SCALING ISSUES IN THE HYDROLOGIC MODELLING OF DISTRIBUTED STORAGES

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Abstract: The application of conventional hydrologic models to catchments with lot level distributed storages (OSD) has been hampered by a lack of understanding of the hydrologic relationship between distributed storages on a subarea and an equivalent lumped storage at the subarea's outlet that could be used in a conventional hydrologic model to simulate the behaviour of these distributed storages. This paper describes the development of scaling relationships that permit lot level storage behaviour to be simulated at a subareal level and the application of these relationships to quantify catchment wide response to varying levels of lot level storage. The paper describes the methodology behind the assessment of PSD and SSR levels for Wollongong and concludes that while the factors involved may change from one region to the next, the procedure outlined can be applied anywhere, and overcomes the need for fine scale (lot level) modelling when simulating the impact of lot level distributed storages (OSD) in a catchment.

Keywords: Hydrologic, Model, Scaling, Distributed, Storage, OSD, PSD, SSR

1. INTRODUCTION

The application of conventional hydrologic models to catchments with lot level distributed storages (OSD) has been hampered by a lack of understanding of the hydrologic relationship between distributed storages on a subarea and an equivalent lumped storage at the subarea's outlet, that could be used to simulate the behaviour of these distributed storages.

This is one of the problems any technical reviewer of an OSD policy faces when trying to develop or refine such a policy. In the absence of an understanding of these scaling issues, most reviewers have been forced to construct complex and costly fine scale (lot level) hydrologic models to quantify catchment response to these distributed storages.

This paper is based on recent work undertaken by the authors, while reviewing the technical requirements of Wollongong City Council's 2004 Draft OSD Policy. Details of the review of Council's OSD Policy generally are reported elsewhere by Silveri and Rigby[2006]. In particular, this paper examines the scaling relationships between Permissible Site Discharge (PSD) and site area and Site Storage Ratio (SSR) and site area, required to control catchment wide discharges in Wollongong.

The investigation into these scaling relationships was broken into three stages involving;

1. A review of peak discharges from sites in Wollongong for a range of locations, percent impervious covers and site areas.

2. A review of storage levels required to maintain post-development site discharges to pre-development levels for a range of percent impervious covers and site areas.

3. A review of PSD and SSR levels required to maintain post-development discharges, anywhere in a catchment, to pre-development levels, for a range of catchments in Wollongong.

The following sections describe the methodology adopted and findings in each of these three areas.

2. SCALING DISCHARGE RATES

The review of peak discharge rate from a site in Wollongong, of varying size and varying levels of impervious cover, was undertaken in a sequential manner by considering:

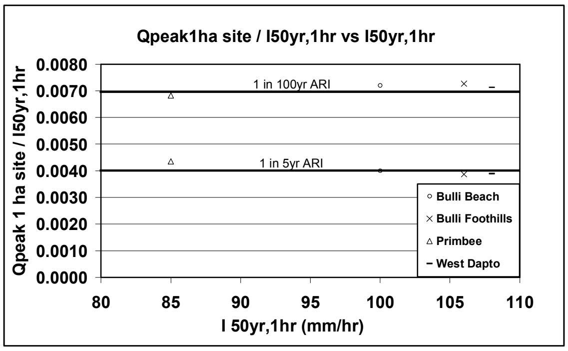
1. The variation in peak discharge from a natural 1ha site, throughout the city.
2. The variation in this natural 1ha peak discharge rate with impervious cover.
3. The variation in this partly impervious 1ha peak discharge rate with area.

To quantify these relationships, simulations were made with the hydrology model WBNM, Boyd, Rigby & VanDrie [2005] using a single subarea model of a 1ha natural (undeveloped) site, at four locations in Wollongong. The four site locations were chosen to represent the limits of the strong east to west rainfall gradient and the lesser south to north gradient present in the Wollongong LGA. Sites were located at:

1. Bulli Beach, to the north of the city, on the coast
2. Bulli Foothills, to the north of the city, below the western escarpment
3. Primbee, to the south of the city, on the coast
4. West Dapto Foothills, to the south of the city, below the western escarpment.

