Use of WSUD 'source control' practices to manage floodwaters in urbanising landscapes: developed and ultra-developed catchments

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ABSTRACT

Natural channels of 'greenfields' catchments provide the first stage of urban waterway evolution that, in time, becomes basic to the formal stormwater networks of developed urban landscapes characterised by underground pipes and hard-lined drainage channels. The stormwater infrastructure of many inner city suburbs frequently display a further level of development – that of 'ultra-development' or overloading. The conventional response to re-growth occurring in both of these categories of landscapes is to upgrade the infrastructure by augmentation or duplication at time intervals of 20 to 30 years. Cost per council associated with these works can run into hundreds of millions of dollars. The paper offers alternative WSUD 'source control' practices that avoid this history. In the case of developed urban landscapes, the *regime-in-balance* strategy (Argue, 2004/2011) is invoked: this requires removal and temporary storage of a set *portion* of the runoff generated on each site. In the case of ultra-developed catchments, the *yield-minimum* stategy is applied: this involves removal and temporary storage of *all* runoff generated on each re-developed site. Options available for disposing of the stored volume include rainwater tanks, roof gardens, open space irrigation, infiltration systems, raingardens, aquifer recharge, etc. Where such options are unavailable – for space, policy or other reasons – the same benefits can be gained by slow-release of stored stormwater in the manner of 'extended detention'. City of Gosnells, Western Australia, has developed a strategy for managing regrowth in its area based on the principles described in the paper: the declared saving by the City is $ 120 million (Tennakoon and Argue, 2011).

KEY WORDS

Detention, development, overloading, regrowth, retention, source control, stormwater, WSUD

1.0 INTRODUCTION

The suite of technical problems that arise when considering the conveyance of stormwater in waterways of the urban landscape may be divided into three broad categories –

1. Those involving the natural channels of 'greenfield' catchments undergoing *first-wave* development;
2. Formal drainage networks (underground pipes and hard-lined channels) of developed catchments experiencing re-development; and,
3. Formal drainage networks experiencing overload from ultra-development and where further regrowth is sought.

The focus of the technical problems faced by those called upon to manage waterways falling within the scope of the first category, above, is distinctly different from those of the other two categories. This (focus) is to protect floodways from urban intrusion and preserve the natural waterways in terms of their morphology and environmental values in as close to their pre-development condition as possible (Argue et al, 2011). It is widely recognised – both in Australia and internationally – that the key requirement here is to ensure that the ARI, Y = 1- to 2-year (locally advised) floodwave magnitude is – approximately – the same after development as before (Engineers Australia, 2006).

It is unfortunate that the bulk of Australian practitioners and municipal agencies alike believe that this objective can be achieved using detention basin technology applied at the point-of-entry to natural waterways of runoff from developed land portions, for example, residential subdivisions, under the so-called "no worsening of peak flow" scenario. The damaging effects of this misconception have been well documented for more than a decade (Roesner, 1997; Maxted & Shaver, 1999; Konrad & Booth, 2005) and more recently by Argue et al, 2012.

The key stormwater management practice which enables acceptable development to occur in 'greenfield' catchments with minimum impact on the environmental values of their natural waterways is that of 'source control': *"hold the rain where it falls"*. The principles of 'source control' can now be found in the best practice stormwater management manual of the US EPA (http://www.epa.gov/oaintrnt/documents/epa_swm_guidance.pdf) as well as those of leading US municipal agencies, for example, State of Pennsylvania (http://www.elibrary.dep.state.pa.us/dsweb/View/Collection-8305), City of Philadelphia (http://www.phillywatersheds.org/what_were_doing/documents_and_data/cso_long_term_control_plan) and State of Maryland (http://www.mde.state.md.us/programs/Water/StormwaterManagementProgram/Pages/programs/waterprograms/sedimentandstormwater/swm2007.aspx).

While this recognition of the benefits of 'source control' measures applied in peri-urban landscapes is timely and to be applauded, corresponding recognition of the potential for use of this technology within the second and third of the three urban landscape categories listed above has not been as widespread. The AIM of this article is to address this deficiency and explain the water-sensitive and economic benefits which follow use of 'source control' rather than conventional practices in city-suburban catchments served by formal drainage networks, and experiencing re-growth and re-development.

