Proof of Concept Analysis of Level Spreader – Grass Filter Strips for Runoff Reduction

Ian Brodie[1]
[1]Faculty of Engineering and Surveying
University of Southern Queensland
Toowoomba QLD

Abstract

A Water Sensitive Urban Design (WSUD) practice that has been implemented in the United States, mainly in North Carolina and Pennsylvania, is the level spreader – vegetated filter strip (LS-VFS). A typical LS-VFS incorporates a bypass structure that diverts excess stormwater flows, usually to a grassed swale and a concrete channel with a level control weir (level spreader) that evenly distributes flow to a downslope vegetated filter strip designed for stormwater infiltration.

Although many of the different elements of a LS-VFS are easily recognisable, the application of LS-VFS systems in Australia has generally received little attention. Given the absence of local information, this paper provides a 'proof of concept' analysis of LS-VFS systems as applied to South East Queensland conditions. The main focus of the analysis is to determine how compatible LS-VFS systems are in terms of meeting the prescribed WSUD frequent flow targets for urban stormwater discharges.

The paper provides background information on LS-VFS design and performance, sourced from a literature review. Key design requirements are identified. A MUSIC model analysis was performed to evaluate the expected runoff reduction associated with a LS-VFS receiving stormwater from a Brisbane residential subdivision. Indicative criteria are proposed for design discharges, soil suitability and sizing of the filter strip dimensions. Recommendations are made for further research and investigation into the application of the LS-VFS technology in Queensland.

INTRODUCTION

A WSUD practice that has been implemented in the USA, mainly in North Carolina and Pennsylvania, is the level spreader – vegetated filter strip (LS-VFS). Figure 1 shows a typical LS-VFS layout, noting however, that there are many variations to the design. A typical LS-VFS has two main components: 1) the level spreader - a concrete channel with a level control weir or lip that evenly distributes flow overland to 2) the vegetated filter strip that is downslope from the level spreader and allows infiltration of stormwater. LS-VFSs may also have bypass channels (grass swales or similar) to limit the stormwater flow into the level spreader and a forebay to capture coarse sediments which may otherwise block the level spreader.

