpose of channel protection, erosion control and/or CSO prevention. Requirements were again varied:

- Extended detention of a particular design storm
  - 12–24 h extended detention of the post developed 1-yr, 24-hr event
- Maximum allowable release rate from the site
  - From 4.2–11.3 L s<sup>-1</sup> per acre
- Match post developed runoff rates to pre-developed rates for specified ARI events
  - i.e. 50% of 2-yr up to 50-yr
- Match post developed runoff durations to pre-developed durations for specified ARI events, or spectrum of events
  - With the aim to increase protection of streams from erosion, the duration standard is seen as harder to meet than the volume standard (Washington SDE, 2011)

In all regulations there are exceptions. Regulations pertained to new development alone; included re-development, either all, or projects above a certain area/ imperviousness/ site disturbance; and/or made allowances for where the receiving water is already degraded. Regardless, the similarity amongst jurisdictions was provision of hydrologic control for frequently occurring, small rainfall events not typically accounted for using traditional stormwater management techniques. The literature concur that in-stream flows should be maintained at pre-development levels for frequently occurring rainfall events (while also controlling total volume and timing of discharge).

### **2.4.3 Variation in interpretation of common terms in guidance documents**

Although there was consistency in the general trends identified in current international stormwater management guidelines promoting LID, minor differences in phrasing and definitions occurred affecting the final stringency of each document.

The definition of “pre-development conditions” varied between jurisdictions. The more stringent definitions encompassed woods, forest, or pasture in good condition while the least stringent referred to the current condition of the site prior to development, even if development was occurring on a brownfield site. The limited scope of this latter definition, development of a brownfield site, does not allow for improvement to an already impaired hydrologic condition.

The parameters of the hydrograph to be matched to pre-development conditions also varied in definition. The US Department of Defence (2010) gave the most stringent definition where pre-development hydrology meant “pre-project hydrologic conditions of temperature, rate, volume, and duration of stormwater flow”. The more lenient definitions referred only to matching peak flow rates post-development to pre-development rates.

Phrasing regarding retention of the WQV gave a variety of definitions. The more stringent requirements were for retention of a particular rainfall depth over the entire site. An alternate option was to capture and treat runoff resulting from a particular rainfall volume, over only the impervious areas of a site.

#### 2.4.4 Drivers behind the move to regulate LID

The majority of the USA LID regulations are driven by combined sewer overflows and changes to National Pollutant Discharge Elimination System (NPDES) municipal separate storm sewer system (MS4) permitting requirements (US EPA, 2010b). In some cases the NPDES MS4 permits are not yet mandated, but jurisdictions strongly recommend the use of LID in preparation for future changes by mandating the use of LID as a first option to mitigate stormwater runoff. Combined sewer overflows are a common driver behind the adoption of LID techniques internationally (New York DEC, 2012, Philadelphia WD, 2009, Atlanta RC, 2008).

Flood mitigation is a driver behind LID implementation in both the UK (British DEFRA, 2011) and the USA (US EPA, 2010a, Nashville and Davidson County MG, 2012). Stormwater devices designed to retain the smaller, more frequent events from surface runoff can also address larger watershed flooding issues.

Three additional drivers are water quality, economic benefit (in comparison to conventional stormwater devices [ponds] and grey infrastructure), and community/quality of life benefit (US EPA, 2010a, US NRDC, 2011, British DEFRA, 2011).

#### 2.4.5 Regulatory recommendations to promote the use of LID

Many conventional end-of-pipe stormwater management practices, and the permit language that drives them, fail to address hydromodification that increases the quantity of stormwater discharges, and cause excessive erosion and stream channel degradation (US EPA, 2010b). The US National Research Council (2008) recommends treating flow as a surrogate for other pollutants and specifically recommends that the volume retention practices of infiltration, evapotranspiration and rainwater harvesting be used as primary stormwater management mechanisms.

The USEPA (2010b) comments that in order for a performance standard requiring predevelopment hydrographs to match post-development hydrographs to be effective, it must clearly identify all hydrograph parameters (volume, rate, duration, and frequency) to be matched. Many current hydrology standards focus only on discharge rate, which is primarily a flood control approach. In addition, a predevelopment condition should also be defined, and that condition should be one that is reasonably 'natural', rather than simply the conditions that existed immediately prior to the current developed site (US EPA, 2010b).

The USEPA (2010b) give example performance standards to reduce stormwater discharges to the MEP. Largely in line with the use of design storms for calculating requirements for stormwater devices, the suggested approach is to include one, or a combination of, the following requirements:

- Minimum storm volume to be retained on site
  - Manage rainfall on-site, and prevent the off-site discharge of the precipitation from [insert guideline, such as "the first 25 mm of rainfall from a 24-hour storm preceded by 48 hours of no measurable rainfall"].
- Minimum storm size to be retained on site
  - Manage rainfall on-site, and prevent the off-site discharge of the precipitation from all rainfall events less than or equal to [insert guideline, such as "the 95<sup>th</sup> percentile rainfall event"].
- Hydrologic analysis



- Preserve the pre-development runoff conditions following construction. The post-construction rate, volume, duration and temperature of discharges must not exceed the pre-development rates and the pre-development hydrograph for 1, 2, 10, 25, 50 and 100 year storms must be replicated through site design and other appropriate practices
- Groundwater recharge requirement
  - Demonstrate through hydrologic and hydraulic analysis that the site and its stormwater management measures maintain 100% of the average annual pre-construction groundwater recharge volume for the site; or
  - Demonstrate through hydrologic and hydraulic analysis that the increase of stormwater discharges volume from pre-construction to post-construction for the two-year storm is infiltrated
- Limiting total impermeable surface (or effective impermeable surface)
  - Minimize total impervious cover resulting from new development and redevelopment to [insert guideline, such as <10% of disturbed land cover and/or limit total amount of effective impervious surface to no more than 5% of the landscape]

Requirements should allow for a combination of canopy interception, soil amendments, infiltration, evapotranspiration, and rainfall harvesting and reuse, rather than relying on one technique, such as infiltration alone, to meet performance guidelines (US EPA, 2010b, US NRC, 2008).

A catchment-wide approach to stormwater management is more effective than purely at a site basis (US NRC, 2008, US NRDC, 2011). Sub-catchment classification allows definition of achievable numerical benchmarks in terms of the MEP, particular to the level of development and associated condition of the receiving waters. The goals for water and habitat quality should become less stringent as impervious cover increases within the catchment. This flexibility recognises the greater difficulty and cost involved in providing the same level of treatment in an intensely developed sub-catchment (US NRC, 2008). An example is listed, based upon condition of the receiving waters and typical associated levels of impervious cover (US NRC, 2008):

- Lightly impacted sub-catchment (1–5% impervious cover, IC)
  - Allow no net increase in runoff volume, velocity and duration up to the 5-yr event
- Impacted sub-catchment (6–25% IC)
  - Manage runoff up to the 2-yr event, achieve 100% runoff retention using LID
- Degraded sub-catchment (≥26% IC)
  - Treat and manage runoff up to the 1-yr event, achieve ≥75% runoff retention using LID

This method should not become an excuse to work less diligently to improve the most degraded waterways—only to recognise that efforts to improve water quality in highly developed catchments are likely less effective overall than efforts in catchments with lower development levels (US NRC, 2008).

## 3.0 Hydrologic mitigation targets for Auckland

### 3.1 Auckland rainfall frequency

As identified in Table 1, retention of a particular percentile rainfall event is a popular method for defining a WQV for stormwater mitigation. This method is referred to as the “rainfall capture rule”. It is recognised as a transparent and defensible WQV estimation methodology which can be universally applied to different climatic and hydrologic regions (Shamseldin, 2010). Shamseldin (2010) recommended the method for estimating WQV in Auckland as it is relatively simple, not data demanding and produces comparable results to other methods.

Shamseldin (2010) generated rainfall frequency spectrum curves for 31 automatic rainfall stations in the Auckland region to investigate whether or not there is a significant spatial variability in WQV estimates across the Auckland region. Figure 5 provides an example of frequency curves using 24-hr rainfall totals from four of the 31 rainfall stations in the Auckland Region.

Shamseldin’s (2010) method for determining the WQV for Auckland is relevant to the current investigation, and the results form the basis for recommendations for LID hydrologic mitigation objectives for Auckland. Historical records were filtered to isolate only 24-hr periods with at least 5 mm of rainfall. A significant assumption was that a total rainfall depth  $\leq 5$  mm does not produce significant runoff. Figure 5 provides the resultant empirical approach to estimate the magnitude of a frequently occurring event based on historical rainfall records around the region. The data cannot be used to estimate 24-hr ARI as non-rain days have been omitted from the analysis. A 24-hr period was selected for analysis, as LID devices such as bioretention cells and pervious paving may require 24-hr emptying time – thus design based on a 24-hr rainfall total would capture/mitigate multiple events in a single day.

