Effects of urbanisation on floods

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A thesis submitted in fulfilment of the requirements for
the award of the degree

DOCTOR OF PHILOSOPHY

from

THE UNIVERSITY OF WOLLONGONG

by

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INTRODUCTION

The transition of a catchment from an initially natural or rural condition to an urban environment involves dramatic changes to water and soil resources on a time scale which is an order of magnitude different to most natural processes. As MacPherson (1975) pointed out, natural changes generally occur in a timescale of eons while man can modify the environment in a number of ways in a matter of years.

Changes to the hydrological regime due to urbanisation processes have been comprehensively described by Savini and Kammerer (1961). They analyse the hydrological effects of changes in land and water use associated with the different stages of urban development. Most of the described modifications to the natural or rural environment have some degree of impact on the flood hydrograph, but the alteration of catchment surfaces and the modification of the natural drainage system have by far the most important consequences.

Catchment surfaces are modified initially by the removal of vegetation and the disturbance of the topsoil. This modifies the patterns of interception, evaporation and transpiration and the infiltration capacity is generally reduced because the compacting of the top layers of soil
blocks or destroys interflow paths. Further changes are introduced when originally pervious surfaces are built up and made impervious. Infiltration is reduced, and rainfall that would originally have replenished the groundwater storage, becomes surface runoff. The texture of surfaces is also modified. Smoother and more uniform surfaces replace rougher natural surfaces. As a consequence of this, the velocity of surface runoff is increased.

The stream network in a natural catchment is the result of the dynamic equilibrium between climatic conditions and the characteristics of the surfaces drained by the network. This network varies seasonally in its extension. The modification of catchment surfaces implies that a different drainage network must be created in order to accommodate the new conditions in which runoff is generated. Modifications to the drainage network can take different forms, according to the stage of urban development. In the initial stages, when the extent of the modified surfaces is still small, the natural streams can be cleared of vegetation, their layout can be rectified and their cross sections made regular and enlarged, to achieve a higher conveyance. In later stages the streams will be lined and finally the drainage system will be partially or totally replaced by a network of underground pipes. This can be clearly seen if suburban areas in different stages of development are compared, and if they are in turn compared with central city areas. In the outer suburbs the main
streams can be left in a nearly natural condition and the adjacent floodplains are free of buildings. In the areas closer to the city the cost of the land will dictate a more intensive utilisation, and so the surface area assigned to the drainage system will be reduced. In these areas the floodplain will be built up and the drainage system will consist of a pipe network. Urban dwellers will tend to forget the former existence of streams except when a rare rainfall event produces flooding.

As mentioned above, the factors that generate increased flooding in urban areas are mainly the sealing of formerly pervious surfaces and the modifications introduced to the drainage system. The proportion with which each factor contributes to the increase in flooding is not easy to measure, as the construction of buildings and the changes in the drainage system are generally introduced simultaneously. Packman (1979) suggests that the sealing of surfaces and therefore the reduction in the time of travel of flow on these surfaces will have a larger impact in the case of small catchments, because surface flow is the process that has longer times as compared to channel flow. The reverse would be true for larger catchments, where channel improvements will account for substantial reductions in the times of travel.

In this study, the hydrological processes that are relevant to the generation of floods in urban areas have been
identified and analysed. The underlying criterion has been to extract as much information as possible on these processes from the analysis of recorded rainfall and streamflow records. Working hypotheses were introduced only on the basis of observation from these data when this first source of information was exhausted. This approach was preferred to the alternative one of proposing a theoretical model and testing it against available data. The volume of good quality rainfall and streamflow data currently available for Australian catchments seemed to warrant that an approach without preconceptions to the analysis of these data could lead to the understanding of the relevant processes involved in the formation of floods.

Cordery and Pilgrim (1979), after reviewing design methods for small hydraulic structures, commonly used in Australian agencies, pointed out the need to develop predictive tools for Australian conditions. They noted that these design procedures have been developed for different environments and have not been validated in Australia. Because the conclusions in this study rely heavily on the analysis of data, it is hoped that they will contribute towards the assessment of flooding in Australian urban catchments.

Data from ten Australian and six overseas urban catchments were collected from stream gauging agencies, and the rainfall-runoff process in each of them was studied and characterised. The joint analysis of the catchments showed
that although they have different geographical and climatological features, there are similarities in their behaviour. Those aspects of the rainfall-runoff process that were found to be common to all catchments were formulated mathematically in a model, and methods to estimate the model’s parameters from catchment characteristics were proposed.

The layout of this thesis is explained in the following paragraphs.

In Chapter 1, studies that have analysed flooding in urban catchments are reviewed. Particular attention is given to the way that pervious and impervious areas were treated in these studies, both in terms of rainfall losses and the routing of runoff. In the last Section of this Chapter some of the most relevant Australian urban studies are reviewed.

The data used in this study is presented in Chapter 2. The general characteristics of the urban catchments studied are discussed in the first Section and then each one of the catchments is described. This description includes their physical characteristics, details of the gauging instruments and a summary of the storm events analysed.

The analysis of rainfall and runoff depths for each catchment is presented in Chapter 3. From the study of event rainfall and runoff depths and by considering the
extent of the impervious areas in each catchment, all the events studied are separated into impervious area runoff events and combined events, where both the pervious and impervious areas of the catchment generate runoff. The joint analysis of the catchments is presented in the last Sections of this Chapter and the similarities found in the generation of runoff in all the catchments are described.

Results from the analysis of rainfall and runoff depths discussed in Chapter 3 are formulated mathematically in Chapter 4. In this Chapter, a loss model that simulates the generation of surface runoff on the pervious and impervious areas of urban catchments is presented.

In Chapter 5, the catchments are analysed as systems that store surface runoff temporarily, and the main characteristics of these systems are identified. The storage behaviour of the impervious areas of the catchment is analysed by studying storm events which only generated runoff from these areas. In this way, the flood response of the impervious areas could be studied in isolation from the pervious areas of the catchment. Particular attention is given to the recessions of observed flood hydrographs and, from their analysis the parameters for the routing of runoff on the impervious areas are derived. Catchment lag parameters derived in this Chapter are linked to catchment characteristics and relations between the impervious area lag parameter and catchment area and slope are presented.
In Chapter 6, the storage characteristics of the pervious areas of the catchment are discussed. Pervious area lag parameters are estimated by extending to these areas the relations derived for the impervious areas in Chapter 5.

The storage characteristics of the pervious and impervious areas of urban catchments analysed in Chapters 5 and 6 are formulated mathematically in a runoff routing model in Chapter 7. All the storm events analysed in this study are simulated with a rainfall-runoff model consisting of the loss model presented in Chapter 4 and the runoff routing model proposed in this Chapter. Results from the simulation are discussed in this Chapter and plots of the observed and simulated hydrographs are shown in a separate Volume. Sensitivity tests of the model’s parameters are also presented in this Chapter.

In Chapter 8 the main conclusions derived from the previous Chapters are presented and discussed.

Some of the data that are referenced in different parts of this thesis are presented in summarised form in the text. The complete data is shown in Appendices.