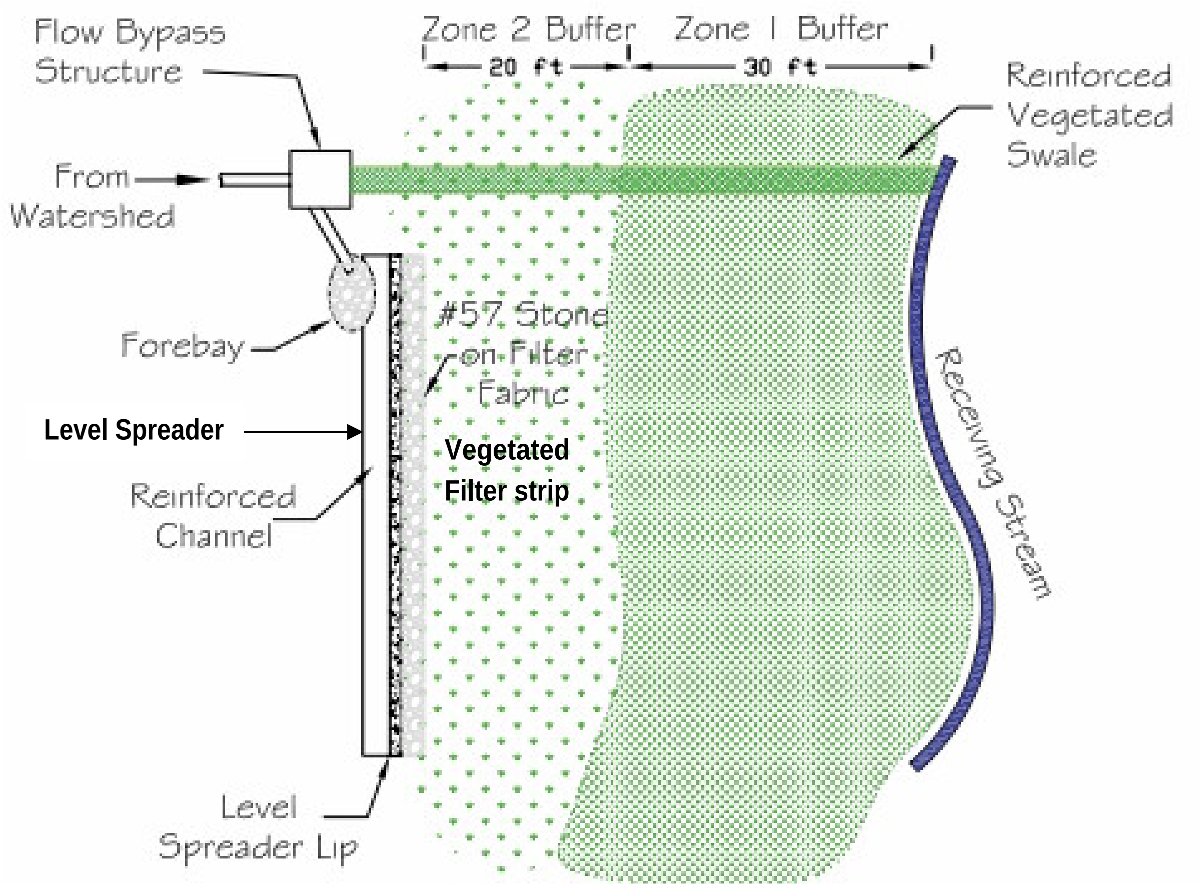

Figure 1 Plan of a LS-VFS (reproduced from Van Der Wiele, 2007)

Although many of the different elements of a LS-VFS are easily recognisable, the application of LS-VFSs in Australia has generally received little attention. Given the absence of local information, this paper provides a 'proof of concept' analysis of LS-VFS as applied to South East Queensland conditions. The main focus of the analysis is to determine how compatible LS-VFSs are in terms of meeting the prescribed WSUD frequent flow targets for urban stormwater discharges (Qld DIP, 2009).

The paper provides background information on LS-VFS design and performance, sourced from a literature review. Key design requirements are identified. A Model for Urban Stormwater Improvement Conceptualisation (MUSIC) model analysis was performed to evaluate the expected runoff reduction associated with a LS-VFS receiving stormwater from a Brisbane residential subdivision. A grassed filter surface was adopted for the MUSIC analysis. Recommendations are made on further research and investigations on the Queensland application of LS-VFS technology.

REVIEW OF LS-VFS DESIGN AND PERFORMANCE

The use of VFS (i.e. without level spreader) to remove pollutants from agricultural runoff has been widely studied and provides a useful starting point. White and Arnold (2009) compiled experimental results from 22 studies and found that soil type, rainfall intensity and runoff loading (total runoff volume/ VFS area, expressed in mm) were key variables affecting runoff reduction. The following empirical relationship was developed by White and Arnold for inclusion in the Soil and Water Assessment Tool using Vegetative Filter Strip Model (VFSMOD) simulations (as insufficient experimental data was available):

RR=75.8 – 10.8 ln(RL)+25.9 ln(KSAT) Equation 1

where RR = runoff reduction (%), RL= runoff loading (mm) and KSAT= saturated hydraulic conductivity (mm/hr) of the filter strip.

Predicted runoff reductions from the White and Arnold study for three soils are presented in Figure 2. Negative reductions (i.e the VFS is a net source of runoff) can occur for low permeability clay soils under moderate loading. Rainfall alone is sufficient to saturate the infiltration capacity of this soil type. Thus, the hydraulic performance of VFS-based systems is very sensitive to infiltration capacity.