Table 1 identified the most common range defining the WQV was 80<sup>th</sup>–95<sup>th</sup> percentile rainfall event. The 90<sup>th</sup> percentile rainfall depth gives a good approximation of the knee/inflection point of the frequency curve for the Auckland Region, and thus could be used as a minimum for the Auckland water quality design storm depth (Figure 5). Figure 6 gives rainfall depth estimates for 80<sup>th</sup>–95<sup>th</sup> percentile events for each of the 31 monitored rainfall stations. The average 90<sup>th</sup> percentile rainfall depth across Auckland region is 31.2 mm.

According to current rainfall-runoff modelling guidelines (ARC, 1999), the 2-yr, 24-hr design storm across the Auckland Region varies from 50 mm south of Drury to 130 mm near Warkworth, with Auckland City, North Shore, Manukau, and Waitakere in the 70–100 mm range. Findings by Shamseldin (2010) show that “frequently occurring events” in the Auckland Region are significantly smaller than the 2-yr, 24-hr event used in conventional stormwater management regulations focusing on flood mitigation. These “frequently occurring”, or 90<sup>th</sup> percentile (31.2 mm), events are even smaller than the 3-mo, 24-hr event, which is in the range of 40–50 mm across the Auckland Isthmus (Shamseldin, 2008).

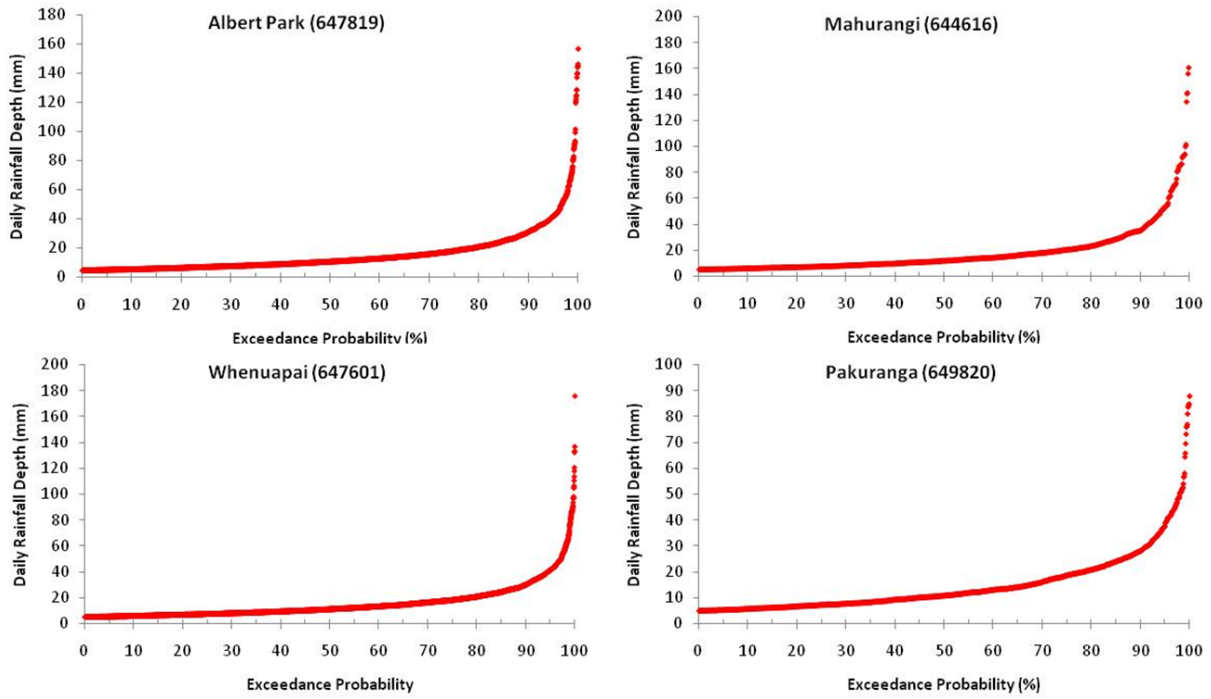


Figure 5 Frequency curves for the daily rainfall depth in the Auckland Region (Shamseldin, 2010)

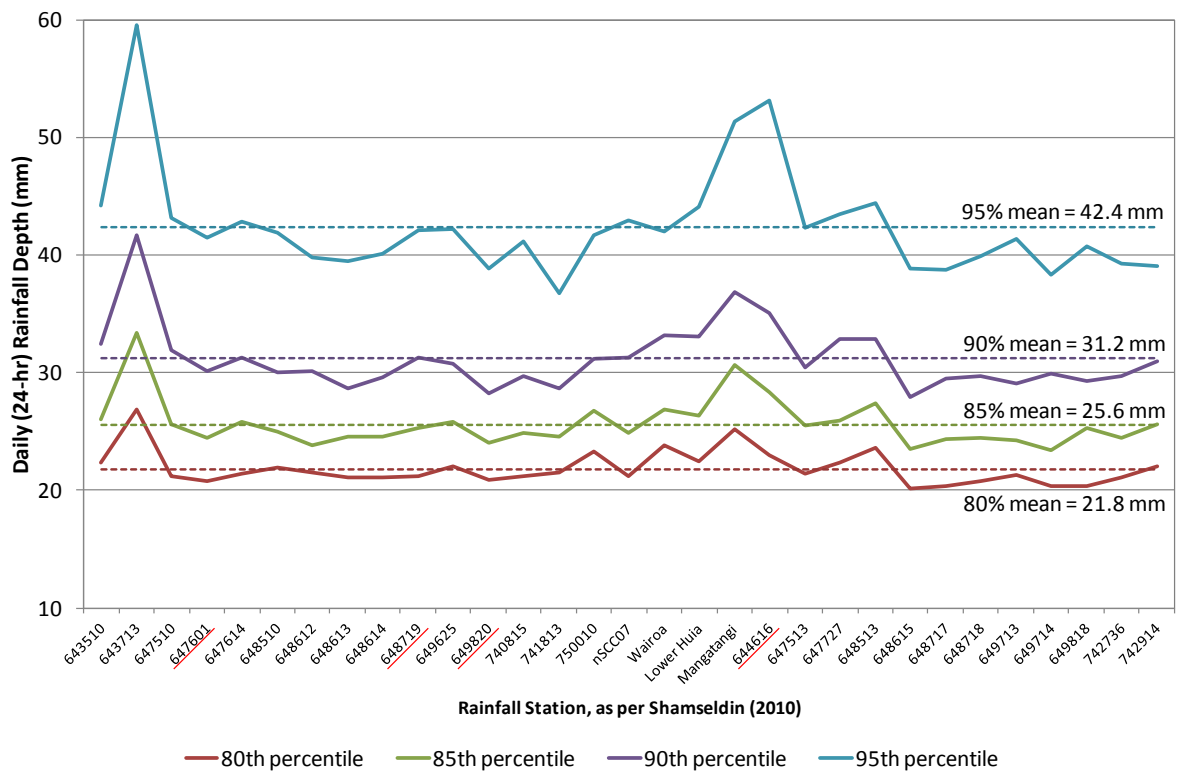


Figure 6 Auckland rainfall event depth estimates for different percentiles, created from data in (Shamseldin, 2010)

## 3.2 Objectives for stormwater mitigation

Traditionally there are three discrete components regulated for stormwater hydrologic mitigation: volume control, peak flow control, and flow release/timing. Progression in stormwater management methods means it is now more common to consider the full hydrologic cycle, taking an overall water balance approach. Based on findings from the literature review, stormwater hydrologic mitigation guidelines for LID device implementation could include all of the following:

1. Rainfall depth to be retained onsite (aligns with “WQV”, Table 1):
  - a. Ideal: manage rainfall on-site, and prevent off-site discharge, from all rainfall events  $\leq 95^{\text{th}}$  percentile rainfall event.
    - i. This would result in more stringent protection against channel forming flows (Figure 2), in addition to water quality mitigation.
    - ii. It would supersede the current Auckland Region extended detention volume of 34.5 mm.
  - b. Minimum: manage rainfall on-site, and prevent off-site discharge, from all rainfall events  $\leq 90^{\text{th}}$  percentile rainfall event.
2. Groundwater recharge requirement (aligns with “Groundwater Recharge”, Table 1):
  - a. Infiltrate onsite to the MEP.
    - i. Where this is not possible, the next option is discharge to a surface water body, followed by reticulation.
  - b. Take into account variation in Auckland’s subsoil, which is not always recognised as suitable for infiltration.
    - i. Amended topsoils and proper preparation of the subgrade for infiltration mean that some infiltration can be achieved even in clayey soils.
3. Hydrologic control (aligns with “Channel Protection/ Erosion Control/ CSO prevention”, Table 1):
  - a. Preserve the pre-development runoff conditions following construction; the post-construction rate, volume, and duration of discharges must not exceed the pre-development levels for all events  $\leq 2$  year ARI event.
    - i. Phrasing may need to consider the fact that achieving identical runoff hydrographs for pre- and post- development is very difficult in practice: “achieved to the MEP” (Argue et al., 2012).
    - ii. Practical implementation may require further research to develop tools such as flow-duration curves using continuous simulation.
  - b. Pre-development must be defined, for example “natural” conditions (i.e. forested) or more lenient (i.e. pasture in good condition).

