HYDROLOGY OF URBAN DEVELOPMENT: WHAT MEASURES, WHAT OUTCOMES?

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ABSTRACT

There is increasing awareness in the stormwater industry of the more subtle long term effects of urban development on urban stream morphology and ecology. Historically we have moved from a flood management approach, through stormwater quality improvement to water sensitive design (WSD) and sustainable management of urban streams. The recent Auckland Unitary Plan included measures targeted at protecting higher value streams.

Despite increased awareness, the practicality of implementing effective measures through statutory and design processes remains a challenge, with outcomes still uncertain. In part this is due to two factors: the difficulty of fully addressing the principle of hydrological neutrality; and the complexity of assessing the effectiveness of those measures on diverse stream environments in terms of base flow, erosion and ecology.

The underlying mechanisms typically used within WSD are retention, extended detention and peak flow attenuation, with treatment design contributing to the mix. While there are guidelines in place for such devices, rules vary across the country, and are typically borrowed and reinterpreted from elsewhere, rather than being validated for a region or site. There appears to be little hydrological simulation to support the design guides.

This paper has drawn on the earlier work investigating urban hydrology and stream erosion that lies behind the current TP10 extended detention requirements. It explores the relative effects of retention and extended detention on stream response to frequent rainfall events, and uses simplified continuous simulation to explore the relative effects of sizing parameters and configuration on the frequency of runoff events and the long term flow duration curve. It is not a comprehensive study, but rather is intended to inform regulators on potential outcomes of their decisions, and spark further analytical investigation into this important subject.

KEYWORDS

Continuous simulation, retention, extended detention, hydrological neutrality, stream erosion

PRESENTER PROFILES

Dr Cameron Oliver has over four years' experience in hydrological and hydraulic modelling for a variety of sectors, including mining, irrigation and public sector infrastructure. Cameron has been involved in water balance modelling, erosion protection design and transient modelling. His PhD research analysed the mixing behaviour of desalination brine outfalls.

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1 INTRODUCTION

Urban development, with its associated increases in impervious ground areas, leads to increases in stormwater runoff volumes and peak flows. In New Zealand the Resource Management Act (1991) requires developers to address the potential for increased risk of damage to other land as a result of inundation or discharge. Local body guidelines generally adapt this principle to specify that during specific events the post-development peak runoff flow rate may not exceed the pre development flow rate, or some percentage thereof. Satisfying such a requirement has been described by some as achieving "hydrological neutrality".

Mitigation approaches available to the stormwater designer can be broadly categorised as a) those that reduce the volume of stormwater ("retention"); and b) those that reduce peak flows but do not change discharge volume. The former group may include soakage to ground from rainwater gardens or pits, or slow abstraction from stored runoff for some other usage. A certain volume may in some cases be maintained permanently for water quality or aesthetic reasons, but this has little effect on discharge flow rates.

The latter group may be further broken down as:

- Extended Detention (ED): water from a typical storm captured in a basin and slowly released downstream over a period of time; *and*
- Peak Flow Attenuation (PFA): water captured and released in such a manner as to reduce flow rate during flood events, such as in a 2 year or a 100 year event.

Council guidelines vary on the end goals that are in view: peak flow attenuation has historically been a focus, but in recent years there has been a shift towards water quality and sustainable management of urban streams. Generally guidelines stipulate specific flood events that devices must achieve a certain performance under.

While such an approach brings many favourable outcomes, its weakness is that long term system behaviour is rarely investigated. The assumption is that if performance is adequate under a limited number of specific design storm events it will also be appropriate under other conditions. This poses the risk of misunderstanding the effect of typical flows in smaller storms, but also introduces the possibility of sizing mitigation measures inappropriately with respect to the range of site-specific meteorological or hydrological data available.

This study is a conceptual modelling exercise aimed at exploring long term system behaviour of mitigation designed for a typical urban development. With a focus on retention and ED devices, the effect of various sizing parameters are investigated over a 31 year period, including a wide spectrum of runoff event sizes, using a historical rainfall record. As a proxy for assessing relative risk of land damage due to flooding, one and two year peak flow rates will be discussed. Flows at this level are considered to be the "bank-full" or "channel forming" flow for typical streams (see for example Henderson, 1966 p. 465); beyond which erosion becomes significantly more likely.

In order to constrain the scope of this study a number of important issues have been parked. Amongst other limitations, stream base flow is not included in the runoff modelling due to the difficulty of defining and calibrating this appropriately. Water quality performance is also ignored in the results analysis, although continuous simulation could be useful for understanding performance of different sized devices in capturing a spectrum of events.

2 METHODOLOGY

2.1 RUNOFF MODELLING

Table 1 presents area and time of concentration data assumed in this study, aimed at approximating a typical Waikato catchment developed for residential use. Pre development conditions are assumed to be 100% pervious.

Table 1: Area and time of concentration for pre and post development model runs

	Pre development	**Post development**			
	Pervious	**Roofs**	**Roads**	**Impervious not captured**	**Pervious**
Area (ha)	78	24	10	13	30
Time of concentration (min)	60	15	15	15	30

Modelling was undertaken using HEC-HMS, both for hydrology and for device hydraulic performance. Hourly rainfall and potential evapotranspiration (PET) records from Ruakura Research Station were obtained for the period 1986 to 2016 inclusive (31 years). Loss from pervious areas was represented by the 'Deficit and Constant Loss' model, which allows both runoff and aquifer infiltration to occur only when the soil is saturated. In this model soil moisture is depleted by evaporation, down to a depth equal to the Profile Available Water (PAW) for the site. Loss from impervious areas was conservatively assumed to be 100%. Finally the SCS Unit Hydrograph transform was utilised for routing purposes.

While the Deficit and Constant Loss model is appropriate for continuous simulation and is conceptually simple with only has two variables, its weaknesses include:

- No limit on rate at which soil moisture can increase. In reality soakage of rainfall into the rooting zone (forming PAW) can only happen at a certain rate, which in turn depends on antecedent conditions; *and*
- A constant infiltration rate is assumed.