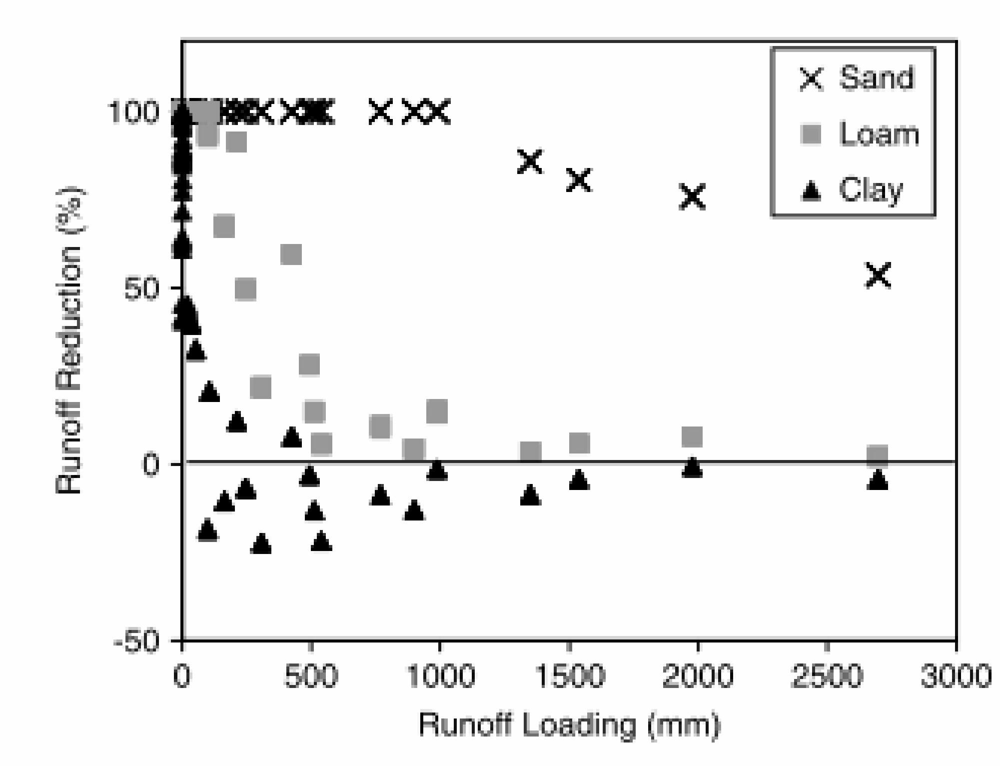

Figure 2 Runoff reduction (%) as a function of runoff loading for three soil types (reproduced from White and Arnold, 2009)

Runoff loading (RL) of Equation 1 is a useful parameter describing the total runoff volume that flows over the VFS surface during an individual storm event. In this paper, it was considered also important to describe the peak discharge over the level spreader – this is defined by the Discharge Loading Rate (QLR) in units of L/s/m: QLR = QP/SL where QP is the peak discharge (L/s) and SL is the spreader crest length (m). Another comparative measure that is introduced in this paper is the Filter Area Ratio: FAR = FA/IA where FA is the surface area of the VFS (m^2) and IA is the impervious surface area of the catchment (m^2).

LS-VFS systems are recognised stormwater best management practices in several US States and a selection of design requirements are summarised in Table 1. There appears to be little consistency in the recommended design discharges and sizing requirements.

Table 1 Basic design requirements of LS-VFS from selected US guidelines

Guideline	Design Discharge	Level Spreader	Grass Filter Strip
Pennsylvania (Rocco 2007)	10 to 100 year ARI (no bypass) Max catchment = 2ha	Expected length range 3-60m 14 m length for every 100 L/s discharge (QLR = 7.1 L/s/m)	Max length = 30m (45m if <1% slope) Max slope = 6% (initial 3m<4%)
North Carolina (Van Der Wiele 2007)	25.4mm/hr storm Bypass to swale	Expected length range 4-40m 14 m length for every 100 L/s discharge (QLR=7.1 L/s/m)	Effective length = 15m Slope 0-8% (initial 3m<4%)
Connecticut (CDEP 2004)	<2 year ARI Max catchment = 0.4ha		Minimum length = 7.6m Slope 2-6%
Maine (MDEP 2006)	32mm-24 hour storm	Max QLR=0.009 cfs/ft = 0.84 L/s/m	Expected length 23-46m Slope <15%

As noted by Winston et al (2010), little research has been completed on measuring the runoff reduction effectiveness of LS-VFS systems. Salient information extracted from studies in North Carolina, Virginia and South Australia is given in Table 2. Size and hydraulic loading measures (FAR, QLR and RL, as defined earlier) have been computed from the published data, so comparisons can be made on an equal basis. In some cases, these measures could not be determined from the data provided.

For a Brisbane residential subdivision, it is expected that an annualised runoff volume reduction of the order of 50 to 65% is required to fully meet the WSUD frequent flow targets (HW, 2007). The limited amount of performance data from North Carolina suggests that a LS-VFS with a Filter Area Ratio FAR of less than 1% would be too small to meet this target.

