STORMWATER 2010
National Conference of the Stormwater Industry Association
Conference Proceedings

THE QUANTITY DOMAIN OF WSUD: FLOODING AND ENVIRONMENTAL FLOWS

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Abstract

A concentration of resources and research effort on the quality and harvesting aspects of WSUD has resulted in the **quantity domain** languishing. The paper attempts to rectify this imbalance by listing eight quantity issues that encapsulate water-sensitive principles: there are many more. Three of these are selected for particular attention – flood considerations in natural waterways; flood management in (formal) stormwater infrastructure; and, environmental values in 'greenfield' waterways.

The **regime-in-balance strategy** (Argue, 2004/2009) is introduced: this requires temporary storage of a "retained volume" having potential for re-use (domestic, soil moisture, aquifer recharge, etc). The option of last resort is release of the stored water into the drainage path. An 'emptying time' criterion is offered to insure against (small) storages being part-occupied during significant storm successions. Application of the strategy together with other design criteria leads to (theoretically) unlimited development possible in 'greenfield' catchments without altering the morphology of their natural waterways. Application (of the strategy) in highly-developed urban landscapes with competent infrastructure leads to the potential for unlimited re-development without the need for upgrade/enlargement for all time.

The article concludes with a review of environmental values in 'greenfield' catchment waterways. This requires joint action in terms of stream morphology and the preservation of low flow behaviour from the natural state through to urbanisation. It is shown that these goals can be achieved through the regime-in-balance strategy acting conjunctively with various WSUD measures. The environmental and economic benefits of the reviewed practices are emphasised.

1 Introduction: the *quality* bias

It is, perhaps, in the nature of things that progress made in any field of human endeavour copies the motion of the pendulum from one extreme to the other before, ultimately, settling down to a balanced course of action giving due recognition to all of (the field's) valid elements. Those with long memories will recall a time (up to the late 1980s) when stormwater considerations were confined to one domain only - that of **quantity** (IEAust, 1958; IEAust, 1977; IEAust, 1987). In those 'bad old days', stormwater **quality** concerns were attracting attention for the first time and stormwater **harvesting** occupied the realm of dreamers.

How that scene has changed ! Take, for example, the (paper) contributions accepted for the present conference. Among those offered for referee-review, the overwhelming majority are **quality-based** articles; the focus of a second wave - about half the quality-based number - is the relatively newly recognised field of stormwater **harvesting**. **Quantity-based** contributions come a distant third. Interestingly, the same disparity is not quite as evident among the non-refereed contributions which are more evenly divided among the three domains. It is clear from this mini-survey where the current interests of academics and industry heavyweights lie !

However, the primary purpose of this article is not to lament the bias that has found its way into the stormwater field in Australia (not so in UK, USA or Europe !), nor to explore how this situation has come about, but, rather, to offer 'a case' which will lead to a true balance between the three domains becoming recognised within a competently- performing stormwater industry.

2. Scope of the *Quantity* domain of WSUD

There are at least eight sub-headings under which components of the *quantity* domain of WSUD might be listed in the process of managing storm runoff in any complex urban landscape such as a typical, present-day Australian city. This is likely to include 'greenfield' areas experiencing 'first generation' urbanisation and areas of well-planned development, as well as suburbs where there is evidence of overcrowding and development/re-development having been poorly-planned. The basic eight sub-headings leading to criteria for managing waterway-related practices in such landscapes are -

1. **Extreme flood flow** (ARI, Y = 50-years, 100-years, etc). [PMF might be adopted because of its potential for loss of life.] The adopted flood criterion defines the extent of floodplain which must be quarantined from urban development. **The consequence:** reduced risk of public injury and property damage and reduced disruption to services;

2. **Channel-forming (or 'dominant') flow** ('greenfield' catchments): This flow - closely related to 'bank full' peak flow or some variant of it (ARI, Y = 1 to 2 years) – should be the same after development as before (development). **The consequence:** promotes waterway stability (morphology);

3. **Channel-forming (or 'dominant') flood hydrograph** ('greenfield' catchments): Item 2, above, is a 'necessary' but not a 'sufficient' condition for waterway stability: "sufficiency" requires similarity of the 'dominant' flood hydrograph - before and after development. **The consequence:** waterway stability and support for dependent, aquatic bio-communities (fauna and flora);

4. **Environmental flows** ('greenfield' catchments)**:** *Low flow* statistics at a significant location of each stream subject to urbanisation should be similar before and after development. **The consequence:** preservation of aquatic bio-communities (fauna and flora) in collaboration with Items 2 and 3, above;

5. **'Regime-in-balance' development strategy** ('greenfield' catchment waterways): This quantity-based design approach requires the **volume** of stormwater passing from each catchment element *before development* (ARI, Y-years) to be equal to that discharged from the same (catchment) element *following development* in the design storm of critical duration. **The consequence:** Minor (if any) change in ARI, Y-years flood peak and hydrograph shape from point to point in natural waterway following development;

6. **'Regime-in-balance' re-development strategy for competently-performing formal drainage network**: This design approach requires the **volume** of stormwater passing from each catchment element *before re-development* (ARI, Y-years) to be equal to that discharged from the same catchment element *following re-development* in the design storm of critical duration. **The consequence:** Minor (if any) change in ARI, Y-years flood peak and hydrograph shape from point to point in formal drainage network following development;

7. **'Yield-minimum' re-development strategy for poorly-performing, formal drainage network in over-developed urban landscape**: This design approach requires the **volume** of stormwater passing from each catchment element *following re-development* to be as close to zero as possible in the design storm of critical duration. **The consequence:** Gradual improvement over

time in performance of the formal drainage network towards competency as re-development proceeds;

8. Items 5, 6 and 7, above, involve requirements for storing and/or using/disposing of stored stormwater, and then releasing remaining water after passage of the design storm at (low) flow rates determined by the need to take account of storm successions. **The consequence:** The "storage empty" assumption can be validly applied in design.

