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An alternative method for on-site stormwater detention design

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Abstract

A widespread approach for the protection of hydrologic conditions in regional catchments is the attenuation of peak discharges through on-site detention. It is common practice and policy for detention to be dimensioned via analysis of the catchment area including or immediately surrounding a development site, with the objective being maintenance of pre-development peak flow conditions at the development site's outlet.

The Regional Effect is a term given to the phenomenon of adverse hydrologic conditions that result from the inappropriate location of stormwater detention systems in a regional catchment. In this paper, an analysis is presented that highlights the inadequacy of site-focussed stormwater detention design with the definition of a Regional Effect Point, at which detention located in the downstream catchment is not beneficial. It is also reasoned that unnecessarily large detention volumes can exacerbate the Regional Effect and should be avoided.

In Queensland, Australia, current guidelines recommend the use of runoff-routing models for dimensioning of on-site detention. As an alternative, some Queensland local councils provide deemed-to-comply solutions that involve basic inputs of site area and land use to calculate on-site detention. Via observations, the volumes produced by deemed-to-comply solutions greatly exceed those calculated by runoff-routing methods.

To improve material and construction efficiency, limit unnecessary land dedication, and seek to reduce the potential for the Regional Effect whilst complying with current mandates for on-site detention, an alternative detention dimensioning method is presented that does not require packaged computer software. The process can be summarised by three interrelated modules: (i) graphical extrapolation of the Rational Method for hydrograph approximation; (ii) depth-storage-discharge programming; and (iii) numerical runoff routing using an alternative solution to the continuity equation given by the Queensland Urban Drainage Manual (2013).

Keywords

on-site detention, flood control, runoff mathematical methods, Regional Effect

Introduction

Recent revisions of the Queensland Urban Drainage Manual (QUDM) (Queensland Government, 2013) have omitted reference to four analytic equations for preliminary detention basin volume specification, i.e., Basha (1994), Boyd (1980), Carrol (1990) and Culp (1948). In lieu of these preliminary design equations, the current manual recommends that designers rely on computer models to undertake runoff routing calculations to determine the effects of urbanisation and calculate on-site detention storage requirements. The given runoff routing methods include RAFTS (Aitken, 1975), RORB (Laurenson and Mein, 2010), WBNM (Boyd *et al.*, 1993; Boyd *et al.*, 1999; Boyd *et al.*, 2012) as well as the time-area runoff routing methods DRAINS/ILSAX (O'Loughlin, 2014) and PC-DRAIN (Badini, 2008). As the only given alternative to the usage of packaged computer models, QUDM includes one brief reference to an explicit solution to the continuity equation, without direction on its usage or application.

A number of local council governments in Queensland override QUDM by providing simple alternatives referred to as 'deemed-to-comply' solutions (Brisbane City Council, 2014; Gold Coast City Council, 2015). Deemed-to-comply solutions provide a means of calculating detention volume based on site area and land use only, often without quantification of runoff and consideration of the development site's location in the regional catchment. As an observation that is supported by this study, deemed-to-comply solutions typically result in an on-site detention volume that significantly exceeds that calculated by runoff-routing or the analytical equations given by earlier revisions QUDM. This suggests that deemed-to-comply solutions may contribute to wasted resources in the over allocation of building materials and land dedication for flood detention in new developments. A second concern, with wider-reaching consequences, is that flood detentions designed by deemed-to-comply solutions may be inadvertently compounding regional flooding and environmental issues via the phenomenon known as the Regional Effect.

This paper addresses two research questions: 1) Could unnecessarily large stormwater detention storage at development sites compound the potential for the Regional Effect? and 2) Could a return to the fundamentals of stormwater detention system design result in optimized outcomes and limit the potential for the Regional Effect?

Detention assessment and design objectives

The design of a new stormwater detention system requires objectives that direct the system's performance criteria. Two primary schools of thought are used to guide the establishment of design objectives by assessment authorities: *micro-management* and *total catchment*, each with significantly different levels of assessment required.

Micro-management objectives

The simplest and more historic design objective, termed the 'micro-management' method (Olenik, 1999), assesses the performance of a detention system at its outlet to the downstream receiving drainage system. Using this objective, the designer relies on the assumption that any adverse impacts on the downstream hydrology are mitigated by ensuring the peak discharge at the outlet from the detention is not increased beyond the pre-development peak. Figure 1 provides a summary of micro-management design objectives, in which the example shows the 'peak control detention' curve reaching a maximum discharge that is equal to the pre-development maximum discharge.

