Effects of urbanisation on floods

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CHAPTER SIX
Storage Characteristics of the Pervious Areas

6.1 Introduction

The behaviour of the pervious and impervious areas of a catchment during a storm event is different in terms of rainfall losses, and also in terms of the storage capacity and in the way water is released from storage.

In Chapter 5, the storage parameters for the impervious areas of sixteen urban catchments were derived from the analysis of hydrograph recessions. Events where only impervious area runoff occurred were identified in Chapter 3 and the recessions from these events provided the means of determining the behaviour of the impervious areas, in isolation from the pervious areas of the catchments.

Storage parameters for the pervious areas cannot be determined from recessions using the same methods, because pervious runoff always occurs combined with impervious runoff, and so the recessions from combined events reflect the characteristics of both the pervious and impervious areas.

The analysis of rainfall and runoff depths, discussed in Chapter 3, showed that only one third of the events in the
data set exhibited runoff generated on the pervious areas of the catchments. The runoff ratio for the larger events, which had combined runoff, was found to vary substantially. This indicated that the size of the active pervious area for a particular event depended on soil moisture conditions and possibly on event characteristics.

The impervious areas, by contrast, generated runoff in all the analysed events and the size of the active (connected) area remained fairly constant for all events. Because of this, all recessions of impervious events in each catchment could be assumed to represent the storage behaviour of the connected impervious area.

These differences between pervious and impervious areas can only be adequately simulated by modelling them separately. Out of the sixteen catchments studied, pervious area runoff was found to be significant in Strathfield, Jamison Park, Fisher’s Ghost Creek, Giralang, Long Gully Creek, Mawson, Curtin and Vine Street catchments. The extent to which the pervious areas contributed runoff in the analysed set of events was discussed in Chapter 3, Section 3.5.2, and Table 3.28 summarised these results. This Table showed that, on average, only 32% of the total runoff for combined events was generated on pervious surfaces. As pervious runoff is typically smaller than impervious runoff for the set of events analysed, the accuracy in the estimation of lag parameters for the pervious areas will have a much smaller
effect on the simulation of the observed floods than the
accurate estimation of the impervious area lag parameters.

In this Chapter, methods to derive pervious area storage
parameters will be analysed and applied to the urban
catchments studied.

6.2 Analysis of Recessions from Combined Events

6.2.1 Plot of \(-\frac{dQ}{dt}\) against \(Q\) for Combined Recessions

Recessions from combined runoff events reflect the storage
parameters of both the pervious and impervious areas of a
catchment. Even though the methods used for estimating
impervious storage parameters are not applicable for
obtaining similar parameters for the pervious areas,
combined recessions can still be plotted together with
recessions from impervious events in order to analyse their
differences.

Figures 6.1 to 6.10 show plots of recessions from
impervious and combined events for ten catchments
(Strathfield, Jamison Pk., Fisher’s Ghost Ck., Giralang,
Curtin, Vine St., King’s Ck., Munkerisparken, East York and
Malvern). As combined runoff was not observed in the data
sets for Maroubra, St. Mark’s Rd. and Clifton Gr.
catchments, the recessions for impervious and combined
events could not be compared. Impervious runoff events were not available for Long Gully Ck. and Mawson catchments, and only three events were available for Elster catchment, and the recession of a combined event with a very small contribution of pervious area runoff was used to derive the catchment lag parameter for the impervious areas in this last catchment. Recessions from the other two events could not be used in this analysis because they were disturbed by continuing rain.

The relation between the lag parameter $K$ and the position of the recessions in Figures 6.1 to 6.10 can be analysed using equation 5.6 in Section 5.2.1 of Chapter 5. The discharge $Q$ from a linear storage with lag parameter $K$ and inflow $I = 0$ is

$$-\frac{dQ}{dt} = \frac{Q}{K}$$ (5.6)

Recessions from a linear storage will plot as straight lines on a double logarithmic graph,

$$\log (-\frac{dQ}{dt}) = \log Q + \log (1/K)$$

These lines will have a 1:1 slope, and their position on the graph will be determined by the value of the intercept, $\log (1/K)$.
Figure 6.1 IMPERVIOUS AND COMBINED RECESSIONS. STRATHFIELD

Figure 6.2 IMPERVIOUS AND COMBINED RECESSIONS. JAMISON PK.
Figure 6.3 IMPERVIOUS AND COMBINED RECESSIONS. FISHERS GHOST CREEK.

Figure 6.4 IMPERVIOUS AND COMBINED RECESSIONS. GIRALANG.
Figure 6.5 IMPERVIOUS AND COMBINED RECESSIONS. CUR'IN.