Table 2 Runoff reduction performance data for grassed LS-VFS monitoring studies (n=number of monitored storms)

Study	Catchment	Level Spreader	Grass Filter Strip	Monitored storms	Runoff reduction
Line and Hunt (2009)- North Carolina	Road and bridge 3.48ha FI=0.49	7.3m long[1]	17.1m long[2] 125m^2 area (FAR 0.73%) 5.2% slope Bermuda grass Sandy soil	n=14 Rainfall 7.4 – 31mm Runoff RL 112-713mm Peak QLR 0.26-2.5 L/s/m	Volume Mean 49% (-11 – 95%) Peak Q Mean 23% (-67 – 80%)
Winston and Hunt (2010) – Louisburg, North Carolina	Highway centre 0.4ha FI=0.73	4m long	7.6m long 30.4m^2 area (FAR 0.85%) Sandy loam with clay subsoil (50 mm/hr)	n=52 Rainfall 1-68mm (median 10.8mm)	[3]For P<12.5mm, Peak Q>65% reduction. Cumulative volume reduction over year ≈40%
Hunt et al (2010) - Charlotte, North Carolina	Residential subdivision 0.87 ha FI=0.45	19.4m long	44.8m long 930 m^2 area (FAR 10.7%) Slope=1.25% Amended sandy loam (60-165 mm/hr)	n=23 Rainfall 2-94.5mm(median 13.5mm) Runoff RL 0.1 -5.6mm	Volume reduction = 100% for 20 storms. Cumulative volume reduction =85%
Yu et al (1993) – Charlottesville, Virginia	Shopping mall 4 ha FI=100%	170 m long	24-30m long 2140 m^2 area (FAR 5.4%) Kentucky grass	n=8 Rainfall 0.5 -95mm	Not reported
Slay (2003) – Mitcham, South Australia	Residential subdivision 4 ha	11.5m long Percolation trench	13.8m long 159 m^2 area (FAR ≈0.8%[4]) Slope=19% Mixed grass	n=5 Low intensity (0.25-5.3 mm/hr)	Not reported
Slay (2003) – Walkerville, South Australia	Residential subdivision 26 ha	35m long Percolation trench	21.5m long 753 m^2 area (FAR ≈0.6%[4]) Slope=6% Kikuyu	n=13	Not reported

Notes: 1. Designed to limit overland flow depth in GFS to 25.4mm for 25.4mm 24-hr duration design storm. 2. Corresponds to minimum flow travel time of 5 minutes for 2 year ARI, 24-hr duration design storm 3. Corresponds to approx r = 1350 mm, assuming IL=1 mm 4. Approximate estimate assuming FI=0.5

A much larger LS-VFS (FAR≈10%) was monitored by Hunt et al (2010) and found to completely intercept runoff from the majority of storm events. It is anticipated that a suitable FAR for the SE Queensland frequent flow target would fall within this indicative range of 1 to 10%. Slay (2003) monitored two LS-VFs systems (FAR <1%) in Adelaide, but did not report runoff reduction. A feature of the Adelaide level spreader design was the use of a gravel-filled percolation trench to evenly distribute flows to the filter strip, rather than a concrete channel.

PROOF OF CONCEPT ANALYSIS APPROACH

The general approach in evaluating the potential of using LS-VFS in South East Queensland was to first establish a suitable design (as expressed by expected values of FAR, QLR etc) and then test this design configuration using MUSIC (Wong et al, 2002). The design configuration was based on the best management guidelines as compiled in Table 1. The hypothetical LS-VFS was assumed to receive stormwater from a Brisbane residential subdivision with a development density of 15 lots/ha. A turf grass, such as kikuyu, with complete coverage on the filter strip was also assumed.

Adopted Filter Strip Area

Selecting the dimensions of the filter strip was the starting point in the proof of concept analysis. Based on Table 1, a 30m strip length down the slope was adopted as longer lengths are expected to produce concentration of flows and hence surface erosion. The length of the level spreader dictates the filter strip width. A 50m strip width was selected (towards the upper end of the expected range). This gives a filter strip surface area FA of 1500m^2.

Adopted discharge loading rate and design discharge

The selected design guidelines (Table 1) point towards limiting QLR to values as low as <1 L/s/m to up to 7.1 L/s/m. These design QLRs are based on ensuring non-erosive flow conditions within the filter strip, which are specific to the vegetation type. A design QLR equal to 7.1 L/s/m was used as it relates to dense grass cover with no existing erosion sites (Rocco, 2007). In conjunction with the adopted 30m strip length, this assumption leads to a design discharge of 0.35 m^3/s.

