Effects of urbanisation on floods

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CHAPTER EIGHT
Summary and Conclusions

8.1 Introduction

Rainfall and streamflow data from sixteen urban catchments have been analysed with the purpose of understanding the rainfall-runoff process in urban areas. The catchments are located in three continents (Europe, Australia and America) and there are differences in their geographical conditions and in the characteristics of urban development. In spite of these differences, similarities in their behaviour during storm events were found. The main results of this study are the identification and physical interpretation of patterns of behaviour that were common to all catchments. These common features were synthesised and formulated mathematically in a rainfall-runoff model.

The main findings in this study are summarised in the present Chapter.

8.2 Separate Analysis of Pervious and Impervious Areas and its Relation to Linearity.

In the analysis of urban flood studies presented in Chapter 1 it was noted that the pervious and impervious areas of urban catchments were, in general, not analysed separately.
In the present study a separate analysis of these areas is made, both in the determination of rainfall losses and in the routing of runoff. This approach was adopted as a consequence of the analysis of rainfall and streamflow data which showed that the differences in the behaviour of the pervious and impervious areas are large enough to merit separate consideration.

Once rainfall losses were computed separately for the pervious and impervious areas, the runoff routing process in all catchments could be simulated with a linear model. This differs from the studies reviewed in Chapter 1, Sections 1.4.2.2 and 1.4.2.3, where nonlinear or quasilinear models were used to represent this process. In these studies, the pervious and impervious areas were lumped together, and it is possible that, if a separate analysis had been made, the runoff routing process could have been well represented with a linear model. In some of these studies, the adoption of nonlinear models was based on assumptions rather than on an exhaustive analysis of the data.

8.3 Rainfall Losses

Direct measurements of rainfall losses are generally not available, and this was the case for the sixteen catchments studied. Due to this, the loss model proposed in this study
could not be tested independently, but the performance of
the rainfall-runoff model as a whole was tested in Chapter
7 and the results were good. The main characteristics of
the loss model adopted are summarised in this Section.

After initial losses are satisfied, the loss model
considers that all rain falling on the impervious connected
areas becomes runoff. This implies that continuing losses
on these areas are negligible or nil.

Both initial and continuing losses on the pervious areas
can be large, depending on soil and storm characteristics
and on the antecedent conditions of soils. The continuing
losses on the pervious areas are made proportional to the
rainfall intensities, in the model, and the sum of the
effective rainfall on the pervious and impervious areas is
adjusted to equal observed runoff.

As initial losses on the impervious areas are small, and as
continuing losses on these areas were assumed to be
negligible, all runoff was assumed to come from the
impervious areas of the catchment for the smaller events.
Runoff was generated on the pervious areas only for the
medium and larger storms in seven out of the sixteen
catchments studied. Large storms were not included in the
data sets of some of these catchments, so pervious area
runoff could occur for larger storms.
Pervious area runoff occurred only for one third of the 353 events analysed and it made up, on average, only one third of the total observed runoff of combined events.

This indicated that impervious areas are the main contributors of runoff for practically all events on urban catchments, even though they are typically smaller than the pervious areas, particularly in suburban catchments.

This finding shows that the lumping of pervious and impervious areas in terms of rainfall losses cannot provide a good representation of this process. Furthermore, as loss models and runoff routing models generally cannot be tested independently, the adoption of a lumped approach in the loss model introduces distortions into the runoff routing part of the model. These distortions could be incorrectly interpreted as nonlinearities or quasilinearities.

8.4 Assessment of the Impervious Connected Area

In Chapter 3, all events were separated into impervious and combined runoff. This separation was made by comparing the runoff ratio of the event with the impervious area fraction in each catchment.

The analysis of the runoff ratio of small events showed that this value was similar for all storms and that it
tended to scatter around the impervious area fraction for a group of eleven catchments (Jamison Park, Fisher's Ghost Ck., Giralang, Long Gully Ck., Mawson, Curtin, Elster Ck., King's Ck. Munkerisparken, East York and Malvern). This indicated that the runoff ratio for small events can be used to confirm the extent of the impervious areas in a catchment, or to estimate its size, if this information is not available.