Because of these weaknesses it proved difficult to determine soil moisture depth and infiltration rate values that generated acceptable runoff results when utilising ongoing rainfall and PET records. Ideally runoff would be calibrated against gauging data, however this is rarely an option for urban development projects. Here the approach taken was to visually and statistically compare pre development runoff from two rainfall events (2 year and 2 month recurrence intervals respectively) to runoff modelled for the same by the SCS method, which assumes "medium" antecedent conditions. Values were nominally chosen to be 20 mm for soil moisture depth and 5 mm/hr for infiltration rate.

As discussed earlier, stream base flow was not modelled for the current study. While this has a significant impact on lower more frequent flow rates—without base flow streams quickly run dry—if it is defined incorrectly there is a risk of making incorrect deductions from simulation results.

2.2 POND DESIGN

Retention ponds were modelled on a lumped basis; i.e. one large device was assumed even though in reality many smaller devices would be built. Extended detention (ED) and peak flow attenuation (PFA) functions were designed in a combined pond. The design was undertaken according to standard guidelines as if this were a subdivision design, rather than using the model to refine the design.

Retention pond volume was computed by multiplying the relevant capture area by a chosen depth of retention (see Section 2.4 for scenario values). A fixed 24 hour drain down time was assumed, and therefore infiltration rate was determined by dividing the depth of retention by this duration.

ED capture volume for a given event depth was calculated using TP10 (ARC, 2003 Section 5.5) with SCS values of 74 for pervious surfaces and 98 for impervious surfaces. Assuming a nominal ED depth of 1 metre and a maximum release rate twice the average release rate (as per TP10), an orifice size was computed for a given drain-down time.

PFA capacity was situated above the ED volume (i.e. assuming ED is full before the peak flow event begins) and was designed to achieve 80% peak attenuation during 2 year and 100 year nested storms, following the Hamilton City Council Standard Stormwater Modelling Methodology (May 2013). Assuming a nominal water depth of 1 metre to attenuate the 2 year event and 2 metres to attenuate the 100 year event, weir widths were determined that achieved necessary peak discharge rates during respective events. Volume to the top of each weir was determined by taking the maximum storage required for a range of rainfall durations[1] under post-development conditions, again assuming a maximum release rate twice the average release rate.

2.3 MODEL SETUP

Hydrologic and hydraulic modelling was carried out using HEC-HMS version 4.2 at a 1 hour time step. A screenshot of model configuration is given in Figure 1. Retention and ED drawdown was verified to occur in HEC-HMS over the correct duration.

[1] Rainfall intensities for nominal local taken from NIWA High Intensity Rainfall System, https://hirds.niwa.co.nz/

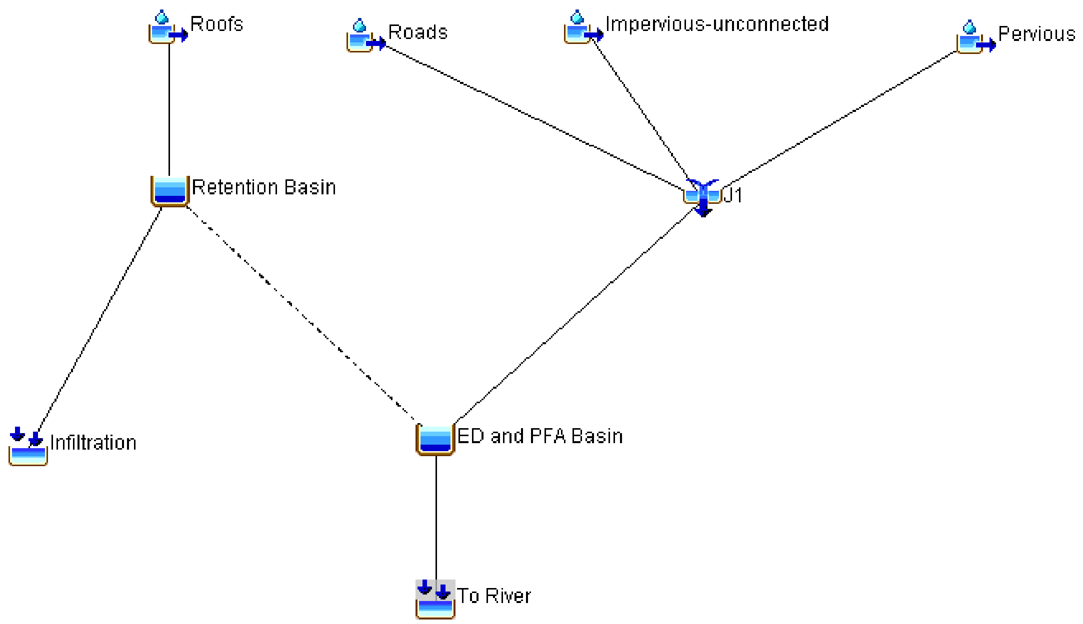

Figure 1: HEC-HMS setup screenshot for typical post-development with mitigation models

2.4 SCENARIOS

Five variables were investigated by this study: retention depth, area subject to retention, ED depth, ED drawdown period, and whether or not PFA is included. A "base case" scenario (S1) was run with nominal values for each parameter, and six scenarios (S2 to S7) adjust one parameter at a time while holding all others at the value used for S1. A further three scenarios (S8 to S10) disable components one at a time. Table 2 lists all scenario parameter values.

Table 2: Scenario variables for present study. Grey cells highlight changes from S1

Scenario	**Retention depth (mm)**	**Retention area**	**ED depth (mm)**	**ED duration (hrs)**	**PFA included**
S1	5	Roofs	34.5	24	Yes
S2	10	Roofs	34.5	24	Yes
S3	15	Roofs	34.5	24	Yes
S4	5	Roofs and roads	34.5	24	Yes
S5	5	Roofs	15	24	Yes
S6	5	Roofs	25	24	Yes
S7	5	Roofs	34.5	48	Yes
S8	(None)				Yes
S9	5	Roofs	(None)		
S10	5	Roofs	34.5	24	No

3 MODELLING RESULTS

When modelling system behaviour for a single design event, detailed hyetograph and hydrograph information can be interrogated for insight. For this study, with 31 years of data at hourly intervals, such an approach was infeasible. Instead it was necessary to look at bulk statistics and plots. A key tool that is used here is the duration curve, as commonly used for hydrological and meteorological data. This graph orders all data and presents the percentage of time that the record value is equal to or greater than a specified level. Flows that occur less than 2% of the time are analysed because this range offers the resolution of both flood events with the potential for stream erosion and of device drawdown behaviour. In addition this range is not significantly affected by the lack of base flow.