This is by no means an exhaustive list: it excludes, in particular, the important quantity issues associated with harvesting storm runoff in the urban landscape and the stormwater (quantity) strategy that should be followed to remedy the legacy of urban over-development. The remainder of this article is limited to, **first**, an explanation of the *regime-in-balance strategy* (Argue, 2004/2009) as it applies to urban development in 'greenfield' or natural catchment environments (Item 5, above) and also to re-development taking place in suburban catchments already provided with competently-performing stormwater infrastructure (Item 6, above). A **second** issue is also addressed: an introduction to criteria relating to *environmental flows* (Item 4, above) and their preservation in 'greenfield' waterways experiencing the impacts of urbanisation.

3. Regime-in-balance strategy – theory background

3.1 The 'greenfield' catchment case

Figure 1 presents, first, the layout of sub-areas of a 'greenfield' or rural basin proposed for urban development. The accompanying graph represents the hydrograph of runoff that can be determined by appropriate hydrological modelling at the (pre-development) catchment discharge point, O, in the 'design' ARI, Y-years storm upon which a proposed stormwater management strategy in the basin is to be based.

The single, shaded element shown in Figure 1 is to be developed first: this might be a rural produce collection centre or a holiday camp or it could be the first of many residential subdivisions. Its **pre-development** contribution is also shown in the graph as a 'mini-hydrograph'. An *enlarged* version of this hydrograph is presented in Figure 2a, labelled as "rural element". Also shown in Figure 2a is the (modelled) hydrograph of runoff from the same element in its developed state, labelled "developed element".

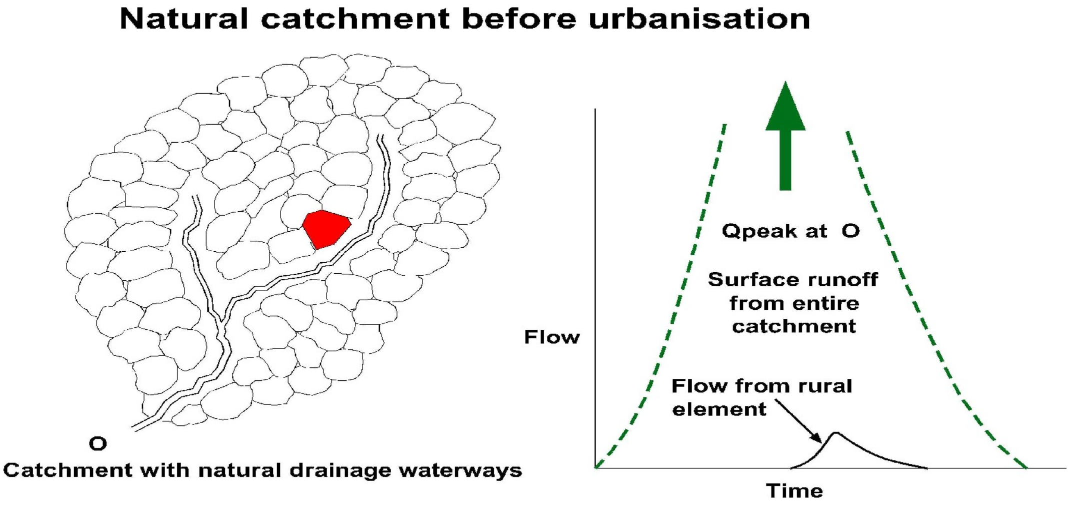

Figure 1:'Greenfield' catchment elements and ARI, Y-years runoff hydrograph

Figure 2b illustrates how the strategy of Item 5, above, *"...volume of stormwater passing from each catchment element* <u>*before development*</u> *(ARI, Y-years)..."* must be equal to the *"... volume discharged from* *the same (catchment) element following development in the design storm of critical duration..."* is applied. It requires retention – at the site – of the volume difference between the runoff hydrographs at the developed and pre-developed sites, labelled on the graph as **volume retained** (shaded).