Requirements could be achieved through a combination of canopy interception, soil amendments, evapotranspiration, infiltration, and/or rainfall harvesting and reuse. Recommendations refer only to the hydrologic basis of design for LID measures; it will be necessary to adhere to appropriate flood mitigation regulations for control of less frequent events such as the 10-yr to 100-yr ARI events

A specified rainfall depth, either as an absolute value or a percentile rainfall event, is recommended for capture and treatment onsite. In keeping with international best practice, the average 90<sup>th</sup> or 95<sup>th</sup> percentile rainfall event across the Auckland region, equivalent to a regional average of 31.2 or 42.2 mm, respectively, is suggested. If a return frequency event is preferred, then as a minimum, the 3-mo, 24-hr ARI event could be targeted for onsite retention, as it is the most frequently occurring of

the frequency-duration charts that will be readily available to practitioners with the publication of GD02 according to the most recent information reviewed herein (Auckland Council, 2013 Draft). It is most comparable to the 95<sup>th</sup> percentile rainfall event for Auckland region.

Extended detention of the 1-yr, 24-hr rainfall event is a common method of control identified in international regulations, and specifically aimed at channel protection (Table 1). Although commonly used, the method is not recommended herein, as it has been identified as inadequate for the prevention of hydromodification due to a lack of volume control within the method (Western Australia DoE, 2009, Argue et al., 2012). With the ultimate goal of preservation, and in some cases restoration, of receiving water ecosystems, a water balance approach aimed at retaining or restoring the predevelopment hydrograph is preferred.

### **3.2.1 Receiving environment variation**

It is important to recognise that different receiving environments may have different targets for stormwater mitigation. Auckland region receiving environments encompass harbours, estuaries, and streams through to both combined and separated reticulation. In addition to aquatic ecosystem concerns such as stream stability and water quality, Auckland has to mitigate the effects of combined sewer overflows.

Guidance for Portland, Oregon (Atlanta RC, 2008) requires a variety of different stormwater mitigation measures dependant on the receiving waters:

- For discharge to a surface water body or separated storm sewer discharging to surface water: detention of the 2-yr post-development peak runoff rate to one-half of the 2-yr pre-development peak rate, and 5-yr, 10-yr, and 25-yr post-development peak runoff rates to equivalent pre-development rates;
- For discharge to a combined sewer: detention of the 25-year post-development peak runoff rate to the 10-year pre-development peak rate;
- Sites discharging into specifically defined rivers (Willamette River, Columbia River, or Columbia Slough) through a private or separated public storm sewer may be exempt from flow control requirements. This exemption is for flow control only; the pollution reduction requirements still apply.

In this example, requirements for discharge to a combined sewer are more stringent than to surface waters. This is an attempt to limit the quantity of stormwater entering the combined sewer system. Stormwater that enters the combined sewer system during low-flow periods is treated at the City's wastewater treatment plants, using costly energy and other resources, and also contributes to overflow events. In all cases, sites are required to infiltrate stormwater onsite to the MEP. Where complete onsite infiltration is not feasible, vegetated onsite retention facilities are required to the MEP. Once the opportunity to use vegetated onsite retention facilities are exhausted, only then is it possible to utilise conventional detention methods.

Recent research investigates the appropriateness of using a single measure such as infiltration as a strict design requirement, and is relevant where this process is physically infeasible or ill-advised. For example, the hydrologically "tight" in-situ soils prevalent throughout Auckland (often clay), areas with significant in-fill, or brownfields/redevelopment sites with contaminated soils challenge feasibility of infiltration. Retention and subsequent evapotranspiration may be achieved through living roofs, but retrofit feasibility depends largely on a building's structural loading capacity, access,

and roof configuration amongst other issues. These challenges do not necessarily mean that an LID approach is infeasible, or that hydrologic mitigation targets of achieving pre-development hydrology are impossible. Emerging research suggests that flow through bioretention can transform the runoff hydrograph into an outflow that mimics pre-development shallow interflow (shallow groundwater flow that recharges streams between storm events) in terms of both flow rate and volume (DeBusk et al., 2011). In other words, infiltration into in-situ soils may not always be strictly necessary to achieve some aspects of pre-development hydrology. While outflow from devices such as bioretention and infiltration practices contributes to achieving mitigation objectives, researchers caution that hydrological processes are complex, particularly in urbanized catchments and significant additional research is necessary (Cizek and Hunt, 2013, DeBusk et al., 2011, Hamel et al., 2013).

Due to the variation in Auckland's receiving environments, recognizing the current international state of the practice, and a clear need for continued research, a staged approach to hydrologic control is suggested:

1. All new development sites will require water quality treatment and on-site retention of the WQV, as defined by (Shamseldin, 2010) (i.e. the 90<sup>th</sup>–95<sup>th</sup> percentile rainfall event) with onsite infiltration of stormwater achieved to the MEP.
2. Where site conditions preclude on-site retention of the full WQV, such as in retrofits, hydrologically "tight" in-situ soils, areas with significant in-fill, or brownfields/redevelopment sites with contaminated soils, water quality treatment and peak flow control to pre-development conditions could be provided to the MEP for the 90<sup>th</sup>–95<sup>th</sup> percentile rainfall event.
3. Sites discharging directly to either the Waitemata or Manukau Harbours, or to open coastal environments, may be exempt from hydrologic control (preservation of the pre-development hydrograph).

Leniency in hydrologic control can be allowed for direct harbour and open coastal discharges as the receiving waters are less susceptible to the effects of hydromodification: stream erosion, sediment and flooding are not predominant concerns.

## 4.0 Design tools for LID systems

Site layout to achieve hydrologic mitigation objectives depends on the types of land uses, arrangement of landscape features, as well as use of engineered devices. Several LID devices, such as bioretention and pervious paving, are usually designed to treat a particular WQV. However, substantial hydrologic control from these devices is realised in the field. Cost-effective design depends on the appropriate selection of device(s) which can be accurately modelled to predict post-development site hydrology.

Preliminary (unpublished) work by UoA shows that modelling of an Albany bioretention cell and the Birkdale Rd. permeable pavement by common theoretical approaches using a stage-storage-discharge relationships does not produce an acceptable calibration to field data. Some overseas design guidance suggests representing catchment runoff controlled by LID devices as “equivalent” land uses by modifying hydrologic model elements such as curve numbers (CN), but often without empirical evidence to support values. Empirical “curve fitting” for bioretention cell hydrologic function for several systems in Maryland, North Carolina, and Pennsylvania, USA shows bioretention cell outflow may be similar to an equivalent land use with  $CN \approx 74-79$  (Traver et al., 2012). For storms with at least 50 mm of rainfall, (Bean et al., 2008) found that permeable pavement discharge could be represented by median  $CN = 45$  based on field monitoring in North Carolina. (Fassman and Blackbourn, 2008) found that a single CN did not adequately mimic permeable pavement discharge in Auckland. Carter and Rasmussen (2006) determined  $CN=86$  for a living roof in Georgia, USA. Using the same calculation method and compiling data from 18 living roof studies including Auckland, literature values from the USA, and unpublished data from several researchers in the USA, an estimated a median  $CN=85$  for full scale living roofs has been suggested (Fassman-Beck and Simcock, 2013). For living roof studies, storms that do not produce outflow cannot be included in the calculation, therefore the CN is not appropriate for the frequently occurring storms (which often do not produce outflow) that are the target of hydrologic control using LID devices. Altogether, traditional CNs are not found to well represent managed flows. Poor model calibration is not surprising; the original method developed by the US DA (1986) was never meant for application in this manner.