To maintain correlation with earlier work on Council's OSD policy undertaken by Associate Professor Boyd of the University of Wollongong and consultants SMEC Australia, the regional lag parameter C was set at 1.31, a zero initial loss was assigned (to refect the burst like character of critical duration rainfall) with a continuing loss of 2.5mm/hr. For all four 1ha sites, the critical burst duration was found to be 25 minutes, although a 90 minute burst produced almost the same peak discharge (an artefact of the temporal patterns and their IFD)

When these peak discharges were divided by the 50year ARI, 1hour rainfall intensity for each site (from the AR&R isohyetal maps), the simple relationship shown in **Figure 1** became apparent for any 1ha natural site in the City.



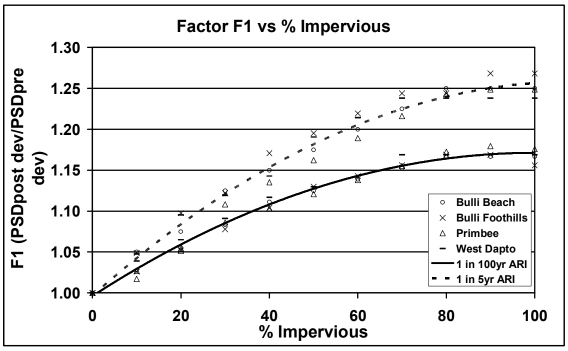
Qpeak 1 ha site –v- I50yr,Ihr
Figure 1

While earlier expectations were that it would be necessary to relate the 5 and 100 year ARI peak discharges to the 2 and 50 year isohyets respectively, it was found that the 2 yr 1 hour isohyet was very close to being a scaled version of the 50yr 1 hr isohyet, permitting both the 5 year and 100 yr ARI peak discharges to be related to the 50Yr 1 hour isohyet. With a maximum error of 7% across the city, the 5 and 100 Year ARI peak discharge rates from a 1ha natural site were found to be;

$$\mathbf{Q}_{\mathbf{5yr\ Nat\ 1ha}} = \mathbf{0.004} * \mathbf{I}_{\mathbf{50\text{-}1hour(mm/hr)}} \quad (m^3/s)$$
$$\mathbf{Q}_{\mathbf{100yr\ Nat\ 1ha}} = \mathbf{0.007} * \mathbf{I}_{\mathbf{50\text{-}1hour(mm/hr)}} \quad (m^3/s)$$

The four 1 ha sites were then remodelled with impervious surfaces ranging from 10% to 90% of the site area for both the 5yr and 100yr ARI events. As shown in **Figure 2**, a strong correlation was found between the developed 1ha site peak discharge rate and the %impervious cover on the 1ha developed site, irrespective of locality in which;

$$\mathbf{Q}_{\mathbf{5yr\ Dev\ 1ha}} = \mathbf{F1}_{\mathbf{5yr}} * \mathbf{Q}_{\mathbf{5yr\ Nat\ 1ha}} \quad (m^3/s)$$
$$\mathbf{Q}_{\mathbf{100yr\ Dev\ 1ha}} = \mathbf{F1}_{\mathbf{100yr}} * \mathbf{Q}_{\mathbf{100yr\ Nat\ 1ha}} \quad (m^3/s)$$



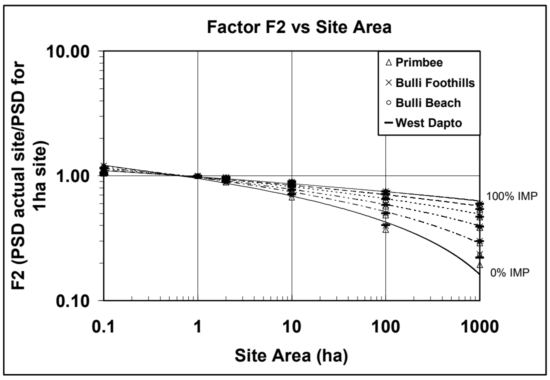
Factor F1 –v- %Imperviousness, 1Ha Site
Figure 2