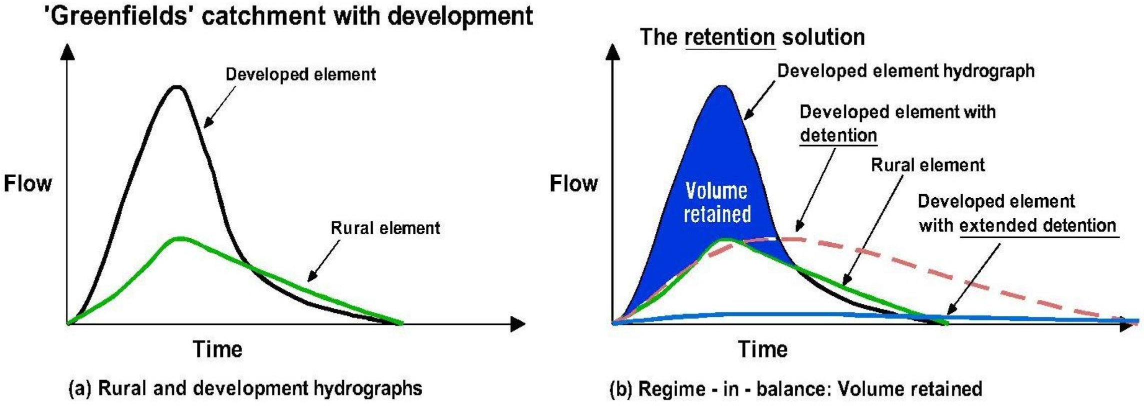

Figure 2: (a) Runoff hydrographs for selected element - pre-development and developed; and (b) regime-in-balance strategy: "volume retained"

[Also shown on the graph is the basin outflow curve (broken) for the conventional *on-site detention solution* to the same design 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 developed element and of the detention basin outflow* for the same element. It is clear that the two storage volumes – that required for the retention solution and that required 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 and disposed of through use (raintanks providing in-house and outdoor supply, industrial uses, 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 low rate of flow – in the manner of "extended detention" – for duration constrained by the requirement of full storage availability in the face of storm successions. This aspect of the strategy is re-visited below under the heading "Emptying time" (Section 4.3).

It follows that, with these provisions in place, the **volume** of runoff discharged from the developed element will be the same as occurred from that same element in its pre-developed state 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 *pre-developed* version and *developed* (incorporating volume retention) version - 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*.]

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

equal 'before' and 'after' (development) surface runoff ***volumes*** *delivered to the drainage path at each catchment element will result in 'before' and 'after' (total) runoff hydrographs with similar characteristics of peak flow and shape. [To achieve this equality, the* ***difference*** *in volume ("volume retained") must be held for at least the duration of the critical storm.]*

This is a remarkable claim because it implies that *any* level of development can occur in a 'greenfield' catchment – from low to high density occupancy – without significantly changing the main characteristics of the (design) flood runoff hydrograph (ARI, Y-years) of the drainage waterway from those it possessed in its natural or rural state.

[It should be noted that this capability of 'retention technology' sits in sharp contrast with the consequence of using a (conventional) detention basin at the discharge point of each catchment element: this leads to progressively greater (hydrograph) peak flows with distance downstream (see Argue and Pezzaniti, 2009)]

3.2. The developed catchment with re-development

The **regime-in-balance strategy** theory developed for 'greenfield' catchments, above, can be applied with little alteration to developed catchment cases having formal drainage infrastructure. Consider the catchment depicted in Figure 3: it represents a fully-developed urban landscape served by a stormwater infrastructure comprising underground pipelines (shown dashed) feeding a hard-lined open channel conveying surface runoff generated in the catchment to the discharge point O. It is assumed that the formal drainage system has been competently designed and is matched to the ARI, Y-years flood condition. The (total) surface runoff hydrograph determined for flow delivered to the discharge point O for the 'design' storm of critical duration (ARI, Y-years) in the catchment is also shown in Figure 3. Runoff from *existing* development of the element shown shaded is included in the 'total' hydrograph as a mini-hydrograph and labelled "developed element". Its magnitude and time-position within the 'total' hydrograph are, both, correctly represented.