Figure 6.6 IMPERVIOUS AND COMBINED RECESSIONS. VINE STREET
Figure 6.7 IMPERVIOUS AND COMBINED RECESSIONS. King's Creek.

Figure 6.8 IMPERVIOUS AND COMBINED RECESSIONS. Munkerisparken.
Figure 6.9 IMPERVIOUS AND COMBINED RECESSIONS. EAST YORK.

Figure 6.10 IMPERVIOUS AND COMBINED RECESSIONS. MALVERN.
Recessions from events classed as combined runoff in Chapter 3, tended to plot to the right of impervious runoff events for Strathfield, Jamison Pk., Fisher’s Ghost Ck. and Vine St. catchments in Figures 6.1, 6.2, 6.3, 6.5 and 6.6.

The estimation of lag parameters from recessions with combined runoff is meaningless, but the fact that combined recessions plotted to the right of the impervious recessions in this group of catchments indicate that combined recessions exhibit a larger value of the storage parameter K than the recessions from impervious events.

If the relationship between the storage parameter, area, slope and surface roughness, suggested by equation 5.30 in Chapter 5, Section 5.7.4.2.3, holds for the pervious areas, larger values of K for combined events would be the result of larger areas, both pervious and impervious, contributing runoff, and of the larger roughness coefficients of the pervious areas.

In Figures 6.4 and 6.7 to 6.10, impervious and combined recessions tended to plot together.

In Figures 6.4 and 6.7, which show the recessions of Giralang and King’s Ck. catchments, there is considerable scatter, but the scatter is larger in the recessions from combined events than in those from impervious runoff.
events. As the recessions from combined events vary according to the sizes of the pervious and impervious areas that become active during the event, it is reasonable to expect more scatter when these recessions are plotted together.

Recessions from five combined events for Munkerisparken catchment are shown in Figure 6.8. Although event 210681 was classed as combined runoff in Chapter 3, the amount of pervious area runoff is negligible, as can be seen by comparing its runoff ratio \(RR = 0.3128\) with the impervious area fraction 0.3120, so it was plotted as an impervious event in Figure 6.8. The other combined events in this Figure have a proportion of pervious area runoff ranging only from 7\% to only 19\%. As the impervious area runoff makes up a large proportion of the total runoff in all these events, the impervious area lag parameter is reflected more strongly in these recessions than the parameter for the pervious areas. This explains that the combined recessions in Figure 6.8 plotted together with the recession from the impervious event.

In each of Figures 6.9 and 6.10 (East York and Malvern catchments), the recessions from only one impervious and one combined event could be used. The proportion of pervious area runoff in the combined events in Figures 6.9 and 6.10 was, in each case, only 2\% of the total observed runoff (Tables D.15 and D.16, Appendix D). As the
impervious runoff, therefore, made up 98% of the total runoff in these two combined events, their recessions mainly reflect the lag parameter of the impervious areas.

6.2.2 Influence of the Pervious and Impervious Lag Parameters.

In order to analyse the extent of the influence of the pervious and impervious lag parameters on a combined recession, recessions from a set of two storages in parallel were simulated and analysed. These storages represented the pervious and impervious areas of an urban catchment and they were linear, with lag parameters $K_1$ and $K_2$. Equation 6.1 represents the recession from these parallel storages.

$$Q = Q_1 + Q_2 = Q_{01} e^{-t/K_1} + Q_{02} e^{-t/K_2} \quad (6.1)$$

where $Q_1$ and $Q_2$ are the outflows from each one of the storages and $Q_{01}$ and $Q_{02}$ are the discharges at time $t=0$. If

$$Q_0 = Q_{01} + Q_{02}$$

is the discharge at time $t = 0$ on the recession, equation 6.1 can be written

$$Q = Q_0 \left[(1-\alpha) e^{-t/K_2} + \alpha e^{-t/K_1}\right] \quad (6.2)$$
and the unknowns are $K_1$, $K_2$ and $\alpha = Q_{01}/Q_0$.

If values are given to the unknowns in equation 6.2, some of its characteristics can be analysed.

The analysis of equation 6.2 showed that the relative values of the storage parameters $K_1$ and $K_2$ and the initial discharges $Q_{01}$ and $Q_{02}$ determined which of the storages was predominantly reflected in the shape of the recession.

If $Q_{01} \gg Q_{02}$ and $K_1$ and $K_2$ were different but of the same order of magnitude, the storage with parameter $K_1$ was dominant, in the sense that the recession had a slight curvature with a slope close to $K_1$ (Figure 6.11).

