REVIEW OF SWALE DESIGN FOR THE AUCKLAND REGION

Jonathan Paterson, Pattle Delamore Partners Ltd.
Bodo Hellberg, Auckland Council Stormwater Technical Services

ABSTRACT

The Auckland Council is in the process of updating Technical Publication 10 'Stormwater Management Devices: Design Guidelines (TP 10). This paper provides a summary of a technical report prepared to inform the review of the TP 10 swale chapter. The report documents the developments in stormwater management swale research that have occurred since the publication of TP 10 in 2003, and uses that to provide a revised design methodology, including new design parameters.

The literature review identified a range of new research that provided additional information on the water quality treatment performance of swales, and the particular mechanisms which affected the performance of the swales in those studies. Limited research on the water quantity management performance of swales was found.

One of the primary objectives of the TP 10 review was to assess the existing design procedure and parameters, and update this where appropriate. The technical report provides guidance for recommended applications of swales, site constraints that will affect the suitability of swales, and details on the principles and processes by which swales provide stormwater management benefits. This paper provides an overview of the key findings and recommendations of the report.

KEYWORDS

Swale, Stormwater Management, TP 10, Auckland Council

PRESENTER PROFILE

Jonathan is a Civil Engineer with eight years professional experience in a broad range of engineering applications. He has specialist skills in stormwater and wastewater management and infrastructure design, and spent one year on secondment to the Auckland Regional Council Stormwater Action Team (now Stormwater Technical Services at Auckland Council).

1 INTRODUCTION

Auckland Council is undertaking a review and update of Auckland Regional Council Technical Publication 10 'Stormwater Management Devices, design and guideline manual' (ARC, 2003), hereafter referred to as TP 10. Part of this project involves the preparation of a series of technical reports on individual stormwater management devices. This paper summarises the key findings and recommendations of the report (Paterson & Easton, 2011).

Stormwater management swales are vegetation lined open channels which provide an open flow path for stormwater runoff. Swales have historically been used for stormwater conveyance, primarily as drains alongside roads without kerb and channel. More recently, as both domestic and international focus on stormwater quality improvement and maintenance of the natural hydrological cycle has increased, the full stormwater management potential of swales has been further investigated, with many potential benefits being identified, including:

- removal of a range of stormwater contaminants through a range of different mechanisms;

- reduction on peak flow rate and velocity and associated increases in lag time; and

- increased opportunity for groundwater recharge through infiltration.

The contents of this paper focus on dry grassed swales, as these are the type of swale most commonly used in the Auckland region. The full technical report includes information on other types of swales, including vegetated, bio-retention and wetland swales (Paterson & Easton, 2011).

2 LITERATURE REVIEW

2.1 CONTAMINANT REMOVAL MECHANISMS

As noted in TP 10, swales provide a range of different contaminant removal mechanisms. In general terms, a dry swale is an open channel which utilises surface vegetation to provide a filter media to filter stormwater and retard flow velocity as it passes horizontally through the vegetation. Studies have reported that sedimentation, rather than physical filtration by the vegetation, is the dominant mechanism for Total Suspended Sediment (TSS) removal in swales (Backstrom, 2002), however that same study noted that swales with dense turf had higher particle trapping performance than those with thinner vegetation. This implies that while denser vegetation may not aid contaminant removal through filtration of particles, it does provide a treatment benefit by providing an obstruction to flow which will increase the Hydraulic Retention Time (HRT), thereby providing a longer time for TSS and adsorbed contaminants to settle out.

Infiltration of stormwater over the length of the swale is another important physical contaminant reduction mechanism as this removes runoff from the surface water system. However, this is thought to generally only occur to a significant degree in swales in areas with high infiltration capacity subsoils (Nara & Pitt, 2005). In general, the studies where real life swales were tested, there were insufficient design details to determine the underlying soil type, and therefore the degree of effect that infiltration played in the contaminant removal performance of the swale.

A range of chemical and biological mechanisms are also thought to provide contaminant removal, however these principally only apply to metals and nutrients. Contact between stormwater contaminants and organic matter in swales can result in complexing, adsorption and chemical conversion of soluble metals contaminants into insoluble forms. Biological mechanisms include the presence of microorganisms which degrade organic contaminants, uptake nutrients and metals by vegetation, and the provision of large surface area of stems, leaves and surface roots for contaminants to adsorb to (Larcombe, 2002). However, the relative effect of these different mechanisms are not well understood, and the relationship between swale inflow rate and nutrient removal has been found to be variable (Deletic & Fletcher, 2006).

2.2 CONTAMINANT REMOVAL PERFORMANCE

The contaminant removal performance of swales has been investigated and reported in a range of literature, with a general trend being that contaminant removal performance generally improves with increased swale length and HRT, but only up to a point. However, there is much variation in the contaminant removal performance reported by the various sources, which is generally attributed to site specific differences.

Khan et al investigated the contaminant removal efficiency of a 60m swale (9 min HRT), and compared that to its performance when the first half of the swale was piped to create a 30m swale (4.6 min HRT) (Khan et al., 1992). Six storms were sampled in each configuration. TSS removal efficiencies were 69% to 97% for the 60m swale, and 6% to 93% for the 30m swale; zinc removal efficiencies were 38% to 84% for the 60m swale, and -65% to 86% for the 30m swale; and copper removal efficiencies were 31% to 61% for the 60m swale, and -114% to 67% for the 30m swale. Note that negative removal efficiencies indicate that the contaminant concentration in the effluent was higher than that of the influent (i.e. a net gain in contaminant load). Short circuiting was noted during dye tests in the 30m swale, and the storms sampled during the 30m experiment were generally of greater intensity than those during the 60m experiment. These combined to further reduce the HRT of the swale, which the authors indicated may have been a significant contributor to the variability of the results derived from the 30m swale.