The US Environmental Protection Agency’s Storm Water Management Model (SWMM) v 5.0.022 includes a subroutine specifically for LID controls. LID devices are modelled with a surface layer, “soil” layer, and storage layer, whereby flow from one layer to another is simulated via infiltration and storage parameters specified for each layer, flux terms and several mass balances (Rossman, 2010). Research by Hohaia (2011) and Torbati (2010) showed that the model was very sensitive to an empirical outlet coefficient when calibrating it with field data from a pervious pavement and a bioretention cell in Auckland. Continuous simulation using either the Western Washington Hydrologic Model (WWHM) or MGS Flood is required for design in that region of the USA (Kirschbaum, 2012). WWHM is regionally-adapted version of the widely known model, HSPF. It uses stage-storage-discharge relationships in a functional table (known as an FTable) for routing through LID controls. The FTables are theoretically developed, based on the geometry of specific to each site design. MGS Flood uses Modified Puls routing. Some verification has been checked with field data from that region.

Advancing the state of the practice in stormwater management includes introducing better technologies and better design tools for ease of application. Multiple stormwater regulatory authorities overseas and researchers (including the authors) advocate design based on a continuous

simulation (long-term modelling incorporating wet and dry periods), rather than the isolated design storm approach. Argue (2008) indicates that design storm approaches do not deal satisfactorily with retention (volume control) devices essential to LID strategies. Quoting Argue (2008) deficiencies of the design storm approach as presented by IEAust (1999) are:

1. Users of the method are required to make professional judgements relating to the likely state of on-site storage – typically empty or half-full – at the commencement of the design storm, and,
2. Design storm temporal patterns, determined by current analytical procedures are, in fact, “embedded” storm bursts: dimensions of storages determined from these (storm) profiles are therefore likely to be undersized (Rigby et al., 2003).

The literature review in Section 2 also clearly identified that receiving environment effects are not linked to a single design storm event, as channel forming flows are not necessarily associated with a particular return period event (Ward et al., 2008, Shields et al., 2003). Nonetheless, development of tools (calculation procedures) to enable design using a locally calibrated continuous simulation strategy requires significant additional research. In the meantime, new or modified hydrologic mitigation objectives for improved receiving environment protection can be easily implemented within the current design storm approach which is familiar to the design community, in lieu of a “do nothing” scenario.

Design tools are proposed to provide a simple estimate for runoff losses through LID devices that is consistent with the initial loss and constant infiltration (ILCI) method guidance in GD02 (Auckland Council, 2013 Draft). The initial loss represents the filling of surface depressions and topsoil storage volume. The remaining rainfall hyetograph is transformed into runoff using either the Kinematic Wave or Unit Hydrograph approach. Both runoff transformation methods are best suited to the use of computer software, such as HEC-HMS or SWMM. Constant infiltration is a continuing loss over the duration of the runoff hydrograph with relatively strictly defined values depending on land use type. The ILCI is the only method recommended in GD02 for sites requiring stormwater treatment devices; however it applies to surface runoff generation. GD02 does not provide guidance on how to account for hydrologic modification due to flow through stormwater management devices. The methods proposed herein are intended to supplement guidance for LID devices in terms of hydrologic effects only. The devices typically associated with LID include:

- a) Bioretention cells
- b) Living roofs
- c) Pervious paving
- d) Grassed swales

Parameters such as effects on time of concentration or lag time are not currently investigated due to complexity. The calculations herein are intended as suggestions inform the series of device design technical reports currently in preparation by Auckland Council. They are not meant as stand-alone design procedures. Devices such as rain tanks are not included as they are easily modelled using stage-storage-discharge relationships. Rain tanks and stormwater re-use are nonetheless considered potentially significant contributors to managing site hydrology.



## 4.1 Design storm and management objective

The recommendation from Section 0 is to manage rainfall on-site, and prevent off-site discharge, from all rainfall events  $\leq 95^{\text{th}}$  percentile rainfall event. However, the ILCI approach from GD02 requires the use of 24-hr ARI design events. The 3-mo, 24-hr design storm (40-50 mm) is the most frequently occurring (i.e. smallest) design event presented in GD02 and closely approximates the 95<sup>th</sup> percentile event (42.4 mm regional average).

The designer must determine the runoff hydrograph from the proposed post-development conditions for the 95<sup>th</sup> percentile event. Determination of the runoff hydrograph could account for any non-structural measures to minimize runoff, such as impervious area disconnection. The area under the resulting hydrograph is the runoff volume that needs to be retained throughout the drainage area using LID devices.

## 4.2 Runoff Retention: Devices in Permeable Soils that Promote Groundwater Recharge

Where site conditions promote infiltration to surrounding soils (i.e. exfiltration from a stormwater device), stormwater devices such as bioretention, permeable pavement, or grassed swales can provide significant runoff abstraction (retention). The volume of runoff that exfiltrates depends on the amount of runoff captured by the device, and the infiltration capacity of the surrounding soils. Design of stormwater devices for infiltration is addressed in either TP10 (ARC, 2003) or the technical reports that update individual device design procedures.

The amount of runoff exfiltrated to surrounding soils (i.e. retained) for a typical design storm event is given by Eq.1:

$$V_{ret} = \text{minimum} ([I \times d \times A_s]; V_{captured}) \quad \text{Eq. 1}$$

Where:

- $V_{ret}$  = retention storage; in this case, runoff volume exfiltrated to surrounding soils ( $\text{m}^3$ )
- $I$  = surrounding soil infiltration rate (m/time); not the surface infiltration into the LID device
- $d$  = device drain time as per device design procedure, usually 24-hr
- $A_s$  = surface area through which exfiltration occurs ( $\text{m}^2$ )
- $V_{captured}$  = total runoff volume captured by the device for a design storm ( $\text{m}^3$ )

For predicting surface runoff, GD02 limits the infiltration rate for earth-worked sites to  $2 \text{ mm h}^{-1}$ . Infiltration rates on earth-worked sites on good draining soils with an initial infiltration rate  $\geq 50 \text{ mm h}^{-1}$  are limited to  $10 \text{ mm h}^{-1}$  (Auckland Council, 2013 Draft). Tyner et al. (2009), Brown and Hunt (2011), and Wardynski et al. (2012), showed enhanced infiltration potential beneath bioretention or permeable pavement systems if the area beneath the treatment device was prepared by raking, trenching, and boring. These methods are recommended to enhance device performance. On-site/in-situ testing of infiltration rates is strongly encouraged to determine appropriate values for  $I$  in Eq. 1.

## 4.3 Runoff Abstraction: Devices with Limited Exfiltration Potential

### 4.3.1 Devices with internal water storage

Even when devices must be designed with underdrains, or where retention would otherwise be limited, media-based LID devices may yet provide significant runoff abstraction. An internal water storage (IWS) layer within pervious pavement and/or bioretention allows for additional time for stored water to exfiltrate. Brown and Hunt (2011) and Kim et al. (2003) showed enhanced hydrologic performance in bioretention systems using an IWS.

The design of IWS is beyond the scope of this report, but may be found in from the North Carolina Cooperative Extension (Brown et al., 2009) and North Carolina DENR (2012). Where an IWS is present, Eq. 1 is modified as:

$$V_{ret} = \text{minimum} (V_{IWS}; V_{captured}) \quad \text{Eq. 2}$$

Where:

$V_{IWS}$  = volume captured by the internal water storage zone during the design storm event ( $\text{m}^3$ )

### 4.3.2 Living roofs and bioretention

Field capacity is the property of a media which allows it to retain moisture against gravity drainage. It is the “sponge” provided by a media-filled system. Strict definitions of and testing methods to quantify field capacity vary, often according to discipline. Nevertheless, in the context of a stormwater control device, some moisture will not drain by exfiltration or via an underdrain. This captured moisture will only discharge from the device via evapotranspiration (in the case of a vegetated device) or direct evaporation (e.g. from pervious paving), thus providing runoff abstraction or retention.

Research by Davis et al. (2012) combining field data from bioretention cells in the Eastern USA and by Fassman and Simcock (2012) on living roofs in Auckland has shown that there is some minimum threshold of rainfall required before outflow or discharge will be observed from these devices. Empirically, these studies have demonstrated the retention benefit(s) of a stormwater device with good field capacity. Field capacity of a media is influenced by characteristics of the media itself. In the case of engineered media common to bioretention or living roof systems, field capacity may be manipulated by design.

Measurement of field capacity is critical to determining the retention storage capacity of a specific stormwater device. Regardless of specific test method, field capacity is usually expressed as a % moisture content per unit volume of media. The total retention storage capacity of a stormwater device is given by:

$$V_{ret} = FC \times V_{media} \quad \text{Eq. 3}$$

Where:

$V_{ret}$  = retention storage capacity of a non-exfiltrating media-filled stormwater device ( $\text{m}^3$ )

FC = field capacity of media (fraction per unit media volume)

$V_{media}$  = total media volume ( $\text{m}^3$ )

Research in Auckland has determined that FC measured as “plant available water” combined with living roof substrate volume as per Eq. 3 is statistically equivalent to the amount of runoff retained for events that provide rainfall of at least  $V_{ret}$  (Fassman and Simcock, 2012). “Plant available water” should be determined by standard agronomic testing by tension plate apparatus over 10–1500 kPa tension (Gradwell and Birrell, 1979). The test method as applied to living roof substrates is described in Fassman et al. (2010b) while the design procedure is in Fassman-Beck and Simcock (2013). For lack of other studies exploring the precision of laboratory methods to predict field behaviour, it is presumed that the agronomic tests for plant available water combined with media volume would also successfully predict bioretention storage potential as per Eq. 3.