From the reference point of an immediately downstream neighbour, the micro-management approach to stormwater detention is an effective strategy to avoid the adverse hydrologic impacts of urban development. For assessment authorities, micro-management policies are easy to implement, enforce and assess. There is a sense of fairness among land developers when

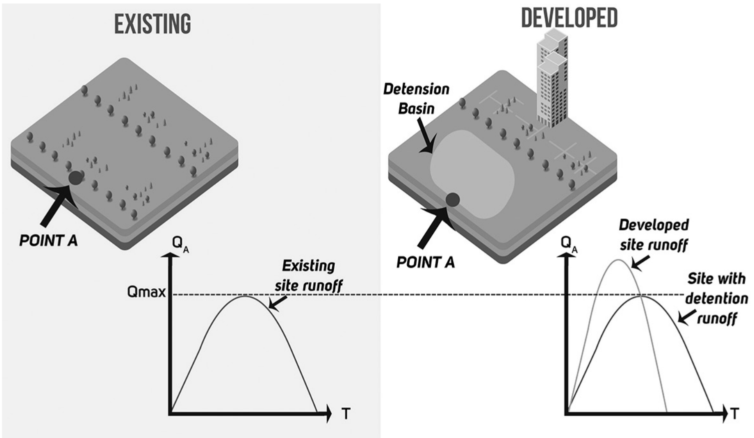

Figure 1 – The micro-management approach to stormwater detention design.

all new development is required to provide detention to account for its own development intensity (Debo, 1982). It is also flexible for unplanned development in expanding communities, as stormwater detention can be installed in parallel with the progress of an evolving city (Shea, 1996).

Total catchment objectives

The more complex alternative to micro-management is the total catchment approach. Using this method of assessment, the objective is to ensure that adverse hydrologic impacts are mitigated at all locations within the catchment. Design objectives that adopt this approach recognise the complexity of regional catchment hydrology, specifically the effect of hydrograph peak timing. Figure 2 provides a diagram of the total catchment approach, in which the subject site discharge (point A) is detained to achieve the required result at the total catchment outlet (point B).

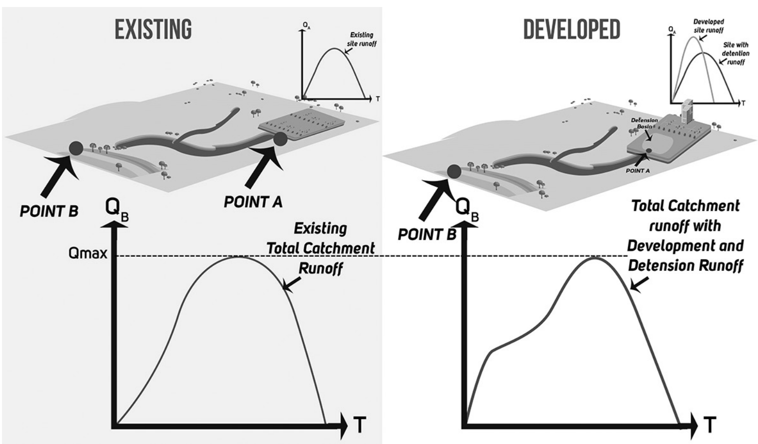

Figure 2 – The total catchment approach to stormwater detention design.

Within the total catchment approach to selecting design objectives for detention systems, there are two sub-categories:

- At-source strategies (Argue, 2004), which require the installation of detention systems at each new development site location individually, independently designed to ensure adverse hydrologic impacts resulting from the associated development are mitigated.
- Distributed detention strategies (Travis and Mays, 2008), which require the identification of specific and optimised locations for the installation of detention throughout the regional catchment, designed as a network.

At-source detention design methods for total catchment objectives are onerous for individual development projects, and are therefore rarely required.

Ideally, for successful flood control, detention systems should be considered as a network, rather than individually. Studies in Asia (Tao *et al.*, 2014; Duan *et al.*, 2016), Europe (Bellu *et al.*, 2016; Ravazzani *et al.*, 2014) and the Americas (Kaini *et al.*, 2007; Shuster and Rhea 2013; Su *et al.*, 2010) have developed effective models and algorithms for optimized distributed detention locations within the regional catchment. In addition to reduced flood risk, regional detention strategies are known to be more efficient and result in as much as 41% less detention storage over the whole catchment (McEnery and Morris, 2012).

Whilst distributed detention is strongly recommended and not debated by this research, major constraints exist with implementation of the theory. Firstly, distributed detention needs to be carefully planned for at a regional scale, often requiring participation by multiple municipalities or even nations. Secondly, distributed detention requires significant land dedication, often at very specific locations that will not achieve the desired outcomes if spatially negotiated. These factors make distributed detention design and implementation a complicated act that is infrequently adopted.

The Regional Effect

McCuen (1974) raised concerns regarding the location of stormwater detention in a regional context, highlighting the fact that the inappropriate location of detention structures can have outcomes that conflict with their intentions. McCuen (1979) further stated that the flow timing change caused by a detention basin can inadvertently result in increased downstream flooding in some applications.

Known as the 'Regional Effect' (Flores *et al.*, 1982; Leise, 1991; Geoff and Gentry, 2006; Seybert, 2006; Saunders, 2008), the notion that inappropriately allocated stormwater detention systems can cause one hydrograph peak to lag or be extended to such a time that it causes a coincidence with another hydrograph peak is generally well acknowledged. Figure 3 shows the Regional Effect graphically, with an elongated detention hydrograph contributing to the peak of the regional hydrograph.

Where stormwater detention design policies include micro-management objectives, there is the potential for unnecessarily large stormwater detention storage to have adverse effects, as well as being a waste of resources. The Regional Effect theory suggests that an unnecessarily large stormwater detention storage at certain locations in a catchment can potentially exacerbate flooding and environmental damage in downstream watercourses.