Larcome (2002) adopted a similar approach to Khan et al (1992) by comparing the performance of a 100m long swale (30 mins HRT) to the performance of a 50m section of the same swale (15 mins HRT). While these swales were located alongside motorways, entry was controlled using timber kerbs to establish a single entry point and no lateral inflow. Both swales were found to produce similar results, with the TSS removal rates for individual events ranging from -107% to 77% for the 100m swale and -54% to 67% for the 50m swale. Metal removal performances were less variable, with zinc removal rates ranging from 41% to 96% for the 100m swale and from 72% to 83% for the 50m swale, and copper removal rates ranging from 13% to 83% for the 100m swale and from 31% to 76% for the 50m swale. The decreased variability in performance of the shorter swale was in contrast to the relationship noted in Khan et al. (1992), however in Larcome (2002) both swales had HRT that were well above 9 minutes, and the author attributed the variability in the performance of the 100m swale to variations in inflow conditions, including sediment concentration, storm intensity, and the duration between storm events.

Yu et al (2001) compared the performance of a 30m swale with and without a check dam located at the mid-point of the swale. The HRT of the swale was approximately 8 mins without the check dam, and approximated 12.5 mins with the check dam. The swale longitudinal grade was 1%, and while this is generally considered too flat to warrant a check dam, it does provide a good example as the use of the check dam at these flatter grades would be expected to affect the overall HRT less than it would when used at steeper grades. The use of the check dam increased the contaminant removal performance of the swale by approximately 30% for TSS and total nitrogen removal, and by approximately 70% for total phosphorous, which attributed to the approximately 50% increase of hydraulic retention time provided by the check dam.

A number of laboratory studies by Deletic (1999, 2001, 2005) have investigated the performance of swales in a laboratory setting using Astroturf lined swales over an impermeable liner. The authors noted that the experimental design was to assess the performance of physical contaminant removal processes, principally filtration and deposition, with results showing that the TSS concentration exhibited exponential decay along the length of the swale, with the majority of the deposition occurring within the first 5m of the swale (1999 and 2001). While this performance is related to the consistency of the Astroturf preventing any short circuiting, similar performance over the upper portion of the swale has been noted by other researchers using real life vegetated swales (Backstrom, 2002; Nara & Pitt, 2005).

Deletic and Fletcher (2006) reported on field sampling of dry swales using artificial runoff and controlled flowrates. The swale tested was 65m long, and flowrates of 2 to 15 L/s were tested, which corresponded to HRT of 22 to 8 minutes respectively. Contaminant removal rates for TSS ranged from 73% to 95%, for total phosphorous 56% to 73%, and for total nitrogen 36% to 57%.

Moores et al (2010) undertook a study of a swale adjacent to a 4 lane motorway in Auckland as part of greater research into road runoff in New Zealand. Based on the information provided in the report, it is understood that runoff entering at the head of the swale had a HRT of around 20 minutes; however, the majority of the flow was entering as lateral inflow continuously along the full length of the swale. Therefore the average HRT was estimated to be approximately half of this, or 10 minutes. Samples were collected from seven rainfall events between February and May 2009, which showed contaminant reduction rates ranging from 17% to 90% for TSS, from 89% to 96% for total zinc, and from 85% to 96% for total copper. The author explained the higher removal rate achieved from metals compared to TSS by noting that "the dry-weight metal concentrations in sediments in treated runoff were much lower than those in untreated runoff at Northcote, suggesting that those discharged from the swale were 'clean' (i.e. derived from less contaminated roadside soils rather than from sediments deposited on the road surface)."(Moores, et al., 2010).

The 'National Pollutant Removal Performance Database' (CWP, 2007) contains contaminant removal performance information collated from 166 individual stormwater treatment practice performance studies. These studies were all quality checked for three criteria, including the number of storm samples collected (five or more), that automated equipment using a flow or time based sampling technique was used, and that the method used to compute removal efficiency was documented. Of these, 17 of the studies were conducted on what they defined as 'Open Channels', which included three on dry swales, 12 on infiltration swales, and two on wetland swales. The contaminant removal efficiencies reported in this document have been reproduced as Table 1.

Table 1: Expected Swale Contaminant Removal Performance (CWP, 2007)

Value	Total Suspended Solids	Total Zinc	Total Copper	Total Nitrogen	Total Phosphorous
Minimum	18	-3	-35	8	-100
Lower Quartile	69	58	45	40	-15
Median[1]	**81**	**71**	**65**	**56**	**24**
Upper Quartile	87	77	79	76	46
Maximum	99	99	94	99	99
1: Where a single value is required, it is recommended that Median values are used.					

2.3 DESIGN BASIS

The relationship between swale design characteristics and TSS removal is much better understood than that for the removal mechanisms of other stormwater contaminants (i.e. removal of metals and nutrients by absorption, adsorption, ion exchange, phytoremediation etc.). In addition, TSS is often used an indicator contaminant for metals and other general stormwater contaminants (ARC, 1992), with the assumption being that by removing a certain proportion of TSS from the stormwater, a sufficient proportion of the other contaminants will be removed as well. Therefore, the swale design process is generally focussed on providing suitable conditions for TSS sedimentation, with other contaminants being removed by sedimentation or other processes occurring in parallel, which is an approach supported by the empirical data in Table 1.

2.3.1 HYDRAULIC RETENTION TIME

The majority of local and international design guidelines stipulate that the key design criterion is a HRT of 9 minutes (ARC, 2003; Khan, et al., 1992; USEPA, 2004; UDFCD, 2008), with the flow conditions within the swale being estimated using Manning's Equation. HRT is used as an indicator of the amount of deposition that will occur over the length of the swale.

The origin of the requirement for the 9 minute HRT appears to be the Khan et al (1992) study which looked at the performance of single 60m long swale and assessed its performance at full length and then at half length (i.e. 30m). Samples were collected from six storms in each configuration, and the authors found that maximum contaminant reduction levels were similar for both lengths, however the performance of the 30m swale was far more variable. Based on field measurements, it was determined that the 60m swale had a HRT of 9 minutes while the 30m swale had an HRT of 4.6 minutes. The authors noted that "it is suggested that a residence time of 4 to 5 minutes is not adequate to assure good pollutant removals" and that "more work is needed before a residence time of less than 9 minutes can be recommended with confidence as adequate for swale design".

The HRT of a swale can be calculated using the following formula:

$$HRT = L / 60V \quad (1)$$

Where: HRT= Hydraulic Residence Time (mins);

L = Swale Length (m); and

V = Flow Velocity (m/s).