In the above relationship, F1 was fitted with a polynomial function in which for a given percent impervious cover (%I);

$\mathbf{F1}_{\mathbf{5Yr}} = -0.00002*(\%I)^2 + 0.0048(\%I) + 0.9966$ ($R^2=0.9984$) and
$\mathbf{F1}_{\mathbf{100Yr}} = -0.00002*(\%I)^2 + 0.0035(\%I) + 0.9962$ ($R^2=0.9975$)

To fully generalise this procedure for a development site of any size and impervious cover, a relationship was also needed to reflect the impact of site area on peak discharge.

To quantify this relationship, the four test sites were again remodelled for both the 5 and 100yr ARI events, reflecting a wide range in both %impervious cover and site area. This modelling was extended from 0.1ha to 1000ha to permit the derived relationships to be used in subsequent catchment scale modelling. The resulting ratios of **F2** (Qpeak-with-imp-anysize/Qpeak-with-imp-1Ha) for the various cases modelled are shown plotted in **Figure 3** against catchment size.



Factor F2 –v- Site Area
Figure 3

A strong correlation was also found between the developed site discharge rate and site area in which.

$\mathbf{Q_{5yr\ Dev}}$ = **F2** * $\mathbf{Q_{5yr\ Dev\ 1ha}}$ (m^3/s/ha)
$\mathbf{Q_{100yr\ Dev}}$ = **F2** * $\mathbf{Q_{100yr\ Dev\ 1ha}}$ (m^3/s/ha)

In the above relationship, F2 was fitted with a family of log functions, each reflecting the level of impervious cover, in which:

$F2_{0\%imp}$ = -0.1147*Ln(Area)+0.9537 (R^2=0.9901) and
$\mathbf{F2_{20\%imp}}$ = -0.0992*Ln(Area)+0.9726 (R^2=0.9925) and
$\mathbf{F2_{40\%imp}}$ = -0.0830*Ln(Area)+0.9712 (R^2=0.9869) and
$\mathbf{F2_{60\%imp}}$ = -0.0706*Ln(Area)+0.9808 (R^2=0.9782) and
$\mathbf{F2_{80\%imp}}$ = -0.0586*Ln(Area)+0.9762 (R^2=0.9588) and
$\mathbf{F2_{100\%imp}}$ = -0.0511*Ln(Area)+0.9821 (R^2=0.9560)

Combining the above relationships lead to a relationship between peak discharge rate at a developing site's outlet, anywhere in Wollongong, for any extent of impervious cover and an area between 0.1ha and 1000ha, in which at the site outlet;

$Q_{5yr\ Dev}$ **= F2 * F1 * 0.004 *I** $\mathbf{_{50-1}}$ (m^3/s/ha)
$Q_{100yr\ Dev}$ **= F2 * F1 * 0.007 *I** $\mathbf{_{50-1}}$ (m^3/s/ha)

Using these relationships, the peak discharge rate from a base 1ha area can be scaled to produce an equivalent peak discharge rate from a larger (or smaller) area, permitting equivalent permissible discharge rates to be scaled from the base 1ha level to a hydrologically similar subarea between 0.1 and 1000ha in size..

This relationship is in itself no more than a simple regional peak discharge model, but in the form derived does permit consideration of scaling relationships between storages as discussed in the following section. It should be noted however, that these relationships are derived from a single subareal model with natural storage only, they should not be used to predict peak discharge from a catchment with significant non-natural storage.