2.0 'SOURCE CONTROL' MATHEMATICAL/HYDROLOGICAL MODELS

2.1 The developed catchment: introducing the *regime-in-balance* strategy

Figure 1 presents, first, the layout of a developed catchment served by a formal stormwater drainage network comprising underground pipes and hard-lined channels. The accompanying graph represents the hydrograph of runoff that can be determined by appropriate hydrological modelling (O'Loughlin & Stack, 2001), at the catchment discharge point, O, in the ARI, Y-years storm upon which the design of the network has been based. It is assumed that the drainage network is competently designed and well-matched to the catchment and that it satisfactorily conveys all storms up to and including the "Y-years" event having critical (storm) duration determined for the defined catchment.

The single, shaded element shown in Figure 1 is proposed for re-development: this may mean change from a 'low' development use, such as a large residential allotment, to a 'high' use, for example, a factory building. Its former ('low') contribution to the total runoff hydrograph is also shown in the graph as a mini-hydrograph labelled "flow from developed element". An enlarged version of **this** hydrograph is presented in Figure 2a, labelled "developed element". Also shown in Figure 2a is the (modelled) hydrograph of runoff from the same element in its re-developed state, labelled "re-developed element".

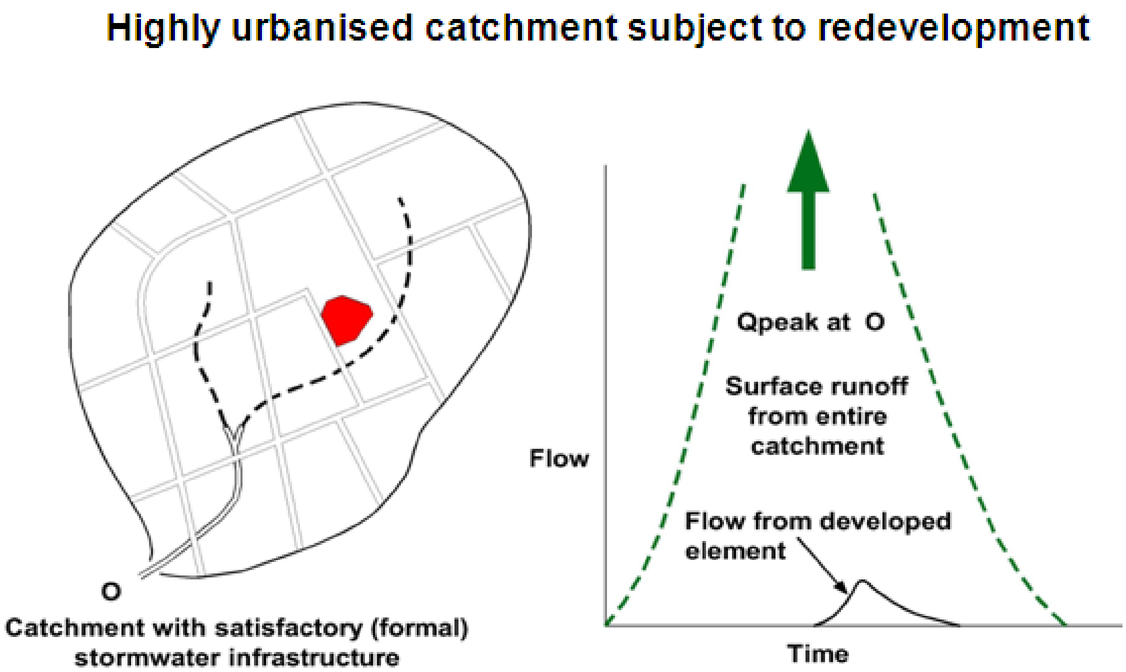

Figure 1: Developed catchment elements and ARI, Y-years runoff hydrograph

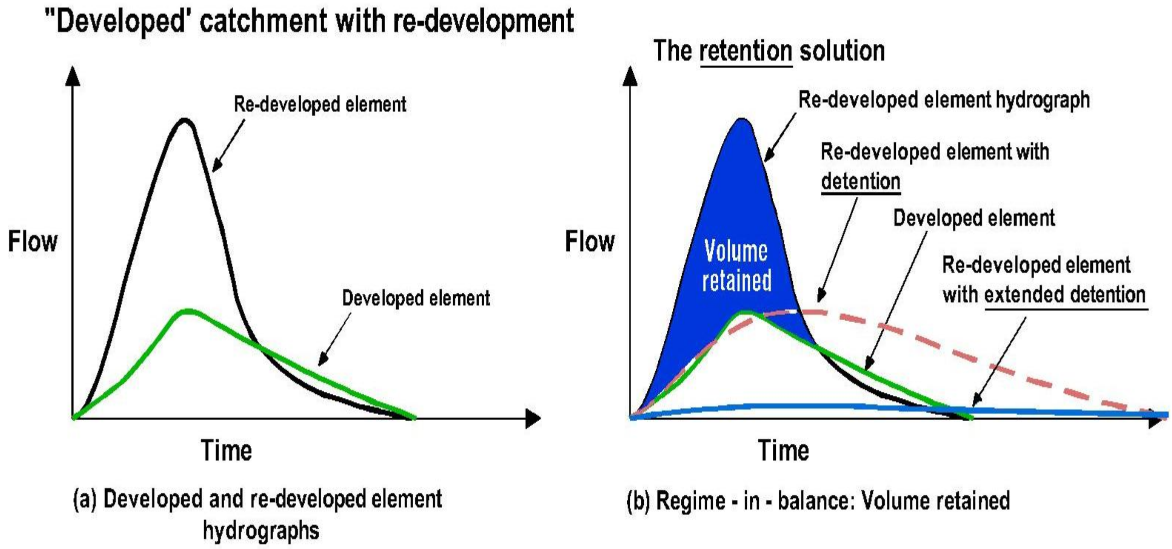

Figure 2: (a) Runoff hydrographs for selected element - developed and re-developed; and (b) *regime-in-balance* strategy: "volume retained"

The 'source control' mathematical/hydrological model that is sought applies the following simple principle:

*"**Volume** of stormwater passing from each catchment element before re-development (ARI, Y-years) must be equal to the **volume** discharged from the same (catchment) element following re-development during the passage of the floodwave in the design storm of critical duration".*

This principle, called the *regime-in-balance* strategy (Argue, 2004/2011), requires retention – at the site – of the *volume difference* between the runoff hydrographs from the (proposed) re-developed site and from its predecessor. This is labelled on Figure 2b as **volume retained** (shaded).