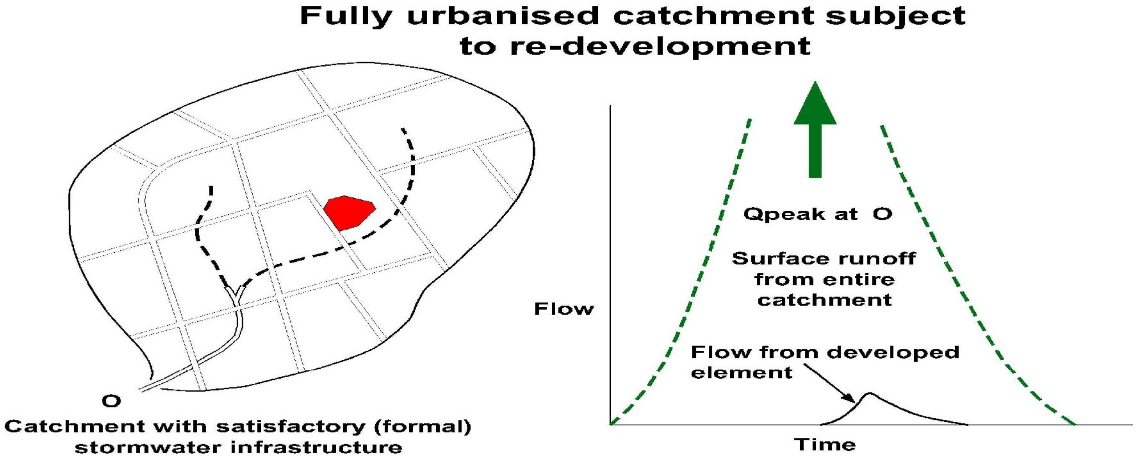

Figure 3: Developed catchment elements and ARI, Y-years runoff hydrograph

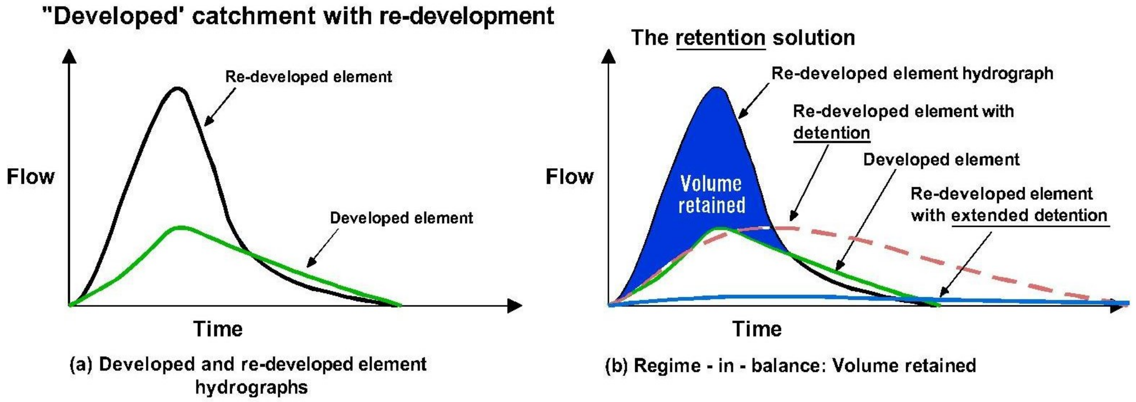

Figure 4: (a) Runoff hydrographs for selected element - developed and re-developed; and (b) regime-in-balance strategy: "volume retained"

Re-development of the (shaded) element is proposed and the changed conditions of runoff for that element are illustrated in Figure 4a. As in the corresponding 'greenfield' catchment scenario, two stormwater management options can be followed. The 'detention solution' leads to an on-site basin holding surface runoff temporarily before release into the formal drainage path; the 'retained volume' approach of the regime-in-balance strategy sees the stored water used or otherwise disposed of, with controlled release into the formal drainage path adopted only as a last resort. Application of the two management solutions to all elements of the catchment as they are opportunistically re-developed leads to two profoundly different outcomes.

Progressive inclusion of (conventional) detention basins leads to progressively increased flood flows downstream for which the common solution is 'staged' infrastructure enlargement or duplication as greater numbers of elements come up for re-development: the need to re-visit the problem say, every 15 - 20 years, as well as the prohibitive cost makes this an option of questionable merit. Alternatively, municipal agencies operating within this scenario can accept progressively reduced flood security for the urban community as re-development proceeds.

The 'retained volume' approach, on the other hand, requires no such modification of the original, competently-performing infrastructure because the mini-hydrograph **volume** delivered at each catchment element committed to opportunistic re-development is unchanged from that of its developed state in both *magnitude* and in terms of its *time-position* in the total 'design' flood hydrograph. Hence, as re-development proceeds there is no significant change in the total 'design' flood hydrograph in terms of both peak flow and shape.

This is an astounding consequence for it implies that an existing, competently-designed, formal stormwater infrastructure (ARI, Y-years) can continue to operate satisfactorily *without restriction on the level of re-development imposed* and *without the need for enlargement or duplication* **for all time**. The basic stormwater management requirement which must be met to take advantage of this consequence is that –
at every site where re-development takes place, the **volume** *of stormwater discharged to the formal drainage path in the design storm of critical duration (ARI, Y-years) is the same after re-development as it was before.*

Of course, such (competently-performing) infrastructure must be kept in good order and condition through regular inspection and repair, but the need for expensive and progressive upgrading is quite unnecessary. 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 (conventional) 'detention solution' practices of the past and embrace the benefits of the 'retained volume' approach in the way they manage stormwater infrastructure in future.

4. Some issues which emerge from the above considerations

4.1 Average Recurrence Interval (ARI, Y-years)

The theory developed above – for 'greenfield' and fully-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 management and municipal authorities in the process of deciding on an appropriate ARI: these objectives greatly affect the "Y-years" that is chosen.

Consider, for example, the ARI which might be appropriate for a 'greenfield' catchment facing an immediate future of development for low density housing and/or 'lifestyle' lots, perhaps, on the outskirts of a large city. A major objective here would be preservation of the environmental values of the catchment's natural waterway, particularly its eco-community (fauna and flora). A 'first order' decision that should be made in this context is delineation of the floodplain associated with the natural waterway (Item 1 in the original list, above): this might be set at ARI, Y = 50- to 100-years; containment of the Probable Maximum Flood (PMF) may be considered in some cases.

But recognition of the importance of *environmental values* of the waterway raises issues in two other quarters, namely, preservation of well-matched *environmental flows* (Item 4 in the original list, above) and management of the so-called "channel-forming" flows in the range ARI, Y = 1- to 2-years to ensure that they are *the same after development as they were before (development)*. The **regime-in-balance strategy** can deliver this latter requirement through its ability to produce *before-and-after* (development) flood hydrographs having *similar peak flows* and *similar shapes* (see above).