If the media’s FC is known, either a living roof or a bioretention system could potentially be designed to retain a designated minimum volume such as:

$$V_{ret} \geq VR_{95} \times A_s \quad \text{Eq. 4}$$

Where:

$VR_{95}$  = Runoff unit volume generated for the 95<sup>th</sup> percentile design storm event (m/m)  
 $A_s$  = surface area of LID system (m<sup>2</sup>)

It is noted that there is a likely maximum applicable threshold of rainfall or runoff for which these relationships hold or are useful. For example, empirical evidence suggests that the maximum event retention measured in 18 living roof studies is approximately 30 mm (Fassman-Beck and Simcock, 2013). Furthermore, it is unlikely to be cost effective to design a living roof to fully retain a 2-yr, 24-hr ARI or larger event as the added structural burden and media costs would outweigh the control of such an infrequently occurring event. The living roof would nonetheless provide meaningful peak flow mitigation and partial retention for these larger events, thereby reducing the size of devices at or below ground level. Empirical analysis of maximum event retention by an underdrained bioretention cell has not been easily identified, but is suggested for further investigation.

### 4.3.3 Pervious paving

Pervious paving may be designed to treat only the water falling directly on it, or it may be designed to also manage run-on from surrounding areas. Lack of capillary forces in the large mineral aggregate that comprises pervious paving’s basecourse (where the majority of runoff is stored during an event) means that FC is likely insignificant. Some runoff losses will occur via wetting and drying of the pavement. Monitoring of pervious pavement installed over clayey soils in Auckland showed that rainfalls less than 7 mm produced insignificant flows. Volumetric runoff coefficients (Table 2) demonstrate that runoff was significantly less than the from an adjacent asphalt catchment monitored concurrently.

Table 2 shows that 49% of rainfall was retained by the Birkdale Rd. permeable pavement system (with underdrains) for at least 50% of the monitored events. A conservative estimate for runoff retention by a permeable pavement with underdrains is suggested by Eq. 5:

$$V_{ret} \leq 0.4P_{95} \times A_{pp} \quad \text{Eq. 5}$$

Where:

$P_{95}$  = unit rainfall from the 95<sup>th</sup> percentile design storm event (m<sup>3</sup>/m<sup>2</sup>).  
 $A_{pp}$  = surface area of permeable pavement (m<sup>2</sup>)

Eq. 5 should not need modification if the permeable pavement system is designed to treat additional source area, as the equation depends only on the permeable pavement surface area.

Table 2 Volumetric runoff coefficients measured at Birkdale Rd. (Auckland) Permeable Pavement Trial (Fassman and Blackburn, 2010).

Percentile*	Asphalt	Permeable Pavement Underdrain
0.10	0.48	0.29
0.25	0.60	0.43
0.50	0.85	0.49
0.75	0.94	0.57
0.90	0.98	0.63
St. Deviation	0.20	0.15

\* Percentiles are with regard to flows measured during field monitoring; they do not specifically correspond to the same rainfall percentiles.

#### 4.3.4 Grassed swales

Grassed swales are predominantly a water conveyance method that also provide water quality enhancement and some flow mitigation. It is not recommended to use the same modelling method as for “capture and treat/mitigate” methods such as living roofs, bioretention, or pervious paving. The other LID systems modelled rely on predominantly vertical migration of water through a highly pervious media or substrate after which water exits the system via gutters, underdrains, or infiltration directly to the sub-soil. An enhanced swale, or bio-swale, can be modelled using the same method as bioretention due to the similarities in design.

Stormwater conveyance through grassed swales is better suited to computer modelling. Liao (2009) investigated multiple means of modelling swales’ hydrology, based on field monitoring of two simple grassed swales in Albany, Auckland. Those results provide the basis for initial recommendations in Table 3, which can be implemented in HEC-HMS. Further research into swale modelling procedures is also recommended, namely by expanding the number of sites considered.

Table 3 Swale Modelling: Initial Recommendations

Model Component	Method	Calibrated Value	Other Notes
Loss	SCS Curve Number	64-70	Green and Ampt infiltration model was not successfully calibrated
Initial Loss		11-16 mm	
Roughness		0.4-0.6	
Overland Flow	Kinematic wave in 2 planes		Separate pervious and impervious areas. Unit hydrograph method resulted in poor calibration.
Channel Flow	Kinematic wave		Applies to flow through swale. Did not calibrate as well using hydraulic routing such as Muskingum Cunge method.

#### **4.4 Role of non-structural methods for hydrological control in an LID site**

An LID site integrates both structural and non-structural methods for preventing runoff generation (source controls), extending flow paths (using swales rather than pipes), and providing multiple opportunities for interception and infiltration (impervious area disconnection).

Non-structural stormwater control measures such as alternative building materials, better site design, downspout disconnection, conservation of natural areas, and watershed and land-use planning can dramatically reduce the volume of runoff and pollutant load from a new development.

Non-structural stormwater control measures should be considered first before structural practices (US NRC, 2008). Increasingly, regulations encourage, or give credit for, the use of non-structural practices such as natural area conservation, disconnection of rooftop runoff, and use of open channels in preference to structural LID methods, such as infiltration devices and rainwater harvesting (Maryland DE, 2009, Nashville and Davidson County MG, 2012, Philadelphia WD, 2011). However, LID methodologies, whether structural or non-structural are recommended in preference of conventional, end-of-pipe stormwater management techniques.

## 5.0 Conclusions

In order to improve the level of receiving water protection in the Auckland region, the Auckland Council promotes the implementation of LID to manage stormwater runoff from developed or redeveloped sites. One of the main technical objectives of an LID approach can be summarized as mimicking the pre-development runoff hydrograph, including flow rates, total runoff volumes, and runoff timing.

The current report attempts to provide a historical perspective on the evolution of stormwater management guidelines as they pertain to controlling, mitigating, or reducing the effects of post-development conditions on the runoff hydrograph, and thus receiving water impacts. Auckland's current guidelines for stormwater control address or are consistent with many of the internationally recognized paradigms. However, newer research and international policies suggest expansion of historic hydrologic mitigation objectives in Auckland is warranted. In order to better align with international approaches to maintain pre-development hydrology, the main suggestion is to consider on-site retention (volume control) of up to the 90<sup>th</sup>-95<sup>th</sup> percentile design storm event. This control should be implemented *in addition to* conventional hydrologic mitigation goals of peak flow controls for 2yr, 24-hr ARI and larger events and should also account for site-specific conditions such as in-situ soils and coastal receiving environments.

In order to operationalize design for on-site retention and at the site- or catchment scale, initial suggestions are made for living roof, bioretention, grassed swale, and permeable pavement design. As Auckland Council develops technical reports for device-specific design, it is presumed that additional research or information may supersede the calculations suggested herein.

This study has been limited to a desktop study with existing information and to developing recommendations that can be implemented within the existing stormwater design approach used in Auckland. It is clear that additional research would further benefit understanding of the influences of development on Auckland's specific receiving environments, and the influences of site constraints on LID implementation. Techniques for modelling the effects of devices on runoff hydrology require significant attention. While the use of design storms seems to prevail amongst international jurisdictional policies, the academic research summarized in Section 2 clearly indicates that a range of conditions should be considered when designing for comprehensive stormwater management. This type of design might best be addressed through continuous simulation.

Finally, the solutions considered herein are focussed on device design as elements LID. This is not intended to suggest that stormwater devices should be considered a panacea. LID relies on a combination of structural devices, source controls, and very importantly, land-use planning for a holistic approach to minimizing the effects of development on receiving environments.

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## Appendix A Discussion papers

# Stream Erosion Discussion Paper

Earl Shaver

2008

## History

The ARC has had a stormwater consents programme for approximately 15 years. That programme has evolved over time from a water quantity only programme to a water quantity/quality programme and more recently to consideration of stream channel erosion as a programme element.

To support expansion of the programme into stream channel erosion criteria there was first recognition that urban stream physical structure becomes adversely impacted due to increased imperviousness and increasing urban land use. Once the impacts were recognised the next step was to investigate how to address the issue.

There were several pieces of work that have formed the basis for the ARC approach to stream channel erosion. These documents are listed in chronological order from first to most recent.