3.1 BASE CASE

Figure 2 presents a duration curve plot for flow downstream of the ED and PFA basin (i.e. "To River" in Figure 1) under pre development, post development unmitigated and scenario S1 conditions.

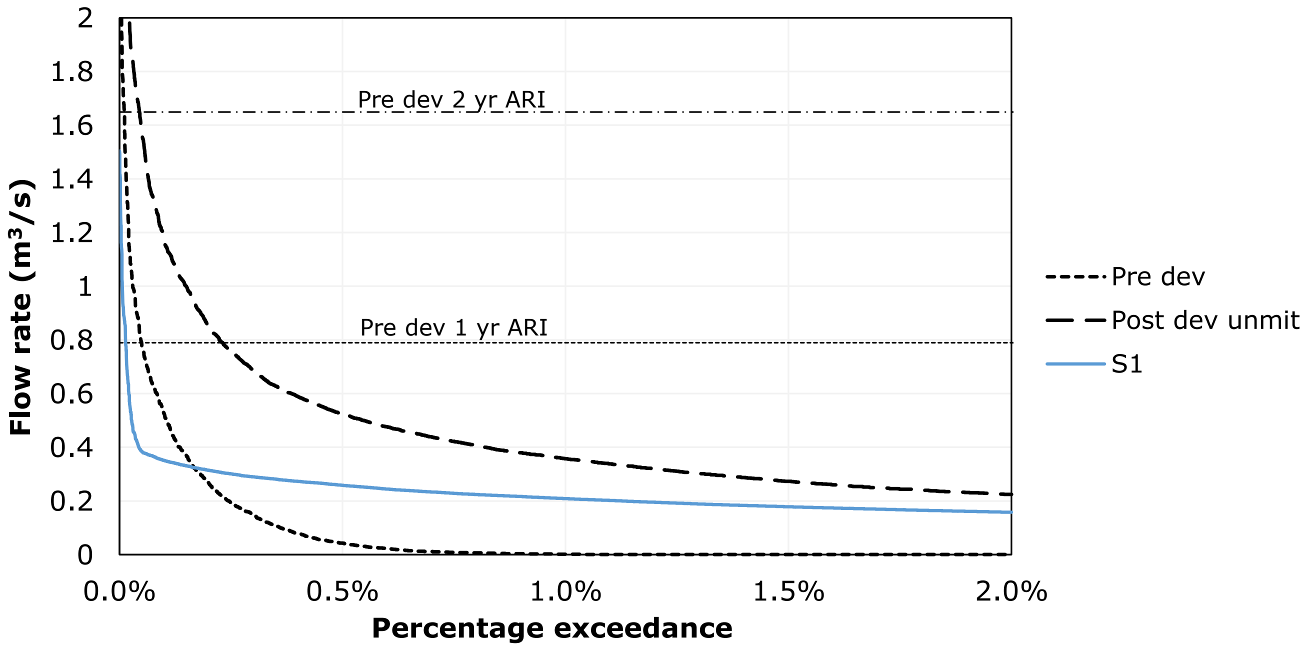

Figure 2: Flow duration curves for pre development, post development unmitigated, and post development base case mitigation scenario (S1)

The only difference between pre development and post development unmitigated scenarios is the change in imperviousness (0% pre development and 62% post development). Increasing imperviousness has three effects on runoff:

- Lowering the time of concentration;
- Increasing the peak runoff flow rate; *and*
- Increasing the number of events that generate runoff.

Time of concentration changes cannot be seen in a duration curve, however Figure 2 does show significantly higher post development flow rates in the 0 to 2% exceedance range. Flow can also be seen to occur over a longer percentage of the record. It should be re-iterated that stream base flow is not modelled: if it were, stream flow would occur even during events that do not generate surface runoff.

In volumetric terms, the effect of development is seen as the area between pre development and post development unmitigated curves. "Hydrological neutrality" in its most complete sense would involve returning post development runoff to exactly its pre development behaviour; however amongst other issues, this would require the increase in volume to be fully infiltrated or redirected elsewhere. Invariably this is not practicable. While small-scale retention devices in the form of rain gardens or similar are increasingly installed, for medium to large runoff events the focus is on attenuation. With respect to duration curves such as seen in Figure 2, the aim is primarily to re-shape the line; making large flows less common but allowing "smaller" flows to occur more frequently.

The scenario S1 curve in Figure 2 therefore represents a typical re-shaped post development curve. The cumulative effects of retention, detention and extended detention are seen here in:

- Lowering flow rates below pre development between 0% and 0.15% exceedance levels; *and*
- Allowing flow rates to be increased above pre development levels beyond 0.15% exceedance.

Note that because PFA devices were designed to reduce peak flows to 80% of pre development levels during 2 and 100 year nested storms, it can be expected that S1 would reduce flows below that of pre development for at least some of the duration curve. With respect to erosion, the statistic of interest is the length of time spent at flow rates equal to or greater than the erosion threshold (nominally assumed as the 1 year pre development level, 0.8 m^3/s). Here we see that S1 out-performs the pre development scenario by a factor of approximately three, suggesting that despite the increase in runoff volume overall, erosion risk could be less than before development began. Consequently we may deduce that flow attenuation occurs for a greater period of the time and to a greater extent than necessary.