The latter property - that of (hydrograph) *shape* similarity - provides a welcome solution to the problem of keeping EPI (erosion potential index) to a value close to unity (the ideal, see NSW Landcom, 2009). SEQ Concept Design Guidelines for WSUD (SEQ Healthy Waterways Partnership, March, 2009; November, 2009) as well as Sydney Catchment Management Authority's recently adopted Guidelines (2010) set EPI = 2 as "acceptable" but have yet to declare how this may be achieved. The SEQ Guidelines incorporate (conventional) 'detention practice' as a given: Argue and Pezzaniti (2009) have shown this technology leads to *channel-forming flow* hydrograph shapes (before-and-after development) many times longer than those given by the 'volume retained' approach described in Section 3.1. The use of (conventional) detention basins to achieve *channel-forming* flow objectives leads to values of EPI much greater than the ideal, 1.0.

A later stage of development/re-development will see the low-occupancy level of the original 'greenfield' catchment upgraded to accommodate housing estates characterised by dwelling units and associated urban infrastructure based on medium-density planning principles. It is certainly possible (and highly desirable) to maintain the environmental integrity of the original waterway – including its defined floodplain - using the regime-in-balance strategy (ARI, Y = 1- to 2-years) even in this scenario. But there is a penalty in the form of flood-impact on the defined floodplain in ARI, 50- to 100-years events. These consequences are not insurmountable – use of low (floodplain) boundary levees, for example, can solve the problem – but they must not be ignored.

However, any higher level of urbanisation than reviewed here, for example introduction of high-rise apartment blocks, shopping centres and/or industrial complexes into the urban 'mix', is likely to bring the question of land use (of the floodplain) to the fore. The ensuing debate – floodplain use as community resource (recreation, sporting venues, low-level agricultural activities such as community vegetable gardens, etc) *versus* use of the land for public buildings and/or commercial/industrial activities including residential – can only be resolved by community consultation. In this context, it is important to point out that there is no technical impediment to application of the regime-in-balance strategy to support the waterway environment at the level of ARI, Y = 1- to 2-years even in these upgraded circumstances. But the consequential stress on the floodplain as a result of significantly greater runoff in rare events (ARI, Y = 50- to 100-years) demands additional containment works (at the floodplain boundaries) above those required by previous development scenarios.

Thus we proceed to the typical, mixed-development suburb with formal stormwater infrastructure illustrated in Figure 3. In this case, the value of "Y" chosen by catchment management and municipal agencies varies greatly with a tendency for regions of lower rainfall – in Australia's south – to assign higher values to "Y-years" than regions in the tropical north. Values of ARI, Y = 5- to 20-years might be expected in Melbourne, Adelaide, Perth and Hobart in urban landscapes wherever overland flow paths are readily available. [ARI up to 50- and 100-years has been used for formal stormwater infrastructure in some situations where overland flow paths are unavailable because of former poor control of urban development.] Practice in Sydney and the NSW major population centres tends to align more with the "southern states" approach in these matters than with Brisbane and Darwin where ARI, Y = 2- to 5-years for stormwater infrastructure is common.

4.2 Critical storm duration

Critical storm duration is a major ingredient of the process of calculating the "volume retained" (requirement) for any developed or re-developed catchment element in which the **regime-in-balance strategy** is applied. This parameter is a characteristic of the catchment and is unique to it. How is it determined ?

In the case of 'greenfield' catchments (illustrated in Figure 1), critical storm duration, Tg, is most easily and satisfactorily determined using the appropriate form of the Bransby Williams formula listed in Chapter 5 of "AR&R – 1987" (I E Aust, 1987) or an update of the corresponding material. This is a conservative approach: conservative, because its value, determined for rural land use, is likely to be longer than (the catchment's) critical storm duration with urbanisation. Experienced practitioners recommend erring on the *longer* than *shorter* side in the matter of critical storm duration.

Critical storm duration, Td, in fully developed catchments (see Figure 3) should be determined for ARI, Y-years by the method described in Chapters 3 and 9 of "AR&R – 1987" or an update of the corresponding material. In this case the value of "Y" is arrived at through consideration of the factors discussed in the previous section.

The **volume retained** introduced in sections 3.1 ('greenfield' case) is the difference between the *before-and-after* (development) surface runoff **volume, Vg,** determined for each developed element in the ARI, Y-years storm of duration Tg. In the developed catchment experiencing re-development (Section 3.2), it is the difference between the *before-and-after* (re-development) surface runoff **volume, Vd,** determined for each re-developed element in the ARI, Y-years storm of duration Td .

4.3 Emptying time

It is of the utmost importance that the storage occupied by the "volume retained", calculated from catchment equivalent impervious area and ARI, Y-years storm of duration T, be cleared (empty) before the arrival of runoff from the next storm of similar magnitude. Concern about the consequences of partial emptying, only, of such storages (between successive events) has been a major discussion point in urban hydrology for the past decade (Kuczera et al, 2003), leading to the call for using *continuous simulation modelling* in competent stormwater drainage design.

While the need for using this approach to design storages (detention or retention) of large size is not disputed, a simpler practice has been proposed (Argue, 2004/2009) for taking account of 'storm successions' in *small* components of urban catchments. This is based on satisfying an emptying time criterion related to the ARI adopted for the design. An 'interim' table of criteria supporting this approach is presented in Table 1.

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

5 Summary – the *regime-in-balance* strategy

The objective of the strategy is to ensure that the *hydrological circumstances* of greatest importance to those responsible for managing urban waterways ranging from natural streams in 'greenfield' catchments facing the earliest stages of urbanisation through to formal drainage paths serving mature urban landscapes, are unchanged by the development or re-development taking place within their catchments. The *hydrological circumstances* are likely to vary greatly: 'channel-forming' flows (ARI, Y = 1- to 2-years) may dominate practice at the rural end of this spectrum; flood-security issues leading to adoption of ARI, Y = 50- to 100-years may be required in highly-urbanised catchments with limited opportunity for use of overland flow paths.