The permissible site discharge rate (PSD) required to match post-development discharges at a local site's outlet, to pre-development (natural F1=1) levels is then for Wollongong,

$\mathbf{PSD_{5yr\ Nat}}$ **= F2 * 0.004 *I** $\mathbf{_{50-1}}$ (m^3/s/ha) **(1)**
$\mathbf{PSD_{100yr\ Nat}}$ **= F2 * 0.007 *I** $\mathbf{_{50-1}}$ (m^3/s/ha) **(2)**

with F2 reflecting site area.

3. SCALING STORAGE RATES

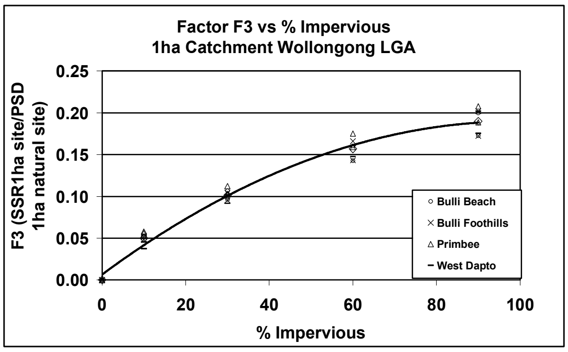
With existing peak discharge rates and 'local' PSD able to be calculated for any site in the city using the above relationships, it is then possible to investigate storage levels required to control runoff peaks at the outlet of a developing site.

To explore local storage relationships, the previous 1ha single subarea WBNM models were used to optimise storage volumes for a range of added impervious cover on each site, such that post-development 'local' (site outlet) discharges did not exceed pre-development levels in a 5Yr ARI or 100Yr ARI event.

In order to investigate this relationship it is also necessary to understand the intended geometry of the storage basin to be constructed at the site's outlet. In this investigation, the basin geometry established in earlier modelling by SMEC Australia[2004] was adopted. This involved a two stage basin in which the first stage storage fills in a 5 year ARI event and second stage storage in a 100 year event, with the 5 year ARI peak discharge equal to the required 5 year ARI PSD and the 100 year ARI peak discharge equal to the required 100 year ARI PSD.

In the following text, storage required to limit discharges to the required pre-development level is expressed in terms of a site storage ratio SSR (m^3/ha).

The resulting ratios of **F3** ($SSR_{1ha\ developed\ site}/PSD_{1ha\ natural\ site}$) for the various cases modelled are shown plotted in **Figure 4** against the percent impervious cover on the developed site(%I).



Factor F3 –v- %Imperviousness. 1Ha Site
Figure 4

As apparent in **Figure 4**, a strong correlation exists between the developed 1ha site SSR and the impervious cover (%I) on the developed 1ha site, irrespective of locality in which;

$\mathbf{SSR_{5yr\ Dev\ 1ha}} = \mathbf{F3} * \mathbf{PSD_{5yr\ Nat}}$ (m^3/ha)
$\mathbf{SSR_{100yr\ Dev\ 1ha}} = \mathbf{F3} * \mathbf{PSD_{100yr\ Nat}}$ (m^3/ha)

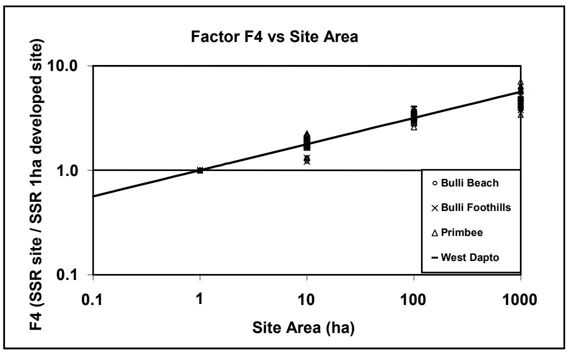
In the above relationship F3 was fitted with a polynomial function in which;

F3=-0.00001*(%I)^2+0.0032(%I)-0.0012
(R^2=0.9996)

To fully generalise this procedure for a developing site of any size and added impervious cover, a relationship was also needed to reflect the impact of site area on storage requirements.