[Also shown on the graph is the basin outflow curve (broken) for the conventional on-site detention solution to the same problem. Those familiar with this design approach will recognise the detained volume required for the basin as the difference between the runoff hydrographs of the re-developed element and of the detention basin outflow for the same element. It is clear that the storage volumes required for the *retention* solution and for the *detention* solution are remarkably similar in magnitude. The hydrological consequences of their roles in temporary storage of surface runoff are, however, profoundly different.]

The 'volume retained' in an application of the *regime-in-balance* strategy is, effectively, quarantined from the floodwave *for (at least) its duration* and disposed of through use (raintanks providing in-house and outdoor supply, industrial uses, bio-retention installations, raingardens, etc), soil moisture enhancement via in-ground "soakaways" or aquifer recharge where possible. Any left-over quantity following these disposal options may be released downstream, but it must be at a very low rate of flow – in the manner of 'extended detention' (US Dept of Transportation, 1996) – for duration constrained by the requirement of full storage availability in the face of storm successions [see Figure 2(b)]. This important aspect of the strategy is re-visited in Section 3.4.

It follows that, with these provisions in place, the volume of runoff discharged from the (proposed) re-developed element will be the same as passed from that same element in its original developed state during flooding and, further, that the time when that contribution reaches the ultimate discharge point, O, will also be the same. An over-riding condition which governs these phenomena is their direct association with the (unique) design storm of critical duration in the catchment.

It is **not** claimed that the two outflow hydrographs generated at the catchment element – its developed and re-developed versions during flooding (incorporating volume retention) - are, necessarily, identical. But that they have the same basic properties – same volume and same time-position within the total (catchment) runoff hydrograph. [The argument here is the same as that which gives us the area-moment formulation in calculus: the **shape** of the element is not important, only its area and position.]