The runoff ratio for small events was consistent and always smaller than the impervious area fraction for the other five catchments studied (Maroubra, Strathfield, Vine St., St. Mark's Rd. and Clifton Gr.). This indicated that not all the impervious areas in these catchments are connected to the drainage system, and in this case the average runoff ratio for the small storms was used to estimate the impervious connected area. Only for Vine St. catchment was the size of the impervious connected area reported, as well as the total impervious area.

The consistency of the runoff ratio for small storms, which was always close to the value of the impervious area fraction for eleven catchments, or always smaller than the impervious area fraction for the remaining five catchments confirmed that the impervious areas are the major contributors of runoff during small storm events.
8.5 Prediction of Runoff Volumes

All rain falling on the impervious areas was transformed into runoff after the initial losses were satisfied. The volume of runoff generated on the impervious areas of the catchment could be therefore well predicted for the small and medium storms, where only the impervious areas contributed runoff.

For the larger storms, for which the pervious areas also contributed runoff, the total runoff volume could not be assessed by relating it to the total rainfall volume alone. The volume of pervious area runoff tended to increase as the size of the storm increased, but the relation showed considerable scatter. In this sense, the pervious areas were found to be less predictable than the impervious areas, as antecedent moisture conditions as well as event characteristics determine the behaviour of pervious areas.

8.6 Estimation of Impervious Area Lag Parameters from Hydrograph Recessions

Hydrograph recessions from impervious events were analysed in Chapter 5 in order to determine lag parameters.

Methods for deriving lag parameters from the recessions of catchments that behave as a single linear or nonlinear
storage were discussed. Semilogarithmic plots of recessions were used to calculate lag parameters for linear storages, and the method that uses the time derivative of discharge was found to give the best results for nonlinear recessions.

Recessions from undisturbed impervious events from all catchments could be approximated by straight lines when plotted on semilogarithmic graphs. The slopes of these lines were used to estimate the lag parameter for the impervious areas, and consistent values of these parameters were obtained for all events on each catchment. This indicated that the runoff routing process in the urban catchments studied is linear. Catchment lag parameters for the impervious areas were estimated by averaging the lag parameters derived for individual events.

8.7 Relation between Impervious Area Lag Parameters and Catchment Characteristics.

The impervious lag parameter $K_I$ for each catchment was calculated by averaging values of the parameter derived for each event. Catchment lag parameters were analysed together with catchment characteristics in order to explore possible relations. Storm characteristics were not included in this analysis as the catchments were found to be linear, and this indicated that $K_I$ is independent of storm size.
A relation between $K_I$ and total area $A$, and between $K_I$ and impervious connected area $A_{IC}$ was found, but it only explained 57% of the observed variation in $K_I$. It was noted that although $A$ and $A_{IC}$ varied over three and two orders of magnitude respectively for the sixteen catchments, $K_I$ varied over only one order of magnitude.

The inclusion of catchment surface slope $s$ as a second regression variable did not improve the amount of variation explained by the previous regression equations. The regression coefficients of both area and slope, 0.22 and -0.06 respectively, were very small and this indicated that $K_I$ is not very sensitive to changes in area or slope.

The plots of the residuals of these relations suggested that there were two relations linking $K_I$ to $A_{IC}$ and $s$. The first relation was applicable to the smaller catchments, for which $A_{IC} < 0.1 \text{ km}^2$ and the value of $K_I$ measured from recessions had an upper limit of 600 seconds. The second relation was valid for the larger catchments for which $A_{IC} > 0.1 \text{ km}^2$ and $K_I$ ranged from 600 seconds to 1200 seconds.

Equation 5.30 gave good predictions of $K_I$ for the smaller catchments ($A_{IC} < 0.1 \text{ km}^2$)

$$K_I = 1374.9 \ A_{IC}^{0.7} \ s^{-0.3} \quad (5.30)$$
where $K_I$ is measured in seconds, $A_{IC}$ in km$^2$ and $s$ in m/m.