To explore this relationship, the four test sites were remodelled for both a 5 and 100yr ARI event, reflecting the possible range in both %impervious cover and site area. This modelling was also extended to cover the full range from 0.1 to 1000ha sites, for use in subsequent catchment scale modelling.

The resulting ratios of **F4** (SSR site-with-imp-any-size)/(SSR site-with-imp-1ha) for the various cases modelled are shown plotted in **Figure 5** against catchment size.



Factor F4 –v- Site Area
Figure 5

A strong correlation was also found between the developed site storage ratio and the site area irrespective of percent Impervious cover in which;

$\mathbf{SSR_{5yr\ Dev}} = \mathbf{F4} * \mathbf{SSR_{5yr\ Dev\ 1ha}}$ (m^3/ha)
$\mathbf{SSR_{100yr\ Dev}} = \mathbf{F4} * \mathbf{SSR_{100yr\ Dev\ 1ha}}$ (m^3/ha)

In the above relationship F4 was fitted with a simple power function in which
F4 = (Site Area)$^{\mathbf{0.25}}$ (R^2=0.9903)

Combining the above relationships lead to a relationship between the SSR required to limit discharges at a developing site's outlet for a site anywhere in Wollongong, for any extent of impervious cover post development and a site area between 0.1Ha and 1000Ha, in which ;

$\mathbf{SSR_{5yr}} = \mathbf{F3{*}F4{*}PSD_{5yr\ Nat\ 1ha)}}$ (m^3/ha) **(3)**
$\mathbf{SSR_{100yr}} = \mathbf{F3{*}F4{*}PSD_{100yr\ Nat\ 1ha)}}$ (m^3/ha) **(4)**

While the preceding relationship provides an explicit solution for SSR when developing PSD and SSR requirements to manage development from a natural site, it does not directly resolve the PSD and SSR required when the pre-existing conditions involve some prior development.

Under these circumstances the pre-development PSD can be directly computed from the natural PSD by multiplying the PSD by F1 (where F1 reflects the level of pre-development impervious cover).

A similar direct procedure for determination of SSR is not however possible. As the above relationships for SSR can be used to directly calculate the SSR requirement for the change from natural to pre-development or natural to post development conditions, the SSR for a partly developed existing site was approximated by the difference between the two SSR levels. This is not an approximation that the authors have validated, but it does meet the requirements for the correct SSR at zero initial impervious cover and when pre and post impervious cover levels are equal.

4. CATCHMENT WIDE MODELLING

Having quantified relationships between PSD and site area and SSR and site area, it is possible to now construct a conventional hydrologic model with a basin at each subareal outlet that simulates the behaviour of distributed OSD basins within that subarea.

This is an important step as it now permits conventional hydrologic models to be used to quantify the impact of alternate OSD policy objectives on PSD and SSR requirements, without having to resort to fine scale modelling.

To explore these relationships, WBNM models of four partly urbanised Wollongong catchments developed earlier by Dr Boyd[1999] and SMEC Australia[2001] were reconfigured to reflect the sampled existing and derived ultimate impervious cover levels. Basic geometric characteristics of the four catchments are set out in Table 1.

Table 1
Catchment Physical Characteristics

Catchment	A (Km^2)	SHP (A/L^2)	L (km)	S (m/km)
LB Kelly Ck	0.48	0.19	1.6	50
Fairy Ck	7.74	0.32	4.9	33
Allans Ck	41.80	0.22	13.9	10
Mullet Ck	72.00	0.21	18.5	3

These models were then used to explore;

1. The impact of ultimate development occurring without OSD

2. The impact of adding OSD on each subarea, sized in accordance with the preceding relationships and factored to control downstream discharges as follows:

   PSD/F5 and SSR*F5 where **F5 = 1**
   (to simulate local outlet control only)

   PSD/F5 and SSR*F5 where **F5 = 1.2**
   (to simulate increased control on post-development site peak discharges)

   PSD/F5 and SSR*F5 where **F5 = 1.5**
   (to simulate further increased control)

In each of the above scenarios incorporating OSD, the required local OSD parameters (PSD and SSR for the 5 and 100yr ARI events) were calculated for each model's subareal outlet using the previously developed relationships, reflecting the subareas location, pre-existing cover, ultimate cover and size.