2.2 The total catchment – integration under the *regime-in-balance* strategy

Having established the (almost) unchanged nature of the basic properties of the elemental flow contribution to the (total) runoff hydrograph following re-development, it is but a small step to *integrate* this across all re-development elements of the entire catchment, leading to the proposition that –

equal 'before' and 'after' (re-development) surface runoff volumes delivered to the drainage path at each catchment element during the passage of the floodwave will result in 'before' and 'after' (total) runoff hydrographs at outflow point, O, having similar characteristics of peak flow and shape. [To achieve this equality, any volume remaining in site storages – after use and other disposal options have been exhausted – should not be released until the main floodwave has passed.]

This is a remarkable claim because it implies that any level of re-development can occur in an already developed catchment – from 'low' to quite 'high' density land uses – without significantly changing the main characteristics of the (design) flood runoff hydrograph (ARI, Y-years) that was well-matched to the capacity of the storm drainage network designed for the *original* developed landscape.

Conventional practice in managing the impact of significant urban re-development calls for upgrading such (formal) drainage networks every 20 to 30 years to take account of regrowth. This involves great cost to the community for infrastructure augmentation as well as disruption to normal activities during the construction process. The *regime-in-balance* strategy incorporating the principle of 'source control', explained above, can avoid these costs and inconvenience. Furthermore, these benefits are matched – seamlessly – to regrowth as it takes place in the catchment and are therefore ongoing *for all time.* The conventional approach, by comparison, expresses itself in surges of upgrade activity which only terminates when re-development reaches the 100% impervious limit characteristic of the typical CBD.

While those encountering this contribution to storm drainage technology for the first time may accept that the *regime-in-balance* strategy could, conceivably, deliver these benefits in cases of *modest* urban regrowth such as the conversion, wholesale, of quarter-acre block development into medium density housing estates, they may be challenged to accept that its scope applies equally to more significant cases of re-development.

Take, for example, the pressures being experienced by many councils across the nation as they deal with new demands and opportunities perceived by the development industry to meet some societal need or a new planning direction taken by government. The rapid growth of the retirement village industry, characterised by quite high density unit-living including multi-storey apartment blocks, is an example of the former; the prospect of concentrations of apartment towers located along the upgraded transport spines of our major cities to cope with anticipated population increase, is an example of the latter. Both of these types of re-development can result in an existing storm drainage network - designed for normal urban flow capacity - being severely overloaded in a relatively short time period. The *regime-in-balance* strategy, with its base firmly set in 'source control' technology applied on a site-by-site scale can deliver on these scenarios also.

This review of the *regime-in-balance* strategy together with its supporting illustrations of application to various development/regrowth urban catchment scenarios presumes that the action takes place in municipal situations where the management of storm drainage has high priority. In such circumstances, the *regime-in-balance* strategy provides a sound and cost-effective basis upon which to plan all future re-development in the sure knowledge that the communities served by the resulting networks will remain flood-secure.

Not all municipal situations can be described in this way and there are many examples of already 'overloaded' drainage networks in our major cities and urban concentrations. What can 'source control' technology offer in these circumstances ?

2.3 Ultra-developed or 'overloaded' catchments in the urban landscape

What are the characteristics of an 'overloaded' storm drainage network ?

A formal drainage network may be described as *overloaded* when the runoff hydrograph resulting from the storm hyetograph used in its original design (ARI, Y-years event) exceeds the conveyance capacity of the network under operating conditions at some later time. **Conventional practice** in designing such a network incorporates some built-in excess to take care of 'future development', otherwise it would become overloaded with the first case of re-development. [How much excess to allow for has always been a major dilemma for conventional practice. The *regime-in-balance* strategy, reviewed above, completely avoids this issue and delivers a network which is always up-to-date with regrowth.]

However, the provision of excess (conventional design) can be reached and passed, unnoticed by a busy municipal agency distracted with the daily problems of 'roads, rates and rubbish' and tight budgets in an environment of strained financial resources. Added to this is the issue which results from the *infrequency* of major floods - say, the 20-years, or 50-years or 100-years event – which makes recognition of overloading difficult to detect until such time as a serious miss-match between catchment runoff and network capacity has occurred, resulting in unexpected flooding with consequent community distress as well as disruption to services and business activities. In these circumstances, analysis may show that 'creeping' re-development has occurred without progressive checks being carried out and a network designed, perhaps, decades before for ARI, Y = 50-years is now "at capacity" under conditions of an ARI, Y = 20-years event.