### McCuen report

Stream channel erosion work was done in the latter part of the 1980's by the State of Maryland (McCuen, 1987). That investigation was one of the first documents to consider stormwater policies related to stream channel erosion. From an Auckland context the major problem with the work was that it was done for non-cohesive soils as opposed to the Auckland situation where cohesive soils dominate. Another weakness was that the document was primarily a desktop study of erosion issues using existing literature to define policy. This document provided initial guidance relating extended detention to reduction in storm flows to reduce stream erosion potential.

### Beca Carter Hollings & Ferner Ltd. Report

Using the McCuen report as a basis, the ARC had Beca Carter Hollings & Ferner Ltd. (2001) do a desktop study considering stable streams versus unstable ones. The results of this study recommended that for stable streams post-development peak flows should not exceed pre-development peak flows. This recommendation requires a stringent analysis relating bankfull flow to shear stress. If the stream has fringing of banks, landslides, bank collapse or streambed undermining then the stream is not considered stable. In the Auckland Region, almost all streams would not be considered as stable.

For unstable streams, the interim recommendation was for detention ponds to be designed for the discharges from a 2-year 24-hour storm from post-development conditions, such that no more than 30 mm of runoff occurs over the 24-hour period, or that the maximum peak outflow is 7.5 l/s per hectare of the site.



## Current policy

The 2001 Beca study was evaluated and slightly modified for greater consistency by establishing a design approach which aims to store and release the first 34.5 mm of rainfall over a 24-hour period.

By going to a policy based on rainfall rather than runoff, the policy accounts for differences in landuse generating different levels of runoff. As a result, the policy does not over-control activities that have lower levels of impervious surfaces.

That policy was incorporated into a stormwater design manual (ARC, 2003) and has been in effect from 2003 to the present time.

## More recent investigations

Recognising that the current policy is based on desktop studies, it was important to conduct physical monitoring to either verify or modify the existing criteria. From that premise, it was decided to conduct a physically based local study

Initially it was thought that one study would provide the guidance needed but the study results raised more questions than answers. Thus there has been more follow on work than expected.

### NIWA (Elliott, et.al., 2005) Report

Recognising that the existing criteria was based on desktop modelling, the ARC wanted to conduct physical studies to either verify the desktop approaches or modify the approach based on physical evidence. As a result, the ARC hired NIWA to conduct field investigations related to stream erodibility.

The aim of the study was to improve the scientific basis for flow controls for erosion in urban streams in Auckland. It included measurements of the erodibility of bed and bank materials, hydraulic measurements and modelling to derive relations between the flow rate in streams and the erosion rate. 112 cross-sections were analysed in an attempt to identify representative stream shapes and dimensions.

The erodibility values varied considerably between locations at a specific site, and between sites. They were not able to resolve this variability. There were some weak indications that erodibility could decrease with increasing clay content but more tests were needed. They proposed a general form for the erosion-velocity relationship to use in the absence of more specific information for a given site.

They recommended that further investigations would be useful and listed a number of items including:

- Erodibility testing to resolve some of the variability,
- Investigations for generalising the erosion-flow curves,
- Taking more velocity measurements at high flows,
- Investigating the suitability of even simpler hydraulic models as a basis for sizing flow-control measures,
- Investigating how erodibility varies with depth into the sediment,
- Investigating additional bank failure mechanisms, and

- Measuring erosion rates in an erosion-prone study reach.

As can be seen, they were recommending a lot of additional work to improve results.

### **Jowett, Elliott (2006) Report**

This study was initiated by the ARC to see if the prior NIWA study could have further information extracted from it without spending millions of dollars and multiple years to further refine the erosion control approach. This study involved a closer evaluation of the prior study results.

This study recommended that an erosion equation for cohesive Auckland streams follow that most commonly used in modelling studies  $E = M_3(\tau - \tau_c)$ . The critical shear stress ( $\tau_c$ ) and erosion rate coefficient ( $M_3$ ) varied considerably between Auckland streams and the authors recommended that additional site specific studies could be carried out to determine relationships between soil properties, as determined by relatively simple jet tests, channel morphology, bank vegetation, and total shear stress at the channel forming (bankfull) discharge. As specific parameters were not developed for individual streams, it was suggested to use the median critical shear stress (c. 33 N/m<sup>2</sup>) and a value of 0.005-0.01 kg/m<sup>2</sup>/s for the coefficient  $M_3$ .

### **Beca Infrastructure (2008) Report**

Beca Infrastructure was commissioned by the ARC to review the NIWA material and make recommendations regarding any changes to the current ARC policy relating to stream erosion.

The results of their analysis were that they could find no justification for recommending changes to the existing guidelines. This was not a vindication of the existing approach but rather an inability to come up with anything better.

They found that despite the significant amount of work that had gone into the development of a regional erosion equation, the complex and variable nature of cohesive sediment transport means the results from the studies were not conclusive. In summary, their conclusions were the following:

- There is benefit to attenuating the two-year storm event, although no testing has been done on the benefits during larger storm events,
- In catchments with high imperviousness greater attenuation than maintaining the pre-development flow rate is needed, and
- Erosion mitigation can be provided with appropriate robust flood attenuation and some extended detention though the need not be as much as 34.5 mm.

### **ARC efforts to refine current policy**

As can be seen, the ARC has put considerable resources into consideration of the stream erosion issue as a component of urban stormwater management. With that said, the additional efforts have done little to provide justification or modification of the existing requirement.

Without good technical support there is no reason to change the existing requirement as it is generally accepted by the consulting and development community. Changes

to that requirement, even if it were relaxed, would come under considerably more scrutiny than the original criteria went through.

## **Where to from here**

A key question relates to whether the approach to finding answers to whether ARC criteria for stream channel erosion control has been correct. Have we been asking the right questions?

The intent all along was to attempt to develop regional criteria that everyone could use to manage their site or subdivision runoff and minimise downstream erosion potential. There are approximately 200 projects per year that require ARC consents. It was considered important that the criteria be simple, easy to understand, affordable, easy to implement and effective at erosion minimisation. Maybe we were trying to make a complex analysis too simple.

It would be good to take a step backward and ask the following questions:

1. Should we be content that what we have minimises stream channel erosion to the extent that can be achieved in a regional based criteria
2. Were we trying to over-simplify a complicated issue
3. Were we correct in how we tried to investigate the issue
4. What steps would be necessary to progress our understanding of the issue further than what it is
5. Is it worth progressing the issue further or is the subject one for which regional criteria may not be the most effective approach

We don't know if we have lost our way a little bit and are concerned that we are no closer after the most recent studies to having a greater comfort level in our criteria or even our approach to gaining a greater understanding.

Any recommendations to provide further direction would be most appreciated.

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October 17, 2008

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Hydraulics  
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Sedimentation  
Water Quality  
Erosion Control  
Environmental Services

Subject: Stream Erosion Guidelines – ARC and Western USA

Dear Mr. Davis,

At your request I have performed a rapid review of stream erosion guidelines in the Auckland Region, New Zealand (NZ) based on material supplied by you and others in your group. I have also prepared a summary of current practice along the western coastal states in the United States of America (US). This letter report contains not only these two items, but also my opinions as to how the former (NZ) compare to the latter (US) guidelines and recommendations for future work in this subject matter.

#### New Zealand

The Auckland Regional Council (ARC) provides erosion control design criteria in Technical Publication No. 10 (ARC, 2003). The current standard is *rainfall* based, and specifies that runoff from a 34.5 mm rainfall event must be stored and released over a 24 hour period in order to minimize potential stream erosion. This leads to the conclusion that land uses with a greater percentage of pervious areas will require less mitigation (probably with a smaller footprint) as more of the rainfall will be lost to infiltration and less converted to runoff.

An excellent summary of the history, recent investigations, and current ARC policies by Shaver (2008) was provided to this reviewer. In addition to outlining how ARC arrived at its current policy, Shaver poses some seminal “big picture” questions. The five questions basically boil down to “should we be content with what we have or can we do better?” recognizing that this is a complex issue that must be simplified enough to be applied as an effective design approach.

One of the complicating factors, as described by Shaver and investigated by the National Institute of Water and Atmospheric Research, Ltd. (NIWA; 2005, 2006) is that streams in the Auckland area are predominantly within cohesive sediments. There is always a great amount of uncertainty in sedimentation and erosion studies for non-cohesive sediments (sands and gravels); dealing with cohesive sediments adds another layer of uncertainty altogether.