2.3.2 EFFECT OF MULTIPLE ENTRY POINTS

It is not uncommon for swales to have multiple entry points, which could be either a collection of concentrated flows entering at specific inlet points, or the use of lateral entry continuously along all or some of the length of the swale. Where a swale has lateral entry, all or part of the inflow will enter along the sides of the swale generally at an angle perpendicular to the swale centre line. This is a key benefit of swales as it allows them to be used for linear infrastructure such as roads and highways, and along the boundaries of large developments such as car parking lots.

Design manuals that include allowance for multiple entries generally recommend that the average HRT needs to meet the 9 minute criteria (Shaver, 2009). Another manual states that where a swale is fed by continuous lateral inflow, that the total HRT should be increased to 18 minutes (WSDE, 2005), which has a similar effect. However, it should be noted that one of the reviewed guidelines recommends 9 minutes for a design HRT, with an minimum acceptable HRT of 5 minutes (USEPA, 2004).

2.3.3 MANNING'S EQUATION

Manning's equation is generally used by swale design guidelines to estimate the flow characteristics in the swale during the design storm event. The equation is used in an iterative process to produce a swale design with characteristics such as length, longitudinal slope, geometry, grass length, flow depth and HRT within a given range.

The key variable in the equation is the Manning's roughness 'n', which in this case is used as a measure of the surface roughness provided by the vegetation in the swale. Laboratory and field experiments have determined that the Manning's roughness will vary across different flow conditions (for example, the WQV event and high flow conveyance event will operate under different conditions with different values for Manning's roughness coefficient). Larcombe (2002) found that in a swale with a set grass height, the Manning's roughness generally decreased with increased water depth and slope, particularly once the water depth reached two thirds of the height of the grass. Other research found similar results by showing empirically that Manning's roughness would decrease with an increased Reynolds number (Kirby et al., 2005), which is similar to the trend known to exist between Reynolds number and Darcy Weisbach friction factors. In general terms, this research showed that as water depth and flow velocity increased, the Manning's number decreased.

However, rather than requiring relatively complex calculations to be undertaken, many design guidelines recommend standard values for Manning's roughness 'n' to be used in the design of swales depending on the flow conditions in the swale (i.e. water quality treatment or high flow conveyance), as shown in Table 2

2.3.4 FALL NUMBER

Deletic has undertaken a series of laboratory studies which focussed on examining the relationship between swale flow and particle settling velocity using Astroturf lined swales over an impermeable liner (Deletic, 1999; Deletic , 2001; Deletic, 2005) and a grass swale (Deletic & Fletcher, 2006). Where artificial swales were used, this was so that filtration and deposition were the only contaminant removal mechanism possible- no infiltration was possible, and the chemical mechanisms present in a real life swale were not present. The results showed that the TSS concentration exhibited exponential decay along the length of the swale, with the majority of the deposition occurring within the first 5m of the swale (1999 and 2001), with a similar observation being made by other researchers (Backstrom, 2002; Nara & Pitt, 2005).

These observations lead to the development of the Aberdeen Equation, which relies on the fall number of a given particle to estimate contaminant reduction. The fall number is the ratio between the time taken for the water to travel through the swale to the time taken for a given particle fraction to settle out of the flow stream. Deletic and Fletcher (2006) estimated the performance of a grass swale using the Aberdeen Equation, and found that the predicted total contaminant load was within 11% of the actual amount.

It is implicit that this method requires the particle size distribution for the specific contributing catchment be known in order to estimate the TSS removal efficiency, and therefore this method has not been widely adopted by regulators for use in design guideline manuals. However, results reported in Deletic and Fletcher (2006) do provide a back calibration to justify swale design based on a 9 minute HRT.

2.4 HYDROLOGICAL CONTROL

The effects of swales on runoff hydrology are explained in qualitative terms, and their use is promoted by many design manuals as a method of either maintaining predevelopment hydrology, or providing a method of restricting the development related hydrological changes (PCG, 1999; Shaver, 2000). There has been little research into quantifying this effect, although it has been noted in research that swales with high infiltration capacity are capable of reducing the amount of runoff ultimately discharged (Backstrom, et al., 2006; Rushton, 2001).

Recent research in New Zealand by Moores et al. (2010) and Fassman et al. (2010) have provided evidence of this effect. Moores et al. (2010) studied the hydrological effect of a swale adjacent to a motorway in Auckland, with data collected for 7 storms between February and May 2009. It is not known whether this swale had an underdrain system. Across those seven events, there was an average reduction in both runoff volume and peak discharge of 84%. The study conducted by Fassman et al. (2010) included hydrological monitoring of two swales across 94 storm events over the course of 16 months. These swales did not have underdrain systems. Over this period, the average reduction in runoff volume was 63.6% and the average reduction in peak flow was 74.5%, with the effect being more marked during smaller more frequent storm events. The underlying soils at both experiment sites had generally low infiltration capacities, which implies that the hydrological benefit provided by swales may not be restricted to only those in areas with naturally high infiltration. This suggests that the key criterion may in fact be the depth and infiltration rate of the topsoil used to line the swales. Further work may be required to investigate whether swales with underdrains provide similar hydrological control.

This reduction in both peak runoff and total volume of stormwater discharged during storm events, particularly smaller more frequent events, implies that swales may be able to provide some contribution to downstream channel protection. This effect has been noted various stormwater design guidelines (Shaver, 2000; KCDEPW, 2007; VDCR, 2011). However, there is currently no accepted method of quantifying this effect in terms of stormwater quantity control, and therefore there is no design methodology available to provide this benefit. Therefore, despite the knowledge that swales provide hydrological benefit, alternative devices will be required for sites that are required to provide water quantity control as part of their development.

2.5 DESIGN CHARACTERISTICS

While the HRT is the key stormwater quality criteria upon which swale design is based, there is a wide range of different characteristics that need to be assessed. Appropriate values or ranges of values have been provided in Table 2 for the most significant design characteristics from a range of literature sources and design guidelines. As swale design is an iterative process, designers may need to test varying different values for each before a suitable design is achieved that meets the 9 minute HRT requirement.