A broad and generalised application of Regional Effect theory is the axiom that stormwater detention is generally not applicable to the lower third of a catchment. This concept can be encountered in some South East Queensland stormwater planning guidelines (Queensland Government, 2013;

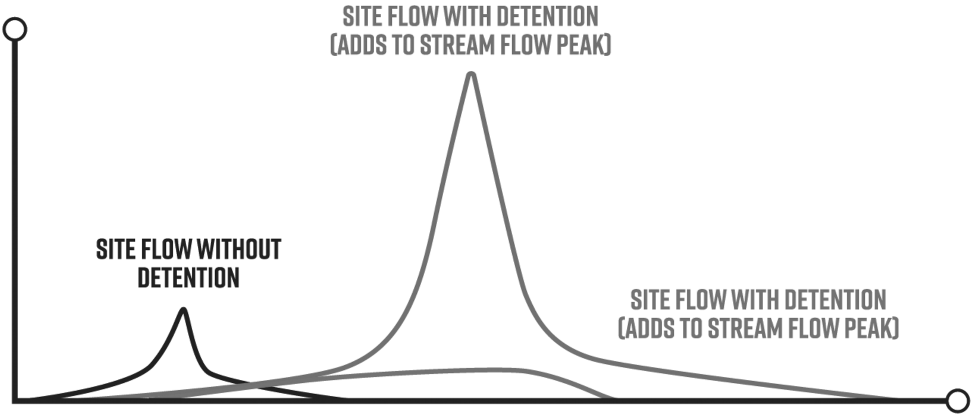

Figure 3 – Hydrograph description of the 'Regional Effect'.

Brisbane City Council, 2014); however, it is usually overruled by direct mandates for stormwater detention to achieve micro-management objectives.

Case study – South East Queensland

South East Queensland, Australia has experienced major regional flooding in recent years, with most flood damage occurring in the lower portions of regional catchments where the major cities are located, including the state's two largest cities, Brisbane and Gold Coast. Brisbane City and the Central Gold Coast are both located within the lowest 10% of the regional catchments (Fig. 4).

South East Queensland has a subtropical climate with high rainfall intensities and rainfall concentrated in the summer months. Notable floods resulting in major damage and deaths in Queensland include the January 1974 and January 2011 events. The most recent resulted in more than one million square kilometres of flooding and an approximate account of damages and losses at $15.7 billion (World Bank, 2011).

In South East Queensland, the micro-management approach to stormwater detention objectives is mandated by current development codes, exemplified by the Gold Coast Healthy Waters Code (2015): "*on site detention systems are designed to restrict peak outflows for Q_2 Q_5, Q_{10}, Q_{20}, Q_{50} and Q_{100} to pre-development conditions*" to achieve the performance outcome of "*demonstrat[ing] no adverse impact on stormwater flooding or the drainage of properties external to the subject site*".

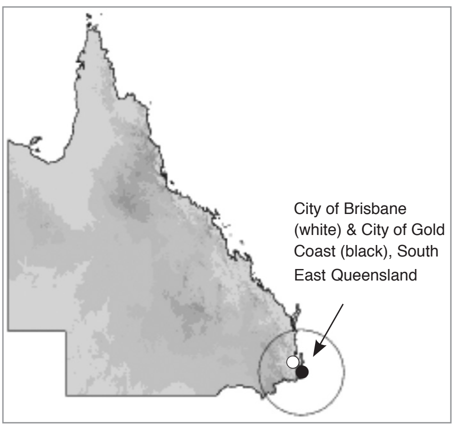

Figure 4 – Case study locality

Confirmation of the Regional Effect

In this paper, South East Queensland catchments experiencing urban development are used to investigate the Regional Effect in practice and consider the potential impact of over-allocation of stormwater detention.

Regional Effect model set-up

A process of numerical experimentation was undertaken in which a development site was conceptualized at ten alternative locations within a regional catchment, each at 10% increments from the outlet of the regional catchment. At each of the ten locations the development site was modelled with three development scenarios: undeveloped, developed without detention, and developed with detention. The detention was dimensioned using WBNM in-built methods with micro-management objectives, i.e., ensuring that the development site discharge is limited to pre-developed peak runoff. The modelled peak discharges at the outlet of the regional catchment were compared for the different development scenarios. The hydrologic parameters of the model set-up are presented in Table 1.

Finding the Regional Effect Point

The intention of the analysis was to locate the 'Regional Effect Point', defining it by the distance at which the development site is located upstream of the regional catchment outlet, as described by Figure 5. Upstream of this location, development with detention designed using micro-management objectives have the desired impact by reducing peak discharge at the regional catchment outlet. Developments with detention downstream of the Regional Effect Point have the opposite effect, resulting in an increase in peak discharge at the regional catchment outlet.

The analysis was performed on six regional catchments. In total, 11,858 runoff routing analyses were performed, accounting for the three scenarios of development, all standard average recurrence interval storm events (1, 2, 5, 10, 20, 50 and 100 years), all standard durations within range of the critical storm (15 minutes up to 1,480 minutes), and ten times for each regional catchment to assess for the shifting locations of the development site. Table 2 provides a summary of the catchments and the Regional Effect Point analysis results.