Figure 3 plots the same data as in Figure 2 but extends the horizontal axis out to 25% and restricts the vertical axis scale. Recalling the lack of base flow we can observe that mitigation causes flow rates to be increased even above post development unmitigated levels beyond approximately 6% exceedance. Modelled flow volume is 26% less in S1 than in post development unmitigated, demonstrating the effect of retention. As volume is equal to the area under the duration curve it can be observed that this volume difference is primarily seen in the reduction of higher flows, where erosion is a risk.

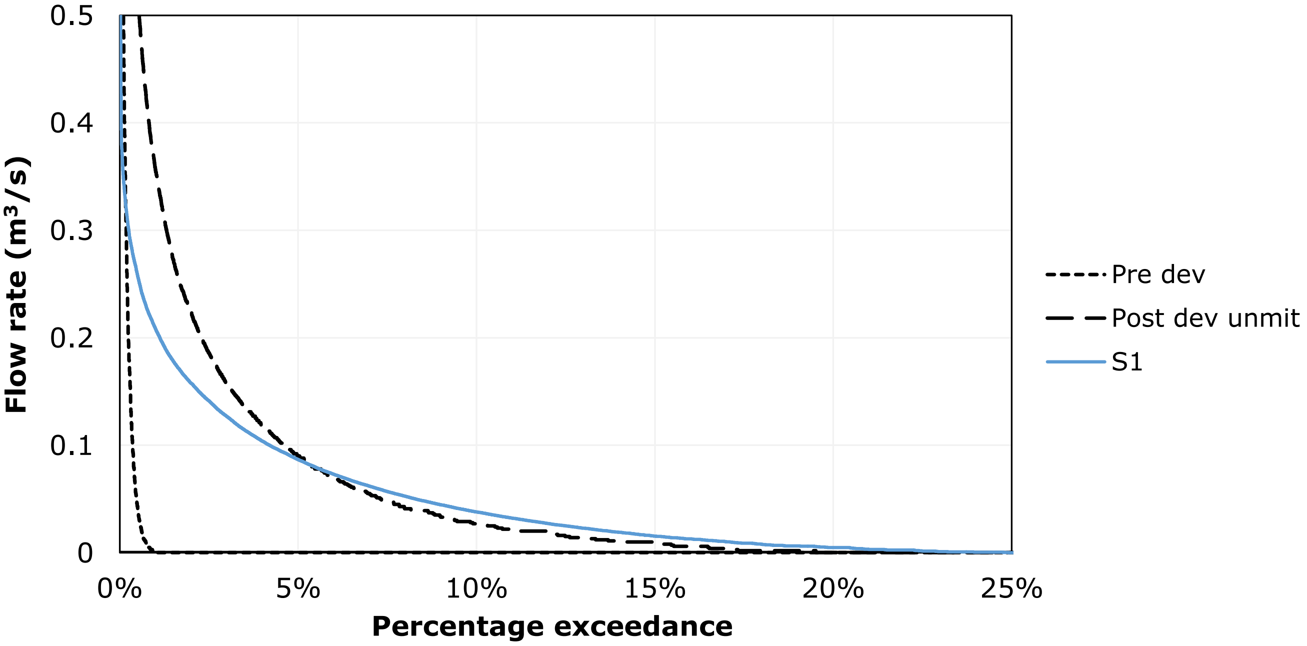

Figure 3: Data from Figure 2 plotted to 25% exceedance

3.2 CONTRIBUTION OF INDIVIDUAL COMPONENTS

Figure 4 plots duration curves for the base case scenario (S1) against scenarios with the same variables but where retention, extended detention and/or peak flow attenuation components have been disabled.

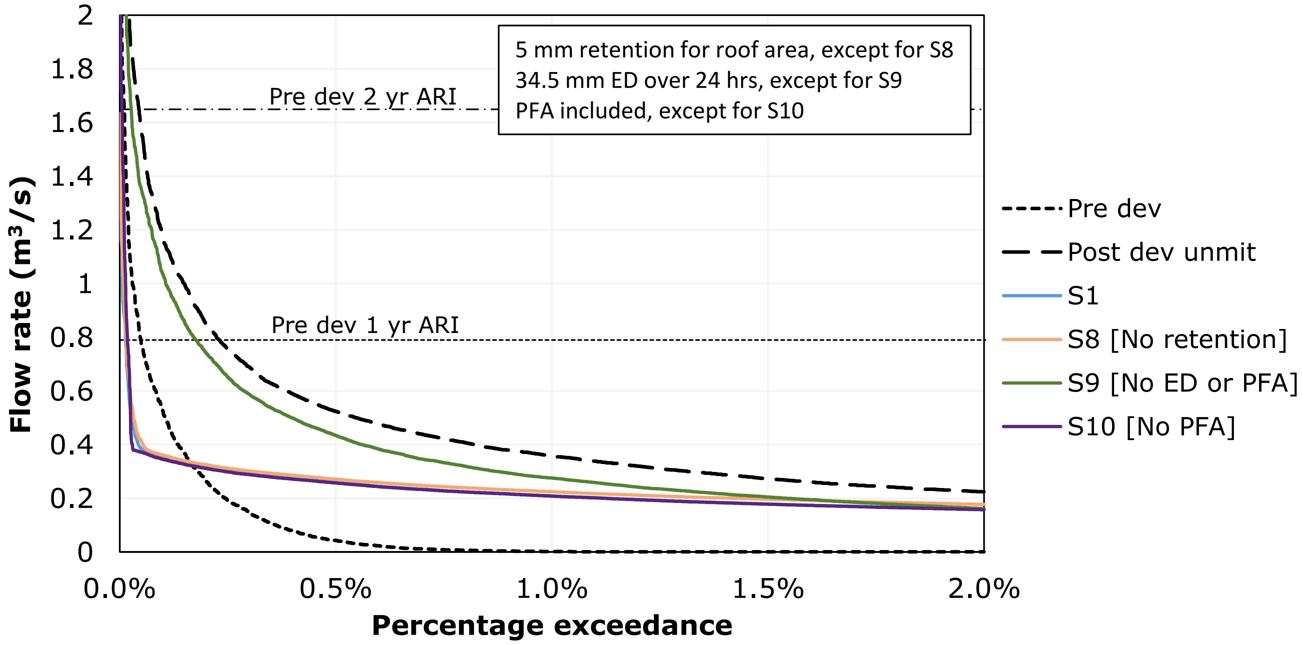

Figure 4: Effect of removing individual attenuation components

S9, which includes retention but no ED/PFA basin, demonstrates consistently lower flow rates than for post development unmitigated. While the percentage reduction is less for larger events than for small, we can observe that ground infiltration for a portion of the catchment (here roofs make up 31% of total area) is capable of reducing flows at least to some extent across the spectrum of event sizes. Nevertheless, flows remain significantly higher than pre development levels, indicating that retention devices will not be able to practically achieve any level of hydrological neutrality by themselves.