A similar relation involving $K_I$, $A_{IC}$ and $s$ for the larger catchments ($A_{IC} > 0.1$ km$^2$) explained 94% of the observed variation in $K_I$, but the sign of the regression coefficient of the slope was positive in this relation, contrary to what was expected. Both the coefficients of area and slope were small, 0.22 and 0.16 respectively, which indicated that the sensitivity of $K_I$ to changes in area and slope was very low. Because of this, this regression equation was considered unsatisfactory and other relations, which are described in the following Section, were explored.

8.8 Clusters of Pervious and Impervious Areas

When the catchment values of the impervious area lag parameter $K_I$ were linked to catchment characteristics, equation 5.30 was found to give very good predictions of $K_I$ for the smaller catchments in the data set, for which $A_{IC} < 0.1$ km$^2$. This was not the case for the larger catchments ($A_{IC} > 0.1$ km$^2$), as $K_I$ increased very slowly with increases in area. This suggested that the impervious areas of urban catchments could be organised in clusters. A cluster of impervious areas would be the set of impervious surfaces draining into a particular branch of the drainage system.

The impervious areas in small catchments ($A_{IC} < 0.1$ km$^2$)
would constitute only one cluster, whereas in the larger catchments \((A_{IC} > 0.1 \text{ km}^2)\) there would be several clusters connected in parallel. If the catchment lag parameter \(K_I\) represented the storage characteristics of one of these clusters, rather than of the total impervious area, the parallel connection of the clusters would explain why \(K_I\) remained fairly constant over a wide range of impervious areas.

The size of the individual cluster of impervious surfaces \(A_{1I}\) in each of the larger catchments was estimated with equation 5.30, using the measured value of \(K_I\), and the number of clusters \(N_I = A_{IC}/A_{1I}\) ranged from 2 to 54.

If allowance is made for the small travel times of flow in drainage systems, as compared to overland flow on impervious surfaces, the clusters of impervious surfaces could be represented by identical storages set in parallel. The lag parameter of the set of storages would be equal to the parameter of a single storage, and recessions from this set of parallel storages would exhibit the same value of \(K_I\) irrespective of the number of active storages for a particular event. This would explain why the value of \(K_I\) calculated from individual events was consistent in each catchment.

The size of the cluster of impervious areas \(A_{1I}\) for each catchment was statistically not related to the impervious
connected area $A_{IC}$ or to the catchment slope $s$. This is consistent with the concept of a cluster being a group of impervious surfaces draining into a particular branch of the drainage system, as, in this case, $A_{II}$ would be more strongly linked to the characteristics of the drainage system, particularly to the drainage density, than to the other characteristics of the catchment.

The number of clusters of impervious areas computed as $N_I = A_{IC}/A_{II}$ was related to the first power of $A_{IC}$, and equation 5.34 was proposed

$$N_I = 1 \quad \text{if} \quad A_{IC} < 0.1 \text{ km}^2$$

$$N_I = 10 A_{IC} \quad \text{if} \quad A_{IC} > 0.1 \text{ km}^2 \quad (5.34)$$

where $A_{IC}$ is measured in km$^2$.

8.9 Estimation of Lag Parameters for the Pervious Surfaces

Lag parameters from the pervious areas of the catchments could not be measured from recessions, as was the case for the impervious areas, because pervious area runoff always occurs combined with runoff from impervious areas.

The results presented in Chapter 5 for the impervious areas were extended to the pervious areas of the catchments in
Chapter 6, by suggesting that pervious areas are also grouped in clusters that operate as a set of identical storages in parallel. The size of the pervious cluster was assumed to be equal to the impervious cluster $A_{1I} = A_{1P}$ for each catchment.

The lag parameter $K_I$ for the impervious areas could be well predicted with equation 5.30, by using $A_{1I}$ rather than $A_{1C}$. It was assumed that this relation also holds for the pervious areas, and so the lag parameter $K_P$ for the pervious clusters was estimated with equation 6.3, which is equation 5.30 adapted to the pervious areas by using $A_{1P}$ and Manning’s roughness coefficient for grassed areas.