As expected, this modelling showed that ultimate development without OSD would lead to unacceptable increases in discharge at many points within each catchment, with peak discharges at several locations increasing by more than 50%.

With 'local' (F5=1) OSD only included in the system, the discharges at the outlet of each subarea were controlled to pre-existing levels, but many locations still had post-development peak discharges unacceptably higher than their pre development levels. It was however noted that in some locations, the addition of OSD actually increased peak discharge relative to the post development 'no OSD' scenario. These locations were typically found in the lower reaches of the mainstream where the addition of OSD caused a lag in local runoff, permitting the local and mainstream peaks to occur closer together. A similar increase in peak flows was observed in some multi-branched stream networks, when OSD in a short arm delayed its flow peak, bringing it closer to the mainstream peak.

As will be apparent from the above, the global addition of OSD at a 'local' rate to a developing catchment can lead to a wide range of flow impacts, but is in itself insufficient to manage discharges post-development on a catchment wide basis.

With an increased level of OSD (F5=1.2) included in the system, most phase related increases became less apparent (due to the increased attenuation) and significant reductions in flow peaks became evident at some locations. Some locations still however had post-development discharges significantly exceeding pre-development levels.

With OSD further increased (F5=1.5), peak discharges at all locations were then close to and in many locations significantly less than pre-existing peak discharge levels. In addition, attenuation associated with this increased level of storage had overwhelmed the increases due to phasing previously evident at some locations.

It should be noted that even at the 'local' OSD (F5=1.0) level, many locations had a post-development discharges that were less than the pre-existing (baseline) level. As OSD is factored up, the number of locations with a significant reduction in peak flow increases. While OSD at about 1.5 times the level for local control was required to limit discharges at all locations to a maximum of 1.05 times the pre-existing level (the Policy objective), the impact of OSD at this level was to reduce the average post development flow peaks in some catchments <u>well</u> below pre-existing levels and to quite dramatically reduce peak flows at some particular locations.

The impact of the proposed OSD (F5=1.5) on peak flows varies considerably from catchment to catchment and node to node as indicated in Table 2.

Table 2
Impact of Proposed (F5=1.5) OSD
on Peak Flows

Catchment	Worst	Avg	Best
LB Kelly Ck	+1%	-6%	-17%
Fairy Ck	+5%	-18%	-37%
Alans Ck	+4%	-5%	-29%
Mullet Ck	+4%	0%	-17%

Note: A positive impact represents an increase in peak flow

On the basis of the above modelling, the policy for managing runoff from development in Wollongong was updated with PSD and SSR levels set at;

PSD(policy 5yr) = PSD(local 5year)/1.5
PSD(policy 100yr) = PSD(local 100year)/1.5
SSR(policy 5yr) = SSR(local 5year)*1.5
SSR(policy 100yr) = SSR(local 100year)*1.5

When combined with the relationships for local PSD and SSR set out in equations 1 to 4, these catchment wide PSD and SSR requirements for development from a greenfield site in Wollongong become;

$$\mathbf{PSD_{5yr} = F2*0.00267*I_{50\text{-}1hour}} \quad (m^3/s/ha)$$
$$\mathbf{PSD_{100yr} = F2*0.00467*I_{50\text{-}1hour}} \quad (m^3/s/ha)$$
$$\mathbf{SSR_{5yr} = F3*F4*2.25*PSD_{5(natural\ 1ha)}} \quad (m3/ha)$$
$$\mathbf{= F3*F4*2.25*PSD_5/F2} \quad (m3/ha)$$
$$\mathbf{SSR_{100yr} = F3*F4*2.25*PSD_{100(natural\ 1ha)}} \quad (m3/ha)$$
$$\mathbf{= F3*F4*2.25*PSD_{100}/F2} \quad (m3/ha)$$

Table 3 sets out earlier PSD and SSR requirements, providing a comparison with those described above. This comparison assumes a natural 1ha site developing to 30% impervious cover in West Dapto. It is of note that if the site was to develop to 80% impervious cover, the WCC [2006] SSR requirements would double, whereas the Boyd and SMEC requirements would not change.