![Figure 6.11 RECESSIÖN WHERE THE STORAGE WITH PARAMETER K1 IS DOMINANT.](image)
If $Q_{01} \gg Q_{02}$ and $K_1 \ll K_2$, the storage with parameter $K_1$ was dominant in the first part of the recession and the slope of this part of the recession reflected $K_1$. The reverse was true for the last part of the recession and $K_2$ was reflected in this last part (Figure 6.12).

![Graph showing discharge over time with different values for $K_1$ and $K_2$.]

**Figure 6.12** $K_1$ AND $K_2$ ARE DOMINANT IN DIFFERENT PARTS OF THE RECESSION

If $Q_{01} \gg Q_{02}$ and $K_1 \gg K_2$ none of the storages was clearly dominant in the recession.

Finally, if the values of $K_1$ and $K_2$ were very close, the recession plotted close to a straight line. In the limiting
case of $K_1 = K_2$, the recession was linear and it plotted as a straight line on a semilogarithmic plot. From the slope of this line a lag parameter $K = K_1 = K_2$ could be obtained. 

Therefore, the shape of the recession from two reservoirs in parallel depended on the storage parameters $K_1$ and $K_2$ of the reservoirs, as well as on the relative values of the initial discharges $Q_{01}$ and $Q_{02}$. As these initial discharges are related to the depth of effective rainfall stored in each reservoir, the ratio $a$ will vary between events. For the small events, all runoff will come from the impervious area storage. The larger events will have combined runoff and the proportion of total runoff coming from the pervious areas will tend to increase with event size. The shape of recessions will therefore vary between events even though they are generated from the same set of reservoirs. Furthermore, the slope in different sections of the recession will vary according to the reservoir which is dominant at that point in time.

6.3 Determination of Parameters for Pervious Area Storages

The pervious area lag parameters cannot be measured by applying the same methods used for the impervious area storages, because pervious area runoff does not occur in isolation from runoff from impervious areas. Some of the results of the joint analysis of the impervious areas of
the catchments presented in Chapter 5 will be extended, in this Chapter, to the pervious areas, in order to estimate pervious area lag parameters.

In Chapter 5 it was found that the impervious areas of the catchments could be grouped in clusters. The runoff response of these clusters was represented by a set of identical linear reservoirs in parallel. In this Chapter, the pervious areas will also be grouped in clusters and their runoff response will also be represented by a set of identical linear storages. This set of storages is placed in parallel with the impervious set, as shown in Figure 6.13.

This disposition has some similarities to the one adopted by Diskin et al (1978). In their study, which was reviewed in Chapter 1, the pervious and impervious areas of urban catchments were represented by two sets of storages placed in parallel (Figure 1.2, Chapter 1). The storages in each set were placed in series, rather than in parallel, as is proposed in this Section.

Support for the concept of parallel reservoirs can be found in the observations of Wittenberg (1975) reviewed in Chapter 1, even though he placed his storages in series, following the ideas of Diskin. Wittenberg analysed the chronological development of urban areas in the Ruhr District in West Germany. He noted that the lag parameters

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and the number of storages in the parallel cascades did not change with increases in urbanisation and that he could adjust the model for different stages of urban development by simply varying the impervious area fraction and adjusting the losses accordingly. He concluded that the parameters of the two cascades of storages were characteristic of the pervious and impervious areas, but did not vary with the extent of these areas.

\[ \text{Impervious Storages} \quad \text{Pervious Storages} \]

\[ K_i \quad K_i \quad K_i \quad \ldots \quad K_i \quad K_p \quad K_p \quad K_p \quad \ldots \quad K_p \]

\[ Q \quad t \]

Figure 6.13 PARALLEL PERVIOUS AND IMPERVIOUS STORAGES

The consistency in the parameters of the pervious and impervious set of storages as the catchments were urbanised observed by Wittenberg indicates that the storages are placed in parallel. If they were placed in series, the lag
parameters of the sets would change with increases in urbanisation, as the construction of new impervious surfaces would add storages to the impervious cascade.

While the number of storages in the impervious set would increase with further urban development, the number of pervious area storages would have the opposite tendency. Nevertheless, if the storages are placed in parallel, the lag parameters for the pervious ($K_p$) and impervious sets ($K_i$), would be a characteristic of each set and would not vary as a result of the areal extent of the pervious and impervious surfaces. The number of storages that becomes active in the pervious set would vary from event to event with antecedent conditions and storm characteristics, while the number of active impervious storages would remain fairly constant for all events.

In Chapter 5 the symbols chosen for the impervious cluster size and the number of impervious clusters were $A_I$ and $N$, respectively. In the following Sections they will be represented with $A_{II}$ and $N_I$.