The results suggest there should not be a rule for excluding detention from any fixed

Table 1 – Hydrologic parameters used in the WBNM model for testing the Regional Effect

Australian Rainfall and Runoff 1987 Rainfall Design Rainfall Temporal Pattern	3
Rainfall station location	-27.9667,153.4167
Mean annual rainfall	1200 mm
WBNM lag parameter	1.6
Initial loss	15 mm
Continuing loss	2 mm
Existing case imperviousness	20%
Development site imperviousness	75%

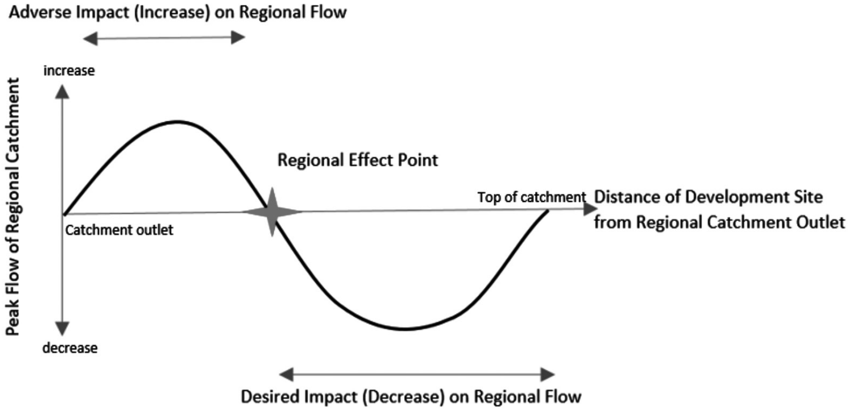

Figure 5 – Regional Effect Point

Table 2 – Summary of catchments and results of Regional Effect Point analysis

	Regional catchment size	**Development site size**	**Location of Regional Effect Point (% upstream of catchment outlet)**
Regional Effect Model Scenario 1	100 ha	1 ha	Does not exist
Regional Effect Model Scenario 2	100 ha	10 ha	Does not exist
Regional Effect Model Scenario 3	1,000 ha	1 ha	26%
Regional Effect Model Scenario 4	1,000 ha	10 ha	21%
Regional Effect Model Scenario 5	10,000 ha	1 ha	46%
Regional Effect Model Scenario 6	10,000 ha	10 ha	32%

portion of a regional catchment without further analysis. The results also indicate a pattern regarding the size of the development site relative to the regional catchment. As described graphically in Figure 6, for development sites that are large compared to the regional catchment, the results indicate that there is no Regional Effect Point, meaning that micro-management policies are effective in protecting the hydrology of the regional catchment. As the development site becomes smaller compared to the regional catchment, the Regional Effect Point appears and moves higher up the catchment.

Detention versus no detention

Table 2 and Figure 6 suggest that a 1 ha development site within a 10,000 ha catchment (scenario 5) can have the potential to increase regional catchment peak runoff when development with detention occurs anywhere in the lowest 46% of the catchment. Figure 7 shows the addition of the results for development occurring without any form of detention and indicates an important finding in the lowest 15% of the catchment. In this zone, development with detention results in increased peak runoff in the regional catchment, not only above the undeveloped scenario, but also above the scenario of development without detention. This is typical of Scenarios 3, 4 and 6 as well.

Further investigation was undertaken at the location along the main regional stream line 10% upstream of the regional catchment outlet. The detention volume calculated

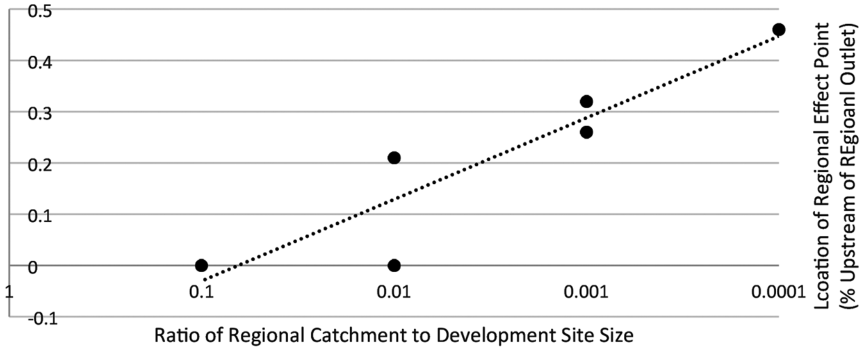

Figure 6 – Location of Regional Effect Point relative to catchment size, based on the results from six catchments used in this case study.