Given these circumstances, it would not be unreasonable for a municipal agency to view a capacity-compromised network as a *lost cause* and be most cautious about any proposal for re-development in the catchment being acted upon on the grounds of aggravating an already dire situation. Such a response would be not only counter-productive from the point of view of new investment and potential rate revenue for council, but also a denial of the opportunity to remedy past miss-management of the network afforded by the prospect of well-ordered re-development. A 'source control' measure – this time, the *yield-minimum* strategy (Argue, 2004/2011) – provides the technical basis for this opportunity.

2.4 The *yield-minimum* strategy

The theoretical base for this 'source control' strategy is almost identical to that of the *regime-in-balance* strategy, reviewed above. The two components of Figure 1 apply equally except that in this case *surface runoff from the entire catchment* (right-hand illustration) includes a peak flow which **significantly exceeds** the defined capacity of the formal drainage network illustrated on the left. As previously, the mini-hydrograph included in the right-hand graphic is that of the site selected for re-development.

In Figure 2, the left-hand illustration is equally applicable to the *yield-minimum* case: this shows an enlarged version of the runoff hydrograph from the site selected for re-development together with its 'new', re-developed runoff hydrograph.

This brings us to the final graph (Figure 2, right hand) and a significant departure from the earlier strategy. The miss-management of past practice cannot be corrected by retaining on site (only) the difference between the 'new' runoff hydrograph and the 'old', as in the *regime-in-balance* strategy: the *yield minimum* approach demands that the **entire volume of runoff** generated on the re-developed site in the design storm event (ARI, Y-years) be retained *during the passage of the floodwave*. The conditions which apply to this 'retained volume' are identical to those of the *regime-in-balance* case: it must be quarantined from the floodwave and disposed of through use (raintanks providing in-house and outdoor supply, industrial uses, bio-retention installations, etc), soil moisture enhancement via in-ground "soakaways" or aquifer recharge where possible. Any left-over quantity following these disposal options may be released downstream after the floodwave has passed, but it must be at a very low rate of flow – in the manner of 'extended detention' (US Dept of Transportation, 1996) – for duration constrained by the requirement of full storage availability in the face of storm successions [see Figure 2(b)].

The ultimate goal of applying the *yield-minimum* strategy is to convert the catchment and storm drainage network serving it from its overloaded condition into a balanced relationship characteristic of *regime-in-balance* waterways. In 'normal' catchment circumstances, this process may take some years to achieve – depending on how bad is the overloading condition, the size of catchment and the rate of controlled re-development (*yield-minimum* strategy) that is takes place.

It is quite possible for the required transformation to take place in one, massive re-development occupying the entire catchment and involving, for example, the construction of a shopping centre taking over the complete area of a formerly overloaded network. Such re-development would need to be carefully planned (hydrology and hydraulics) and would be more complex to design than a simple *yield-minimum* strategy application. However, the ultimate goal would be the same: to deliver a system with catchment and (original) drainage network matched to *regime-in-balance* strategy requirements.

A more likely scenario would involve regrowth within the catchment of the overloaded network, applying the *yield-minimum* strategy opportunistically to site-by-site re-development. Unlike the single "...massive operation..." considered above, this approach would not deliver an immediate overall solution but, rather, a satisfactory outcome in the fullness of time: the 'satisfactory outcome' is, of course, a good match between runoff generated in the catchment in the ARI, Y-years event and the capacity of the storm drainage network *as originally designed*. With this stage reached, the *yield-minimum* strategy can be abandoned and the subsequent history of the catchment and drainage network could be the same as for any *regime-in-balance* application.