The duration curve for S8, which includes ED and PFA but no retention, is very similar in shape to that of the base case (S1). With retention removed more water enters the ED/PFA basin: this is verified by examining total outflow volume, which for S8 is 34% greater than for S1. This in turn means that the ED/PFA basin stays slightly more “full” than it would have otherwise. However between 0% and 2% exceedance, flow behaviour is dominated by the presence of the ED/PFA basin, and removing retention has no perceptible effect.

Running the model with retention and ED but without PFA capability (S10) shows again a very similar curve as seen in S1 or S8. The exception is that the “knee” of the curve is sharper and beyond this point the curve rises more rapidly. This is because ED spillway flow rates are effectively unconstrained. Note that in the more extreme events the modelled flow rates are not a good representation of peak flows because of the long timestep, and therefore it is difficult to draw clear conclusions about these peaks.

3.3 RETENTION DEPTH

Figure 5 plots scenarios that vary the depth of retention provided. For all cases the same ED and PFA configuration is maintained.

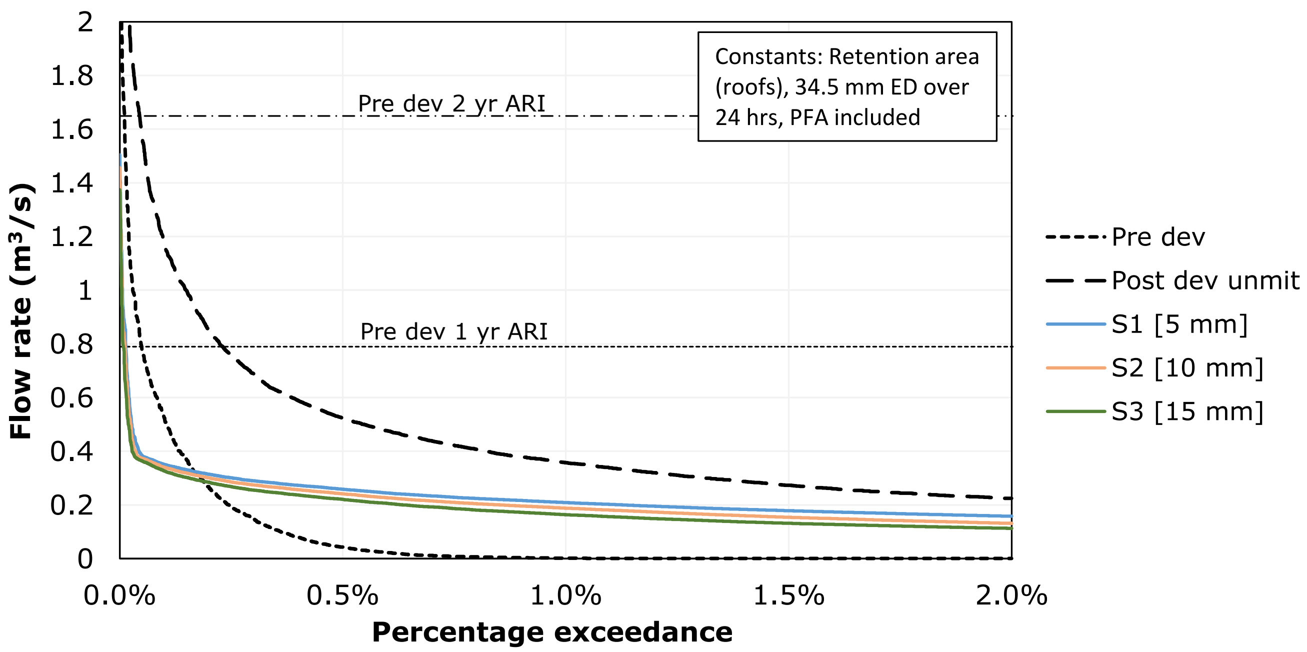

Figure 5: Effect of retention depth (values in square brackets)

The effect of changing retention depth is seen in the "tail" of each duration curve. While the "knee" of the curve stays in approximately the same position (approximately 0.38 m^3/s at 0.04%), at lower percentage exceedance levels flow rates reduce with increasing retention depth. Table 3 demonstrates that volume lost to infiltration within the retention basin increases with its depth: the corollary is that total outflow volumes, or area under equivalent duration curves, must decrease at the same time.

Table 3: Volumetric percentage loss to infiltration within retention basin

Scenario	**Retention depth (mm)**	**Percentage infiltration relative to:**	
		Total runoff	**Roof runoff**
S1	5	26%	53%
S2	10	38%	76%
S3	15	43%	87%

Exceedance levels beyond 2% represent the more everyday flow levels, and therefore these observations indicate that with increased retention depths, ongoing stream flows would be closer to pre development (base flow influenced) levels. However in this region flows are already much lower than those likely to cause stream erosion, so retention benefits are more likely to be those regarding maintenance of base flow.

3.4 RETENTION AREA

Figure 6 plots the effect of including retention for a larger portion of the total catchment. 5 mm of retention is provided for roofs (24 ha) in S1 and for both roofs and roads (34 ha) in S4. S1 and S4 curves are indistinguishable in this figure, however total discharge volume from S4 is 14% less than from S1. It is at higher exceedance levels (such as to 20%) that flow and therefore volume differences become apparent. For erosion purposes increasing retention area is of similarly limited benefit, and the principal advantage will be in maintaining base flow.