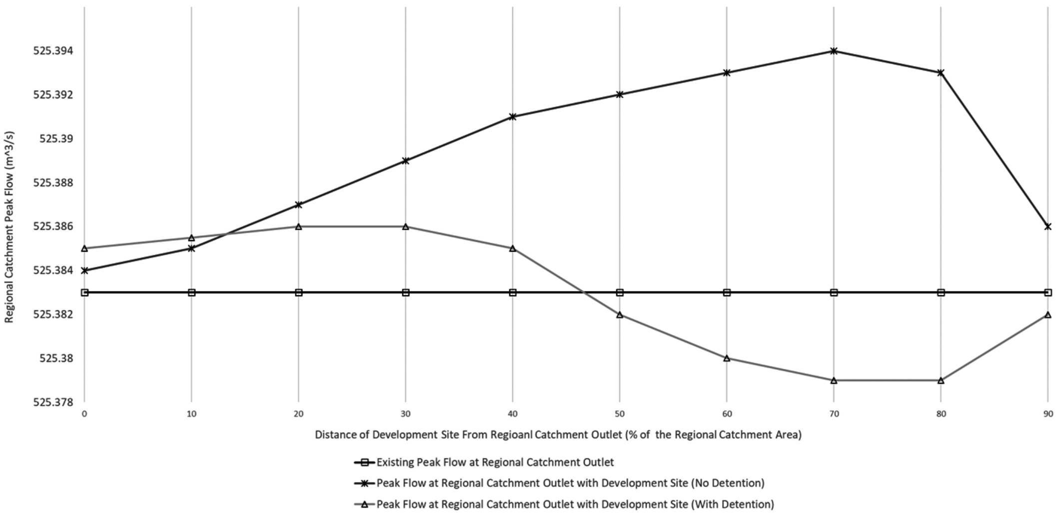

Figure 7 – Regional Effect model Scenario 5 results

using WBNM (260 m^3) was replaced with the deemed-to-comply calculation (320 m^3) and the results were exacerbated, showing that at this location detention is not only worse for the regional hydrology than inaction, but also that over-allocation of detention at this location can lead to adverse hydrologic conditions in terms of increased peak flow at the catchment outlet.

Optimised detention design method development

A method for detention dimensioning was developed that is recommended for consideration by practitioners charged with the responsibility of designing stormwater drainage and detention systems for small development sites, where the Rational

Method is considered to be a suitable means of stormwater runoff determination.

Inflow hydrograph approximation

Peak flows for design storm events can be estimated simply using the Rational Method (Eq. 1) (Mulvaney, 1851; Kuichling, 1889), one of the oldest and most widely-adopted approaches. The inputs include site area (*A*), rainfall intensity (*I*), and a Runoff Coefficient (*C*) that accounts for aerial and groundwater infiltration losses. The subscripts $_y$ and $_t$ relate to storm event recurrence interval and storm duration, respectively.

$$Q_{y,peak} = \frac{C_y I_{y,t} A}{360} \quad (1)$$

The hydrologic assessment and design of detention systems requires review of both critical and non-critical storm durations (t_d), where a critical storm duration is that which matches the time of concentration of the catchment. To allow for this assessment, graphical extrapolation of the Rational Method results is suggested, adopting the triangular or trapezoidal method as relevant.

Graphical representation of the triangular method (Abt and Grigg, 1978; Donahue *et al.*, 1981; Chow, 1988; Hong *et al.*, 2006; Hong, 2008) is shown in Figure 8. Equation 2 is recommended for using the triangular extrapolation of the Rational Method for determining an inflow hydrograph for a storm event.

$$Q_y(t) = \begin{cases} C_y I_y A \frac{t}{t_c} \ \langle for\ t \leq t_c \rangle \\ C_y I_y A \left(\frac{t_r + t_c - t}{t_r}\right) \langle for\ t > t_c \rangle \end{cases} \quad (2)$$

Based on a study of 500 catchments by Hong *et al.* (2006), the time from the storm peak to the end of the stormflow portion of the hydrograph (t_r) is recommended as 1.76t_c, where t_c is the catchment time of concentration.

An alternative is the trapezoidal method (Burton, 1980; Guo, 1999; Hong *et al.*, 2006), which is recommended for non-critical storm events, where storm duration exceeds the catchment time of concentration. Graphical representation of the trapezoidal inflow hydrograph approximation is provided in Figure 9. Equation 3 is recommended for using the trapezoidal extrapolation of the Rational Method for determining an inflow hydrograph for a storm event.

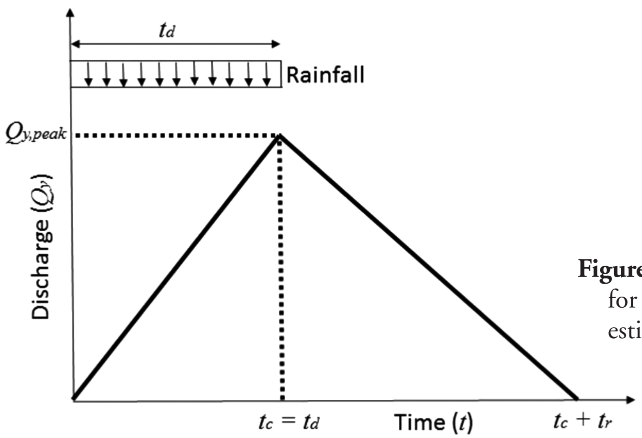

Figure 8 – Triangular method for storm hydrograph estimation.