2.5 A final word on the 'source control' strategies

The particular benefit that is likely to attract the attention of municipal agencies and their practitioners in both the *regime-in-balance* and *yield-minimum* strategies is that of avoiding, totally, the *"...costs and inconvenience..."* that are necessary elements of conventional up-grade practice. While it is true that this is no idle claim – City of Gosnells in Western Australia is currently showing a storm drainage network cost-saving of $ 120 million using these technologies (see Tennakoon & Argue, 2011) - 'source control' strategies **do** (must !) involve investment costs that are imposed on a (re-development) site-by-site basis rather than to the broad stormwater infrastructure. "There's no such thing as a free lunch !" applies just as much to stormwater management in Australia in the 21st Century as it did in the harsh economic times of the Great Depression in the United States where the adage originated.

The nature of this *investment cost* as well as its magnitude are, clearly, case-specific matters which raise some vital questions. First: is the overall cost that follows implementation of the 'source control' option less than the cost involved in conventional upgrade practice ? Second: are the owners who take over the re-developed properties expected to carry the full weight of this cost - passed to them by developers – or should councils share this burden with (re-development) owners ? And in this (latter) scenario: what proportion should be applied to each partner ? The discussion/negotiation of these (economic) matters needs to take account of the particular advantage which the 'source control' practices hold over conventional upgrades for council investment: this would be called upon *progressively* over time as opportunities for re-development were taken up, and not as massive injections applied at time intervals of 20 to 30 years.

Clearly, these are questions that await further enquiry involving economic evaluation as well as discussion and negotiation. However, it would be tragic should implementation of the 'source control' strategies reviewed in this article flounder through intransigence on the parts of the basic stakeholders – councils and the development industry – thereby denying the community at large potential cost-savings as well as significant resource benefits.

Of course, competently-performing stormwater infrastructure must be kept in good order and condition through regular inspection and repair, and this involves maintenance cost, whether the network is designed according to 'conventional' or the 'source control' strategies. However, in an Australia facing the prospect of urban population increase unprecedented in our history, together with greater demands on the public purse for schools, health care and improved transportation systems, it behoves stormwater engineers to abandon the wasteful practices of the past and embrace the potential cost-savings and other benefits of the 'source control' technologies in the way they manage stormwater infrastructure in future.

3.0 IMPLICATIONS AND CONSEQUENCES

Provision of a 'source control' mathematical/hydrological model which can be applied across the full range of urban landscape cases from 'greenfield' catchments experiencing urbanisation through to scenarios involving re-development in ultra-developed or (hydrologically) overloaded urban settings, represents a welcome contribution to the methodology of flash-flood management. Some amplification and qualification of various aspects of these strategies, however, is warranted and needs to be understood before they can be put into practice. A selection of these is reviewed below.

3.1 'Volume retained': options/opportunities within re-development scenarios

The essence of the *regime-in-balance* and *yield-minimum* strategies described above is their reliance on a set quantity of floodwater being temporarily quarantined (off-line) from the waterway. The destiny of this stored volume can vary greatly depending on the circumstances of terrain, geology, land use, hydrological objectives and amenity goals with which the strategy planners are prepared to engage.

Consider the simplest of these destinies : the retained volume (roof runoff portion) can be held in rainwater tanks – above- or in-ground - and used to replace mains water in a variety of domestic and/or industrial uses. In situations where discharge to sensitive receiving environments is of particular concern, then part of the retained water (surface runoff) can be diverted to off-line stormwater quality improvement facilities such as bio-retention installations, raingardens, constructed wetlands, etc.

Recognition of the *regime-in-balance* and *yield-minimum* strategies as set, primarily, to achieve flood management objectives provides no conflict, whatever, between use of part of the 'volume retained' for flood management purposes *and* to meet stormwater quality improvement goals: a project calling for satisfaction of *both* sets of objectives – the common experience - can be readily accomplished within a single, dual-purpose installation incorporated into a re-development case.

A comprehensive listing of the destinies and options that designers/planners should consider for the 'volume retained' includes -

- Allocation of part of the volume to green roofs and/or roof gardens;
- Diversion of portion of the water to in-ground "soakaway" devices to enhance soil moisture in the catchment and hence support vegetation;
- Recharge of deep aquifers;
- Baseflow supply to local streams.