2.5.1 LONGITUDINAL SLOPE

Longitudinal slope has a number of effects on swale performance. In general terms, the greater the slope, the faster the water will pass through the swale and the shorter the HRT will be. The range recommended by the literature (provided in Table 2) is generally from 1% to 5%, with under drains required when the slope is below this range and check dams when above it. However, longitudinal slope has also been shown to have an effect on vegetation cover, with slopes of between 1.5% and 2.5% being shown to provide consistently denser vegetation cover than slopes outside this range (Colwell, 2000). Dense and even vegetation cover is important to prevent short circuiting by diffusing flow over the full width of the swale. The optimum wet swale longitudinal slope is 1% to 2% (Clayton & Scheuler, 1996; VDCR, 2011).

2.5.2 VELOCITY

The recommended maximum water quality design storm velocity is generally around 0.3 m/s, which is a practical restriction in order to provide adequate HRT in channels without them needing to be excessively long (Clayton & Scheuler, 1996).

The recommended maximum high flow velocity is generally around 0.8 m/s to 0.9 m/s, which generally relates to the expected erosive velocity in the swales. Higher velocities are possible where local soil and grass types combine to form particularly stable channels. One guideline recommends allowing peak flow velocities up to 1.5 m/s for the 2 year ARI event and up to 2.1 m/s for the 10 year event due to the relative infrequency of these events (Clayton & Scheuler, 1996).

2.5.3 GEOMETRY AND LENGTH

The geometry of the swale is primarily associated with maintenance issues as the side slopes need to be gentle enough and the bases wide enough to allow full access for mowing equipment. When parabolic channels are used, care needs to be taken to ensure the slope transfers at the margins are not too significant. Trapezoidal channels are most commonly used due to their design simplicity, and recommended side slopes and base width details are detailed in Table 2. The minimum length for a swale is generally accepted to be 30m, which is related to the relationship between HRT and the flow velocity required for water quality treatment.

2.5.4 STORM CONVEYANCE VELOCITY

While swales have principally been discussed in relation to their use as stormwater treatment devices, they also need to be designed to convey storm events in a safe manner that avoids nuisance flooding up to the design storm of the local network. In doing this, the swale needs to be designed in order to limit the peak flow below a level that will cause erosion within the swale or damage to the erosion. Recommended values range between 0.8 m/s (the maximum velocity recommended by TP 10 2003) and 2.1 m/s depending on the type of vegetation, the erosion resistance of the soils, and the return period of the flow event.

2.5.5 VEGETATION AND WATER DEPTH

One of the most significant contrasts between TP 10 (2003) and the other literature contained in Table 2 is the recommended design flow water depth relative to the grass height. TP 10 (2003) allows for the water level during the water quality design event to be 100mm above the grass height. However, other references contained in Table 2 recommend that the water level be no higher than one half to two thirds of the grass height (Clayton & Scheuler, 1996; Khan, et al., 1992; WSDE, 2005) or up to the full grass height (Shaver, 2009), and that the maximum water depth should be 100mm total with a minimum grass height of 150mm (Clayton & Scheuler, 1996; PBES, 2004).

Table 2: Design Criteria and Parameters Compiled from Various Design Guidelines

Design Guideline	Maximum Velocity	Longitudinal Slope	Grass Height or Water Depth	Residence Time	Bottom Width	Length	Side (batter) Slope	Manning's Roughness
ARC TP 10 (2003)	0.8 m/s for water quality storm	1-5%	Maximum water depth above vegetation 100 mm	9 min	2 m	≥ 30 m	3H:1V	Varies depending on grass height and water depth. Formula provided
Khan et al. (1992)	0.27 m/s	2-4%	Water depth < ½ grass height	9 min for 80% TSS removal				
Clayton and Sheuler, CWP (1996)	0.3m/s for WQV, 1.2-1.5m for 2 year ARI, 2.1m/s for 10 year ARI	1-4%	100mm water depth during WQV, 150mm grass height				4H:1V (3H:1V minimum)	Ranges from 0.15 for flow<2/3 grass height, 0.03 for flow>2xgrass height
US EPA (2004)	0.27 m/s for water quality design, 0.8-1.8m/s for high flow event	2-6%		9 min (> 5 min minimum)	2.4 m (0.6 m minimum)	61 m (≥ 30 m)	4H:1V (3H:1V minimum)	Varies depending on water depth. Design charts presented.
Portland BES (2004)	0.27 m/s for water quality design, 0.9 m/s for high flow event	0.5-5% Ground slope of drainage area 5% max.	Max. water depth at 100 mm	9 min	0.6 m for private 1.2 for public swales	≥ 30 m	4H:1V	0.25
Western Washington (2005)	0.3m/s for design event, 0.9m/s maximum	1.5-2.5%	Water depth 50mm if mowed frequently, 100mm if not	9 min direct inflow, 18 min continuous inflow	0.6-3m	33m	3H:1V (4H:1V preferred)	0.2-0.3 depending on mowing frequency
UDFCD (2008)	<0.3 m/s for 2 yr storm peak flow rate	0.2-1% maintained by check dams. Ground slope of drainage	Maximum water depth is 0.3 m at 2 yr peak flow	10 min	0.6-1.5m		4H:1V (5H:1V preferred)	0.05-0.06

		area 5% max.						
Shaver (2009)	0.8 m/s for WQV <1.5 for 10 year ARI	2-5%	Water depth < Grass Height, both 100-150mm	9 min	2m max	$\geq$ 30 m	4H:1V	0.25 for WQV 0.03 for 10 year ARI

As noted, thick and even vegetation cover in grassed swales is important to prevent short circuiting by diffusing flow over the full width of the swale. Research has indicated that the most significant environmental factor affecting vegetation cover is the presence of heavy shade (Mazer et al., 2001). Beyond this, inundation suppresses germination and other vegetal functions, with data showing that frequency of inundation over summer is negatively correlated with vegetation growth. Shade is a site issue, but inundation can be affected by the longitudinal slope and the local soil type, with flatter slopes and lower infiltration capacity soils allowing water to stand for longer. In addition, local inundation can retard vegetation growth immediately behind check dams.

2.5.6 CHECK DAMS

Check dams are utilised in swales to reduce the flow velocities, thereby preventing erosive flows and increasing the HRT to enable an improved pollutant removal efficiency. Check dams should be constructed of durable, non-toxic materials such as rock, brick, concrete or from inert timber materials that do no leach contaminants.