Application of the **volume retention** principle – the basis of the strategy - at all points along this spectrum of practices leads to continued management of the affected waterways *without the need for alteration or upgrade*. A wide range of uses of the retained (stormwater) volume is recommended – domestic/industrial (non-potable) supply, soil moisture enhancement, aquifer recharge, etc – with (slow) release to the drainage path the option of last resort. *Continuous simulation modelling* or use of an *emptying time criterion* (small systems) can be employed to solve the problem of ensuring that storages associated with the 'retained volume' take proper account of the consequences of successions of storms of 'design' magnitude.

6 Environmental flows: an introduction

6.1 *Low flows* and flood-based hydrology

The primary goals of satisfying the *environmental flow* criteria in a natural or rural waterway facing the early stages of urbanisation are associated with preserving – as closely as possible – its *low flow* regime, a range of flows significantly smaller than those responsible for the *channel-forming* flood flows (ARI, Y = 1- to 2-years), discussed in Section 4.1, above. It is important to understand the differences between *environmental flow* and *flood management hydrologies,* despite the fact that both involve analyses using the same streamflow database.

The analyses which must be undertaken within the scope of *low flow* hydrology are not totally divorced from those of flood hydrology. Indeed, the highest flow of a particular *low flow* sequence – called the *threshold flow* – can be assigned an average recurrence interval such as ARI, Y = 3-months or 2-months or 1 month, etc. However, this property (of the *low flow* sequence) is of less importance than is the *statistical description* of the run of smaller flows – including periods of zero flow - which comprise it. The "sequence" (of flows) referred to here is termed a **spell** in the literature of environmental flow hydrology.

Thus, the ARI concept is replaced in the analysis of *low flow* streamflows by a new, statistical parameter –

"% of time flow exceeded"

and it is *this* parameter plotted as the independent variable against **flow** (expressed, typically, as ML per day) which enables both the performance of a waterway in its pre-developed state and when impacted by development to be quantified.

Another aspect of the *low flow* regime which distinguishes it from flood-based hydrology is the observation that the **total** quantity (volume) of flow which makes up this regime is at least 95% – sometimes as high as 99% (Smakhtin, 2001) - of total (average) annual flow. Flood wave volumes of events of magnitude ARI, Y= 2-years and above represent, *on average*, less than 0.5% of this flow (Engineers Australia, 2006).

A further recognition that emerges from these considerations is the fact that the range under discussion here embraces flows of (relatively) low velocity which, therefore, provide little disturbance to established fauna and flora colonies inhabiting the drainage path. The association between *low flows* and stream-based eco-communities is well recognised (Samkhtin, 2001; Lee et al, 2008; Walsh et al, 2009).

It may therefore be concluded from these observations that the *low flow* regime of a waterway – expressed quantitatively in terms of appropriate streamflow analysis statistics – provides the key to understanding how streams 'behave' in their natural or rural state and, perhaps more importantly, how the impacts of urban development can be understood, measured and managed to retain waterway environmental values.

6.2

6.3 Quantifying the 'performance' of a waterway before and after development

The first step towards the goal of providing sustainable management of streams serving 'greenfield' catchments facing urbanisation is to develop a hydrological model of the pre-developed catchment and validate it against recorded flow data stretching over (preferably) several decades. This task was undertaken and satisfactorily accomplished by Lee et al (2008) using the well known SWMM model as available in August, 2006 (US EPA, 2005). The SWMM model was chosen by the researchers because of its ability to account for "...infiltration of rainfall to unsaturated soil layers, percolation of infiltrated water into groundwater, and interaction between groundwater and streams (surface water)". The Scott Creek catchment (26.8 km^2) in the Adelaide Hills was chosen for the study: the analysis used streamflow records for the period 1970 to 2003 inclusive.

This process produced, firstly, the statistical relationship between "% of time flow exceeded" and Flow (ML per day) for the waterway and, secondly, the outcome of the SWMM model created to simulate it. These are illustrated in Figure 5.