Table 3
PSD and SSR Comparison for 1ha Site at 30%

Source	WCC Prev	Boyd [1999]	SMEC [2001]	SMEC [2004]	WCC [2006]
PSD_5 l/s	252	na	na	150	280
SSR_5 m^3	37	na	na	175	53
PSD_{100} l/s	587	100	200	280	490
SSR_{100} m^3	56	890	450	400	93

5. CONCLUSIONS

It is concluded on the basis of this investigation that;

1. In Wollongong the 5Yr and 100Yr ARI peak discharge rates (Qp) at the outlet of a site from 0.1 to 1000ha in area and 'natural' levels of floodplain storage can be calculated from;

   $$\mathbf{Qp_5 = F2 * F1 * 0.004 * I_{50\text{-}1}} \quad (m^3/s/ha)$$
   $$\mathbf{Qp_{100} = F2 * F1 * 0.007 * I_{50\text{-}1}} \quad (m^3/s/ha)$$

   where F1 is a factor reflecting the level of impervious cover and F2 the site area.

2. When developing a site, the permissible site discharge PSD required to control <u>local</u> site discharges, to pre-development (natural) levels is for Wollongong,

   $$\mathbf{PSD_5 = F2 * 0.004 * I_{50\text{-}1}} \quad (m^3/s/ha)$$
   $$\mathbf{PSD_{100} = F2 * 0.007 * I_{50\text{-}1}} \quad (m^3/s/ha)$$

   where F2 is a factor reflecting site area.

3. In Wollongong the 5Yr and 100Yr ARI storage ratios SSR(m^3/ha) required for <u>local</u> control of discharge at a site's outlet can be calculated from;

   $$\mathbf{SSR_5 = F3*F4*PSD_5/F2} \quad (m^3/ha)$$
   $$\mathbf{SSR_{100} = F3*F4*PSD_{100}/F2} \quad (m^3/ha)$$

   where F3 is a factor reflecting the post-development level of impervious cover and F4 the site area.

4. When a site is partly developed at the base date, the PSD can be directly obtained from the preceding PSD levels factored up by F1 (the factor reflecting percent impervious cover of the base site). SSR can not however be directly determined and has been approximated in the Wollongong Policy as the difference between that required for a transition from natural to the post-development state and that required for the transition from natural to the pre-development state. Further investigation is desirable to better validate this procedure.

5. These local outlet PSD and SSR requirements can be used to scale the lot level distributed storages to equivalent subareal storages so that the performance of distributed storages can be simulated

throughout a catchment with a conventional hydrologic model.

6. With no more than a 5% increase in peak discharges permitted anywhere in a catchment, runoff from ultimate development of a natural site in Wollongong will be controlled to the 1982 (base date) level by an OSD requirement that sets;

   $\mathbf{PSD_{5yr} = F2*0.00267*I_{50\text{-}1hour}}$ (m^3/s/ha)
   $\mathbf{PSD_{100yr} = F2*0.00467*I_{50\text{-}1hour}}$ (m^3/s/ha)
   $\mathbf{SSR_{5yr} = F3*F4*2.25*PSD_5/F2}$ (m3/ha)
   $\mathbf{SSR_{100yr} = F3*F4*2.25*PSD_{100}/F2}$ (m3/ha)

   With local basins designed such that SSR_{5yr} develops at PSD_{5yr} and SSR_{100yr} develops at PSD_{100yr}.

7 REFERENCES

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