3 DESIGN METHOD AND CRITERIA

This section contains the swale design methodology and associated criteria recommended for adoption in the Auckland region. As shown in Table 1, there is a wide range of reported contaminant removal performances for swales that used the same key design criteria related to HRT. While use of the 'Fall Number' method discussed in section 2.3.4 would allow for swale designs to be targeted to specific TSS removal performances, the range of performance for this method infers that much of the variability can be attributed to factors outside of the control of the designer (for example, construction, operation and maintenance, and inflow contaminant concentration). Therefore, it would be overstating the accuracy of current knowledge to provide a methodology for swale design that was based on a target contaminant reduction performance.

The selected design methodology is based on that contained in TP 10, and utilizes the Manning's equation to iterate and optimize different design parameters to achieve a suitable design. This method is generally similar to the method used by the most national and international guidelines, including all those listed in Table 2 There are however two key amendments being made to the design criteria contained in TP 10 2003; the maximum allowable water depth (relative to grass height) and velocity during the water quality design event. This is in order to bring the local design methodology into line with that used in other national and international guidelines.

3.1 DESIGN PARAMETERS

The recommended design criteria for swales are contained in Table 3 below, which has been generally based on the values contained in TP 10 other than where the literature consistently recommended a contrasting value. Where this has occurred, further discussion around the justification of selecting differing criteria to that in TP 10 has been provided in subsequent sections.

3.1.1 WATER VELOCITY DURING WQV EVENT

The maximum water quality design event velocity recommended in TP 10 was 0.8 m/s, compared to the approximately 0.3 m/s recommended in all literature sources contained in Table 2 other than Shaver (2009). The 0.3 m/s is generally a practical restriction in order to provide adequate HRT in channels without them needing to be excessively long (Clayton & Scheuler, 1996), thereby increasing the number of sites and developments that they could be suitable for, and has therefore been recommended for use in the technical report. It should be noted that Shaver (2009) is a design guideline document for state highway infrastructure, and as such there are minimal limitations on the lengths of swale for this application. In this specific application (i.e. swale alongside a highway), 0.8m/s is considered to be suitable.

Table 3: Recommended Swale Design Criteria for adoption in the Auckland Region

Parameter	**Abbreviation**	**Recommendation**
Longitudinal Slope	S	1-5%
Hydraulic Retention Time	HRT	9 minutes
Water Quality Design Storm Velocity		0.3 m/s
Water Quality Design Storm Depth	d	Less than or equal to design vegetation height (150 mm max)
Water Quality Design Storm Manning's Roughness	n	0.25
High Flow Max Veloctiy		1.5 m/s
High Flow Max Depth	d	300 mm deep or 150 mm below top of swale, whichever is less
High Flow Manning's Roughness	n	0.03
Design Vegetation Height		150mm
Vegetation Type		Fescue, Rye and Clover mix
Length	L	> 30m
Base Width	b	0.6 – 2 m
Side Slopes	zh:1v	4h:1v or flatter where space allows
Check Dams		Required when longitudinal slope >5% to reduce effective grade to 2%. Max height equal to WQV storm design depth (150mm max)
Level Spreaders		Good practice at all inlets, integrate with Check Dams when longitudinal slope >5%
Under-drains		Required when longitudinal slope <2%
Note: A shaded cell indicates that the recommended value is different to that contained in TP 10 2003.		

3.1.2 WATER DEPTH

The maximum water depth during the water quality design event recommended in TP 10 was 100mm above the top of the vegetation. It is unclear why this was, as no support was found in any literature or design guidelines for water quality design event depths in excess of the vegetation height. The literature and design guidelines contained in Table 2 recommend water depths of either one half, two thirds, or equal to the design vegetation height. The recommended water depth for the design method in this report is equal to the design vegetation height, with a maximum of 150mm. This upper level depth has been selected to align the recommendations of this report with other local and international guidelines while deviating from the existing protocol as little as possible.

3.1.3 MANNING'S ROUGHNESS COEFFICIENT

In TP 10, the Manning's roughness coefficient used for swales was determined through application of a set of empirical formulas developed in a local study (Larcombe, 2002) which required the longitudinal slope and design storm depths as inputs. While swale design is inherently and iterative process often requiring a number of steps before a suitable design is reached, the inclusion of a formula to determine the Manning's roughness based on the flow depth and longitudinal slope, which are all interrelated variables, introduced an additional layer of complexity. Using the method in Larcombe (2002), the Manning's roughness ranges from 0.1 to 0.2 for 150mm long grass and a flow depth of 100mm (i.e. a design storm event situation), and from 0.03 to 0.06, and for 150mm long grass and a flow depth of 300mm (i.e. a high flow conveyance situation). A similar approach was taken by USEPA (2004) where design charts were used to related flow depth to Manning's roughness.

However, the remainder of the literature and design guidelines in Table 2 used set Manning's roughness coefficients for different design flow situations, often recommending one value for the water quality design flow and another for high flows. The pragmatic approach of having set Manning's roughness coefficients for specific flow conditions has been adopted for the swale design method detailed in this report, with recommended Manning's roughness coefficients of 0.25 for the water quality design flow where the flow is fully contained within the design vegetation height, and 0.03 for high flows where the vegetation is submerged.

3.1.4 SIDE SLOPE

Side slopes of no steeper than 3(h):1(v) were recommended in TP 10, however the international literature and design guidelines contained in Table 2 recommended that slopes no steeper than 4(h):1(v) be used, with 5(h):1(v) slopes used where possible. This is generally to improve the ease of maintenance. However, the use of these flatter slopes means that the swale will be wider, which may present issues where they are installed on sites with space constraints. Therefore, where possible, it is recommended that swale side slopes be 4(h):1(v) or flatter where space allows, but that steeper slopes can be considered for suitability where constrained by space availability for the swale.

3.1.5 MULTIPLE INLETS

Where a swale has more than one inlet, the average HRT for the entire swale shall be a minimum of 9 minutes or longer. The average HRT for multiple inlets can be estimated using the effective swale length (L_{eff}) calculation, as follows:

$L_{eff} = (L_1Q_1 + L_2Q_2 + L_nQ_n) / (Q_{tot})$ (2)

Where L_n =length of swale from inlet n to end of swale,

Q_n = design flow into swale from inlet n; and

Q_{total} = total flow into swale from all inlets

Where a continuous lateral inflow occurs, the length to the end of the swale is taken from the midpoint of the length of lateral contribution (i.e. if a swale is 100m long, and there is lateral inflow between 40 m and 80 m from the end of the swale, the net length to the end of the swale from that lateral inflow is 60 m).