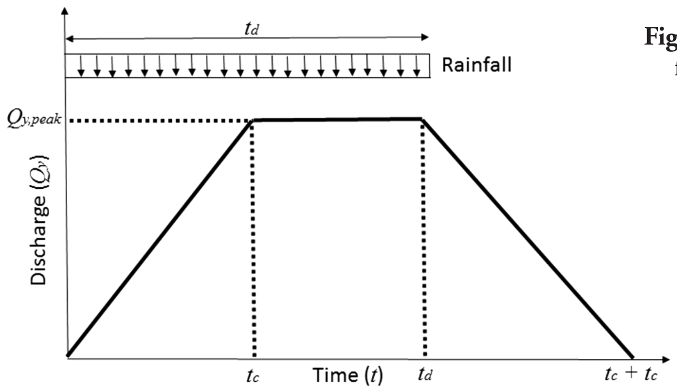

Figure 9 – Trapezoidal method for hydrograph estimation.

$$Q_y(t) = \begin{cases} C_y I_y A \frac{t}{t_c} \langle for\ t < t_c \rangle \\ C_y I_y A \langle for\ t_c \le t \le t_d \rangle \\ C_y I_y A - \frac{C_y I_y A}{t_d}(t - t_c) \langle for\ t > t_d \rangle \end{cases} \quad (3)$$

Detention design parameters (Height-Storage-Discharge function)

Detention tank volume

An idealized detention volume can be used for typical small scale urban development application that considers rectangular tanks with vertical walls. The detention storage volume follows the form:

$$S = H \times B \quad (4)$$

where B is the detention base area, S is the detention storage volume, and H is the maximum detention height.

Piped outflow – low stage piped outlet to atmospheric conditions

In situations where a low flow outlet pipe is not under pressurized conditions (i.e., the detention water depth is lower than the outlet pipe diameter and a tail water condition is not specified for the downstream outlet), the Manning equation (Chow, 1959) can be applied to solve for piped flow discharge:

$$Q_{dis} = \frac{1}{n} A_w \left(\frac{A_w}{P}\right)^{\frac{2}{3}} S_g^{\frac{1}{2}} \quad (5)$$

where Q_{cap} is the capacity of the outflow pipe, n is the Manning coefficient, A_w is the wetted area of pipe flow, P is the wetted perimeter of pipe flow and S_g is the slope (gradient) of the outlet pipe.

Piped outflow – pressurized outlet flow conditions

For conditions where the detention depth is either higher than the outlet pipe diameter or a tail water condition is specified for the downstream outlet, the outlet pipe arrangement is considered to flow under pressure. Pressurised flow through the pipe can be calculated using the head loss form of the Darcy–Weisbach equation (Brown, 2002):

$$\frac{\Delta h}{L} = f_D \frac{1}{2g} \frac{V^2}{D} \quad (6)$$

$$Q_{dis} = A_p \left[\sqrt{\left(\frac{2gD(h_{tank} - h_{DS})}{L f_D} \right)} \right] \quad (7)$$

Where: $\frac{1}{\sqrt{f_D}} = -2\log\left(\frac{5.76}{Re^{0.9}}\right)$

and $R_e = \frac{\rho}{\mu}VD$ (8a & 8b)

where L is the length of the conduit, f_D is the Darcy Friction Factor, V is the pipe velocity, D is the pipe diameter and g is the gravitational constant. The parameter h refers to water surface elevation and the subscripts $_{tank}$ and $_{DS}$ refer to the water level inside the detention system and downstream of the detention outlet, respectively.

As a generalisation, flow through the outlet pipe of a detention system is considered 'turbulent', and in the range of the 'smooth pipe law' (Colebrook *et al.*, 1939) for detention design applications. Fluid dynamic viscosity (μ) may be assumed as 0.9×10^{-3} kg/(m s) and fluid density (ρ) may be assumed as 1×10^3 kg/m^3. Using these values, experimental results that reflect typical detention outlet conditions produce Reynolds number (R_e) results in the order of 5000-8000.

Weir flow

At the higher stages of the detention outlet a weir may be specified to account for high level bypass or overflow. Weir flow capacity is calculated as depth above the weir level as follows (Queensland Government, 2013):

$$Q_{weir\,cap} = C_w L_w h_{weir}^{\frac{3}{2}} \quad (9)$$

where C_w is the weir coefficient (1.66 for sharp crested), L_w is the weir length, and h_{weir} is the water depth above the weir overflow.

Combined Height-Storage-Discharge function for detention basin (rating curve)

The design dimensions and outlet options can be combined to generate a rating curve for detention routing that follows the overall form:

$$Q_h = \begin{cases} \frac{1}{n}A_w\left(\frac{A_w}{P}\right)^{\frac{2}{3}} S_g^{\frac{1}{2}} + C_w L_w h_{weir}^{\frac{3}{2}} \langle for\ h \le D \rangle \\ A_p\left[\sqrt{\left(\frac{2gD(h_{tank} - h_{DS})}{Lf_D}\right)}\right] + C_w L_w h_{weir}^{\frac{3}{2}} \langle for\ h > D \rangle \end{cases} \quad (10)$$

where Q_h is the staged storage outflow and h is the incremental depth of the detention system. The peak outflow of the basin is limited to the maximum basin storage by the form:

$$\lim_{h\to H} f(h, D, L, f_D, h_{weir}) = Q_h \quad (11)$$

Runoff routing (continuity equation)

The final process of the proposed detention design procedure involves the routing of the extrapolated Rational Method inflow hydrograph through the detention system to produce a modified, 'detained' hydrograph output. For this application, the inflow hydrograph (I) is routed though the design detention storage (S) using an explicit solution of the continuity equation to create an outflow hydrograph (Q):

$$\frac{dS}{dt} = I(t) - Q(t) \quad (12)$$

Explicit solution to the continuity equation

Integration of the continuity equation to provide for an iterative numerical solution is performed as follows:

$$\int \frac{dS}{dt}dt = \int I(t)\ dt - \int Q(t)\ dt \quad (13)$$

With a known incoming hydrograph and a known height-storage-discharge function for the design detention system, the continuity equation can be rearranged to make all known factors of an incoming time step equal to the unknown factors of the outlet discharge as follows:

$$\frac{2(S_{i+1} - S_i)}{\Delta t} = (I_{i+1} + I_i) - (Q_{i+1} + Q_i) \quad (14)$$

$$(I_i + I_{i+1}) + \left(\frac{2S_i}{\Delta t} - Q_i\right) = \left(\frac{2S_{i+1}}{\Delta t} + Q_{i+1}\right) \quad (15)$$

where the subscripts $_i$ and $_{i+1}$ represent positively-ascending time step intervals.