Adopted Residential Catchment, Target Reduction and Runoff Loading

A Residential 'A' Greenfield catchment with a development density of 15 lots/ha was selected. This is consistent with Healthy Waterways (2007) as being a common development type in South East Queensland. Regional MUSIC modelling guidelines (Healthy Waterways, 2009) can be used to generate the expected fraction impervious of the catchment (0.56 from Table 3).

As the fraction impervious exceeds 40%, the hypothetical residential subdivision should have measures in place to capture the equivalent of 15mm/day runoff from the impervious surfaces (Healthy Waterways, 2007). Captured stormwater should be extracted from storage within 24 hours in readiness for the next storm.

Table 3 Fraction impervious for hypothetical Brisbane Residential A subdivision

Surface type	Surface FI (% of surface area)	Surface composition (% of total catchment)	FI contribution (% of total catchment)
Road reserve	60	25	15
Roof	100	32.5	32.5
Ground level	20	42.5	8.5
Total FI			56

The catchment area can be back-calculated, as the design discharge has been established (0.35 m^3/s). A nominal 20-minute time of concentration is adopted for the residential subdivision. It is assumed that the LS-VFS would need to have sufficient hydraulic capacity to handle a design storm corresponding to the time of concentration. The adopted time of 20 minutes is significantly shorter than the storm durations used in US design (typically 1 hour to 24 hour, Table 1), but is considered appropriate to the subtropical rainfall climate of Brisbane where short duration-high intensity storms are not uncommon. Ignoring the relatively small losses associated with impervious surfaces, the corresponding design rainfall intensity is 15mm/20 minutes or 45 mm/hr. To put this intensity in perspective, the 1 year ARI-20 minute design rainfall intensity at Brisbane Aero is 67 mm/hr. This places the adopted design rainfall intensity at less than 1 year ARI, which is considered appropriate for WSUD design.

Using the Rational Method, the impervious area IA can be estimated to be 2.8ha. This gives a total catchment area for the residential subdivision equal to 5 ha (as FI=0.56). A catchment of this size is comparable to actual LS-VFS system catchments monitored in USA and South Australia (Table 2). The estimated FAR is 5.3% (within the 1-10% range expected to meet the frequent flow targets). The target runoff volume (15mm x 2.8ha impervious area) is 420 m^3, which gives a runoff loading RL of 280mm for the adopted 1500m^2 filter strip. As indicated by Figure 2, there is scope for reasonable runoff flow reductions at this loading for non-clay soils.

MUSIC ANALYSIS

Rainfall Data and Model Scenarios

MUSIC is the model of choice for WSUD evaluation in South East Queensland and was used to model the hypothetical Brisbane LS-VFS. Rainfall data at 6-minute increments recorded at Brisbane Aero for the year 1990 was used in the simulation, together with daily potential evapotranspiration data. These datasets accompany the MUSIC version 4 software. Monthly rainfalls are given in Table 4. Rainfalls in 1990 were wetter than average.

Table 4 Monthly Rainfalls (mm) for 040223 Brisbane Aero

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1990	127	359	193	207	171	80	37	7.6	6.0	41	55	85	1370
Mean	158	175	139	90	99	71	63	43	35	94	97	126	1190

Modelling of runoff generation from the 5ha residential catchment was performed in accordance to regional guidelines (Healthy Waterways, 2009). LS-VFS is not specifically included as one of the available MUSIC treatment nodes, so the filter strip was simply modelled as a broad, shallow grass swale. A mown grass (50mm height) and a 5% filter surface slope were used in the analysis. Flows exceeding 0.35 m^3/s were bypassed.

The MUSIC modelling that was undertaken was a preliminary 'proof of concept' analysis and is expected to provide conservative estimates of LS-VFS performance. In the analysis it was assumed that the LS-VFS was the sole WSUD measure which is typically not the case. For example, rainfall tanks are a mandatory requirement under the Queensland Development Code but these were not included in the analysed scenarios.

Four development scenarios were evaluated; 1) No development – assuming all the catchment was pervious, 2) Residential A with no stormwater controls, 3) Residential A with 15mm stormwater capture and controlled release over 24 hours, consistent with the SE Queensland frequent flow management target and 4) Residential A with LS-VFS. The infiltration rate of the filter strip in Scenario 4 was adjusted until the runoff generation mimicked that for Scenario 1. A range of indicators (Table 5) were applied in comparing the predicted flows from each development scenario.