3.1.6 HIGH FLOW CONVEYANCE

The swale needs to be designed to pass the design storm used for local stormwater infrastructure sizing at the site without causing erosion or scour in or downstream of the swale, or causing nuisance flooding by spilling over into adjacent properties. It is recommended that the maximum flow depth during the high flow event does not exceed 300mm (UDFCD, 2008), and that a minimum freeboard of 150mm is allowed for between the top water surface during the high flow event and the tops of the swale banks.

To calculate the high flow conveyance performance of the swale, it is recommended that the swale be treated as a two zone flow system, with the first zone being below the design vegetation depth, and the second zone being above it. Zone one represents a semi-dead zone that will pass only the peak flow rate of the water quality design event, while zone two represents an active flow zone that will pass the difference between the peak flows of the conveyance and water quality storm events.

The depth of zone two can be calculated as follows:

$d_2 = d_t - d_f - d$ (3)

Where d_2 = the effective depth of zone 2,

d_t = total swale depth;

d_f = freeboard depth; and

d = design vegetation depth.

3.2 PHYSICAL DESIGN

Physical design of the swale components will be undertaken as described in TP10.

3.2.1 CROSS SECTIONAL GEOMETRY

As noted in section 2.5.3, trapezoidal channels are those most commonly used for design purposes, and are also considered to generally represent the performance of parabolic swales. Therefore, it is recommended that all swales be designed assuming a trapezoidal cross section, with the formulae for cross section area (A, m^2) and hydraulic radius (R, m) as follows:

$A = bd + zd^2$ (4)

$R = A / (b + 2d \times (z+1)^{0.5})$ (5)

Where: b = Base width of channel (m);

d = water depth (m); and

z = side slope (z(h):1(v).

3.2.2 INLET DESIGN

Swale inlets need to be suitably designed to prevent localized scour that could be caused by high inflow velocities. While lateral inflow swales generally don't require inlet protection, swales that are fed by pipes or concentrated overland flows require some manner of protection and flow distribution mechanism to mitigate the erosion potential at the inlets. The most common method used for swales is to use a rip rap apron for erosion protection and/or a level spreader for flow distribution. The design of appropriate erosion protection is dependent on the flow characteristics of the incoming pipe or overland flow path. Guidance for this is currently available in Chapter 13 of TP 10.

3.2.3 CHECK DAMS

Check dams are required where the longitudinal slope of the swales exceed 5% to reduce the effective grade. The following formula has been developed to determine the spacing between check dams (Lcd, m) and number of check dams (Ncd) within a swale (USEPA, 2004):

$L_{cd} = 1/S_{eff} \times (h_{cd} / ((S_{act} / S_{eff}) - 1))$ (6)

$N_{cd} = L / L_{cd}$ (7)

Where h_{cd} = the height of the check dams, m;

S_{act} = actual longitudinal slope, m/m;

S_{eff} = effective longitudinal slope, m/m (2% recommended); and

L = total length of the swale, m.

3.2.4 UNDERDRAINS

Where dry swale longitudinal slopes are below 2%, underdrains are recommended to prevent stagnation and saturation of the swale bed. These drains should be constructed along the centerline of the swale underneath the base of the swale topsoil bed. The drains should comprise slotted drainage coil within a trench of drainage aggregate lined with filtercloth constructed at the same grade as the swale (0.5% minimum).

3.3 DESIGN PROCESS

3.3.1 METHOD

The proposed design method is based on the TP 10 method, which uses Manning's equation to ensure that the flow during the water quality design event occurs within the bounds of the criteria recommended in Table 3 above. This represents the generally accepted design method used in the majority of international literature and design guidelines, including those detailed in Table 2. The design process is summarized in Figure 1 and Figure 2 below, with recommended values for the variables contained in Table 3