A variation of Equation 15 is provided in QUDM (2013) and recommended as an acceptable alternative to the use of a computer model for the final sizing of a detention system, but without any practical advice regarding runoff routing or usage of the equation. An alternative, more practical rearrangement of the equation is:

$$\frac{I_i + I_{i+1}}{2} + \left(\frac{S_i}{\Delta t} + \frac{Q_i}{2}\right) - Q_i = \left(\frac{S_{i+1}}{\Delta t} + \frac{Q_{i+1}}{2}\right) \quad (16)$$

The left hand side of Equation 16 can be solved at each time step based on the previous time step results, starting with an initial inflow and storage equal to zero. The solution to the left hand side of Equation 16 is used at each routing time step to explicitly reference the design rating curve developed by Equation 10 to extract the storage and corresponding outflow for the following time step. Solving for storage as a whole number, as opposed to Equation 15, gives the designer better appreciation of the detention storage volume as well as the ability to more easily iterate and optimize the detention design, ensuring optimal storage usage and limited superfluous volumes. A graphical presentation of the solution to the continuity equation applied to detention basin design is provided in Figure 10.

Validation and comparison of detention design method

To validate the hydraulic calculations presented in the proposed design methodology, hydrograph outputs from runoff routing software (WBNM) were used to overwrite the Rational Method extrapolation input. Eight hypothetical South East Queensland locality sites between 0.05 ha and 1 ha in area were considered with the hydrologic parameters provided in Table 3. The results indicated precision in hydraulic calculations with a

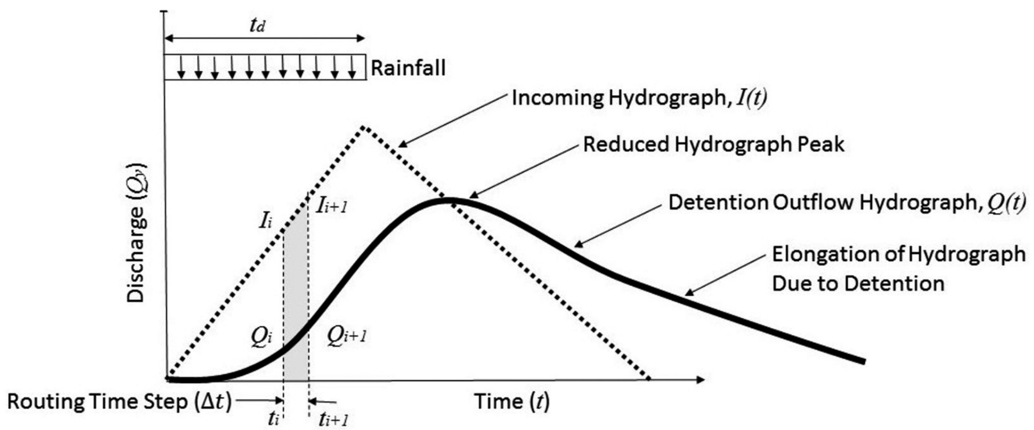

Figure 10 – Graphical summary of explicit solution to the continuity equation.

Table 3 – Hydrologic parameters used for validation of Ronalds & Zhang method

	Pre-Developed sites	Developed sites
Imperviousness	0%	90%
Rational Method C10 value	0.60	0.90
WBNM lag parameter	1.6	
WBNM initial loss	15 mm	
WBNM continuing loss	2 mm	
ARR1987 zone	3	
Rainfall station location	-27.9667,153.4167	
Mean annual rainfall	1200 mm	

variation of ±5% for detention volume and ±5% for detention water depth, where the WBNM model outputs are considered as the base and the methodology presented in this paper (referred to as the *Ronalds and Zhang method*) is considered to be the variation.

Comparison with other accepted methods

Figure 11 shows the results of a comparison on detention dimensioning methods using South East Queensland rainfall data and eight hypothetical development sites (catchments), ranging in size from 500 m^2 to 10,000 m^2. For each, the Ronalds and Zhang method was used to size the hypothetical detention systems in accordance with the recommendations of this paper. The results are compared to deemed-to-comply solutions for detention volume determination (Brisbane City Council, 2014), sizing of detention systems using WBNM, as well as the four analytic equations for preliminary sizing of detention that were published in the 2008 edition QUDM but removed from the provisional 2013 edition, i.e., Basha (1994), Boyd (1989), Carrol (1990) and Culp (1948).