The final option. There are many real-world circumstances where opportunities for distributing collected storm runoff along the lines suggested above are limited or they may conflict with current council policy. In situations such as these and after every possible avenue of application/disposal has been exhausted, the *left-over* 'volume retained' should be passed to the stream or waterway, *at a very slow rate of flow.*

There are two reasons for this (final option) provision. First: it is vital that all assigned storages are empty and ready to receive rainfall or runoff produced by the next significant storm on the catchment, whenever it may occur (see Section 3.4, below); and, second, the outflow from assigned storages under this option must not impose a flow load on the receiving waterway that is in any way recognisable as a flood wave. This latter condition demands that any held-over storage be drained *slowly,* employing the practice termed "extended detention" in the international literature (US Dept of Transportation, 1996): a graphical representation of this is included in Figure 2(b).

3.2 Average Recurrence Interval (ARI):

The theory developed above – applicable to 'greenfield' catchments as well as highly-developed catchments – stops short of specifying a value(s) for the "Y-years" ARI in each case. The reason for this is the range of objectives open to catchment managers and municipal authorities in their consideration of local goals and circumstances.

The case of 'greenfield' catchments and their supporting waterways is complicated by the need to respect the floodplain and keep it free of urban encroachment (typically, ARI, Y = 50-years to 100-years is used), but also to maintain channel-forming flows and waterway environmental values (ARI, Y = 1- to 2-years), see Engineers Australia, 2006; Argue et al, 2011; Argue et al, 2012.

The question of design ARI applicable to the cases specifically addressed in this article – developed and ultra-developed catchments undergoing further re-development (illustrated in Figure 1)– also involves an ARI-dichotomy, not unlike that of 'greenfield' catchments. Formal street drainage networks are designed, typically for ARI, Y = 2- to 5-years in Australia's tropical north and for ARI, Y = 5- to 10-years anywhere south of Brisbane. Main trunk drains into which the runoff collected by street drains ultimately passes, are designed, typically, for ARI, Y = 50 to 100-years throughout the nation.

A major consideration which determines the level of flood protection provided to the community in case-by-case urban settings is the availability of *overland flow paths*. The lower limits of the ARI ranges suggested in the foregoing paragraphs tend to be acceptable where such paths are readily available as a result of good forward planning or 'by accident': the upper limits, where they are not.

3.3 Detention or retention ?

An important matter that arises in urban stormwater management, following resolution of the ARI issue, is: what technology should be employed to achieve peak flow reduction – detention or retention ? Clearly, this question is settled in favour of *retention* in the explanation offered in Section 2, above: however, can sound reasons be proposed for this choice in the face of Australian practice's almost universal 'love affair' with (conventional) detention technology ?

The case against use of detention basins in 'greenfield' developments is outlined in Section 1: retention practice is a 'must' in this domain (Argue, 2012).

In relation to the developed and ultra-developed catchments undergoing further regrowth: consider the information provided in Figure 2(b). Here we have the principal consequences of the alternative technologies – detention or retention practices – clearly displayed. The 'volume retained' approach provides opportunities for a wide range of environmentally productive practices to be instituted including rainwater harvesting (for domestic or industrial uses), application of water to open space areas and garden beds to enhance soil moisture levels, potential for water diversion into shallow and deep aquifers, and use of water to convey pollutants to *raingardens* and similar bio-retention facilities for treatment. Water exiting a (conventional) detention basin – as Figure 2(b) shows clearly – has only one destiny, 'to waste'.

Retention practice, applying WSUD 'source control' principles, is the preferred option across the full range of waterway domains.

3.4 Storm successions and 'emptying time':

It was noted under the 'final option' heading (Section 3.1), above, that emptying of assigned storages between successive storms was a vital element of the successful operation of any practice that depends on the technology of storage to achieve flood management goals. But it was also noted that such emptying should not create flood-wave conditions in the receiving waterway. These two requirements present the designer with an apparent conflict which can only be resolved by recourse to a criterion which provides guidance on *"...the time available to empty the storage before the arrival of the next design storm"* An answer to this question enables a drainage flow rate to be determined and, hence, an assessment of whether this (flow rate) constitutes a flood threat within the receiving waterway.

The preferred method for solving this problem is to use continuous simulation modelling based on a long-period rainfall record for the catchment in question – measured or derived - which includes periods of particularly severe storm activity. This approach should be followed in all large-scale flood mitigation schemes.