Table 5 Selected indicators for frequent flow management

Indicators	Description
Annual Runoff Volume	Cumulative flow volume over the full year period (mm/yr)
No runoff occurrence	Proportion of time that no runoff (<0.1mm/day) occurs during the full year period (%)
Relative Frequency 0.1-1mm	Ratio of the number of days that runoff between 0.1 to 1mm/day was generated and the number of simulation days (%)
Relative Frequency 1-5mm	Ratio of the number of days that runoff between 1 to 5mm/day was generated and the number of simulation days (%)
Relative Frequency 5-15mm	Ratio of the number of days that runoff between 5 to 15mm/day was generated and the number of simulation days (%)
Relative Frequency>15mm	Ratio of the number of days that runoff exceeding 15mm/day was generated and the number of simulation days (%)
Peak Q1	Peak discharge corresponding to period of 1 hour 1 year ARI rainfall intensity[1] (m^3/s)

Notes: 1. This rainfall corresponds to 36.9mm/hr and occurred within the simulation at 9.00, 24/02/1999.

MUSIC Model Results and Discussion

MUSIC model estimates of daily runoff plotted against daily rainfall for each development scenario are presented in Figure 3. Under the No Development scenario assuming 100% pervious catchment, minimal runoff occurs for rainfalls less than 25mm/day. There is significant scatter in the runoff response to larger rainfalls as soil moisture conditions at the commencement of rainfall differ between events. The Residential A No Control scenario shows a more linear trend with runoff being initiated at low rainfalls.