## United States

### *Background*

Changes in the magnitude, relative proportions, and timing of sediment and water delivery due to land use changes (urbanization and agricultural), leading to channel adjustments and increased flood frequencies, were documented as early as 1966 (Leopold, 1968). In general, the effects of urbanization on perennial streams in humid regions have received much more attention than impacts to arid systems (such as found in the southwestern U.S.). Early efforts to reduce the effects of hydrograph modification (also called “hydromodification”) from proposed land use changes (most usually urban development) were in the eastern U.S. and Ontario, Canada. In the western U.S., the first regulatory response to hydromodification was in western Washington State, beginning with the Puget Sound Stormwater Management Manual in 1992 and evolving into the Western Washington Stormwater Manual (Washington Department of Ecology, 1992, 2001). More recently in California, State Regional Water Quality Control Boards (the state regulatory agencies that issue stormwater permits to municipalities and counties) have been requiring development of hydromodification management plans (HMP’s) in order to meet the goals of the Federal National Pollutant Discharge Elimination System (NPDES). Efforts in California are either in place or underway in Alameda, Contra Costa, and Santa Clara Counties in Northern California, and Los Angeles, San Diego, Riverside and San Bernardino Counties in Southern California.

### *HMP Goals*

The first California Bay Area (Northern California) permit to include the new requirements was in October 2001, which amended Provision C.3. of the Santa Clara Valley Urban Runoff Pollution Prevention Program’s reissued NPDES permit. Provision C.3. contains requirements to address impacts of new and redevelopment projects on beneficial uses of streams resulting from both pollutants in stormwater runoff and erosion caused by changes in the amount and timing of stormwater runoff. Under Provision C.3.f. – *Limitation on Increase of Peak Stormwater Runoff Discharge Rates*, new and redevelopment projects above certain impervious surface thresholds must include measures to address changes in runoff due to increases in impervious surfaces created by the project and to control runoff in a manner to protect streambeds and banks from erosion. The permit provision specifically requires the development of a HMP which would prioritize stream segments, establish in-stream and runoff criteria, and provide guidance on management measures, which could include a combination of onsite, in-stream, and regional control strategies. The Regional Board prescribed the following:

Post-project runoff shall not exceed estimated pre-project rates and/or durations, where the increased stormwater discharge rates and/or durations will result in increased potential for erosion or other adverse impacts to beneficial uses, attributable to changes in the amount and timing of runoff (Provision C.3.f.i).

HMP goals from other regional boards, incorporated into local ordinances by counties and/or municipalities, are along the same lines. Attached are excerpts from the San Diego Stormwater Manual (see G.3.1.) and the new San Diego County Ordinance No. 9926 (Section 67.812(b)) that state HMP goals for San Diego County (San Diego County, 1993, 2008).

### *Methodology*

In contrast to the ARC focus on controlling a volume of runoff, the methodology followed along the US west coast has focused on controlling a range of discharges judged to do the most work in channel processes. The general approach that was developed in western Washington and is also being used in other west coast areas is to perform continuous hydrologic simulation. Modeling is performed to simulate flow characteristics over a “significantly long enough time” to evaluate the effects of both proposed land use changes and mitigation measures (if necessary). Hydrologic models are prepared that reflect existing and proposed land uses, soil types, vegetation, etc. and simulations are made for at least three cases: 1) existing conditions, 2) post project conditions without mitigation, and 3) post project conditions with mitigation measures in place. The goal of the modeling exercise is to minimize changes in flow frequency and duration to below the regulatory levels. While not discussed in this letter, a number of flow mitigation devices and methods such as detention and low impact development (LID) practices are available to the designer. The general focus of the regulations has been on the range of flows with a recurrence interval between 2 and 10 years (here denoted Q2 and Q10). Focus on this range of discharges is based on many geomorphic and sedimentation studies that show that the majority of work performed by flow on a channel occurs in this range. Thus flow modification to acceptable levels is used as a surrogate for minimizing channel modification.

Plans that have been adopted in the San Francisco Bay Area (Contra Costa, Santa Clara, Alameda) and approaches under consideration in other areas of California (Sacramento, Los Angeles) vary as to the emphasis placed on flow control versus other approaches. However, there is a general consensus that both the frequency and duration of flows must be controlled, necessitating continuous simulation hydrologic modeling for evaluating potential impacts of development (as opposed to design storm methods typically used in flood control analysis). It is also generally accepted that events smaller than Q10 are the most critical for hydrograph modification management. It should be noted the HMP methods developed are intended to be easily implemented for development review. In most areas the option is left open to perform detailed geomorphic/ engineering study in lieu of using the simplified methods.

There are, however, a number of problems and concerns with implementation of the continuous hydrologic simulation methodology described above. At the beginning of the process, obtaining enough quality rainfall data for input to a hydrologic model is often problematic. Generally, rainfall is needed at intervals not greater than one hour, and over a period of record of 30 years or more. Where rainfall data is lacking, researchers have resorted to interpolation methods, synthetic methods to fill data gaps, and synthetic gage records often incorporating multiple gages. Another issue relates to the appropriate model to use, and its availability and ease of use for the development community or their engineers. In the case of western Washington and San Francisco Bay Area counties, a simplified new model was developed that could be used easily and inexpensively by developers. Work was performed by a consultant using the HSPF

hydrologic model to prepare the appropriate input parameters and menu choices for the simplified model.

There is also a question about the appropriate lower end of the flow range to use for hydromodification regulation. The Santa Clara HMP focused on the use of detention basins for hydrograph modification management and therefore strongly emphasized the lower flow control limit for site runoff. This HMP defined the lower flow control limit as the flow rate ( $Q_c$ , expressed as a percentage of  $Q_2$ ) that generates the critical shear stress on a channel; that is, the minimum flow that could initiate erosion in the channel bed and banks. The Santa Clara HMP estimated  $Q_c$  to be  $0.1Q_2$ , based on an estimate of bed and bank material shear resistance at selected cross sections in two creeks. As a result of that study, both the Santa Clara and Alameda HMP's adopted  $0.1Q_2$  as the lower limit for flow control regulation. However, this lower limit was based on a very small, and perhaps not representative, sample and needs to be evaluated further. Some work in that area is currently being performed in San Diego County and elsewhere in Southern California (e.g., SCCWRP, 2005, 2008).

A third limitation of the methodology, especially pertinent to the ARC, is that this methodology was largely developed for streams with non-cohesive sediments.

Other open questions, not necessarily tied to this particular method, include the appropriate areal limits for application of the regulations, the distance downstream from the project that one should track hydromodification impacts, the percent of impervious area in a catchment at which channels begin to degrade, and the effectiveness of watershed and stream channel controls.

#### Comparison – key points

The biggest difference between the ARC and western US approaches is that the former uses a rainfall volume (applied to, not runoff from, a catchment) approach while the latter uses a flow approach. Both of these approaches, however, sidestep direct computation of critical shear stress in a receiving stream, instead using the indicated volume or flows as surrogates.

Because neither method uses critical shear stress directly, whether the channel is formed in cohesive or non-cohesive material does not enter into either.

#### Recommendations

Based on my opinions and professional experience I offer the following recommendations:

1. Regardless of method chosen, there should be some accepted level of dynamism in receiving streams, or at least certain reaches of the same. The goal should be prevention of “unraveling” of streams, but not removing natural sedimentation processes.
2. NIWA has evaluated several sites for values of critical shear stress that can be used in classical cohesive erosion equations, and also investigated erosion versus discharge relations, as described in their reports. However, has anyone investigated how the current standard 35.4 mm rainfall volume, applied to watersheds with “typical” loss rates for the Auckland area (based on



soils, land use, etc.) is converted to runoff and translated to effective shear stresses on the channel? Perhaps this hydrologic analysis has already been accomplished. I believe that, combined with the NIWA work, this could shed light on if the current rainfall volume standard is a reasonable indicator of erosive shear stresses.

3. I commend ARC for the studies that it has funded and recommend that the organization continue to explore methods and methodology to effectively regulate effects from development. Mitigating hydromodification effects in order to prevent unwanted changes to environment and habitat is a challenge and an active research area around the world. I do not recommend changing the current standards based on current knowledge; however, I think that combining hydrologic tests with the NIWA results may shed light on how the current rainfall standard relates to effective shear stress in the channel (recommendation #2).

I earnestly hope that this work fulfills your needs at this time. Please do not hesitate to contact me if you have any questions.

Sincerely,

A handwritten signature in cursive script that reads "Martin J. Teal". The signature is written in black ink and is positioned below the "Sincerely," text.

Martin J. Teal, P.E., P.H., D.WRE  
Vice President

Attachments:

References

Excerpt from San Diego County Stormwater Manual

Excerpt from San Diego County Permit 9926

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***COUNTY OF SAN DIEGO***  
**STORMWATER STANDARDS MANUAL**



**Appendix A to the Watershed Protection,  
Stormwater Management and Discharge Control Ordinance**

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An Excerpt From The San Diego County Code Of Regulatory Ordinances

(Amended by Ordinance No. 9589 (N.S.), adopted 8/5/03)  
(Amended by Ordinance No. 9518 (N.S.), adopted 1/10/03)  
(Ordinance No. 9426 (N.S.), adopted 2/1/02)

- G.2.1.2: Permit applications shall include details and drawings of the BMPs proposed to be implemented, and any other storm water-related forms designated by the issuing Department.
- G.2.1.3: Permit applicant shall certify that the BMPs proposed to support the permit application will be installed, monitored, maintained or revised as appropriate to ensure continued effectiveness.