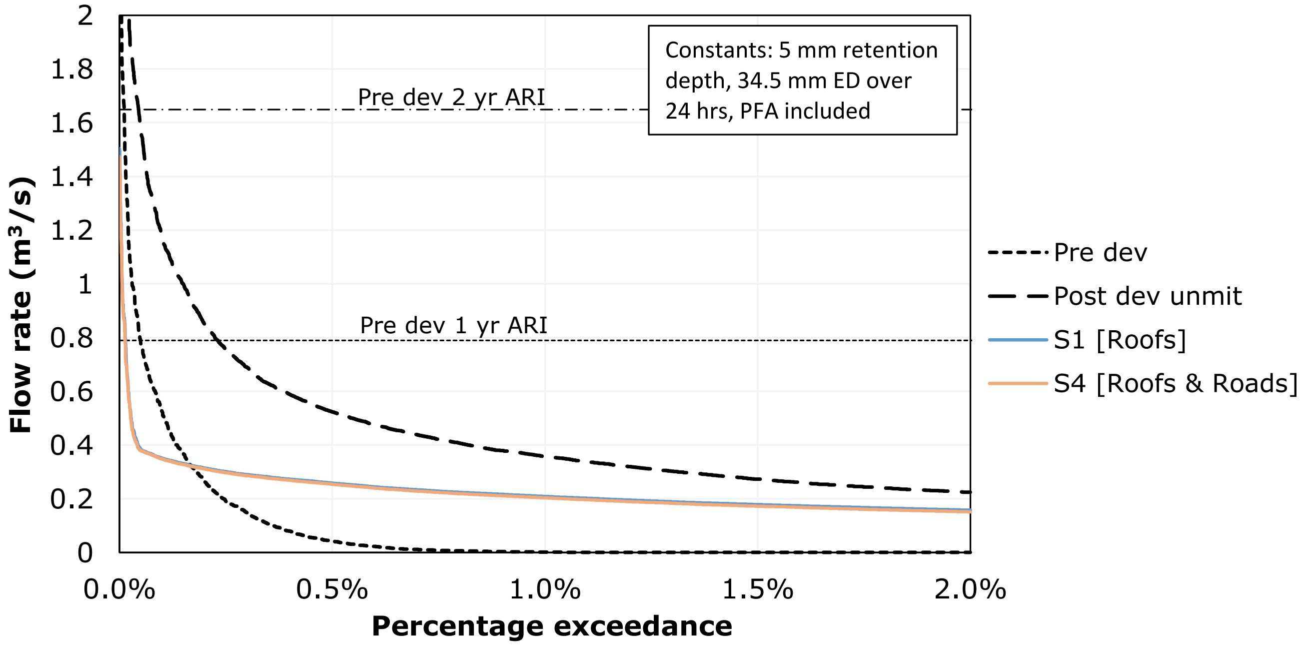

Figure 6: Effect of retention area

3.5 EXTENDED DETENTION DEPTH

Figure 7 plots the effect of varying ED event depth. As the attenuation under base case (S1) is relatively high, lower ED depths are examined: 25 mm for S6 and 15 mm for S5.

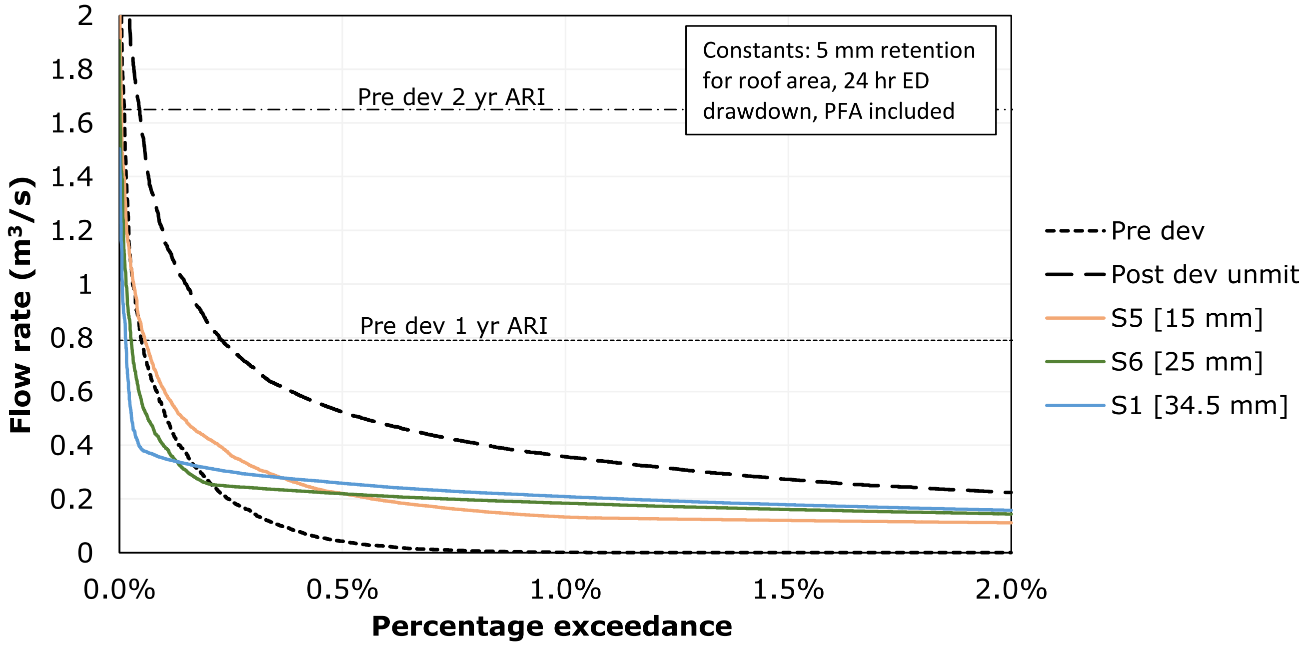

Figure 7: Effect of ED depth (values in square brackets)

In S1 a distinct knee is visible at 0.38 m^3/s, the flow corresponding to a full ED pond and beyond which the 2 year PFA weir becomes active. An equivalent knee can be seen for S6 at 0.25 m^3/s. For S5, the ED pond becomes full at 0.13 m^3/s, and although its equivalent knee is indistinct the event occurs at an exceedance level of approximately 1%. As the ED pond becomes smaller its effectiveness in re-shaping the duration curve is reduced, and flow behaviour is dominated by retention and PFA devices. As a thought experiment we may envisage that the duration curve of a system with retention and PFA but no ED at all would be similar to that of S5, albeit with higher flow rates because basin outflow rates would be less constricted.