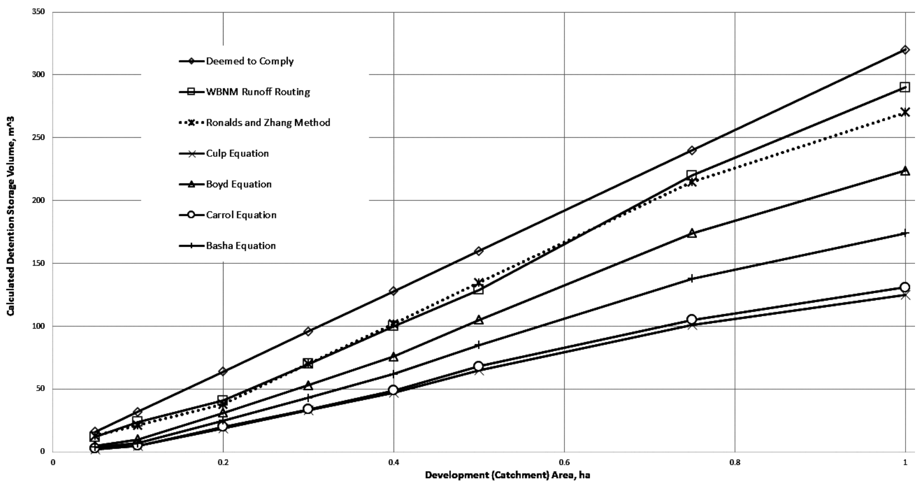

Figure 11 – Comparison of stormwater detention storage volume results derived from various methods.

The results presented in Figure 11 demonstrate three key findings:

1) the proposed methodology described by this paper achieves detention dimensioning outcomes that closely reflect the WBNM runoff routing model,
2) the preliminary analytical equations significantly underestimate detention requirements, justifying their omission from recent editions of QUDM, and
3) the deemed-to-comply solutions provide results that are larger compared to the other methods, justifying the concerns and recommendations presented in this paper.

Discussion

Parameterisation of inflow hydrographs using the triangular or trapezoidal methods is simplistic in application, without regard for temporal patterns. It is known that a rainfall hyetograph does not follow the perfect pattern of a triangle or trapezoid; however, it is also known that rainfall may not consistently follow any one predictable pattern. Australian Rainfall and Runoff (Babister *et al.* 2016) recommends using an ensemble or a Monte Carlo analysis of rainfall patterns. For regional catchment analysis, the concept of multiple temporal patterns may be justified as it provides a more realistic representation of natural flood generation processes, considering the influence of all probability distributed inputs (Nathan and Weinmann, 2013). However, for the design of a development site-scale stormwater detention system, where all surrounding pipework is dimensioned using a static Rational Method calculation, the triangular and trapezoidal methods are considered to be as reasonable as any other single temporal pattern.

The recommendation for triangular or trapezoidal extrapolation is limited to the size of development sites included in this study. The durations of storm events resulting in high peak discharges for the catchments assessed are typically short and their Australian Rainfall and Runoff temporal patterns result in fast, front- loaded hydrographs that reasonably reflect the triangular extrapolation method shape. For larger catchments, the effect of temporal pattern diversity becomes too significant to recommend triangular or trapezoidal extrapolation.

The analysis of the Regional Effect Point provided is simplistic and undertaken only to justify the need for improvement upon deemed-to-comply solutions. It does not consider a suitable range of catchment variables and alternatives to confirm a method for determining the location of Regional Effect Point for unrelated catchments. Further work to confirm or provide means to calculate the location of the Regional Effect Point should use ensemble or a Monte Carlo analysis for the regional catchment modelling, along with a wider range of catchment variables.

The hydraulic equations for detention outflow provided by the Ronalds and Zhang method are theoretical without experimentation to confirm applicability to local conditions or typical on-site detention dimensions. Minor differences exist in the programming of hydraulic outflow conditions in each of the computer models recommended by QUDM. Recent experimental developments of detention outflow equations by Hong (2010) are not considered by any of the current computer models. An experimental review of hydraulic outflow equations could therefore lead to improved accuracy and confidence in the Ronalds and Zhang method.

Conclusion

This paper has shown that unnecessarily large stormwater detention storage at development sites located within certain portions of a regional catchment can compound the potential for the Regional Effect. The

Regional Effect Point is a location in the regional catchment at which on-site detention in any areas downstream will not achieve the mitigation of regional peak flow increase, and that unnecessarily large stormwater detention can be worse for regional conditions than optimally sized systems.

A simplistic method for estimating the required size of stormwater detention using fundamental methods has been presented. Referred to as the Ronalds and Zhang method, it is suggested that the alternative method can be used to more accurately calculate the required volumes of stormwater detention, in lieu of methods such as deemed-to-comply solutions that have been shown to over-estimate the required volumes.

This research has not provided a means to avoid all potential for the Regional Effect. However, it has been shown that unnecessarily large stormwater detention storage detention does not do this either. In an ideal world with unlimited time and resources available to designers, the potential for Regional Effect should be assessed as part of the design process for every on-site stormwater detention system. As a practical and feasible alternative, stormwater detention volumes should be carefully calculated using fundamental hydrologic and hydraulic ana—lysis to avoid unnecessarily large stormwater detention storage, improving construction material efficiency, land use efficiency and reducing the potential for the Regional Effect.

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