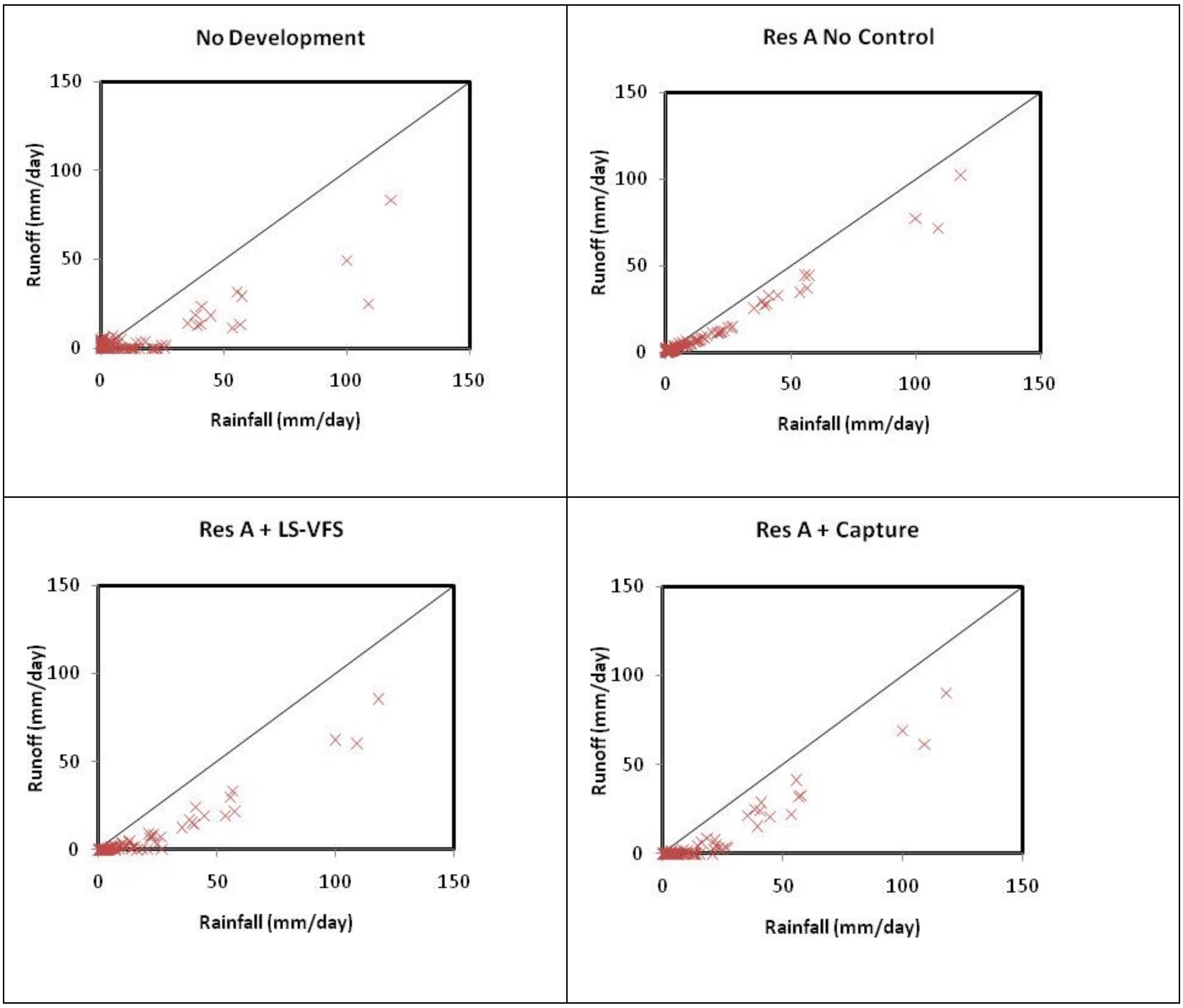

Figure 3 Rainfall-Runoff plots for adopted development scenarios

Predicted flow indicators for each scenario are presented in Table 6. The No Development scenario represents the flow management benchmark with no runoff 75% of time. In this analysis, daily runoff less than 0.1mm is regarded as a trace, and included as no runoff. Residential A with No Control increases the annual runoff volume by approx 80% with runoff occurring on more days. Relative frequency increased, although the increase in the 1 to 5mm range was not as marked as predicted for the other runoff ranges. A relatively small increase in Peak Q1 was estimated; this may be due to elevated antecedent soil moisture conditions coinciding with this individual event within the historical simulation period.

Table 6 Flow indicators estimated by MUSIC analysis of four development scenarios

Indicators	No Development	Residential A No Control	Residential A Capture[1]	Residential A LS-VFS[2]
Annual Runoff Volume	516 mm	937 mm	540 mm	513 mm
No runoff occurrence	75.1%	63.0%	91.5%	83.3%
Rel. Frequency 0.1-1mm	7.4%	12.9%	1.4%	6.3%
Rel. Frequency 1-5mm	11.8%	13.7%	2.7%	5.2%
Rel. Frequency 5-15mm	3.6%	6.8%	0.8%	2.2%
Rel. Frequency >15mm	2.2%	3.6%	3.6%	3.0%
Peak Q1	1.08 m^3/s	1.11 m^3/s	0.99 m^3/s	1.07 m^3/s

Notes: 1. Capture of 15mm with emptying of storage within 24 hours 2.Infiltration rate of filter strip = 50 mm/hr (sandy loam)

Residential A with Capture is in accordance to the prescribed frequent flow requirements of capturing the first 15mm of runoff (HW, 2009). This strategy reduces the annual runoff volume generated from the developed catchment to close to the No Development benchmark. The proportion of time no runoff occurred increased significantly from 75% to 92%. Rapid drawdown of the capture storage (within 24 hours) means that this approach is efficient in intercepting almost all runoff for small-to-moderate rainfalls. This outcome is reflected by the substantially reduced frequency across all runoff ranges less than 15mm (compared to No Development). Runoff capture has no effect of reducing the frequency of Residential A runoff exceeding 15mm/day, although some decrease in Peak Q1 is predicted.

The infiltration rate of the grass filter was adjusted in the Residential A with LS-VFS scenario until the annual runoff volume matched the No Development Scenario. This was achieved with 50 mm/hr infiltration, which is representative of the saturated hydraulic conductivity of a sandy loam soil (eWater, 2009). However, the subgrade soil would need to have a similar saturated hydraulic conductivity to achieve these results. Compared with Residential A with Capture, the LS-VFS had the effect of mitigating, but not completely intercepting, the runoff from small-moderate rainfalls (<15mm), which lead to a closer reproduction of the No Development runoff frequency. The LS-VFS strategy also performed better in terms of occurrence of no runoff.

CONCLUDING REMARKS

The MUSIC analysis suggests that LS-VFSs can play a viable role in achieving WSUD frequent flow management objectives set for South East Queensland. It was predicted that a grassed filter strip (50m wide by 30m long, 5% slope) is expected to be a feasible runoff reduction option for a Brisbane Residential A subdivision (15 lots/ha) with a 5ha catchment area. An infiltration rate of at least 50mm/hr into the filter strip would be required. Theoretically, the LS-VFS performed better in mimicking pre-development hydrology than an equivalent 'capture and release' strategy sized in accordance to meet SE Queensland frequent flow management targets.