The pre development 1 year average recurrence interval (ARI) level of 0.8 m^3/s is exceeded less often than in pre development for ED depths of 34.5 or 25 mm, but at an ED depth of 15 mm this flow level is exceeded slightly more often. Note that this graph is not directly equivalent to a peak flow analysis, and therefore it is difficult to infer magnitudes of 1 year peak flows for each series individually.

3.6 EXTENDED DETENTION DURATION

Figure 8 plots the effect of ED drain down duration. Doubling drain down from 24 hours to 48 hours halves the maximum orifice flow rate and therefore lowers the knee position. A secondary consequence is that the gradient of the duration curve below the knee is shallower for a 48 hour drain down, as more time is spent emptying the ED basin. It can be inferred that decreasing drain down time below 24 hours would conversely increase the knee flow rate and steepen the gradient of the curve below the knee. For the scenarios tested there is little difference in the duration curve at higher (erosive) flows, but generally speaking increasing drain down time decreases the volume available for any events following soon after another, and therefore decreases overall attenuation capability.

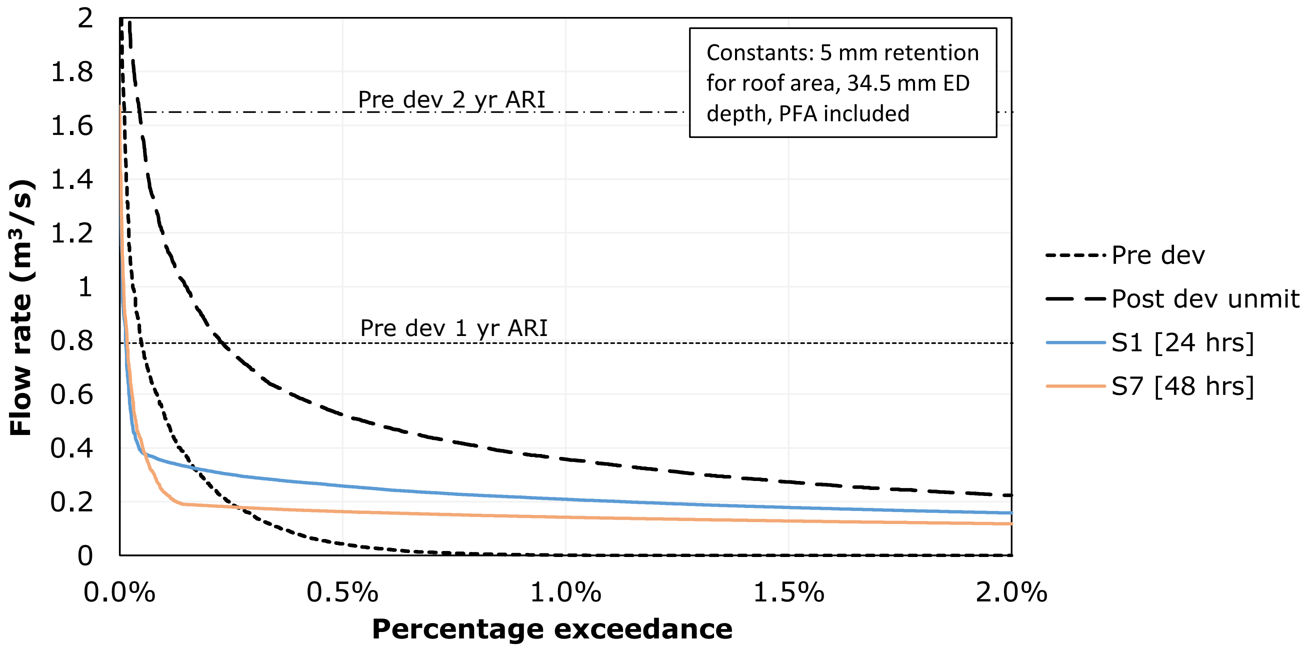

Figure 8: Effect of ED duration (values in square brackets)

3.7 PEAK FLOWS

Because of the length of simulation undertaken for this study a relatively large (1 hour) time step was used. As a consequence peak flows are not accurately represented and are not a focus of this paper. In general terms the model has sought to achieve peak flow attenuation to 80% of the pre-development 2 year rate, and this has been achieved by all scenarios except for S9, which excluded both ED and PFA.

With an ED depth of 34.5 mm for most scenarios the volume retained in the ED basin is significant relative to the 2 year storm. Therefore this component has a substantial effect in achieving peak flow attenuation in those more frequent storms.

4 DISCUSSION

This study is a desktop modelling exercise with many simplifications. Bearing this in mind a variety of observations can be made. Table 4 lists notable benefits and limitations of each device discussed thus far with respect to modelling results in Section 3.