An alternative approach is available for use with relatively small or minor flood management operations: this employs a table of (target) emptying times which vary (directly) with storm magnitude, represented by average recurrence interval (ARI) – Table 1. The table is based on anecdotal rather than scientific evidence and is an interim measure pending more rigorous research/investigation. However, it has been well-received over the past seven years by practitioners in the cyclone-prone regions of tropical Australia as *"...practical ..perhaps a bit conservative..."* and provides, at least, a good first approximation method for setting (target) outflow rates for minor flood control storages.

TABLE 1

INTERIM RELATIONSHIP BETWEEN ARI AND 'EMPTYING TIME'

Ave Recurr. Interval (ARI), Y-years	1-year or less	2-years	5-years	10-years	20-years	50-years	100-years
Emptying time, **T** in days	0.5	1.0	1.5	2.0	2.5	3.0	3.5

Application of the Table 1 criteria in any practical case leads to storage outflow rates which are, typically, quite low. Practitioners encountering this for the first time must resist the temptation to treat such flow rates as *minimum* (required) values which can be exceeded, thoughtlessly, to achieve an engineering outcome. This action is counter to the basic intention of a valid 'source control' practice and runs the risk of outlet works (pipe diameters, etc) being dimensioned to create the hazardous *"... flood-wave conditions in the receiving waterway"* which must be avoided. The storage outflow rates which arise from either continuous simulation modelling or use of Table 1 should be seen as 'target' values: infrastructure designed to meet this requirement should neither exceed nor fall short of the 'target' by a significant margin.

4.0 CONCLUSION

WSUD 'source control' principles are proposed for use by Australian stormwater management practitioners as they engage with the many problems created by regrowth in already-developed catchments served by formal drainage networks. The paper opens with a brief review of best US practice relating to **'greenfield' catchments** experiencing *first wave* development: 'source control' principles are noted as fundamental to solving the problems posed by this scenario.

The theory base of 'source control' practice is then explored for the particular case of re-development in an already **developed catchment** with formal stormwater infrastructure. This explanation contains two "solutions" to the re-development problem: that offered through the *regime-in-balance* strategy (Argue, 2004/2011) leading to purposeful retention of runoff – the 'volume retained'; and that offered by detention technology. The 'volume retained' approach is shown to be consistent with water-sensitive principles, providing opportunities for harvesting rainwater as well as promoting soil moisture enhancement, pollution treatment/ control, aquifer recharge, etc. The alternative – use of conventional detention basins – discharges its component of stored water, effectively, to waste thereby violating water-sensitive principles.

Adoption of the *regime-in-balance* strategy for all subsequent re-development is shown to provide – through 'source control' principles - a seamless transition into more intense levels of urban development *without the need for (stormwater) infrastructure augmentation.* The conventional approach to urban regrowth expresses itself in surges of stormwater infrastructure upgrade – every 20 to 30 years – at high cost and with considerable disruption to community activities during the construction process. The ‘source control’ approach is, clearly, of (financial) advantage to councils but this benefit needs to be shared/negotiated with developers acting on behalf of the ultimate bearers of the cost burden: property-owners.

The problems posed by catchments within which development has proceeded to the point where the stormwater infrastructure is overloaded, are also addressed in the paper: these are the **ultra-developed catchments**. A different approach is offered for these – the *yield-minimum* strategy. In this case the ‘volume retained’ comprises the *entire body of stormwater* generated on each re-developed site. By this means, it is possible to compensate for poor past management which has led to overloading of catchment (stormwater) infrastructure and, in time, to restore ‘balance’ between the quantity of runoff generated in the (design) ARI, Y-years event and the capacity of the infrastructure to satisfactorily convey that load. As in re*gime-in-balance* systems, the ‘volume retained’ in an application of the *yield-minimum* strategy provides many opportunities for water-sensitive principles to be employed including stormwater harvesting, pollution control/treatment and soil moisture enhancement. .

It is hoped that the principles of ‘source control’ technology described in this paper for the particular cases of regrowth in already-developed catchments will resonate with those who manage the considerable personpower and financial resources presently devoted to this area of the municipal industry and, as a result, that they will take full advantage of the environmental and cost-effective benefits that those principles entail.

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