The footprint of the filter strip is equivalent to 5.3% of the impervious surface area of the residential subdivision. This footprint is relatively large for a flow reduction measure when compared with possible alternatives such as detention basins or more compact underground storages. The role of LS-VFS in achieving additional WSUD objectives such as pollution reduction, as well as other potential benefits such as the 'passive' irrigation of green open space within the VFS, would need to be considered to enhance the overall viability of LS-VFS.

This proof of concept analysis indicates that LS-VFS has promise as a WSUD measure within South East Queensland and further research is warranted. This research could include:

- Investigation into the pollution reduction and passive irrigation benefits of these systems
- Installing and monitoring a LS-VFS within the local region to confirm performance
- Providing better methods of predictive analysis, such as developing a LS-VFS treatment node for the MUSIC model. The analysis in this paper is based on a 'grass swale' MUSIC treatment node which uses a constant infiltration rate into the VFS surface. This is simplistic as actual infiltration will vary with soil moisture conditions and other factors.

REFERENCES

CDEP (2004). Vegetated Filter Strips and Level Spreaders, In Connecticut Stormwater Quality Manual, Connecticut Department of Environmental Protection

eWater (2009). MUSIC Version 4 User Manual.

Healthy Waterways (2007). Water Sensitive Urban Design – Developing Design Objectives for Urban Development in South East Queensland, Water By Design Publication, November 2007.

Healthy Waterways (2009). MUSIC Modelling Guidelines for South East Queensland, Water By Design Publication, December 2009.

Hunt, W.F., J.M. Hathaway, R.J. Winston and S.J. Jadlocki (2010). ‘Runoff Volume Reduction by a Level Spreader-Vegetated Filter Strip System in Suburban Charlotte, N.C.’ Journal of Hydrologic Engineering, Vol . 15, No. 6, pp 499-503.

MDEP (2006). Stormwater Management for Maine: Volume III BMPs technical design manual. Maine Department of Environmental Protection. Augusta, Maine

Qld DIP (2009). South East Queensland Regional Plan 2009 -2031 - Implementation Guideline No. 7 - Water Sensitive Urban Design: Design Objectives for Urban Stormwater Management, Queensland Department of Infrastructure and Planning, Brisbane.

Rocco, D. (2007). Level Spreaders and Off-Site Discharges of Stormwater to Non-Surface Waters. Watershed Management Program, Pennsylvania Department of Environmental Protection.

Slay, P.G.R. (2003). Grass Filtration – An Innovative Approach to the Treatment of Urban Storm Water. M.Eng.Sci. Thesis, University of Adelaide.

Van Der Wiele, C.F. (2007). Level Spreader Design Guidelines, Final Version Effective Date January 1 2007, North Carolina Division of Water Quality.

White M.J. and J.G. Arnold (2009). ‘Development of a Simplistic Vegetative Filter Strip Model for Sediment and Nutrient Retention at the Field Scale’. Hydrological Processes, Vol. 23, pp. 1602-1616.

Winston, R.J., W.F. Hunt, D.L. Osmond, W.G. Lord and M.D, Woodward (2010). ‘Field Evaluation of Four Level Spreader- Vegetative Filter Strips to Improve Urban Stormwater Quality’. Journal of Irrigation and Drainage Engineering, Vol . 137, Issue 3, pp 170-182.

Winston, R.J. and W.F. Hunt (2010). ‘Low Impact Development Benefits of Level Spreader-Vegetative Filter Strip Systems‘. ASCE Low Impact Development 2010, Redefining Water in the City, April 11-14 2010, San Francisco, USA.

Wong T.H.F., T.D. Fletcher, H.P. Duncan, J.R. Coleman and G.A. Jenkins (2002). ‘A Model for Urban Stormwater Improvement Conceptualisation’. Proceedings of the International Environmental Modelling and Software Society, Lugano, Switzerland, pp. 48-53.

Yu, S.L., M.A. Kasnick and M.R. Byrne (2003). A Level Spreader/Vegetative Buffer Strip System for Urban Stormwater Management. In Integrated Stormwater Management, ed. R. Field, M.L. O’Shea and K.K. Chin, Boca Raton, Florida, Lewis Publishers