6.3.1 Pervious Area Lag Parameter for Small Catchments ($A_{IC} < 0.1 \text{ km}^2$)

In Chapter 5, the impervious areas of the smaller catchments where $A_{IC} < 0.1 \text{ km}^2$ were represented by one
storage element \((N_I = 1)\). The catchments in this group were Maroubra, King’s Ck., St. Mark’s Rd., Clifton Grove and Munkerisparken. Only King’s Ck. and Munkerisparken exhibited some pervious area runoff, therefore only the pervious area lag parameters derived for these two catchments could be tested by simulating observed storm events with the rainfall-runoff model presented in Chapter 7.

The pervious areas of these five catchments were also very small, ranging from 0.02 km\(^2\) for King’s Ck. catchment to 0.27 km\(^2\) for Maroubra (Table 6.1), and they were represented with one storage element \((N_p = 1)\). The lag parameter \(K_p\) of this storage element was estimated using equation 5.28 which gave good prediction of \(K_I\) for these catchments (Chapter 5, Section 5.7.4.2.3). If a shape factor \(g = 1\) is used, representing a square surface, equation 5.28 can be written

\[
K_p = A_p^{0.7} n_p^{0.6} s^{-0.3} \quad (6.3)
\]

where \(A_p\) is the pervious area \((m^2)\), \(n_p = 0.055\) is Manning’s roughness coefficient for grassed areas and \(s\) is the catchment’s surface slope. Table 6.1 shows the values of \(K_p\) for this group of five catchments.
TABLE 6.1 Pervious Area Storage Parameters

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Pervious Area (km²)</th>
<th>Surface Slope</th>
<th>No. Perv. Clusters</th>
<th>A₁p (km²)</th>
<th>Kp (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maroubra</td>
<td>0.2748</td>
<td>0.0998</td>
<td>1</td>
<td>0.274800</td>
<td>2248.0</td>
</tr>
<tr>
<td>Strathfield</td>
<td>1.1700</td>
<td>0.0097</td>
<td>30.18</td>
<td>0.038763</td>
<td>1148.4</td>
</tr>
<tr>
<td>Jamison Pk.</td>
<td>0.1323</td>
<td>0.0200</td>
<td>3.33</td>
<td>0.039683</td>
<td>939.6</td>
</tr>
<tr>
<td>Fisher’s Gh.</td>
<td>1.4464</td>
<td>0.0776</td>
<td>7.85</td>
<td>0.184218</td>
<td>1832.3</td>
</tr>
<tr>
<td>Giralang</td>
<td>0.7200</td>
<td>0.0451</td>
<td>10.25</td>
<td>0.070199</td>
<td>1097.5</td>
</tr>
<tr>
<td>Long Gully Ck.</td>
<td>4.7800</td>
<td>0.0900</td>
<td>23.40</td>
<td>0.204278</td>
<td>1884.1*</td>
</tr>
<tr>
<td>Mawson</td>
<td>3.3000</td>
<td>0.0555</td>
<td>24.43</td>
<td>0.135051</td>
<td>1630.5</td>
</tr>
<tr>
<td>Curtin</td>
<td>2.2301</td>
<td>0.0682</td>
<td>90.72</td>
<td>0.245816</td>
<td>2330.8</td>
</tr>
<tr>
<td>Vine St.</td>
<td>0.4802</td>
<td>0.0041</td>
<td>6.87</td>
<td>0.069728</td>
<td>2242.7</td>
</tr>
<tr>
<td>Elster Ck.</td>
<td>25.0825</td>
<td>0.0144</td>
<td>203.55</td>
<td>0.123224</td>
<td>2291.9</td>
</tr>
<tr>
<td>King’s Ck.</td>
<td>0.0174</td>
<td>0.0120</td>
<td>1</td>
<td>0.017400</td>
<td>615.0</td>
</tr>
<tr>
<td>St. Mark’s Rd.</td>
<td>0.0382</td>
<td>0.0025</td>
<td>1</td>
<td>0.038200</td>
<td>1707.2</td>
</tr>
<tr>
<td>Clifton Gr.</td>
<td>0.0633</td>
<td>0.0500</td>
<td>1</td>
<td>0.063300</td>
<td>989.7</td>
</tr>
<tr>
<td>Munkerispar.</td>
<td>0.0443</td>
<td>0.0100</td>
<td>1</td>
<td>0.044300</td>
<td>1249.4</td>
</tr>
<tr>
<td>East York</td>
<td>0.7905</td>
<td>0.0109</td>
<td>21.01</td>
<td>0.037628</td>
<td>1086.0</td>
</tr>
<tr>
<td>Malvern</td>
<td>0.1510</td>
<td>0.0200</td>
<td>5.47</td>
<td>0.027581</td>
<td>728.3</td>
</tr>
</tbody>
</table>