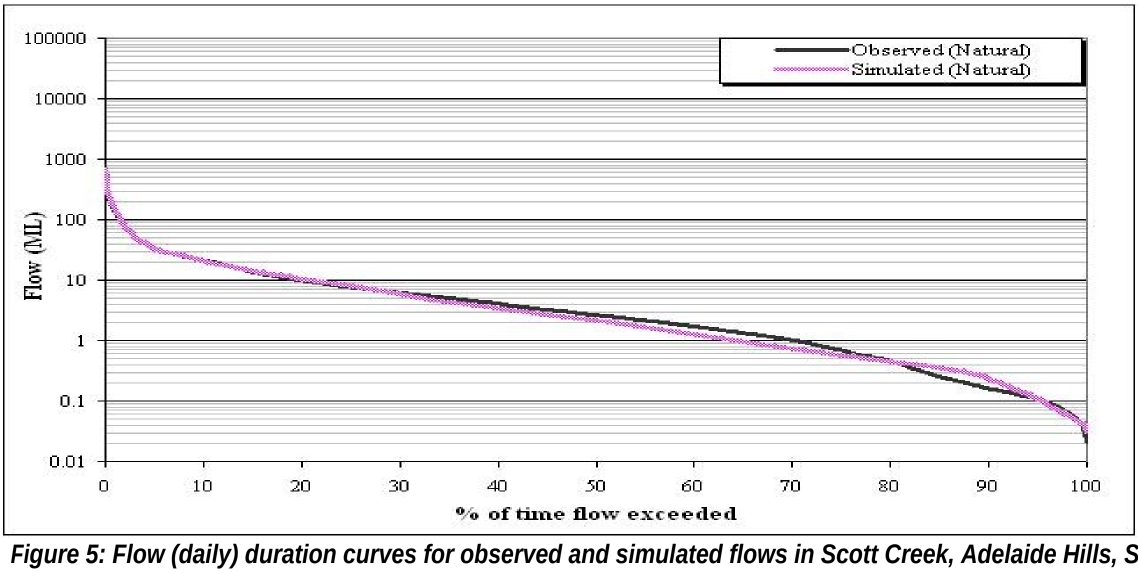

Figure 5: Flow (daily) duration curves for observed and simulated flows in Scott Creek, Adelaide Hills, SA (streamflow data set: 1970 to 2003)

With a credible hydrological model developed, it is then possible to explore the impact of various development scenarios on the 'greenfield' waterway. This was carried out for the Scott Creek case: three scenarios were investigated –

- 35% of catchment assigned to connected impervious;
- 50% of catchment assigned to connected impervious;
- 65% of catchment assigned to connected impervious.

The curves corresponding to these cases are illustrated in Figure 6.

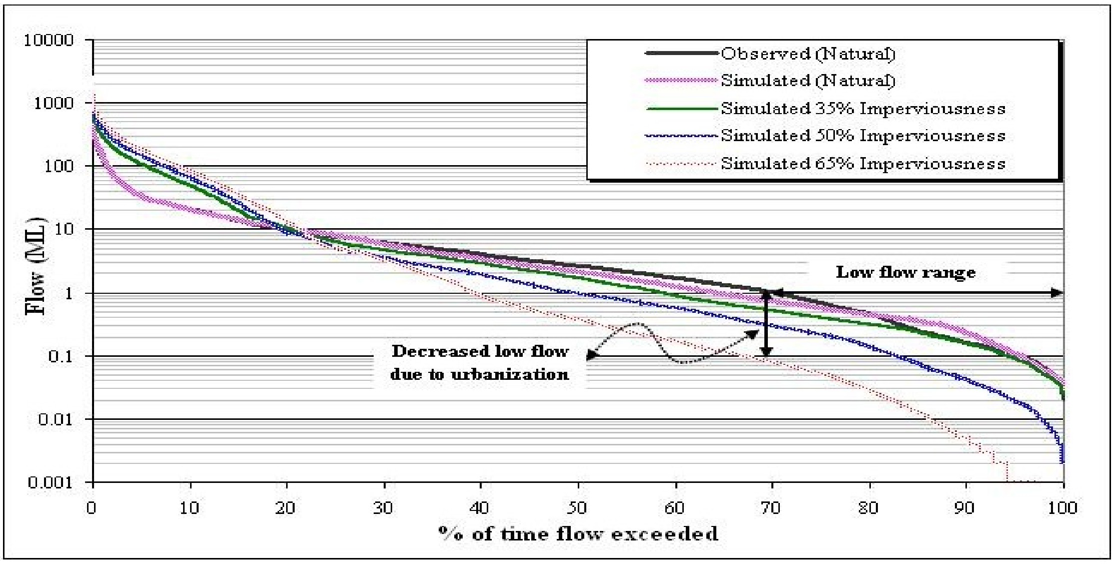

Figure 6: Daily flow duration curves for Scott Creek (pre-development) and three levels of development.

It is noted that 35% impervious area connected directly to the creek produced a modest *redistribution* of flow **from** the range 25% - 80% **into** the 0% - 20% range: this observation is consistent with the expectation of decreased *low flows* and higher peak flows following urbanisation. The corresponding curves for 50% imperviousness and 65% imperviousness indicate far more dramatic "redistributions". Such analysis demonstrates clearly – and quantitatively – the impact of urbanisation on the environmental health of dependent waterways in 'greenfield' catchments.

6.4 WSUD quantity domain measures required to maintain environmental values

The final stage of the Lee et al (2008) study was to explore practices incorporating WSUD measures that were able to restore the (daily) flow duration curve to approximately its original (pre-development) state despite urbanisation. Two measures were trialled –

- **WSUD Measure 1:** A network of infiltration facilities – one in each sub-catchment – occupying 5% plan area (of sub-catchment); overflow was passed directly to the waterway;
-
- **WSUD Measure 2:** A network of 1.0 m deep retention basins, each occupying 0.3% of sub-catchment plan area; outflow by 'extended detention' (slow) release to the waterway.
-

The results of these trials are presented in Figure 7 for the particular case of the Scott Creek catchment with 50% impervious area directly connected to the waterway.