8.10 Rainfall-Runoff Model

All events were simulated with the rainfall-runoff model presented in Chapters 4 and 7. The model consists of a loss component and a runoff routing component and two branches representing the pervious and impervious areas of the catchment.

The loss model calculates effective rainfall by considering initial losses on the pervious and impervious areas, and by assuming that continuing losses are nil on the impervious areas, and that they are proportional to rainfall intensities on the pervious areas.
The runoff routing component of the model consists of two sets of identical storages in parallel, representing the pervious and impervious areas of the catchment.

The reproduction of observed hydrographs with this model was good, both in terms of the peaks and the overall shapes of the hydrographs. This indicated that the distribution of observed runoff between the pervious and impervious branches of the model is valid. It also confirmed that the runoff routing process in these catchments is linear and that it can be represented with sets of parallel linear storages. The ability of the model to simulate observed storms also indicated that the lag parameters measured from recessions were good estimates of the lag parameters of the impervious surfaces, and it validated the methods used to obtain these parameters.

8.11 Discussion

A set of methods for separating impervious from combined events and for deriving lag parameters from streamflow data was presented in this study. The methods are very simple and straightforward and therefore very easy to apply.

The success in deriving information from the data using these methods relies heavily on the quality of the
available rainfall and streamflow data. If the quality of the data is poor, the methods will tend to give inconsistent results.

Nevertheless, the data needed to apply these techniques is of a relatively low sensitivity to errors. Rainfall and runoff depths and hydrograph recessions can normally be measured with less error than, for example, rainfall intensities or hydrograph peaks. Peak flows are particularly subject to large errors because rating curves are rarely tested for the higher range of flows. Rainfall depths can be controlled with readings of nearby raingauges, and inaccuracies in hydrograph recessions can also be detected during the analysis of data, as was the case in Maroubra, Strathfield and Jamison Park catchments. In all three catchments the shape of the last part of the recessions was suspect and the existence of sediment deposits near the gauging station was thought to be the cause for the anomalous shape. The tendency of sediment to accumulate in the proximity of the gauging stations, and the intrusion of tree roots in the drainage pipes, in the case of Jamison Park catchment, were later confirmed to be the factors that distorted the recessions from these catchments.

The rainfall-runoff model proposed in this study formulates mathematically the behaviour of urban catchments in terms of rainfall losses and of the runoff routing process, based
on observations from rainfall and streamflow data. The model makes allowance for the differences in the behaviour of pervious and impervious areas. This is an advantage over models that do not consider these areas separately, in that this model reproduces reality more closely. If the behaviour of the impervious areas of a catchment, in particular, is well understood and adequately represented, errors in forecasting the effects increases in urbanisation have on the flood hydrograph can be reduced.

The connected impervious area fraction, which is one of the parameters of the model, can be measured on the catchment or, alternatively, it can be estimated from the runoff ratio for small events.

The lag parameter for the impervious areas can be calculated from undisturbed recessions of impervious runoff events. These events can be identified and separated from the combined runoff events by comparing their runoff ratio with the impervious area fraction.

The lag parameter for the pervious areas can be estimated with equation 6.3. The smaller catchments, consisting of only one cluster of impervious areas, will generally have only one cluster of pervious areas, and so $A_{IP}$ will be equal to the total pervious area. For the larger catchments, the size of the pervious and impervious clusters were assumed to be equal.
All the parameters of the model can, therefore, be calculated directly from rainfall and streamflow data, with the exception of the lag parameter for the pervious areas, which cannot be measured from hydrograph recessions.

The simulation results using the model without calibrating its parameters are very good, and this indicates that both the conceptual background of the model is correct and that the methods used for obtaining the model's parameters are adequate.

The fit of some of the storms presented in Volume 2 could be improved if the lag parameters of the model were adjusted. It must be noted that improvements in the reproduction of peaks could be accompanied by poorer fits in the overall shape of the hydrograph. The improvements are, nevertheless, bound to be marginal, as the model with uncalibrated parameters explains a large proportion of the total variance observed in the rainfall-runoff process of the analysed catchments.