* The pervious area parameter $K_p$ adopted for Long Gully Ck. catchment was calculated from hydrograph recessions in Chapter 5, Section 5.6.6. As this catchment is mainly rural, a value of $K_p = 1454.4$ seconds could be obtained from recessions of events where the amount of impervious runoff was much smaller than the runoff coming from the pervious areas of the catchment. The value of $K_p$ from mainly pervious runoff recessions compares well with the value of $K_p = 1884.1$ seconds in Table 6.1, calculated using equation 6.3. This agreement between the values of $K_p$ for Long Gully Ck. catchment provides an independent check of the assumptions and methods used in this Chapter for the calculation of $K_p$. 

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6.3.2 Pervious Area Lag Parameter for Large Catchments ($A_{IC} > 0.1 \text{ km}^2$)

In the case of the small catchments in Section 6.3.1, it was assumed that the pervious areas were grouped into a single cluster, given that the pervious areas of these catchments were small (0.02 km$^2$ to 0.27 km$^2$). For these catchments $N_I = N_P = 1$.

If $N_P$ is assumed to be equal to $N_I$ for the larger catchments, the following situation arises. At a particular stage of urban development, a catchment would be composed of $N_I$ clusters of impervious areas. It would also have $N_P = N_I$ clusters of pervious areas and the size of the pervious cluster would be $A_P/N_P = A_{1P}$.

If this catchment was urbanised further, the number of impervious clusters would increase. This is intuitively correct, and it is also confirmed by equation 5.34 in Chapter 5, Section 5.7.4.3.3., which indicates that $N_I$ increases proportionally to $A_{IC}$.

For this new stage of urban development, and if $N_P = N_I$, the number of pervious clusters $N_P$ would be larger than for the first stage of urbanisation, therefore the size of the pervious cluster would decrease accordingly. As this is not reasonable, then $N_P$ should not be equal to $N_I$. 

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The number of impervious clusters was shown to be related to
the first power of the impervious connected area \((N_I \propto A_{IC})\). If a similar relation exists between \(N_p\) and \(A_p\) then
\(N_p\) could be related to \(A_p\), \(N_I\) and \(A_{IC}\) by

\[
N_p = A_p \cdot \frac{N_I}{A_{IC}} \tag{6.4}
\]

Equation 6.4 also implies that \(A_{1P} = A_p/N_p = A_{1I}\). 
Therefore, the size of the pervious and impervious clusters
would be equal and the size of each pervious cluster would
not vary with further urban development. With further urbanisation \(N_I\) would increase and \(N_p\) would decrease accordingly.

In order to obtain a value of the lag parameter for the
pervious areas of the catchments analysed, it will be
assumed that the sizes of the pervious and impervious
clusters are equal.

The lag parameter \(K_p\) for the cluster of pervious surfaces
\(A_{1P} = A_{1I}\) can be estimated with equation 6.3, if \(A_{1P}\) is
used rather than \(A_p\)

\[
K_p = A_{1P}^{0.7} \cdot n_p^{0.6} \cdot s^{-0.3} \tag{6.3}
\]

where \(K_p\) is measured in seconds, \(A_{1P}\) is measured in \(m^2\), and
\(n_p = 0.055\) is Manning’s roughness coefficient for grassed
areas.
The sizes of the pervious clusters for all catchments, as well as the number of clusters $N_p$ and the lag parameters $K_p$ are shown in Table 6.1. For the small catchments ($A_{IC} < 0.1$ km$^2$) $N_p = 1$ and so the size of the cluster of pervious areas in Table 6.1 is equal to the pervious area. For the larger catchments, the number of clusters in Table 6.1 was calculated with equation 6.4, the cluster size of pervious surfaces was made equal to the cluster size of impervious surfaces and the lag parameter $K_p$ was calculated using equation 6.3.

As the lag parameters that represent the runoff routing process on the pervious areas cannot be measured from recessions, the accuracy of the values adopted can only be tested when observed storms are simulated. Pervious area lag parameters $K_p$ were calculated in this Chapter by assuming that the sizes of the pervious and impervious clusters are equal. It was also assumed that equation 5.28 (Chapter 5, Section 5.7.4.2.3) which relates the lag parameter to area and slope can give good estimates of $K_p$. As pervious area runoff is small when it is compared to impervious area runoff, the accuracy in determining pervious area lag parameters has less influence on the results of the simulation than impervious lag parameters. Results from the reproduction of the complete set of storms available for this study are presented in Chapter 7 and in Volume 2.