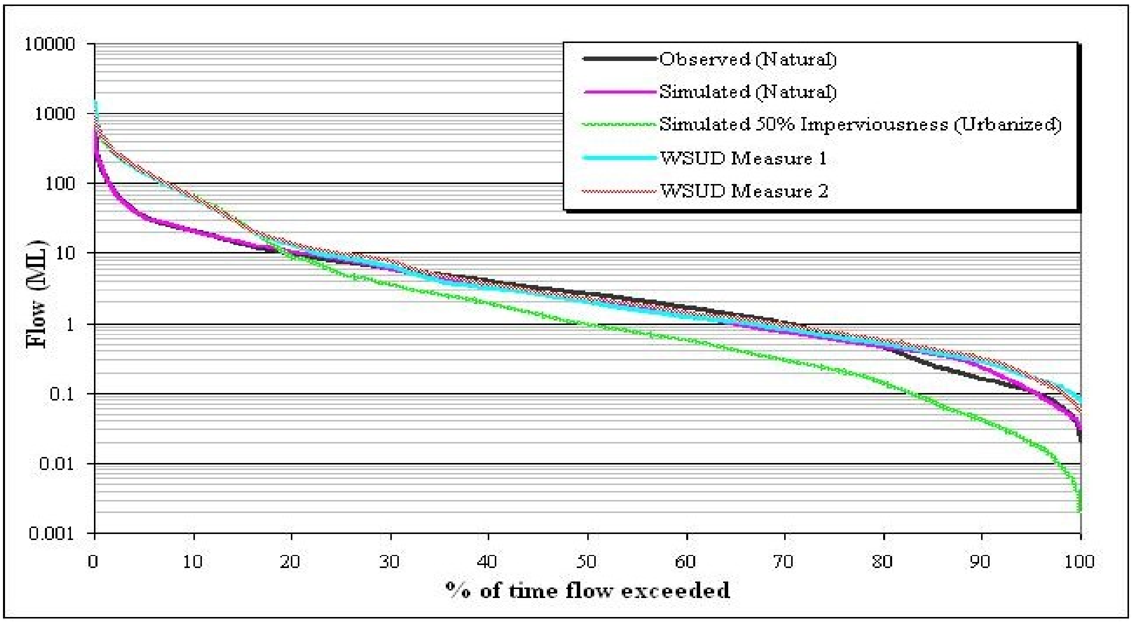

Figure 7: Scott Creek with WSUD measures 1 and 2 applied to the "50% connected impervious" case.

Figure 7 shows WSUD Measures 1 and 2 applied in the Scott Creek catchment as being capable of satisfactorily cancelling the adverse effects of urbanisation, certainly at the level of 50% imperviousness, and providing a *low flows* regime little different from that of the waterway in its natural state. There is a considerable armoury of WSUD practices which could be considered for similar duty with every likelihood that acceptable and cost-effective measures can be found to achieve such similarity of *low flows* performance with that of natural streams and, therefore, the preservation of environmental values despite urbanisation.

7. Discussion-Conclusion

There is evidence that the stormwater industry including practitioners and researchers with interests in the field has been misled into believing that the paramount goal of water-sensitive urban design should be to improve the quality of urban storm runoff through an arsenal of treatment and pollution control measures. In recent time, a new focus has been added – that of stormwater harvesting. While both of these fields are worthy of considerable attention, their overwhelming pre-eminence at the expense of the 'third domain' of WSUD – that arising from stormwater **quantity** issues and practices – is to be deplored.

The present paper has attempted to provide 'a case' for greater recognition of the **quantity domain** within the industry and, to that end, has explored three, only, of the multitude of areas and fields that fall within the quantity ambit. These are quantity-related issues associated with –

1. the good management of floodwater generated in 'greenfield' or rural catchments undergoing urbanisation;
2. the measures that should guide the process of re-development in highly urbanised landscapes served by well-performing, formal drainage networks; and,
3. the analytical approach which should be employed, first, to quantify the *low flows* performance of natural waterways and, second, to incorporate catchment-wide WSUD measures that ensure *low flows* preservation in the face of urban development.

The first of these includes a strategy for maintaining the morphology of natural streams and waterways – and, hence, support for dependent bio-communities – despite urbanisation. The **regime-in-balance strategy** can be interpreted, theoretically, into any level of urban development while, at the same time, preserving the morphology-dependent environmental values of a stream. In practice, it is likely that economic forces – floodplain use for development *versus* recreation and community uses – will decide, finally, when a natural waterway is "undergrounded" or hard-lined.

The second issue, above, is also focussed on the **regime-in-balance strategy**: this time it (the strategy) contributes significantly to solving the stormwater infrastructure upgrade/enlargement dilemma set by projections for Australia's urban population. It is validly claimed that application of this strategy to a competently-designed and well-performing (formal) stormwater network will lead to accommodation of any level of re-development without the need for infrastructure alteration *for all time*. This element of WSUD practice could well prove to be its greatest attribute for governments and cash-strapped municipal agencies in the decades ahead.

The third item, above, returns to the plight of waterway bio-communities (fauna and flora) under stress in 'greenfield' or rural catchments experiencing urbanisation. Attention to stream morphology (first item, above) is a *necessary* condition for the preservation of these species, but not a *sufficient* requirement. Their survival requires *both*.

It is hoped that the matters explored and reviewed in this article will awaken a much needed interest on the part of researchers and practitioners in the **quantity domain** of water-sensitive practice. Those who answer this call will find the experience rewarding in the extreme through their contribution to the preservation of the nation's 'greenfield' waterways and to the 'bottom line' of both central and local government.

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