Figure 1: Design Method Flow Chart for Water Quality Treatment Design

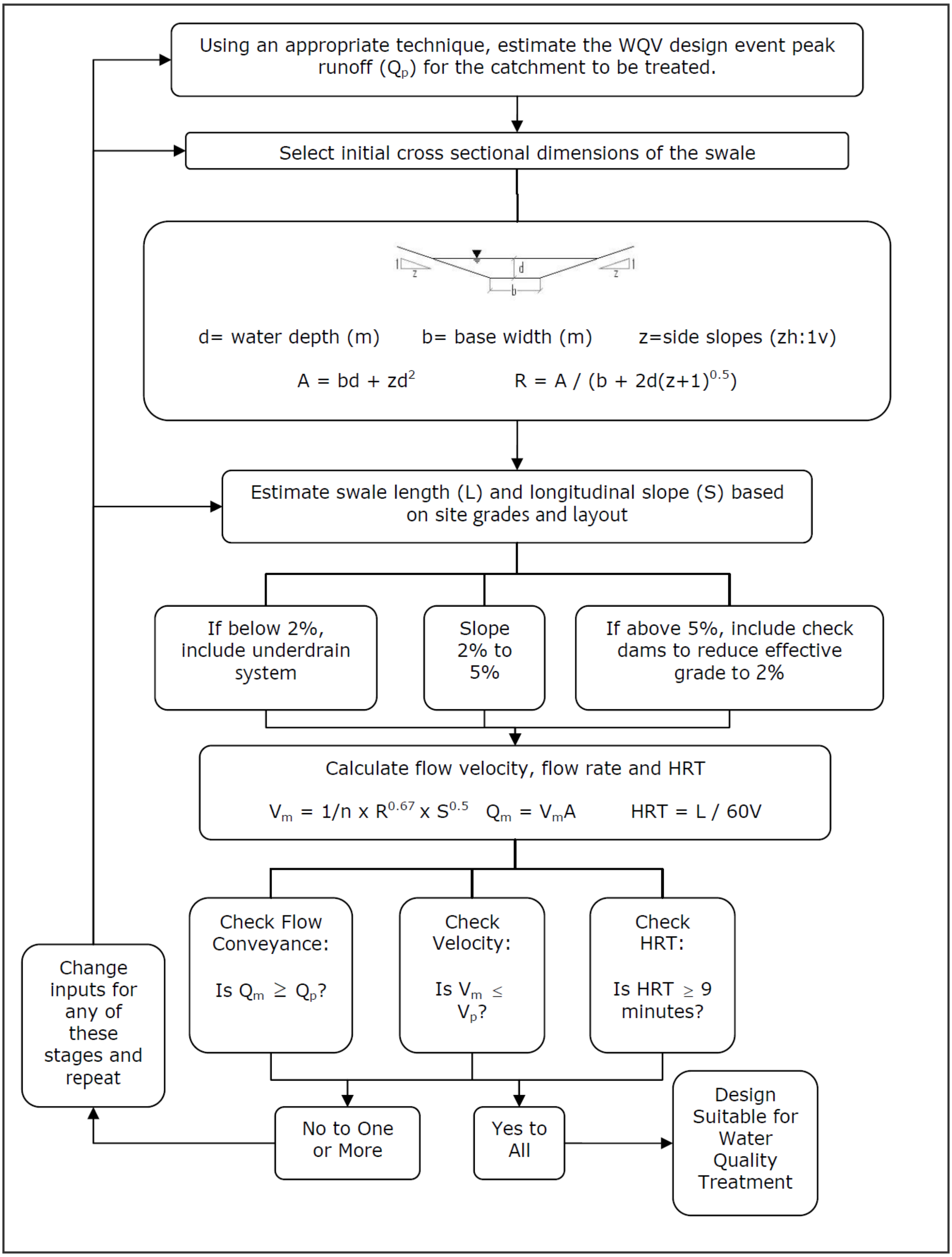
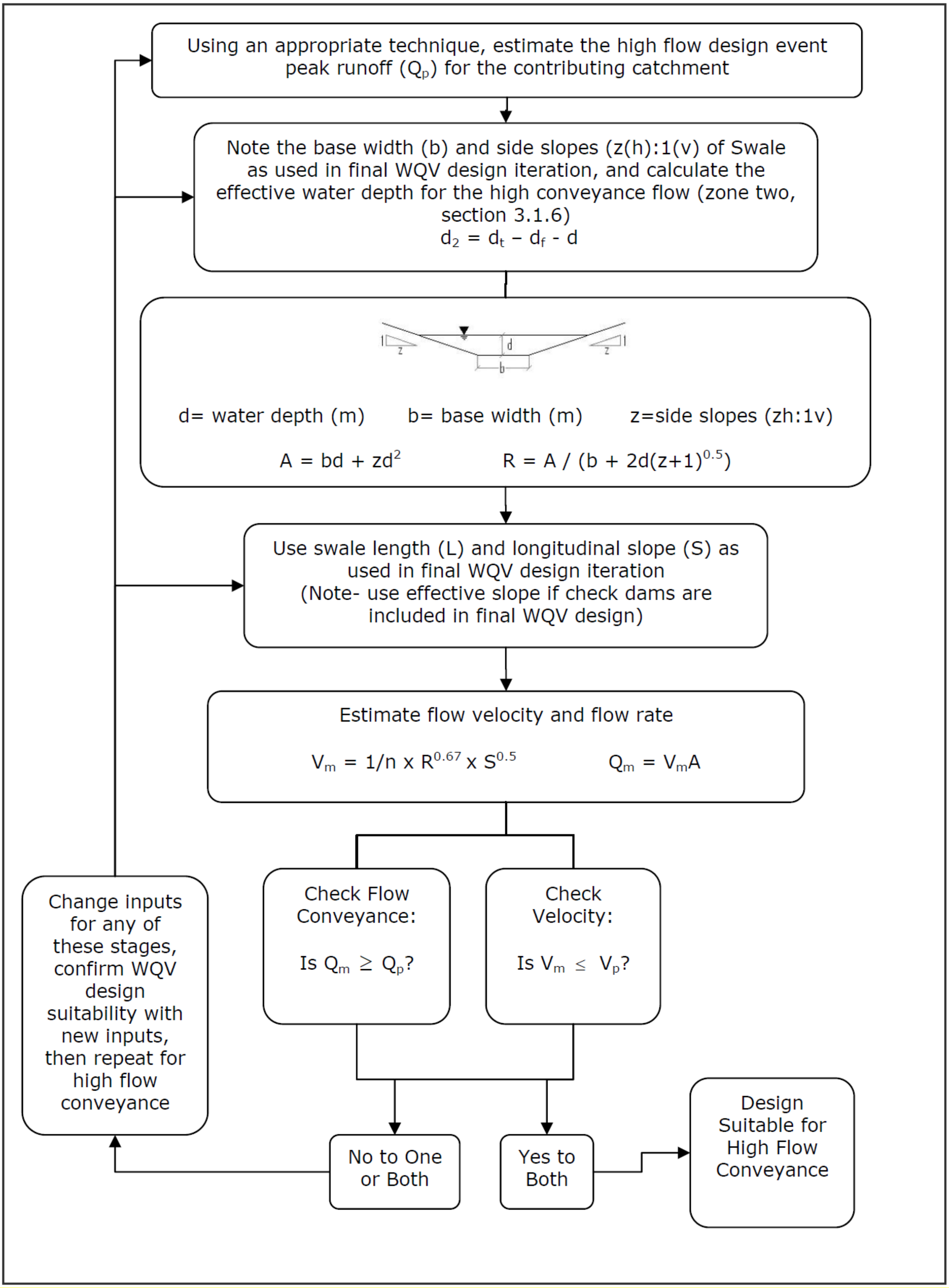


Figure 2: Design Method Flow Chart for High Flow Conveyance Design



3.3.2 ITERATIONS

Where the design checks on the flow rate, velocity and HRT indicate that a change to the inputs are required, the choice of which inputs to change will need to be made based on engineering judgment that takes into account past experience as well as knowledge of what is practical at the site. Table 4 below has been included to provide coarse suggestions for design iteration suggestions depending on the design check that failed.