Table 4: Benefits and limitations of retention, ED and PFA devices

	Benefits	**Limitations**
Retention	Valuable for the long term health of a stream, helping to prevent significant increases in everyday post-development flow rates, and (though not explicitly modelled) contributing to sustained base flow.	Has little impact on attenuation of 1 year peak flows or larger, particularly if ED and/or PFA devices are also installed. Does not provide significant benefit for erosion reduction.
ED basins	Effective at keeping large flows below pre development levels and can contribute significantly to attenuation of 1 and 2 year peak flows, at least for an ED depth of 34.5 mm and drain down time of 24 hours. Significant in reducing duration of flows above rates that might exacerbate stream erosion.	Can attenuate flow for longer and to a greater extent than necessary. Minimal stream erosion benefit from extending to 48 hour drawdown.
PFA basins	Important for satisfying regulatory conditions on post-development peak flows at specified return periods, mitigating flood risk downstream.	Do not contribute significantly to attenuating flows below those at its design return period levels, especially if not built in conjunction with retention or ED

In this study peak flow rates at the 2 year level were significantly less than 80% of pre development for most scenarios. This was in part an artefact of inconsistencies between runoff assumed for pond sizing calculations and the characteristics of runoff modelled in HEC-HMS. More importantly this was because of the assumption that the ED basin is full before the design PFA event begins. This resulted in over-conservative attenuation on occasions where the PFA basin became active.

As discussed in Section 3.1 attenuation performed in the base case scenario (S1) was greater than necessary for erosion purposes, as the percentage of time spent at flows equal or above the pre-development 1 year ARI level was much less than in the pre-development scenario itself. Further to this it has been demonstrated that the ED basin performed some peak flow attenuation for more frequent flood events (1 and 2 year floods) despite not being designed for this purpose. This suggests that an ED event depth of 34.5 mm, as per TP10, may be larger than necessary.

TP10 (ARC, 2003, pg 3-13) describes the origin of this depth as:

> "For unstable streams the interim recommendation [by BCHF, 2001] is for detention ponds to be designed for the discharges from a 2 year ARI 24 hour storm from post development conditions, such that no more than 30 mm of runoff occurs over the 24 hour period…
>
> The initial BCHF information has been modified for greater consistency with the design approach used in TP 10 which aims to store and release the first 34.5 mm of rainfall over a 24 hour period."

This BCHF (2001) report looked at hydrology and shear stress in representative streams to determine what ED approach would best protect streams from erosion, and made recommendations. ARC subsequently reworked it to achieve a similar outcome with a different method of calculating. Subsequent work by NIWA and Beca for ARC (unpublished) suggested that a smaller ED value could be just as effective in the context of small Auckland stream in cohesive sediments, but TP10 has not been updated.

The results presented in this study suggest that ED event depths smaller than 34.5 mm could be effective in addressing the risk of stream erosion as a result of urban development, at least in the Waikato region. Reducing the ED basin volume and increasing that of the PFA basin would likely be a more effective use of storage volume. This possibility should be assessed further on a site-specific basis by analysis of shear stress and accumulations of "excess work done" on representative stream sections.

It is important to note that all three device types have a role in effective post-development flow mitigation. Properly designed peak flow attenuation may by itself achieve some erosion protection outcomes, yet other outcomes will not be achieved because relatively high flows are allowed to continue unabated for a significant proportion of time. Retention devices offer a reduction in flow volumes, but as Section 3.2 demonstrated it is unlikely that they could deliver sufficient peak flow attenuation on their own in any practical context to address stream erosion and flood peak attenuation.

ED and PFA devices are alike in so far as they cannot reduce total outflow volume, rather their purpose is to re-shape the outflow rate. They may attenuate "high" flows, but a designer must ask, what flow rate is it acceptable for "ongoing" runoff be increased to? It appears undesirable to increase the 1 year ARI peak flow rate or the percentage of time for which it is exceeded, but is it acceptable to increase the 6-month or 1-month peak flow for instance? The answers to these questions will be driven by a combination of considerations, from statutory to ecological health and to aesthetic preference.

There are few generally-applicable design targets that are relevant to lower flows, and continuous simulation demonstrates that clear guidance is needed. Complete "hydrological neutrality" is not an option and so we must reach a consensus on what form or level of flow modification is appropriate. What is evident is that such questions are seldom asked, or able to be addressed, by designers because of the current focus on event-based analysis. Continuous simulation, even at the simplified level undertaken here, helps in understanding the effect of different options through the full hydrological cycle.

5 CONCLUSIONS

This study has examined the long term system behaviour of mitigation designed for a typical urban development. The functions of retention, extended detention and peak flow attenuation devices have been examined along with the effect of various sizing parameters. It has been demonstrated that each device type is important in contributing to holistic flow management across a spectrum of event sizes. Retention is the only component that can reduce flow volumes, and while it has little effect on peak flood flows it is important for maintenance of base flow characteristics (though not explicitly tested here). Extended detention is effective in reducing the duration of flows above rates that might exacerbate stream erosion. Peak flow attenuation is important for mitigating flood risk downstream and satisfying regulatory conditions on post-development peak flows.

Relative erosive risk has been assessed in this study by way of time spent at or above flows corresponding to 1 and 2 year pre-development peak flow levels. It is important that for any given project application of this method, further work is undertaken that examines erosion risk in more detail, especially with respect to site-specific studies of shear stress.

It has been demonstrated that with respect to flow mitigation devices "bigger is better" or "longer is better" are not always true. It is important to understand the interactions and long term impact of each component. Here with respect to the base case scenario, S1, it is likely that reducing the ED basin volume and increasing that of the PFA basin would be a more effective use of storage volume and achieve better overall outcomes.

The term "hydrological neutrality" is sometimes used to describe mitigation that attenuates peak flows to pre-development levels at specified return periods. However as seen clearly in duration curves this measure pertains to flow behaviour in only a fraction of each year. Flow mitigation invariably involves re-shaping the duration curve: reducing high flows but increasing smaller flows. True hydrological neutrality — that of achieving post-development characteristics that exactly match pre-development characteristics — is rarely practicable. Therefore it is important that as a community of regulators, designers and stakeholders we reach a consensus on what form or level of flow modification is appropriate.

Continuous simulation is an approach that can be applied to any context that would traditionally be modelled using individual storm events. The challenges presented by continuous simulation are different, such as in obtaining suitable rainfall and PET data, calibrating runoff model parameters and managing large result datasets. However the benefits in understanding holistic system behaviour are significant, offering the opportunity to better optimise designs and to inform more robust discussion of desired outcomes.

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