## **G.2.2 Construction-Phase Requirements**

During construction, all development projects must comply with the state General Stormwater Permit for Construction Activities, if applicable; with the conditions imposed in permits required for construction; and with County ordinances and sections for construction activities.

## **G.2.3 Additional Requirements in Permits; Role of Guidance**

- G.2.3.1: Urban land development activities that require a discretionary County permit are subject to the applicable requirements in the Ordinance and this manual, and to any additional requirements imposed in County permits or Orders. Those additional requirements may implement the Ordinance or other County ordinances, or may be imposed to reduce or mitigate the environmental impacts of the permitted activity.
- G.2.3.2: Permits may modify the minimum BMPs specified in Parts G.4 and G.5 below by approving specific BMPs as alternatives. Any such alternative BMP must be at least as effective as the BMP the alternative replaces.
- G.2.3.3: County permits or orders approving or requiring the use of alternative BMPs may take into account any guidance issued pursuant to section 67.804(h) of the Ordinance, in the manner authorized by that section.

## **G.2.4 Non-Storm Water Discharges**

Dischargers shall identify and implement BMPs to address all potential non-stormwater discharges from the permitted activity.

## **G.2.5 Industrial Facility General Permit Coverage**

Prior to commencing industrial operations, any new industrial facility subject to the State General Industrial Storm Water Permit must provide evidence to the County that the Notice of Intent required to be filed under that general permit has been filed.

## **PART G.3—ENVIRONMENTAL PERFORMANCE STANDARDS**

### **G.3.1 Flow Control and Erosion Prevention**

- G.3.1.1: Post-construction peak runoff flow rates and velocities from the project site shall be maintained at levels that will not cause a significant increase in downstream erosion.
- G.3.1.2: Measures to control flow rates and velocities shall not disrupt flows and flow patterns that are necessary to support downstream wetlands or riparian habitats. Diversion of runoff to regional facilities shall not be allowed to deprive immediate downstream habitats of the minimum flows and /or over-bank flow events they need.

- G.3.1.3: If peak stormwater runoff discharge rates or velocities would be increased by the project, the project proponent shall submit an evaluation by a qualified engineer to determine impacts to the downstream channel extending to a major receiving water. Such evaluations shall address the erosive effects of post-construction discharges, in combination with other development-related discharges in the area, on the types of soil and vegetation downstream; any other applicable considerations; and mitigation measures.
- G.3.1.4 Where effective, acceptable measures to prevent erosion include but are not limited to minimizing the amount of new impervious surface created, retaining or constructing vegetated swales and buffers, and the use of velocity reducers, drop structures, and energy dissipation can help to achieve these standards. Where these measures are not sufficient to achieve these standards, runoff must be captured and released in a more controlled manner. “Hardening” natural downstream areas to prevent erosion is not an acceptable technique for meeting these performance standards, unless pre-development conditions are determined to be so erosive that hardening would be required even in the absence of the proposed development.
- G.3.1.5: Mitigation structures put in place to control peak runoff flow rates and velocities shall be designed for a 10-year 6-hour storm event.

### **G.3.2. Water Quality Protection**

- G.3.2.1: Pollutants in non-storm water and storm water discharged from each project (or discharged to waters of the state within the project area) shall not cause or contribute to an exceedance of receiving water quality objectives.

Whether a project meets this standard will depend on the waters affected by the project, on the water quality objectives established for those waters at the time the project is proposed, and on the amount and type of pollutants discharged by the project. The question is whether increased pollution from the project (together with pollution from other sources) would be likely to result in water quality violations that would not otherwise occur.

- G.3.2.2: Pollutants in non-storm water and storm water discharged from each project (or discharged to waters of the state within the project area) shall not significantly degrade receiving water quality.

- G.3.2.3: Pollutants in non-storm water and storm water discharged from each project (or discharged to waters of the state within the project area) must be reduced to the MEP.

Whether this standard is met is both a technical and an economic determination. If the project fulfills the requirements in Parts G.4 and G.5 of this section, it shall be deemed to have fulfilled requirement G.3.2.3.

- G.3.2.4: Pollutants in non-storm water and storm water discharged from each project (or discharged to waters of the state within the project area) shall not cause or contribute to a condition of "pollution", "contamination" or "nuisance" as those terms are defined in the State Water Code, section 13050 subsections (k), (l) and (n). (“Pollution” is an unreasonable interference with a beneficial use assigned to a specific water body in the RWQCB Basin Plan. “Contamination” involves a threat to public health. A “nuisance” is a condition that affects a considerable number of persons, and “is injurious to health, or is

From San Diego County Ordinance, March 2008.

(10) Implement buffer zones for natural water bodies, where feasible.

(b) Hydromodification management.

(1) Post-construction peak run-off flow rates and velocities from the project site shall be maintained at levels that will not cause a significant increase in downstream erosion.

(2) Measures to control flow rates and velocities shall not disrupt flows and flow patterns that are necessary to support downstream wetlands or riparian habitats. Diversion of run-off to regional facilities shall not be allowed to deprive immediate downstream habitats of the necessary natural low flows levels experienced during the dry weather season or over-bank flow events.

(3) Hardening natural downstream areas to prevent erosion is prohibited, except where pre-development conditions are shown, to the satisfaction of the County, to be so erosive that hardening would be required even in the absence of the proposed development.

(4) Interim hydromodification criteria for priority development projects disturbing 50 or more acres.

(A) Estimated post-project run-off durations and peak flows shall not exceed pre-project durations and peak flows.

(B) The project proponent must use a continuous simulation hydrologic computer model such as US EPA's Hydrograph Simulation Program—Fortran (HSPF) to simulate pre-project and post-project run-off, including the effect of proposed BMPs, detention basins, or other stormwater management facilities utilizing the entire rainfall record, and shall show the following criteria are met:

i. For flow rates from 20% of the pre-project 5-year run-off event (0.2Q5) to the pre-project 10-year run-off event (Q10), the post-project discharge rates and durations shall not deviate above the pre-project rates and durations by more than 10% over more than 10% of the length of the flow duration curve.

ii. For flow rates from 0.2Q5 to Q5, the post-project peak flows shall not exceed pre-project peak flows. For flow rates from Q5 to Q10, post-project peak flows may exceed pre-project flows by up to 10% for a 1-year frequency interval. For example, post-project flows could exceed pre-project flows by up to 10% for the interval from Q9 to Q10 or from Q5.5 to Q6.5, but not from Q8 to Q10.

(C) Priority development projects disturbing 50 acres or more are exempt from the requirements of section 67.812(b)(4) if:

i. The project would discharge into channels that are concrete-lined or significantly hardened, such as with rip-rap or sackcrete, downstream to their outfall in bays or the ocean.

ii. The project would discharge into underground storm drains discharging directly to bays or the ocean.

iii. The project would discharge to a channel where the watershed areas below the project's discharge points are highly impervious (>70%).

iv. The project proponent conducts an assessment incorporating sediment transport modeling across the range of geomorphically-significant flows that demonstrates to the County's satisfaction that the project flows and sediment reductions will not detrimentally affect the receiving water.

(c) Treatment control BMPs.

(1) All treatment control BMPs shall be designed to meet the design storm criteria required under the California Regional Water Quality Control Board, San Diego Region Order No. R9-2007-0001, NPDES Permit No. CAS 108758.

(2) One or more structural treatment BMPs may be used for a single project or combination of projects. Any such shared BMPs shall be operational prior to the use of any dependent development or phase of development. The shared BMPs shall only be required to treat the dependent developments or phases of development that are in use. Interim stormwater BMPs that provide equivalent or greater treatment than is required by this chapter may be implemented by a dependent development until each shared BMP is operational. If interim BMPs are utilized, the BMPs shall remain in use until permanent BMPs are operational.

(d) Whether or not a County permit or approval is required, and whether or not a post-construction stormwater management plan is required to be submitted, all dischargers engaged in land development or significant redevelopment activities shall implement post-construction BMPs in the following areas, if applicable, to the project:

(1) These BMPs can include structures to convey run-off safely from the tops of slopes, vegetation or alternative stabilization of all disturbed slopes, the use of natural drainage systems to the MEP, flow and velocity controls upstream of sites; and stabilization or permanent channel crossings, unless the crossing is not publicly accessible and is not frequently used.