Table 4: Suggested Design Iterations

Failed Design Check	**Suggested Changes to Design Inputs**
Q_m Q_p	Increase design water depth, base width or side slopes Decrease catchment area draining to the swale
V_m V_p	Decrease actual longitudinal slope Decrease effective longitudinal slope by including check dams
HRT < 9mins	Increase actual swale length or effective swale length by diverting higher proportion of flows to the head of the swale Decrease actual longitudinal slope or effective longitudinal slope by including check dams

4 CONCLUSIONS

The objective of this paper was to summarise the key findings and recommendations of a technical report on stormwater management swales that has been prepared as part of Auckland Council's TP review and update process. This has included a literature review summarising the current state of knowledge of swales sourced both from academic literature as well as existing design guidelines, which was then used to develop a set of design parameters for swale design in the Auckland Region, some of which differ to those contained in TP 10. The design methodology has not been changed, however, new flow charts have been developed to further explain the method.

Based on the use of this design method, it is anticipated that stormwater management swales will generally provide contaminant removal rates in line with those presented in Table 1, which has been reproduced from Table 7 from CWP (2007). Where a specific value is required, it is recommended that the median values are used.

While evidence of hydrological benefit of swales has been presented and discussed, there is currently no accepted method of quantifying this effect in terms of stormwater quantity control, and therefore there is no design methodology available to provide this benefit. Therefore, despite the knowledge that swales provide hydrological benefit, alternative devices will be required for sites that are required to provide water quantity control as part of their development.

ACKNOWLEDGEMENTS

The work presented in this paper was funded by the Auckland Council. Views expressed in this paper are those of the authors and do not necessarily represent policy or position of the Auckland Council.

The authors would also like to thank Roger Seyb of Pattle Delamore Partners and Matthew Davis of Auckland Council for their constructive input through the peer review process.

REFERENCES

Auckland Regional Council (1992). Stormwater Treatment Devices: Design Guideline Manual (1 ed.): Auckland Regional Council.

Auckland Regional Council (2003). Stormwater Management Devices: Design Guideline Manual (2 ed.): Auckland Regional Council.

Backstrom, M. (2002). Sediment transport in grassed swales during simulated runoff events. Water science and technology, 41-49.

Backstrom, M. (2003). Grassed swales for stormwater pollution control during rain and snowmelt. Water science and technology: a journal of the International Association on Water Pollution Research, 48(9), 123.

Backstrom, M., Viklander, M., and Malmqvist, P. (2006). Transport of stormwater pollutants through a roadside grassed swale. Urban Water Journal, 3(2), 55-67.

Clayton, R. and Scheuler, T. (1996). Design of Stormwater Filtering Systems: Center for Watershed Protection, Ellicott City, MD.

Colwell, S. R. (2000). Characterization of performance predictors and evaluation of mowing practices in biofiltration swales.

Centre for Watershed Protection (2007). National Pollutant Removal Performance Database (Vol. 3). Ellicott City, Maryland: Centre for Watershed Protection.

Deletic, A. (1999). Sediment behaviour in grass filter strips. Water science and technology, 39(9), 129-136.

Deletic, A. (2001). Modelling of water and sediment transport over grassed areas. Journal of hydrology, 248(1-4), 168-182.

Deletic, A. (2005). Sediment transport in urban runoff over grassed areas. Journal of hydrology, 301(1-4), 108-122.

Deletic, A., and Fletcher, T. D. (2006). Performance of grass filters used for stormwater treatment - A field and modelling study. Journal of Hydrology, 317(3-4), 261-275.

Fassman, E. A., Liao, M., Shadkam Torbati, S. , and Greatrex, R. (2010). Stormwater Mitigation through a Treatment Train (Final Draft): Prepared by Auckland Uniservices Ltd for Auckland Regional Council TR2010/019.

Khan, Z., Thrush, C., Cohen, P., Kulzer, L., Franklin, R., Field, D., Koon, J., and Horner, R. (1992). Biofiltration swale performance, recommendations, and design considerations. Municipality of Metropolitan Seattle: Water Pollution Control Department.

Kirby, J. T., Durrans, S. R., Pitt, R., and Johnson, P. D. (2005). Hydraulic resistance in grass swales designed for small flow conveyance. Journal of Hydraulic Engineering, 131, 65.

Larcombe, M. (2002). Removal Of Stormwater Contaminants Using Grass Swales. Report for Auckland Regional Council.

Mazer, G., Booth, D., and Ewing, K. (2001). Limitations to vegetation establishment and growth in biofiltration swales. Ecological Engineering, 17(4), 429-443.

Moores, J., Pattinson, P., and Hyde, C. (2010). Enhancing the control of contaminants from New Zealand's roads: results of a road runoff sampling programme. New Zealand Transport Agency.

Nara, Y., and Pitt, R. E. (2005). Sediment Transport in Grass Swales. University of Alabama, Birmingham.

Paterson, J. S. W., and Easton, H. E (2011). Swale Design Review and Recommendations (Draft September 2011): Auckland Council

Portland Bureau of Environmental Services. (2004). Stormwater Management Manual. Portland, Oregon.

Prince George's County (1999). Low Impact Development Hydrologic Analysis, Prince George’s County, Maryland.

Rushton, B. T. (2001). Low-impact parking lot design reduces runoff and pollutant loads. Journal of Water Resources Planning and Management, 127(3), 172-179.

Shaver, E. (2000). Technical Publication 124: Low Impact Design Manual for the Auckland Region: Auckland Regional Council.

Shaver, E. (2009). Stormwater Treatment Standard for State Highway Infrastructure (Draft March 2009): New Zealand Transport Agency.

United States Environmental Protection Agency. (2004). Stormwater Best Management Practice Design Guide: Volume 2 Vegetative Biofilters. Washington DC: Office of Research and Development.

Urban Drainage and Flood Control District. (2008). Urban Storm Drainage Criteria Manual, Volume 3. Structural BMPs. Denver, Colorado.

Virginia Department of Conservation and Recreation (2011). Virginia Stormwater Management Handbook Volumes I and II. Richmond, Virginia: Virginia Department of Conservation and Recreation; Division of Soil and Water Conservation.

Knox County Department of Engineering and Public Works. (2007). Knox Couty Stormwater Management Manual. 2- Technical Guidance.

Washington State Department of Ecology. (2005). Stormwater Management Manual for Western Washington, Volume V Runoff Treatment BMPs: Washington State Department of Ecology, Water Quality Program, Lacey, Washington.

Yu, S. L., Kuo, J. T., Fassman, E. A., and Pan, H. (2001). Field test of grassed swale performance in removing runoff pollution. Journal of Water Resources Planning and Management(May/June 2001).